

Final submission

by George Tucker

Submission date: 22-Mar-2024 09:03AM (UTC+0000)

Submission ID: 227531334

File name: 18041_George_Tucker_Final_submission_461145_218263235.doc (8.99M)

Word count: 9716

Character count: 50605

INVESTIGATION INTO SCALING OF CONTROLLED FRAGMENTING CASES

by

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Project submitted as part of the requirements
for the award of BSc (Hons) OME

March 2024

Declaration of Originality

I, George Tucker, declare that I am the sole author of this Project; that all references cited have been consulted; that I have conducted all work of which this is a record, and that the finished work lies within the prescribed word limits.

This work has not previously been accepted as part of any other degree submission.

Signed : 

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ABSTRACT/SYNOPSIS

Fragmentation arena trials assess munition performance when evaluating the suitability of a new system. As the net explosive quantity (NEQ) of a system increases, the size, complexity, and cost of such a trial also increases. An investigation has been conducted to examine whether there is a relationship between scaled versions of controlled fragmenting cases, and the formation of their fragments. If a meaningful relationship determined, then it may be possible for munition designers to evaluate their designs using scaled-down cases explosive charges. This would have the benefits of reducing time, costs, and environmental impact. Whilst simultaneously reducing the severity of the explosive hazard. The primary findings are that there does not appear to be a clear relationship between scale and fragment formation. However, due to experimental errors, further investigation into this avenue of research is recommended.

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ACKNOWLEDGEMENTS

I would like to thank my project supervisor for helping me through my final year project and providing many pearls of wisdom over the course of several project meetings.

I wish to thank my fellow apprentices and the apprentice team at Dstl who have always been there to support me and offer me advice.

Finally, thanks is due to my non-apprentice colleagues who have offered their support to me with training or advice to complete this degree.

SECTION 1 INTRODUCTION

1.1 PREFACE

This report examines the findings of research carried out to investigate scaling controlled fragmenting cases, and how this affects the fragmentation that is produced. The reason for this research was to attempt to fill an identified knowledge gap, as well as to potentially provide benefit to those who work in munition design and evaluation.

1.2 AIM

The primary aim of the research was to use modelling software to establish the presence of any form of relationship between scaling of a case and the fragments that are produced. With the secondary aim being the determination of the nature of such a relationship.

1.3 OBJECTIVES

The objectives of the research were as follows:

- To provide background knowledge and understanding of the area of research and how it might be implemented within industry.
- Conduct a literature review for research that already covers this area of experimentation.
- Use design of experiment theory to create a suitable test series that could be explored using modelling software.
- Analyse the results of the modelling to determine if any meaningful relationship can be identified.
- Suggest improvements and areas for further study if appropriate.

1.4 REPORT CONTENT

This report is broken into several sections:

Section one illustrates an overview of the report. It details the aims and objectives that once achieved will bring success to this research.

Section two concentrates on background research and covers where the need for this study has arisen from, and where or how its findings could be applied.

Section three details the experimental journey, including resource management and a design of experiment approach to the research.

Section four reviews the modelling set up and parameters used to perform the tests outlined in section three.

Section five displays the results from the modelling simulations and the data that can be extracted from them.

Section six focuses on the analysis of the results obtained from the successfully run simulations.

Section seven expands upon the initial analysis to discuss the reasons behind the collected results and the limitations associated with them.

Section eight contains the conclusions from this research.

Section nine explains the future scope and direction of research in this area and how it would be best achieved.

Section ten contains a reflective summary concerning the journey undertaken by the principal researcher for this project.

SECTION 2 BACKGROUND

2.1 FRAGMENTING MUNITIONS

Fragmentation is one of the primary methods of incapacitating targets during warfare. Primarily used to defeat personnel, and soft-skinned vehicles fragmenting munitions have been commonplace on the battlefield throughout history, with their use continuing to the present day. Examples of such munitions include grenades, anti-personnel mines, and artillery shells. [15]

Fragmenting munitions defeat targets by transferring kinetic energy to damage the target. [15] Depending on the nature of the target, a different threshold of kinetic energy will be required (e.g. fragment size of 2 grains to defeat personnel) [14]. Because of this, munition designers need to generate fragments of a certain mass and velocity at the point of initiation to be effective. There are several ways to achieve the desired fragment mass and velocity within a munition. For example, varying explosive fill, casing material and the mode of fragmentation.

2.2 FRAGMENTATION METHODS

The different modes of fragmenting a munition case are as follows:

- Natural fragmentation – fragmentation caused by the fracturing of a munition case when subjected to the intense pressures experienced by the detonating explosive fill. The size of fragments that form will depend on the type of explosive and the case material. The explosive properties of the chosen fill such as power index, velocity of detonation (VoD), and brisance are the key explosive parameters driving fragmentation. For the case material, parameters such as hardness, yield stress, and grain structure will be important in the fracture mechanics of the case. Small defects within the case's material structure will act as the origin for fractures. Therefore, the treatment and finish of the case also influence the fragments that form.
- Fire-forged/formed or controlled fragmentation– this method of fragment formation works by scoring a pattern into the casing of a munition. These score lines act as introduced defects in the fragment formation process. In this way, the fragments are likely to form along the defect lines, and in this way is the size of the fragment controlled.
- Pre-formed fragmentation – this method of achieving a desired fragment relies on introducing a sleeve or other section of material that has already been manufactured to the desired shape and size. For example, a layer of ball bearings that sits between the explosive fill and the munition case, or

metallic cubes arranged in a similar fashion. These fragments are intended to be projected from the munition when detonation of the main fill occurs without undergoing further fracturing or distortion. In this way, the desired fragment size is controlled by the manufacture of the fragment itself, and not as a by-product of the events of detonation of a main fill. [14]

2.3 EVALUATING FRAGMENTING MUNITIONS

A common method of testing fragmenting munitions is to perform a fragmentation arena trial. During the trial, the fragmentation size, velocity, and distribution of a munition can be assessed. This usually involves setting up a semicircle of fragmentation collection packs, usually referred to as frag packs, with the munition placed at the centre. This comprises the arena hence the name of this particular trial set-up. When the munition functions, the fragmentation packs collect the fragments that can then be recovered after the trial. By keeping a record of the location of each pack, the distribution of fragments can be assessed; therefore, a density map of how fragments are projected around a munition can be created. The energy of such fragments can be evaluated by looking at the depth of penetration into the target. Additionally, trip screens can be used to give an indication of fragment velocity, however these may only measure the initial impact velocity depending on the type used. By placing the munition in various orientations within the arena, an assessment can be made about the fragmentation projection distribution around the munition, therefore allowing the overall performance to be evaluated. [5]

There are several trial-design considerations when performing such a trial. For instance, as the NEQ of a system increases, so does the size of the required arena. This in turn may limit where the trial can be conducted due to site NEQ limits and increases the amount of materials and personnel to construct the arena. This has the knock-on effect of increasing the time between shots. Additionally the munition will require more material to construct, which can increase production costs, especially if testing a novel design or explosive.

If it is possible to reduce the size of the munition: time, money, material and environmental impact can be reduced. To understand if it is possible to scale down such trials and still achieve representative data, the relationship between scaling and fragment formation must be examined.

2.4 PREVIOUS RESEARCH

This investigation is concerned primarily with the scaling of controlled or fire-forged fragmenting munitions. As such, works in this field were assessed at the project's concept stage to ensure it had not been done before.

Work on fragmenting munitions has been carried out for many years, and papers examining the effect of munition scale on the formation of natural fragments have been carried out before. [8] However, no evidence could be found of papers examining the interaction between a scale function and the effects on the fragments formed for controlled fragmenting cases. These papers mainly concern themselves with identifying the distribution of fragment masses [1] of cases when altering parameters such as case material and explosive fill [3] or focus on the validation of naturally fragmenting modelling [6]

SECTION 3 METHODOLOGY

3.1 RESOURCE MANAGEMENT AND PLANNING

It was decided that a purely modelling-based investigation would be used for this project. The reasons for this were as follows:

- Ability to test a wide range of factors with minimal cost – e.g. no manufacturing and tooling costs arising from multiple designs.
- Reduced project risk – to do a live explosive trial requires more funding to be secured, in addition to the potential for other priority work pushing the project back beyond the deadline or being called off due to weather conditions etc.
- Reduced safety risk – many iterations can be examined with the modelling giving an indication of what factors may be significant in affecting the results. Then a live explosive trial can be designed examining only those factors. This eliminates the need for as many experimental runs with live explosive material; therefore lowering the risk in the eventuality the project is taken forward to trial.
- Flexibility in experimental design – this allows for more reactive corrections should factors and test runs need to be changed.
- Shorter delivery time – this negates lead times for ordering explosive materials, getting cases made, having charges assembled etc.
- Reduced environmental impact – by performing this research completely through modelling, it minimises the impact on the environment, as no explosive products are released into the environment; also there is no impact from noise pollution. Additionally, by identifying test serials that are not worth running, this approach can reduce the amount of live explosive test runs.

3.2 EXPERIMENTAL APPROACH

To help determine the factors and simulations, design of experiment theory was employed to reduce the amount of tests required, whilst still providing an adequate spread of data that could be analysed and provide initial conclusions that may inform future studies.

To this end, several different design of experiment techniques were investigated such as screening, definitive screening, [18] Taguchi arrays, and mixed-level design. Ultimately, the Taguchi array was selected for this investigation as it provides the ability to examine a large amount of factors without the need for a large amount of test serials. Additionally the results can be used to provide an indication as to whether a factor has an effect on the outcome of a serial. [17]

More specifically, an L16 (26) (43) Taguchi array was chosen as this type of design comprises of six two-level factors, and three four-level factors. There are smaller arrays that can be employed, as well as arrays with fewer levels. However, this array was selected to cover a wider range of factors and provide depth to the study in the form of scaling allowing for multiple scaling factors to be applied.

The 7 different factors and their corresponding levels were as follows:

- Four-level factors
 - Scale
 - Scoring pattern
 - Thickness of case
- Two-level factors
 - Case yield stress
 - Explosive power index
 - Scoring depth
 - Scoring profile
 - Internal/external scoring
 - Scoring thickness

These factors were subsequently used to form a test matrix using the Taguchi format displayed in Table 1:

Table 1 - Initial Taguchi Matrix

Test Serial	Scale (%)	Pattern	Case Thickness (%)	Factors Case material hardness	Velocity of Detonation	Scoring Depth (%)	Scoring Profile	Internal/external scoring	Scoring thickness
1	100	none	25	Cast iron	TNT	25	V	Internal	A
2	75	square	50	Cast iron	TNT	50	U	External	B
3	50	triangle	75	Steel	RDX	25	V	External	B
4	25	diamond	100	Steel	RDX	50	U	Internal	A
5	100	none	50	Steel	RDX	25	U	Internal	B
6	75	square	25	Steel	RDX	50	V	External	A
7	50	triangle	100	Cast iron	TNT	25	U	External	A
8	25	diamond	75	Cast iron	TNT	50	V	Internal	B
9	100	none	75	Cast iron	RDX	50	U	External	A
10	75	square	100	Cast iron	RDX	25	V	Internal	B
11	50	triangle	25	Steel	TNT	50	U	Internal	B
12	25	diamond	50	Steel	TNT	25	V	External	A
13	100	none	100	Steel	TNT	50	V	External	B
14	75	square	75	Steel	TNT	25	U	Internal	A
15	50	triangle	50	Cast iron	RDX	50	V	Internal	A
16	25	diamond	25	Cast iron	RDX	25	U	External	B

After completing the table, Computer Aided Design (CAD) software was used to draft some of the cases. After these initial designs were drawn and reviewed with the modelling team, it was decided that some of the geometries needed to be revised. This was due to the limitations of meshing an explosive case in the available software. The primary limitations were that it would be too difficult to mesh a diamond-patterned case (shown in Figure 1), as well as adjust the scoring profile to a V shaped groove.

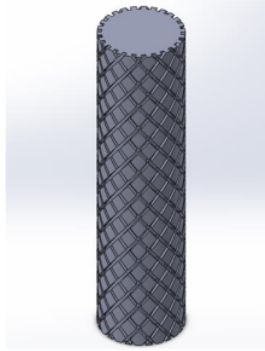


Figure 1 - Diamond pattern fragmenting case

To this end, a new set of case designs were listed, alongside a new Taguchi test matrix. The revised matrix can be found below as Table 2:

Table 2 - Revised Taguchi Matrix

Test Serial	Scale (%)	Pattern	Case Thickness (% of diameter)	Case Hardness (rockwell)	Velocity of Detonation	Scoring Depth (% of case thickness)	Scoring Density ¹	Internal/external scoring	Scoring width ²
1	100	square	2.5	4340	TNT	25	Coarse	Internal	A
2	100	vertical rectangle	5.0	4340	TNT	50	Fine	External	B
3	100	horizontal rectangle	7.5	Armco Iron	RDX	25	Coarse	External	B
4	100	irregular	10.0	Armco Iron	RDX	50	Fine	Internal	A
5	75	square	5.0	Armco Iron	RDX	25	Fine	Internal	B
6	75	vertical rectangle	2.5	Armco Iron	RDX	50	Coarse	External	A
7	75	horizontal rectangle	10.0	4340	TNT	25	Fine	External	A
8	75	irregular	7.5	4340	TNT	50	Coarse	Internal	B
9	50	square	7.5	4340	RDX	50	Fine	External	A
10	50	vertical rectangle	10.0	4340	RDX	25	Coarse	Internal	B
11	50	horizontal rectangle	2.5	Armco Iron	TNT	50	Fine	Internal	B
12	50	irregular	5.0	Armco Iron	TNT	25	Coarse	External	A
13	25	square	10.0	Armco Iron	TNT	50	Coarse	External	B
14	25	vertical rectangle	7.5	Armco Iron	TNT	25	Fine	Internal	A
15	25	horizontal rectangle	5.0	4340	RDX	50	Coarse	Internal	A
16	25	irregular	2.5	4340	RDX	25	Fine	External	B

The changes to the matrix were as follows:

- The cases with no scoring were removed as it was decided that naturally fragmenting cases have been researched before, and a case with no scoring would not allow for any of the other factors to be tested in each serial. Additionally, the triangular pattern of fragments would suffer from the same issues with meshing as the diamond pattern, and thus was removed from the test matrix.
- Horizontal and vertical fragment scoring patterns were introduced to replace the triangular and no scoring pattern factors.

- The diamond pattern fragments were replaced with an irregular pattern of fragments that are still oriented in an X/Y fashion, meaning there are no diagonals to cause issues with meshing.
- The scoring profile was replaced with scoring density, a 2-level factor with either a dense or sparse level. The dense level containing approximately double the amount of fragments than the sparse one.

3.2.1 Taguchi Factors explained:

With so many factors affecting geometry, priority was placed on defining parameters as ratios or percentages of other dimensions to ensure proportionality between each case design. For example, it is impossible to set fixed scoring depths at 5 mm and 15 mm, if the case thicknesses were to range from 2.5 mm – 20 mm. The interplay between each factor had to be considered carefully before assigning different values or constraints. Below is a summary of each Taguchi factor included in the test matrix and how it is defined:

- Scale factor – this represents a uniform geometric scaling of a design to a percentage of its original dimensions. E.g. a 1 m X 1 m X 1 m cube would become 0.5 m x 0.5 m x 0.5 m at 50%.
- Pattern – this denotes the desired shape of each fragment. The four different fragment patterns chosen were square, horizontal and vertically oriented rectangles, and an irregular pattern blending square and rectangular fragments. This represents a case design whereby there are more than one desired target for a munition to defeat e.g. Infantry and light vehicles, each requiring fragments of different masses to defeat. The pattern dimensions are discussed in greater detail in the CAD design process section.
- Case thickness – this was set as a percentage of the case diameter.
- Case material hardness – two different Rockwell hardness values were chosen for the cases. However, it must be noted that the only way to achieve this was to alter the materials themselves. For simplicity within the table, the material identifiers are used for reference, these were 4340 steel and Armco Iron. The values of hardness for 4340 steel and Armco Iron are C-30 and F-72 respectively.

- Velocity of detonation – as with the case material hardness, two different values for velocity of detonation of the explosive were selected for use in the matrix. Again, to change these values required a change in explosive material. The two explosives chosen were trinitrotoluene (TNT) and composition-4 (C4), as these were available in the impetus library, with velocities of detonation of 6930 ms⁻¹ and 8092 ms⁻¹ respectively.
- Scoring depth – this factor was set at either 25% or 50% of the case thickness. This means that it was dependant on the case thickness and could only be ascribed after the thickness had been calculated for that serial.
- Scoring density – the coarse level of density was selected as the baseline for this factor. It was originally achieved by creating a square fragment whereby the arc length of each fragment was subtended by an angle of 45 degrees. This arc length then dictated the height of each fragment. Once this had been completed, the fine fragment density was simply twice as dense as the coarse fragment density.
- Internal/External scoring – this simply denotes whether the scoring of the case is on the internal surface or the external surface of the case wall. Internal fragments will have a marginally smaller surface area due to a slightly smaller arc length.
- Scoring width – the width was set at two levels, A and B. The factor is set as an expression of the scoring depth so that a current width is maintained across each depth for both A and B, and so that width B is always twice the size of width A.

This is illustrated in Figure 2:

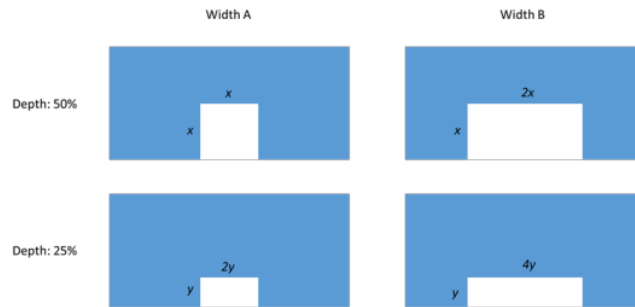


Figure 2 - Scoring width derivation diagram

For this factor the scoring depth was identified first, the value of which is dependent on the case thickness for that test serial, then the width can be calculated with $A = x$ for a depth of 50%, or $A = 2y$ for a depth of 25%. For level B, the width is given by $B = 2x$ for a depth of 50%, and $B = 4y$ for a depth of 25%.

3.3 PREPARATION

Case design process:

Each test serial required a unique CAD model that reflected the design parameters from the Taguchi matrix. This equated to a total of 16 CAD geometries that were created using the Solidworks CAD software package from Dassault Systems [12].

As explained previously, the Taguchi array required the implementation of a variety of different parameters to each shell case. For simplicity, it was decided to apply these sequentially to an original shell case design. The final parameter to be implemented would be the scale factor. This was to save time having to convert every other dimension to be relative to the scale.

The original shell case design was a cylinder measuring 600 mm in length, with a radius of 75 mm. These dimensions were chosen to simulate a 155 mm artillery shell; a munition that is commonplace in modern day conflicts across the globe,

and employed by many different armed forces. Example case dimensions of which were obtained from an open source report:

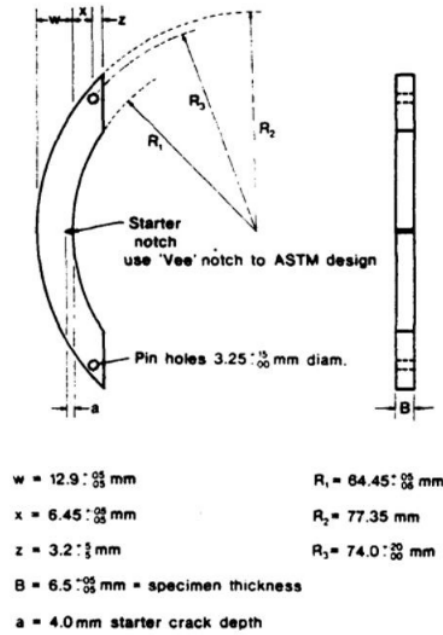


Figure 3 - 155 mm case example dimensions [16]

The following workflow of features was employed in the creation of each test serial case:

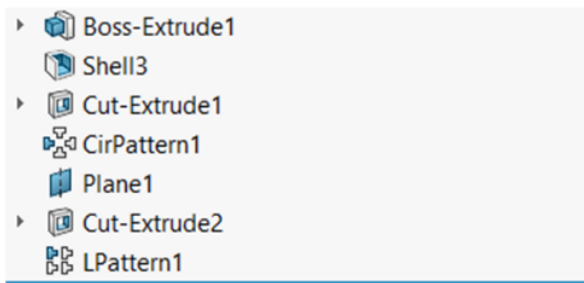


Figure 4 - Solidworks feature workflow

First, a cylinder was hollowed out to the appropriate thickness for the serial, dictated as a percentage of the diameter and shown by the shell function (Figure 5).

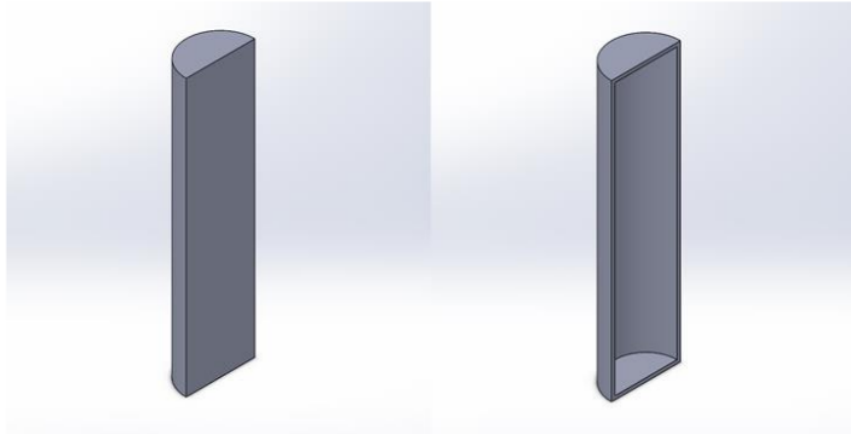


Figure 5 - Case design step one

Next, a single vertical recess was added to generate the vertical grooves on the case (Figure 6 right hand image).

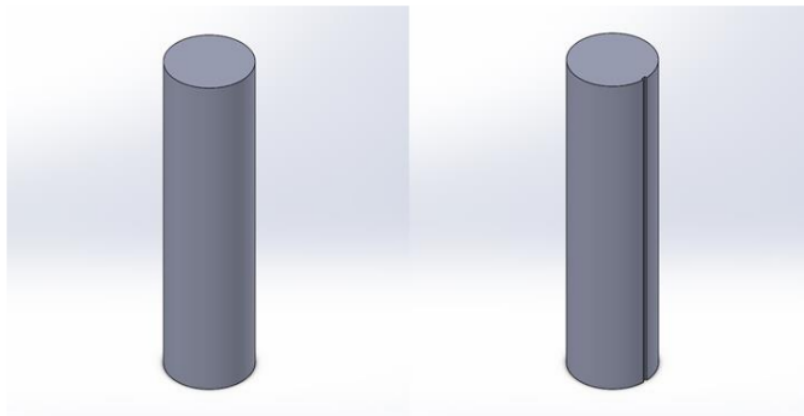


Figure 6 - Case design step 2

This recess was then patterned around the circumference which could be internal or external depending on the test serial requirements (shown in Figure 7). Note that the fragments are always formed by a groove cut into the case, regardless of whether it is on the external or internal face so the minimum wall thickness is the same in either configuration.

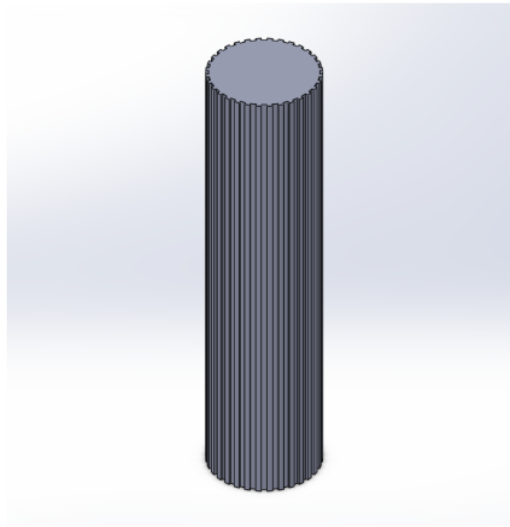


Figure 7 - Case design step 3

A horizontal groove is made half way up the case following the circumference of the case showcased in Figure 8.

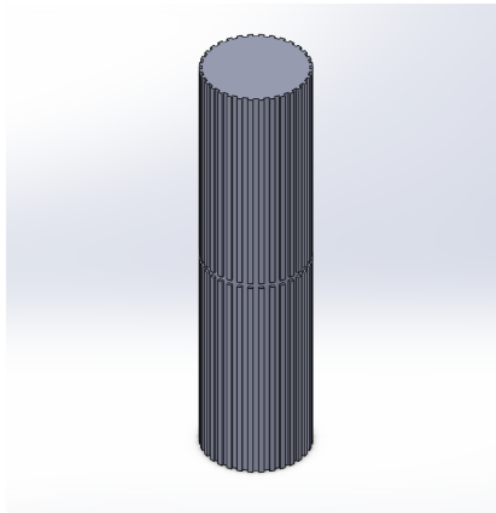


Figure 8 - Case design step 4

Finally, horizontal groove is then linearly patterned along the cylindrical axis (Figure 9). The areas bounded by these grooves are the finished controlled fragments.

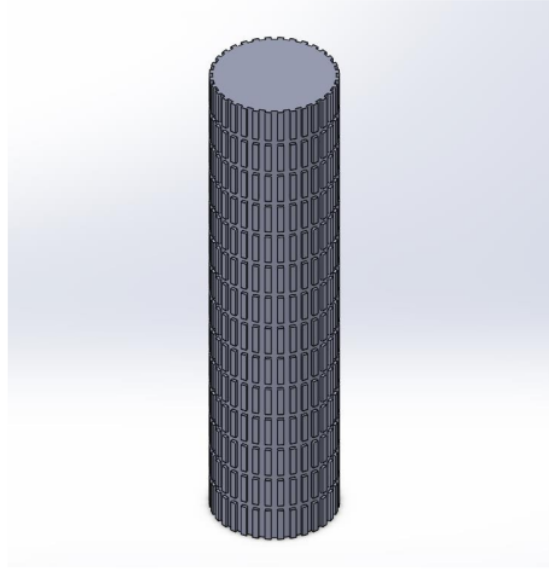


Figure 9 - Case design step 5

The different fragment shapes are derived from a basic square fragment design and were altered to generate vertical and horizontal rectilinear fragments. To attempt to establish a common fragment area these rectangles were generated by reducing and expanding alternating sides of the original fragment by the value of $\sqrt{2}$. This means that for horizontal rectangular fragments there are fewer around the circumference but more along the length of the case, the opposite is true for the vertical rectangular fragment pattern.

The final fragment pattern involved a mixture of square and rectangular segments in an alternating pattern. Not only did the fragments in each row alternate, they were rotated sequentially by a certain number of degrees for each layer (the angle

depending on the size of the fragments in the pattern). In effect, staggering the fragments down the length of the case.

The finished case CAD models for test serials 1-4 are shown below in Figure 10. Images of the cases for test serials 5-16 can be found in Appendix A – Case Designs.

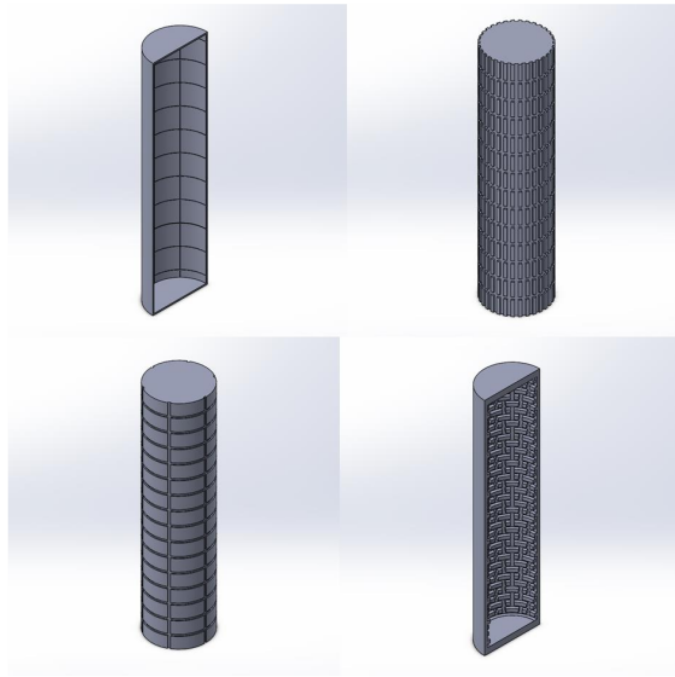


Figure 10 - clockwise from top left: serials 1-4

After the CAD models were finished, the geometries required meshing. This was done using Hypermesh 2022 software [13].

A case geometry is imported into the software; this provides a wire-mesh framework (Figure 11) on which nodes can be placed which are then used to create elements that form the mesh. It was advised to use a 1 mm resolution mesh for the simulations, so no element is bigger than 1 mm³. Due to the nature of the case geometries, some elements did have to be smaller than 1 mm to account for the dimensions of some of the smaller grooves at the smaller scale factors. The mesh, once complete, can then be imported into the modelling software for simulations to be run.

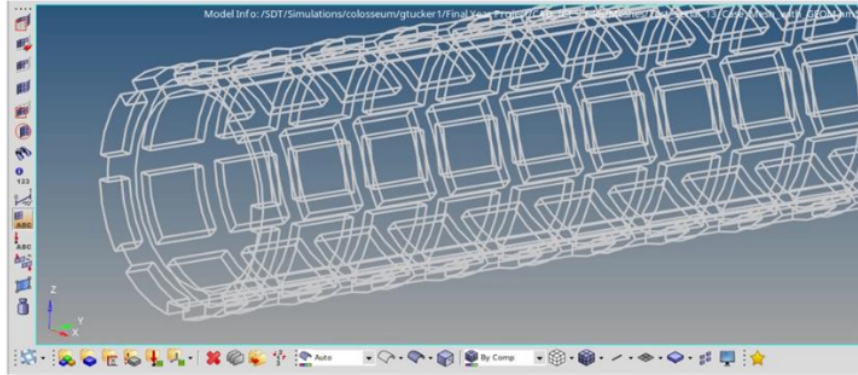


Figure 11 - Imported CAD geometry wire-mesh

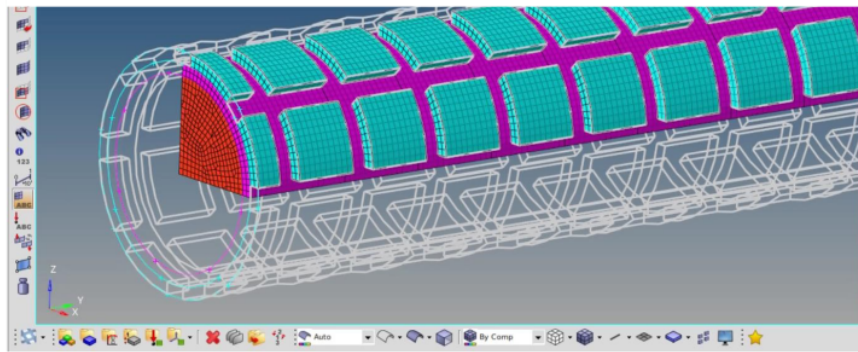


Figure 12 - Meshed case design with elements for the fragments, case wall, and case end caps, picked out in cyan, magenta, and red respectively

Whilst meshing the cases, it was noticed that there were two design errors in test serial 5 and 14. They both had the incorrect case thickness applied; however, it would have taken too long to re-model, re-import and re-mesh the cases. So a note was made on each deviation to make sure the results could be processed accordingly.

SECTION 4 TESTING

4.1 MODEL PARAMETERS

The modelling software Impetus [2] was selected for the purpose of simulating the test serials. Impetus is a software that allows for several different modelling techniques such as Lgrangian modelling and Smoothed Particle Hydrodynamics (SPH) modelling.

Initially materials and material models had to be identified for the casing material that was going to be used. From the Taguchi matrix, two materials with different hardness values were required. These were chosen as Armco steel 4340 for the hard material, and Armco iron for the softer material.

The properties for each material model as input into the impetus software were as follows:

Table 3 - Case material properties

Material	Material Property Parameter										
	Density (ρ)	Young's Modulus (E)	Poisson Ratio (ν)	Initial Yield Strength (A)	Hardening Parameter (B)	Hardening Parameter (n)	Strain Rate Hardening Parameter (C)	Thermal Softening parameter (m)	Melting Temperature (T_m)	Strain rate Parameter (ϵ_0)	Specific Heat Capacity (C_p)
4340 steel	7.83E-06	2E02	0.29	0.792	0.510	0.26	0.014	1.03	1793	0.001	477
Armco Iron	7.89E-06	2.07E02	0.29	0.175	0.380	0.32	0.06	0.55	1811	0.001	452

[10]

For the cases a Johnson-cook material damage model was used with the following parameters:

Table 4 - Case material damage model properties

Material	Material Damage Model Property						
	Erosion Element Flag	Damage parameter (d_1)	Damage parameter (d_2)	Damage parameter (d_3)	Damage parameter (d_4)	Damage parameter (d_5)	Reference Strain Rate ($\dot{\epsilon}_0$)
4340 Steel	2	0.05	3.44	-2.12	0.002	0.61	0.001
Armco Iron	2	-2.2	5.43	-0.47	0.016	0.63	0.001

[10]

These damage models control how elements fail and can seed failure points within the material itself that aim to replicate physical material failure mechanics.

An element test was carried out on a simple cube of these materials to ensure that the model was suitable and elements would not distort and cause errors during the simulation.

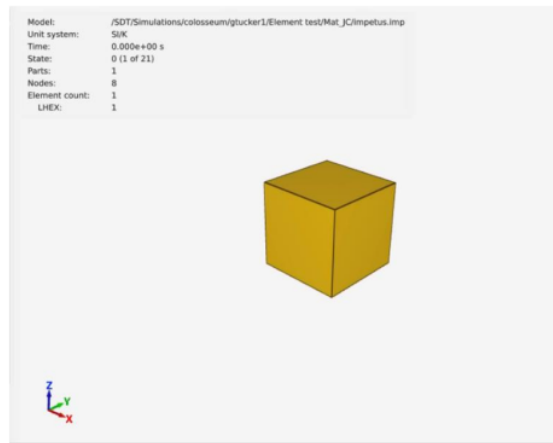


Figure 13 - Element test pre-loading

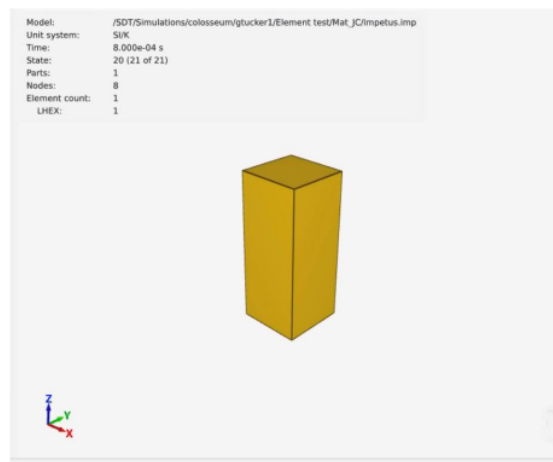


Figure 14 - Element test post-loading

Once the case material models had been established and the parameters placed within the simulation set-up, the rest of the simulation could be created.

The following parameters in Table 5 were used for all of the models:

Table 5 - Model base simulation parameters

Simulation Parameters			
Units	Run Time	Initial Temperature	Symmetry Conditions
mm/kg/ms/K	2	293	XZ planes

These can be seen in Figure 15 within the modelling script. All script pages can be found in Appendix B – Impetus Simulation Scripts.

```

3 #
4 *UNIT SYSTEM
5 MMKGMS, K
6 *PARAMETER
7 tend = 0.2, "Termination time"
8 num_imp = 10, "Number of .imp files"
9 num_ascii = 1000, "Number of .out time steps"
10 num_db = 2, "Number of database and state files"
11 nres = 2, "Number of cyclic alternating files"
12 T0 = 293, "initial temperature"
13 *TIME
14 [%tend]
15 *OUTPUT
16 [%tend/%num_imp], [%tend/%num_ascii], [%tend*%num_db], 3
17 , , , [%nres]
18 #
19 # --- CONSTRAINTS ---
20 #
21 *BC SYMMETRY
22 ZX
23 #
24 # --- INITIAL CONDITIONS ---
25 #
26 *INITIAL TEMPERATURE
27 P, 101, 123
28 *FUNCTION
29 123
30 %T0
31 #
32 # --- SPH ---
33 #
34 *GEOMETRY_PART

```

Figure 15 - Impetus project model script

The simulation run-time was selected to allow for all of the explosive material to react and to allow time for the fragments to form. This value was chosen based off previous similar work, and for the initial test serial, showed fragment formation.

This time was then kept the same in each run for simplicity.

The explosive fill was not meshed, and so had to be defined by a region within the model space. This was done by measuring the internal cavities of the CAD geometries and creating a new geometry with the same dimensions. For the internally scored cases, the explosive geometry was defined by the inner surface of the fragment, meaning that there was no explosive fill within the notches themselves. This was done for efficiency as creating a matching fill would have taken too much time.

The two different explosives chosen were TNT and C4, due to having different velocities of detonation and well-understood material and explosive properties. This was useful as they could be selected straight from the Impetus material library when initially looking at a Lagrangian model.

A detonation point was selected at 2.5 mm within the explosive, regardless of the case design or scale.

Initially the model was intended to be run as a Lagrangian simulation. However, the estimated time for the first test serial to complete was approximately 140 hours. As this was not practical due to a limited number of cores available, and limited time, it was decided to attempt to run the simulations using an SPH model instead.

To alter the model in this way, fluid material properties and Jones-Wilkins-Lee (JWL) equations of state (EOS) for the explosive fills had to be inputted manually into the model script. The values for these can be seen in Table 6 and Table 7 respectively:

Table 6 - Explosive fluid material properties

Material	Fluid Material Properties	
	Density (ρ)	Linear Bulk Modulus (K)
TNT	1.63E-06	5.2
C4	1.821E-06	2.2

[11]

Table 7 - Explosive JWL EOS coefficient values

Material	JWL EOS				
	A	B	R_1	R_2	ω
TNT	371.2	3.23	4.15	0.95	0.3
C4	718	11.8	4.7	1.3	0.25

[9]

The SPH model cut down the run time from 140 hours to approximately 30 minutes. The SPH model script was duplicated for the other runs with the parameters altered in each one to represent the serials in the Taguchi matrix. After the models had run, they were post processed within the impetus software. This gives the option to identify individual fragments that have formed from an event and to measure their physical properties. Due to a difference in each simulation's results, not every run produced identifiable fragments and so some had to be discounted for the purposes of results collection. However, these runs (3, 4, 5, and 7) are mentioned in the discussion section of the report.

SECTION 5 RESULTS

5.1 SIMULATION RUNTHROUGH

Each run took a different amount of time, with the longest being 4 hours 26 minutes, and the shortest being 1 minute 1 second.

Using the software's post processing interface, the simulation results at sampled time-steps can be viewed, showing the fragmentation process:

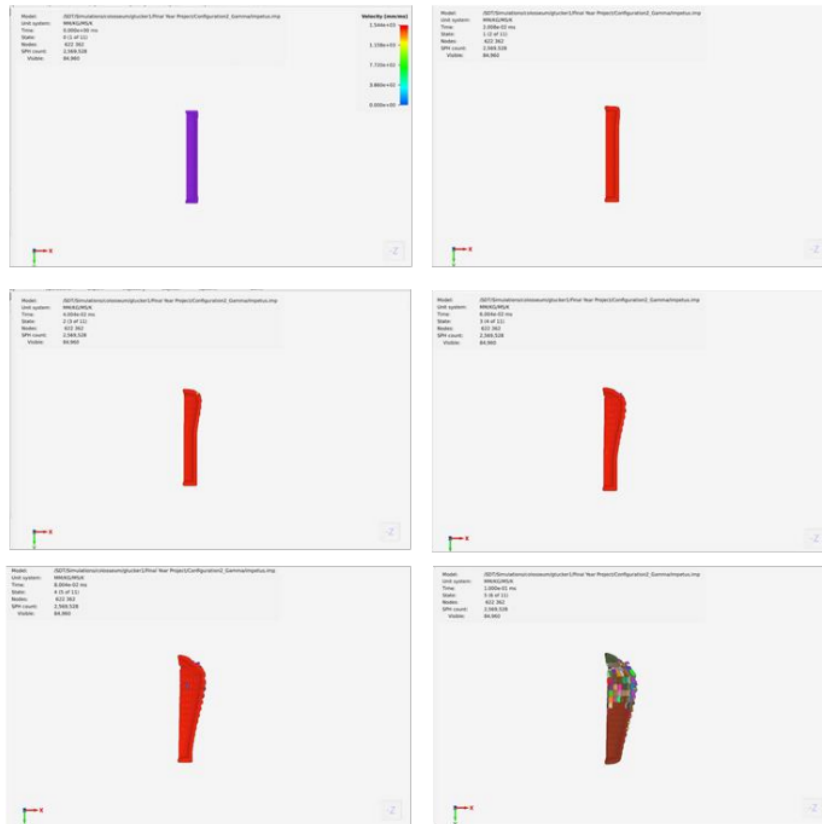


Figure 16 - Test serial 2 post-processing results for time steps 0-5

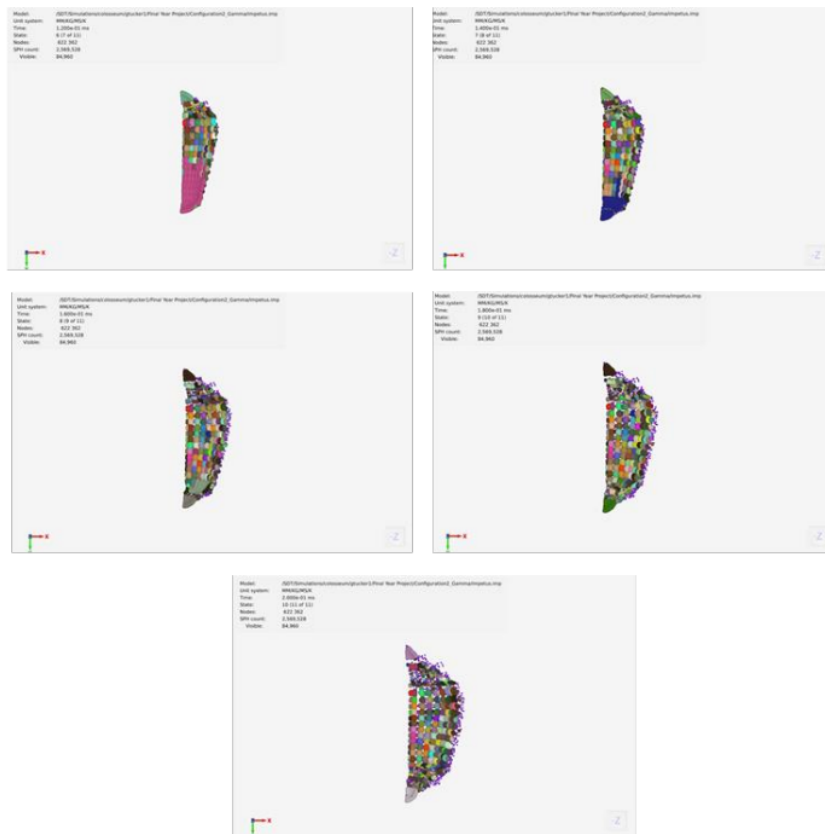


Figure 17 - Test serial 2 post-processing results for time steps 6-10

The simulation end state of case fragmentation for each test serial can be found in Appendix C – Post-Processing of All Test Serials.

5.2 FRAGMENT SELECTION

Using the software's fragment selector tool, distinct fragments were selected (figure) and the fragment data exported to excel.

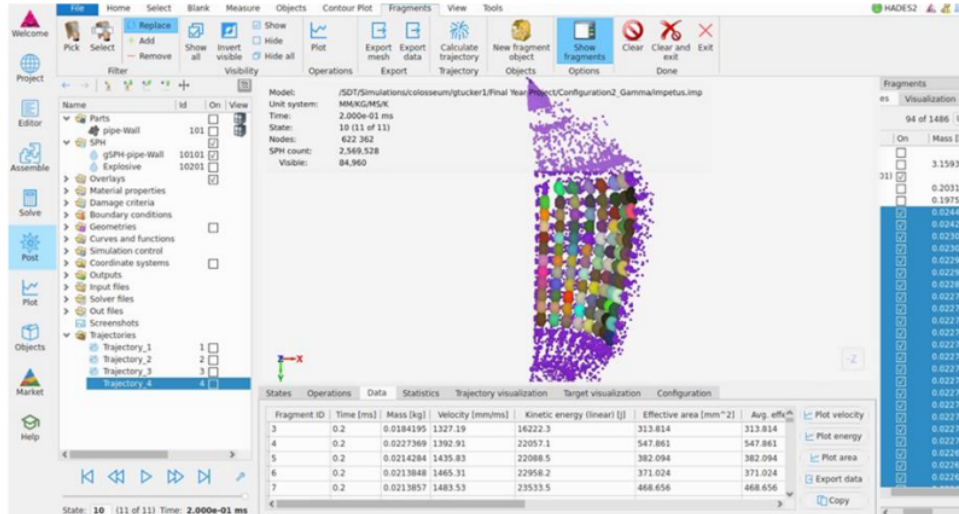


Figure 18 - Selected fragments (coloured) amongst total fragments (purple) for test serial 2

5.3 FRAGMENT DATA

An example section of the fragment data output table is seen below in Table 8:

Table 8 - Extracted fragment data

Time [ms]	Fragment ID	X coordinate of fragment center of gravity [Coordinate [m]]	Y coordinate of fragment center of gravity [Coordinate [m]]	Z coordinate of fragment center of gravity [Coordinate [m]]	Displacement of the fragment in X direction [Displacement [m]]	Displacement of the fragment in Y direction [Displacement [m]]	Displacement of the fragment in Z direction [Displacement [m]]	Displacement magnitude of the fragment [Displacement [m]]	Velocity of the fragment in X direction [Velocity [m/s]]	Velocity of the fragment in Y direction [Velocity [m/s]]	Velocity of the fragment in Z direction [Velocity [m/s]]	Velocity magnitude of the fragment [Velocity [m/s]]	Effective area of fragment [Area [m ²]]	Effective radius of fragment [Radius [m]]	Fragment mass [Mass [kg]]	Linear kinetic energy [Energy [J]]	Surface area of fragment [Area [m ²]]	Cavity area of fragment [Area [m ²]]	Average effective area of fragment [Area [m ²]]
1.20e+00	34	1.47e+03	1.71e+03	1.20e+03	1.20e+03	1.01e+02	9.75e+02	1.55e+03	1.20e+03	1.01e+02	9.75e+02	1.55e+03	3.68e+02	1.08e+01	1.41e+02	1.68e+04	1.34e+03	3.10e+02	3.68e+02
1.20e+00	35	1.20e+03	1.71e+03	1.47e+03	9.74e+02	1.01e+03	1.20e+03	1.55e+03	9.74e+02	1.01e+02	1.20e+03	1.55e+03	4.78e+02	1.23e+01	1.42e+02	1.70e+04	1.40e+03	4.00e+02	4.78e+02
1.20e+00	36	1.87e+03	1.75e+03	2.16e+03	1.52e+03	1.05e+02	1.75e+03	1.54e+03	1.52e+03	1.05e+02	1.75e+03	1.54e+03	1.15e+03	1.91e+01	2.42e+02	2.82e+04	3.42e+03	8.54e+02	1.15e+03
1.20e+00	37	1.80e+03	1.59e+02	5.60e+02	1.46e+03	9.22e+01	4.55e+02	1.53e+03	9.22e+01	4.55e+02	1.53e+03	9.20e+02	1.71e+02	1.82e+02	2.14e+02	2.86e+03	7.21e+02	9.20e+02	
1.20e+00	38	1.71e+03	1.63e+02	8.25e+02	1.39e+03	9.60e+01	6.70e+02	1.54e+03	1.39e+03	9.60e+01	6.70e+02	1.54e+03	4.18e+02	1.15e+01	1.60e+02	1.91e+04	1.41e+03	3.52e+02	4.18e+02
1.20e+00	40	1.57e+03	1.71e+03	1.07e+03	1.27e+03	1.03e+02	8.72e+02	1.55e+03	1.27e+03	1.03e+02	8.72e+02	1.55e+03	5.08e+02	1.27e+01	1.33e+02	1.59e+04	1.40e+03	4.01e+02	5.08e+02
1.20e+00	41	2.15e+03	1.74e+03	1.87e+03	1.75e+03	1.05e+02	1.52e+03	1.53e+03	1.75e+03	1.05e+02	1.52e+03	1.53e+03	6.38e+02	1.43e+01	2.41e+02	2.84e+04	1.89e+03	4.73e+02	6.38e+02
1.20e+00	42	5.61e+02	1.29e+02	1.80e+03	4.55e+02	9.26e+01	1.46e+03	1.54e+03	4.55e+02	9.26e+01	1.46e+03	1.54e+03	6.40e+02	1.43e+01	1.81e+02	2.14e+04	1.89e+03	4.97e+02	6.40e+02
1.20e+00	43	8.25e+02	1.64e+02	1.71e+03	6.70e+02	9.64e+01	1.39e+03	1.54e+03	6.70e+02	9.64e+01	1.39e+03	1.54e+03	5.50e+02	1.32e+01	1.60e+02	1.91e+04	1.84e+03	4.61e+02	5.50e+02
1.20e+00	44	1.67e+03	1.70e+02	1.57e+03	8.71e+02	1.01e+02	1.71e+03	1.55e+03	8.71e+02	1.01e+02	1.71e+03	1.55e+03	7.52e+02	1.55e+01	1.35e+02	1.61e+04	2.37e+03	5.93e+02	7.52e+02

The primary output of interest is fragment mass and so all tables were filtered to produce a final mass-list of fragments from each run. This list of fragment masses was then used to generate mean values for each simulation (shown in Table 9) which could be compared against predicted mass values.

Table 9 - Average fragment mass for each test serial

Test Serial	Average fragment mass (kg)
1	0.0171682
2	0.0217935
3	N/A
4	N/A
5	N/A
6	0.00894508
7	N/A
8	0.0236453
9	0.00302263
10	0.0187673
11	0.0016843
12	0.00382263
13	0.00285087
14	0.000438464
15	0.000026604
16	2.31443E-05

SECTION 6 ANALYSIS

6.1 DATA PROCESSING

After the average mass of fragments produced in each simulation was calculated, the values could be compared against a value of predicated fragment mass which was generated using the CAD model dimensions. The predicted mass being the product of the volume of the scored fragment and the density of the material used in that test serial. By calculating the percentage difference from the predicted value of fragment mass with the actual formed fragment mass, the results from the test serials can then be compared.

Table 10 - Average fragment mass compared to predicted fragment masses

Predicted fragment masses from geometries						
Test Serial	Fragment area (mm ²)	Fragment Thickness (mm)	Fragment Volume (mm ³)	Fragment Mass (kg)	Average fragment mass (kg)	Percentage difference to predicted fragment mass
1	3022	3.75	11332.5	0.088733475	0.0171682	-0.806519467
2	255	7.5	1912.5	0.014974875	0.0217935	0.45537691
3	2261	11.25	25436.25	0.200692013	N/A	N/A
4	130	15	1950	0.0153855	N/A	N/A
5	268	5.62	1506.16	0.011883602	N/A	N/A
6	1298	2.81	3647.38	0.028777828	0.00894508	-0.689167649
7	315	11.25	3543.75	0.027747563	N/A	N/A
8	708	5.62	3978.96	0.031155257	0.0236453	-0.241049427
9	125	5.62	702.5	0.005500575	0.00302263	-0.450488358
10	258	7.5	1935	0.01515105	0.0187673	0.238679827
11	125	1.87	233.75	0.001844288	0.0016843	-0.086747592
12	519	3.75	1946.25	0.015355913	0.00382263	-0.751064614
13	110	3.75	412.5	0.003254625	0.00285087	-0.124055767
14	43	0.94	40.42	0.000318914	0.000438464	0.374866814
15	124	1.87	231.88	0.00181562	0.000026604	-0.985347157
16	30	0.94	28.2	0.000220806	2.31443E-05	-0.895182649
			1	0.0000783		
			1	0.0000789		
	4340 Steel Density	Armco Iron density				
	0.0000783	0.0000789				

The results are then further refined by comparing the mean value of all of the fragment masses for each factor varied in the Taguchi matrix to give an indication whether if, and how, factors have an effect on the outcome. As there was only one simulation done for each test serial, this is a very simple examination of the potential factor influence. For example, to plot the effect scale had on the fragment formation, the mean fragment mass was taken from each of the serials at 100% scale. This was repeated for the serials at scales of 75%, 50%, and 25%, and the results plotted on a graph. If a simulation failed to produce any identifiable fragments then it was discounted from the results list. Consequently, mean values for different runs may have been influenced by the number of identifiable fragments available.

6.2 POST-PROCESSING GRAPHS

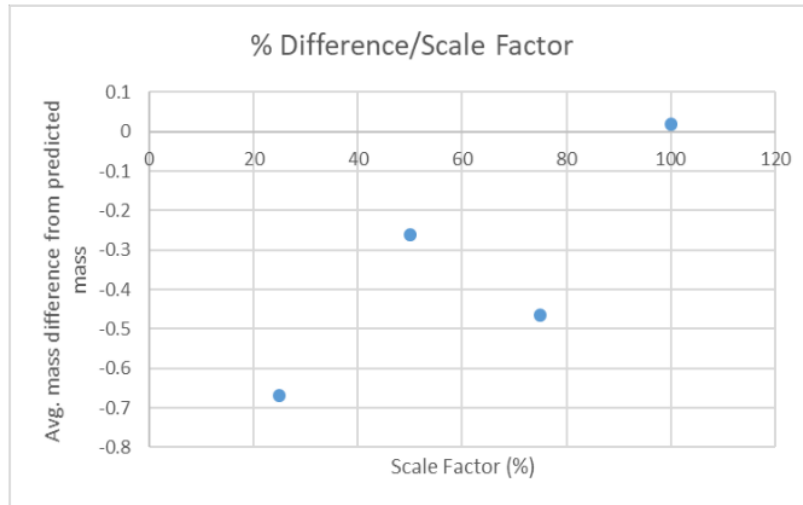


Figure 19 - Graph displaying percentage mass difference plotted against case scale

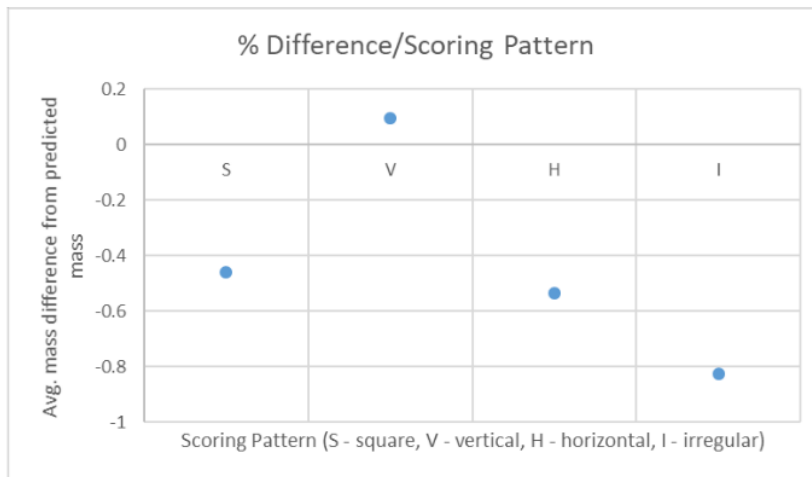


Figure 20 - Graph displaying percentage mass difference plotted against scoring pattern type

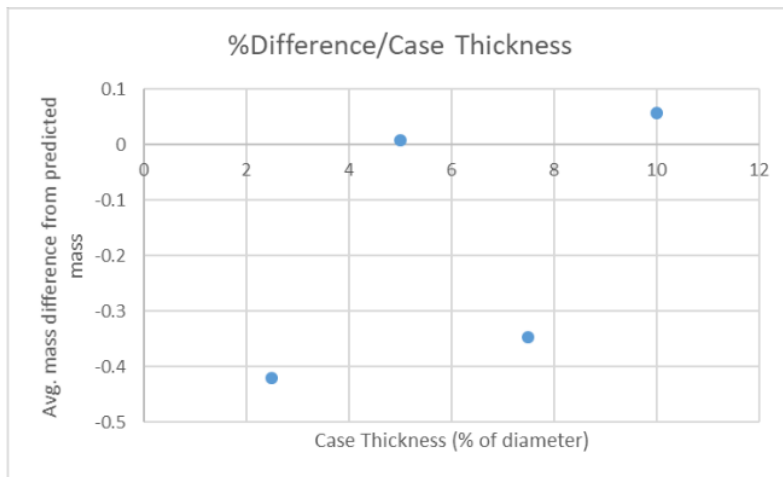


Figure 21 - Graph displaying percentage mass difference plotted against case thickness

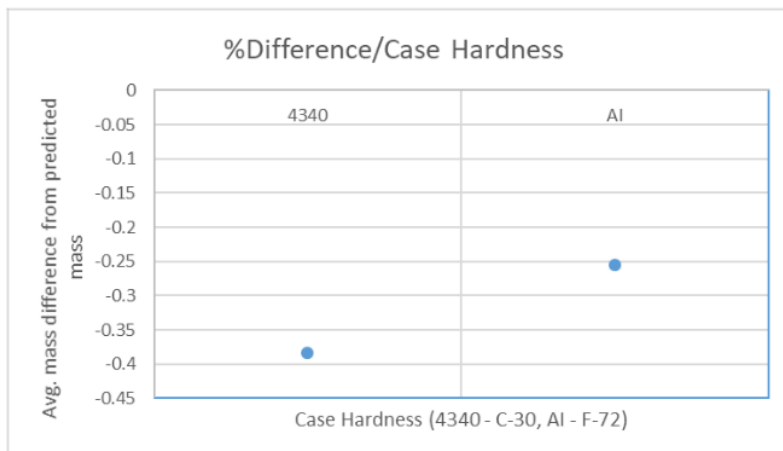


Figure 22 - Graph displaying percentage mass difference plotted against case hardness

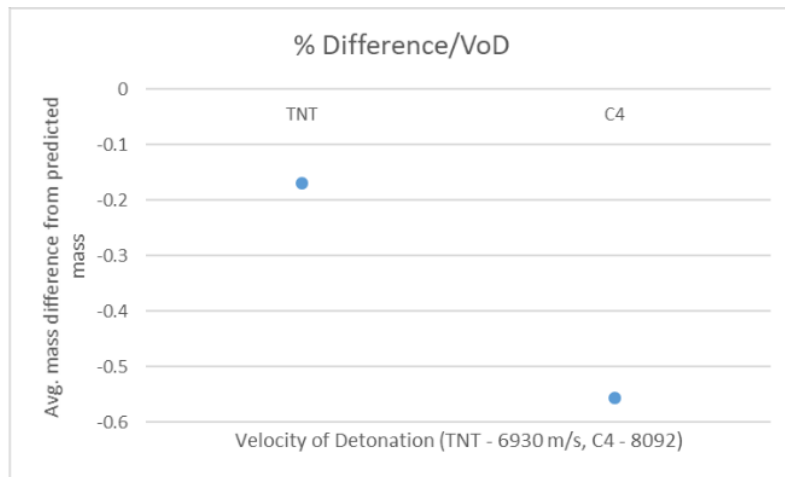


Figure 23 - Graph displaying percentage mass difference plotted against VoD

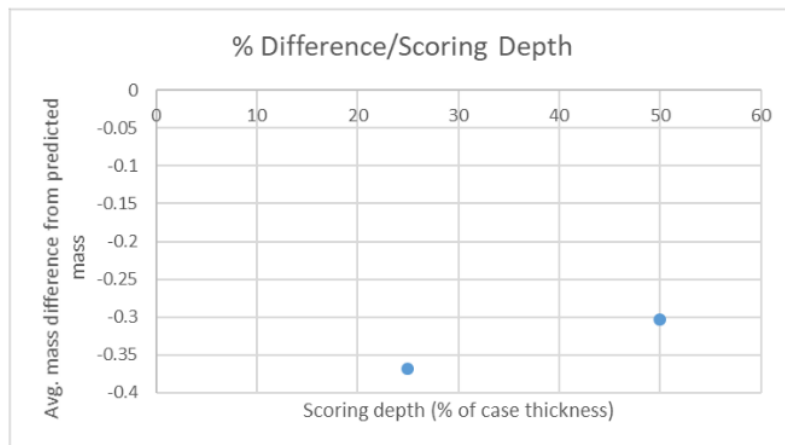


Figure 24 - Graph displaying percentage mass difference plotted against scoring depth

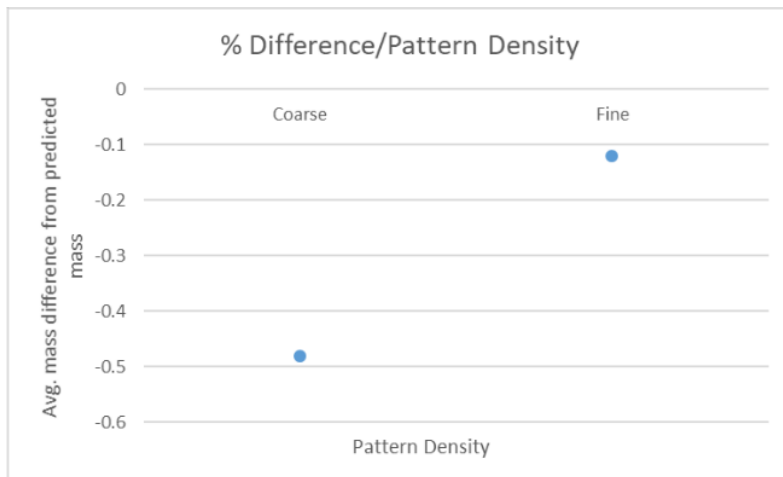


Figure 25 - Graph displaying percentage mass difference plotted against scoring pattern density

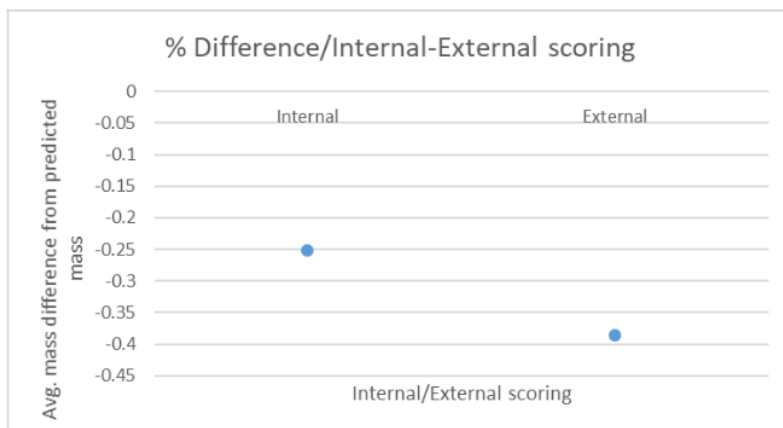


Figure 26 - Graph displaying percentage mass difference plotted against internal/external scoring

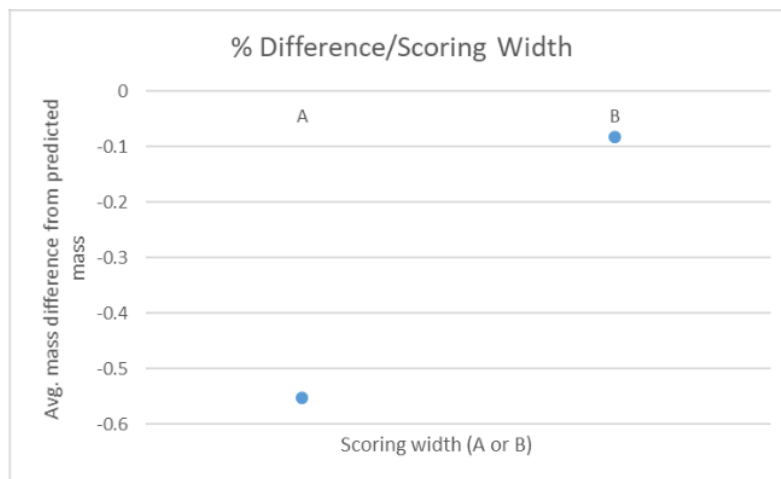


Figure 27 - Graph displaying percentage mass difference plotted against scoring width

6.3 RESULT BREAKDOWN

Due to missing data points and failed simulations, further fine tuning of the simulations and more runs would be required to make a more informed analysis on the influence of each factor in the design of the model.

Within the results, relationships can be suggested between factors influencing the casing designs. But due to the limitations in many circumstances there are not enough data points to conclude the exact nature of this relationship such as if its linear or exponential.

Aside from the three four-level factors (scale, pattern, and case thickness), it appears that the other factors (scoring width, case hardness, VoD, scoring depth, scoring density, and internal/external scoring) have the effect to reduce the size of fragments formed when compared to the predicted fragment masses.

The results and interpretations for the three four-level factors are impacted the most by the irretrievable data from test serials 3, 4, 5, and 7. Instead of 4 data points each, several factor levels only had 2 results to calculate an average.

The largest range in average percentage difference can be found in the scoring pattern graph, with a range of 0.918053 (~91.2%).

The smallest range in average percentage difference is the scoring depth with a value of 0.06477 (~6.5%).

6.4 ANALYSIS BY FACTOR

Analysis by Taguchi Factor:

- Scale – The collected data indicates that scaling down the charge size has a negative impact on the formation of fragments of the desired size (Figure 19). The four data points suggest a linear correlation, however more data gathered at different scales would be able to reinforce this conclusion.
- Scoring pattern – The results indicate that the scoring pattern does have some influence over the size of the fragments produced, however no discernible relationship can be determined from the graph (Figure 20).
- Case thickness – There is no clear relationship when examining the case thickness results against mass percentage difference of fragments (Figure 21).
- Case hardness – Although all values had a negative percentage mass difference, the gradient between the two data points was not as great as for other factors indicating case hardness has a less significant impact on the fragments that formed (Figure 22).
- Velocity of Detonation – The results for this factor indicate that an increasing VoD increases the difference in magnitude between the predicted and measured fragment masses. However, as there are only two data points the type of relationship cannot be reliably inferred (Figure 23).
- Scoring depth – This factor had the lowest range of results suggesting it has the least impact on the outcome on fragment formation in the simulations. The deeper scoring patterns did come out as slightly closer to the mass of predicted fragments by a 6.5% difference. The reasons for this impact could be that the introduction of any defect, no matter how deep, is enough to cause a successful fracture throughout the entirety of a case (Figure 24).

- Pattern density – The results indicate that the coarse patterns produced a percentage deviation from the predicted fragment mass almost 4 times greater than the fine fragment pattern density (Figure 25). One possible explanation for this could be the propensity for very large fragments to begin fragmenting naturally over their surface.
- Internal/External scoring – It appears that having a fragment pattern scored on the inside or outside of the case does not have a significant impact on the fragments that are formed compared with other factors. Out of the two levels, it appears that internal scoring produces better results than external scoring. These results could indicate that as with the scoring depth factor, the presence of an introduced defect into the material surface is all that is necessary to create a controlled fragment (Figure 26).
- Scoring width – The results show that this factor appears to have a significant effect on the resulting fragment size. The finer scoring size performing notably worse than the wider scoring size. This could potentially be down to the interplay between the CAD model, meshed model, and simulation resolution sizes (Figure 27).

SECTION 7 DISCUSSION

7.1 SIMULATION DATA ISSUES

The issue with the simulations that produced no data was an inability to select a discernible fragment in the post-processing screen. This occurred due to the modelling software identifying the particles that formed the fragments as one large fragment, instead of several smaller ones.

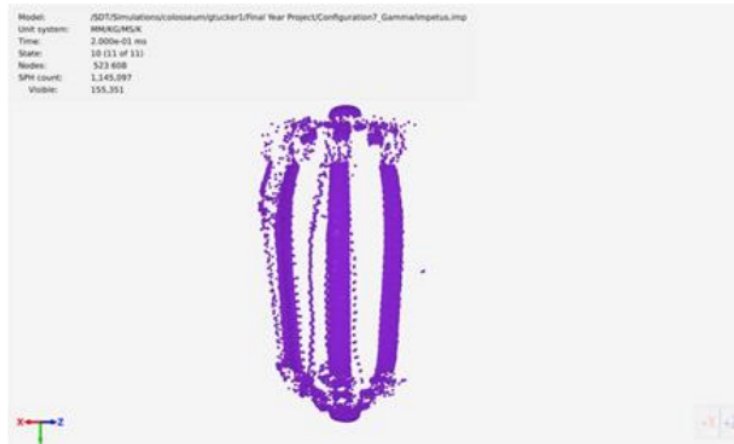


Figure 28 - Test serial 7 post-analysis results



If it was possible to break these areas up, or alter the parameters of the fragment picker tool to increase the criteria as to what is identified as a fragment, then it may have been possible to still extract data. However, these are not features that are available in the software. Additionally an alternative would be to re-run these simulations for a longer run-time and see if the fragments that appear to be forming, continue to do so and reach a state where they are identifiable. This would involve several test runs to find a time stamp that worked for all of the irretrievable test serials, and then the other serials would need to be re-run with the same run time to ensure that fragments were measured with the same amount of formation time in each test serial.

Due to the extra time this would have taken, it was not possible to carry out additional run-time simulations in this study.

7.2 GENERAL MODELLING LIMITATIONS

Modelling cannot be used as a substitution for real-world trials, and can only give an approximate solution to a given problem. However, it can be very useful in providing an indication as to what results may be expected. If physical trials can be conducted later, these can then be used to validate modelling the results. In the instance of this study, the problem is novel, and so there is no way to validate any of the results using existing trials data. Additionally, the modelling carried out is deterministic and will produce the same results with each re-run given the same parameters. Conversely, in reality many minor noise factors will interfere with the performance of a system and cause a spread of data for each identical experimental run. Probabilistic modelling is one route in which a spread of data can be created for the same initial parameters, however to employ such a strategy was beyond the remit of this study.

7.3 STUDY SPECIFIC LIMITATIONS

Due to the time constraints on the project, several limitations and caveats have to be applied to this modelling set-up and the results it has produced.

7.3.1 Run time

The primary issue with the simulation run time is that it was based on a best estimate derived from existing experience within the modelling team. As discussed previously, limited run time is the likely reason for test serials 3, 4, 5, and 7 failing to produce useable data. Not only should the run time be adjusted to allow for full fragment formation in all test serials, but also fragments should be examined to ensure they reach a steady state. This would mean that they have all ceased deforming, which may result in measurements being taken at different time-steps for each test serial to ensure that fragments have reached their individual steady states. This could easily be achieved by using the same impetus fragment tool and examining the surface area of each fragment to see at what point they all cease changing.

Related to the run-time issue, some of the models (e.g. serial 1), that were slower in forming their fragments compared to those that easily formed discrete fragments (e.g. serial 2), had less data points to calculate the average fragment mass. For example, test serial 1 only had ten fragment mass measurements, whereas test serial 2 had 105 identifiable fragments.

7.3.2 Lack of convergence study

Another consideration when discussing the results of this modelling is the lack of a convergence study. To enhance the quality of the conclusions that can be drawn from this study, the simulations should be run with increasing resolution parameters. This is to ensure that element resolution is not inhibiting the deformation of the mesh into fragments. Again, this can be examined by measuring either the masses or the surface areas of fragments after each run, to see if they are converging towards a constant value or if they are still changing with each increase in resolution. With so many test serials, all containing meshes of different sizes and complexities, this would have been far too time-consuming for this scoping study.

7.3.3 Subjectivity in fragment identification

For some simulations determining what is identified as a fragment was subjective to the extent it may affect the conclusions. This is due to the nature of the post-processing interface, and how fragments are formed of groups of particles, which are defined by their proximity to each other. As a result, is difficult to select the correct fragments and ensure that all of them are captured. A range filter for fragments is not available and so it is only possible to select all fragments greater than a certain mass value and then deselect undesired fragments. These include fragments forming towards the end caps that are not affected by the pattern and so are to be discarded in each analysis.

7.3.4 Limitations of results due to amount of data

Due to the inability of some test serials to generate any data, and the fact that only one experiment ran, it is difficult to place any certainty in the simulation results. Taguchi matrices work best when several different experiments can be run, with the addition of noise factors, which can then be used to calculate signal to noise ratios for different factors. These help to identify whether a factor is having a significant effect on the results of each experiment, and to see if noise factors are also a potential threat to results.

7.3.4 Interplay of factors

With such a scenario there are many factors that can be explored, however due to the nature of the Taguchi matrix, only 9 could be examined in this study. Additionally, some factors come with additional factors attached to them. For instance, changing the velocity of detonation is only achievable by changing the explosive fill. This in turn changes several other parameters such as power index, which may then further influence a change in the result. It is difficult to track how many different parameters and permutations there are available whilst conducting such a study. Another example is changing the hardness value of the case. This is done through changing the case material, which in turn, affects properties such as density, grain structure, yield stresses etc. All factors such as these cannot be isolated, and although they may have an effect, it is harder to determine what the dominant factor would be within the set of attached factors.

SECTION 8 CONCLUSIONS

Without further work, there is not enough evidence to answer the question “can scaled explosive charges be used to assess controlled fragmenting cases?”

However, the limited results would indicate that as a case is scaled down in size, the deviation from the predicted fragment mass increases. Therefore, it would be unlikely that a scaled trial could be used to provide indicative data.

The results also indicate that out of all the factors examined, the case material hardness, scoring depth, and locating the scoring grooves on the inside or outside of the case have minimal impact on the deviation from predicted masses, compared to all the other Taguchi matrix factors.

Conversely, without understanding any underlying co-dependencies that may exist between factors, the use of Scaled controlled fragmenting cases cannot be discounted. Whether this be scaling down to a cut-off point, until which the deviation in the result is deemed acceptable or useful. Alternatively, if the deviation from desired fragments is in some way proportional so that it can be adjusted using a scale factor.

SECTION 9 RECOMMENDATIONS

9.1 IMMEDIATE ACTIONS

The results of this study should be used to form the foundation of further investigations to produce a more robust data set with the following immediate remedial improvements:

- Adjust the CAD models so that they accurately represent the Taguchi matrix.
- Adjusted run-times to allow all cases to form into fragments and reach a steady state i.e. no longer changing shape
- Convergence studies using increasingly fine element resolutions
- New arrays used to give greater confidence to results and better identify what factors are most influential on results.

9.2 IMPROVED MODELLING

After the previous steps have been taken, if further investigation is deemed of value successive tranches of modelling can be carried out, but using fewer factors examined in greater detail to better understand their relationships with the outcomes. For example, the factors that did not appear to show much of an effect such as scoring depth or internal/external scoring, could be replaced with other factors of interest. Additionally, a different type of array could be used to either reduce the number of experimental runs, whilst being able to adjust and conduct different arrays in the same time, or examine fewer factors in greater depth using arrays with a higher level value.

To factor in noise, probabilistic modelling could be employed to introduce variance into the starting conditions of each simulation. For instance, material defects can be seeded throughout the case geometry increasing the likelihood of fracture lines appearing on any surface. All of the above options would require a lot more planning and time to implement and complete all test serials, as well as analyse the data afterwards.

9.3 LIVE TRIALS

Finally, if the results are within the appropriate statistical tolerance then any interactions that are deemed reliable can be examined using live explosive trials. This method would be far more expensive and heavily rely on the design of experiment process to maximise the potential data that can be gathered in the minimal number of runs.

9.3.1 Live Trial requirements

If this research strand were to be continued via live explosive trials then the following workflow would be recommended:

Identify fewer factors to investigate and focus on how they will affect the outcome. These factors can be set at different levels using another design of experiment approach to allow for an efficient testing regime. This is even more important with live trials to ensure value for money. Using such techniques will help to further reinforce or counter conclusions drawn from any modelling work. Primarily such tests should focus on validating results that suggest a relationship between case scale and the fragments produced, and identify the nature of that relationship such as proportionality.

Once the designs to be tested have been outlined, these would need to be designed in CAD and drawings then sent out to manufacture. Important points to note here would be to design the cases for manufacture and note which additional features are required for filling/initiation. Modifications would need to be made to allow for space to insert a detonator and a booster pellet to allow for successful initiation of the main fill. Depending on the fill used, they could be melt-cast or hand-stemmed, and post filling machining operations could be carried out, such as drilling out a space for a detonator/booster assembly.

After manufacture, radiographs should be taken of each filled case. This allows any filling defects to be detected. Updated technology such as CT scanning could be used to improve confidence that there are no defects in the fill that may influence the results, or produce anomalies.

Small scale hazard testing and compatibility testing data would need to be obtained or generated for all of the different test serial explosive/casing arrangements. This is to ensure that the articles to be trialled are safe to handle and store.

Once the above has been completed, the additional trials planning and preparation that takes place with any trial would need to be completed. This includes trials planning, risk assessing, range identification and hire, instrumentation and equipment, and logistics and explosive movement paperwork. The trial itself would need to capture the fragments of each test serial so that they could be analysed post-firing. This could be done with an arena-trial set up, with fragmentation packs radially surrounding the warhead casing – placed at a distance determined by the modelling to be great enough such that Fragments have fully formed to use space efficiently

SECTION 10 RESEARCH REFLECTION

Ultimately, this piece of research has been a long and arduous process.

In terms of time management, several issues arose, not only due to having to manage standard workflow commitments, but also due to conflicts in availability of other staff who were required to provide training and education on software such as Hypermesh and Impetus. Additionally, before training could even begin, access and permissions had to be obtained to use the software that is located on a virtual machine operated by the parent company. Access was requested at the beginning of October 2023 after the first few project supervisor meetings, however access was not made available until late-November 2023. This delay in access was an unknown and unforeseen hurdle that delayed the project.

Further to delays in getting access to the software, the time required to become proficient enough to generate all the materials required to run the simulations took longer than anticipated. Fortunately, the researcher was already competent with CAD design software, however the unfamiliarity with modelling was telling. Without prior understanding of how meshing works, time was wasted in creating prototype designs that were deemed unfeasible to mesh by modelling team consultants. Additionally, the training burden led to more lost time whereby trying to mesh a single CAD file initially took almost a day and a half. Towards the end of the project, this time was reduced to approximately 2 hours to mesh the final case.

The meshing difficulty was an unforeseen circumstance as impetus had been suggested as being simple to add geometries into for simulations. However, due to the more complex nature of the CAD models produced for this investigation, they required a more nuanced meshing approach in the Hypermesh software. To compound difficulties, this software is operated on license and due to limited copies, could only be accessed when there were licenses free. Due to the relatively low importance of this research project, being able to access the software was not always possible. Furthermore, the virtual environment where all the software is located was overhauled and updated during the time of this project, causing issues with importing/exporting information and machines having to be restarted due to errors.

All of the above limited the amount of time that could be dedicated to the project (funding for time was finite and had to be redressed for extra training allowances once meshing was identified as a requirement). This is the main factor as to why the project was forced to progress without doubling back to change designs and parameters, as this would have risked not getting all the simulations run on time. Instead, any errors or discrepancies were recorded to ensure candour about the work and any results.

Despite the difficulties encountered with such a project, the experience has allowed for several skills to be developed, in addition to a greater understanding and comprehension on what is possible via modelling. The benefits have been:

- Introduction to design of experiments
- Basic ability to mesh shapes using Hypermesh in preparation for modelling
- Basic understanding of Impetus software and how to create and run simulations using it
- Appreciation of the detail that goes into modelling and simulation of scenarios, including foundational work such as obtaining validated material models, performing element tests, and conducting resolution studies.

If this research were repeated, the biggest recommended change would be to simplify everything as much as possible. The primary aim being the ability to

adjust CAD models/meshes faster, and to have more time to focus on running simulations and refining them as opposed to only performing a few simulation runs on more complex geometries.

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APPENDICES

APPENDIX A – CASE DESIGNS

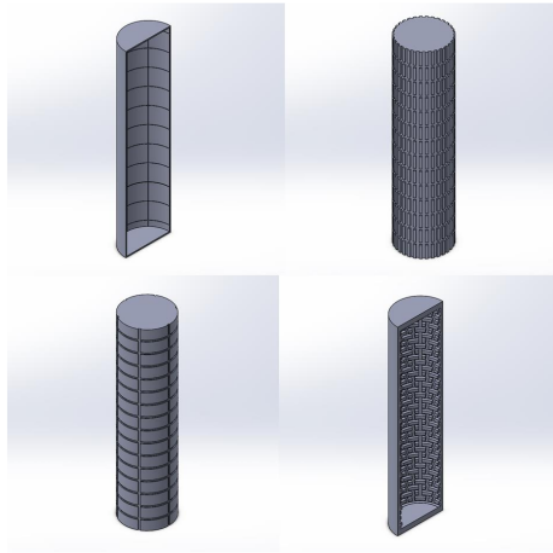


Figure A1 - From top left: case designs 1-4

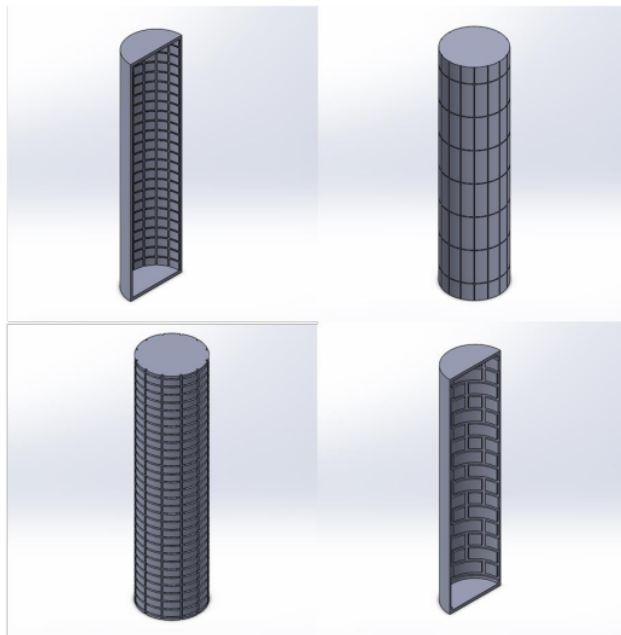


Figure A2 - From top left: case designs 5-8

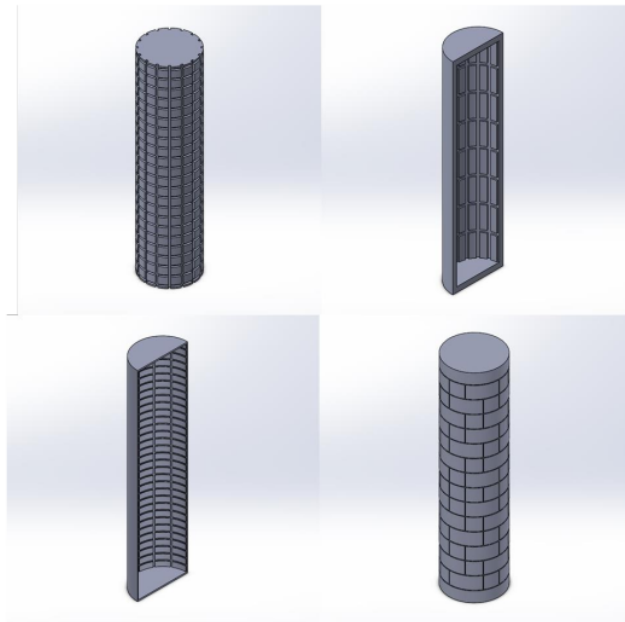


Figure A3 - From top left: case designs 9-12

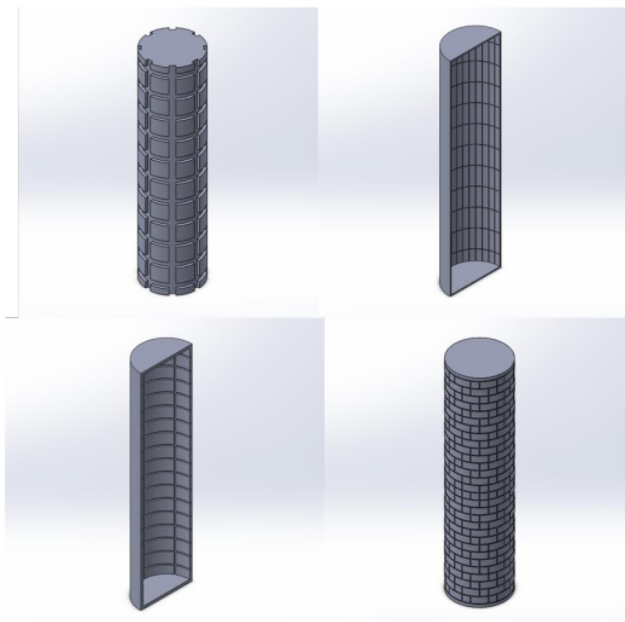


Figure A4 - From top left: case designs 13-16

APPENDIX B – IMPETUS SIMULATION SCRIPTS

```

1 #
2 #UNIT SYSTEM
3 #MKS/US, K
4 #PARAMETER
5 tend = 0.2 , "Termination time"
6 num_inp = 10 , "Number of .inp files"
7 num_ascii = 1000 , "Number of .out time steps"
8 num_db = 2 , "Number of database and state files"
9 nres = 2 , "Number of cyclic alternating files"
10 T0 = 293 , "Initial temperature"
11
12 #TIME
13 [tend]
14 #OUTPUT
15 [tend/num_inp], [tend/num_ascii], [tend/num_db], 3
16 #
17 # --- CONSTRAINTS ---
18 #
19 #BC SYMMETRY
20 ZK
21 #
22 # --- INITIAL CONDITIONS ---
23 #
24 #INITIAL TEMPERATURE
25 P, 101, 123
26 #FUNCTION
27 123
28 #T0
29 #
30 # --- SPH ---
31 #
32 #GEOMETRY PART
33 10101
34 #SPH
35 10101,10101,1,1,1
36 10201,10201,1,1,1
37 #
38 # --- PART ---
39 #
40 #PART
41 "pipe-wall"
42 101, 999, 101, 0, 0, 2.0
43 #
44 # --- INCLUDE ---
45 #
46 #INCLUDE
47 Variables.k
48 #INCLUDE
49 material_generic.k
50
51 #MATERIAL RIGID
52 "Rigid"
53 999,7.85e-6
54 #MATERIAL JC
55 "4340 steel - Original Johnson Cook Paper"
56 4340, 7.83e-06, 2.08e02, 0.29, 4340
57 0.792, 0.530, 0.26, 0.034, 1.03, 293, 1793, 0.001
58 477
59 #PROP DAMAGE JC
60 "4340 steel - Original Johnson Cook Paper"
61 4340, 2
62 0.05, 1.44, -2.12, 0.002, 0.61, 0.001, 293, 1793
63 #
64 # --- Pipe - Low hardness iron
65 #
66 #MATERIAL JC
67 "A500 Iron - Original Johnson Cook Paper"
68 20, 7.89e-06, 2.07e02, 0.29, 20
69 0.175, 0.300, 0.32, 0.06, 0.55, 293, 1811, 0.001
70 452
71 #PROP DAMAGE JC
72 "A500 Iron steel - Original Johnson Cook Paper"
73 20, 2
74 -2.2, 5.43, -0.47, 0.036, 0.63, 0.001, 293, 1811
75 #
76 # --- Equation of State
77 #
78 #EOS GRAINEISEN
79 "Iron Alip - CTH EOS Lib"
80 101, 1.456, 1.65
81 #
82 # --- Explosive Materials
83 #
84 #MATERIAL EXP TNT---
85 #
86 #MATERIAL FLUID
87 "TNT"
88 10201,1.63e-6,5.2,...,10201
89 #EOS_JWL
90 10201,371.2,3.23,4.15,0.95,0.3
91 1.073566
92 #
93 # --- MATERIAL EXP C4---
94 #
95 #EOS_JWL
96 10999, 710, 11.0, 4.7, 1.3, 0.25, 0.18
97 #
98 #MATERIAL FLUID
99 10999, 1.021e-6, 2.2,...,10999
100 #END
101
102 # --- MESH ---
103 # --- Change your geometry
104 #
105 #INCLUDE
106 Configuration1.k
107 #
108 # --- Explosive Volume ---
109 #
110 #GEOMETRY PIPE
111 "Charge shape"
112 10201
113 0, 3.75, 0, 0, 596.257, 0, 71.249
114 #
115 # --- gSPH PARTS ---
116 #
117 #PART
118 "gSPH-pipe-Wall"
119 # --- column two in part - 4340 Hard Steel, 20 softer iron
120 10101, 4340
121 #PART
122 "Explosive"
123 # --- column two in part - 10201 TNT, 10999 C4
124 10201, 10201
125 #
126 # --- Detonation location ---
127 #
128 #DETONATION POINT COORDINATE
129 0, 5, 0, 0, 0, 0

```

Figure B1 – Impetus simulation scripts from L-R: model parameters, material properties, simulation variables

APPENDIX C – POST-PROCESSING OF ALL TEST SERIALS



Figure C1 – From L-R test serials 1 and 2 resulting fragmentation



Figure C2 – From L-R test serials 3 and 4 resulting fragmentation



Figure C1 – From L-R test serials 5 and 6 resulting fragmentation



Figure C1 – From L-R test serials 7 and 8 resulting fragmentation

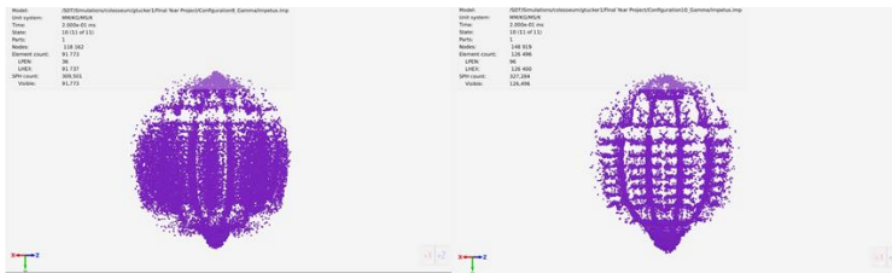


Figure C1 – From L-R test serials 9 and 10 resulting fragmentation

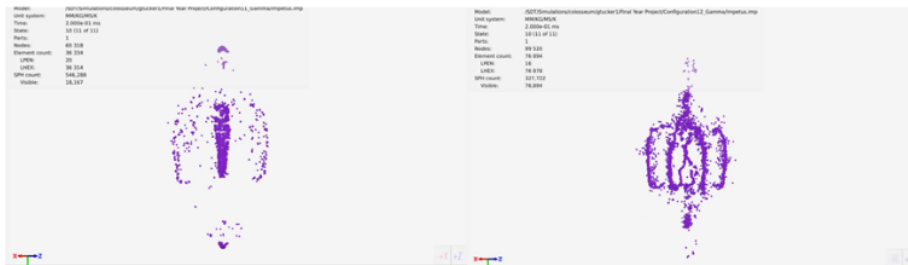


Figure C1 – From L-R test serials 11 and 12 resulting fragmentation



Figure C1 – From L-R test serials 13 and 14 resulting fragmentation



Figure C1 – From L-R test serials 15 and 16 resulting fragmentation

Final submission

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

Please ask Jenni Steen for your marking sheet for feedback.

77 /100

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