The Demonstration of a Predictive Modelling Approach to the Design of Mass Efficient Fragment Mitigation Systems

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Abstract

The advent of Polymer Bonded Explosives (PBX) and other mitigation technologies have provided the weapon engineer with the ability to design weapons which are safe with respect to thermal threats. The threat of high speed fragment impact continues to challenge the weapon engineer and often results in compromises to mitigate the threat. A simple warhead solution comprises a thick and therefore heavy metal case backed by a rubber liner. This can represent a parasitic mass to the system and increased collateral damage, both are undesirable.

QinetiQ undertook a project to demonstrate the potential mass efficiencies of using a fragment mitigation system comprising combinations of alternative materials and demonstrate a highly efficient design process utilising predictive modelling tools and small scale laboratory tests to design them.

The project considered a baseline cylindrical PBXN110 filled warhead with a steel case and rubber liner known to reduce the hazard reaction to type V from a STANAG 4496 fragment. Four materials were selected which had potentially beneficial properties. The material shock properties were predicted and validated against small scale laboratory tests. The QinetiQ modelling tools (GRIM (Eulerian) and DYNA (Lagrangian) hydrocodes with the CHARM ignition and growth model) were then applied to identify six design options. The designs offered a 20% to 60% mass saving, one also offered a volume saving.

A fragment firing programme was then completed to confirm the predictions. Four of the designs resulted in a type V reaction or less, the reaction in two of the designs could have had the potential to build to a type IV reaction.

The project showed that it was possible to significantly reduce the case mass and still mitigate fragment hazards. It also showed that it was possible to design mitigation systems in a highly efficient manner through the use of predictive modelling tools. The capability could also support the design of packaging to mitigate threats.

Introduction

Technological advances in the design of explosive ordnance are making possible the development of a range of munitions termed Insensitive Munitions (IM) or Munitions à Risques Atténués (MURAT) which are less vulnerable to accidental and combat stimuli than previous weapons. Such munitions remain effective in their intended application, but are less sensitive than their predecessors to extreme but credible environments such as heat, shock or impact.

While the introduction of IM into service is intended to enhance the survivability of logistic and tactical combat systems and minimize injury to personnel, IM also have the potential to provide more cost effective and efficient transport, storage, and handling of munitions. The policy for the introduction, assessment and testing of IM is addressed in STANAG (Standardisation Agreement) 4439.

During its life cycle (storage, handling, transportation, operational deployment), a munition may encounter different types of unplanned stimuli (hazards) that can cause an energetic response. Fragment impact is one of these stimuli. A simple fragment mitigation system often comprises a thick and therefore heavy metal case backed by a rubber liner. This can represent a parasitic mass to the system and increased collateral damage, both are undesirable.

This work aimed to demonstrate the capabilities of a highly efficient design process utilising a combination of modelling tools and small scale laboratory tests to design example mass efficient fragment mitigation solutions. The effectiveness of the designs and the mass efficiencies potentially achievable would be ultimately demonstrated in a fragment firing programme.

The QinetiQ modelling tools applied were the GRIM Eulerian and DYNA Lagrangian hydrocodes with the CHARM [1] (Cook-Haskins Arrhenius Rate Model) ignition and growth model together with the QinetiQ Porter-Gould QSPM (Quantitative Structure Property Modelling) EOS (Equation of State) technique [2].

The methodology applied was:

- To predict the EOS of the candidate materials
- Where possible to validate the EOS
- Identify salient material attributes and design potential mitigation systems
- Simulate the fragment impact and estimate the likely response
- Perform an iteration cycle to improve mass efficiency
- Confirm the predictions with CHARM

The fragment mitigation system would be designed from layers of Dyneema®, S2 Glass fibre reinforced polymer (GFRP), foamed EPDM (Ethylene Propylene Diene Class M) rubber and foamed aluminium. These materials were pre-selected and pre-supplied as candidate materials based upon their expected energy absorbing, shock mitigation and/or strength properties.

A configuration relevant to medium size weapon systems was chosen as the example warhead. It was cylindrical in form and 100mm in diameter. The mass efficiencies were calculated per unit length, it was filled with PBXN110, a HMX-HTPB PBX. The cylindrical form would largely preclude large case thicknesses on mass efficiency; however a 30mm limit was applied to the case thickness to ensure the warhead remained relevant to a range of missile systems. The baseline case specification was an 8mm steel backed by a 3mm butyl rubber, a case design known to exhibit a type IV/V reaction in fragment impact tests.

The objective was to reduce the response of a PBX filled munition to type V reaction (energetic material ignites and burns without propulsion; debris stays in area as defined in NATO (North Atlantic Treaty Organisation) AOP (Alliance Ordnance Publication)-39 [3]) or better in the STANAG 4496 test.

Mitigant Material Selection

The materials were pre-selected as candidates based upon their reported characteristics:

- **Dyneema®** is generally agreed to have a better ballistic response under impact compared with conventional fibre reinforced polymer armour material e.g. glass fibre reinforced polymers (GFRP) under certain ballistic threats. Work carried out by QinetiQ has identified significant distinct differences in energy absorption mechanisms between these materials.
- **S2 GFRP** composites have a wide range of applications as structural materials. The S2 GFRP is made from S2 glass-woven roving in a polyester resin matrix. The density of this material ranges from 1.85 - 2g.cm^{-3}, providing lightweight and enhanced ballistic resistance. Composite materials possess some clear advantages

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over more conventional mitigation materials such as a high specific modulus, high specific strength and also shock resistance properties.

- **EPDM rubber** has a low density and low impedance allowing thin layers of the rubber to be used in contact with higher density materials in order to reduce the shock transmission and mitigate the high shock peak pressures that can initiate the explosive.
- **Foamed aluminium** has a very low density and hence lends itself to very lightweight fragment mitigation solutions. The yield stress of these foams is less than aluminium but the Crush Plateau Zone can be very large. These materials can, therefore, absorb large amounts of energy before they compact and fail. Foamed aluminium perform best when used in conjunction with a large metal plate.

Material Model Construction and Validation

The EOS were created from first principles for each material. Material testing was then undertaken using the 50mm calibre single stage gas gun facility at the Cavendish laboratory in Cambridge University, shown in Figure 1 for GFRP. Pressure gauge data was used to provide shock velocity/particle velocity data to validate the EOS.

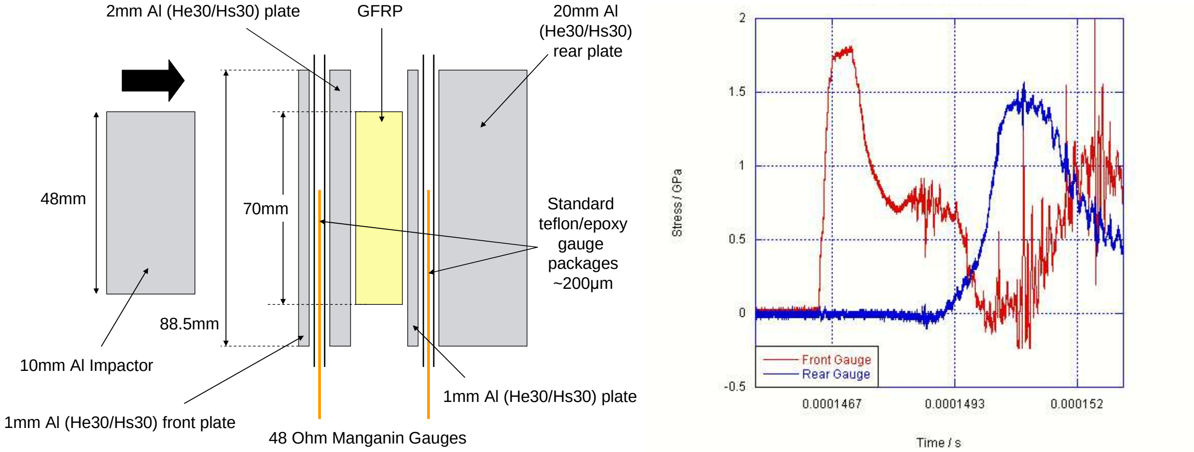

Figure 1: Setup and stress traces for testing of GFRP plates in anvil setup at 253ms^{-1}.

A comparison of the Porter Gould EOS (curve) with data (points) provided by Cavendish Laboratory is shown for Dyneema® and S2 GFRP in Figure 2. The foamed aluminium material model was validated through modelling the experimental set up and comparing trace data as shown in Figure 3. Cavendish laboratory was unsuccessful in recording the transmitted shock through EPDM rubber and consequently this EOS could not be validated.

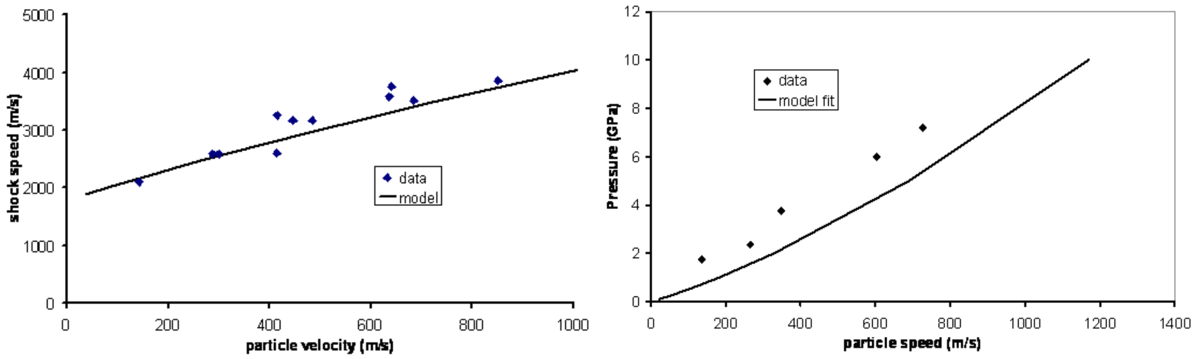

Figure 2: Porter Gould EOS vs. experimental data for Dyneema® (left) and S2 GFRP (right).

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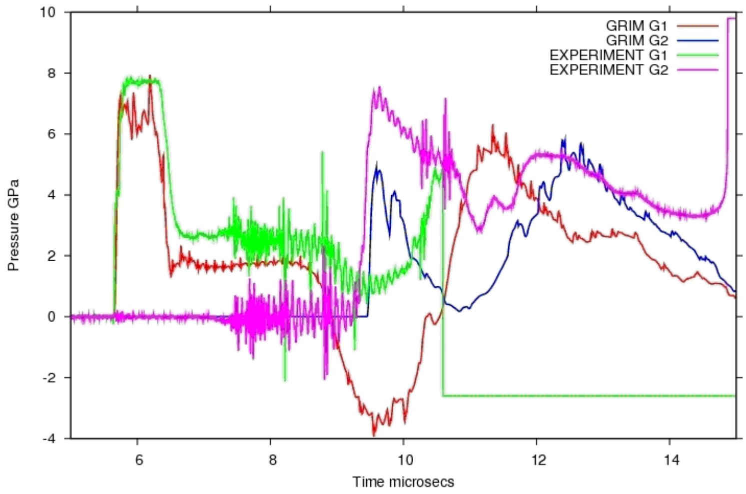

Figure 3: Simulation comparison with plate impact experimental data of aluminium foam

Appliqué Design

In order to assess and evaluate different design concepts, simulations were carried out using the QinetiQ Eulerian Hydrocode GRIM to model fragment impacts of explosive charges protected by these appliqués. Simulations were carried out in 2D to take advantage of the axisymmetric nature of the scenario. All impacts at an impact velocity of 2530ms^{-1}were simulated with 0º obliquity as shown in Figure 4. The resolution was defined, from QinetiQ experience, to enable accurate prediction of the shock transmission and deformation/fracture of the barrier and response of the explosive behind. The steel fragment as specified in STANAG 4496 is also shown in Figure 4.

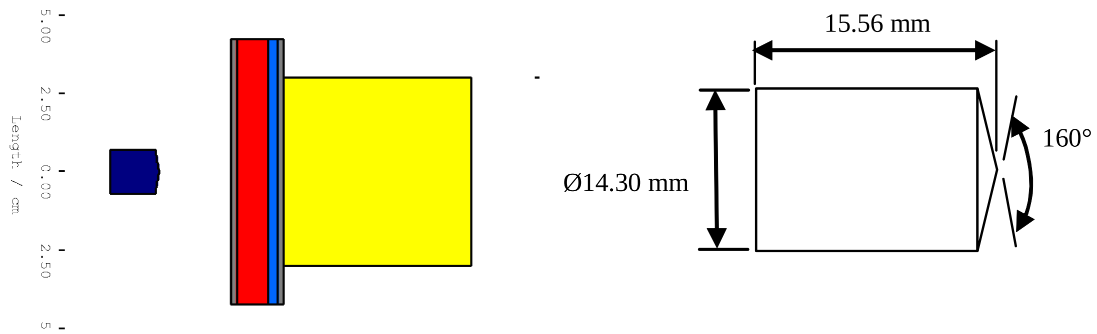

Figure 4: Simulation setup and STANAG 4496 fragment.

Previous firings by QinetiQ had been conducted against PBXN110 charges with protective cases of EN24 condition T steel and butyl rubbers. Within the firing set there were two shots which resulted in a small degree of reaction; these were used as the baseline, Table 1. The methodology applied the threshold obtained from a simulation of the 12.65mm EN24-T barrier, since a validated butyl rubber EOS was unavailable.

Barrier type	**Velocity (m.s^{-1})**	**Event Type**
EN24-T (12.65mm)	2592	IV
EN24-T (8mm) + Butyl (3mm)	2589	IV/V

Table 1: Baseline experimental shots

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Design options were assessed on the attributes of the pressure and energy profiles permitted to transmit into the explosive by the barriers. The most effective mitigation designs were thinned down such that they gave a mass reduction of at least 20% over the 8mm steel/3mm butyl rubber baseline whilst maintaining equivalent or greater shock mitigation.

Since the materials were pre-supplied in set thicknesses, it was not possible to infinitely vary the thickness of each layer. None of the layers were thinner than 1mm, this also avoided increasing the resolution in the simulations to accurate resolve very thin layers in this demonstration programme.

The down-selected design concepts assessed via the simplified pressure/energy methodology were then confirmed via modelling studies using the CHARM ignition and growth model in the QinetiQ Lagrangian code DYNA. CHARM primarily predicts whether a shock to detonation reaction (STD) will occur, however it can also provide some guidance for other reaction types without actually predicting violence.

Figure 5 shows that very little explosive was predicted to undergo an STD reaction.

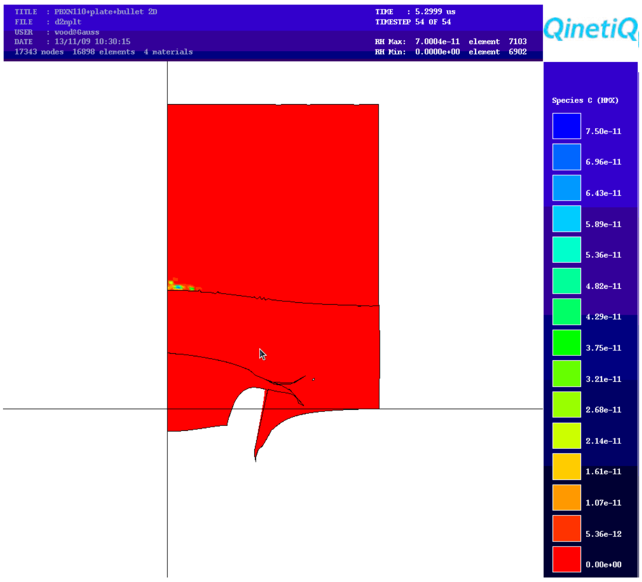

Figure 5: Final product concentration at 5.3µs after impact (very little reaction)

Five design solutions with 20-40% mass reduction were identified for the firing programme with three firings to be carried out of each design. A sixth, thinner, design (60% mass reduction) was also identified to be tested should the initial five design solutions effectively mitigate any violent reaction in the explosive. Ultimately, all six designs, summarised in Table 2, were tested during the firing programme.

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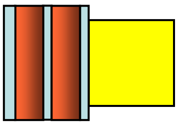
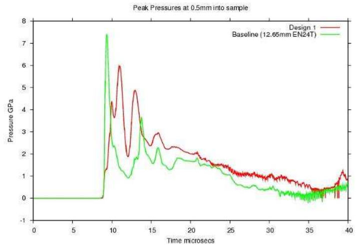
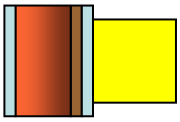
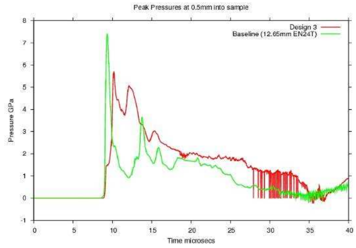
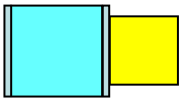
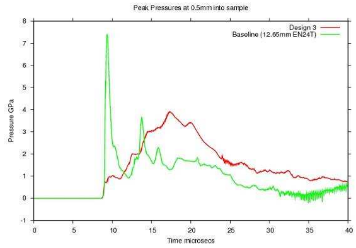
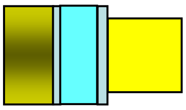
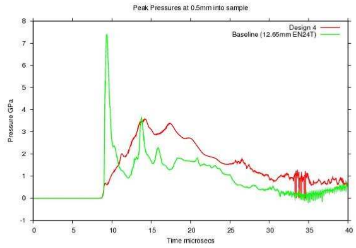
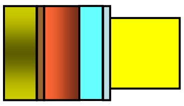
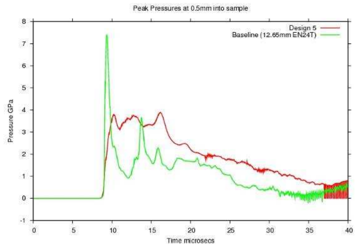
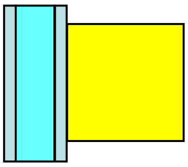
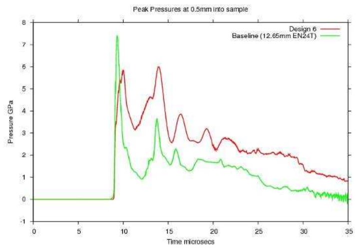
	Layers	Graphical representation	Mass $(g.cm^{-1})_1$	Thickness (mm)	Predicted pressure profile$_2$
1	2mm Steel /5mm Al Foam /1.5mm Steel /5mm Al Foam /1.5mm Steel		189 (-21%)	15.0	
2	2mm Steel /10mm Al Foam /2mm EPDM Rubber /2mm Steel		179 (-25%)	16.0	
3	1.5mm Steel /20mm Dyneema /1.5mm Steel		164 (-32%)	23.0	
4	10mm GFRP /1.5mm Steel /7mm Dyneema /2mm Steel		190 (-21%)	20.5	
5	6.5mm GFRP /1.5mm EPDM Rubber /7.5mm Al Foam /5mm Dyneema /1.5mm Steel		142 (-41%)	22.5	
6	1.5mm Steel /5mm Dyneema /1.5mm Steel		96 (-60%)	8.0	

$_1$Masses are given per 1cm length of a 100mm calibre warhead. Reductions are compared against the 8mm steel/ 3mm rubber baseline as percentages.
$_2$Predicted pressure profiles (red) are compared against the profile predicted for the 12.65mm steel baseline (green).

Table 2: Summary of design solutions tested

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Firing Programme

Figure 6 shows the experimental setup of the target. The energetic material target was placed on a 6mm thick 150mm x 150mm steel plate and was orientated to present the target to the fragment aiming point as well as acting as a "witness" to the degree of reaction of the test charge following fragment impact. An orthogonal mirror was used for initial firings to establish the pitch and yaw of the fragment prior to impact. The instrumentation fielded on this trial included high speed Phantom cameras, high rate framing cameras and a VALYN VISAR system.

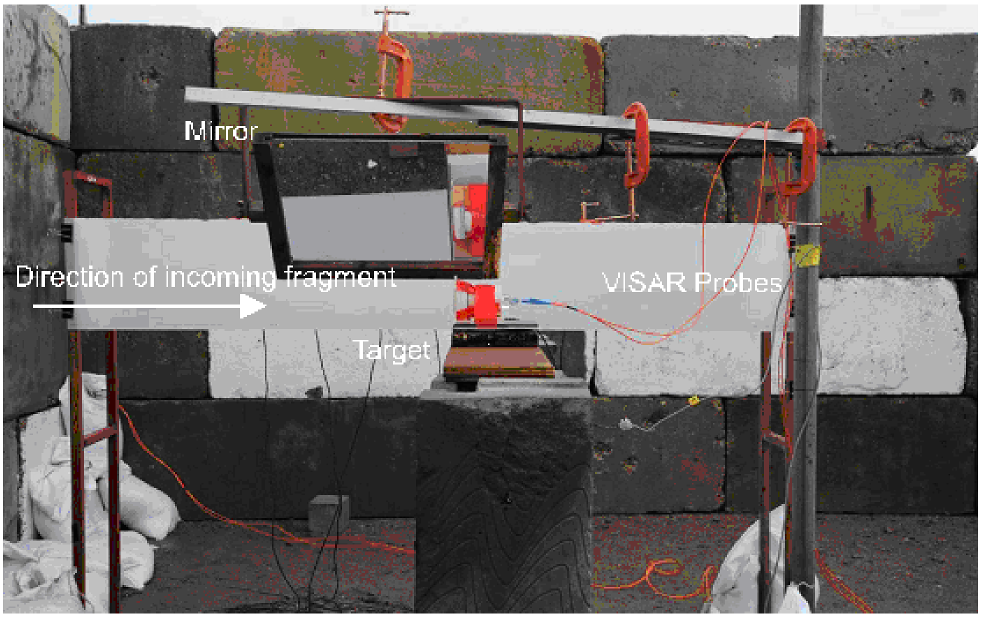

Figure 6: Setup of target.

Results

The results are discussed in terms of violence of the event. Table 3 tabulates all the firings against PBXN110 charges covered by the various appliqué barrier configurations. The table is ordered in terms of increasing beam dent depth. Thus, by this measure, the least violent reactions are to the top of the table and the most violent towards the bottom. There was some overlap in performance of the barrier designs.

Observations from the results indicate firstly that the beam dent depth is broadly in agreement with the severity of the ignition and subsequent burn as depicted in the frames for each shot. Secondly, there is a general trend for increasing violence as the overall barrier thickness decreases. It was also noticeable that the foamed aluminium produced significant light output on impact indicating a significant burning reaction. Evidence did not suggest that reaction of the aluminium increased the violence of the PBXN110 response.

The barrier configuration that gave the smallest indication of ignition on the high-speed video record and the smallest dent in the steel witness plate, appeared to consist of a sandwich of 10mm GFRP/1.5mm, Steel/7mm and Dyneema/2mm Steel. However, this was also one of the thickest barriers used at total width of 20.5mm. If this barrier were deployed as a munition casing then it would be expected to perform well under the fragment impact conditions of this trial.

None of the configurations tested here showed anything other than a partial burning of the explosive charge and most of the charge remained unreacted. It was, however, shredded by both the initial shock wave on impact and the penetration of the fragment. As predicted there were no detonations in any of the experiments.

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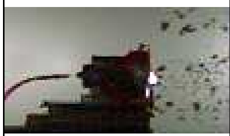
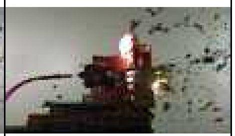
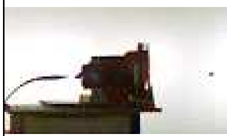
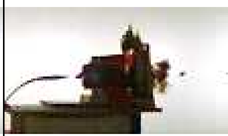
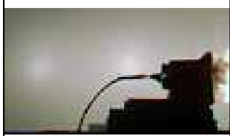
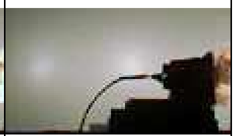
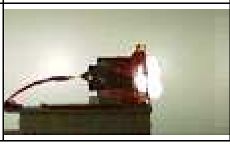
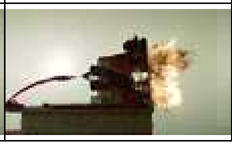
Target No.	+10µs	+30µs	Beam dent depth (mm)	Barrier configuration	Total barrier thickness (mm)	Event type
4			16.6 17.2 17.2	10mm GFRP /1.5mm Steel /7mm Dyneema /2mm Steel	20.5	IV/V IV/V V
5			17.2 17.9	6.5mm GFRP /1.5mm EPDM Rubber /7.5mm Al Foam /5mm Dyneema /1.5mm Steel	22	V V
3			18.0 22.5 25.0	1.5mm Steel /20mm Dyneema /1.5mm Steel	23	V IV IV
1			21.3 21.7 26.1	2mm Steel /5mm Al Foam /1.5mm Steel /5mm Al Foam /1.5mm Steel	15	V V IV
2			23.1 27.6	2mm Steel /10mm Al Foam /2mm EPDM Rubber /2mm Steel	16	IV IV
6			27.9 31.0	1.5mm Steel /5mm Dyneema /1.5mm Steel	8	IV IV

Table 3: Phantom records up to 30µs after impact tabulated in order of beam dent depth.

Conclusions

This programme has shown that it is possible to reduce the mass of munition casing and still achieve IM status for fragment impact tests. Table 4 ranks the designs tested by dent depth and summarises the resulting event type for each design.

This programme successfully demonstrated and validated the QinetiQ methodology to be capable of designing IM cases from first principles. The methodology comprises the following steps:

- Predict and validate the EOS
- Identify salient material attributes and design potential mitigation systems
- Simulate the fragment impact, estimate the response and iterate design
- Confirm the predictions with CHARM

Subsequently, all of the selected design solutions performed better than the steel baseline, as predicted. In time this capability should be able to 'design materials' for maximum mitigation. This work has identified material combinations which are effective at mitigating fragment impact. The function of these combinations has been to absorb the energy of the impact and cause a gradual increase or "smoothing" of the initial shock wave that the explosive charge experiences.

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Target No.	Layers	Mass (g/cm)	Thickness (mm)	Mean beam dent depth (mm)	Average Event Type
4	10mm GFRP /1.5mm Steel /7mm Dyneema /2mm Steel	190 (-21%)	20.5	17.0	V/VI
5	6.5mm GFRP /1.5mm EPDM Rubber /7.5mm Al Foam /5mm Dyneema /1.5mm Steel	142 (-41%)	22.5	17.6	V
3	1.5mm Steel /20mm Dyneema /1.5mm Steel	164 (-32%)	23.0	21.8	IV
1	2mm Steel /5mm Al Foam /1.5mm Steel /5mm Al Foam /1.5mm Steel	189 (-21%)	15.0	23.0	V
2	2mm Steel /10mm Al Foam /2mm EPDM Rubber /2mm Steel	179 (-25%)	16.0	25.4	IV
6	1.5mm Steel /5mm Dyneema /1.5mm Steel	96 (-60%)	8.0	29.5	IV

Table 4: Summary of design properties and resulting responses

The aim of this project was to mitigate fragment impact. For a munition in service the hazards from unexpected stimuli will not be restricted to impacts of the STANAG specified fragment. Adaptations of these designs and the use of different combinations could exploit different characteristics and combat different hazards identified by the risk analysis.

This methodology should be considered for application in the design of future weapon systems to reduce mass and collateral damage. It could also be applied to design packaging solutions for in-service weapon systems with undesirable IM characteristics.

References

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2 D Porter, P Gould, “Multiscale modelling for equations of state” J. Phys. IV France, 110. DYMAT Porto, Portugal, September 2003.

3 [NATO] Alliance Ordnance Publication (AOP-39) Ed 1, Guidance on the Development, Assessment and Testing of Insensitive Munitions (MURAT).

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