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STRUCTURAL BALLISTIC ARMOUR FOR TRANSPORT AIRCRAFT

I.Horsfall, S.J.Austin, W Bishop*

Cranfield University, RMCS Shrivenham, Swindon, UK

***Aero Consultants (UK) Ltd, Cambridge, UK.**

ABSTRACT

This paper describes the structural response of a current ceramic-faced composite armour system and a proposed structural armour system for aircraft use. The proposed structural ballistic armour system is shown to be capable of providing significant structural integrity even after ballistic impact whilst providing ballistic protection equivalent to an existing appliqué system. The addition of a carbon fibre reinforced plastic front panel to the existing ceramic faced composite armour system improves the bend strength by a factor of three and improves the energy to break by almost an order of magnitude.

Keywords: Impact and ballistic (E), mechanical (E), selection for materials properties (H)

INTRODUCTION

Military transport aircraft are often required to operate in support of peacekeeping and evacuation operations where there is a significant risk from attack. Electronic defensive aids may be employed to counter guided weapons, however in low intensity conflicts there is a continual threat from sniper fire. During operation into Sarajevo airport in 1994, the threat from small arms fire was sufficient that the Royal Air Force and other NATO air forces chose to armour their aircraft[1]. A number of RAF C-130 Hercules aircraft had armour protection fitted around the cockpit to protect the flight crew. The armour was manufactured by Aero Consultants UK Ltd and consisted of glass ceramic tiles bonded to an aramid composite backing. This was fitted over the existing aircraft structure around the cockpit to protect the crew and vital aircraft systems (Figure 1). The armour system was not expected to support load and was simply bolted over the existing plywood floor. A typical armour kit covered 18.2m^2 of the cockpit walls and floor with a total weight of 585kg.

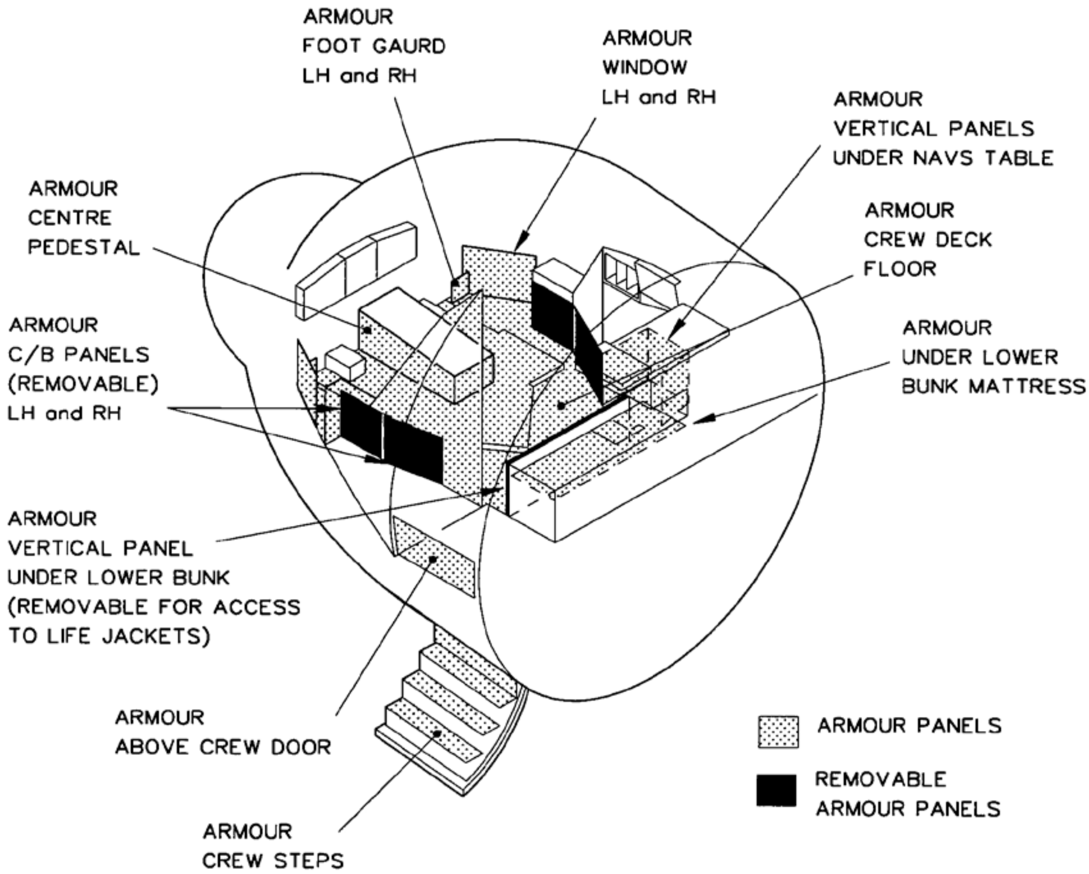

Figure 1. Armour layout on an RAF C130 Hercules.

Ceramic faced armour of this type is designed to function by using a hard ceramic layer to disrupt a projectile and a ductile backing to absorb the projectile's energy. This results in extensive comminution of the ceramic at the impact site together with more widespread cracking[2]. The composite backing is extensively delaminated both internally and at its interface with the ceramic. It is usual to bond a spall shield, typically a single layer of glass fibre reinforced plastic (GFRP), to the impact face of the ceramic in order to suppress forward spall generation. The spall shield also serves to preserve the mechanical integrity of the armour system in order to achieve some degree of multi hit capability[3].

The armour panels fitted to C130 Hercules aircraft were designed as a removable system that was placed on top of the existing plywood floor panels. Although this allows removal and consequent weight saving when the aircraft is used in peacetime, it represents a considerable parasitic mass from a structural standpoint. When installed as a floor armour system the backing material would be uppermost with the spall shield at the lower surface. Normal loads on the floor would produce a tensile stress in the lower face of the ceramic and the spall shield. The low toughness of the ceramic and relatively low strength of the spall shield would normally be insufficient to support the floor loads. However if the spall shield was thickened or made from a stronger material then it would be possible to produce a system of considerable strength. Such a system could permanently replace the existing plywood floor panels and would support all structural floor loads in addition to providing armour protection. The armour manufacturer proposed a modified armour system with an aluminium face bonded to the glass ceramic in place of the GFRP spall shield.

When installed in the aircraft the aramid face would be uppermost with the aluminium plate on the bottom and the glass ceramic sandwiched between (Figure 2). Thus the aluminium layer would serve as a tension member to support floor loads. This was

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shown to increase the load carrying capacity of the floor by 60% whilst reducing the total floor thickness from 22mm to 17mm and resulting in a 14% weight saving[4].

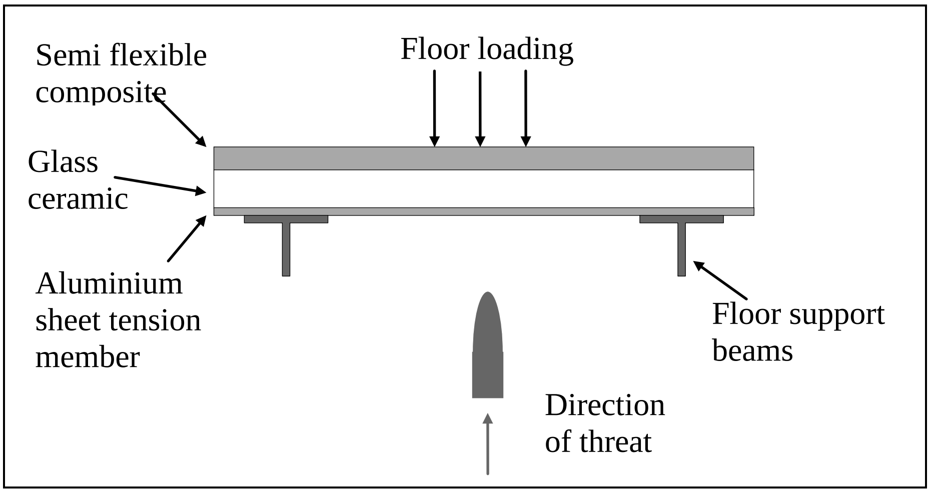

Figure 2. The structure of a proposed structural armour.

In practice a structural armour must meet the structural requirements in both an undamaged state and after suffering a ballistic impact. In this work it was decided to develop the structural armour concept further, and in particular to determine the residual structural capability of such armour after ballistic impact.

ARMOUR CONSTRUCTION

The armour fitted to RAF C-130 Hercules aircraft is ARMOURTEK™ 8.5GS. This consists of tiles of lithium zinc silicate glass ceramic of 8.5mm thickness, bonded to a semi flexible backing. The backing is an aramid composite consisting of twelve layers of plain weave aramid fibre in a rubbery thermoplastic matrix. A single layer of GFRP spall shield is bonded to the outer face of the ceramic to provide handling protection to the ceramic and to suppress front face spalling during ballistic impact. The properties of the components are given in table 1.

Table 1 Mechanical properties of armour components

Material	Thickness (mm)	Tensile strength (MPa)	Stiffness (GPa)
Lithium zinc silicate glass ceramic	8.5	153	90
12 layer aramid thermoplastic composite (backing)	5.5	280	1.5
Fibredux 916 glass fibre epoxy (spall shield or structural layer)	.25 or 2	285	20
Aluminium alloy (aluminium structural layer)	0.91	400 (Yield)	70
CFRP laminate 0/90 unidirectional composite (CFRP structural layer)	2.0	400	67

The original proposal for the structural armour floor was to modify ARMOURTEK™ GS by bonding a 0.91mm thick aluminium alloy sheet to the front (lower) face of the armour. However it was thought that higher specific properties could be obtained by using a lightweight composite face instead of aluminium. Simple beam theory was used to calculate the properties of modified systems. Calculations were performed for the existing armour materials (ARMOURTEK™ GS), a system with the GFRP spall shield increased to 2mm thickness (ARMOURTEK™ GFRP) and a system using a 2mm carbon fibre reinforced plastic face (ARMOURTEK™ CFRP). The ARMOURTEK™ CFRP system had a single layer GFRP spall shield applied over the CFRP in order to prevent electrolytic corrosion of the aluminium support structure in the aircraft. These systems are illustrated in figure 3 and the calculated mechanical properties are given in table 2.

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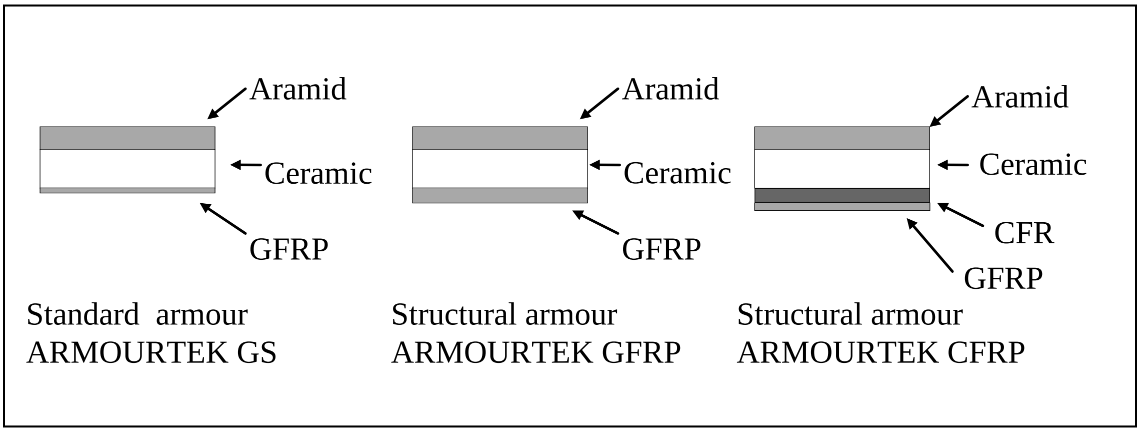

Figure 3. A comparison of the standard and structural armour layouts.

Table 2 Calculated bend strengths and stiffness

Material	Bend Strength (kPa)	Bending stiffness (GPa)	Areal density (kgm^{-2})
ARMOURTEK™ GS	1.899	4.189	29.3
ARMOURTEK™ Aluminium	2.678	5.388	34.7
ARMOURTEK™ GFRP	2.487	5.148	32.0
ARMOURTEK™ CFRP	4.207	7.375	32.2

On the basis of this analysis it was decided to employ a carbon fibre reinforced plastic (CFRP) as the structural layer. An experimental program was instituted to measure the structural and ballistic properties of the ARMOURTEK™ CFRP system.

EXPERIMENTAL AND RESULTS

The bend strength of the armour systems was initially assessed by bend tests on small coupons. Later tests were performed on complete armour panels before and after ballistic impacts. Strength after ballistic impact was also assessed by compression tests on complete armour panels. The ballistic performance of the armour systems was assessed against 7.62x51 L2A2 NATO ball round in terms of the V_{50} ballistic limit velocity.

Bend strength tests

Bend strength was determined using a 4-point bend test on samples measuring 200mm long and 50mm wide which were cut from larger panels. This test was performed on 8mm structural plywood (the standard C-130 floor material to Mil-P-6070), ARMOURTEK™ 8.5 GS (the standard armour system), and ARMOURTEK™ CFRP. The results are given in table 3; each figure is an average of three tests.

Table 3 Bend tests on test coupons

Material	Maximum load (kN)	Bending strength (kPa)	Deflection at maximum load (mm)	Energy at maximum load (J)
Plywood	1.94	0.72	7.74	9.42
ARMOURTEK™ GS	5.04	1.86	1.77	3.57
ARMOURTEK™ CFRP	15.27	5.63	4.04	28.23

The load displacement response of each of the three materials is shown in figure 4. The load on the plywood is seen to increase smoothly with displacement up to failure. For the ARMOURTEK™ GS the load increases up to an initial failure at just over 5kN when the ceramic fails, after this a lower load is then supported by the spall shield until final failure. The ARMOURTEK™ CFRP shows a similar response up to about 7KN load when the ceramic fails leading to a series of small load drops and an apparent decrease in stiffness. Failure of the CFRP occurs at the maximum load of over 15kN after which the GFRP spall shield supports a lower load until final failure.

Further 4-point bend tests were performed on complete 200mm x 155mm armour panels. ARMOURTEK™ GS panels were tested in several conditions: as received, after non ballistic impact (repeated blows with a 1kg hammer, sufficient to crack the tile), non penetrating ballistic impact (7.62 NATO ball 814ms^{-1}) and penetrating ballistic impact (7.62 NATO ball 880ms^{-1}). It was concluded, as might be expected, that a penetrating ballistic impact produced the greatest degradation in strength. Therefore the ARMOURTEK™ CFRP panels were tested in the as received condition and after a penetrating ballistic impact, the results for both armour types are given in table 4. It should be noted that the bend strength in the panels is significantly lower than that measured in the smaller test coupons. This was probably due to a lack of sufficient rigidity in the 4-point loading fixture, which was not designed for specimens of this size.

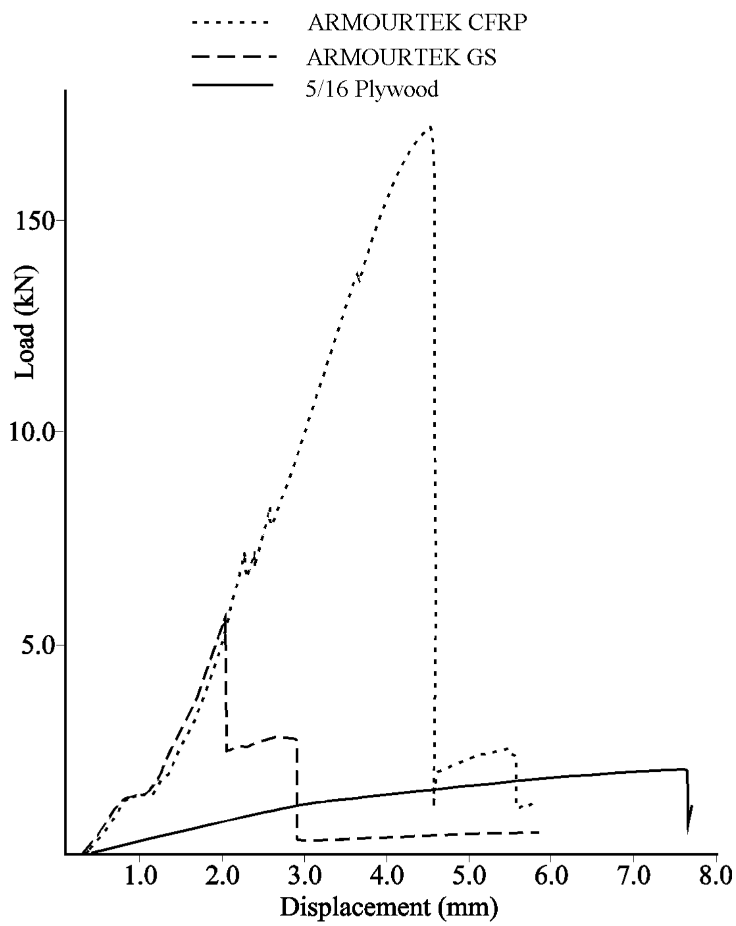

Figure 4. Load displacement plots for test coupons of plywood, standard armour and CFRP structural armour.

Table 4 Bend tests on armour panels.

Panel	Maximum load (kN)	Bending strength (kNm^{-1})	Deflection at failure (mm)	Flexural stiffness (GPa)
ARMOURTEK™ GS As received(E9)	14.97	1.84	2.25	2.92
Post impact	7.80	0.89	3.9	0.484
Post non -penetrating ballistic impact	7.83	0.90	4.1	0.530
Post ballistic impact	3.06	0.38	3.5	0.26
ARMOURTEK™ CFRP As received	27.62	3.39	3.2	3.43
Post penetrating ballistic impact	13.35	1.64	6.75	0.64

Ballistic Tests

The NATO standard 7.62x51mm L2A2 ball round was used as the ballistic threat. This is a streamlined projectile consisting of a lead/antimony core with a guilding 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 projectile velocity was measured by optical gates 2m and 6m in front of the target.

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[5]. 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. The V_{50} ballistic limit velocities of ARMOURTEK™ GS and ARMOURTEK™ CFRP are given in table 5. It should be noted that the velocity spread for the ARMOURTEK™ GS panels is slightly greater than that allowed in the test standard however this does not have a significant effect on the result.

Table 5. Ballistic test results.

Material	Ballistic limit velocity (ms^{-1})	Spread of data (ms^{-1})
ARMOURTEK™ GS	851	43
ARMOURTEK™ CFRP	868	25

Compression after ballistic impact

The compressive strength of the panels was assessed using a method promulgated by the Suppliers of Advanced Composite Materials Association (SACMA)[6]. In the SACMA test a panel subjected to a low velocity impact at its centre. The impacted test panel is placed in a restraining frame that prevents buckling and the panel is then compressed along an axis parallel to its faces. The SACMA compression test and fixture was used on panels, which had been subjected to a penetrating ballistic impact. The results are given in table 6. Figure 5 shows the load vs. displacement response of the two armour types.

Table 6. Compression after impact

Panel	Maximum load (kN)	Maximum stress (MPa)	Compressive modulus (GPa)
ARMOURTEK™ GS	14.4	6.19	0.70
	8.85	6.67	0.58
Average	11.63	4.99	0.64
ARMOURTEK™ CFRP	111.9	41.8	3.06
	96.6	36.1	4.33
Average	104	38.9	3.70

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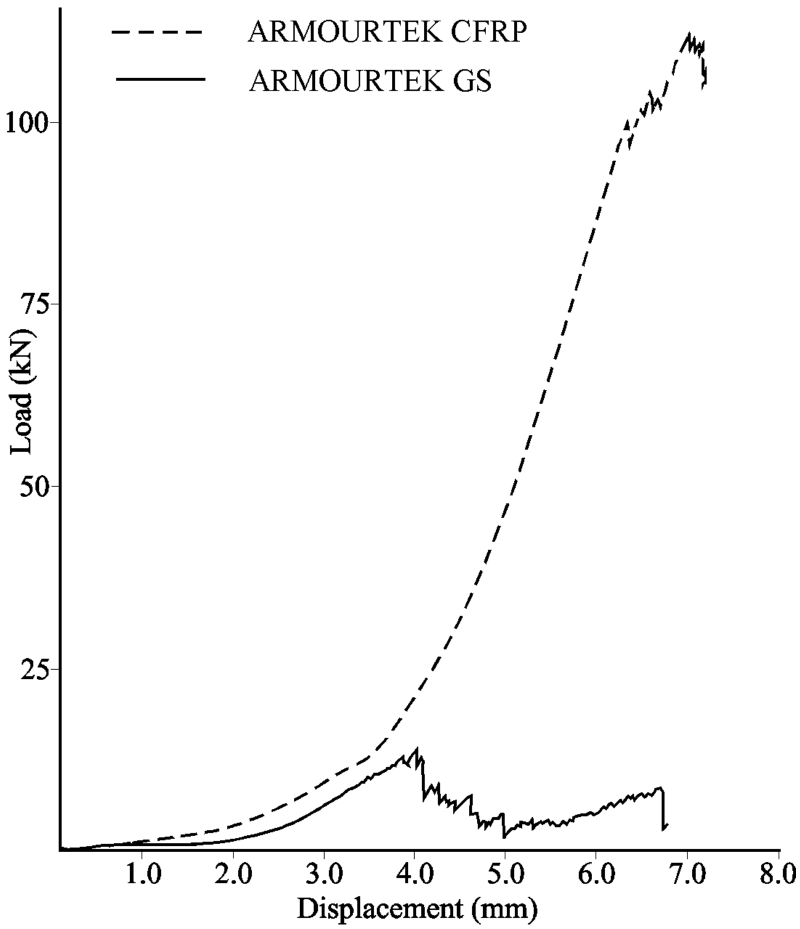

Figure 5. Compression after impact response of standard and structural armour systems.

DISCUSSION

The calculated bend strength of the armour systems agrees well with the values obtained in 4-point bend tests on the test coupons. Bending tests showed the standard armour to have more than twice the strength of the plywood and the structural armour to have more than five times the strength of the plywood. The ARMOURTEK™ GS results have a much wider range than the results for the ARMOURTEK™ CFRP as the former relies on brittle failure of the ceramic which is inherently more variable. The ARMOURTEK™ GS panels fail catastrophically when the ceramic cracks at a load of approximately 5kN. Although the ultimate strength of ARMOURTEK™ CFRP panel is substantially greater than that of the standard armour cracking of the ceramic appears to occur at similar loads. In the standard armour this cracking results in a sever reduction in strength whilst in the CFRP system the only effect is to marginally reduce the stiffness. Therefore the CFRP layer only slightly increase the load at which damage occurs but does produce a much more graceful failure. It should be noted that the load required to initiate damage in the armour systems is approximately three times the maximum load sustained by the plywood panel.

Table 7 A comparison of calculated and actual bend strengths

Material	Calculated strength (MPa)	Actual strength, test coupons (MPa)	Actual strength, full panel (MPa)	Post ballistic strength (MPa)
Plywood		0.715		
ARMOURTEK™ GS	1.899	1.861(1.44-2.11)	1.835	.376
ARMOURTEK™ Al	2.678	1.870		
ARMOURTEK™ CFRP	4.207	5.637(5.58-6.34)	3.385	1.636

The structural capacity of the various systems can also be assessed in terms of the energy required to cause failure or damage. The much greater stiffness of the armour systems compared to the plywood leads to a relatively low energy to failure even considering the relatively high strength levels. The standard armour requires only half the energy to failure of the plywood. However the structural armour requires at least twice as much energy as the plywood to cause failure. The standard armour is seen to be capable of supporting floor loads but would have an inferior response to impact loads and would be prone to catastrophic failure. The structural armour system combines superior load carrying capacity with an increased energy to failure and a relatively graceful failure mode.

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Comparison of the post ballistic impact response shows a clear advantage to the ARMOURTEK™ CFRP system. The ultimate strength of the ARMOURTEK™ CFRP after ballistic impact is similar to that of the undamaged ARMOURTEK™ GS.

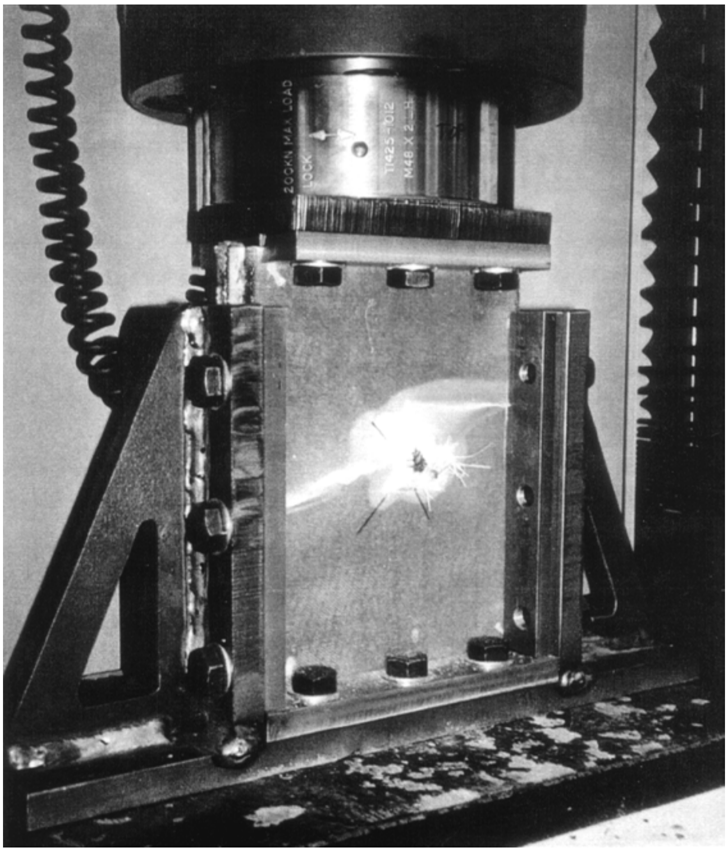

Figure 6. CFRP structural armour panel failing in compression after ballistic impact.

The distinction is even more evident in the compressive response. The CFRP system shows between 5 and 10 times more strength than the standard system. The standard system completely delaminated during the compression test so that the backing, ceramic, and spall shield became completely disconnected and the system collapsed. However the CFRP system showed a progressive failure with damage extending along a well defined failure surface normal to the load axis and emanating from the impact site (figure 6).

The presence of the CFRP layer preserves the structural integrity of the panels after ballistic impact so that a high degree of residual strength remains. This might be expected to enhance the response to multiple ballistic impacts. Previous work[3] has shown that the preservation of structural integrity and containment of the ceramic results in good ballistic performance even when ceramic contains cracks.

The ballistic performances of the standard and CFRP system are essentially similar. The presence of the CFRP layer results in only a small improvement in ballistic limit velocity. Both systems recorded ballistic limit velocities greater than the normal muzzle velocity for the test round.

CONCLUSIONS

A structural ballistic armour system has been described which can support cockpit floor loads even after ballistic impact whilst providing ballistic protection equivalent to an appliqué system.

The addition of a CFRP front panel to an existing ceramic faced composite armour system improves the bend strength by a factor of three and improves the energy to break by almost an order of magnitude.

The addition of the CFRP layer produces a more graceful failure with or without ballistic impact damage and preserves the structural integrity of the armour system.

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Horsfall, Ian

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