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Energy transfer in ballistic perforation of fibre reinforced composites

E. P. GELLERT, S. D. PATTIE, R. L. WOODWARD
DSTO Aeronautical and Maritime Research Laboratory, P.O. Box 4331, Melbourne, Victoria 3001, Australia
E-mail: evan.gellert@dsto.defence.gov.au

High speed cine techniques have been used to examine the perforation of thin targets constructed of glass fibre reinforced plastic (GRP), Spectra (Allied Signal) and Kevlar (Du Pont) composites as well as nylon and Kevlar fabrics. From the film record the kinetic, strain and (for the composites only) delamination/surface energy terms were evaluated for the rear layer of material. Simple models for the deformation of the panels were used to compare these energies, summed for all layers, with the projectile energy loss. All the energy terms are shown to be significant. The Kevlar fabric does not fit the pattern of the other materials, in that for this material nearly all the projectile energy appeared as tensile strain energy in only the rear layer of the target. This result was a consequence of the high apparent strain observed in the fabric, and is not simply explained. Energy terms not evaluated, but which may be significant, are crushing and ejection of fibres for GRP composites and spalling of matrix phase with the Spectra composites. The work highlights many of the features which need to be accounted for in modelling ballistic perforation of fabric and fibre reinforced composite materials.

1. Introduction

Since World War II, synthetic textiles and impregnated glass fibre laminates have been used to protect personnel against ballistic threats [1]. Progress with the commercialization of fibres and resins has seen glass reinforced plastic (GRP), Kevlar, nylon 66 and polyethylene used in personal armour vests, helmets, pilot seats and spall liners, particularly where irregular fragments are the defined threat. Studies of ballistic penetration of fabrics and composites have examined fibre response [2, 3], mechanisms of deformation [4, 5] and failure [6, 7] as well as energy absorption [7–11]. Despite elucidating many characteristic features of fabric and composite behaviour, no single model has emerged which allows a quantitative description of the processes. This is partly a consequence of the vast difference in behaviour between fibre types and between fabric and composite constructions.

It is clear that deformation processes change as the projectile proceeds through a target [4], the early phase being dominated by acceleration of target material, compression and crushing ahead of the projectile, and shear. The latter stages are characterized by stretching of fibres, delamination and dishing which continues during and after perforation. In order to better understand the early phase of target compression, earlier work has focussed on thick targets [5]. In the present study thin targets were used to minimize the aspect of compression and acceleration of a large mass of material directly ahead of the projectile, thus emphasizing the response expected from the rear face of a composite target which may include the acceleration of a broad dish of material. The process is considered to be a rigid-body penetration for the composite and fabric targets.

High speed cine photography was used to examine target response, and the target energy absorption as fibre stretching, delamination and kinetic energies were estimated. A range of fabric and composite types enabled comparisons of the principal features of the deformation and failure processes.

2. Experimental procedures

The composites and fabrics for ballistic testing are described in Table I. All targets were 300 mm squares of woven fibre either impregnated with Derakane 8084 vinylester resin (Dow), or stitched along one axis at line spacings of 30 mm. The composite panels were hand layed-up by brush-impregnating successive plies, then curing the panel at ambient temperature in a press at a 2 MPa pressure. The samples were then post-cured for 1 h at 90 °C and 2 MPa.

The ballistic testing was undertaken using 5.59 mm diameter (0.22 inch Calibre), 1.1 g mass fragment simulating projectiles [12]. The projectiles were fired from a gas gun at velocities just above the ballistic limit determined for nominally identical targets. The ballistic limit is the velocity at which the projectile is equally likely to undergo complete penetration or

TABLE I Composite material and fabric details

Material	Fabric	Resin	Number of plies	Nominal ply weight ($g\,m^{-2}$)	Thickness (mm)	Areal density ($kg\,m^{-2}$)
E-glass composite	Woven roving E-glass Style AR 106	Derakane 8084	11	630	4.7	8.1
Kevlar composite	Kevlar 29 Style 735	Derakane 8084	14	480	7.3	8.1
Spectra composite	Spectra 1000 TrtA	Derakane 8084	20	200	7.0	5.5
Kevlar fabric	Kevlar 29 Style 735	–	14	480	9.1	6.6
Nylon fabric	Courtauld ballistic nylon, plain weave 14 ends, 13 picks	–	20	285	9.2	5.7

TABLE II Composite and fabric ballistic performance and tensile ductility

Material	Ballistic limit ($m\,s^{-1}$)	Tensile fracture strain	Apparent maximum strain in ballistic impact	Tensile strength (MPa)
E-glass composite	356 ± 14	0.021	0.036	308
Kevlar composite	458 ± 10	0.052	0.063	400
Spectra composite	366 ± 14	0.074	0.045	750
Kevlar fabric	474 ± 5	0.035	1. 0.15 2. 0.18	1200
Nylon fabric	422 ± 5	0.21	1. 0.195 2. 0.16	365

TABLE III Energy data from ballistic tests

Material	Projectile			Penetration	Target energy term (J) Rear layer (whole-target summed as Fig. 2b)		
	Velocity ($m\,s^{-1}$)	Kinetic energy (J)	Kinetic energy loss (J)		Strain	Kinetic	Delamination
E-glass composite	370	75.3	68.2	Yes	2.5 (27.5)	1.2 (13.2)	1.5 (15)
Kevlar composite	475	124.1	115	Yes	6.3 (88.2)	4.0 (56)	1.3 (16.9)
Spectra composite	390	83.7	79	Yes	3.0 (60)	1.3 (26)	< 0.9 (< 17.1)
Kevlar 1.	466	119.4	119.2	No	74.5 (1043)	0.4 (5.6)	–
Fabric 2.	476	124.6	123.8	No	54.1 (757)	0.5 (7)	–
Nylon 1.	427	100.2	99	No	7 (140)	0.8 (16)	–
Fabric 2.	441	107	78	Yes	3 (60)	1.8 (36)	–

incomplete penetration. The composite panels were clamped with metal strips, and the fabric targets were bolted and clamped about the perimeter in such a way to ensure minimum interference with the camera field of view. A high speed cine camera was used to observe a silhouette of the rear of the target during penetration, and the free flight of the fragment simulating projectile after perforation. From measurements taken from consecutive frames it is possible to calculate the kinetic energy of the moving rear layer of the target. From the diameter of the bulge, the area of delamination could be estimated and combined with the fracture toughness, (strain energy release rate in opening mode, G_1) to give a delamination energy value. The fibre strain energy was calculated from the profile by assuming the fibres were stretched across the deformation cone in two orthogonal directions.

3. Results and discussion

Table II gives values of the ballistic limit for the composites, the tensile fracture strain (quasi-static) and the apparent maximum strain obtained from the deformation cone profile in the ballistic tests. In Table III are presented the energy data obtained from analysis of the high speed film. In some cases firings were repeated, and the calculated energy data were consistent for the repeated shots. For the high-speed film record, perforations were achieved for all material types except for the Kevlar fabric despite firing at above its ballistic limit.

For the calculation of kinetic energy of the rear layer of material, the deformation cone was divided into 10 to 15 annular segments of equal radial increment. The mass of each segment was calculated from the geometry and material area density per ply, and the velocity of each segment was calculated from the displacement between successive frames of the high speed film.

Values of bond strength between the plies, in terms of the strain energy release rate G_1, for the calculation of delamination energy, were known from earlier mechanical tests on E-glass and Kevlar composites, but not for the Spectra, for which a value less than for Kevlar was assumed.

The strain energy in the deformed material was calculated using the elastic modulus of the composite, or of the fibre in the case of the fabrics, and the measured fibre strain to deduce an energy per unit volume. The tensile strain in the fibres varies from a maximum value in the plane through the axis of the cone to zero at the edge and this was accounted for in calculating an average strain energy per unit volume in the deformed material. Fibre extension was obtained from the geometry of the cone.

As Table II shows in some cases the apparent maximum strain in the ballistic test is greater than the material measured (quasi-static) tensile fracture strain. For cases in which this did not occur, the measured strain from the cone geometry was used with the area of the cone and the layer thickness to calculate total strain energy. However, where the apparent maximum strain exceeds the tensile fracture strain it was assumed that the latter figure limits the maximum achievable strain, and that tensile strain in the fibres extends beyond the area of the cone, as has been observed experimentally [2, 3]. In this case the radius from the impact point to which the deformation extends, l, is given by:

$$l = R\varepsilon_A/\varepsilon_T \quad (1)$$

where R is the radius of the deformation cone, ε_A is the apparent maximum strain in the ballistic test and ε_T is the maximum strain in tension.

The form of the deformed region, as required by this fibre deformation illustrated schematically in Fig. 1, is then a cross rather than a cone, and deformation in this form is typically observed in penetration of oriented fibre composites [4, 13–15].

For the ballistically impacted Kevlar 29 yarn the form of the stress/strain curve was linear to fracture, so that the strain energy per unit volume was one half the product of stress and strain. For the nylon yarn the stress/strain curve was bi-linear and this was taken into account in the calculations which treated the strain as elastic. Errors in measuring target deformation from the film frames and the approximations used to estimate the area of the deformation zone will mean that the target energy term data given in Table III is approximate only.

Tables I and II show that, as expected, the fabrics perform better in terms of ballistic limit on an areal density basis than do the composites. Table III suggests that this is achieved by absorbing a higher proportion of the energy as tensile strain energy rather than as kinetic energy. For fabrics the delamination energy term is zero. Table III also shows that for the composites, the kinetic and delamination energy terms are significant if account is to be taken of all the energy removed from the impacting projectile, and these

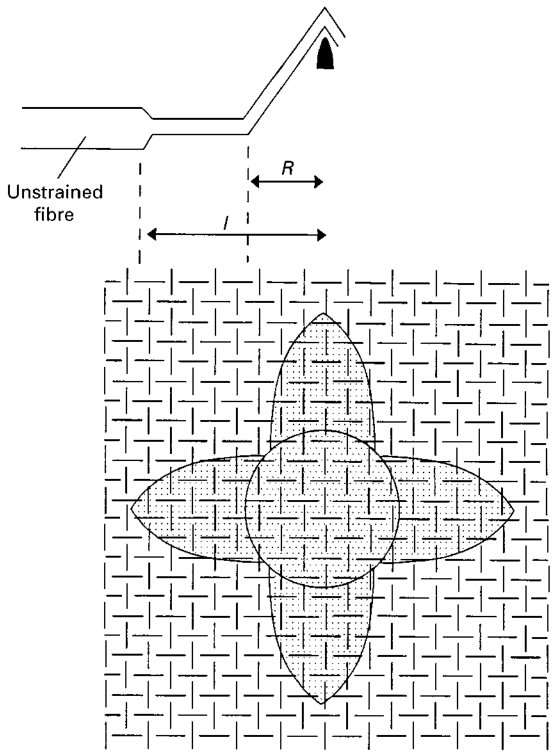
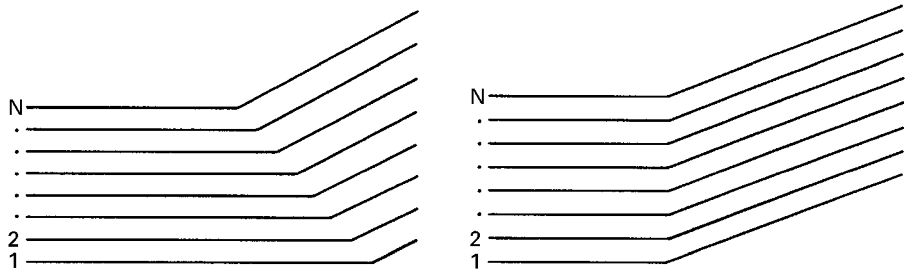


Figure 1 Zone of principal deformation (cross shaped) observed in woven fibre composites under point impact normal to the fabric plane.

terms then, should be included in models of composite perforation. Except for Spectra, these results are generally consistent with those of Zee and Hsieh [8], who also consider matrix fracture and friction, but do not include composite kinetic energy. The work of Zhu *et al.* [6] did not attribute significant absorption of energy to the delamination mechanism for a Kevlar composite. There is some interchange between energy terms as the kinetic energy is dissipated in matrix fracture and fibre strain energy until the motion ceases, and for some composites fibre and matrix fragmentation is important, as discussed later with reference to film evidence.

Fig. 2 (a and b) presents two simple postulates for the nature of the deformation; either the radius to which deformation occurs increases with thickness, Fig. 2a, or it is nearly constant through the thickness, Fig. 2b. In any real system the outcome is expected to be somewhere between these extremes, however delamination at the exit side should be greater largely because there is diminishing restraint to crack opening as the projectile approaches the exit side, and this is generally observed to be the case.

The laws for summing energies, assuming similarity between layers, are given in Fig. 2 (a and b), and using these with the data of Table III, the total of the energy components can be compared with the kinetic energy lost by the fragment. This suggests that the model with the radius of deformation independent of thickness is a better approximation in allowing a reasonable energy balance for these thin targets. The Kevlar fabric, as Table III shows, gives an anomalous result in that a large amount of kinetic energy of the projectile has been translated to strain energy of the one rear layer of the target. The Kevlar fabric case fits neither model.



$$\sum E_{\text{Kinetic}} = E_{N\ \text{Kinetic}} \sum_{1}^{N} \left(\frac{n}{N}\right)^4 \qquad \sum E_{\text{Kinetic}} = N E_{N\ \text{Kinetic}}$$

$$\sum E_{\text{Strain}} = E_{N\ \text{Strain}} \sum_{1}^{N} \left(\frac{n}{N}\right)^2 \qquad \sum E_{\text{Strain}} = N E_{N\ \text{Strain}}$$

$$\sum E_{\text{Delamination}} = E_{N\ \text{Delamination}} \sum_{1}^{N-1} \left(\frac{n}{N}\right)^2 \qquad \sum E_{\text{Delamination}} = (N-1) E_{N\ \text{Delamination}}$$

(a) (b)

Figure 2 Deformation of successive plies in a point-impacted multi ply construction idealized to (a) radii of deformation increasing through the thickness or (b) radii of deformation constant through the thickness. Respective energy terms are given.

The strain energy term in the final layer of Kevlar fabric is high as a consequence of the high apparent strain in the deformation cone, even though the use of the model of Fig. 1 in calculating total strain energy reduced the total strain energy term compared with assuming all the strain was accommodated in stretching within the observed cone of deformation. The approach is consistent with the experimental observations of Petterson *et al.* [2] and Jameson *et al.* [3]. In doing the calculations according to the model of Fig. 1 the maximum strain was taken as the yarn quasi-static tensile fracture strain. This is consistent with elongations of Kevlar fibres being comparable, at quasi-static and ballistic strain rates [16]. If the apparent strain is used for the calculations, then the strain energy in the rear layer of fabric is found to be much greater, even though distributed over a smaller area.

There are two possibilities to explain the result with Kevlar. The first is that the actual fibre strain in the ballistic test is much less than the fibre tensile fracture strain measured quasi-statically and that the radial extent of straining is much further from the cone base. However for this explanation to give similar strain energies to those observed in the other material combinations requires an unrealistically low fibre strain, less than 0.01. The second possible explanation is that on rupture of the impact side layers of the Kevlar fabric, most of their absorbed kinetic and tensile strain energy is dumped into the rear layer, so that the calculated strain energy in this rear layer does actually reflect most of the initial projectile kinetic energy.

In neither case for the filmed ballistic tests of the Kevlar fabric did the fragment perforate, and for nylon it was observed that when perforation did not occur the strain energy was greater, although only by a factor of two, see Table III. It is not possible to completely interpret the Kevlar fabric behaviour from the evidence gained from these tests, however the second possible explanation does at least accord with conservation of energy requirements.

Some further insight into mechanisms can be obtained from careful examination of the high speed cine film and selected frames for each material are shown in Fig. 3(a–e). In the perforation of the E-glass (GRP) composite, Fig. 3a, the ejection of fragmented glass and matrix material is seen. The energy of fragmentation and the residual kinetic energy of this debris has not been accounted for in our calculations, however Greaves [17] has identified this as important in the initial stages of perforation of GRP composites. Some fibres are seen ejected from the Kevlar composite target of Fig. 3b, however this is less noticeable than with the E-glass composite.

Continued radial expansion of the deformed cone for the Kevlar composite after perforation, is evident in Fig. 3b. The Spectra composite also shows this continued radial expansion following perforation, which appears to be accompanied by a cloud of ejected resin projected away from the rear surface, Fig. 3c. It was not possible after the event to identify the area of resin matrix material detached. Nevertheless, the cloud of ejected material was considered to result from a weak fibre/resin bond in the Spectra composites.

The higher apparent strain for the Kevlar fabric when compared to the Kevlar composite is seen from Fig. 3(b and d). The nylon fabric had a high cone angle before perforation, Fig. 3e, and this was maintained for the case where the fragment did not penetrate. After perforation the peak of the cone collapsed in recovery, but the deformed zone continued to expand radially, an indication that the tensile strain extended

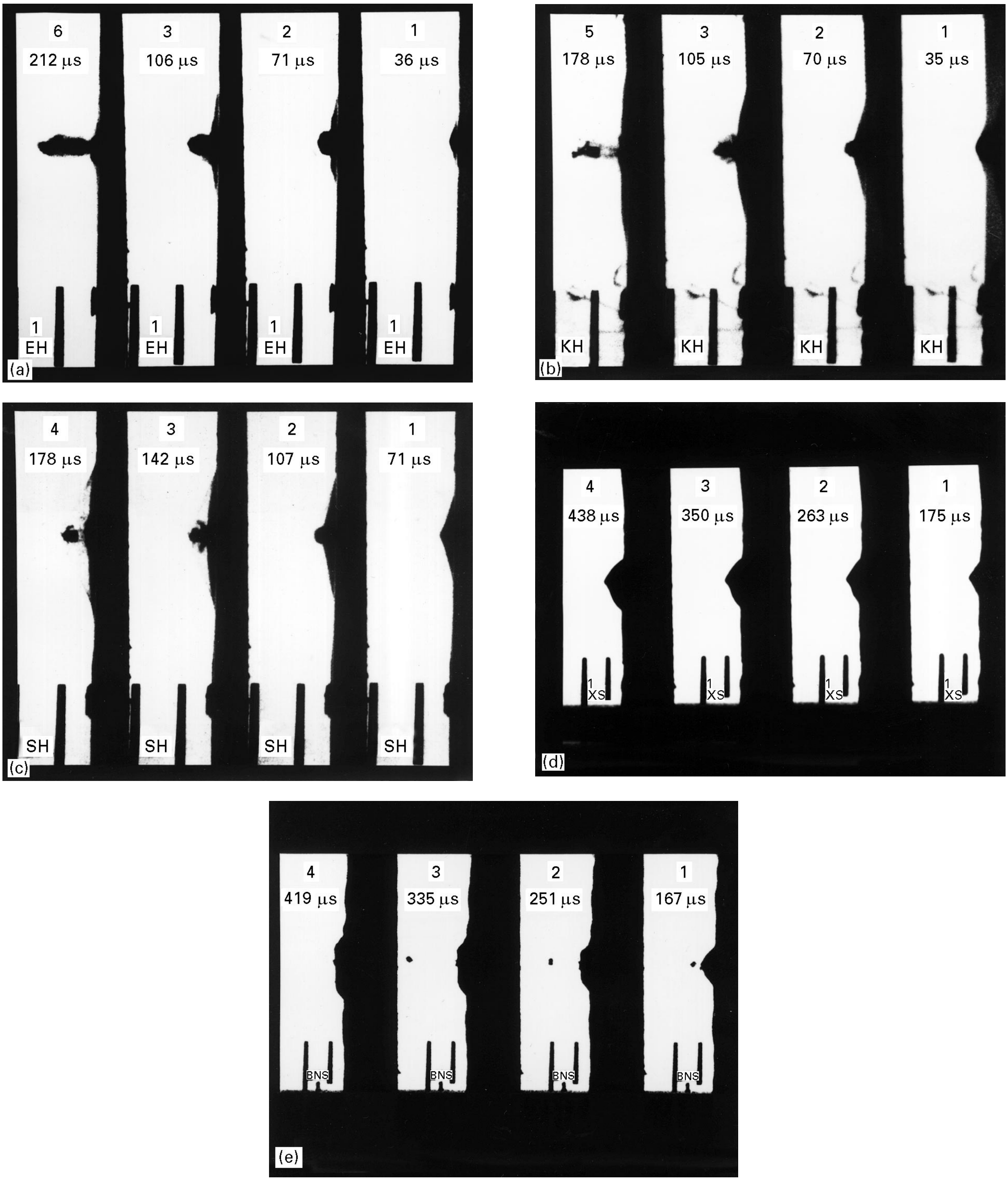


Figure 3 High speed cine frames showing deformation of the target backface with trajectory from right to left through the frame centres. The targets are (a) E-glass composite (GRP), (b) Kevlar composite, (c) Spectra composite, (d) Kevlar fabric and (e) Nylon fabric are shown over four frames indicating the time after impact (μs).

well beyond the cone, consistent with the model of Fig. 1, otherwise the stretched fibres would just be pulled flat in recovery.

4. Summary

This work has sought to understand the perforation of fibre composite and fabric materials for ballistic protection in terms of the energy absorbed as strain energy, delamination energy and kinetic energy. Each of these terms is shown to be significant. Examination of high speed film illustrates fibre fragmentation and ejection, and post perforation fabric recovery effects. For these thin targets, a model assuming each layer deforms to a similar extent laterally, and delaminates to this extent for the composites, allows the sum of the energy terms to be of the correct magnitude compared to the energy lost by the projectile. For the Kevlar fabric an anomalously large strain energy is observed in the rear layer of fabric, however, the present results are not sufficient to explain this effect. The apparent strain in the deformed cone suggests in some cases that fibres are in tension to a radius beyond the deformed cone, particularly for the case of the Kevlar fabric.

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