Composites for Ballistic Applications

Professor Paul J Hogg

Department of Materials
Queen Mary, University of London

THE NEED FOR COMPOSITE ARMOUR

The desirability of a composite solution for armour protection arises from the parallel needs for mobility and transportability (1).

Armour vehicles have traditionally been protected by armour based on steel. This gives rise to extremely heavy structures which provide logistical problems due to the need to transport the vehicles to a battle site. This may be undertaken for short distances by the vehicle's own power, by transporters for medium distances by road, or by ship if the distance is long and the transport is overseas. Mobility and speed of the armoured vehicle is a key component in its survival in a combat situation and hence the lower the weight, the faster and more manoeuvrable the vehicle can be for a given powerplant. With the current battlefield technologies, emission due to the powerplant, including heat, can be used by an enemy for targeting purposes and the philosophy of avoiding detection in order to survive requires smaller powerplants not bigger ones.

In the modern age rapid response is an increasingly important factor and the ability to transport military vehicles by air is increasingly desirable. However, the standard weight of a main battle tank, typically over 60 tonnes, is far too high for most military transports. Smaller vehicles could however be conceived at or around the 23 tonne limit of a Hercules if the armour protection was reduced in weight. "Fly-light-fight heavy" philosophies relating to the separate transport of a vehicle and its armour are being explored, with obvious risks if the armour is delayed! This realisation has lead to a number of prototype composite intensive armoured vehicles. In the USA the United Defense CAV-ATD composite armored vehicle has been produced, figure 1, while in the UK Qinetiq (formerly DERA) has produced an armor vehicle with a full glass fibre composite hull, the ACAVP – Advanced Composite Armoured Vehicle Platform, figure 2

Weight savings produced by these designs have been impressive in absolute terms, but less impressive as a fraction of the total weight of the vehicles. External armour, running gear and engines, turrets and armament all contribute to a significant fraction of the total vehicle mass. The probable solution to producing an armored vehicle with the weight characteristics required for rapid transportation will have to involve carbon fibre hulls. This is some way off in terms of development, let alone production. In the meantime lightweight composite armour will be used to improve speed and survivability in fighting vehicles and to provide additional protection to other vehicles such as the armoured Land Rovers used by both police and military services worldwide, figure 3.

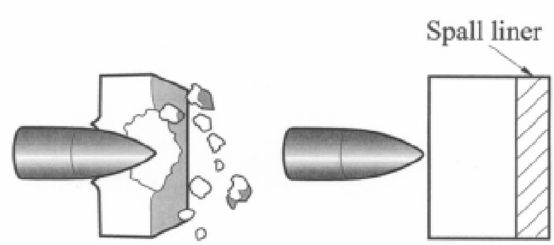
Figure 1 The United Defense CAV-ATD composite armored vehicle

Figure 2 The QinetiQ ACAVP – Advanced Composites Armoured Vehicle Platform

Figure 3 Armoured Land Rovers (CAV-100) with body armour based on S-2 glass fibre panels produced by National Plastics.

HOW DOES ARMOUR WORK

The role of armour is to protect a person structure or device. This is done by absorbing the kinetic energy of the projective. The energy may be absorbed by plastic deformation or fracture processes. It is usually desirable to ensure that if fracture processes occur in an armour system, that fragments of that armour and/or fragments of the projectile, do not themselves damage whatever is being protected.
This means that with certain armours there can be significant danger from spalling of material at the back face of a protective panel and an additional spall layer may be added to catch shrapnel-type fragments, figure 4.



Figures 4 Spalling at the rear of a ballistic impact (from Edwards ref 1)

An armour plate may have to fulfil two functions – a protective role and a structural role. If the material used for the armour is fulfilling both roles then it usually provides protection by having sufficient strength not to be ruptured during the impact. The tensile strength under high strain conditions will be the key factor in determining the thickness of material that must be used.

However there are many different types of projectiles that can be used to attack and penetrate an armour with armour piercing rounds driven by kinetic energy, chemical energy, and each type of round requires a somewhat different solution from an armour, figure 5. In some cases it may be sensible to allow the armour to deform over a large range in order to slow down and stop the projectile, whereas in other situations this may not be possible due to space constraints. The different projectile may concentrate the point of attack at certain places, and then it may be desirable for the armour to act to spread the area over which the projectile is damaging the material. For these reasons it is often desirable for armour to be based on a multimaterials, multilayer arrangement, with different layers providing specific functionality in the armour.

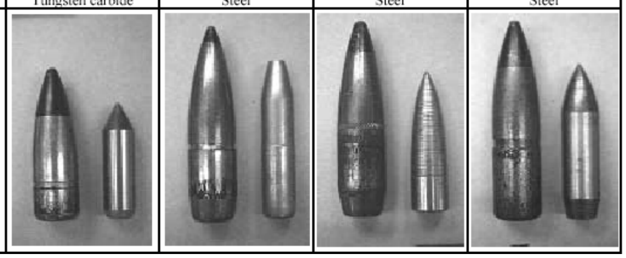
Ammunition	7.62×51 FFV Bofors AB	7.62×51 Hirtenberger Patronfabrik	7.62×51 AP Fabrique National	30-06 AP M2 US Government Arsenal
Total weight (g)	8.21	9.45	9.75	10.69
Core weight (g)	5.93	4.32	3.8	5.17
Core diameter (mm)	5.59	5.59	6.08	6.22
Core nose angle (deg)	58	flat - 2.27mm	45	54
Core hardness (Hv)	1450	750	870	785
Core material	Tungsten carbide	Steel	Steel	Steel
Complete projectiles and disassembled cores				

Figure 5 A selection of different military rounds (1)

Typical modern lightweight armour would now comprise a ceramic face plate with a more flexible backing layer. The role of the ceramic outer layer is to blunt the projectile and dissipate the load over a wide area. The ceramic layer will fracture during impact and the extent of fracture or rubblization, should be maximised but contained. The role of the ceramic is akin to provide a high speed wear process to destroy the projectile.

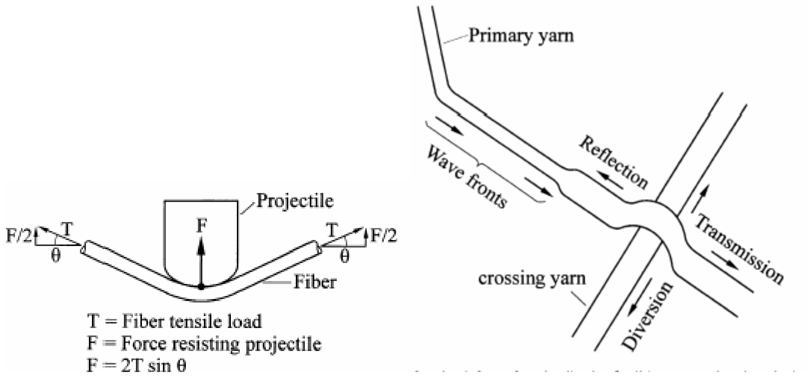
In this form of armour, the flexible backing plate will deform with the projectile and provide an integral structure while the round is slowed. If the round manages to penetrate the ceramic layer then it should be significantly slowed and the backing layer will catch the projectile or pieces of projectile (and pieces of ceramic) until the outermost layers exceed their tensile strains to failure.

Armours may be designed to meet specific threat levels, usually defined as a combination of projectile mass and velocity. It is important in some situations, where the threat is small arms fire up to heavy machine guns, to provide for a multi-hit capability as well as resistance to a single shot. This introduces a need for the damage process that results from each ballistic impact to be contained within the minimum area possible.

BALLISTIC PERFORMANCE OF COMPOSITE MATERIALS

The ability of a material to provide a useful contribution to an impact event depends on the hardness of the materials, which is critical for blunting a projectile, and the strain to failure which determines the ability of that material to absorb energy via a global deformation process involving either brittle cracking in the case of ceramics and composites, or plastic deformation in the case of some metals.

Composite materials rely primarily on brittle microfracture events to absorb energy. This means that the ultimate energy absorption is largely controlled by the strain to failure of the fibres. Once the fibres have ruptured the armour collapses and no further energy is absorbed. Composites based on high strength, high elongation to failure thermoplastic fibres might be expected to absorb energy via plastic deformation and drawing of the fibres. This process can happen effectively in dry un-impregnated fibres arranged in a textile form, but the ability of the fibre to deform in this way is severely restricted in a composite and energy absorption can be disappointing.



Figures 6 The load conditions on fibres in a woven textile during penetration rupture (after Edwards, ref 1)

For fibre composites where the fibres are bound with a matrix system, the fracture processes can be considered to operate in two separate phases. The high speed of the ballistic event means that dynamic effects do not give the target time to deflect with the impacting projectile. Initially the projectile will penetrate the sample by a inducing compression and shear failure. As the projectile slows it will begin to deform the plate in a manner more equivalent to slower speed deformation and the plate will bend. This gives rise to tensile elongation, delamination and fibre pullout and this is illustrated in figure 7.

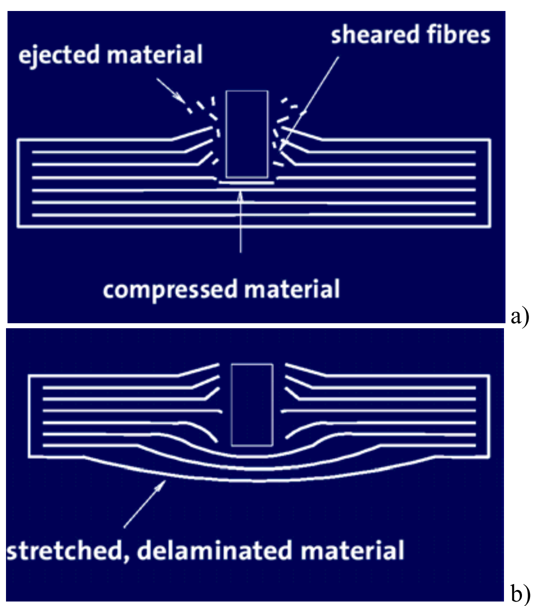


Figure 7 Ballistic impact of a composite plate a) The initial entry phase of the projectile results in a combination of compression and shear failure in the materials. b)This is superceded by tensile deformation and delaminations during the exit phase. (Courtesy QinetiQ)

In general terms glass fibre composites outperform carbon fibre due to their greater strain to failure, while S-2 glass fibre composites have outperformed E-glass for similar reasons. When the energy absorption is considered as a function of areal density then carbon becomes more competitive and this is a key factor when lightweight armour is being considered. The absolute performance of a composite panel is improved by increasing the fibre volume fraction in the laminate. However when the areal weight for a given protection level is considered, a high volume fraction may not be so desirable, figure

8 shows the relationship between V50 (velocity to ensure 50% of impacts penetrate the target) and areal weight of the glass fibre composite target for targets with different thicknesses and a common volume fraction and different volume fractions but a common thickness.

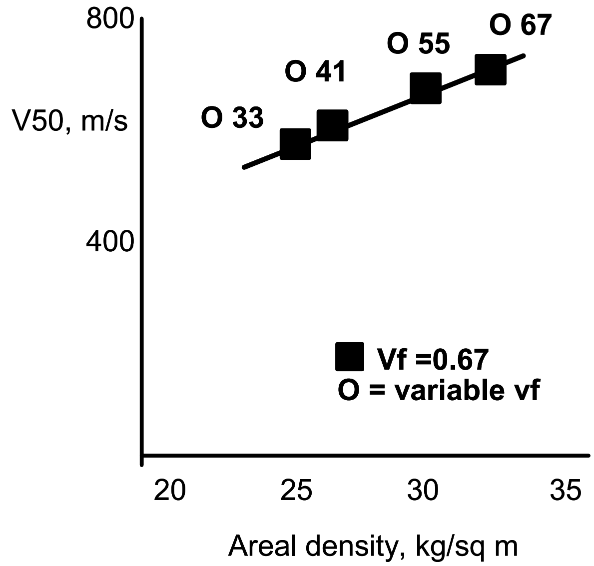


Figure 8 The relationship between V50 and composite areal weight (Courtesy QinetiQ)

Composites are soft armour materials. This means that their ability to withstand penetration from a shaped or pointed charge is limited. At the same time the hertzian contact forces that are generated upon impact are reduced compared to hard materials and most failures in simple composite plates involve bending. A hard surface layer would induce very high contact forces and the facture process could be very different.

The relative performance of different materials is difficult to judge from literature data that is available. This is largely due to problems in finding comparable methods of assessment, but also due to the fact that the performance of a ballistic panel of any material is not simply a function of its thickness. The ballistic performance is usually rated according to V50 rating. This data is often presented in absolute terms, sometimes as a function of thickness and sometimes by weight. Given that the data is also determined by the nature of the projectile (mass, shape etc) it can be seen that comparisons can be difficult – particularly if those presenting the data are not wholly objective themselves.

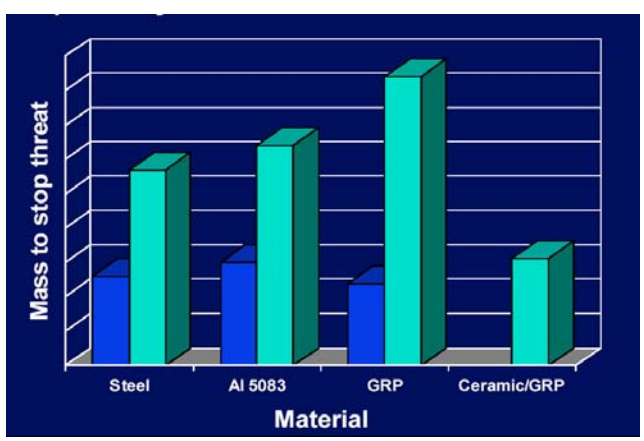


Figure 9 Comparison of different materials on the basis of weight of panel required to meet a given threat (Courtesy QinetiQ)

The plot above, figure 9, shows that there is little to choose between glass fibre composites and steel or aluminium on an absolute weight basis for the mass of a plate required to meet a given threat level.

One of the complicating factors however in interpreting such data relates to the interaction of the projectile and the ballistic specimen. If the specimen is thin, and energy absorption is related to bending deformation, then an increase in thickness should result in an increase in energy absorption as reflected by an increased V50 number. If however the increased stiffness of the panel changes the dynamics of the interaction, with the panel becoming sufficiently stiff that contact forces become the dominant factor, then the mode of failure can change. The failure modes will become dominated by shear and plug deformation and the energy absorption may decrease. This is illustrated by some work undertaken on laminates reinforced with aramid fibres, figure 10.

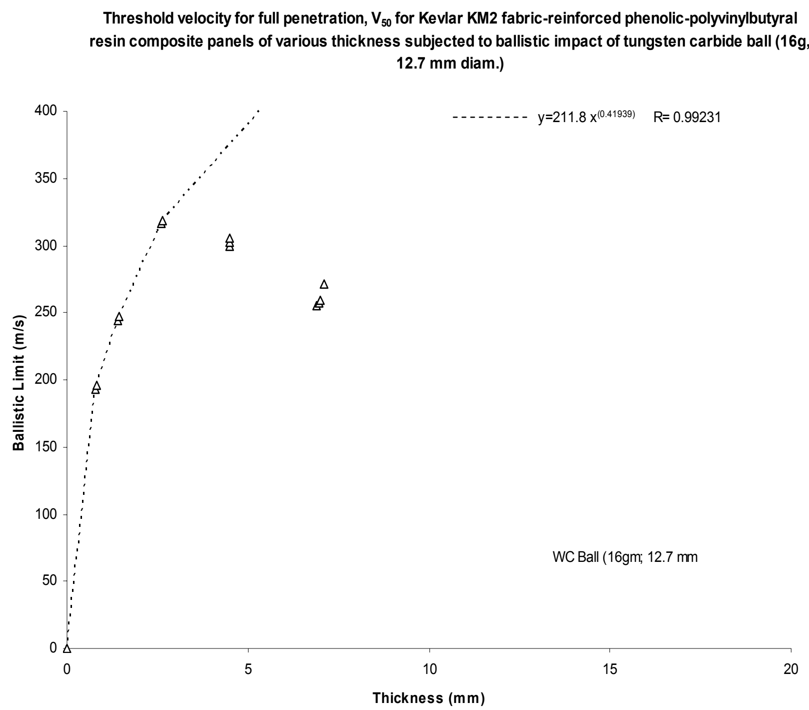


Figure 10 Changes in threshold V50 velocity for a given projectile as a function of thickness for aramid reinforced laminates (2).

The ability of a given type of composite to absorb energy depends on the type of fibre that is being used. The following tables such that there is a progressive improvement in the energy absorption capabilities, as measured by the V50 threshold (labelled V1 in the table) and the change from carbon fibre to PE fibres to PBO fibres, table 1.

Table 1 also indicates the difference between the V50 determined using a round ball projectile and a FSP round (which stands for fragment simulation projectile). Table 2 on the other hand present some data that illustrate tow key points. Firstly the effect of resin matrix is minimal, as the data is generated with polyurethane and a vinyl ester resin. Secondly the energy absorbed during ballistic impact is significantly greater than that absorbed during conventional falling weight impacts. The ballistic energy is similar to that absorbed when the dry fabrics are punctured in a slow test, table 2.

Table 1 Effect of reinforcement (3)

projectile	Areal weight kg/m^2	V_1 m/s	E_1, J	Specific V_1 $m^3/kg\ s$
Quasi-isotropic carbon fibre reinforcement in an epoxy matrix				
FSP	8.77	257	36.8	29.4
FSP	8.48	276	42.5	32.6
ball	8.78	274	33	31.2
Quasi-isotropic SK66 polyethylene fibre reinforcement in an epoxy matrix				
FSP	6.35	321	57.6	50.6
ball	7.88	431	81.7	54.7
Quasi-isotropic PBO fibre reinforcement in an epoxy matrix				
FSP	7.97	447	112	56.1
ball	7.88	431	81.7	54.7

Table 2 Effect of resin matrix and impact speed (3)

Energy Absorption (J) for full Penetration			
	Static Puncture (0.00025 m/s)	**Drop Weight Impact (3.78 m/s; 12.3 Kg)**	**Ballistic Impact (220-260 m/s; 1.1g)**
Spectra 900 Vinylester 5-ply composite laminate	31.9	16.9	35.6
	26.4	16.5	32.6
	26.3	16.3	32.6
		15.9	28.5
			21.0
average	28.2	16.4	30.1
Spectra 900, Polyurethane 5-ply composite laminate	26.9	15.7	32.9
	25.4	14.7	27.9
	25.2	14.7	26.2
	22.9	14.4	22.5
	22.3	13.4	20.3
	21.4	13.1	
	21.4	14.3	26.0
	1.17	1.14	1.16

The use of combinations of fibres and novel textile forms may provide further benefits to composite armour systems, either as stand along armours or as part of multicomponent armour systems. Recent data generated on toughened RINO fabrics where the main structural reinforcement is E-glass fibres shows remarkable improvements over conventional fabric reinforcements, albeit at impact speeds, figure 11.

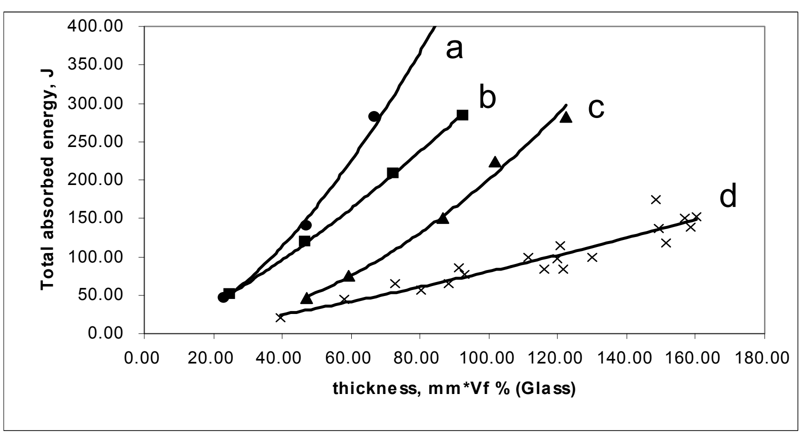


Figure 11:Energy absorption in impact of RINO toughened fabric laminates a) with polyester, b) with epoxy resins compared to c) thermoplastic PP matrix laminates and d) conventional fabrics with thermoset matrices

MULTI-COMPONENT ARMOURS

The most effective armours are not single component systems based on steel, composite or other systems, but multicomponent armours that combine layers of dissimilar materials. The components usually include an outer ceramic layer which acts to blunt and wear down the projectile, but where the ceramic layers are supported by a more flexible strong backing layer whose function includes catching the slowed remnants of the projectile. Figure 12 shows schematically the way that the ceramic transfers the impact forces to the underlying backing layer.

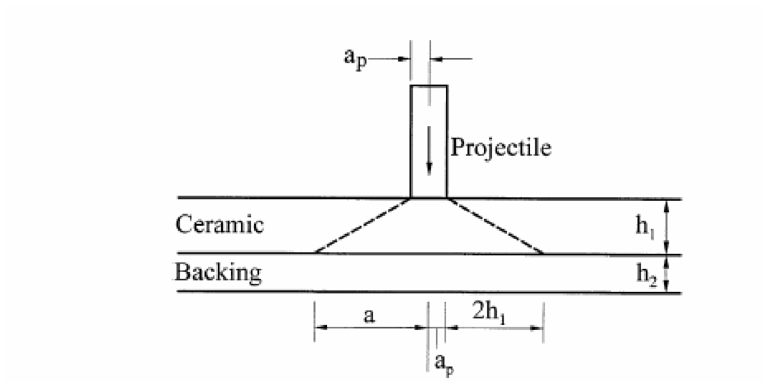


Figure 12. Cone of damage formed in ceramic face plates in composite amour (ref 1) .

The initial multicomponent composite armours were based on ceramic outer layers supported by steel or more usually aluminium layers. Fibre composites have now become recognised as the materials that provide the best combination of performance and weight.

Multicomponent composite armour systems are designed to provide protection by a controlled disintegration. Consequently most of these systems are not used to provide the basic structure of a vehicle such as the hull or a battle tank, but are applied as secondary appliqué armour. These systems can be removed, repaired and replaced as necessary.

The performance of an appliqué armour system is assessed in a slightly different way to primary armour. The main function of the appliqué armour is to moderate the initial impact and as such it can be deemed to be successful if the projectile penetrates but does so in such a way that the threat to the primary armour is reduced by a satisfactory margin.

A range of standard requirements have been identified based on a set spectrum of standardised threats. The standards passed by NATO are known as STANAG 4569, table 3.There are five identified threat levels and when tests are performed by subjecting panels to these threats, the success or otherwise is based on the damage sustained by a thin metal witness foil positioned behind the armour itself.

The design of a composite, multi component appliqué armour is tailored to meet the threat level appropriate to the end-use. The thickness of ceramic tiles, which are usually alumina, would be typically 8mm for level 2 threats and up to 25mm thick for level 4. The backing fibre composite layers could be 12mm and 60mm respectively.

Most armours would also posses an external fibre composite layer covering the ceramic tiles to provide general protection from minor damage.

More complex armour designs include layers of elastomers positioned behind the ceramic tiles which are intended to improve the multi-hit capacity of the armour.

Table 3 NATO STANDARDIZATION AGREEMENT (STANAG)

PROTECTION LEVELS FOR OCCUPANTS OF LOGISTIC AND LIGHT ARMOURED VEHICLES OCCUPANTS

Level	KE-Threat	Reference-Artillery-Threat
5	Automatic Cannon: APDS Ammunition Distance: 500m Angle: frontal arc to centreline: ±30^o sides include; elev. 0^o	Artillery: 155mm Estimated range of burst: 25m Angle: all around Elev. 0^o – 90^o
	Ammunition: 25mm x 137 APDS-T, PMB 073 V500: 1258m/sec;Vo: 1335m/sec**	
4	Heavy Machine Gun: AP ammunition Distance: 200m Angle azimuth 360^o; Elev. 0^o	Artillery: 155mm Estimated range of burst: 25m Angle: All around Elev. 0^o – 90^o
	Ammunition: 14.5 mm x 114 API/B32; V=911 m/sec**	
3	Assault and Sniper rifles: AP tungsten carbide core Distance: 30m	Artillery: 155mm Estimated range of burst: 60m Angle: azimuth 360^o Elev. 0^o – 30^o
	Ammunition: 7.62 mm x 51 AP (WC); V=930 m/sec** 7.62mm x 54R B32 API; V=854m/sec**	
2	Assault Rifles: Armour piercing steel core Distance: 30m Angle: azimuth 360^o; elev. 0^o – 30^o	Artillery: 155mm Estimated range of burst: 80m Angle: azimuth 360^o Elev. 0^o – 22^o
	Ammunition: 7.62 mm x 39 API BZ; V=695 m/sec**	
1	Assault Rifles: Ball ammunition Distance: 30m Angle: azimuth 360^o; elev. 0^o – 30^o	Artillery: 155mm Estimated range of burst: 100m Angle: azimuth 360^o Elev. 0^o – 18^o
	Ammunition: 7.62mm x 51 Nato ball; V=833 m/sec 5.56mm x 45 Nato ss 109; V=900m/sec 5.56mm x 45 Nato M 193; V=937m/sec**	

**V=Figures are mean values: tolerance of striking velocity for an individual shot is ±20 m/sec

The ability of the armour to withstand multiple hits is partially dependent on the restricted fragmentation of the ceramics tiles. It is ideal for the ceramic to fragment extensively behind the projectile but to restrict the lateral extent of fracture. To assist this the size of the ceramic tiles are limited and they are often hexagonal in shape.

The other contributory factor is the degradation of the fibre composite backing structure which becomes extensively delaminated. Stitched fabrics are now being explored in the USA in an attempt to restrict the spread of delaminations and to improve multi-hit performance as part of an overall optimisation of armour construction, figures 13..

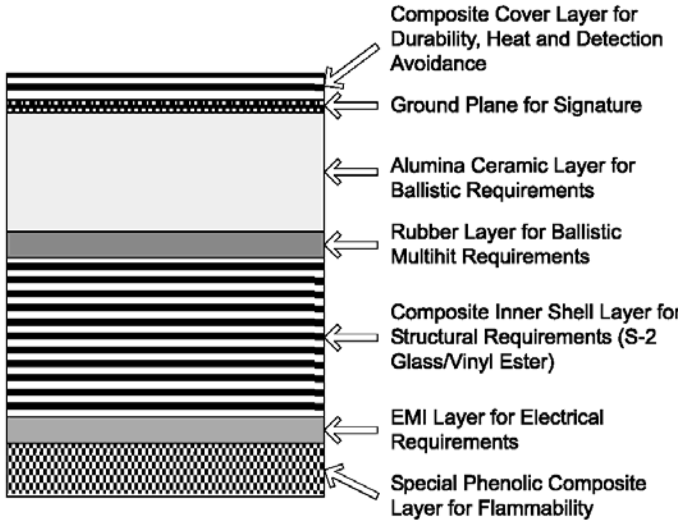


Figure 13 Proposed construction of lightweight composite armour developed by the US Army (ref 2).

Another development emanating from the USA is the use of aluminium foam layers between the ceramic and the backing plates, figures 14. The use of aluminium foam not only is claimed to improved multi-hit capabilities but restricts the back face deflection on the armour minimising the intrusion into any compartment or system that is being protected, (2)

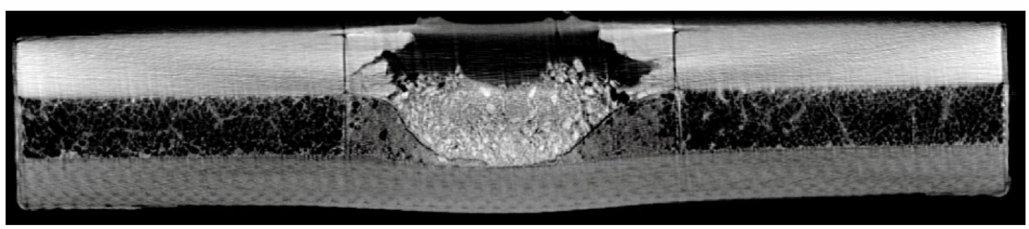


Figure 14 Composite multicomponent armour incorporating aluminium foam after ballistic impact.

In addition to these developments, materials innovations are always being considered with new organic fibres such as PBO and M5 and even the incorporation of shape memory alloy wires

The more complex the armour system, the more expensive it becomes to manufacture. In addition to layers of ceramic tiles, composite backing plates, elastomers or aluminium foam layers, it may be necessary to incorporate separate inner and outer composite layers with improved fire performance, possibly manufactured from phenolic plates. Manufacturing costs increase dramatically, not simply because of the cost of the materials involved but due to the multiple manufacturing stages for separate production and assembly of the various elements. Many manufacturers are exploring integrated manufacturing techniques based on infusion processes. These processes are compatible with the use of stitched performs for the composite backing plate and can be use to surround and encapsulate the ceramic tiles.

The US Army Research laboratories in conjunction with the Centre for Composites at the University of Delaware has culminated in a number of novel manufacturing concepts for armour. These include VARTM and CIRTM (3). VARTM is a process variant designed to eliminate waste components generated during conventional vacuum infusion processing, whereas CIRTM is a co-injection process whereby different resin systems are infused into specific layers of the composite/armour perform simultaneously, allowing phenolic layers and epoxy layers to be produced in a one shot process.

POTENTIAL

The global political situation with the threat of direct conflicts and terrorist attacks is increasing the interest in protection and armour for people, vehicles and structures. The market for composites in military vehicles is large and growing. The potential for applications in non-military use is also enormous.

The industry could usefully do with more robust design tools in order to design composite armour for specific threat levels and better manufacturing systems to provide that armour cost effectively. It is probable that much of the armour required for the major manufacturers of military vehicles will be produced in-house, especially if the main hulls are to be produced from composite systems. The market for additional appliqué armour and armour for "up-armouring" conventional vehicles looks however to be considerable and only likely to grow in the current uncertain world climate..

ACKNOWLEDGEMENTS

Most of the data present in this report has been generated by the University of Delaware, US Army Research Laboratories, QinetiQ. The author is grateful to these organisations for the use of their results in compiling this overview.

REFERENCES

1 M. Edwards "Land Based Military Applications" section 6.37, Comprehensive Composite Materials, published by Elsevier.
2 B.A.Gama, T.A.Bogetti, B.K.Fink. C.J Yu, T.D.Claar, H.H.Eifert, J.W.Gillespie Jr, "Aluminium foam integral armour: a new dimension in armour design", Composite Structures, 52, (2001), 381-395
3 B.K.Fink, J.W.Gillespie Jr "Cost effective manufacturing of damage tolerant integral armour" ARL Technical Report ARL-TR-2319, Sept 2000