Mitigation of Bullet and Fragment Threats Using Armours and Other Protective Systems

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Introduction

The main purpose of mitigation systems is to ensure that both the likelihood and the severity of an event are reduced and that the amount of collateral damage is also minimised. Figure 1 illustrates an unmitigated explosive event of the type that one seeks to avoid.

Figure 1: A typical violent reaction

Attack by bullets or fragments represents a serious IM threat for a wide range of weapons in storage and transport. Protective measures against these may be incorporated into the packaging or form part of a vehicle structure. Armours constitute an important of protective material of this type. Unlike the situation with normal armour applications, it may not be necessary to completely arrest the threat bullet or fragment, merely to reduce its speed. An alternative approach is to use measures that can reduce the effect of a bullet or fragment of given velocity on the energetic filling of the munition. This latter concept is complementary to the use of armours. Both approaches (armour and non-armour) are discussed in this paper.

The type of material used to reduce the severity of the impulse transmitted to an explosive or propellant is also capable of modifying the shock transmitted into a munition through its mountings. This aspect is also covered.

1. Armours

QinetiQ has conducted studies on armour systems capable of providing the necessary degree of protection. In general, the approach has been to make use of armour data and modelling that is generally available and to supplement this by some of QinetiQ's own models as well as some selected ballistic trials. Naturally all such solutions have mass, lost volume and cost penalties associated with them and clearly for any particular application a protection system may be ruled out on any of these grounds. The paper describes a considerable body of information on such armour systems that QinetiQ has assembled, and also describes trials that have been carried out to determine residual velocities. This has been supported by ballistic penetration modelling. For simple metallic armours the THOR equations and other basic models give some indication of the residual velocity, but for more complex and muti-layered armours more detailed non-linear dynamic modelling is required, and the AUTODYN® hydrocode has been used for this purpose.

For any projectile within the wide spectrum of bullet and fragment threats, covering a range of masses, shapes, hardnesses and velocities, suitable armour solutions have then been identified and the areal densities and thicknesses quantified for the candidate protection systems based on them.

2) Bullet and Fragment Threats

Two scenarios encompassing bullet and fragment impact threats have been specified within STANAG 4439 "Policy for Introduction, Assessment and Testing for Insensitive Munitions (MURAT)".

The bullet threat (STANAG 4241) consists of the 0.5" M2 AP (armour piercing) round. The fragmentation threat (STANAG 4496) consists of a 14.3 mm cylindrical FSP (fragment simulating projectile). Two velocities are given, approximating to airburst fragmenting warhead threats.

In all cases the protection must be such that the response of munitions upon impact by these projectiles is no more severe than a burning reaction (Type V). Table 1 summarises the dimensions and impact energies of the STANAG threats.

	Calibre (mm)	**Mass (g)**	**Strike velocity (m/s)**	**Impact Energy (kJ)**
0.5 M2 AP Brass-cased, hardened steel core, pointed nose.	12.7	45.5	850±20	16.44
FSP Mild steel (270 HB) cylinder, 20° Conical nose.	14.3	18.6	1830±60	31.14
	14.3	18.6	2530±90	59.53

Table 1: STANAG 4439 ballistic threat requirements.

The lower velocity fragment forms a broadly similar level of threat to that of the AP round. The higher velocity fragment is far more severe.

Effective protection against either AP rounds or fragmentation threats relies upon two mechanisms; the shattering of the hardened steel core in the AP round and the deformation and retardation of fragments.

The former mechanism relies upon the *hardness* of an armour system to fracture the AP projectile core. The latter mechanism relies upon *toughness* and absorbency to dissipate the kinetic energy of a high velocity fragment.

3) Material Properties and Armour Types

To offer effective protection against both the AP bullet and the fragment threats an armour material needs to be both hard and tough. For the extremes of hardness and toughness these properties are inversely proportional; ultra-hard materials tend to be brittle, ultra-tough materials tend to be soft. Moderately hard, moderately tough armours are achievable to a limited extent using monolithic metallic plate, such as RHA steel or other alloys. This approach, however, comes with a large weight penalty.

For higher hardness, materials such as ceramics offer superb AP protection. However, they require a tough backing material, such as a fibre composite or a metallic plate, both for structure and to absorb fragments from an impact. Laminar armours such as these can offer highly effective lightweight armours and can readily be optimised for either fragment or bullet protection, but they are typically high cost.

An extension of laminar systems is the use of spaces between armour layers. These allow incoming projectiles to be fragmented or tumbled between the lamina, thus reducing their energy density in further impacts. Spaced arrays are typically formed from perforated steel or fibre composites (GFRP). Considerable weight savings can be achieved with these systems, although they require high volume in order to be fitted.

The Venn diagram in Figure 2 shows some materials arranged as to their weight, thickness and cost – three of the main constraints within armour design. Note that the space for an 'ideal' armour material at the centre of the plot is empty. An armour design is generally always a compromise between the three given constraints.

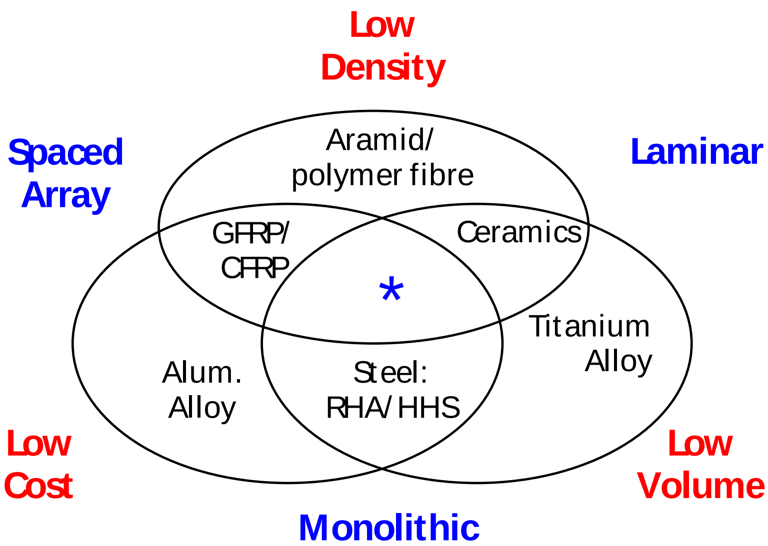

Figure 2: Venn plot showing typical armour materials arranged according to the constraints of weight, thickness and cost. Superimposed in blue are three generalised armour design types, also arranged to the same constraints.

The typical armour weight requirements to meet the STANAG 4569 bullet protection levels[11] for three different material types are shown in figure 3, which also includes the requirements for the IM bullet threat as a comparison. This figure has been compiled by a combination of a literature review, some specific ballistic trials and ballistic penetration modelling.

The computer modelling results indicate that the severity of the IM fragment threat at 1830 ms^{-1} is approximately equivalent to STANAG 4569 Level IV, i.e. 14.5mm AP. Note that whilst the FSPs used in STANAG 4569 are slower than the IM fragment they are also much larger.

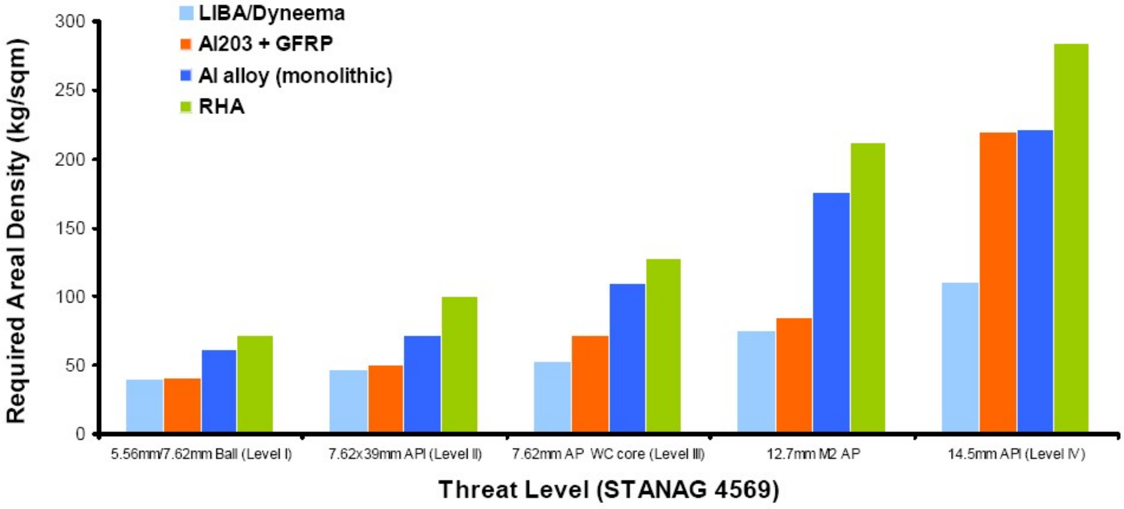

Figure 3: Weight (areal density) requirements for different armours to meet various bullet threat levels (Levels I-IV of STANAG 4569)

4) Residual Velocity Modelling

It is known that a major issue with bullet and fragment attack is the vulnerability of an explosive filling to shock induced detonation. In general, armour design is based on the criterion that a projectile must be prevented from penetrating the armour so as to prevent injury to life. However, as previously stated, the protection of munitions only requires that in the worst case a controllable burning reaction is initiated. This means that if an armour system can also be used to slow down projectiles to below known the shock-detonation threshold of the explosive this will be an acceptable outcome. Knowledge of the residual velocity of a projectile after penetrating armour systems, and its likely mass and shape, is, therefore, highly valuable in designing for IM.

Because armour traditionally deals with penetrate/no penetrate testing, comprehensive residual velocity data for known projectiles and materials are scarce. QinetiQ has, therefore, developed a modelling capability to begin to capture this information.

The AUTODYN-2D hydrocode (by Century Dynamics) has been used to model the non-linear dynamic behaviour of the AP bullet and fragments impacting a number of typical armour materials. From this model a series of residual velocity curves have been obtained, and hence the capability to optimise laminar and spaced systems. Figures 4 and 5 depict screen shots from AUTODYN and Figure 6 shows a selection of residual velocity curves.

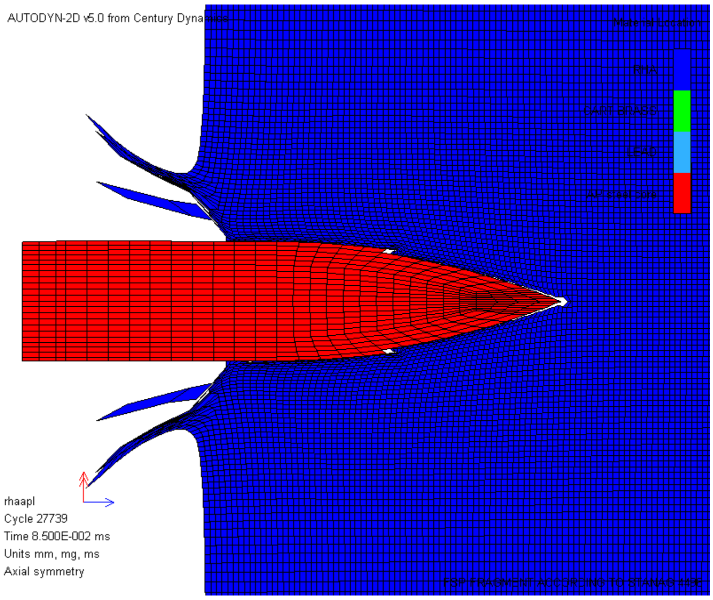

Figure 4: AUTODYN-2D screen-shot of 0.5" M2 AP round impacting thick RHA.

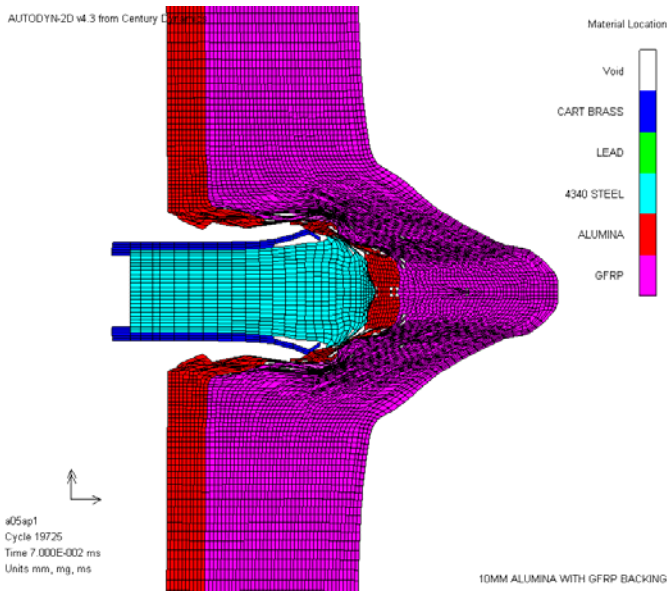

Figure 5: 0.5" M2 AP impacting a laminar ceramic/fibre composite armour system. The model depicts the erosion of the AP bullet tip.

Whilst computer modelling saves considerable resources compared to the experimental testing of materials, the highly complex interaction of materials and their algorithms in a multi-layered impact model creates plenty of scope for error. To ensure that the residual velocities obtained from the model were realistic they were validated during and after development using known experimental test data.

A number of range trials were employed to gather data. This involved the ballistic testing of a sample set of materials of varying thickness under STANAG 4241 conditions. Residual velocities were obtained using flash X-ray photography, which also yielded information on the deformation, fracture and tumbling of projectiles after penetration. A selection of data points is also plotted in Figure 6, showing good agreement with the modelling results.

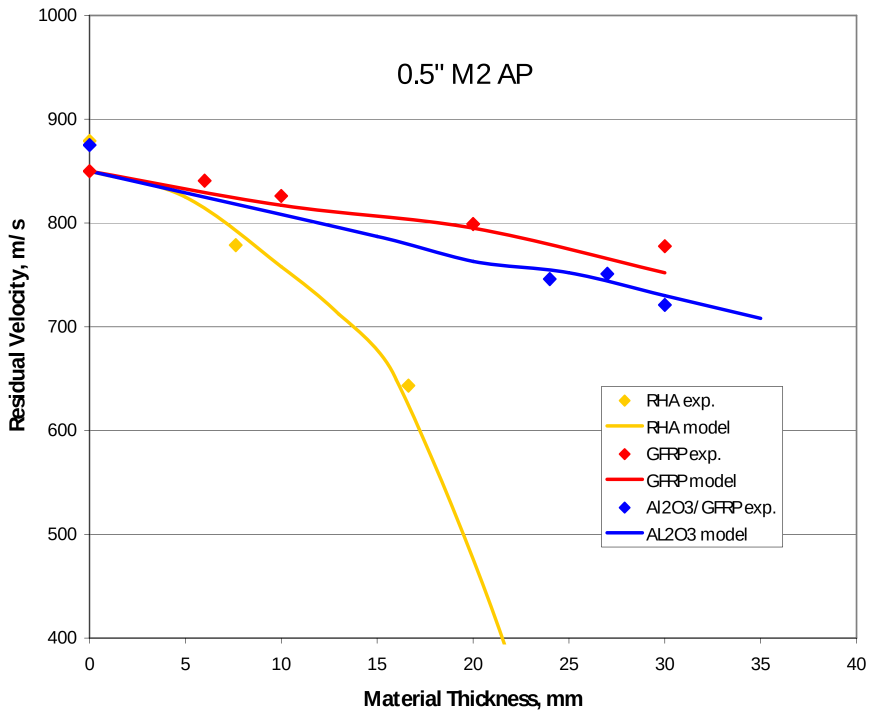

Figure 6: Modelled residual velocity curves for RHA (yellow), Glass fibre (GFRP – red) and Alumina ceramic/GFRP (blue). Experimental data points are also shown, validating the modelling results.

5) Shock and Energy Absorption by Non-Armour Protective Materials

This section discusses two techniques which, although they cannot be classified as armours, can act in a complementary manner in mitigating impact threats.

A major consideration in the protection of energetic materials from the effects of impacting projectiles is minimisation of the role of the shock generated on very high velocity impacts. Even when perforation is not achieved, it is sometimes the case that initiation is caused by shock alone. Studies on the modulation of the shock experienced by systems using techniques developed by QinetiQ from its earlier work on acoustics have enabled new shock absorbing materials to be developed. These synthetic polymeric materials possess remarkable shock-absorbing characteristics, which QinetiQ has optimised through material composition and format, as shown in figure 7. This material is ideally suited to a shock-absorbent liner application by virtue of its dynamic mechanical properties. It has a low dynamic modulus and high visco-elastic loss compared with polyurethanes for example. In solid sheet form its compliance is determined by the complex plate modulus (M*), where

$$M^* = K^* + 4G^*/3$$

and where K* is the complex bulk modulus (~2.5 GPa) and G* the complex shear modulus (~1 MPa).

Figure 7: A sheet of formed polymeric shock absorbing material

The inclusion of an additive to the material and modification to the profile or topology of liner surface as shown in figure 7 can significantly reduce K* and G* and hence M* by 1 to 3 orders of magnitude. This increases the compliance, allowing more shear strain energy to enter the material where it can be dissipated by the associated, high visco-elastic losses.

Four liner materials were tested, one without additive and three with different percentages of additive. All four options are capable of reducing the probability of detonation of HE in containers lined with these materials. Impact velocities were increased by ~10% with no detonation for each case. It is expected that profiled liner materials will be even more effective, since the conical protrusions allow more gradual, non-linear deformation as the pyramid structures on one face are compressed. Moreover, such structures situated beneath a fibre-reinforced polymeric material, such as GRP, permits it to deform and delaminate due to impact. This is a significant mechanism in the protection performance of such materials.

The foamed butyl rubber approach is equally applicable to projectile packaging for reducing the effects of air blast. Thus a hardened container can reduce the amplitude of the pressure wave, but high acceleration levels may yet be transmitted to the projectiles inside. A study has been carried out which drew on the findings from a recent small programme which characterised the dynamic mechanical properties of a number of composite 3D woven pre-forms. These pre-forms consist of two woven roving, fibre sheets, loosely linked together with through or Z plane fibre reinforcement. The CAPATEX family are low-cost COTS polyester materials (glass and carbon fibre variants are also available) that can be infused with a bespoke resin or foam to provide it with shape and multi-functionality. For experimental study some prototype collars ~10mm thick and 60mm diameter (an example is shown in figure 8) were fabricated and infused with a visco-elastic resin and used to support a dummy projectile (400mm x 60mm diameter). This was mounted on an aluminium panel which was then impacted with an instrumented force hammer and the acceleration at the point of impact and that transferred to the missile were measured. The simple test supported by some predictive modelling illustrated their capability for isolating the impact but it is stressed that this is not a high velocity, high strain rate test. The isolation performance of the collar can be controlled by changes to its through-plane stiffness and length.

Figure 8: A viscoelastic missile isolation collar

Acceleration transfer measurements have been carried out; (a) where the CAPATEX has been formed into semi-cylindrical cups (see figure 8) to support the missile by infusing only the outer layers with a viscoelastic resin and (b) where the through-plane fibres have been additionally infused. Each variant was formed into collars 200mm and 50mm long. Effectively the stiffness of the isolators is varied by the matrix resin modulus and by the length or number of the collars. The longer collars were used as single isolators but in the case of the 50mm collars, two were used. Figure 9 illustrates the isolation capability of the 50mm collars expressed as Fourier transforms of the input and output signals. Thus the red line is the input inertance (acceleration/force) at the point of impact on the aluminium plate and the blue line is that transferred to the missile.

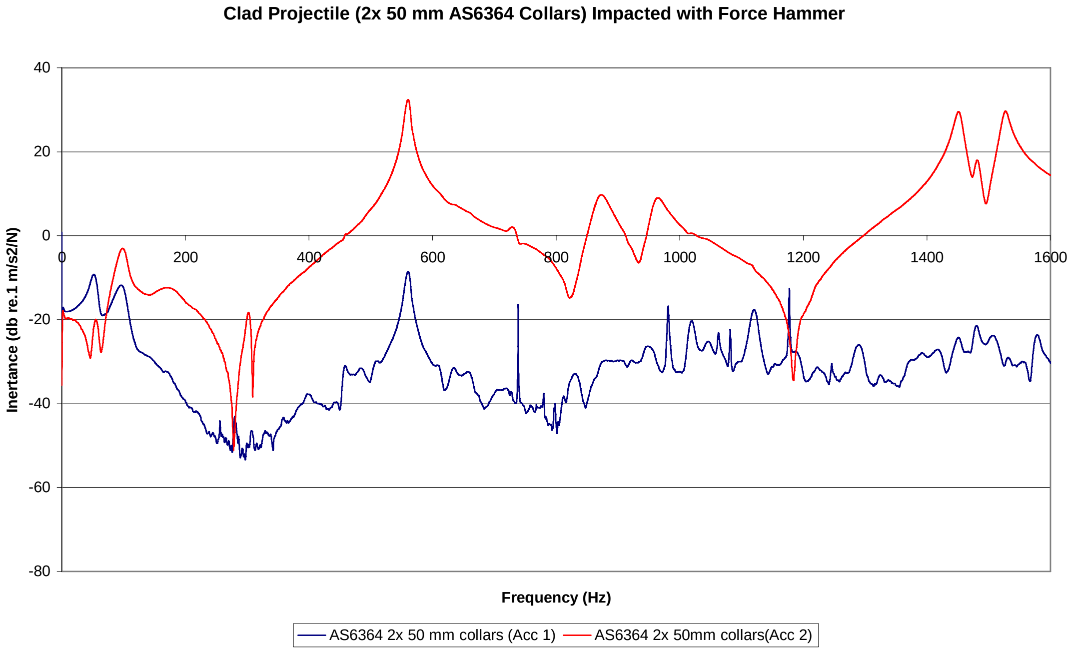

Figure 9: Fourier transforms of the input signal received by the collar and the output signal transferred to the munition

The acceleration levels are substantially reduced at high frequencies but there is a cut-off frequency at around 70Hz. At frequencies below the cut-off there is an increase in the acceleration caused by the mass/spring resonance associated with mass of the missile reacting with the stiffness of the collar. This is a natural effect and will exist with all forms of packaging. The cut off frequency can be selected by choice of visco-elastic resin and the resonance peaks seen in figure 9 can also be shifted by this means. It is not known at this stage whether the frequency band in which amplification occurs is damaging or what the cut off frequency should ideally be. A compact polystyrene foam of the type often used for commercial packaging for example, would be a lot stiffer and it is possible that the frequencies that are damaging to munitions might be enhanced. Liners with packing collars of various stiffnesses be undertaken to help establish this.

6) Conclusions

Armour design can be useful for the protection of munitions and their ability to conform to IM standards. As well as offering full protection against bullet and fragmentation threats, armour can also be used to slow down projectiles, thus saving redundant weight.

The capability to realistically model projectile impacts and their residual velocities for a wide range of materials and bullet and fragment types provides a powerful tool in the optimisation of armour systems. Using its expertise in armour, computer modelling and test and evaluation, QinetiQ has developed a strong capability in this area.

The use of visco-elastic materials appears to be a valuable means of augmenting the effect of armours, either as munition liners to raise the critical impact velocity for SDT, or as a means of reducing the severity of the shock transmitted to a packaged weapon through its mountings.

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