

## THE EFFECT OF MATRIX TYPE ON THE BALLISTIC AND MECHANICAL PERFORMANCE OF E-GLASS COMPOSITE ARMOUR

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Composite materials used as a spall lining in armoured fighting vehicles (AFV) must have good ballistic qualities as well as structural characteristics that can withstand applied loads, before and after impact. This paper investigates whether there is a relationship between ballistic and mechanical properties of glass fibre reinforced plastic material. Impact damage on the composite panels was caused by ballistic and drop-tower tests using .30 calibre fragments at 500 to 700 m/s and a Rosand machine at 50 J impact respectively. An ultrasonic C-scan determined the subsequent delamination size, which was expected to be inversely proportional to the Mode I experiments determining the delamination resistance ( $G_{1C}$ ). The results showed a slight relationship between three composite panels, where reduction in  $G_{1C}$  followed an increase in ballistic properties.

### INTRODUCTION

Fragmentation is the main reason why spall linings are required in AFV, so this paper is concerned with secondary projectiles of approximately 500 to 700 m/s. Another aspect is the structural integrity of the material that is essential for the AFV as delaminations are an inevitable consequence of impact damage. Forms of failure include matrix and shear cracking, delamination, fibre fracture and surface damage. In 1991 Cantwell and Morton [1] investigated low velocity impacts on different carbon fibre reinforced plastic (CFRP) arrangements and established the material behaviour after impact damage.

In the UK, DERA have developed an AFV that uses a composite hull, replacing the aluminum and steel materials. The advantages are that the AFV is lightweight thus improving performance and ballistic properties are increased. In addition, survivability is increased as the vehicle is made from one component so there are fewer weak points and corrosion by salt water and wet environments is eliminated. In applications such as this, the composite panels are required to support some or all of the vehicles structural loads.

## MATERIALS

The composite panels all contained the same woven E glass fibre plies, but with different matrix materials. SC1008 phenolic resin was used in four samples and epoxy resin was used in the fifth. The phenolic resin samples were modified by the addition of PVB as a flexible agent, which is the rubbery substance in the material, or amino silane to promote the matrix bonding.

No.	Composition
1	SC1008 phenolic resin with PVB 50:50
2	SC1008 with 10% PVB
3	Epoxy mix 57
4	SC1008 phenolic resin
5	SC1008 with amino silane

Sun and Rechack [2] placed extra resin in the interfaces and discovered that although this reduced the occurrence of delaminations, due to reduced shear stresses within the laminate, the compressive strength was decreased.

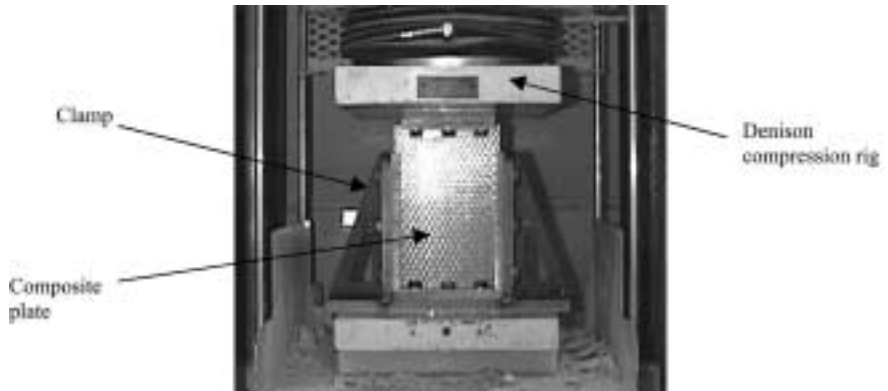
## EXPERIMENTAL PROCEDURE

Ballistic tests used .30 calibre fragments simulating projectiles (FSP) [3] at a range of 10 m. Projectile velocity was measured using two LED photodetectors at 6 m and 14 m from the gun. The experiment worked at a compromise between the RARDE 802 [4] and NATO [5] standards. A set of velocity values were produced within a 30 m/s range (RARDE 802) and consisting of 3 penetrated values and 3 held values (NATO). Using these figures, the  $V_{50}$  was determined for each sample.

A Rosand Instrumented Falling Weight impact test with an impactor of 25 mm diameter and mass 2.484 kg was utilised to hit 210 mm x 160 mm sized panels. The aim was to reach impact energy of 50 J. Zhou and Davies [6] of Imperial College had used ultrasonic C scan to determine delamination area and crack propagation and it proved to be very useful. Hence, the delamination area and crack front of these impact samples were determined with an ultrasonic C scan employing a 2.25 MHz submersion probe.

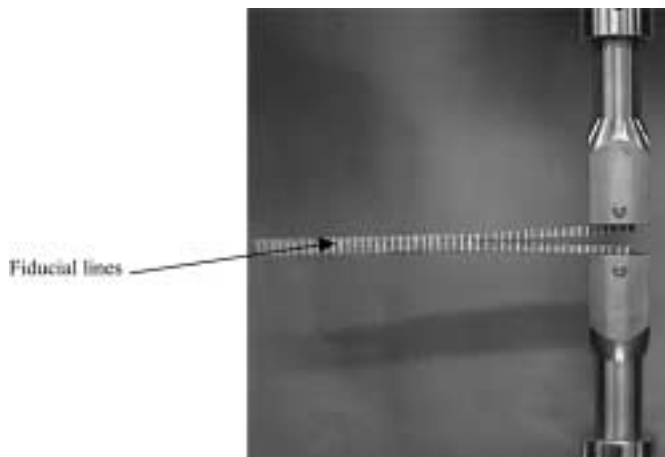
As structural behaviour after impact was an issue, compression after impact (CAI) tests were performed using a Denison compression rig where maximum load endurance is 3000 kN.

Figure 1: CAI Test Apparatus.



As Cantwell and Morton [1] discovered delaminations were one of the primary damage failure modes after impact, double cantilever beam (DCB) mode 1 delamination resistance tests were carried out adopting the experimental compliance method. Composite strips of 250 mm x 25 mm x 12 mm were marked at 5 mm intervals and load blocks were glued to the sides. This apparatus is shown in Figure 2.

Figure 2: Mode 1 Delamination.



A PolyTetraFluoroEthylene (PTFE) starter film inserted during manufacture was used to provide crack initiation. With the Instron machine, load (P) vs. displacement ( $\delta$ ) was achieved (see Figure 3) and the load at each 5 mm crack propagation interval was recorded. Compliance (C) was then determined by equation 1.

$$C = \frac{\delta}{P} \tag{1}$$

This is used to plot log C vs. log (delamination length, a). The gradient of this graph (n) is an element in equation 2 for determining  $G_{1C}$ .

$$G_{1C} = \frac{nP\delta}{2Ba} F \tag{2}$$

Where F is the large displacement correction:

$$F = 1 - \frac{3}{10} \left( \frac{\delta}{a} \right)^2 - \frac{3}{2} \left( \frac{\delta l_1}{a^2} \right) \tag{3}$$

[B = width of specimen, 25 mm.  $l_1$  = distance from centre of loading pin to midline of composite strip, 16 mm]

$G_{1C}$  can then be plotted as seen in Figure 4 and its value can be taken by reading the average value of the plateau.

Figure 3: Load vs Displacement.

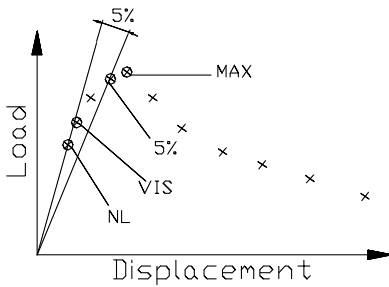
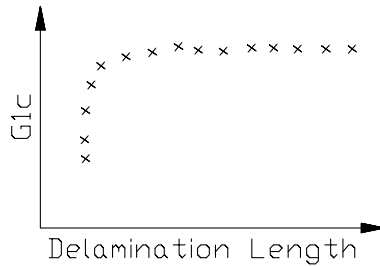


Figure 4:  $G_{1C}$  Results Presentation.



## RESULTS

The results of the five tests that were carried out are shown in table 1.

Table 1: Results of the Five Test Procedures

Material	V <sub>50</sub> (m/s)	C-Scan Delamination Area (mm <sup>2</sup> )	CAI – Max Load (kN)	Mode I – G <sub>1C</sub> (J/m <sup>2</sup> )
Phenolic resin+PVB 50:50	581.3	545	146.9	4124.95
Phenolic resin+10% PVB	670.9	2817	206.2	404.30
Epoxy mix 57	651.2	215.5	409.8	229.09
Phenolic resin	601.2	1483.5	96.2	761.66
Phenolic resin+Amino Silane	589.6	2408.5	254.2	58.87

From visual inspection, the front face of the ballistic panels displayed a smaller detached area than the corresponding back face detachment. In all cases, the delaminated perimeter spreads out from the central impact point and surface cracking was seen near the vicinity of all the projectile entrances. The front face of the ballistic panels showed “tufts” of fibre protruding away from the projectiles point of entry. Similarly, these were also located where the projectile had exited. Back face observations showed that the smallest and most localised detachment areas were from the epoxy panel whilst emerging adjacent delaminations occurred in all the phenolic matrix samples. When the detached areas on the back face of the phenolic resin and the resin with 10% PVB panels were gently depressed, these areas sprang back to a greater extent than similar areas on the other panels.

Figure 5: Front Face of Epoxy Ballistic Panel.

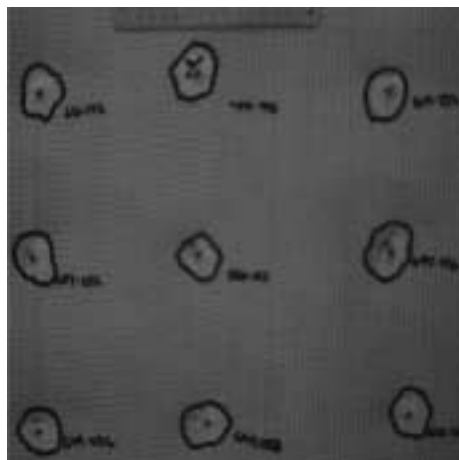
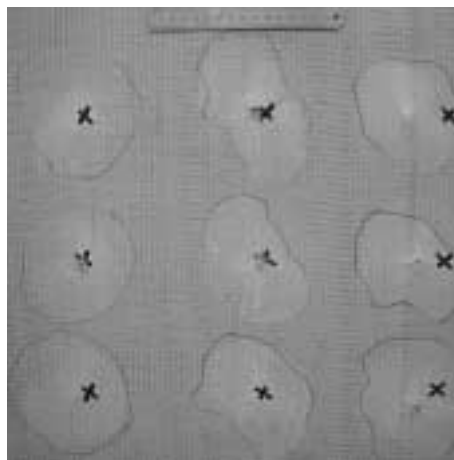


Figure 6: Back Face of Epoxy Ballistic Panel.



Due to glass being an attenuating material, delamination detection on glass fibre reinforced plastic (GFRP) composites using the C scan gave quite an indistinct image, as there was very little signal reflected back to the receiver. This was especially evident in the phenolic resin and resin with amino silane specimens hence the results are only approximations.

During the CAI tests, cracking sounds due to fibre breakage were heard, except in the phenolic resin sample where complete fracture followed only a few fibre breakages. All the failures were situated at the centerline of the composite panel (perpendicular to the line of force) and through the impact point.

When following the progress of the crack in the DCB mode 1 experiments, the crack tended to propagate through two to four fiducial lines concurrently, but other than this, the advancements were quite steady.

## DISCUSSION

Figure 7: Comparing  $G_{1C}$  and  $V_{50}$  Results.

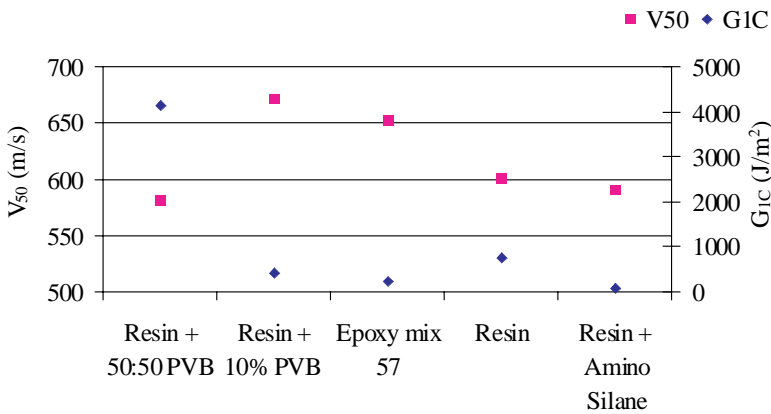
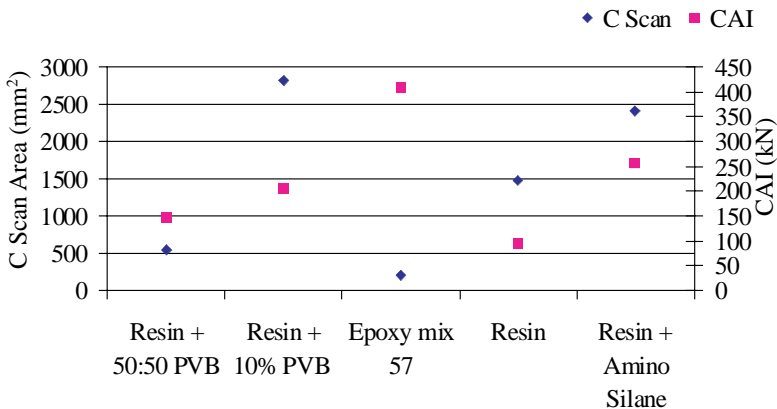


Figure 8: Comparing Delamination Area and Maximum CAI Load.



Figures 7 and 8 shows the trend of the results. It was predicted that the delamination resistance test data would be approximately proportional to the CAI test and inversely proportional to the C scan results. Unfortunately, the data does not show such a trend. However, there is a slight inverse relationship between the ballistic properties and the resistance to delamination. Also, Figure 8 illustrates that as delamination area increases, the CAI maximum load reduces.

Griffin [7] conducted experiments where five different reinforcements were set in the same matrix and impacted. The maximum energy that these plates could absorb was the same, therefore showing the damage initiation is governed by the matrix properties and that the fibre properties are virtually unrelated in this aspect. This was also confirmed from analysis by Strait [8]. Considering this, the epoxy sample was expected to have a relatively high ballistic limit, as it is a very tough material. This is also why it performed very well under high compressive stresses.

Taking into account the comparable panels: phenolic resin with 50:50 PVB, phenolic resin with 10% PVB and the phenolic resin samples, there was a slight inverse relationship between delamination resistance and ballistic properties. The fracture toughness of the resin with 50:50 PVB was high but only performed reasonably in the CAI test and was the worst with respect to the ballistic data. Therefore, in this case, it is not the optimal choice for use as an AFV spall liner.

The resin with 10% PVB specimen had good ballistic properties and although the overall mechanical characteristics were only mediocre, it is sufficient for the application. In addition, this material achieved the largest delamination area of 2817 mm<sup>2</sup>, which coincides with its relatively low  $G_{1C}$  result, as they are expected to vary inversely.

At 601.2 m/s, the  $V_{50}$  of the phenolic resin itself was average and the delamination resistance test gave relatively high  $G_{1C}$  from the materials investigated in this project. However, the compressive strength was low compared with the other composites.

While the epoxy sample would seem like a very good possibility for a spall liner, it is unfortunately more flammable than the phenolic resin samples. Therefore, the choice of a suitable spall lining would predominately lie with the resin with amino silane and the resin with 10% PVB specimens. Although the ballistic properties of the resin with amino silane are relatively low, they are sufficient and the mechanical characteristics are good. The other possibility being the resin with 10% PVB sample, which has better ballistic qualities, however the CAI results are slightly lower.

## CONCLUSION

The development of composite hull vehicles has highlighted the need for both structural and ballistic properties in composite armour materials as they are equally as important. Thus, the aim was to investigate if there is a relationship between these two aspects.

This investigation did not confirm past research on the impact damage of composite materials. This was due to the predictions of  $G_{1C}$  being proportional to the CAI test and inversely proportional to the C scan results, which were not apparent in these results. However, there was an approximate inverse relationship between the  $G_{1C}$  and  $V_{50}$  results and between the C scan and CAI data.

The material with the best  $V_{50}$  ballistic properties was the phenolic resin with 10% PVB. The material with the best overall mechanical properties was the epoxy panel as it had the highest CAI load of 409.8 kN.

This investigation found that the materials with the best structural and ballistic properties were the phenolic resin with amino silane and phenolic resin with 10% PVB specimens. These would be the most suitable materials for an AFV spall lining.

## ACKNOWLEDGEMENTS

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