

Determining the Fragmentation Effects of an 81mm Mortar Shell against Building Materials

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Charlotte Knight

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Abstract

During a weapon strike, civilians in buildings have a high potential for injury due to fragmentation. Different building materials offer different degrees of shielding to this fragmentation. As building materials are constantly evolving, the shielding effects of newer materials must be assessed in order for collateral damage estimation to remain accurate.

By contributing additional elements to an 81mm mortar shell arena lethality trial, this project aimed to determine and validate the Thor equation constants for sandwich cladding, corrugated steel and mild steel to characterise the risks of fragmentation to civilians inside structures. Trials results were compared against modelled data and Mott's theory for fragment fly out, as well as Gurney equations and past trials data to determine their accuracy.

Fragment velocities produced by the shell aligned with previous trials data, however the Gurney equation under predicted the results. Within the arena, fragment fly out matched well with results predicted by the model and Mott's theory, highlighting areas of greatest lethality and thus collateral concern. Thor equation constants could not be determined due to incorrect labelling and data processing of trials materials. Further work on conducting gas gun trials to collect this data was recommended. Overall, the trial highlighted the complexities around the organisation, data capture and analysis surrounding explosives trials, providing valuable lessons learnt for future trials work.

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Introduction

Collateral damage is defined as injury inflicted on something other than an intended target [1]. The Law of Armed Conflict, states 'when military objectives are attacked, civilians and civilian objects must be spared from incidental or collateral damage to the maximum extent possible'. Therefore, whilst conducting weapon strikes, nations are required to reduce the risk of collateral damage. Failure to accurately estimate collateral damage could lead to deaths and injuries to civilians whilst also making individuals and countries liable for prosecution, causing political and reputational damage [2]. To therefore accurately understand the collateral effects from a strike, parameters such as the weapons effects, the target scene, and the location of civilians needs to be estimated.

The Collateral Damage Model (CDM) is a UK Government Business Critical model developed by the Dstl Weapons System Effects (WSE) Team to provide collateral damage and risk assessments of UK weapons pre-strike [3]. The Model enables human casualties and building damage from blast and fragmentation effects to be calculated. It also considers weapon delivery errors, providing an accurate representation of the collateral effects in a scene.

To determine a weapon's effects, data from existing weapon systems are loaded into the Model, displaying the weapons unique fragment distribution pattern. These weapons can be virtually inserted into the target scene to provide an understanding of the collateral effects to personnel in the open and any structures modelled.

For civilians inside structures, the construction of a building, and the materials it is made from can affect its ability to shield against weapon fragments. Light structures, made from thinner materials such as steel and aluminium offer little resistance to high velocity fragments, whereas thicker materials such as masonry and concrete are more effective in resisting fragments [4]. The Model uses Thor equations to determine the velocity of weapon fragments after perforation through materials, providing an insight into human injury.

As new building materials are developed, it is important their shielding effects can be determined to predict the risks to civilians inside. The Thor equation includes constants that are specific to each type of material. For new materials to be introduced, these constants must be determined experimentally.

This project aims to determine these constants for three commonly used building materials: sandwich cladding, corrugated steel and flat mild steel. As sandwich cladding is made up of two layers of rigid material bound to either side of a lightweight core, the project will determine if a singular equation is sufficient to predict fragmentation effects or if multiple equations are required. This should then feed into future work regarding the modelling of multi-layer materials. Differences in fragment trajectories in flat steel and corrugated steel will also be compared to determine if material shape affects fragmentation path. Mild steel will be used to validate existing data within the Model.

To collect this data, an opportunity to join onto an existing Dstl lethality trial for an 81mm mortar shell was discovered, funded, organised and then executed by the author. This enabled the team to conduct the trial at low cost, utilising Suitably Qualified and Experienced Personnel (SQEP) within the company to assist with the cost, procurement and planning aspects. Across Dstl, trials are not always conducted collaboratively, so this report aims to highlight the benefits of this opportunity.

To feed into the trials design, Mott's theory was used to indicate fragment fly out from the shell, highlighting where smaller, potentially more lethal, fragments are formed. The CDM was also used to build a representative arena trial, and visualise the fragment hits on materials already within the Model. To determine Model accuracy, these results were compared against the trials data. The shell's fragment velocity was also predicted by the Gurney equation for comparison against previous trials data.

The WSE Team, in which CDM resides, currently lacks a trials capability. They rely on existing weapon trials within the organisation to assist in the organisation of trials and data attribution. Therefore, this project aims to develop a trials capability within the team. Through this work, valuable lessons on trial design, instrumentation and data analysis will be learnt and captured through the team's knowledge management processes. By expanding this knowledge, it should enable the team to create its own SQEP for running trials that support the CDM, reducing dependency on other teams within the company.

Background Research

Material Selection

The three materials chosen for this study are sandwich cladding, corrugated steel and flat mild steel.

Cladding refers to components that are attached to the primary structure of a building to form non-structural external surfaces. Compared against traditional building materials, such as masonry, cladding is easier to install, more sustainable, versatile and provides thermal insulation. Consequently, it is increasingly being used in construction projects across the globe.

The type of cladding used within a structure is dependent on the abilities said structures require (aesthetics, durability, strength etc.) For this project, sandwich cladding, traditionally used in warehouses, industrial buildings and transport buildings was investigated, to enhance the modelling of urban battlespaces [5].

Corrugated steel was also selected due to its wide use and availability globally. It is currently regarded as the best material available for industrial large scale roofing. Its quick installation and versatility makes it appealing across a range of structures from hospitals to airports [6]. In third world countries, corrugated steel sheets are also found in slums to offer some protection against the elements [7]. This material also allows the effect of material shape on a fragments path through a material to be explored.

Several building materials already exist within the CDM, and have pre-existing Thor equations attributed to them. To confirm the validity of such equations, mild steel was selected for inclusion in the trial, as it was cost effective, light, and presented less manual handling constraints when compared to heavier materials such as concrete.

Fragmentation

Fragmentation based weapons are commonly used in an anti-personnel role or against lightly armoured vehicles.

Upon detonation, the blast wave breaks up and accelerates the casing to form high-energy fragments which fly out in numerous directions. The size, shape and mass of these fragments is dependent on the weapon system used. There are two main categories of fragmentation: natural and pre-formed

Pre-formed fragmentation is produced when shells are pre-etched with grooves on their interior or exterior. The size and depth of these grooves weaken the shell structure, allowing fragments of these sizes to be produced upon detonation, as shown in Figure 1.

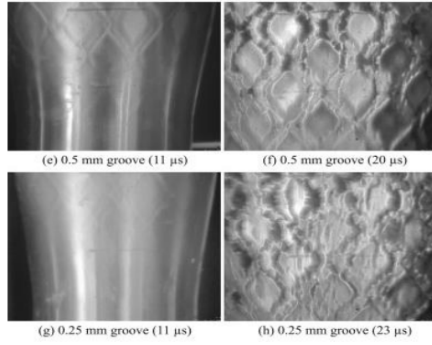


Figure 1- A shell with pre-formed fragmentation detonating to release uniformly sized fragments [8]

Natural fragmentation is produced without any pre-etched components within the shell. The size and shape of fragments is a dependant on the casing material. Materials with high ductility often produce larger, slower fragments, whereas brittle materials produce smaller, faster fragments. This can cause some fragments to cause high levels of injury, whilst others may not produce the desired lethality effect [9].

If the fragment's material is stronger than the target material, it will penetrate the material given a high enough velocity. These fragments impart kinetic energy to the surrounding buildings, causing them to fracture, deform or disintegrate [10]. This can cause severe structural damage, and compromise the integrity of the area around it. Fragments can also cause injury to personnel within these structures, if their velocity after penetration is great enough. This velocity can be predicted by Thor equation.

The Thor Equation

The Thor equation, seen in Equation 1, is a 5 dimensional equation which correlates the mass and velocity of fragments with damage to plates, to allow the residual velocity after plate penetration, V_r , to be calculated. It was created in 1976 from data collected by the Ballistic Analysis Laboratory U.S in 1961 and the Ballistic Research Laboratory U.S in 1963.

Equation 1- The Thor equation [11]

$$V_r = V_s - 10^c (tA)^{\alpha} m^{\beta} (\sec \phi)^{\gamma} V_s^{\lambda}$$

The variable V_s is the fragment striking velocity in feet per second, m is the weight of the original fragment in grains (1kg is 15432.4 grains), ϕ is the angle between the trajectory of the fragment and the normal to the target material in degrees, t is the target thickness in inches and A is the average impact area of the fragment in square inches.

The constants c , α , β , γ and λ are dependent on the target material used. These constants were previously collected experimentally, using regression analysis on trials data from high explosive shells. These fragments varied in weight from ~0.3 to ~31 grams [11] [12].

This equation determines whether a weapon's fragmentation has sufficient kinetic energy to penetrate or perforate through a material. If perforation occurs, the fragment's residual velocity will enable the fragment's kinetic energy to be calculated. This will then feed into the human injury prediction, allowing an estimation of human injury to occur in CDM.

For new materials to be added to the Model, their unique set of constants need to be determined. For this, the equation variables need to be collected from trials data, to allow the equation to be rearranged and plotted on a graph to provide the equation constants. Once determined, this could enable the complete equation to be formed and added into the CDM. Here, the operator can alter factors such as material thickness and fragment velocity (determined by the weapon data), to provide the data for their own scene requirements.

An arena trial was chosen as all variables could be determined at the same time within a singular weapon firing, providing accurate weapon data to feed into the CDM.

Arena Trials

In an arena trial, the weapon is placed in the centre of the arena, with fragment capture materials surrounding it, often in a circular shape, as shown in Figure 2. The area itself is typically split up into the polar zones of the weapon. These help determine which segment of the weapon each fragment originated from, determining areas of the most lethality.

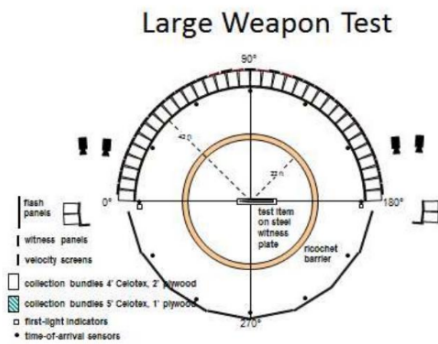


Figure 2- An example of a typical arena trial and its instrumentation set-up [13].

Arena trials enable fragment mass, location and velocity to be measured, making them suitable for determining the Thor equation parameters.

Capturing Fragment Mass and Location

To measure fragmentation, strawboards that adhere to DEF STAN (Defence Standards) 93-59 Chipboard (For Use at Proof and Experimental Establishments) must be placed into the arena. These are used to capture the fragments that are produced from the weapon. The bursting strength of these strawboards is tested using Mullen Test apparatus to ensure the ultimate tensile stress of each material is within agreed limits. This calibrates the strawboard so it can be used for weapon and explosive testing.

After a weapons trial these fragments are then picked out of the strawboards, with their location and mass recorded. Here, the fragments are analysed to try and spot fragments specific to a certain part of the weapon, for example parts of the weapon's fins or tail section. They are also checked to see if they are magnetic. This can also help determine what part of the weapon the fragment came from, or if it even came from the weapon at all (e.g. it could be a piece of the charge stand).

Recording the location of fragments post firing enables them to be compiled within a 3D point cloud. As the strawboards do not completely surround the weapon in an arena trial, this data gets revolved around the central point of the weapon to provide a 360° degree view of the weapon's fragmentation effect. Any unique fragment, such as rocket fins, must be analysed by Subject Matter Experts (SMEs) to ensure that it is not being incorrectly extrapolated across the entire weapon axis, preventing warheads with 4 fins appearing to have 20.

The fragment point cloud visually indicates if the weapon detonated uniformly and if the fragment fly out was as expected. This then feeds into the lethality and collateral models for that weapon system, as areas of low and high lethality can be displayed.

To determine the number of strawboards required per firing, the NATO ARSP-03 Volume II is used [14]. This volume provides all the equations required for setting up an arena trial and capturing all the data afterwards, as per the NATO standards. This makes weapon testing across multiple countries and systems comparable, allowing data to be widely shared.

Capturing Fragment Impact Velocity

To capture the fragment striking velocity, velocity foils are typically used. These compare the time stamp from the weapon detonation against the time stamp created when a fragment hits them. As they are placed a known distance away from the weapon, this allows the velocity of fragments to be calculated.

There are two different types of velocity foil: 'Make' and 'Break' foils. Break foils are the simplest type of foil, and are shown in Figure 3. They include a complete electrical circuit with a current going through. When the fragment strikes, the circuit is broken and the time stamp recorded. After this first fragment penetrates however, no more data can be collected. Therefore, only the velocity of the fastest fragment can be recorded.

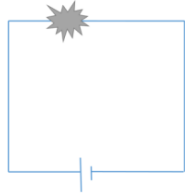


Figure 3- A simplistic diagram of a 'Break' foil with the grey star representing an incoming fragment

Make foils, however, can record multiple fragments at the same time, as shown in Figure 4 which demonstrates a topside view of the panel. As shown, the circuit is initially broken, until the fragment, shown in grey, connects the circuit, as shown by the orange lines. This then sends a signal to the system, allowing its timing data to be recorded. As the fragment then passes through the circuit, it leaves the circuit open again, ready for another fragment to close it, and send a new signal.

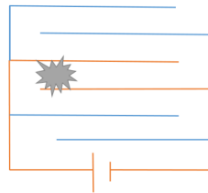


Figure 4- A simplistic diagram of a 'Make' foil with the grey star representing an incoming fragment

Whilst this method allows multiple fragment velocities to be captured, the wires often get destroyed by passing fragments, reducing the area available to complete a fresh circuit. In addition, multiple fragments hitting the foils at the same time can produce messy signals which can be complex to clean and attribute each signal to a certain fragment [15].

The exact time the weapon detonates must also be identified. For this, high voltage detonators such as RP-83s are used, as they provide a faster response time compared to low voltage detonators. Additionally, velocity foils need to be measured and surveyed within the arena to a high level of accuracy.

Capturing Fragment Velocity after Material Penetration

The number of strawboards the fragment has passed through can demonstrate how much of the fragment's kinetic energy has been absorbed by the strawboards. As the fragment's mass is recorded, this allows the fragment impact velocity to be calculated using the McMahon fragment penetration equation, shown in Equation 2.

Equation 2-The McMahon Fragment Penetration Equation [16].

$$V_s = \frac{KP}{M^{\frac{1}{3}}\rho^{\frac{2}{3}}} + V_L$$

In this equation, V_s represents the Strike Velocity (ms^{-1}). K is the constant for a given fragment shape and fragment capture material. P is the penetration depth (mm). M is the mass of the fragment (mg), ρ is the density of the fragment ($gm\ cm^{-3}$) and V_L is the limiting velocity(ms^{-1}), where the fragment does not penetrate further into the witness pack. For a spherical fragment, this is $205\ ms^{-1}$ [16].

Mortars

As mentioned previously, this experiment will be utilising empty space in an 81mm mortar shell trial. These weapons are widely used across a range of military applications, and present collateral risks to both civilians and the UK's own deployed forces.

Mortars are smooth-bored indirect-fire infantry support weapons. They fire explosive projectiles at low velocities, and steep trajectories, making them ideal for firing over, into, or out of the enemy's line of sight [17]. Mortars are one of the most responsive indirect fire weapons, engaging targets quickly and at shorter ranges than conventional artillery. They are small, light and are incredibly portable in the field.

Present day mortars consist of a lightweight tube that rests on a base plate, and is supported by a bipod, as shown in Figure 5. The weapon is activated by dropping a mortar shell onto a firing pin within the tube. This ignites the shell's propellant, which launches it towards the target, imparting the recoil force directly into the ground [18].



Figure 5- An example of a Russian mortar [19]

In battle environments, mortars are often used to engage with enemy positions not protected by reinforced overhead cover, such as trench lines and gun pits due to their high arching trajectory. They are also used in defence from ground assault. Additionally, they are used to provide smoke cover to either screen friendly forces or to blind enemy observation, as well as illuminating areas of the battlespace at night.

The Circular Error Probable (CEP) is the radius of which half of all weapons fired are expected to impact within. This mortar can be used both guided, achieving a small CEP, however unguided the CEP is an order of magnitude greater [20]. This wide margin of error means it is significantly harder to predict the true collateral effects of these systems. With 76% of mortar attacks undertaken by foreign forces occurring in populated areas the inaccuracy of the mortar fire means the effects cannot be reliably contained within the target area. Therefore, vulnerable buildings such as schools, hospitals and churches can be caught within the munition impact distribution area [21].

The majority of mortar injuries are caused by explosively propelled fragments which are released upon impact. The 81mm mortar shell fragments naturally, so fragment shapes sizes and masses are incredibly difficult to predict through modelling [22]. Therefore, these must be determined experimentally. This trial should assist in building up an expected fragment profile of the shell.

Predicting Fragment Size and Fly Out

Work to predict the size and distribution of fragments was first completed by Mott in World War 2. This work created the following assumptions:

- Small fragments are produced when the ratio between the explosive mass and case mass is ~ 1 (thin walled case). This casing must also have limited ductility, and has to contain a brisant explosive.
- Large fragments are produced from the shell having a thick, ductile case and a less brisant explosive [22].

Whilst Mott's theory may be correct for cylindrical charges with a constant case size, as shown in Figure 6, the mortar does not have a constant case size, making fragment predictions more difficult. The casing thickness itself reduces towards the direction of the tail. These fragments are therefore likely to be smaller than other sections of the weapon.

The nose contains a thick casing, along with the fusing mechanism; therefore it is likely these fragments will be much larger than that of the main body. Similarly, the tail section is separate from the explosive itself, and is made up of much thicker material. It is thereby assumed from Mott's theory to produce a low number of large fragments. This theory is supported by the work of Nyström, whose work indicated the nose and tail end of bombs will break up into a smaller number of massive fragments and the body will break up into many small fragments [23].

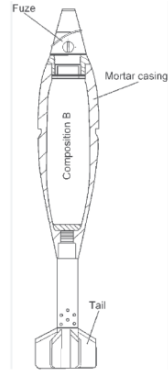


Figure 6- An 81mm mortar shell [24]

Predicted Fragment Velocities

To estimate fragment velocity, past trials data on a range of 81mm mortar systems have been analysed. Overall, peak fragment velocity occurred at 110° Angular Polar Zone (APZ), at just over 2000m/s [25].

The Gurney equations are a set of formulae used in explosive engineering to predict how fast fragments are released on detonation of an item of ammunition, as in Equation 3. In this, V is the fragment's initial velocity, $\sqrt{2E}$ is the Gurney Constant determined by the explosive used, M is the mass of the case and c is the mass of explosive used.

Equation 3- The initial velocity of fragments in a cylindrical casing [26]

$$V = \sqrt{2E} \left(\frac{M}{C} + 0.5 \right)^{-0.5}$$

These equations were derived by combining the kinetic energies of the fragments with the kinetic energy of the explosive gasses, to determine the total amount of explosive energy released. This allowed the fragments initial velocity to be calculated [27].

Using open source literature, the shell contains 0.7 kg of TNT, and has a shell casing mass of 3.1kg [28]. This provides a Gurney velocity of 1053 m/s, which is significantly less than the trials data above has suggested. This could be due to the assumptions made within the Gurney equation that do not consider the casing material, or the size of distribution of fragmentation. The trial should clarify this further.

Predicted Fragmentation Effects

Combining both theories, it is assumed that the larger fragments based around the shell's nose and tail will have lower initial velocities, thus lower impact velocities into the fragmentation packs. Similarly, there will be an increased quantity of smaller fragments produced by the munition body with higher velocities.

Methodology

The Trial Background

This project utilises an existing Dstl 81mm mortar arena trial set up to determine the mortar's lethality effects. During background research into this project, it was realised that not all the arena space was being utilised to its maximum potential. Therefore, a collaborative opportunity was suggested which enabled valuable CDM data to be collected alongside the main lethality data whilst presenting limited additional risks in terms of cost and time.

This opportunity allowed:

- The team to conduct a comparatively low cost trial using an in-service munition required by the Model
- The author to utilise the other project's pre-existing trials expertise, to shape the trial's design, and organise pre and post-trial activities
- The author to build confidence in starting to organise and design trials to suit the team's requirements

For both trials to occur simultaneously, equipment had to be positioned so it did not interfere with any other data being collected. This was critical, as blast gauges were already being used in the arena, so any additional reflections from added materials could affect their pressure data. Additionally, the added materials were analysed during the initial trials planning stages to ensure they posed no additional health and safety risks to the main trial occurring.

Materials

To minimise impact onto the trial, 2 lots of 3 different materials were selected. This reduced the footprint of this work on the overall trial whilst providing enough validated data to feed into the Model. These were:

- 1 mm flat mild steel – this was selected as the CDM models all materials as 1 mm thickness, then extrapolates the data depending on the required wall thickness in the scene. A 1 mm selected thickness reduced the amount of error from this extrapolation, whilst keeping material costs and weight down for manual handling purposes.
- 0.5 mm thick corrugated mild steel – this was chosen as it was the most common thickness used commercially [29].
- 137 mm core sandwich cladding – this was chosen a representative cladding thickness from a literature review [30].

Each material was purchased from a builder's merchants, and thus emphasising the representative nature of the cladding on modern buildings.

Material Packs

A material pack comprises of strawboards on the bottom layer, followed by the material then velocity foils which face the munition, as seen in figure 7. Foils were connected to the material using tape, and the materials were banded to each arena column. 70 strawboards were specified per pack, to reliably collect all of the high-energy fragmentation and give an indication of fragment velocity after penetration through each material. They will also indicate if the corrugation of the mild steel had any effect on the fragment path, or whether a similar trajectory to the flat steel was observed.

'Make' velocity foils were selected to ensure multiple fragment velocities could be recorded during each firing. Due to restrictions in the number of channels available for collecting data from the foils, only 18 foils could be used per firing. For the corrugated steel and cladding materials, four 40 cm² velocity foils were placed on the materials, as per Figure 7. For the mild steel, only one foil was used, and this was placed in the centre of the material. As this material was only used for validation purposes against existing data, it was deemed the least important, thus requiring less foils than other materials.

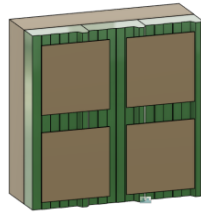


Figure 7- A CAD drawing of the cladding and strawboard

Modelling

To ensure the optimum positioning of the material packs in the space available, modelling was required. The CDM was used to replicate the arena set-up and weapon detonation, providing fragment fly out information. As the CDM is only used by suitably trained analysts in the WSE Team, considerable training was undertaken to enable the scene to be built and the Model to be run.

As the 6 packs could be placed anywhere above or below the 13 pre-existing columns in the arena, it was critical the scene was modelled to determine their optimal placement. To obtain the highest quantity of results, packs were placed where the highest density of fragments were predicted, as this was most likely to cause the most damaging effects.

Using CDM, the scene was modelled using all the dimensions received within the trials plan. The strawboards were built as 1m x 3m walls so the fragment distributions could be seen for all strawboards locations, thus the best positioning of materials could be determined. Owing to classification restrictions, such images cannot be included within this report.

Upon firing the horizontal and vertical shots, the majority of fragmentation lay within the 90-120° APZ (column 7-9) of the warhead for each shot type, with the highest density of fragment occurring in APZ 105 (column 8). This matched up with previous trials data, and with Mott's theory mentioned above. As the cladding material was deemed the most important, this was placed in column 8, with the corrugated steel in column 7, and flat steel with the least amount of expected fragments within column 9.

Trial Set Up

The final trial set up is shown in figure 8. It consists of three horizontal and one vertical firings. The mortar shell itself will be 1.5m above ground. The radius for this trial is 3.821m, calculated using the NATO Allied Range Safety Publication (ARSP) 03 Volume II [14]. Fragments will be captured through strawboard witness packs, and velocity foils provided by both teams. Additionally, each shot will be recorded by two high-speed cameras to capture the emergence of fragmentation from the warhead and subsequent strikes onto the witness materials.

To determine the reference time for the velocity-foil timing data, the shell will have three break wires placed with equidistant spacing.

To prevent ricochet, sandbags were placed around the weapon.

The CDM packs are positioned in columns 7-9 of the arena. This matches up with the predicted angular bands.

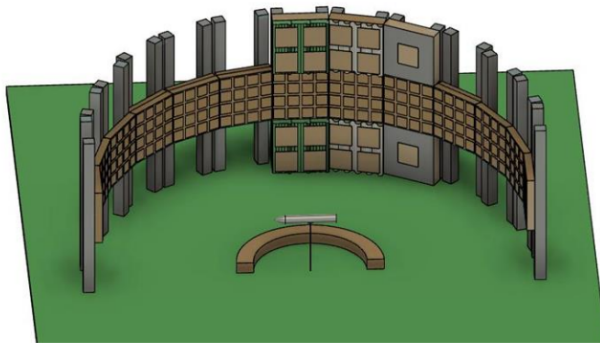


Figure 8- A CAD drawing of the strawboard side of the trials set up

The Trial

The trial was conducted at the Cranfield Ordnance Test and Evaluation Centre (COTEC) Forward Battery.

Before the trial commenced, the shell's fuse was removed and replaced with a representative plug containing booster explosive. This enabled a high voltage detonator to be fitted, allowing the munition to function statically within the arena.

Firings 1-3 includes the shell in a horizontal orientation, with the nose facing column 1, numbered from left to right as shown in Figure 14. An inert munition was placed upon the polystyrene block to ensure the shells location was included within the arena survey data. The polystyrene block supports the munition before firing to ensure it stays in place, whilst not adding any additional fragmentation into the arena.

The materials are seen at the top and bottom of columns 7-9, as agreed within the trials specification.

As seen below, the sandbags were significantly larger than modelled in Figure 9. When a tape measure was placed between the centre of the munition and the bottom of the lower strawboard level, the tape skimmed the top of the strawboards, indicating a chance fragments at this angle could be ricocheted off the sandbag. This could have reduced fragment capture at lower levels. Unfortunately this set-up could not be altered within the time frame.



Figure 9- A pre-firing photo of the trials site

Unfortunately, during several firings not all the required strawboards were positioned behind the materials, despite this being within the trial's specification. On several occasions, this led to fragmentation passing straight through the boards and not being captured. Consequently, no data could be collected on such fragments aside from their velocity and positions.

On firing 2, the flat steel sheets were not added into the arena, despite being within the trials specification. By the time the trials conducting officer (TCO) was notified, the arena had already been surveyed, and inclusion of the sheets would significantly delay the firing. Therefore, they were not able to be added.

Lastly, due to communication issues, only 16 velocity channels were available for use during each firing. Therefore, foils on the flat steel were not used to allow measurements to be taken on the cladding and corrugated steel, as the higher priority materials.

Results

Velocity Foils

Timing data was captured for all firings except firing 3 where there was a pod failure affecting all channels.

Timing data was converted to give a velocity using the assumptions shown in Appendix A. Figure 10 displays the peak fragment velocity, for each material and location between the horizontal firings. As seen, there is minimal velocity variance between the two firings. However, there is a significant velocity difference between columns 7 (corrugated steel) and 8 (cladding).

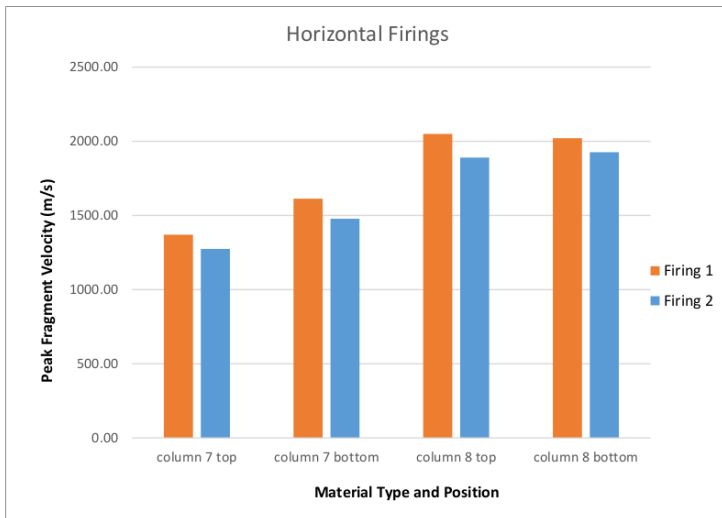


Figure 10- Chart showing the differences in peak velocity across horizontal firings

Figure 11 displays the fragment velocities for the vertical firing. As seen, there is a significant difference between the velocities of the top and bottom packs.

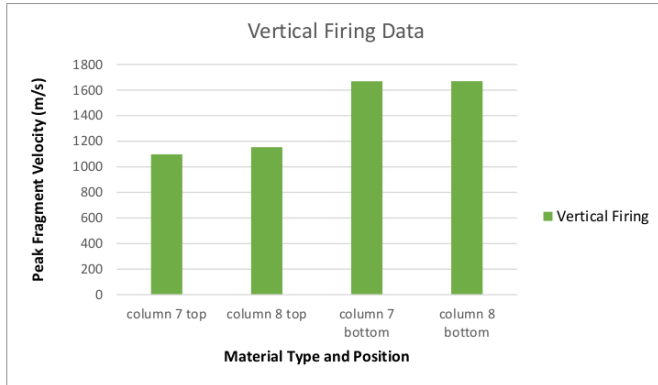


Figure 11- The peak velocities measured in the vertical firing

Figure 12 combines all the peak velocity measurements for each of the firings. As demonstrated, the horizontal firings often produce higher velocities compared to vertical firings. Across the three firings, the velocity of the bottom packs were significantly higher than the top packs.

The vertical firing also offered significantly less variation between striking velocities compared to the horizontal firings. The bottom packs contained only a 0.35m/s difference in measurements, whereas for horizontal firings 1 and 2, they were 408m/s and 449m/s.

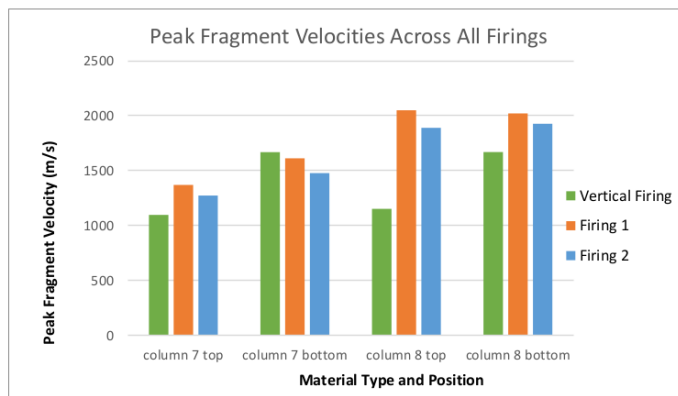


Figure 12- A summary of the peak velocity data from both the horizontal and vertical firings

Fragment Data

The location of fragments, as well as their respective masses were measured using the methodology in Appendix B for both the materials and the strawboards behind. This was then compiled into Excel scatter graphs.

Despite being specified to the contractor, the strawboard and materials were not properly labelled post firing. Instead, photos of the trials site and materials during picking were used to assist the data consolidation. Comparisons were also attempted between attributed data and non-attributed data within the arena, comparing the scatter graphs in an attempt to line up the material fragment holes with the collected fragments.

Figure 13 displays an attempt of this technique for recording the fragmentation data for firing 3, bottom cladding. The purple squares indicate where fragment holes were measured on the top row of added materials. The other coloured circles show where fragments have been recovered from strawboards of different layers behind the same pack. As seen, some fragments seem to appear from nowhere, and there is little correlation between holes in the front cladding, with the collected fragments within the strawboard. This lack of data assurance has prevented this data being used as the fragment's path cannot be fully tracked from the mortar to the last strawboard layer in the arena. In addition, it makes it impossible to distinguish between fragments that have fully perforated the material, and fragments that have been captured within the material and not perforated through. Consequently, a lot of this data cannot be used.

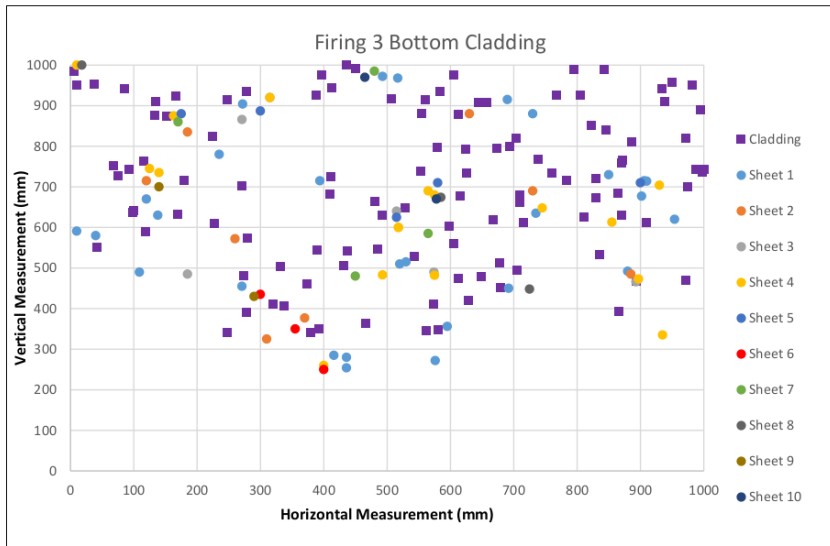


Figure 13- An image displaying where fragments were measured on the materials compared to the strawboards

Fragment Frequency

Fortunately, the front layer of data from each material was able to be validated with photographs in their arena location. For each top layer, the number of holes in the front face of the material from fragments was either recorded during fragment picking, or captured through photography analysis.

This information is recorded in Figure 14 for the horizontal firings. Unfortunately, data could not be recovered for firing 3, top corrugated material as the fragment impact data was unable to be verified against the trials imagery. Flat steel sheets were also not placed into the arena on firing 2, despite being in the specification, so this data is also missing. As seen, column 8, where the cladding was placed, features the highest intensity of fragments across all horizontal firings.

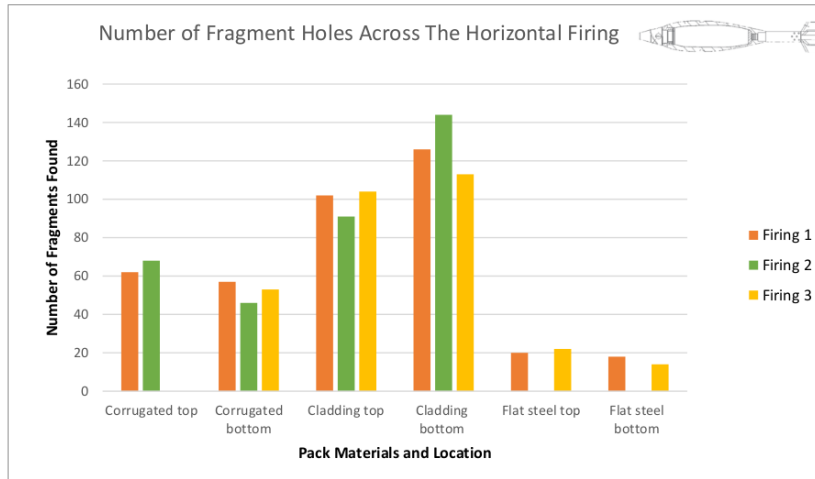


Figure 14- The number of fragment holes across each strawboard for the horizontal firings. The orientation of the warhead within the arena is in the top right corner.

For the vertical firing, shown by Figure 15 the overall number of fragments found decreased compared to the horizontal firing. Column 8 was still the column with the highest amount of fragment hits.

Overall, for both firings, the bottom packs contained a higher density of fragments compared to the top packs.

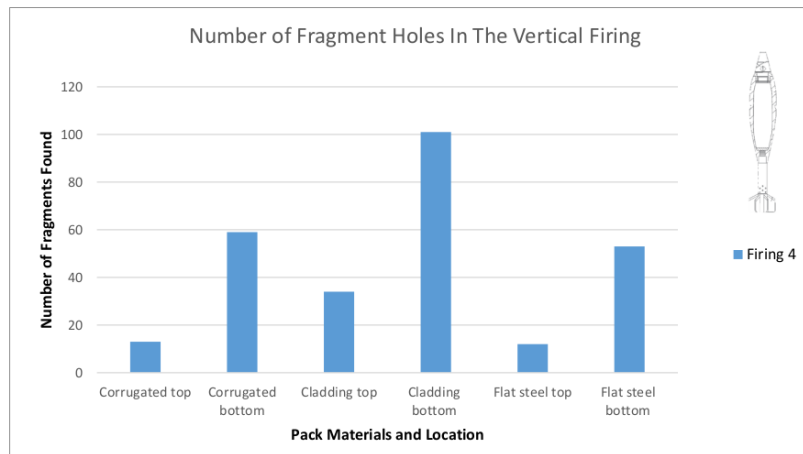


Figure 15- The number of fragments across each strawboard pack within the vertical firing. The mortar orientation within the arena is in the top right corner.

Analysis

Velocity Foils

Results from Figure 12 prove the calculated Gurney velocity for shell fragments is significantly lower than that experienced from the trial, however does align with previous trials results.

Among other factors, the Gurney equations assume a uniformly distributed explosive, and a uniform thickness of the case. As seen by Figure 16, this is unrealistic for this shell type, which clearly has a varied thickness of casing, along with an un-evenly distributed explosive. Different case thicknesses will result in produced fragments having different masses and thus travelling at different velocities to that expected.

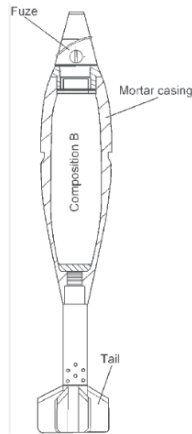


Figure 16- An 81mm mortar shell [24]

The foils also highlight differences in velocity between the columns, as predicted by the CDM. This could also be due to the tapered casing thickness of the mortar. Past the 90 degree point (column 8), the casing thickness decreases, resulting in smaller, lighter fragments being formed. These fragments will therefore have higher velocities than their 90 degree counterparts (column 7).

The velocity foils on the bottom packs displayed higher velocities compared to the top packs. The reasoning for this remains uncertain, due to the axial symmetry of the munition theoretically producing a similar velocity of fragments.

One possible explanation is that the mortar shell breaks up naturally, and there is no pre-etched fragmentation pattern. This could have naturally produced smaller, higher velocity fragments from the top of the munition, and larger, slower velocity fragments at the bottom. Whilst the likelihood of this occurring on two firings was incredibly slim, it could be a contributing factor to the significant velocity difference.

Another possibility is the shell's fusing being slightly off-centre, causing an asymmetric detonation within the munition. This may have caused the bottom of the mortar to function before the top, attributing to the differences in time and hence velocity measurements.

Due to time and software constraints, the survey data from the trial has not been analysed. This data provides a three dimensional view of the trials site pre-firing, providing the GPS coordinates of every item within the arena. Analysis of this would have provided more exact measurements between the munition and the material packs, potentially accounting for this velocity inconsistency.

As the strawboard data could not be correctly attributed to the correct material, the exact position of the fragment with the highest timestamp could not be determined. This prevented the exact distance from the shell and hence the most accurate velocity data being used.

During the vertical firing, significantly lower fragment velocities were observed compared to the horizontal firings. This aligns with Motts theory mentioned previously. Figure 17 displays the location of the mortar in proximity to column 7. As seen, the nose of the shell is closer to the top materials, and the bottom of the packs aligns with the tail. Therefore, larger, slower fragments will be formed, accounting for the lower velocities.



Figure 17- An inert representative mortar round positioned for firing 4

Strawboard Data

As previously mentioned, issues surrounding the labelling of the materials and its corresponding strawboard has meant the strawboard position and velocity data cannot be used.

Figure 18 displays one of the labelling issues, where two materials had been incorrectly labelled as 'COTEC 4.8 TOP'. Whilst a photograph of the arena post firing was able to correctly attribute the pack to the correct location, it made the subsequent strawboard behind it hard to attribute accurately, as sufficient photographs were unavailable.



Figure 18- 2 different cladding sheets incorrectly labelled

When packs were labelled externally, they were unclear. The cladding shown in Figure 19 was not labelled. Therefore, to correlate it with the labelled strawboard data, multiple scatter graphs showing fragment positioning had to be individually compared. This was made difficult by the low angle of the photo, making it hard to determine the exact position of the fragments. The lack of labelling of the sheets also made the correct orientation of the data unknown, increasing the difficulty in this task. As a culmination of such uncertainties, the resulting data did not align with any confidence, as previously displayed in Figure 13.

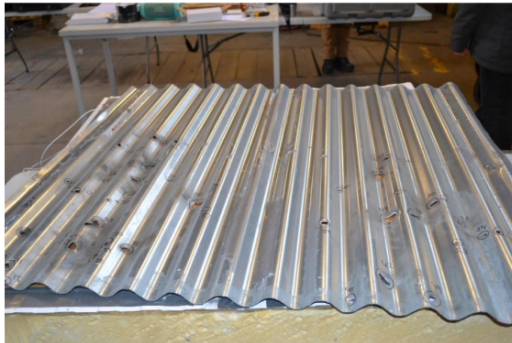


Figure 19- An unlabelled image of some corrugated steel at an angle that makes it hard to spot where the fragments were positioned

When picking the strawboards, the measurement data was transferred to paper sheets, which was then later added into Excel. This method was employed as non Dstl staff were assisting with the picking, so could not have their own laptop. Whilst translating written numbers into a text format, there is a high likelihood some numbers may have been misinterpreted (i.e. a 9 written as a 4). In addition, due to the high quantity of data being processed, there may have been some incorrect number transference. Whilst every effort was made to reduce this (picking and checking several numbers at random on every sheet), there remains a risk of re-occurrence.

Some images were taken of the labelled material complete with strawboards, but not of the bare material. Therefore, from the holes in the velocity foil, it was difficult to determine the expected holes into the bare metal as the fragment may have stopped, or broken up before impacting the steel. Figure 20 displays an example of this, where the shadows from the corrugations make it incredibly difficult to distinguish the actual fragment holes.



Figure 20- An unlabelled corrugated material post firing

Lastly, not all the data was recovered for each of the materials and strawboards, creating additional ambiguity in attempting to match up data sets.

Consequently, the fragment path from the shell to the furthestmost strawboard could not be determined. This prevented the fragment masses, residual velocity, the angle between the trajectory of the fragment and the normal to the target material, and the average impact area of the fragment required for the Thor equation to be measured. Therefore, no Thor equations could be produced for any of the new materials, and no data could be compared against the existing Thor equation for the mild steel. This also prevented the different material shapes (flat and corrugated mild steel) fragmentation paths from being compared.

[Fragment Frequency](#)

As demonstrated by Figure 21, the highest number of fragments was recorded in column 8 during horizontal firings. As well as matching the CDM predictions, this aligns with Mott's theory. As the thinnest section of the casing was opposite the column, a higher frequency of small fragments has been produced.

In a combat scenario, mortar shells are fired with a parabolic trajectory, ideally detonating as close to vertical as possible. Therefore, results from this orientation provide the greatest insight into how the shell would behave in the battlespace.

Within the vertical firing, less fragments were captured compared to horizontal firings. This is because there was a lower surface area of the shell facing the packs compared to the horizontal firings, as the munition was longer than it was wide. This resulted in less fragments being captured. This concept is displayed in Figure 21, which demonstrates the fragment fly out from a 120mm mortar shell. As seen, fragments fly out across the full 360° around the shell. As only 45° of this could be captured by the materials, across two different heights, this accounts for the decrease in fragments compared to the horizontal firing.

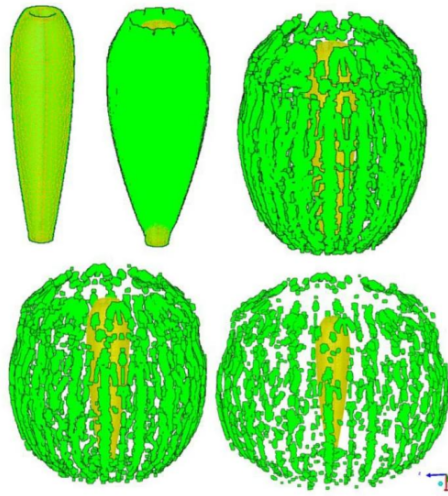


Figure 21- Fragment fly out for a 120mm mortar shell [31]

Future Recommendations

Trials design

Due to the availability of channels, the project was only allowed to include 16 velocity foils. To therefore maximise the amount of data that could be collected, the foils were very large. This could have made it harder to attribute the specific fragment that obtained the highest velocity due to the frequency of fragments that entered that space. Therefore, in future trials a higher frequency of smaller velocity foils are required to obtain a higher degree of certainty of fragment measurement.

When building the fragment packs, the foils were not able to sit flush to the corrugated and cladding materials due to their large size and limited flexibility. Therefore, in future trials, velocity foil dimensions need to be amended so they can fit and be taped correctly to their corresponding material. This may require some physical testing, to ensure the foils can bend and flex true to its material.

Fragmentation Picking Process

Manual fragment picking is time intensive and is prone to errors. Firstly, there is no guarantee that every single piece of fragment has been removed from the strawboards, as they were often less than 0.01g and hard to spot. Picking the fragment itself can often lead to pieces breaking off, as the tweezers cause the already delicate fragments to break off. Secondly, the repetitive manual measurements can often mean accuracy is reduced as the day continues- workers tire and concentration lapses. Lastly, as the fragment holes are different sizes, it is up to personal judgement to determine their mid-point for measurement. This can soon lead to compound errors across multiple strawboard packs, altering the apparent fragment path.

Whilst using strawboards for weapon trials is currently mandated by NATO, there are alternative techniques used by industry and academia that can capture similar results without physically capturing the fragments. 3D optical diagnostics are capable of measuring the speed, size and mass of fragments. This methodology does not physically capture the fragmentation, allowing fragments to perform naturally within the arena, providing the most accurate data for fragment fly out. As fragments do not require picking, this eliminates the human errors previously mentioned, reducing the degree of uncertainty around the dataset. Whilst still in its early stages, novel methodologies such as this should be researched and utilised for future weapon trials to ensure a high standard of data is available for processing [32].

Strawboard Identification

As previously discussed, due to errors in labelling, photographing and picking the strawboards, most of the data has become invalid.

To prevent this issue occurring again, the materials and strawboards should be labelled by the technical lead, or if unavailable, clear instruction on a labelling convention must be sent to the trials manager/ trials staff during the planning phase. This will eliminate any ambiguity in the strawboard/ material's arena location. This should be completed pre-firing. In addition, the material and its corresponding strawboard should be placed on the same pallet to make identification easier. This enables all materials of a trial segment to be processed at once, immediately identifying data gaps.

Data should be added directly onto the laptops live during strawboard picking. This reduces any ambiguity in handwriting, as well as immediately highlighting any data gaps. Adding the data directly onto the laptop also decreases the time taken to process the data as data does not need to be replicated within different formats. Therefore, it is recommended that during the picking, a Dstl staff member collates the photography data, as well as the fragments' mass and location data to ensure the data reaches the required standard.

The technical lead should attend all fragment picking dates where possible, or have delegated another team member to keep track of the data. This ensures any data gaps are dealt with immediately before materials are sent for disposal.

When photographing each material, an image should be taken of the label first, then the complete material with strawboards, then the labelled bare material showing fragment holes before imaging the label again. This helps "sandwich" the photography data making it easier to attribute each material and firing.

Photography should occur on each trials segment in the order it was picked. Materials should be photographed at 90°, to enable graphs to be placed directly on top of them for easy visual comparison.

If deadlines allow, data should only be processed once everything had been fully received. The two month gap between receiving selected strawboard data and receiving the trials photographs occasionally meant graphs were incorrectly referenced to locations. This increased the time taken to complete the task as scatter graphs often had to be re-attributed to different data sets.

Blast and Fragmentation Loading

Whilst the Thor equations view fragmentation separate to blast, the way most weapons damage structures involve a combined effect of these. Whilst cased charges exhibit lower blast pressures than bare explosives (due to energy losses during the case break-up) they often elicit more severe structural responses.

Figure 22 shows the variations between the arrival times of the blast wave and the fragments at various standoff distances. With increasing distance, fragments will arrive before the blast wave as they are less effected by air resistance.

In the orange region, fragments damage and weaken the structure, resulting in the blast wave causing increased damage upon its arrival. Where fragments and the blast wave arrive at similar times, this can still be the case, due to its longer duration.

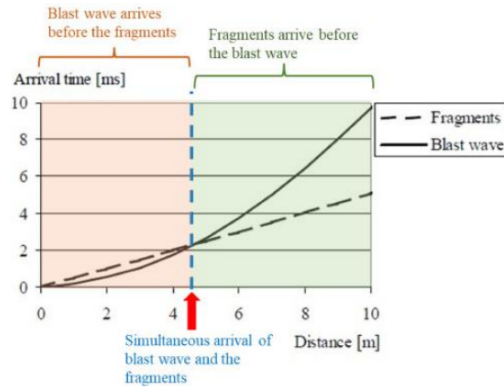


Figure 22- Graph displaying when the fragmentation and blast wave arrive in relation to each other and distance [33].

Figure 23 then displays the significance of investigating these combined effects. As shown, the combined effects can cause a higher deflection of a concrete wall, potentially causing a higher degree of damage overall.

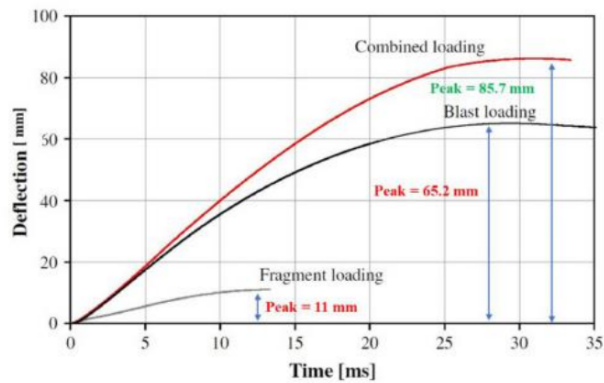


Figure 23- The separate and then combined effects of blast and fragmentation against a concrete wall [33].

Due to the close proximity of the materials to the weapon, the blast wave arrived before the fragments, thus producing no additional effects. However, this dual effect will be seen during operational weapon use, and therefore requires further investigation to ensure it does not increase or decrease any collateral or lethality estimations [33].

Gas Gun Trials

Whilst in concept, the 81mm mortar trial design appeared to fulfil all the requirements for Thor equation generation, in reality there was too many factors at play to generate valid results.

Therefore, for future work, it is recommended smaller scale trials are conducted, using a second stage gas gun. This device uses both gunpowder and the compression of a light gas is to propel projectiles at high velocities, mimicking the fly out of fragments after weapon detonation [34].

This technique should provide the team with more control of the trials variables, allowing components to be easily switched out if required. This work will also be easier to run independently as a team, without relying on other teams and organisations, ensuring more efficient communication. Another benefit is the ability to rapidly collect and analyse data after each firing- something that hindered the analysis of the strawboard data for the mortar trial. It also is cheaper to run and is a lower risk than a full scale weapons trial.

Conclusion

As a result of this project, and the intervention into an extant lethality trial, the Weapon Systems Effects Team were able to complete their first collateral damage trial for many years. This collaborative opportunity allowed the author to gain experience in the design, planning and implementation of a weapon systems trial at a significantly reduced cost. It has also highlighted the relative ease of collaboration on Dstl trials, which should be shared internally to encourage multiple projects to utilise singular trials.

From the trials data, the Model was shown to predict fragment fly-out accurately, providing information on zones of high and low lethality, supported by Mott's theory. This maintains the Model's accuracy in collateral damage estimation for operational weapon strikes.

Unfortunately, Thor equation data could not be generated or validated, as due to labelling errors, the fragment path could not be determined, and thus the equation values not calculated. In addition, the effect of the corrugation of mild steel compared to flat steel could also not be determined. Despite this, the trial provided a beneficial learning opportunity for the organisation, design and conduct of energetic trials. From this trial, future work into smaller, gas gun testing has been recommended, that should enable more reliable and thus accurate data to be created.

Reflection

This project highlighted the benefits but also the additional risks associated with piggy backing on extant lethality trials. Unfortunately, due to internal factors this project could not be added onto the formal contract between Dstl and COTEC. Consequently, this had a severe impact on the assistance COTEC were able to provide. In addition, there were multiple breakdowns in communications that made the trial significantly more stressful than expected.

Whilst every effort was made by both COTEC and myself to ensure the data was obtained to a high standard, this poor communication coupled with scheduling clashes with academic commitments meant data could not be collected at the quality expected. In future trials, I plan to make communication clearer between customers and colleagues to ensure all project requirements are met by providing a list of actions against deadlines.

All of these lessons have been captured and retained as part of the WSE team's knowledge management process. Through organising and validating the design aspects of the trial with SMEs across the company, I have obtained many useful points of contact to be used for future trials. I look forward to using the knowledge and skills learnt from this trial to assist with future trials work.

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Appendix A

Figure 24 shows the geometries assumed to calculate the distances for the peak fragment velocity measurements.

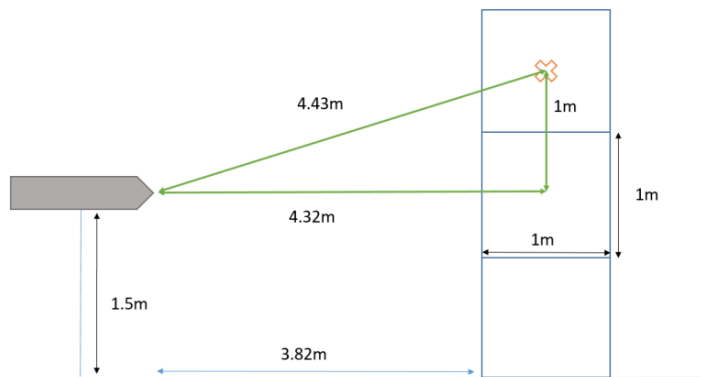


Figure 24-The calculations completed to determine the distance between the mortar and the strawboards

Appendix B

To understand where fragments hit, and how much energy they had, the strawboards and materials required processing.

The origin point was written on the bottom left hand side of the materials. Unfortunately, not every single piece of strawboard and CDM material was labelled by COTEC, often making it difficult to differentiate which way was up. It was hoped that after all the data for that section is compiled, any boards placed the wrong way would be easy to spot and then amend.

Next, all the velocity foils were removed to show the full extent of the damage. Any holes in the material were circled and then numbered. The pack was then photographed to show all these numbers, in case there were any issues with the measurements.

First, the area would be searched for fragments. A magnet would be placed over every fragment hole, and any fragments discovered would be removed, and then weighed on a balance. The fragment would then be placed in a plastic bag attributed to that pack. All fragments found would be added to a spreadsheet for that layer, detailing if there was any fragments found, and if so their weight and if they were magnetic.

Through doing this, it was realised how difficult collecting fragments from the cladding materials were, as they were about 16cm thick- making it difficult to dig out the fragments. It was quickly decided that to save time, these fragments would be left buried within the cladding. The fragments were originally required to give an indication of what fragments can be stopped by these collateral materials. However, data from the other team's packs can instead be used as a direct comparison. Their strawboard had no material in front of it, meaning a direct comparison can be made between our collateral packs and their bare strawboard.

Next, the fragments holes were measured from the (0, 0) point, demonstrated within Figure 25. Occasionally, the fragment holes were grouped together if fragment break up was suspected (lots of tiny holes around a bigger hole). In this situation, the largest hole location would be recorded. These hole locations would be compared against the other strawboard packs to provide an idea of the fragments path through the material.

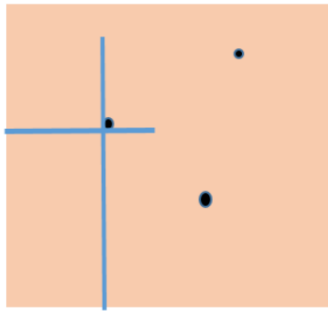


Figure 25-An example of how fragment penetrations were measured from a strawboard

Determining the Fragmentation Effects of an 81mm Mortar Shell against Building Materials

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS
Please ask Jenni Steen for your marking sheet for feedback.

84/100

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