Special Issue Article

JSA

J Strain Analysis
47(7) 396–405

DOI: 10.1177/0309324712448298
sdj.sagepub.com
SAGE

The impact of structural composite materials. Part I: ballistic impact

Paul J Hazell[1] and Gareth J Appleby-Thomas[2]

Abstract

Composite materials are increasingly being used in the design of structures that will be subjected to high-velocity impact during their lifetime. In this review we will look at the recent advances in our understanding of how rigid composite materials behave under high-velocity impact. In particular, this review will focus on rigid structural composites such as carbon fibre reinforced plastic and glass fibre reinforced plastic laminates and what we have learned with regards to how they respond under ballistic-loading conditions. We will focus on a velocity regime that includes impacts from explosively-driven fragments, ice particles and bullets. The hypervelocity-impact response and how these materials behave under one-dimensional shock loading will be studied in an accompanying review (Part II).

Keywords

Impact, composites, ballistic, failure

Date received: 29 November 2011; accepted: 23 April 2012

Introduction

There exists a large body of work examining the low-velocity impact regime of composite targets. These have been thoroughly summarised in a number of reviews[1–6] with more limited contributions given over to high-velocity impacts.[2,3,4,7] These latter-mentioned reviews were carried in the 1990s and cover many of the salient papers on the impact of composites. Given the growing threat to structural composite materials to high-velocity impacts from improvised explosive devices, man-portable air defence weapon systems, guns, space debris and meteorites there has been an evolving body of work that has occurred in recent years. Therefore, it is timely to address specific reviews on the high-velocity impact, penetration and shock behaviour of rigid composite materials. In this review we will focus on the ballistic response of rigid composite materials. Consequently, results where the impact velocity is less than 2 km/s are of interest with the majority of research papers focussing on velocities in the range of 300 m/s to 1000 m/s. Higher velocity impacts will be considered in the accompanying review.

To study the terminal-ballistic behaviour of composite materials, a projectile is typically accelerated towards the target using a gas gun (or propellant-based gun) of some description. Such guns work by generating a driving pressure behind the projectile whether by the sudden release of a gas contained in a high-pressure reservoir (such as helium or nitrogen) or by burning propellant in a breech. The driving pressure accelerates the projectile to its target. Occasionally, it is prudent to use a saboted projectile to achieve higher velocities or where different projectile geometries are studied using the same apparatus. The projectile maybe stripped from the sabot using a sabot stripper allowing the projectile to carry on towards the target. As composite materials can be particularly sensitive to impact damage, care is taken in ensuring that the stripped sabot does not impinge on the target. A suitable velocity system is employed to record the velocity of the projectile which may involve the use of two spatially separated optical light-gate systems connected to a timer. The response of the target is commonly interrogated using high-speed video imaging.

Usually there is some measure of the ballistic limit of the laminate. This is typically defined as the velocity at which perforation (or complete penetration) of the laminate only just occurs. Occasionally, the ballistic

[1]School of Engineering and Information Technology, University of New South Wales, Australia
[2]Cranfield Defence and Security, Cranfield University, UK

Corresponding author:
Paul J Hazell, School of Engineering and Information Technology, UNSW Canberra, University of New South Wales, Northcott Drive, Canberra, ACT 2600, Australia.
Email: p.hazell@adfa.edu.au

limit is defined by establishing a V_{50} velocity as is commonly done with military armour systems.[8,9] The V_{50} defines a velocity at which there is 50% probability of partial penetration and 50% probability of perforation of a specific target. It is usually evaluated by using an experimental range where the velocity of the bullet can be measured and is able to be varied by virtue of changing the gas pressure or mass of propellant used. In the establishment of a V_{50}, the velocity of the projectile is varied until the target is perforated by a number of separate projectiles at velocities that all lie close to the velocities of several bullets that did not perforate the target. The mean velocity of the bullets is known as the V_{50} velocity.

Carbon fibre based composite materials

Carbon fibre composite materials have been used extensively in a wide variety of applications in recent years from bicycle frames to bridges. They have also been found to be very useful in the design of aerospace structures and recently there have been a number of aircraft that have been mostly made from these materials (e.g. the Boeing 787 Dreamliner). Consequently, it is likely that most, if not all, of the next generation of civil and military aircraft will be manufactured from carbon-based composite structures (e.g. see Soutis[10]). The reason for their use in aerospace structures is clear: they have excellent stiffness properties as well as good tensile properties whilst their bulk densities are relatively low (ca. 1.5 g/cc). Carbon fibres in particular have very good stiffness and strength values with the tensile modulus reaching as high as 1000 GPa and tensile strengths reaching values of 3.8 GPa (e.g. Amoco Thornel K-1100X[11]). They also possess a very low (in fact, slightly negative) coefficient of thermal expansion as well as good thermal and electrical conductivity.

However the response of carbon fibre composite materials to impulsive loads is known to be poor and this is due to the brittleness of the epoxy resin and the low strain-to-failure of the carbon fibres ($< 1\%$) leading to a poor trans-laminar strength. This is true whether the impulsive load is from a low-velocity impact such as when a tool is dropped onto the laminate[4] or from a high-velocity impact such as the release of a blade from an engine onto the engine casing; runway debris striking the underside of wing structures; high-velocity ice impacts[12] or where a fragment from an anti-aircraft munition impacts the structure of the aircraft e.g. see Taylor et al.[13]

Most high-velocity studies with carbon fibre reinforced plastic (CFRPs) to date have been done using single specimens of relatively thin laminates that offer very little protection against high-velocity projectiles. These studies have shown that they provide very little protection against high-velocity threats.

Penetration and failure mechanisms

Despite carbon fibre laminates finding their way into military aircraft structures as early on as the 1960s, it took an additional 15 or so years for extensive studies on these materials' high-velocity impact response to be published. Early published works of Cantwell and Morton[14–17] and Cantwell[18] showed a number of facets to the high-velocity impact response of these materials. Through a series of impact experiments they have shown that high-velocity impacts generate large areas of matrix cracking, fibre fracture and delamination within the target. With relatively low impact energies, where the projectile was a 6-mm diameter steel sphere, they showed that damage initiated at ply on the rear side of the target due to flexural action. In thicker, stiffer targets, damage occurred in the uppermost plies caused by the large contact stresses around the projectile. In further studies they showed that increasing the velocity of the projectile resulted in a localised response to the target which is somewhat different to low-velocity impacts where the areal geometry of the target is important.

The analysis of the failure modes carried out by Cantwell and Morton[16,17] on perforated samples revealed the formation of a conical-shaped shear plug. This resulted in a shear surface extending away from the point of contact at approximately 45°. They suggested that three energy-absorbing mechanisms are active during low-velocity impact, namely; elastic flexural response of the target, delamination and target shear out. For high-velocity impact, the elastic flexural response of the target can be ignored[17] due to the failure occurring at a more localised level.

For both low-velocity and high-velocity impact conditions they assumed that the shear surface area formed by the penetrating projectile was given by

$$A_s = \sqrt{2}\pi t(t + 2r) \tag{1}$$

where t is the target thickness and r is the projectile's radius. To estimate the energy required to shear out the material, the transverse fracture energy was measured by applying a shear force to a coupon using a universal testing machine and measuring the load-displacement response; the energy required to cause fracture was then calculated by measuring the area under the resulting curve. They estimated that the transverse fracture energy was 37.25 kJ/m^2 for a four-ply $(\pm 45°)_s$ carbon fibre composite. For both the low and high-velocity impact examples, this simplified analytical model based on energy conservation appeared to work well. However, the authors pointed out that there was a disparity in the results for the higher velocity impacts against relatively thick laminates. This was due to a change in penetration mechanism that resulted in the model predicting a greater shear zone than there actually was.

Further approaches to modelling these materials have been presented by Lee and Sun[19] who used static punch tests as a basis for modelling the penetration of a CFRP material. Like Cantwell and Morton, they applied quasi-static data from punch tests to predict the failure under ballistic loading conditions with good results. In their work, they used computational approaches to predict the ballistic limit assuming that the composite behaved as a homogeneous, transversely isotropic continuum. Using quasi-static data to predict dynamic penetration results suggests that strain-rate induced strengthening effects have little influence on composite penetration despite the resin matrix exhibiting strain rate sensitivity.[20] However, it should be pointed out that there is little agreement as to whether polymer composite structures exhibit strain-rate sensitivity.[21]

Caprino et al.[22] compared the results from a simplified Cantwell–Morton model to that of a model developed by a Reid and Wen.[23] In this work, the Reid-Wen model used a different approach to establish the critical energy to achieve perforation of the laminate. They attributed perforation to the magnitude of the contact pressure at the projectile–surface contact. The contact pressure was decomposed into two parts: (a) the static resistive pressure, given by the static linear elastic compressive limit of the laminate in the through-thickness direction and (b) the dynamic resistive pressure, arising from strain-rate effects. Of the two models that Caprino et al. studied they showed that when compared to empirical data, the Reid and Wen model was effective in predicting the influence of panel thickness on the perforation energy but failed to account for the projectile's diameter. Whereas, the Cantwell–Morton model yielded a good estimate of both the perforation energy and the residual velocity as a function of the target thickness and projectile diameter.[22]

At higher velocities[24] it appears that these materials become extensively particulated and the effect of the delamination on the projectile's kinetic energy absorption becomes negligible. The sequence of events for a high-velocity projectile striking a target at 1199 m/s is shown in Figure 1. As the projectile contacts the CFRP material, light is emitted (frame B). At 125 μs a plume of particulated CFRP material has been formed, the forward front of which precedes the projectile. Simultaneously, material is seen to have been ejected backwards from the impact surface. At 187.5 μs the projectile starts to emerge from the cloud of dust. At 250 μs (frame E) the projectile is clearly defined. The large fragments formed maintain a velocity similar to the projectile (c. 1062 m/s) whereas the large volume of lighter-weight particles is slowed. By 312.5 μs (frame F) the lighter-weight particles have decelerated substantially and are moving with an average linear velocity of 200 m/s.[24]

The percentage of kinetic energy absorbed by the laminate appears to reach a plateau at elevated velocities, that is, for 5HS woven laminates at least. Figure 2 indicates the percentage change of kinetic energy due to the perforation of a 6-mm thick CFRP laminate. Here, the maximum impact velocity was 1875 m/s. It can be seen that above an impact energy of ca. 2000 J, the percentage KE of the projectile that is absorbed is constant. This work also showed that the level of delamination in the sample was roughly constant implying that at increased impact velocities, the majority of the energy that is dissipated in the CFRP laminate is from

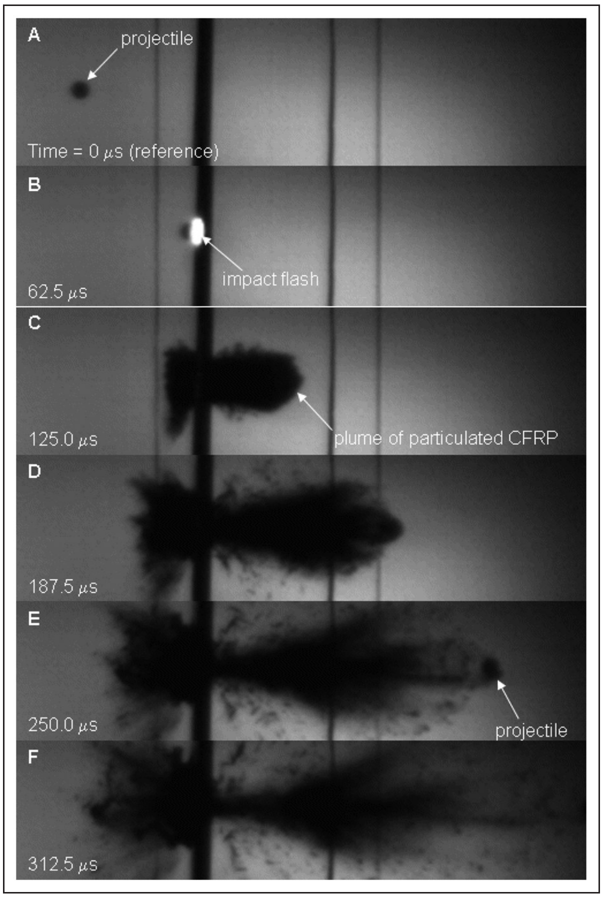

Figure 1. High-speed video images taken at 16,000 frames-per-second showing the perforation of a 6-mm CFRP laminate; impact energy = 5150 J (1199 m/s); after 24. CFRP: carbon fibre reinforced plastic.
Reprinted from Hazell et al.[24] with permission from Elsevier.

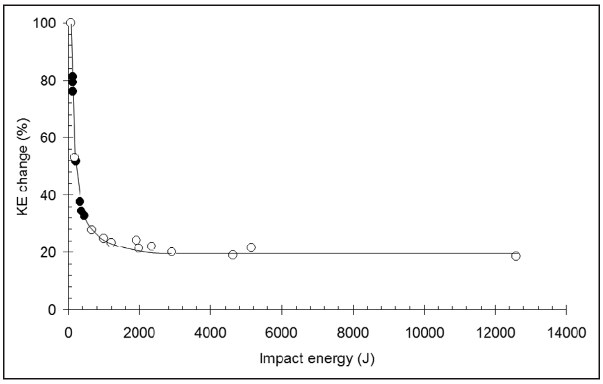

Figure 2. Percentage change in KE due to the perforation of a 5HS 6-mm thick CFRP laminate; the different shading in data points indicates two separate experimental trials; after Hazell et al.[24]
KE: kinetic energy.
Reprinted from Hazell et al.[24] with permission from Elsevier.

the comminution of the CFRP material and in the kinetic energy transferred to the particulated material. Given the low trans-laminar strength of these CFRP laminates and the weakness of the exposed fibres caused by the matrix particulation, the authors concluded that the majority of the projectile energy is given up to the kinetic energy of the particulates.[24]

Relatively few studies have also been done on the oblique penetration of CFRP laminates. Most impacts from high-velocity projectiles will occur with some degree of obliquity and consequently, it is important to understand the effect that obliquity has on a penetrating projectile. Oblique impact studies have been carried out on these materials in the hypervelocity-impact[25,26] and ballistic loading regimes.[27–29] In particular, Lopez-Puente et al.[28] have presented work on the normal and oblique penetration of CFRP laminates using both a gas gun and the finite element commercial code ABAQUS/Explicit. The projectile they used was a 7.5 mm tempered steel sphere. They showed that the maximum damage inflicted by the projectile at the ballistic limit was produced at normal incidence. Furthermore, below the ballistic limit, the extent of damage for normal impact was larger than that for the oblique impact. However, the extent of damage at higher velocities appeared to be greater for oblique impacts. Further oblique work has been presented in Hazell et al.[27] where it was shown that for targets that were impacted at an oblique angle, more of the kinetic energy was transferred from the projectile to the target material when compared to the same thickness of target that was subjected to a normal incidence impact. The authors also showed that this was merely due to a geometrical effect. Thicker panels appeared to behave more efficiently by absorbing more kinetic energy per effective linear thickness at the lower impact energies where petalling was a dominant factor in the penetration. This advantage seemed to vanish as the impact energy was increased. Whereas for high-energy projectiles striking thick composite panels above the ballistic limit (ca. 12-mm thick)[29] it was found that both the energy absorbed per-unit-thickness of laminate and the level of damage as measure by C-Scan was similar when the panels were perforated at normal and oblique incidence.

The effect of fibre type and stacking pattern on ballistic performance

There is a large body of evidence that suggests that the lay-up type and sequence has little effect on the performance of a two-dimensional (2D) laminate when the material is subjected to a high-velocity impact.[27,30,31] This appears to be contrary to what has been observed during low-velocity impact where woven laminates appear to offer advantages[32–35] and where the stacking sequence has an effect.[4]

Fujii et al.[30] noted that that there was little difference in the absorbed energy when cross-ply [0/90] laminates were compared to woven laminates. They did note however, that increasing the tensile strength and fracture energy of the fibre resulted in an improvement in ballistic performance of the laminate. Tanabe et al.[31] also showed no difference in energy absorption between cross-ply and woven laminates. However they concluded that high tensile strength fibres should be used on the rear surface of the laminate to maximise energy absorption of the projectile. Hammond et al.[36] showed that thin laminates of different quasi-isotropic lay-ups did exhibit a difference in energy absorption. Despite this, they noted that the measured difference was small and was well within their experimental error. However, they also pointed out that unidirectional composites were significantly weaker than the other lay-ups.

The effect of stitching the carbon fibre tows on the ballistic response has been studied by Hosur et al.[37] In this work, aerospace grade plain and satin weave carbon fabrics were used to manufacture the laminate using a SC-15 epoxy resin system. For fabrication of stitched laminates, a three-cord Kevlar thread was used to stitch the fabric preform in a lock-stitch fashion. Impacts were carried out using a fragment-simulating projectile that was in the shape of a chisel-nosed cylinder. Impact velocities of up to 275 m/s were achieved. For the stitched laminates, results of this study indicated that the resulting ballistic damage was contained within the stitched zone. However, the velocity at which complete penetration of the laminate occurred was higher for the unstitched laminates by virtue of more extensive damage. They also found that satin weave laminates exhibited higher ballistic performance in most of the cases. For example, they showed that the ballistic limit of the satin-weave laminates was up to 38% higher when compared with the plain-weave laminates, with a larger improvement in performance noted for the thinner laminates. Ultimately, such an increase in ballistic performance can be achieved by adding layers of Kevlar® behind the carbon fibre composite.[38]

Temperature effects

The effect of cold temperatures on the ballistic performance of these laminates is of great interest although to date, relatively few studies have concentrated on this. Examination of the low temperature response of CFRP laminates is important not least due to the low temperatures that aircraft are subjected to with increasing altitude. The outside temperature can range from −55 °C to + 50 °C depending on the altitude and the location of the aircraft and therefore there is a requirement to understand the response of these materials at these types of temperatures.

For relatively low velocities of impacts (ca. 100 m/s) it has been shown that temperature affects the extent of delamination, with lower levels of delamination being observed with increasing temperature.[39] Lopez-Puente et al.[40] have studied the effect of low temperature on the high-velocity impact response of CFRP laminates. In this work two different laminates were tested: a tape laminate with stacking sequence $[\pm45, 0, 90]_s$ and an eight-layer plain woven laminate. The tape laminate was less effective against impact than the woven laminate at both below and above the ballistic limit. That is, the velocity at which complete penetration occurred. They found that lower temperatures had a detrimental effect on the impact behaviour of the quasi-isotropic tape laminate tested. However, where the impact velocity exceeded the ballistic limit, they showed that temperature has no effect on damage extension implying that the energy absorbing characteristics at room temperature are similar to that at lower temperatures experienced by high altitude aircraft.

High-velocity ice impacts

In recent years there has also been a few studies examining the high-velocity impact of hail-stone projectiles. Although the terminal velocity of hail stones is relatively low (i.e. 30 m/s) compared to other loading regimes covered in this paper. The question still remains as to whether hail stones pose a risk to supersonic aircraft where the relative contact velocity is high. There is a further challenge to these types of investigations in that hail stones have an onion-like construction that may affect their failure on contact with the CFRP laminate. Kim et al.[41] conducted a study into the effects of ice impacts on CFRP structures. Layered ice projectiles, designed to partially simulate the 'onion-like' layered nature of real hail stones, with diameters of 25.4, 42.7 and 50.8 mm were accelerated to 30–200 m/s. Targets had dimensions of 305 mm × 305 mm and were between 1.42 and 2.62 mm thick, comprising AS4 carbon fibres pre-impregnated by either 977-3 (five harness satin weave) or 8552 (eight harness satin weave) toughened resin. High-speed video footage of impact events clearly showed ice projectiles shattering on impact, with the debris flowing radially over the target surface away from the point of impact. Ice has been shown to be not only strain-rate dependant, but also, particularly at elevated strain-rates where fragments remain confined, to maintain a substantial strength after brittle fracture. The trials undertaken by Kim et al.[41] led to a generalised qualitative damage scale based on the perceived degree of CFRP damage. At one extreme, Type I damage corresponded to barely visible surface fibre-layer delamination. At the other, Type V damage represented a clean hole in the target where impact velocities/energies were such that there was insufficient time for bending of fibres to occur. The energy at which damage was first observed (corresponding to the threshold velocity identified elsewhere by Hou and Ruiz[42]) was termed the failure threshold energy (FTE); shown to correspond to the interlaminar shear strain energy concentrated about the point of impact. Failure was observed to be highly localised about the point of impact implying that relatively small test panels could represent the damage mechanisms likely to be encountered by larger structures. Interestingly, the FTE was observed to vary linearly with CFRP panel thickness. Further, in some cases where no damage was initially observed, multiple projectiles were used to impact the same target panel until the damage threshold was reached. In such cases the damage thresholds were essentially the same as those where a single projectile with higher impact energy was employed – suggesting that damage is cumulative in such structures.

The importance of understanding ice-impact phenomena was highlighted in the return-to-flight program initiated after the tragic loss of the Space Shuttle Columbia. While the damage leading to the loss of the Orbiter arose due to detachment of foam insulation, impact due to water ice formation on insulation/around cryogenic fittings and subsequent detachment was highlighted[43] as a significant potential hazard. Further, ice impacts are unusual in that multiple impacts at a particular point on a structure may be encountered. E.g., rather than a single or low number of impacts which might follow collision with elements of a fragmenting munition or foreign objects on a runway, the nature of a hail storm means very-many such impacts localised within a small CFRP area may occur.

Glass fibre based materials

Glass-fibre-based materials have been used in all types of military environments ranging from mine countermeasure vessels[44,45] to armoured fighting vehicles.[45] They are extensively used in conjunction with ceramic materials to absorb the energy of a blunted projectile.[46–48]

GFRP materials generally demonstrate a good resistance to shock loading and unlike carbon-based composites they demonstrate reasonable energy absorption when subjected to ballistic attack. Consequently, for protection measures these materials are more important.

Penetration and failure mechanisms

There have been several studies that have focused on the penetration and failure mechanisms of these materials. Mines et al.[49] studied the penetration behaviour of woven, z-stitched (± 45° z-stitch E-glass fabrics supplied by Tech Textiles) and through-thickness z-stitched glass polyester laminates for a number of laminate thicknesses, a number of geometries, and masses of projectiles. They identified three modes of energy absorption: local perforation, delamination and friction between the projectile and the panel. They also reported that the woven and the z-stitched samples behaved in a similar manner. Their evidence suggested that the local energy absorption was dominated by shear effects during penetration. Similar evidence has also been seen by Naik et al.,[50,51] Naik and Doshi[52] and Gama et al.[53] In particular, Gama et al.[53] partitioned the penetration mechanisms into five stages, namely: impact contact;

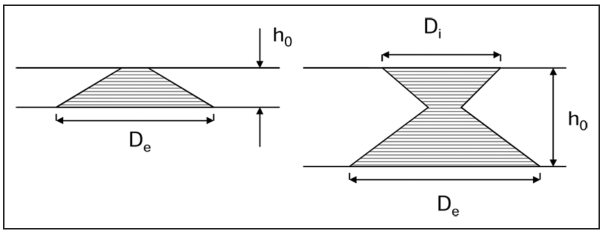

Figure 3. Differences in the type of damage for thin GFRP targets and thick GFRP targets; adapted from Gellert et al.[54] h_0 is the laminate thickness whereas D_i and D_e represent the delamination extent on the target's incidence and exit sides respectively.
Adapted from Gellert et al.[54] with permission from Elsevier.

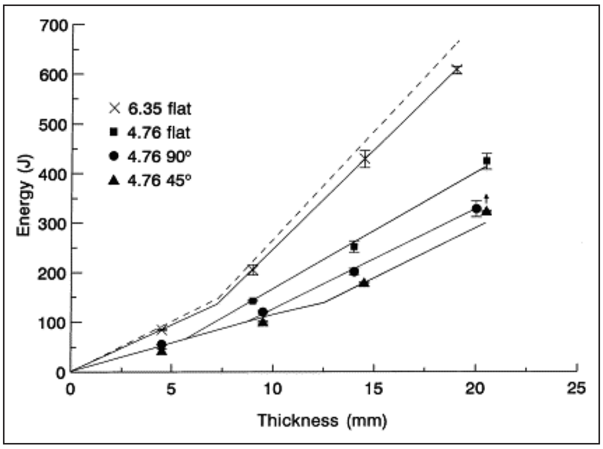

Figure 4. Kinetic energy at ballistic limit vs. target thickness for projectiles impacting GFRP targets.[54]
Reprinted from Gellert et al.[54] with permission from Elsevier.

hydrostatic compression of the composite; compression-shear; tension-shear and structural vibration. It has also been shown that changes in thickness have an important role in the penetration mechanisms. Gellert et al.[54] noticed that the penetration of varying thickness of GFRP materials resulted in a bi-linear relationship when energy at the ballistic limit was plotted against target thickness. This was also found to be the case for a broad range of reported composite ballistic impact data. Increasing the thickness of the GFRP target resulted in two characteristic patterns of delamination (illustrated schematically in Figure 3). For thin targets the damage was in the form of a cone of delamination opening towards the target's rear surface. This cone increased in diameter and height with increasing target thickness, until with sufficiently thick targets a cone of delamination opening towards the impact side was also added.

The reason for this was due the way in which the target failed during ballistic penetration. A change in perforation mechanism was observed from largely dishing in thin targets to a combination of indentation and dishing for thick targets and was largely affected by projectile shape and diameter (see Figure 4). For thin targets, the projectile nose shape (flat-nosed or conical) did not affect the energy absorption characteristics of the target; however for the thick targets the conical projectiles were more effective. This appears contrary to the observations in carbon/epoxy targets where conical projectiles appeared to perform less well compared to flat-ended projectiles.[55] However, this is likely to be down to the propensity of the carbon/epoxy target to fail through shear plugging. Importantly, Gellert et al. concluded that the indentation phase is a significant absorber of energy in GFRP targets and indicated that it should be maximised in any bonded composite armour design.

For thin composite materials it is anticipated that the strength and the strain-to-failure of the fibres is particularly important to accommodate the tensile strains that occur due to the dishing. Consequently, for these structures, using the higher strength S-glass fibres as opposed to the E-glass fibres is desirable.[56]

Naik et al. have also shown how impact energy is partitioned during ballistic impact loading.[57] Using an analytical formulation presented in Naik and Shrirao,[51] they showed how the energy absorption can be partitioned during the ballistic penetration of 2D woven E-glass epoxy composite ($t = 2\,mm$; $\rho = 1.75\,g/cc$). The result shown below in Figure 5 is for a calculation where the composite is impacted at just below the ballistic limit (i.e. where the projectile has not completely penetrated the composite). The main energy absorbing mechanisms were: fracture of primary yarns and deformation of secondary yarns. In particular, a significant amount of the kinetic energy of the projectile was transferred to the kinetic energy of a cone of material

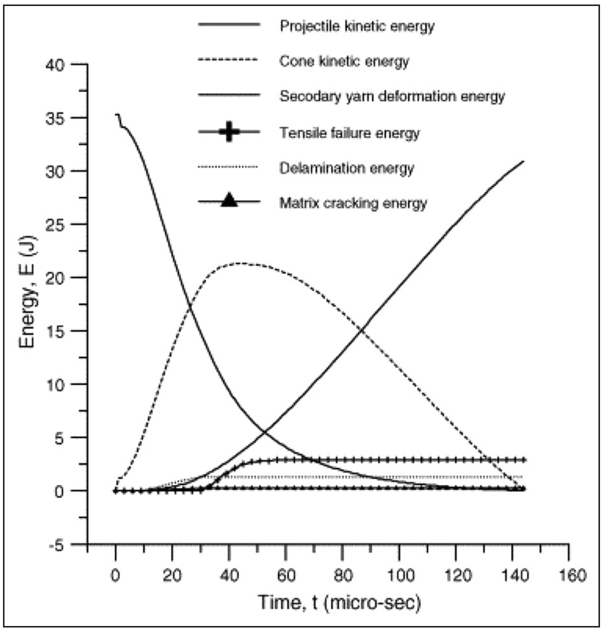

Figure 5. Energy absorbed by different mechanisms during ballistic impact event, v = 158 m/s, projectile mass = 2.8 g, h = 2 mm, d = 5 mm, after Naik et al.[57]
Reprinted from Naik et al.[57] with permission from Elsevier.

that was ejected from the rear surface as well as deforming the secondary yarns.

Damage from ballistic impact conditions can also be affected by the number of simultaneous impacts that the laminate experiences such as the situation where an exploding artillery munition propels multiple projectiles to the target. Using a unique gas-gun arrangement, with three barrels with an angular separation of 120°, Deka et al.[58] showed that the progressive time-dependant damage due to sequential impacts resulted in an increased performance of an S2 glass/epoxy laminate when compared to simultaneous impacts. Specimens subjected to sequential impact exhibited an average of 10% greater energy absorption with a corresponding 18% increase in delamination damage than specimens impacted simultaneously. The energy absorption of the laminate was influenced by the stress wave interactions, particularly along the primary yarns and also the amount of delamination that developed.

The effect of laminate make up on ballistic performance

Various attempts have been made to analyse the penetration of composite materials and these are generally based on energy-balance equations where the kinetic energy of the projectile is balanced with the energy required to cause shear failure of the composite, delamination, tensile failure of the yarns, kinetic energy of the resulting fragments and so on.[50,53,59,60] Some choose to decompose the resistance offered by the composite into two stress terms - namely the static and dynamic resistive component and derive terms for each based on the shape of the projectile penetrating the composite and the energy required to penetrate the depth.[23,61] Nevertheless, in the formulation of analytical models (and of course, validation of computational models) the geometry of failure is also important. Also important, is the strain wave propagation along the length of the fibres/yarns[50] which for soft fabric constructions at least, is one of the several mechanisms of absorbing energy.[62] The addition of the reinforcements of either the thermoset or thermoplastic type clearly has an effect on the penetration mechanisms. This has been shown by Lee et al.[63] who compared dry fabrics (i.e. without a resin in place) to a composite structure (where either a vinyl ester resin or aliphatic ester type polyurethane was used) on the ballistic performance of Spectra® 900 reinforced composites. The effect of adding the resin reduced yarn mobility and ultimately resulted in higher energy absorption through yarn fracture. However, they noted that the resin matrix itself does not absorb much energy in itself. Nevertheless, small improvements in the ballistic performance of GFRP composites have been seen with the addition of carbon nano-tubes to the resin.[64]

It is perhaps no surprise that the type of reinforcement used in rigid composite construction is also critical. Wrzesien[65] has shown that complimenting the glass-fibre reinforcement with a steel wire added to the resistance to ballistic penetration. Although there is an obvious weight penalty due to the addition of the relatively dense steel (and in this case, brass coated), on a weight-by-weight basis it has shown to be efficient at resisting penetration. Consequently increasing the strength of the fibres should improve the ballistic performance of the composite. On the other hand, Woodward et al.[66] examined the ballistic performance of semi-infinite composite materials with various reinforcement including (S2) glass, Nylon and Kevlar® materials (all with evidently different tensile strength values). Unusually, all target structures were at least 150 mm square and 150 mm thick and therefore the projectile was subjected to inertial confinement throughout the penetration phase. Using a simple energy balance, a value for the mean pressure was established and found to be highest when the glass reinforced material was tested. The mean resisting pressure was calculated according to

$$PAd = \frac{1}{2}mv^2 \tag{2}$$

and for GFRP, they measured a value of 1190 MPa which was twice that measured for the Kevlar-based composite. It was demonstrated that for GFRP crushing fracture of the composite occurred immediately ahead to the penetrator and they pointed out that this was seen to be responsible for a large amount of energy absorption during the early stages of penetration in finite-thickness targets.[67] High tensile modulus and good bonding between the fibre and the matrix were identified as important parameters for ballistic resistance. However, it should be pointed out that as this was effectively a semi-infinite target (i.e. where the thickness exceeded the penetration depth) some of the 'break-out' mechanisms seen by others were not evident.

The post-impact structural behaviour of composites is of particular interest when consideration is given on where they would be applied. In load bearing structures such as ships and composite armoured vehicles (such as the Advanced Composite Armoured Vehicle Platform[56]) it is critical to understand the degradation of strength and stiffness when the material has been subjected to blast and impact loading. And, certainly for blast loaded structures, this has been a critical path of study e.g. Mouritz.[68]

Stitching should also have an effect on the ballistic behaviour of the composite[49,69] principally because of their improved impact damage tolerance.[70] Kang has shown that the mechanical properties of a stitched composite (in the Z axis) are superior to unstitched composite materials with energy absorption being superior when compared to unstitched composites.[71] Whereas, Mouritz[69] has shown that applying a Kevlar® through-the-thickness stitching to the yarns using a modified lock-stitch pattern improved the structural behaviour of an E-glass-based composite. He showed that it reduced the amount of delamination damage caused by an explosive blast although they noted that the stitching had only a small effect in reducing the level of damage from the ballistic impact. Similar limited results have been seen in CFRP materials.[37]

Three-dimensional (3D) woven composites offer the possibility of providing enhanced ballistic protection by virtue of the architecture providing strength and stiffness in the Z-plane and enhanced damage tolerance.[72] There have been relatively few studies that have explored the advantages of these types of materials under ballistic loading although they have been show to offer improvements over 2D composites in the design of ceramic-faced armour systems.[73] Under dynamic impact tests there have been several studies that show 3D woven composite exhibit higher energy absorbing abilities under repeated impact when compared to 2D composites. Importantly, it has been shown that under low-velocity impact, 3D composites spread the damage from the impact over a wider area than 2D composites.[74] However, the question still remains as to whether this behaviour is translated for higher-rate ballistic impacts. Jia et al.[75] studied the ballistic behaviour of these materials computationally and experimentally and noted that during ballistic penetration, that delamination was inhibited due to the presence of the Z-plane reinforcement. They concluded that the energy absorption was predominately owing to shear failure on the impact surface and tensile and shear failure on the rear surface of the target ultimately leading to target failure. On the other hand, Walter et al.[76] experimentally investigated the ballistic performance of a thick 3D woven glass-based composite made of 27 layers of tows stacked in a cross-ply sequence and showed that under high-velocity impact, the Z-plane reinforcement did not stop delamination. They also noted very different failure mechanisms due to different bullet morphologies underlining the complex failure mechanisms of these materials.

Summary and concluding remarks

Carbon fibre based laminates have very poor translaminar properties that result in relatively poor ballistic performance values. Nevertheless, an understanding of the failure during ballistic impact is important, not least, so that routes to the enhancement in ballistic performance can be advanced. Most studies, have concentrated on the ballistic impact of spherical projectiles on these laminates with relatively little attention given in the open literature to ice impacts and bullets.[77] On the other hand, the energy absorbing properties of glass fibre reinforced materials is well known and these materials are already being used extensively in protective applications. Importantly, they have shown to be efficient at absorbing energy from blunt stimuli (e.g. where the composite is located behind a hard disrupting ceramic face resulting in global deflection of the plate) or from relative sharp projectiles. It appears too that there is still a lot to learn regarding the high-rate ballistic behaviour of 3D woven (or stitched) composite glass-based composite materials due to their complex failure mechanisms. One possible route of investigation is to pursue mesoscale modelling to elucidate the ballistic-impact mechanics of such composites and efforts in this regard are only just getting started (e.g. see Grujicic et al.[78] and Yen[79]). The shock response of both of these materials has also been of interest in recent years and is complex due to the multiple phases (and physical geometries of the constituent materials) within the laminate and there are still lessons to be learnt on the behaviour of these materials when shocked. In particular, one question that remains is how we can characterise the strength of these materials when they are shocked? This will be addressed in an accompanying review (Part II).

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