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RESIDUAL STRENGTH OF COMPOSITES AFTER BALLISTIC IMPACT

I.Horsfall, C.H.Watson, C.Boswell

Cranfield University, Defence Academy of the United Kingdom, Shrivenham, Wilts, UK

This paper describes the effect of penetrating and non-penetrating ballistic impacts on the structural integrity of composite panels. A commercially available glass polyester laminate was subjected to impacts from 7.62mm ammunition at up to 800ms^{-1} and 12.7mm ball bearing impacting at up to 125ms^{-1}. The strength of the panels was determined by a compression after impact test conforming to SACMA SRM 2R-94 [1]. The compressive strength of the panels was determined in the 'as manufactured' and impacted condition. A further set of panels was sectioned after impact in order to assess damage morphology.

It was shown that the loss in panel strength was directly proportional to the kinetic energy absorbed from the projectile irrespective of whether the panel was perforated. This shows the dilemma facing the designer of a structural composite armour as the traditional approach of designing an armour just thick enough to defeat the threat will result in a minimum residual strength. From a structural perspective it would be desirable either to dramatically overmatch the threat or to allow easy perforation in order to maximise residual strength.

INTRODUCTION

Composite materials are widely employed in both structural and ballistic applications however it is rare for their ballistic and structural properties to be exploited at the same time. In ballistic applications composites are typically used as absorbers or catchers where they are required to absorb the kinetic energy of a soft or disrupted projectile [2] [3]. Energy absorption is often accomplished by exploiting the high work of fracture of long fibre composites and promoting large-strain inelastic deformation mechanisms which result in extensive cracking delamination and debonding within the composite structure [4].

In structural applications composites are often optimised in order to reduce the chance of damage by designing them to be damage tolerant, physically protecting them or minimising their exposure to in service damage. Impact damage is known to be a particular problem particularly in the case of non-penetrating impact which can result in extensive internal damage without any permanent deformation to the exterior surface, this is often referred to as barely visible impact damage (BVID). Cantwell and Morton [5] showed that delaminations were one of the primary damage modes after impact loading. Damage, whether visible or not, can immediately compromise the structural integrity of the system or it can serve as a nucleus from which more extensive breakage can propagate.

Composites have been used as the main structural materials in a number of armoured vehicle technology demonstrators. Currently the only operational system has been the UK SNATCH Landrover which has a composite monocoque but still retains a metallic chassis as the main structural member for the automotive components. A prime consideration in the application of composite for vehicle hulls is their resistance to conventional impact from wear and tear and the more severe impact damage from ballistic impact. Previous work has investigated the effect of variability in the composite manufacture in order to attempt to connect factors such as matrix toughness, static mechanical properties and ballistic properties. In the present work a single composite material has been examined and the effect of relatively high energy and low energy impacts has been investigated in terms of the residual compressive strength of the material.

TEST MATERIALS

The monolithic composite panels where obtained as commercial items from Meggitt Composites Ltd. The materials were 36-40 structural armour of 10mm thickness which consisted of E-glass plain weave fabric within a polyester matrix. Samples were prepared by cutting 150mm x 200mm test panels from a single large panel of the material.

IMPACT TESTS

Ballistic impact tests used the NATO standard 7.62x51mm ammunition. This has a streamlined full metal jacket projectile consisting of a lead/antimony core with a gilding metal jacket. It has a mass of 9.33g and a normal muzzle velocity of 840ms^{-1}. The round was fired from a proof housing at a range of 10m from the target panels. A laser designator was used to achieve accurate aiming and the impact velocity was measured by optical gates positioned 2m and 6m in front of the target. For penetrating shots a second pair of sky screens 2m and 6m behind the target measured the exit velocity.

The target panels were rigidly clamped around their periphery to a rigid steel frame. Each panel was subjected to a single centrally positioned impact. The V_{50} ballistic limit velocity was obtained using the procedure described in NATO STANAG 2920 [6]. This dictates that the limit velocity is the mean of 6 shots: the three highest velocities, which do not fully penetrate the target; and the three lowest velocities which fully penetrate the target. The 6 tests shots must cover a velocity range of no more than $40ms^{-1}$. The velocity of the projectiles was adjusted by varying the propellant charge in the cartridge case.

Low velocity impact tests were conducted with a ball bearing launched from an air cannon. The 12.7mm diameter hard steel ball bearing had a mass of 8.35g and was launched at a typical velocity of $125ms^{-1}$. The sample mounting was the same as used for the high velocity ballistic tests, and projectile velocity was measured by optical gates at the muzzle of the gun 100mm apart and 750mm from the target.

COMPRESSION TESTS

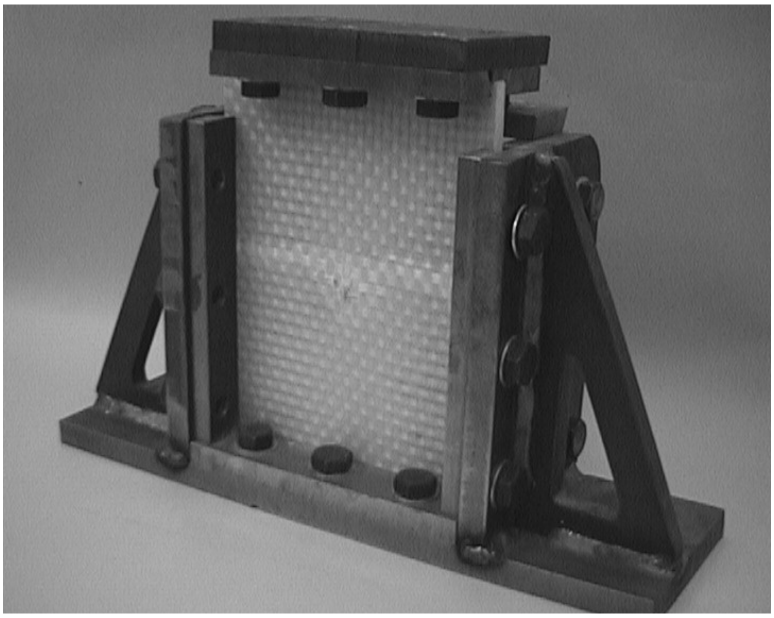

Figure 1: Compression after impact test rig showing failure from central damage point.

Compressive strength was assessed using a constrained compression test according to the SACMA SRM 2R-94 procedure, often referred to as a compression after impact test (CAI) [1]. The sample is subjected to a single centrally placed impact and is then placed in a restraining frame to prevent buckling. The panel is then compressed along an axis parallel to its faces and longer side. The SACMA compression test and fixture was used on panels, which had been subjected to penetrating and non- penetrating impact. During loading the initial damage caused by the impact is propagated to the edges of the specimen resulting in a sudden loss of strength. A panel which has failed in this way is shown in Figure 1. The panels showed a linear increase in load up to failure. So it was possible to measure the modulus from the displacement to failure and the load at failure. This measurement is only approximate as it does not correct for test machine compliance but is sufficient to allow a comparison between different panels.

RESULTS

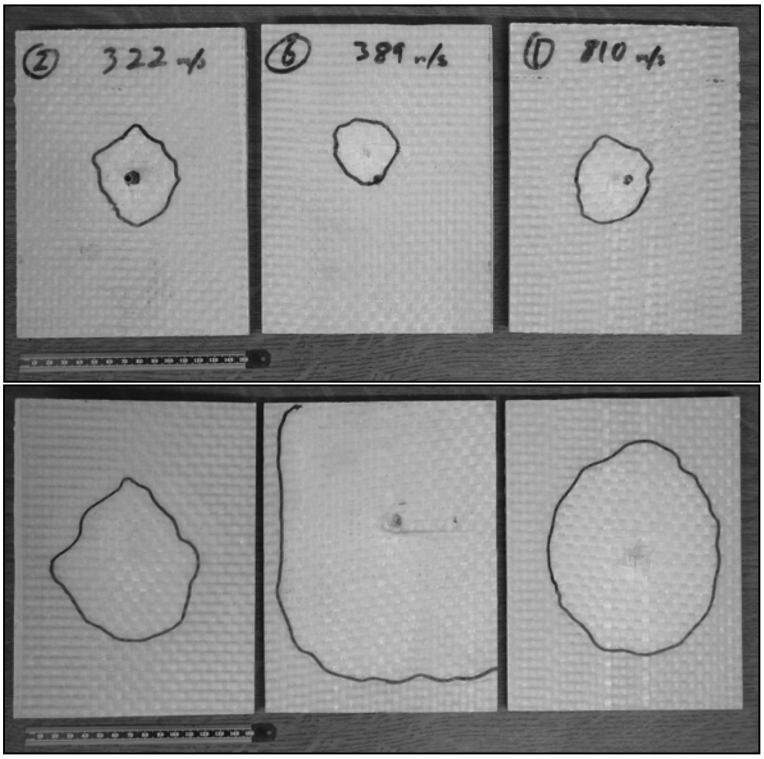

Figure 2: Photographs of test panels showing the impact face (top row) and corresponding rear face (bottom row). Impact conditions were (from left to right) 322ms^{-1} non-penetrating, 389ms^{-1} penetrating and 822ms^{-1} penetrating, all with 7.62x51mm bullet.

The ballistic limit velocity was measured as 410ms^{-1} although the spread (47ms^{-1}) was somewhat outside the limits set in STANAG 2920. The panels showed extensive delamination which was visible on both the front and rear faces as shown in figure 2. The delamination visible on the rear face extended up to the edges of the test panel for impacts close to the V_{50} but was contained within the panels for impacts significantly higher or lower than V_{50}.

Figure 3 shows the CAI test results for undamaged panels, one impacted at 125ms with a ball bearing and further panel impacted at up to 800ms^{-1} with the 7.62mm bullet. Data is shown for both non-penetrating and penetrating impacts. The results show that both the strength and apparent modulus decreased to a minimum for impacts near the ballistic limit velocity. However, for impact further above the ballistic limit the panel strength was not reduced as much. For instance a fully penetrating impact at 800ms^{-1} caused similar loss in strength and modulus as non-penetrating impact at only 125ms^{-1}.

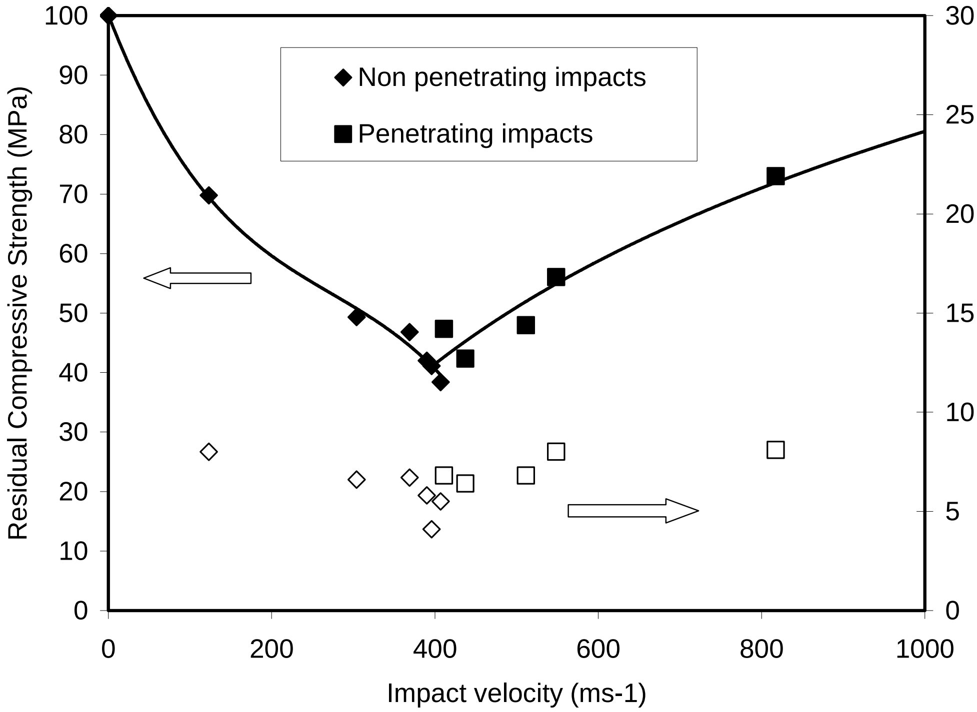

Figure 3: Compressive strength (solid symbols) and modulus (open symbols) plotted as a function of impact velocity.

This data can also be plotted in terms of the energy absorbed by the panel. For non-penetrating impacts this was assumed to be equal to the impact velocity whilst for penetrating impacts it was taken as the difference in kinetic energy calculated from the impact and exit velocity of the projectiles. Figure 4 shows this data and it can now be seen that the strength reduction is directly related to the absorbed energy whether or not the projectile penetrates the panel.

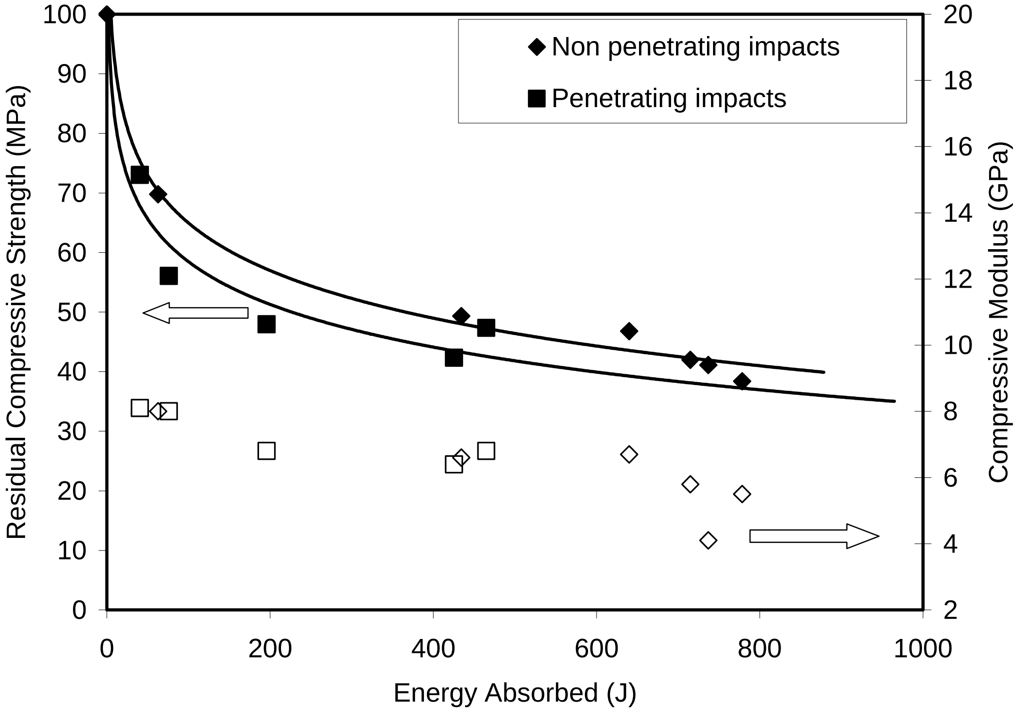

Figure 4: Compressive strength (solid symbols) and modulus (open symbols) plotted as a function of absorbed energy.

DISCUSSION

An initial examination of the Figure 4 shows an extremely good correlation between absorbed energy and post impact compressive strength. This is to be expected as there is ample evidence that for any particular composite material the delamination area scales with impact energy [7], and the post impact strength scales with delamination area [2].

Some of the assumptions made are only approximations, for instance the absorbed energy is probably somewhat less than simply the impact energy of a non-penetrating projectile. The ball bearing projectiles retain a large part of their initial energy as they rebound from the target, whilst the 7.62 mm bullets will dissipate significant energy by their own plastic deformation. However the overall principle still appears to be sound.

This work indicates that the effect of penetration and the resulting hole in the composite is insignificant compared to the delamination damage extending out from the hole. This is in some ways influenced by the test technique as the CAI test is, in effect, a damage propagation test rather than a compressive strength test.

The important aspect of this from the point of armour design is that in attempting to achieve the lightest armour solution, i.e. one that has a ballistic limit just above the threat projectile velocity, it is likely that structural damage will be maximised. If the primary aim is to preserve structural integrity, as might be the case for an aircraft structure, then the composite must either be very thick or very thin compared to the thickness needed to match the threat.

CONCLUSIONS

Strength degradation of composite panels is proportional to impact velocity for non-penetrating impact, but inversely proportional to impact velocity for penetrating impacts.

For both penetrating and non-penetrating impact the residual strength of composite panels is proportional to the absorbed kinetic energy.

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