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**ACDB 5015 – Advanced Physics**  
**Design of shaped charges**

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## **Academic integrity declaration**

I declare that:

- the thesis submitted has been written by me alone.
- the thesis submitted has not been previously submitted to this university or any other.
- that all content, including primary and/or secondary data, is true to the best of my knowledge.
- that all quotations and references have been duly acknowledged according to the requirements of academic research.

I understand that to knowingly submit work in violation of the above statement will be considered by examiners as academic misconduct.

## **Abstract**

Abaqus CAE 2024 is used to perform two 2D simulations of a simple 60mm diameter shaped charge. One containing TNT and one containing HMX. A brief explanation on shaped charges, a review of shaped charge simulation literature and the physics being employed by Abaqus [behind the scenes](#) is included. The report discusses errors encountered when modelling high strain rate simulations in Abaqus and potential ways to overcome them. The report concludes that Abaqus is an effective tool for prototyping shaped charge designs although it demands a level of user proficiency and should be supplemented by real world trials.

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# 1 Introduction

With the advent of modern technology computer aided numerical simulations can speed up the process of safely evaluating the performance of explosive devices. This report will be performing analysis and review of shaped charge modelling using the Abaqus Finite Element modelling software package from Dassault Systèmes. A brief overview of shaped charges and a literature review of articles concerning numerical simulations are included before discussing the material models and equations of state used for the simulations in this report. The scope of the report is to achieve a functional 3d simulation of a shaped charge of simple design with results that somewhat align with what is expected by a real-life shaped charge of similar materials and to evaluate the performance of Abaqus in achieving this from the perspective of a relative beginner to shaped charge modelling.

## 1.1 Shaped Charges

A shaped charge is a device generally cylindrical or rectangular in nature. The inside contains an explosive fill oftentimes with a cavity in the shape of an inverted V. The shape of this cavity is usually defined by a liner constructed from a ductile material. Detonation of the explosives creates very high localised forces and shockwaves which rapidly propagate towards and compress the metal liner under very high pressures and strain rates inwards to the central axis of the cavity. This forms thin high velocity jet of metal that is capable of deeply penetrating incredibly dense materials as the velocity of the jet and stagnation pressure exceeds the strength of the target material. The depth penetrated by the shaped charge is usually deeper than that of the cavity. The formation of the jet and its penetrative capability is often referred to as the Neumann or Monroe effect. The tip of the metal jet can reach velocities exceeding 10,000 m/s depending on the parameters of the shaped charge design. Shaped charges have a plethora of applications such as penetrating and defeating armoured targets to cutting beams in construction. [1] [2]

## 2 Literature Review

Below a literature review has been conducted on some existing studies into experimental modelling and finite element analysis of shaped charges.

Alan Cantovic [3] researches the influence of different shaped charge liner materials using finite element analysis by numerical simulation performed with the Ansys AUTODYN program. Using a shaped charge modelled after a panzerfaust 30 high explosive anti-tank warhead. For the numerical analysis and modelling Cantovic is using a Euler solver for the initial jet formation and following up with a Lagrange solver for modelling the penetration. It is stated that due to the rapid distortion of the mesh of the materials during detonation that an entirely Lagrangian approach would cause the solver to stop working. The shock Hugoniot is used to inform the Mie-Gruneisen Equation of state to model the collapse of the liner and the JWL Equation of state is used for modelling the explosive. It was possible to validate the model using existing data on panzerfaust 30 trials and the research concluded that liner material does have an impact on penetration depth.

[\[4\] examines](#) the potential performance of a novel linear shaped charge with a bi apex liner angle. The article mentions that the shape of the liner can have a dramatic effect on the formation of the jet and research has generally been focused on liners with a single apex angle. The author discusses the modelling software AUTODYN stating its ability to allow the application of different modelling algorithms such as Euler, Lagrangian, Arbitrary Lagrangian Euler (ALE), and Smooth Particle Hydrodynamics (SPH) to solve the fluid–structure problems. However, as they are examining a linear cutting charge which is uniform throughout its length the model can be done in 2D using the multi-material Eulerian algorithm. The [charges liner](#) used for the experiment which was then validated by the simulation has a charge diameter of [10mm. Likely smaller](#) than what would be used for real world applications. Liner thickness and explosive type was also examined in this research, and the article concludes that for 8701 explosive the bi apex liner does improve penetration depth whereas

COMP B explosive requires a different apex angle and liner thickness for optimal penetration.

Finite Element Simulation of Shaped Charges [5] discusses the application of an analysis of shaped charges using a Lagrangian Finite Element code. With the advantages being access to the history of the metal liners deformation and the disadvantage being that Lagrangian does not deal well with large deformations of materials therefore, heavy use of a technique called Adaptive Meshing is required. Due to large deformations of the material causing errors in the Lagrangian calculations adaptive meshing can be used to re-mesh the material at the point of excessive deformation to continue the calculations.

[1] [contains](#) a large amount of information on theoretical modelling of shaped charges with mention to adaptive meshing and general design parameters of shaped charges such as cone angle, charge diameter, explosive fill effects on performance, liner materials, casing material etc. It serves as good resource for designing a shaped charges and the approach to theoretical modelling.

William Walters [6] provides an overview of the concept of shaped charges discussing the high strain rates and over static pressures relating to the formation of the jet. The document's appendix features a useful reference image of a real-life shaped charge jet formation. This document provides a good overview of the concept of shaped charges. The author produced a book with J.A Zukas [6] The fundamentals of shaped charges which is often referenced in articles pertaining to shaped charges. The book published in 1989 covers subjects such as the numerical theories behind shaped charge jet formation i.e. the Birkoff et al. theory, the PER theory and hydrocode simulation. Although numerical simulation today is mainly handled by the software [7] is a valuable resource to understand the development behind shaped charge modelling.

Study of existing literature on finite element modelling of shaped charges such as in the aforementioned [1], [3], [4], [5], [6], [7] and [8], [9] [10] [2] [11] [12] contain common threads that have influenced the choice of shaped charge design and analysis methods used in the report; Most use a shaped charge of smaller dimensions than what is used for real-world applications, the cone angle

of the apex of the liner is between 40 degrees and 60 degrees, liner thickness between 0.6 and 2.4 mm which is most often made from copper. For the modelling most articles mention that a Lagrangian only approach will cause errors due to large deformation of the mesh. Adaptive meshing is the most used solution although some mention SPH. Johnson-Cook material model is often used as are the Mie-Gruneisen and Jones-Wilkins-Lee equations of state.

## **3 The Shaped Charge Design**

### **3.1 Abaqus Sketching Tool**

Figure 1, Figure 2 and Figure 3 below display the dimensions of the shaped charge designed for this simulation. They were drawn using the sketching tool in Abaqus. The sketching tool uses metres as its unit of measurement and inside the sketcher it is possible to visibly display the lengths and widths of elements of the sketch. Figure 1, Figure 2 and Figure 3 were used as is for the initial 2D simulations. However, during troubleshooting to improve the performance of the 3D simulation it became apparent that there are certain quirks of the Abaqus sketching tool to be aware of. For example, provided close examination of the inside of the top of the sketch of the case in Figure 1 the line appears slightly off 90°. Since the sketcher automatically snapped to this position it was assumed that it was perpendicular to the side of the case. It was later discovered that the snapping feature does not automatically snap to 90-degree angles. Another quirk encountered with the editor is that it would appear to automatically snap sketched lines together cleanly. However, during troubleshooting issues with the 3D simulation it was discovered that without paying careful attention and zooming in enough to ensure the lines were joined as intended in the editor. Sketch errors such as in Figure 4 were due to over reliance on the unreliable snap feature. The two lines did not meet and a third connecting sub-millimetre small line was generated to fill the gap. For the 3D simulation phase numerous passes of the sketched sections were made to resolve any such errors see Figure 5. For future modelling it is recommended to take extra care in the sketching tool when using

Abaqus as these slight inconsistencies may have affected the results of the 2D simulations.

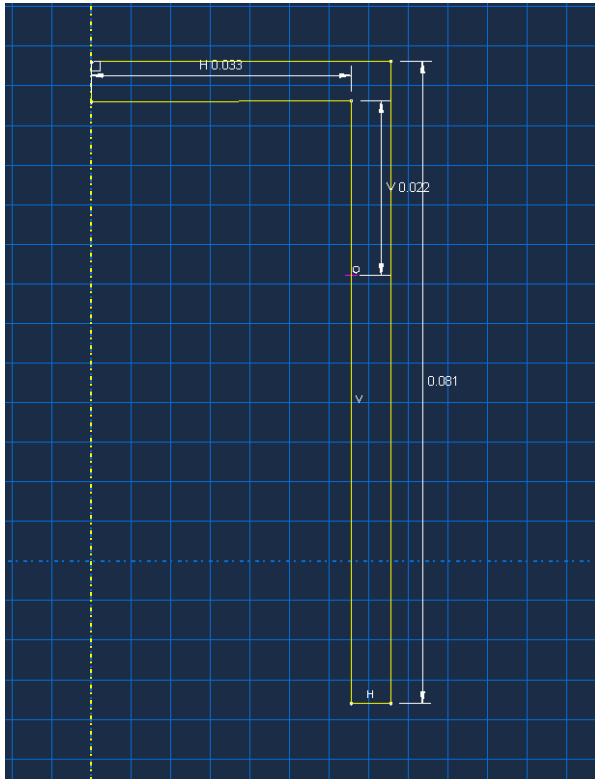


**Figure 1. Case Dimensions**

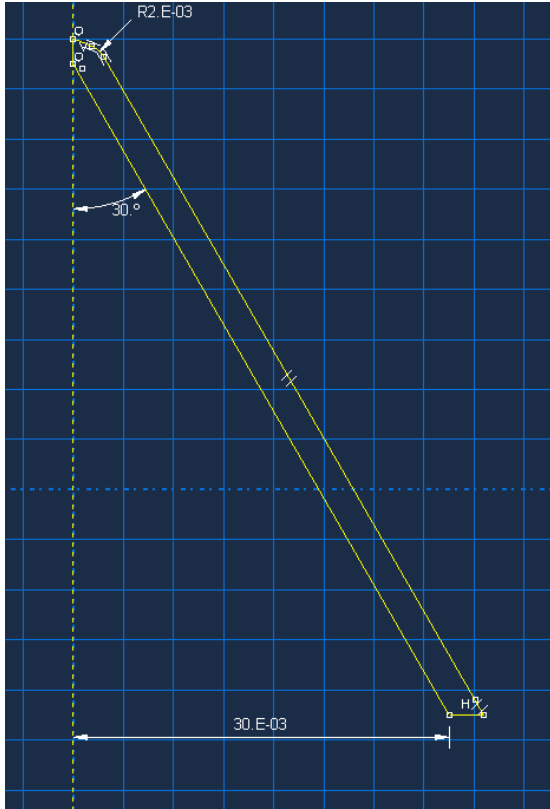


**Figure 2. Liner Dimensions**

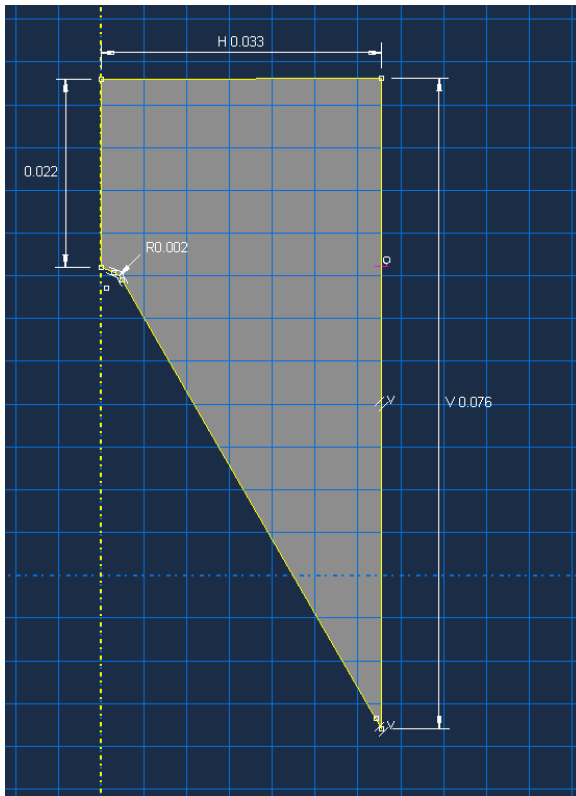


**Figure 3. Fill dimensions**

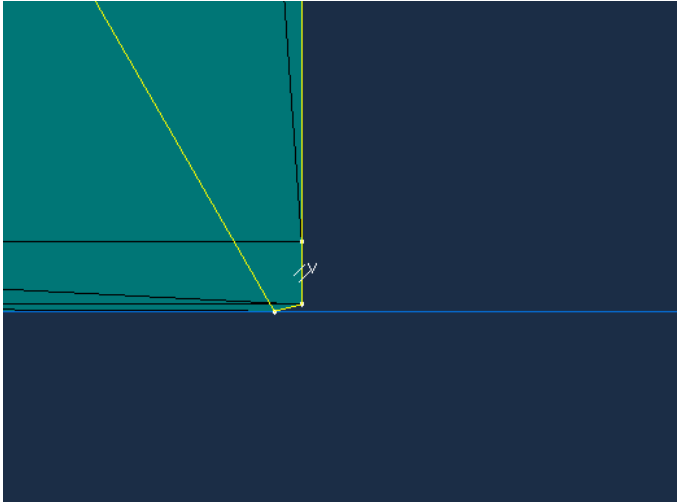


**Figure 4. Fill Sketch Error**

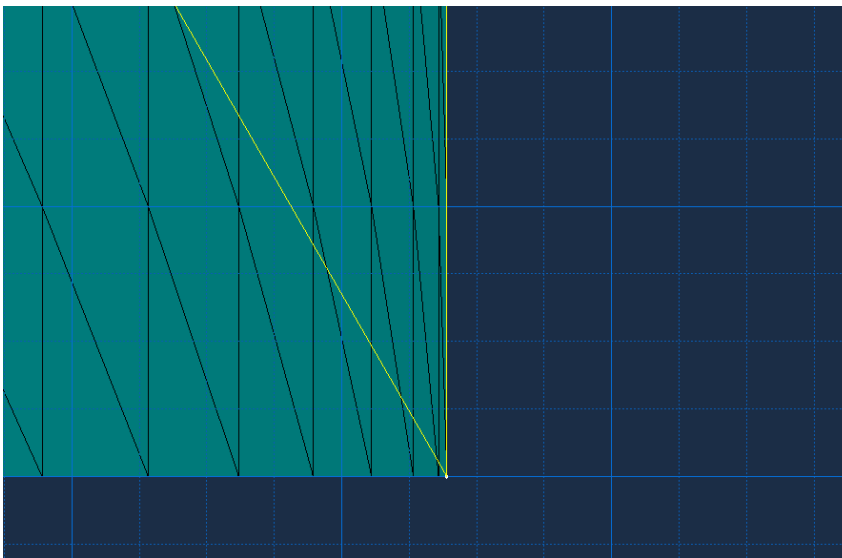


**Figure 5. Sketch Error Fixed**

### **3.2 Dimensions and Design Decisions**

The two main factors influencing the dimensions and design decisions for the model used for this simulation are firstly, what sizes of charge diameter and apex angle are being used for the articles on modelling shaped charges. Charge Diameter (CD) being the total diameter of the widest end of the conical shaped liner. A literature review of articles such as [4], [8], [10] revealed that generally between 10mm and 60mm charge diameters were used. Although the model of

the shaped charge in the Panzerfaust 30 (klein) had a charge diameter of around 90mm [3] as this reports main focus is on finite element modelling of a shaped charge in Abaqus without a more specific goal in mind it seemed appropriate to choose the middle ground of 60mm for the charge diameter of this model. The angle at the apex of the cone was determined from reading "Fundamentals of Shaped charges" [7] in which a conical angle of 60-degrees is mentioned. Again, for simplicity 60-degrees was then chosen for this model. However, upon further reading it should be noted that any angle between 42 and 60 degrees should result in good performance of the charge. The note on liner thickness from the same book which reads ""The Liner Wall Thickness Another critical liner design variable is the wall thickness. Typically, uniform wall thicknesses range from about 1 to 4 % of the charge diameter. However, liner wall thicknesses of up to 8% or so have been used." [7, p310] also influenced this design. Here the middle ground of 4% is chosen which resulted in a liner thickness of 2.4mm. [7] also states that "Head Height" which is the distance from the apex of the liner to the top of the case i.e. how much explosive fill is between the detonator and the apex of the liner affects performance of the charge. Because this report's focus is not heavily weighted on examining the performance of the charge design and mostly focused on the process of modelling a shaped charge in Abaqus software a "Head Height" of 22mm as seen in Figure 3 was chosen for the design which leads into the second factor that majorly determined the dimensions of the shaped charge. The software itself and familiarity with the software. Due to relative unfamiliarity with the software and modelling process once the dimensions of the liner were researched. The dimensions for the case and explosive fill were designed around simplicity of construction within the sketching tool. A sketch of the liner was saved as a construction guide and then imported into a new sketch in which the case was then drawn around it. To keep the numbers simple using the length indicator display a line was drawn for the case height of 80mm and then to avoid any potential interference from the case prior to detonation a thickness of 5mm looked appropriate. Once the Case and Liner were complete the process of importing a saved sketch was repeated to generate the explosive fill dimensions. Computer simulations can have problems with

infinitesimally small dimensions such as the point of a triangle when it comes to meshing and simulating contact therefore the apex of the liner was smoothed into a rounded shape as seen in Figure 2. This was not the case for the contact between the tip of the outer edge of the bottom of the liner and the case. Resulting in a sharp point in the explosive fill seen in Figure 5 (more on meshing and element distortion when discussing the simulations.), Potentially causing errors this maybe an area to explore in subsequent modelling attempts. Finally for the purpose of simplicity there was no “foot” added to the bottom of the liner which may improve obturation of the gases created when the explosive detonates. This type of foot can be seen at Figure 4.3.1 showing the dimensions of the Panzerfuast 30 charge in [3]. This is because in many other articles that research jet performance such as [10] there is no “foot” on the bottom of the liner in their design meaning it is possible to omit this feature as was decided for the liner in this report to keep the sketching process simple.

### **3.2.1 Shaped Charge dimensions quick reference**

Please refer to Figure 1, Figure 2 and Figure 3 for visual reference.

**Total Length of charge:** 81mm

**Total Diameter including case:** 70mm

**Case thickness:** 5mm

**Head Height:** 22mm

**Cone Angle:** 60°

**Charge Diameter (CD):** 60mm

**Liner wall thickness:** 2.4mm

## 4 The Material Properties

### 4.1 Case and Liner

For the case carbon steel grade 1006 is used in the simulation. It is a versatile and common steel grade used for many applications and should serve its function of containing the charge for long enough for a suitable jet to form post detonation. For the liner Copper was chosen. Copper is a common choice of material for shaped charge liners due to its ductility and low cost and acceptable performance [3]. The strength model that is used for this simulation is the Johnson-Cook (J-C Model) [13]. There are other strength models available however, should the results of this simulation require real life validation at any point it is easier to obtain the [data](#). As opposed to the very high strain rate metal deformation tests required for the Steinburg-Lund strength model [10].

The [yield stress](#) in the J-C model can be expressed in the following equation:

$$\sigma = (A + B\epsilon^n)(1 + C \ln \dot{\epsilon}^*)(1 - T^{*m})$$

**Equation 1. Johnson-Cook Strength**

Key:

- $\sigma$  = stress
- A = initial yield stress
- B = strain hardening constant
- $\epsilon^n$  = equivalent plastic strain
- C = Strain rate hardening constant
- $\dot{\epsilon}^*$  = normalised effective plastic strain rate
- m = thermal softening coefficient
- $T^* = \frac{T - T_{room}}{T' - T_{room}}$
- $T_{room}$  = room temperature
- $T'$  = melting temperature of the material

The Johnson-Cook Properties used for Copper and Steel 1006 in the simulation are shown in the table below. Also included are the additional parameters required by Abaqus for simulating the material accurately.

|                                   | <b>Copper</b> [10], [14], [15] | <b>Steel</b> [10], [16] |
|-----------------------------------|--------------------------------|-------------------------|
| <b>Density (kg/m<sup>3</sup>)</b> | 8940                           | 7874                    |
| <b>Young's Modulus (Gpa)</b>      | 130                            | 206                     |
| <b>Poisson Ratio</b>              | 0.34                           | 0.29                    |
| <b>A (Kpa)</b>                    | 9x10 <sup>4</sup>              | 3.5x10 <sup>5</sup>     |
| <b>B (Kpa)</b>                    | 2.92x10 <sup>5</sup>           | 2.75x10 <sup>5</sup>    |
| <b>N</b>                          | 0.31                           | 0.36                    |
| <b>C</b>                          | 0.025                          | 0.022                   |
| <b>M</b>                          | 1.09                           | 1.00                    |
| <b>T (K)</b>                      | 1790                           | 1811                    |

**Table 1. J-C Parameters**

## 4.2 Explosives

For the 2D simulations in this report two types of explosive fill were assessed - Trinitrotoluene (TNT) and HMX. The 3D simulation used TNT. The explosives will be represented using the Jones-Wilkins-Lee Equation of State (JWL EOS). An EOS is the relationship between local density (or specific volume), local specific energy (or temperature), and hydrostatic pressure [3]. The JWL EOS is an often used EOS in numerical software simulations for shock initiation [17] and can be expressed in the following equation:

$$P = A \left( 1 - \frac{\omega}{R_1 v} \right) e^{-R_1 v} + B \left( 1 - \frac{\omega}{R_2 v} \right) e^{-R_2 v} + \frac{\omega e_0}{v}$$

**Equation 2. Jones-Wilkins-Lee Equation of State**

Key:

- $v = \rho_e / \rho$  = relative volume between the detonation products and undetonated high explosive.
- $P$  = pressure
- $\rho_e$  = The density of the explosive material
- $\rho$  = the density of the detonation products
- $e_0$  = specific internal energy
- $A$ ,  $B$ , and  $C$  = linear coefficients
- $R_1$ ,  $R_2$ , and  $\omega$  = non-linear coefficients

The values for  $P$ ,  $v$  and  $e$  and for the linear coefficients ( $A$ ,  $B$ ,  $C$ ) and the non-linear coefficients ( $R_1$ ,  $R_2$ , and  $\omega$ ) that are shown in Table 2. JWL EOS. have been sourced from scientific journals on explosives. These values were likely determined by comparing EOS calculations with experimental data derived from tests such as the cylinder test and then attempting to fit the EOS as close to the shock Hugoniot relationship curve as closely as possible to verify its accuracy [17]. The Shock Hugoniot from the Rankine-Hugoniot equations for shock jump conditions display a relationship between any of these two variables: shock velocity, particle velocity, pressure, density, energy. When comparing the relationships of these variables using most organic materials and metals the relationships have been observed to be approximately linear and is represented as the following [3] [17]:

$$U = c_0 + su_p$$

**Equation 3. Hugoniot in Materials**

Key:

- $U$  = Shock Velocity
- $c_0$  = Bulk Sound speed in Unshocked Material
- $s$  = Hugoniot slope Coefficient
- $u_p$  = Particle Velocity

More information on how the coefficients in the JWL EOS are derived and comparison with the Shock Hugoniot conditions can be read in Calibration of Jones–Wilkins–Lee equation of state for unreacted explosives with shock Hugoniot relationship and optimization algorithm [17].

| <b>JWL EOS</b>                                  | <b>TNT [12], [8]</b> | <b>HMX [18], [9], [19]</b> |
|-------------------------------------------------|----------------------|----------------------------|
| <b><math>\rho</math> (kgm<sup>-3</sup>)</b>     | 1630                 | 1890                       |
| <b>Velocity of detonation (ms<sup>-1</sup>)</b> | 6930                 | 9140                       |
| <b>A (GPa)</b>                                  | 371.2                | 773.98                     |

|                                                     |                    |                    |
|-----------------------------------------------------|--------------------|--------------------|
| <b>B (GPa)</b>                                      | 3.210              | 11.8               |
| <b>R1</b>                                           | 4.15               | 4.2                |
| <b>R2</b>                                           | 0.95               | 1.0                |
| <b><math>\omega</math></b>                          | 0.30               | 0.3                |
| <b>Pre-detonation bulk modulus (GPa)</b>            | 21                 | 39                 |
| <b>Detonation energy Density (Jkg<sup>-1</sup>)</b> | $4.29 \times 10^6$ | $6.32 \times 10^6$ |

**Table 2. JWL EOS**

The JWL parameters for TNT and HMX in Table 2. JWL EOS used for the simulations are the result of some trial and error using the figures provided in the listed sources. This is because the parameters available online differ slightly between sources and some of the variables resulted in the simulation crashing. The crash was potentially caused by the parameters in question causing elements of the explosives' mesh during detonation to travel at velocities relative to their mass that would cause errors in the simulation's numerical algorithm. Further analysis of this error is recommended as it is outside of the scope of this report to confirm if this was the true cause of the error.

## **5 2D Simulations**

### **5.1 The Simulation Setup**

In Abaqus CAE 2024 the sketches of the Case, Explosive Fill and Liner were made into an assembly and assigned their respective material properties with the JWL detonation point placed at the top of the line of symmetry in the explosive fill. In the Step module which governs the simulation a step using Abaqus' dynamic, explicit solver was created. This Abaqus solver uses Lagrangian

numerical calculations [20]. The simulation was set to run for  $50 \times 10^{-6}$  seconds and was set to output the result every  $1 \times 10^{-6}$  seconds. In the load module a boundary condition of mechanical symmetry across the X axis was created to prevent the application simulating any elements crossing over the line of symmetry for the model and causing any errors and visual artefacts when extruding the model to give the illusion of a 3D jet forming. Abaqus needs to be informed that the elements in the assembly are contacting each other. Therefore, in the interaction module a general contact ALL\* explicit contact is setup with frictionless behaviour for the mechanical tangential behaviour and hard contact for the normal behaviour.

## 5.2 The Mesh

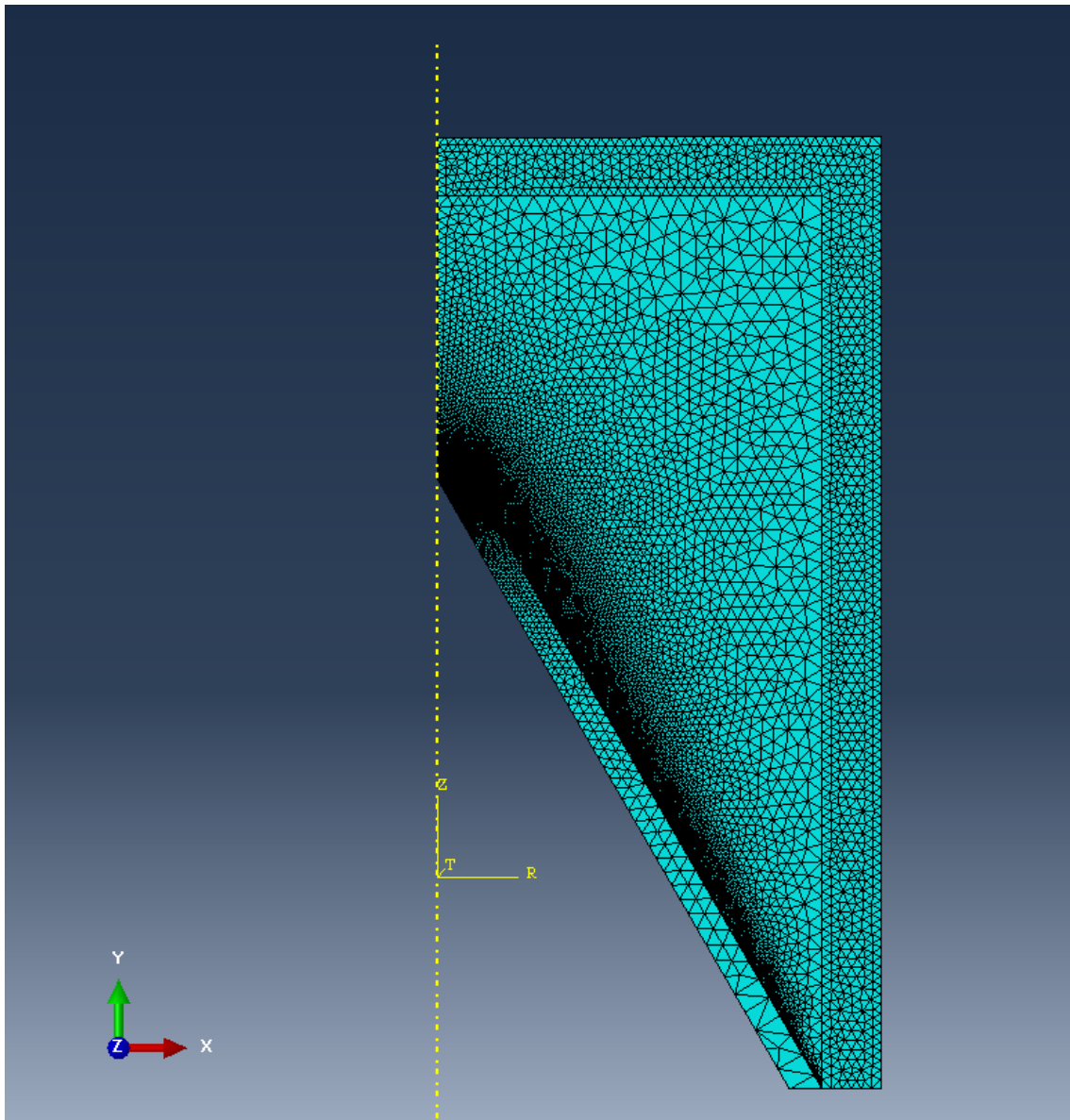


**Figure 6. 2D Simulation Mesh**

The 2D simulation mesh was designed around the concept of the most detailed sections of the mesh being the areas that play the strongest role in the formation of the jet. In Figure 6 the most granular meshing is concentrated at the apex of the liner and along the liners edge in the explosive fill as it was initially deduced that this would provide the best results for simulation speed and accuracy. When meshing assets for simulations if resources are limited, it is unwise to simply finely mesh all the elements as this will consume a large amount of processing power

simulating sections that are of low importance to the result. However, this mesh does have several issues that were not recognised until the 3D simulation:

- There are non-uniform vertices clearly visible at the detonation point and towards the foot of the liner. Likely caused by the sketching errors mentioned previously.
- There is a large discrepancy in mesh element size between the case and the fill and the fill and the foot of the liner. This can cause errors during high strain rate simulations in Lagrangian as the elements distort and overlap each other.
- There is a highly detailed mesh at the apex of the liner and around that area of the explosive fill. However, the granularity of the mesh at the detonation point is very coarse which may have also led to errors in the simulation as those large elements would have distorted greatly from the force of the detonation.

### 5.3 TNT results

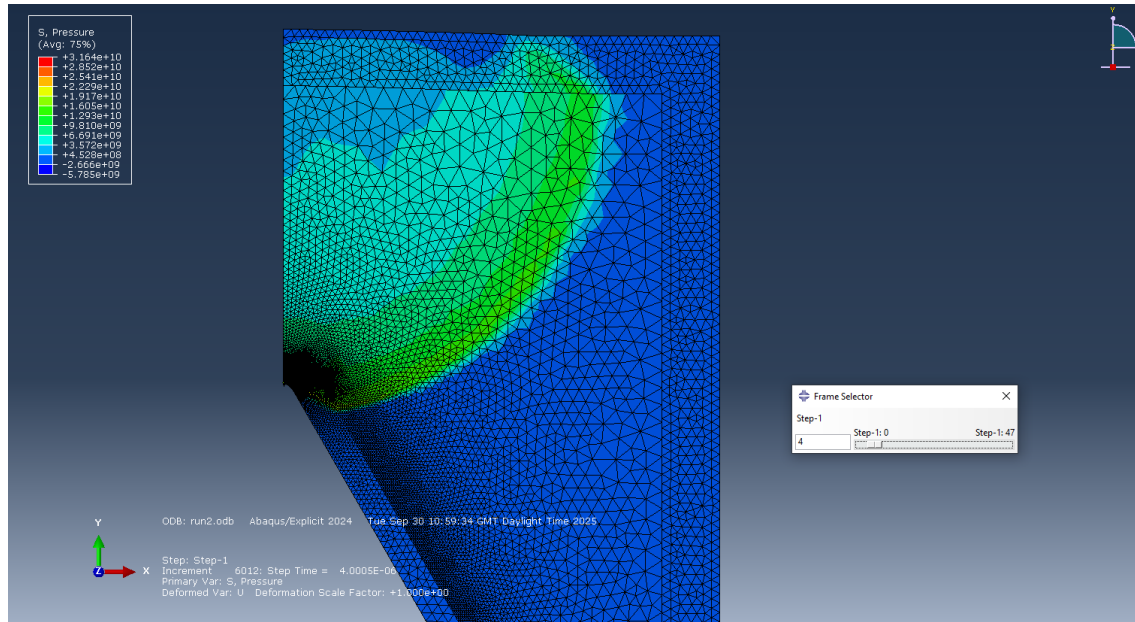


**Figure 7. TNT Pressure Wave**

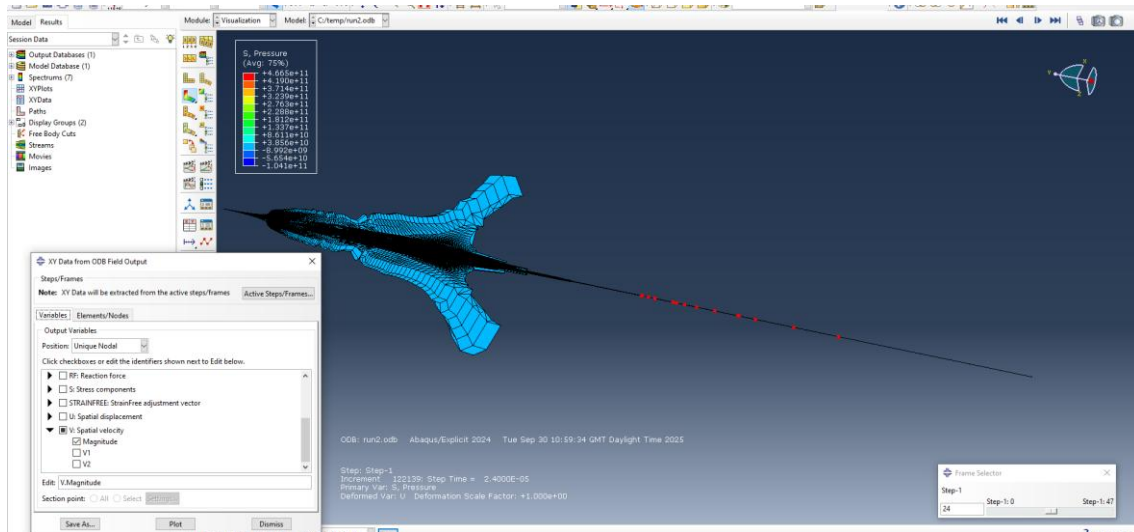


**Figure 8. TNT Jet**

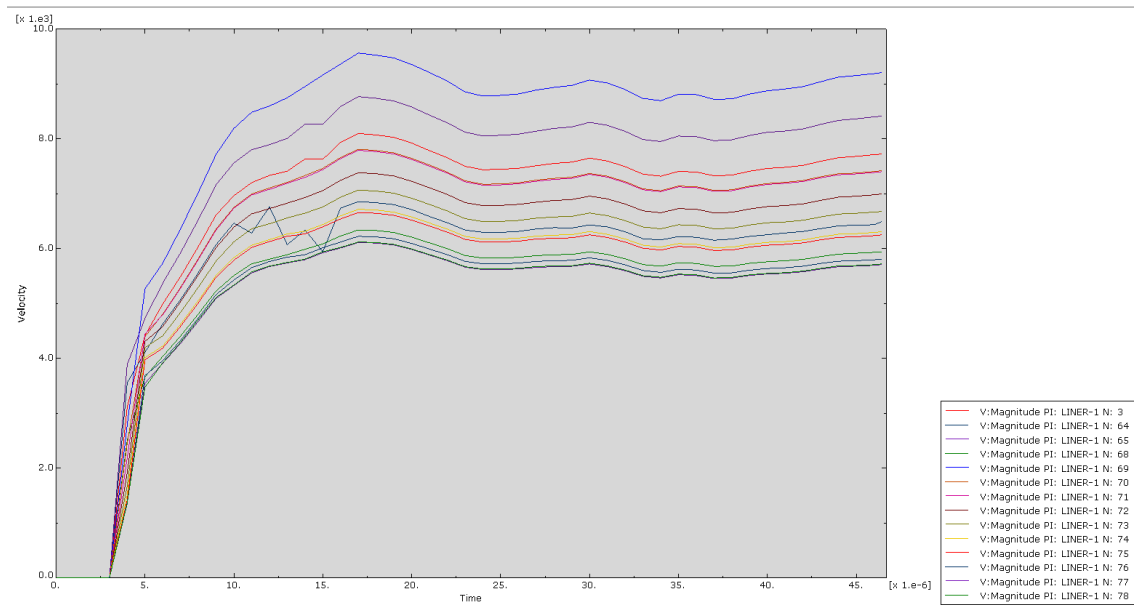


**Figure 9. TNT Velocity / Time**

Figure 7 shows a pressure wave exceeding 13GPa contacting the apex of the liner enough for the copper liner to undergo phase transformation and plastically flow at the extremely high strain rates [21]. The simulation Figure 8 shows the result of the liner collapsing and forming a jet of super high velocity copper. The red dots on the image are the nodes that were selected to plot a velocity over time graph seen in Figure 9. This graph shows that those elements in the copper liner accelerated dramatically up to 8000 m/s over a very short timeframe and

then plateaued as they travel through the vacuum in the simulation. The simulation errored at around 45  $\mu$ s.

### 5.4 HMX Results

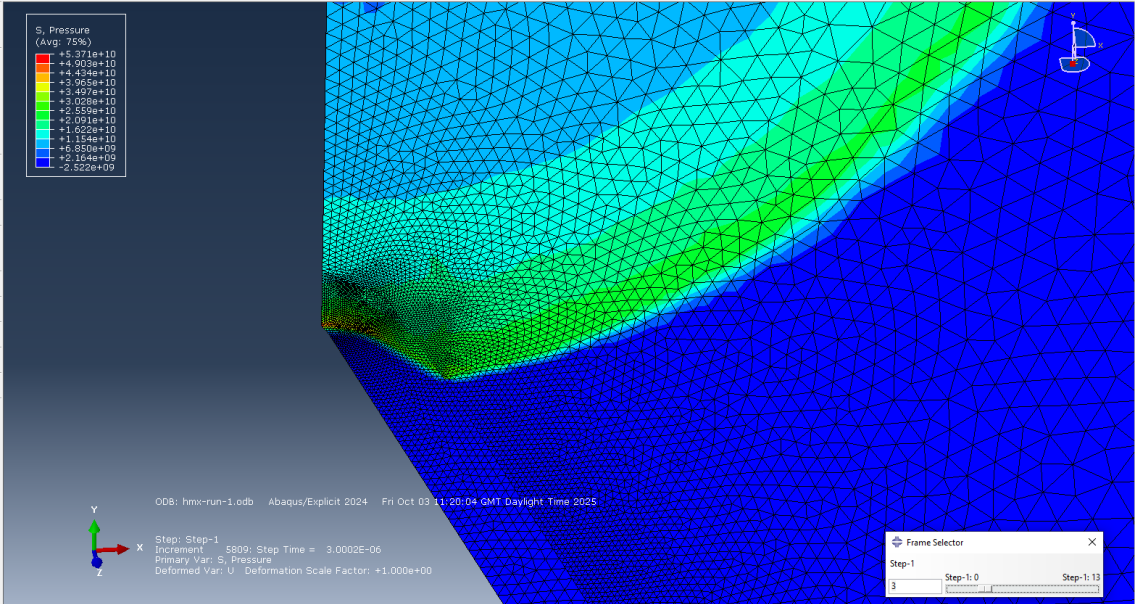


Figure 10. HMX Pressure Wave

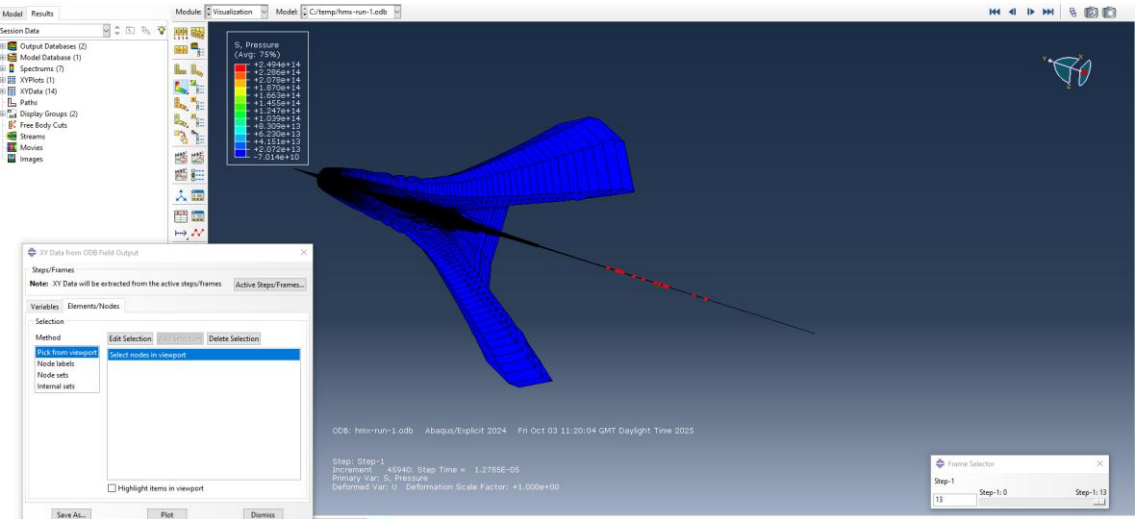


Figure 11. HMX Jet

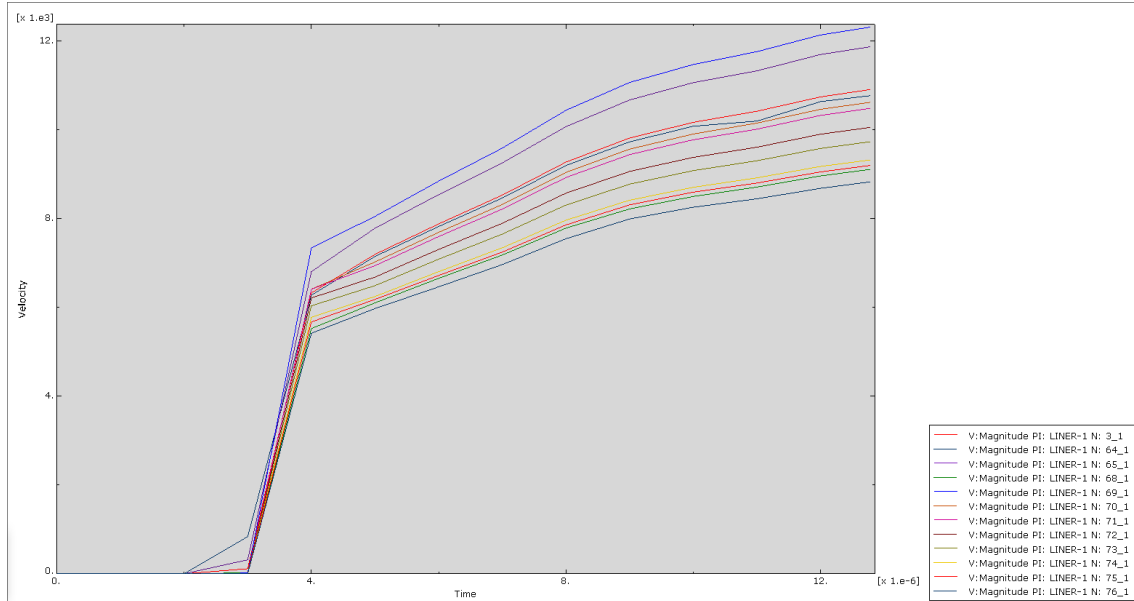


**Figure 12. HMX Velocity / Time**

The pressure wave generated by the HMX Figure 10 is even greater than the TNT exceeding 20 GPa as it contacts the liner. This will certainly result in liner deformation and formation of the high velocity shaped charge Jet. Even greater speeds of 12000 m/s can be observed on the graph at Figure 12. These results are as expected because HMX has a greater velocity of detonation and energy density than TNT which would result in a greater magnitude of forces contacting the copper liner. The HMX simulation crashed very early at around 12  $\mu s$ . The greater energy created from the detonation of the HMX likely amplified the speed and magnitude at which the elements in the simulation deformed until the numerical calculations errored. This was probably further exasperated by the poor sketch quality and mistakes during meshing mentioned previously.

## 5.5 HMX Arbitrary Lagrangian-Euler (ALE)

To attempt to increase the time before the simulation fails the Arbitrary Lagrangian-Euler (ALE) solver also known as adaptive meshing was applied to the HMX model. In the Euler method physical deformation of the mesh is not included in the calculations but the structure movement is considered as a flow of medium through the elements [22]. Making it useful for large deformation of elements that would be expected from high strain rate events such as an

explosives detonation. Lagrangian is better for simulating the deformation of the mesh. ALE takes advantage of both methods and attempts to re-mesh the elements while using Euler to maintain the consistency of the simulation whenever an error occurs from too much deformation [11]. ALE is currently considered the best option for explosives simulation modelling.

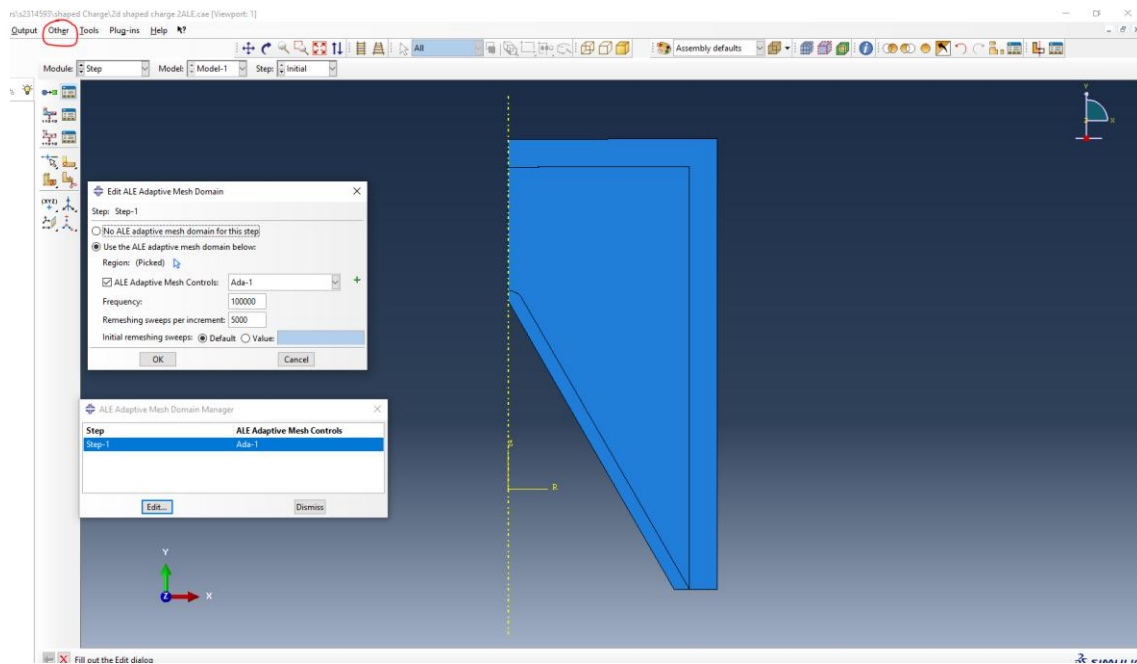


**Figure 13. ALE Settings**

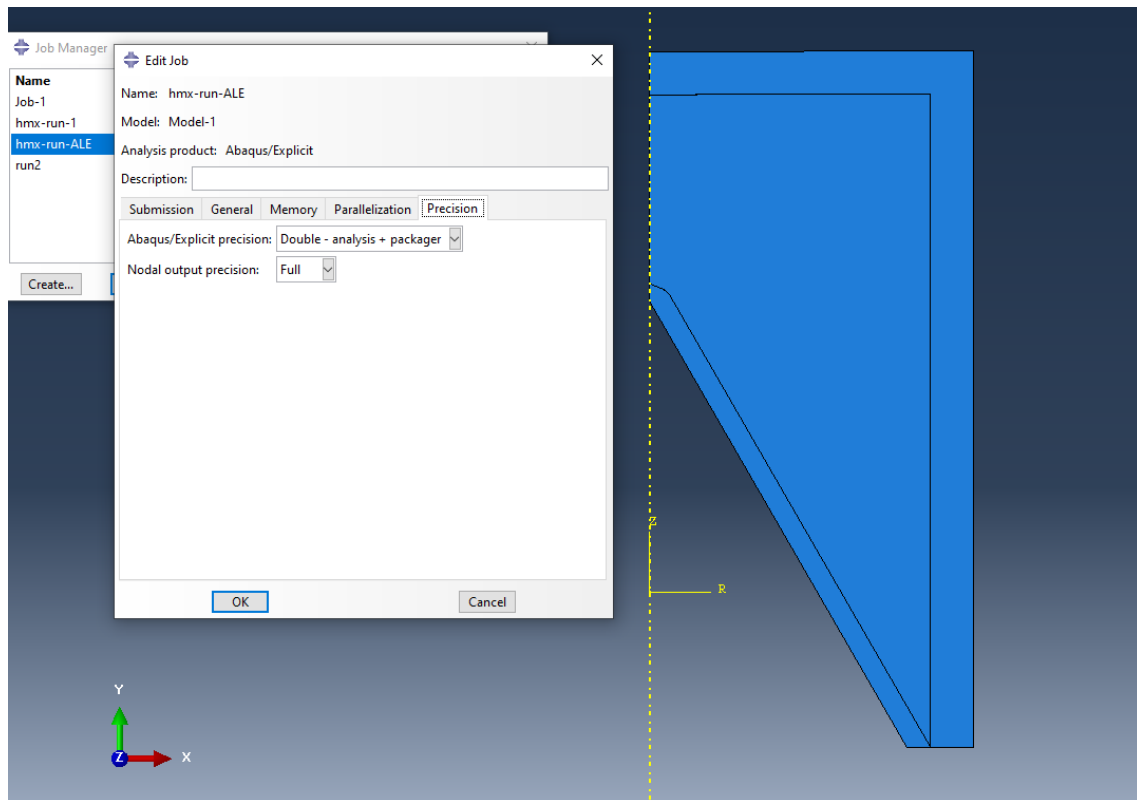


Figure 14. Further ALE settings

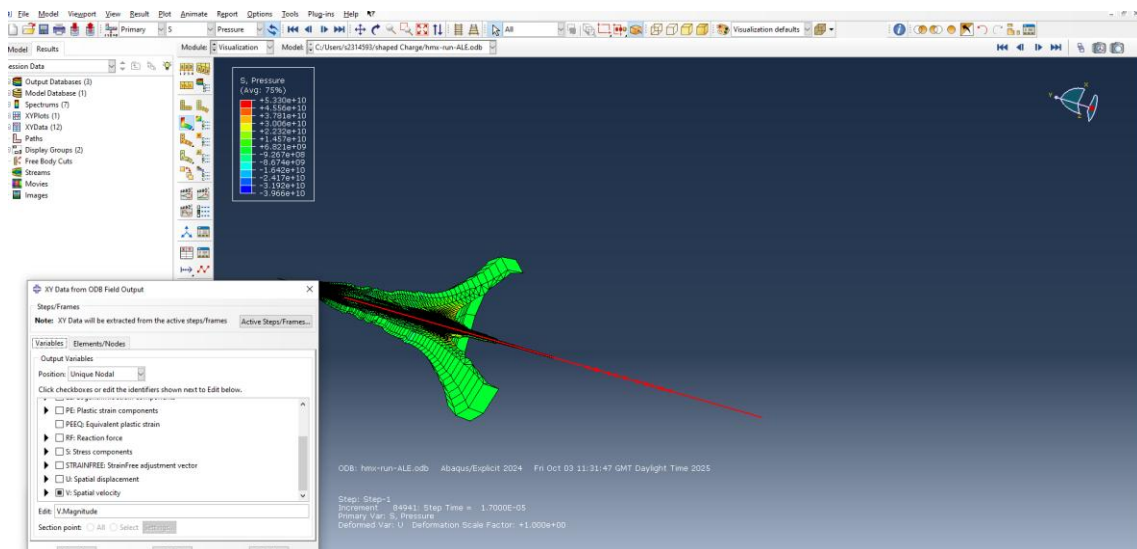


Figure 15. HMX Jet ALE

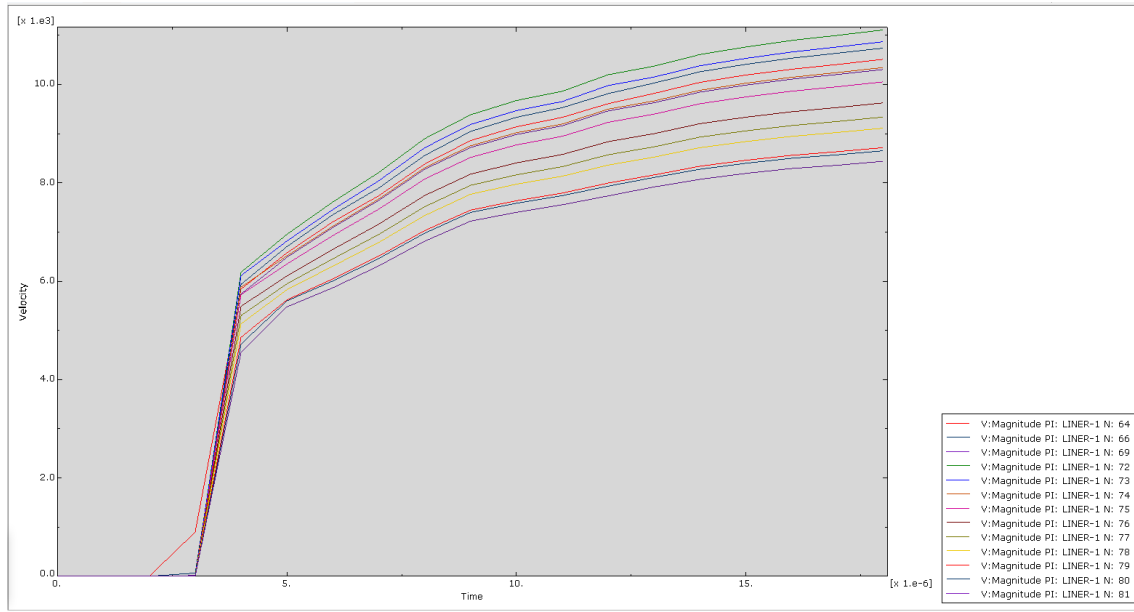


**Figure 16. HMX Velocity / Time ALE**

Adaptive meshing improved the time before the simulation failed by 4  $\mu\text{s}$  leading to a full run time of 16  $\mu\text{s}$ . It may be possible to further increase the time before failure by editing the frequency and remeshing sweeps in Figure 13 alongside further advanced settings. However, the goal of this report is to explore shaped charge modelling in Abaqus in both 2D and 3D. Therefore, it was concluded that it would yield better results to continue to the 3D simulation with the TNT fill as the simulation ran for considerably longer. It was also concluded that there was no reason to use ALE for the 2D TNT simulation because the velocity graph shows a plateau suggesting that the jet formation had mostly completed therefore there was no need to attempt to prolong the length of the simulation before it fails.

## 6 3D Simulation

To create the model for the 3D shaped charge the sketched parts used in the 2D simulation were revolved 180° around the centre axis. The setup of the load, interaction and step modules was able to remain the same.

## 6.1 Troubleshooting

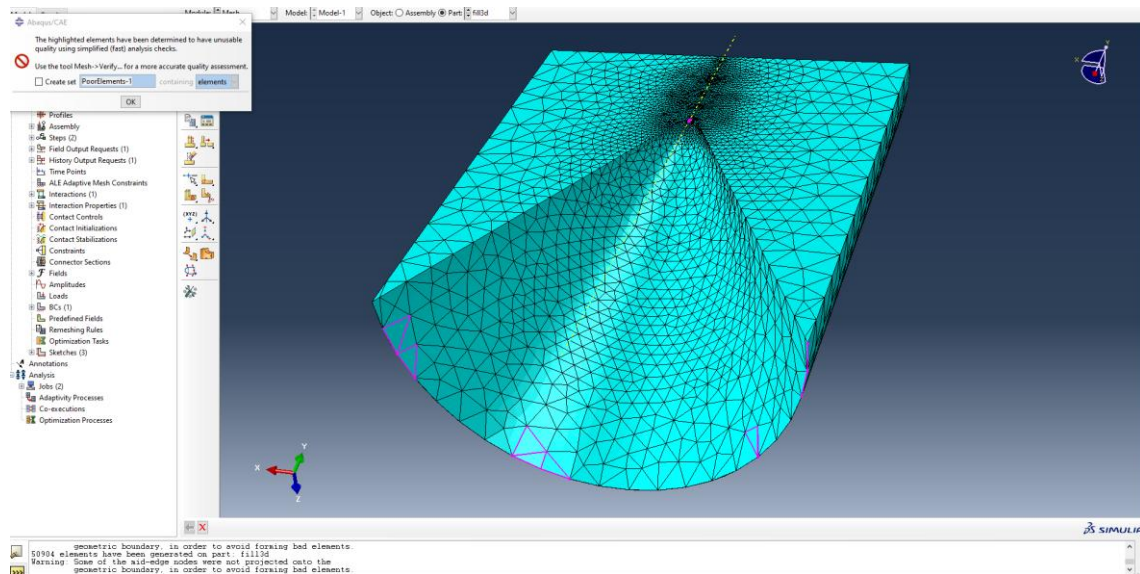


**Figure 17. Mesh Error**

During the meshing process an error was encountered seen at Figure 17. Abaqus highlighted the potential elements that could cause issues. This error was initially ignored. The mesh for the 3D model was set very fine for the first run of the simulation and the job took around an hour to complete despite failing at around 12  $\mu$ s. Figure 18, Figure 19.

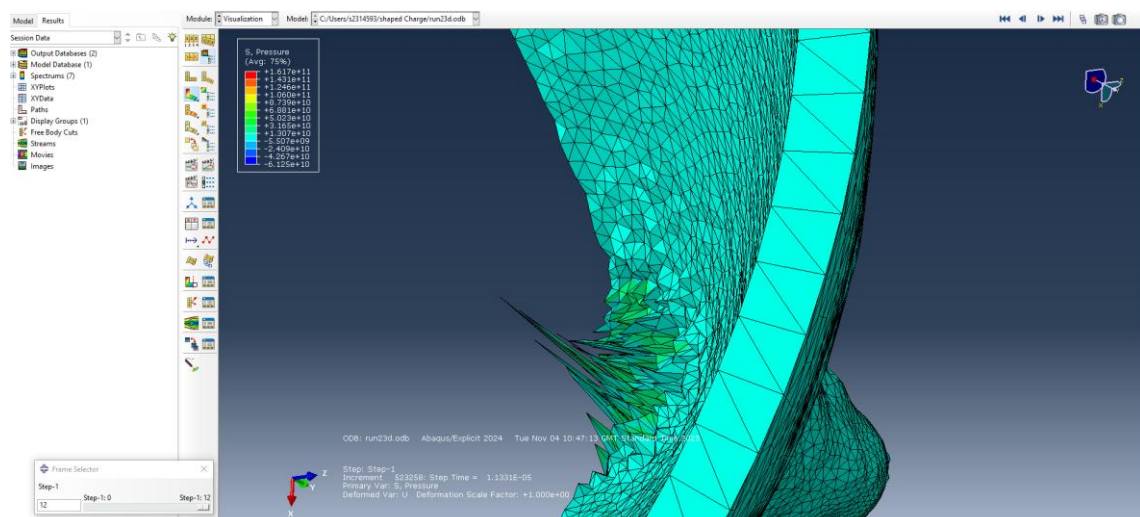


**Figure 18. TNT 3D first pass**

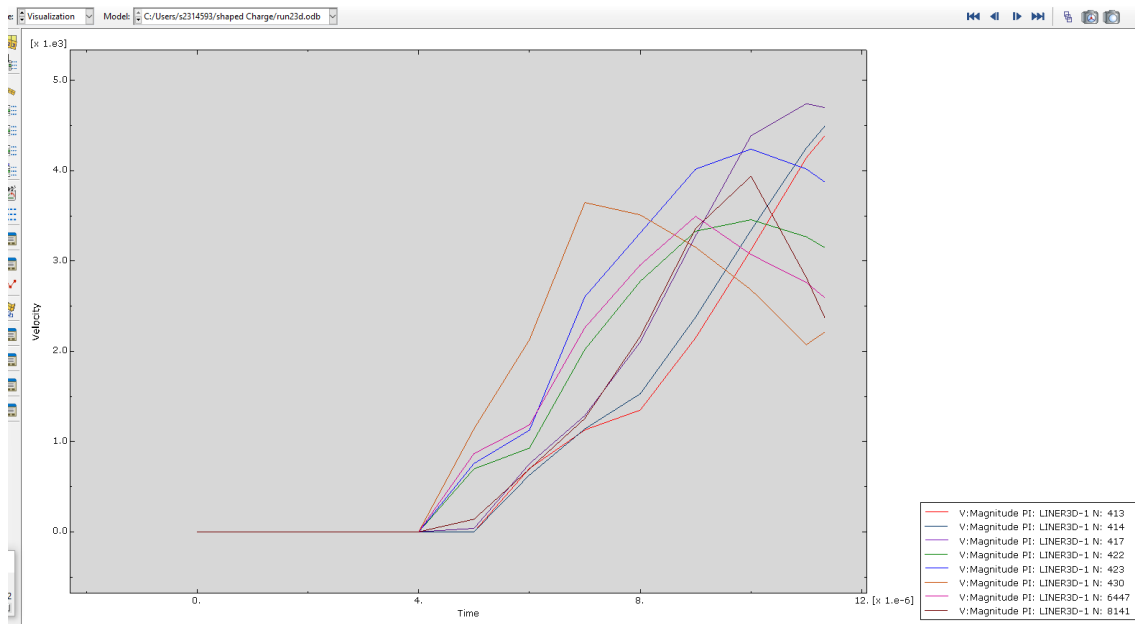


**Figure 19. TNT 3D First pass Velocity / Time**

It is evident from Figure 19 that this simulation did not run for long enough to achieve good results. Research of similar issues online suggested that the mesh was the culprit. Despite numerous iterations of coarser and finer meshing of the parts the results did not improve.

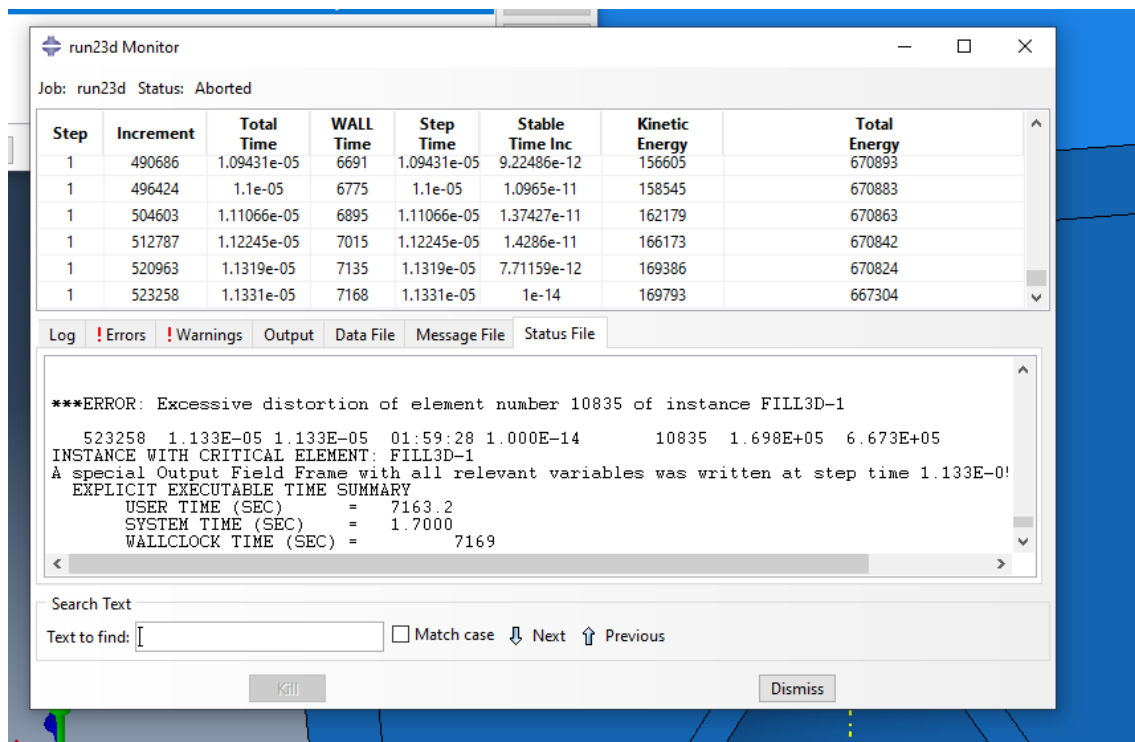


**Figure 20. Excessive Distortion of element**

The most common error prior to the simulation failing was excessive distortion of elements in the fill section.

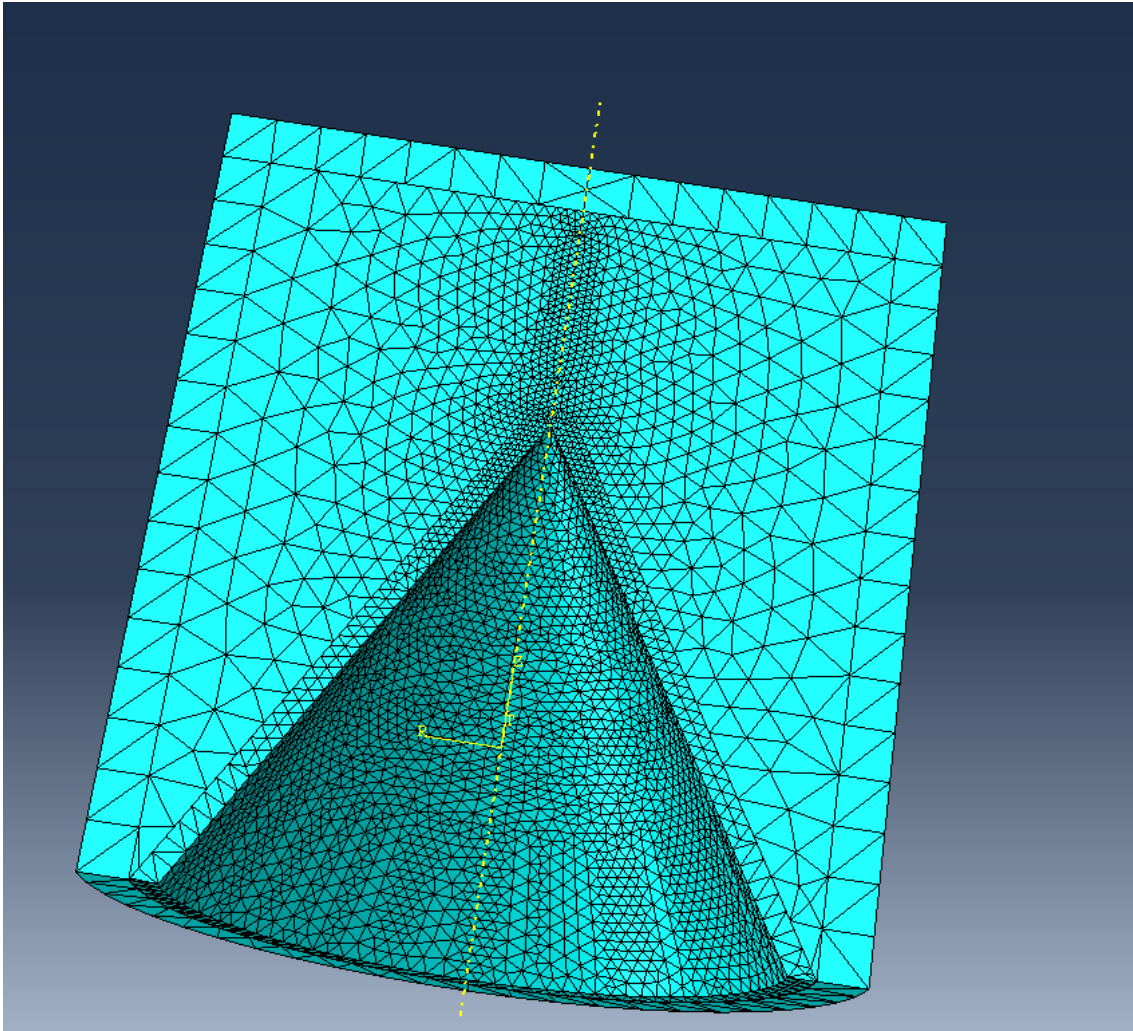


**Figure 21. TNT 3D Mesh Iteration 2**

The second iteration on the mesh produced a much faster runtime of the simulation however it still failed with the same error as Figure 20. There are some visible issues with iteration two of the mesh:

- Unneeded node in in the case centreline visible as an “x”.
- Asymmetry on the fill mesh around the foot of the liner.
- Asymmetry on the liner mesh at multiple locations.

Using the built in Abaqus function to identify areas of the mesh that were problematic revealed the potential cause of the asymmetry. See Figure 22, Figure 23

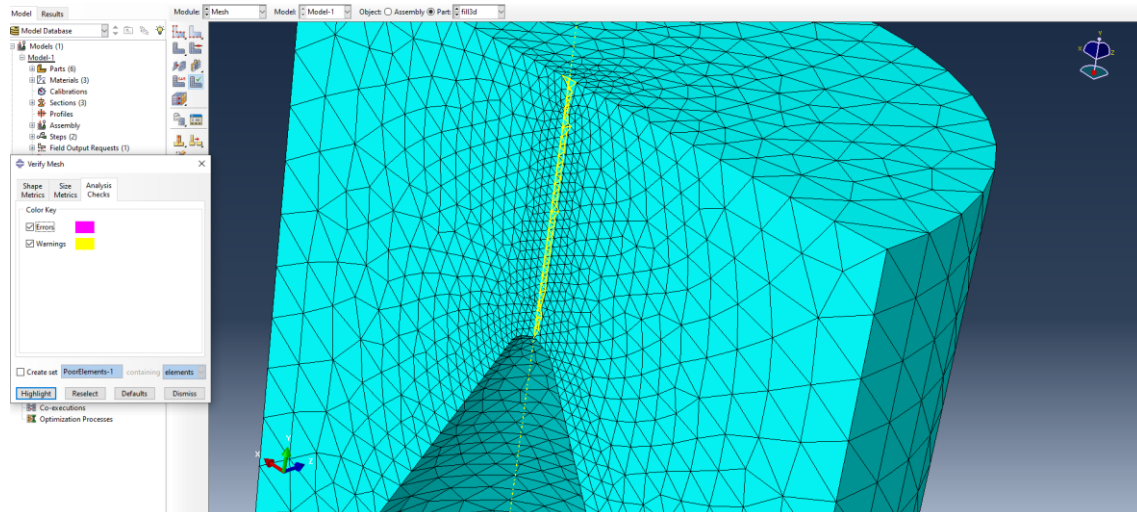


**Figure 22. Centreline warning**

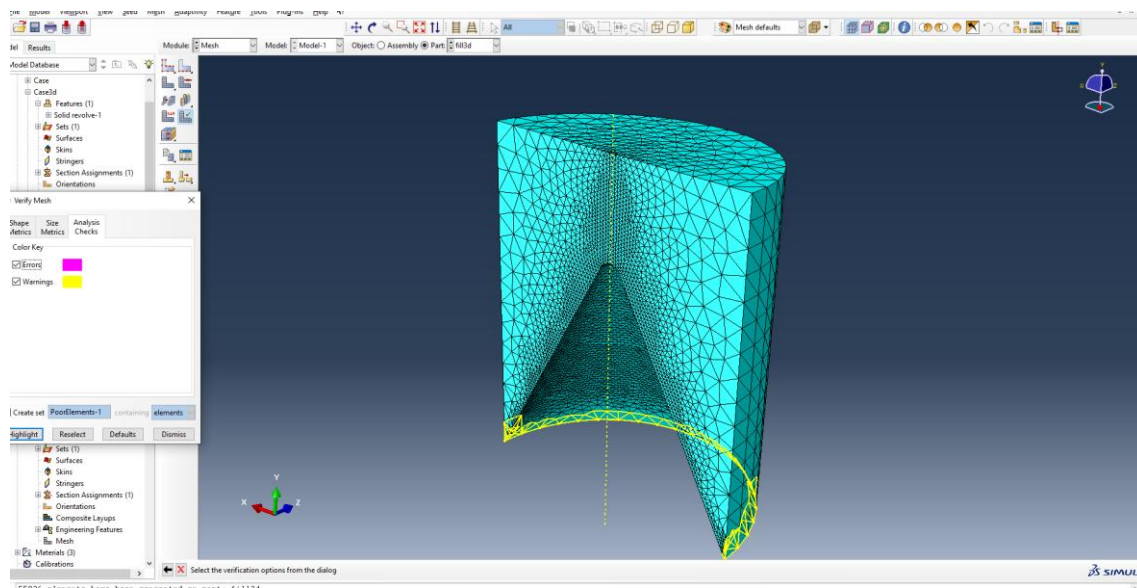


**Figure 23. Explosive Fill skirt warning**

All these elements highlighted as a warning were resolved by tidying up the initial sketch and fixing areas such as non-uniform joins that can be seen in Figure 4. There were also a few errand nodes in the mesh caused by accidental clicks in the sketching tool which were also deleted. Tidying up the sketch led to excellent results and a faster time to run even with a fine mesh.

## 6.2 3D TNT Result

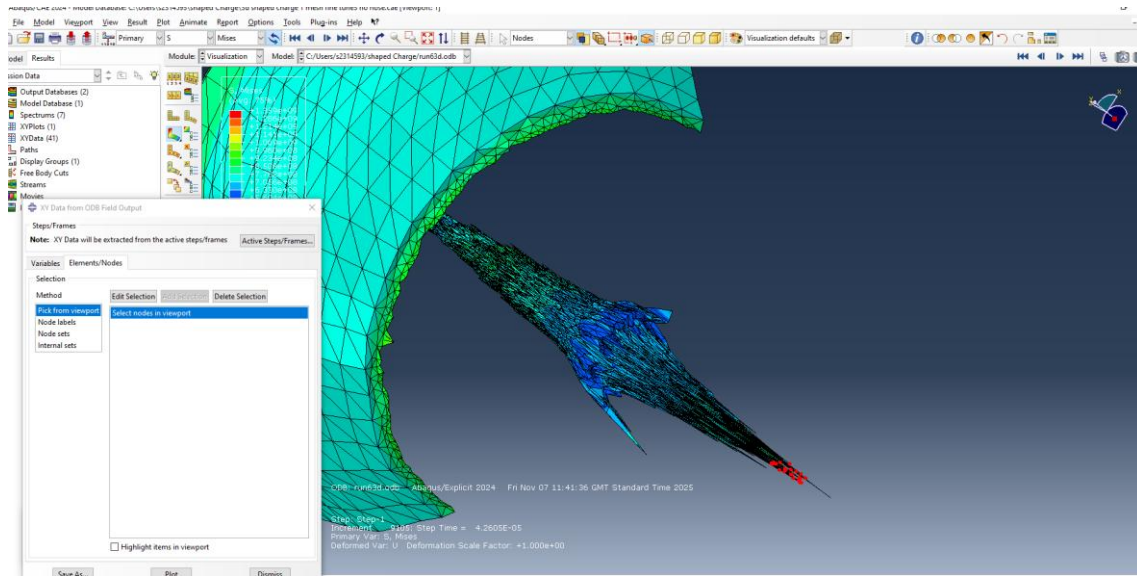


**Figure 24. TNT 3D Jet**

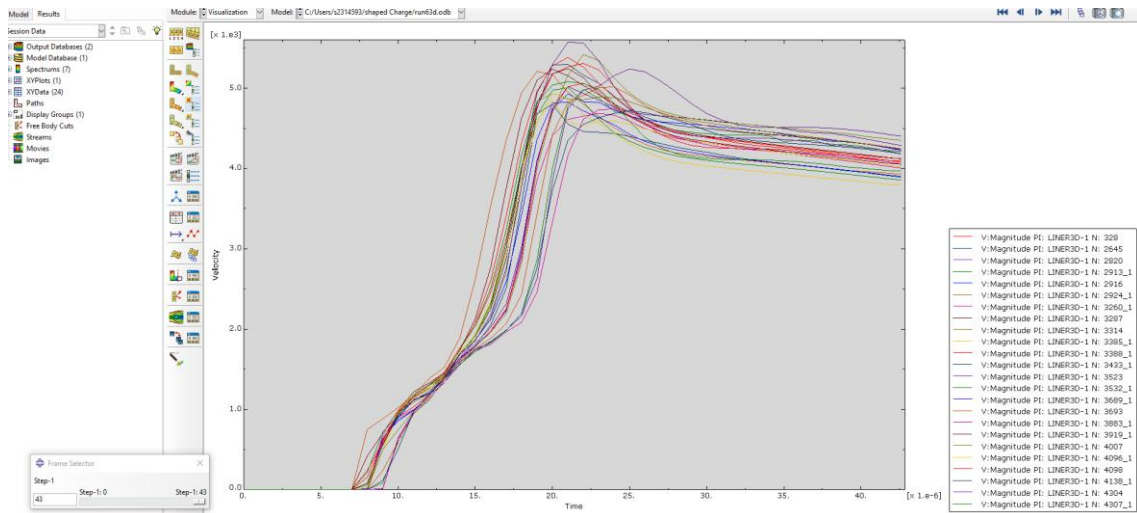


**Figure 25. TNT 3D Velocity / Time**

The visualisation demonstrates the jet formation of the copper liner in Figure 24. Although the simulation fails before it completely forms the velocity plateaus at around 4000m/s in Figure 25. That is around half of the jet velocity of 8000m/s seen in Figure 9. This anomaly is likely to be caused by the mass distribution and momentum of the elements spreading over 3 dimensions in the numerical simulation as opposed to 2 dimensions. Interestingly, the results of this 3D simulation for Jet velocity aligned with the results in [4] for TNT filled charge with

a copper liner. Suggested the model is reasonably accurate. However, the design parameters of the liner itself, its thickens and the amount of explosive used in [4] does differ from this report.

### 6.3 3D TNT ALE

Multiple attempts were made to get the simulation to run with adaptive meshing to try to improve the run-time before failure without success.

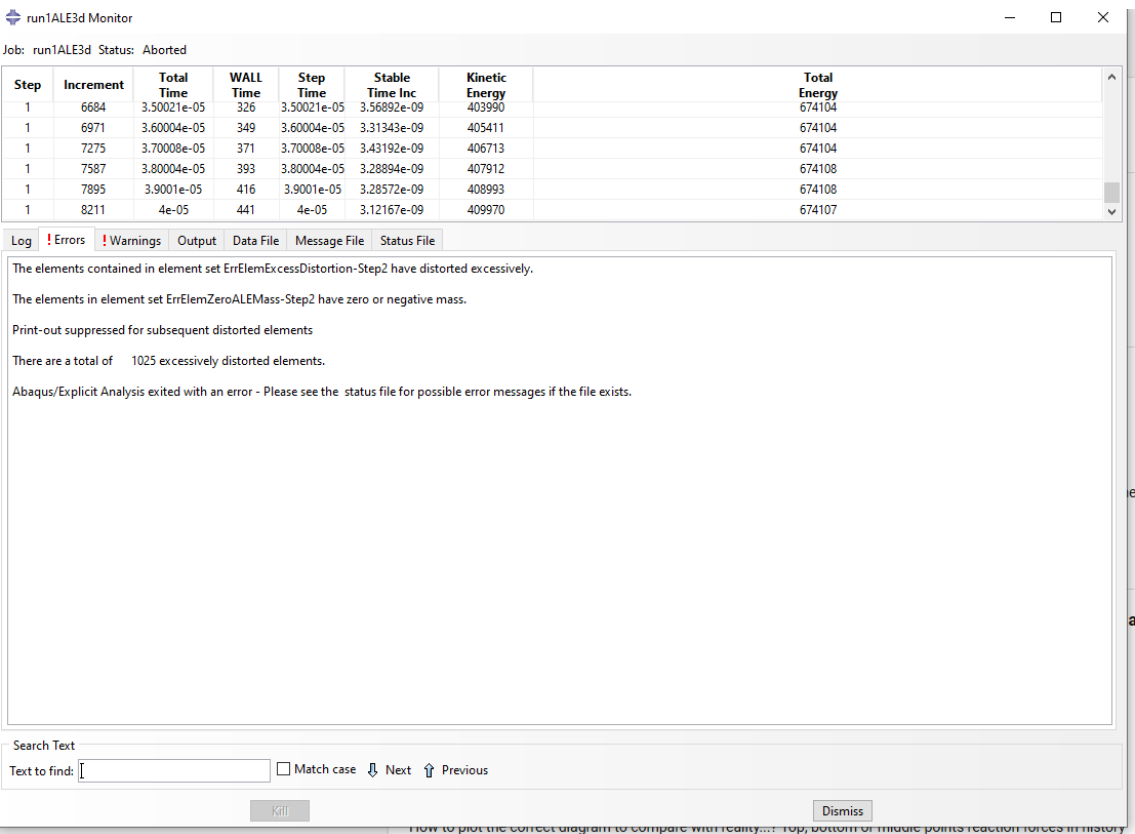


**Figure 26. ALE Error**

Despite multiple re-meshes, setting a custom viscosity, generating custom contact pairs for the parts, creating a new simulation step that only applied adaptive meshing at the point of failure and sourcing settings for the adaptive meshing increments and frequency online the error seen in Figure 26 always happened. It was suggested that this is a problem with Abaqus CAE 2024 however, this was unable to be tested due to lack of access to the previous version.

## 6.4 Smooth Particle Hydrodynamics

Smooth Particle Hydrodynamics (SPH) is a relatively new method for high strain rate simulations like shaped charges. The elements are represented by particles instead of mesh element vertices. The elements interact with each other in a radius of influence calculated by a mathematical Kernel interpolation function. This method has the advantage of being able to easily handle the large deformations caused by high strain rate simulations but it is difficult to represent the boundary surfaces [8] [22].

### 6.4.1 3D TNT SPH

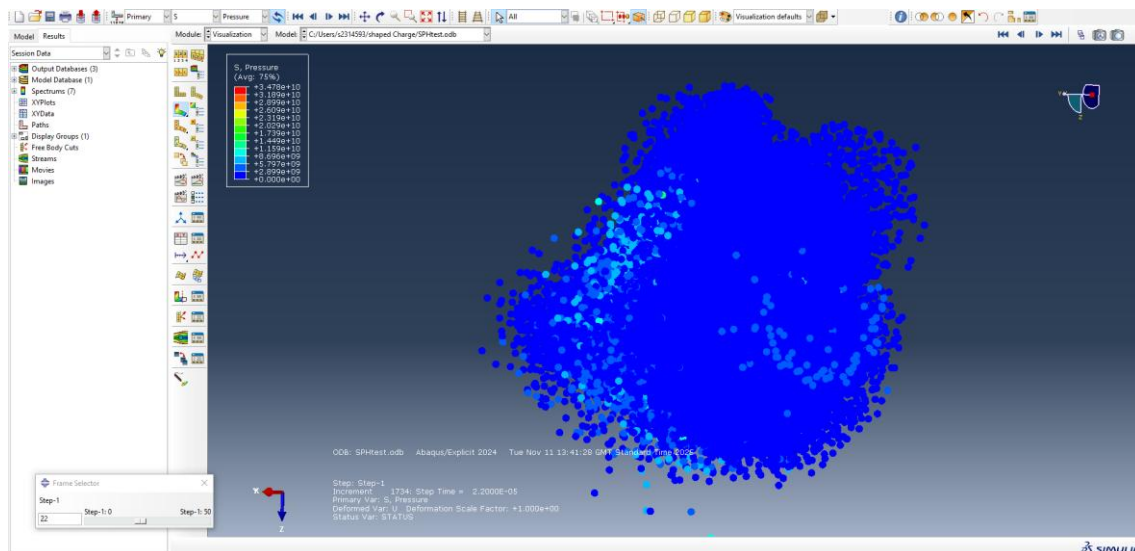


**Figure 27. SPH first attempt**

Initial attempts to run the simulation with SPH resulted in the particles ignoring the boundary conditions. This was solved by manually adding the following line into the script the governs the simulation variables under the element properties section - ELEMENT CONVERSION=BACKGROUND GRID.

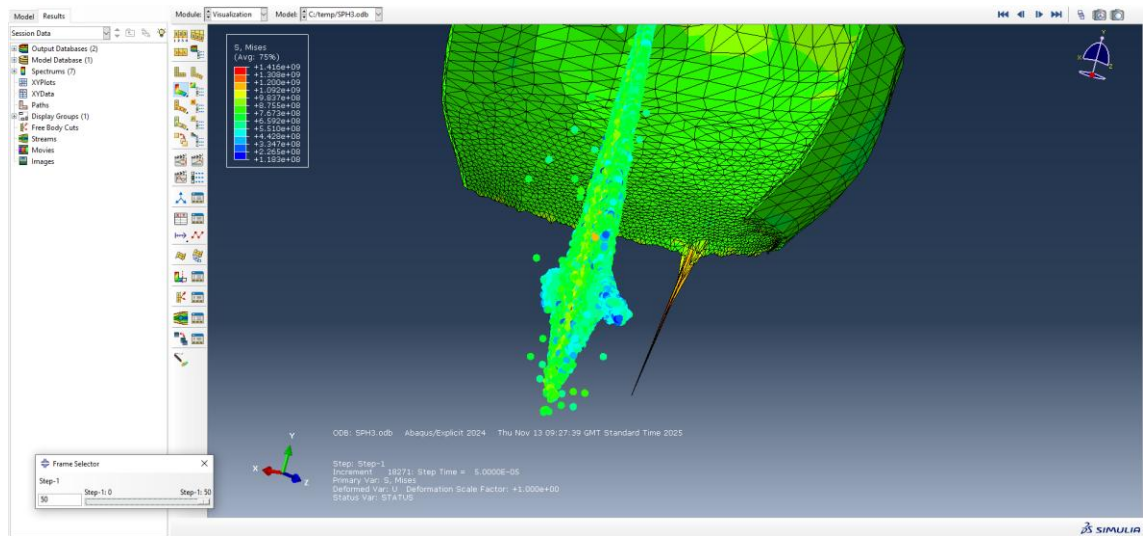


**Figure 28. SPH TNT with case**

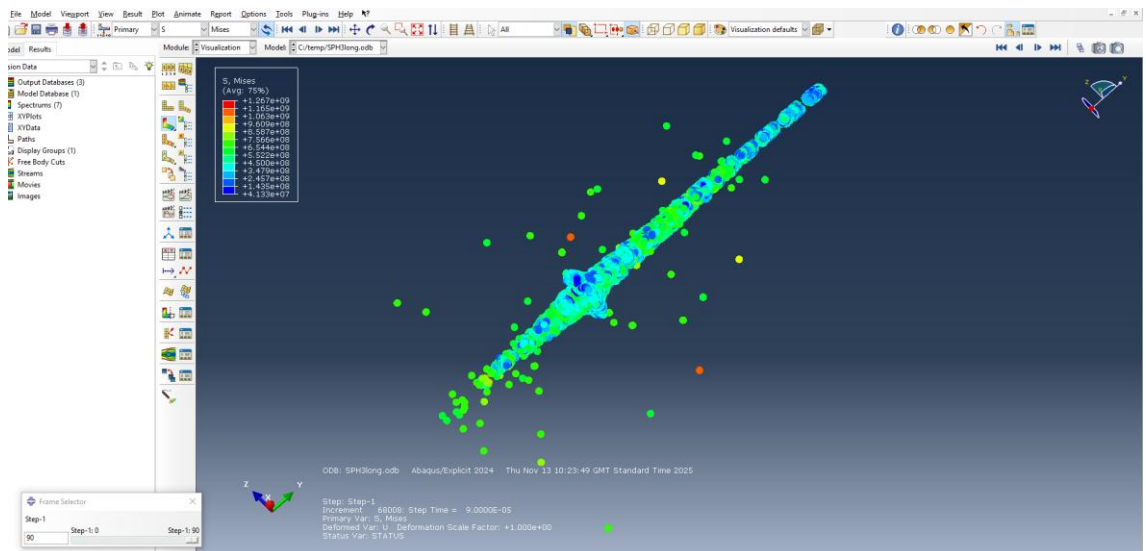


**Figure 29. SPH TNT JET**

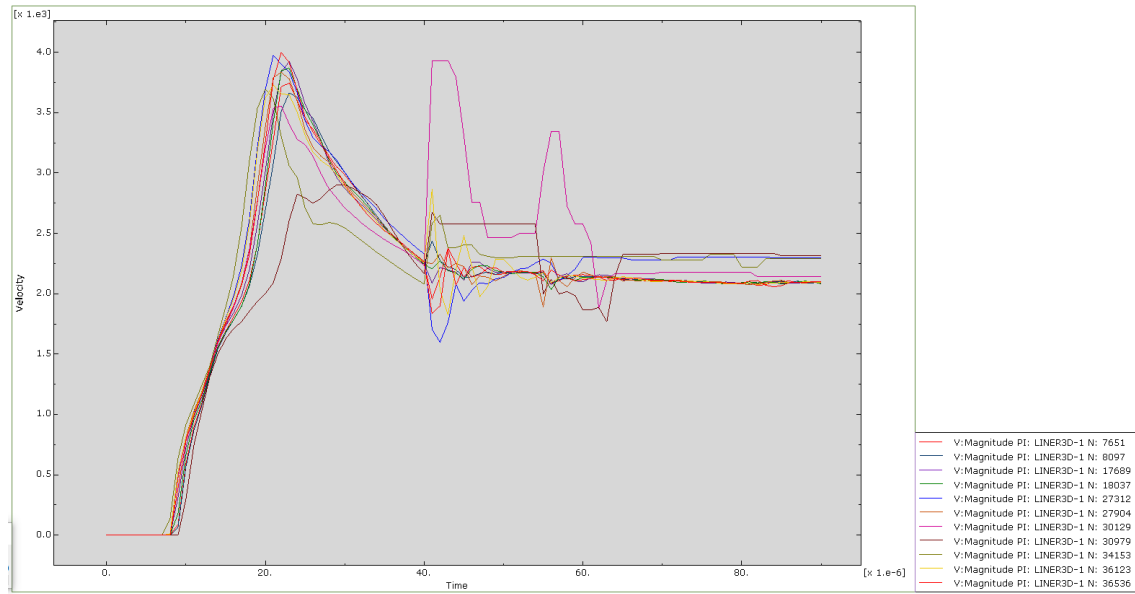


**Figure 30. SPH TNT Velocity / Time**

Using SPH the simulation was able to run to completion for an extended time of 90  $\mu\text{s}$  despite the errand case element deformation Figure 28. Figure 29 shows a fully formed shaped charge Jet. However, the Velocity / Time graph Figure 30 represents an inadequacy in using SPH at its current level of development for high strain rate simulations as it can be observed that the velocity is considerably slower than the lagrangian simulation and the velocity of some particles fluctuates wildly.

## 7 Conclusion

Abaqus CAE is a good option for shaped charge simulations capable of producing decently accurate results for evaluating novel designs. The Abaqus package demands a level of user proficiency to achieve the best results and even then, real life verification of the design is highly recommended. During the process of modelling the shaped charges for this report it was learned that to achieve the best results with Abaqus the following is worth attention:

- Accuracy and fidelity of the design sketches.
- Correct material properties. These may need to be manually acquired through appropriate tests if using bespoke materials. (This report was

focused on Abaqus simulation therefore all the properties were sourced from online)

- Multiple mesh iterations to get the best results e.g. Finer meshing on the areas of most interest, coarser mesh on less affected areas and not too much variance in mesh granularity between contact areas.
- Ensure there are no Errors highlighted in the mesh using the built in tools.
- Performing 2D simulations to verify the model's functionality before moving onto a more complicated simulation can be an effective prototyping method.

It is unfortunate that ALE did not function for the 3D simulation to be able to compare it to the lagrangian results. since ALE is the industry standard for explosives simulation. A beginners attempt to use SPH was made for this report. It would be an interested topic to investigate further by following the developments with SPH modelling and developing a further report attempting to implement an accurate SPH simulation with results the reflect real life shaped charge results. This is because if SPH can achieve accurate results the simulation run time and its ability to manage huge deformations is very efficient and could save the modelling industry time and money.

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