

ACDB5015 – Advanced Physics of OME

Shaped Charge Design

Using FEA software to design, model, simulate and critically analyse shaped charge designs and their validity incorporating understood theory around blast physics, stress and strain in three dimensions.

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PLEASE NOTE: The charge designs featured in this report are all theoretical but based on real literature examples. All information relating to the system used for this assignment was taken from publicly available, open-source literature.

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Abstract

This report aims to utilise existing understanding of shaped charge theory, influenced by scientific understanding of blast, and mechanical stress and strain in three dimensions, to design two viable shaped charges in two-dimensional analysis in Abaqus CAE, compare the results, and then take one design into a full three-dimensional analysis – including the use of different meshing techniques to enhance the model and provide the best possible results.

Building from existing theory, two viable shaped charge designs were developed, comparing the difference in jet velocity created by using different shaped copper liners, one with a conical shape and apex half angle of 45° , and one with a rounded, arced liner. Whilst both produced useful, fast-moving jets, the higher velocity conical liner design was taken forward to a full 3D design.

Full analysis of the 3D model of the cone liner, utilising advanced meshing techniques such as graduated meshes and smoothed particle hydrodynamics, produced results largely in line with existing shaped charge theory in terms of pressure, stress and velocities experienced during a shaped charge detonation. Whilst the advantages of using software such as Abaqus for these simulations are pronounced, the process of fault-finding and refinement done in obtaining working simulations serves as a reminder that, in many cases, the quality of results obtained correlate directly with the quality of work performed to get the simulation running in the first place.

Introduction to Shaped Charge Theory and FEA

Shaped Charge Theory

History

Shaped charges play a key role in military use, most notably for the purpose of defeating armoured targets, such as tanks. The early history of the shaped charge dates back to the 18th Century, where engineer Franz von Bader noted that forming a hollow in an explosive charge can concentrate explosive effects [1]. However, the work done by Bader was restricted to black powder and propellants, rather than high explosive hollow charges.

[1] notes that Charles E. Monroe's work in the field of shaped charges in the late 19th century proved a turning point. He was detonating explosives in contact with steel plates, whereby the explosives being used were inscribed with the US Navy initials 'USN'. When detonated, the initials were reproduced on the plates. He also noticed areas where cavities that had

formed inside the explosive charge had gone on to penetrate the plates further than where there were none. The phenomenon that causes the observation is named the Monroe effect.

Extensions of Monroe's work led to the creation of modern military shaped charges, which were further developed and used extensively in the Second World War for target penetration, such as on tanks, fuel containers and bunkers [2].

Today, they are a common component of the modern military arsenal.

Function

Explosive charges in cylindrical form with a detonator at one end and a cavity at the other are called hollow charges. As per [2], the cavity may take one of a variety of geometric shapes, such as cones or hemispheres. When the explosives inside the charge initiate, the detonation products, travelling at immense speed and carrying immense energy, are focused towards a small area, which creates a large force across the localised area or point.

The targeted force is then able to penetrate deeper than a regular explosive charge, due to the same pressure operating over a much smaller area.

Hollow charges can be lined with a material, typically metal, to utilise the concentrated force at the cavity to produce a jet, which is formed when the intense detonation pressures cause the liner to collapse and be accelerated away from the point of detonation at speeds of up to 8km/s [2]. This is called a shaped charge.

The stresses and strains that take place during liner collapse and jet formation are enormous. Large scale distortion of the liner material takes place in a matter of seconds, stated in [2] to be in the range of 10^4 - 10^7 /s due to the significant shear stresses deforming the liner from the detonation pressure. Hydrodynamic pressure on the liner material from the detonation wave during liner collapse can reach peaks of 200GPa, averaging around 20GPa across the whole process [2].

The velocities, pressures and strains involved in such a short time mean that penetration is achieved not through the thermal decomposition of the target on impact, but through the displacement of armour material – meaning the jet actually pushes target material apart to penetrate its target [2].

In theory, as posed in [3], by increasing the pressure, and therefore the velocity of the formed jet, the penetrative ability of a shaped charge will also increase. Operating with a standoff distance, the distance between the charge and the target, allows for much longer, faster jets to form, and greatly increases penetrative ability. However, this relationship is limited. Shaped charge jets have a much higher velocity at the tip than they do at the rear, and so the

ability to increase penetration only goes so far as until the jet breaks up, at which point its penetrative abilities fall away significantly. Therefore, balancing all components of the charge is essential to meet requirements.

Modelling the impact of shaped charge initiations is a complex and highly mathematical process. To solve models of these high strain-rate impacts would take time, and trialling them in the real world would be costly.

In modern computing, finite element analysis (FEA) packages such as Abaqus allow for ever-more-accurate design, test and evaluation of high complexity maths and physics problems in shorter time and at lower cost.

Understanding Direct and Shear Stress

Liner collapse and jet formation within shaped charges is driven by the intense pressures and stresses imparted on to the cavity liner during charge detonation. The two key stress types that drive jet formation are direct and shear stresses.

Direct stress is measured in the same way as pressure, either hydrodynamic or hydrostatic depending on whether or not the object under pressure is moving. It is the force per unit area acting on the object, and measures the level of compression (negative stress), or tension (positive stress) acting on the object [4]. In shaped charges, the detonation wave acting on the cavity liner is a compressive wave, creating significant compression within the liner as it collapses under the compressive stress.

Shear stresses are different in nature. Still measured as the force acting on an object per unit area, shear stress is a measurement of translational stress in an object [4], such as the forces generated per unit area of two faces of an object as they slide past each other. Shear stresses in shaped charge jets as they form are large, often causing extreme rates of strain across the material as long jets form within a fraction of a second. Von-Mises stress, interchangeably referred to a volume averaged shear stress or equivalent plastic stress, averages the shear stresses acting in all directions in order to determine a single value of shear stress acting at a point on the object. It is used to determine when an object will yield under loading [5]. Von-Mises stresses can provide a simplified understanding of the three-dimensional nature of shear stress, giving a simplified averaged value across all directions.

Design Principles

Explosive Properties

As a starting point, a viable geometry was created to ensure consistency across testing. There are clear relationships between geometries in shaped charge design, where evidence exists that certain design choices can predictably influence outcomes. Firstly, the choice of energetic material in the charge plays a key role. Detonation pressure is directly correlated to the square of the detonation rate [6], therefore an explosive with a higher detonation rate has the ability to greater affect the target by way of generated pressure increasing the velocity of the produced jet.

Of the typical secondary explosives used in shaped charge detonations, the detonation velocities of them are displayed in table 1.

Explosive Composition	Velocity of Detonation (m/s)
Composition B	8470
HMX	9110
PETN	7920
RDX	8440
TNT	6850

Table 1: Comparison of detonation velocities of typical secondary explosives. [7]

From table 1, HMX was selected as the explosive composition used throughout the investigation.

Charge Geometry

There are a number of other key rules outlined within military research literature, as per [6].

- Cone apex angle should be a minimum of 45 degrees
- Cone liner thickness should be between 0.01 and 0.06 cone diameters, increasing from the lower to the higher limit in the case of thicker casing
- Most effective explosive composition relates to its rate of detonation.
- Liners are often made of copper, due to their ductility.
- Once charge length exceeds 3 cone diameters, negligible progress is made in penetration.
- There is a decrease in penetration performance when the ratio of charge diameter to cone diameter increases beyond 1.2-1.25, despite more explosive charge being used.

- At regular standoff distances, peak performance is achieved with cone angles between 45 and 90 degrees.

Based on these fundamental rules, the permanent geometry of the cone was designed, with the following relationships to enhance performance:

- Casing material: Steel 1006
- Liner material: Copper
- Energetic material: HMX
- Charge length / cone diameter ratio: 3
- Charge diameter / cone diameter ratio: 1.2
- Cone liner thickness / cone diameter ratio: 0.06 (6%)
- Apex angle for conical design: 90°

Following these relationships, the precise measurements for the shaped charge were:

- Cone diameter: 60mm
- Charge diameter: 72mm
- Charge length: 180mm
- Liner thickness: 3.6mm

Material Properties

Dynamic models involving detonations are high velocity, high stress, high deformation situations, which need to take in to account the properties of materials well beyond their regular elastic regimes. The data found for steel and copper also accounted for their inevitable rapid plastic deformation and, ultimately, possible fracture, using Johnson-Cook values for plastic behaviour and damage during high strain rate interactions.

For HMX, values to solve the Jones-Wilkins-Lee (JWL) equation of state were found. JWL describes the thermodynamic behaviour of explosive compositions during a detonation [8].

In order to maximise the accuracy of the simulation in Abaqus, the following properties were found for the materials being used in the investigation.

Property	Steel 1006	Copper
Density (kg/m ³)	7890 [9]	8930 [9]
Modulus of Elasticity (Pa)	210X10 ⁹ [10]	133x10 ⁹ [11]
Poisson's Ratio	0.3 [10]	0.35 [11]

Bulk Modulus (Pa)	140x10 ⁹ [10]	135x10 ⁹ [11]
Yield Stress (A), Pa	3.5x10 ⁸ [9]	9x10 ⁷ [9]
Strain hardening constant (B), Pa	2.75x10 ⁸ [9]	2.92x10 ⁸ [9]
Strain hardening coefficient (n)	0.36 [9]	0.31 [9]
Material constant (C)	0.022 [9]	0.025 [9]
Strain rate coefficient (m)	1 [9]	1.09 [9]
Melting point (K)	1811 [9]	1790 [9]
Fracture constant D1	0.05	N/A
Fracture constant D2	3.44	N/A
Fracture constant D3	-2.12	N/A
Fracture constant D4	0.003	N/A
Fracture constant D5	0.61	N/A

Table 2: Material properties for steel and copper to be used in the shaped charge model.

Property	Value
Density (kg/m³)	1891
Velocity of detonation, D (m/s)	9110
Coefficient A (Pa)	773.98x10 ⁹
Coefficient B (Pa)	11.18x10 ⁹
Coefficient R1	4.2
Coefficient R2	1
Coefficient omega	0.3
Detonation energy density, E_o(J/kg/m³)	5.7403x10 ⁶
Pre-detonation bulk modulus, B_o(Pa)	10.5x10 ⁹

Table 3: Jones-Wilkins-Lee (JWL) equation of state properties for HMX to be used in the shaped charge model.

These explosive and material properties would remain constant throughout the investigation.

Constant Parameters

As well as material properties, several in-program parameters were kept constant to maintain consistency.

- All simulations were set up to run for a total of 100x10⁻⁶ seconds.
- All surfaces were set to maintain hard contact with each other, meaning that all surfaces are treated as rigid and there is no penetration or sliding between surfaces.

- The detonation point of the HMX within the charge was set to be the very top centre of the fill.

By introducing controlled parameters, differences in results could only be affected and explained by the investigated properties.

2D Shaped Charge Designs

Design and Setup

Charge One – Conical Liner

To begin with, three individual sketches were created within the Abaqus sketch window, one for the liner, one for the charge casing, and one for the explosive fill. Figure 1 shows these sketches side by side, with dimensions determined from the research as per [6].

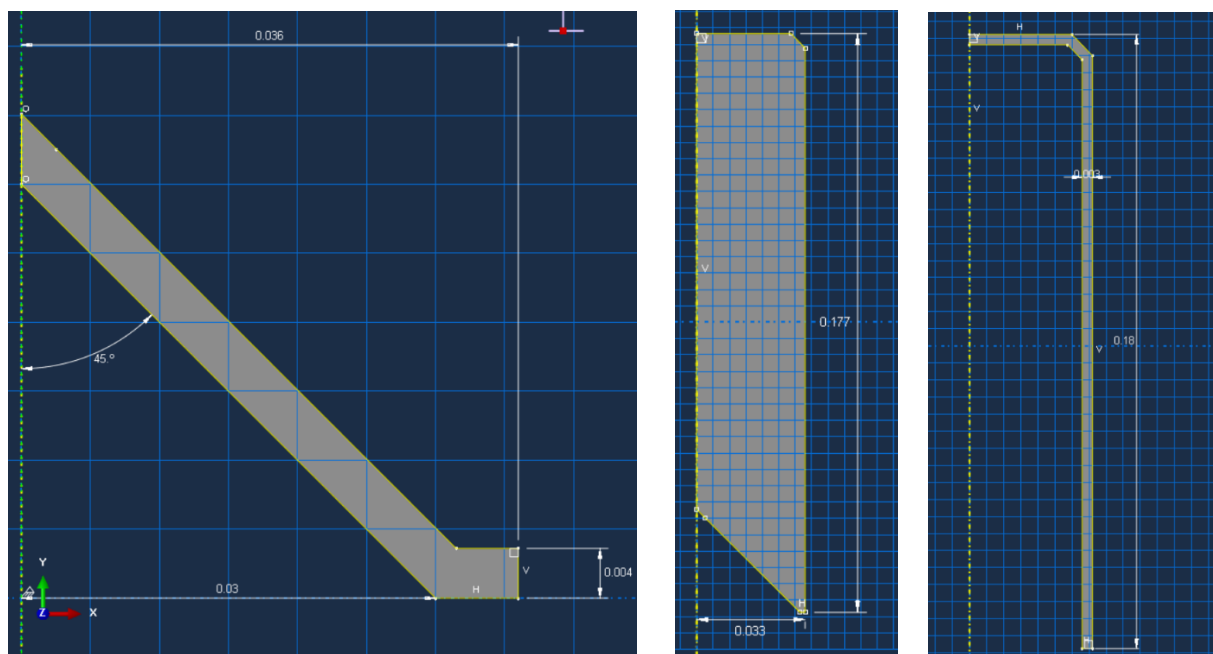


Figure 1: Abaqus sketches of the liner, charge fill and casing.

The three individual sketches were then assembled in to a single entity. Each individual component was then assigned the correct material, whose properties had been populated in the software's material editor using the previously determined values from literature searches. Verification of the assignment of materials is shown in Figure 2.

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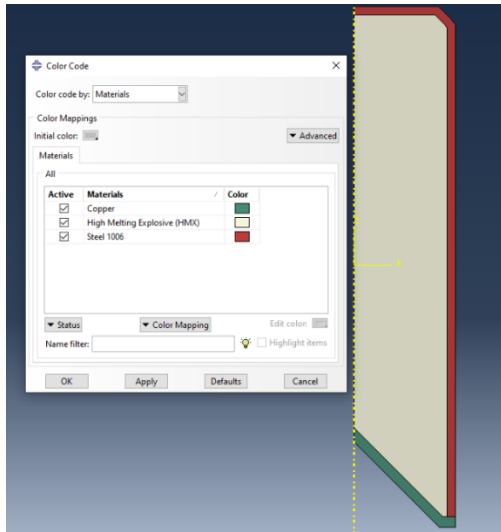


Figure 2: Materials and material properties correctly assigned to each component of the charge design.

Following application of the control parameters previously referenced, a mesh was applied to the charge. Initially, the mesh in Figure 3 was used, attempting to use a finer mesh in the key areas of the simulation, where the highest strain rates were anticipated, within and in the area immediately surrounding the liner of the charge. Attempting to run the simulation with this mesh failed, as there were several instances of overclosure and surface penetration within a few frames of the simulation starting. This was especially prevalent around the area of the point of detonation, where fill was immediately penetrating through the rigid casing. It was established that the cause of this was the stark difference in coarseness between the mesh at the detonation point, and the casing surrounding it.

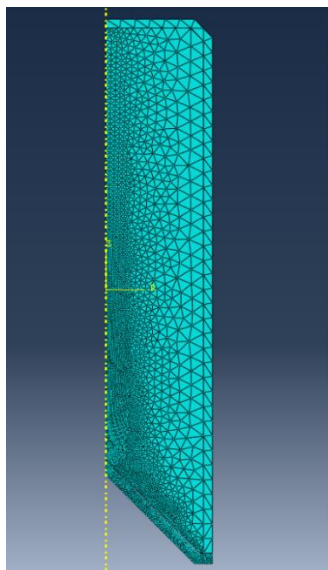


Figure 3: Initial mesh of the charge, showing a finer mesh in areas of expected high strain, becoming more coarse as it moves outwards.

To solve this problem, and to make use of the 250,000 node limit, the mesh was made more uniform, introducing a finer mesh in the previously coarse areas. This would increase the time required to complete the simulation, but significantly decrease the risk of uncontrolled distortion or penetration. Figure 4 shows the mesh that was used to complete the simulation.

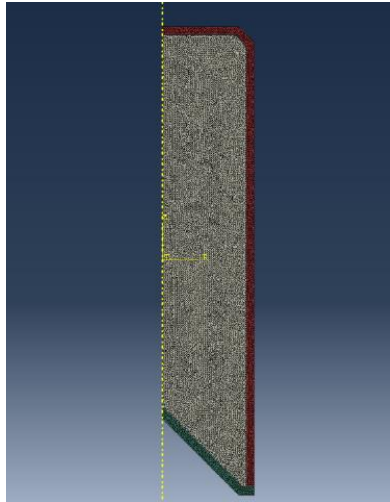


Figure 4: Finer mesh used in the final 2D conical liner simulation.

Charge Two – Arc Liner

Construction of the second 2D design, replacing the conical liner with a smoother arced liner, happened in a very similar fashion. The sketch of the casing and from Figure 1 was re-used, with a new sketch being produced for the new liner. The sketch from Figure 1 was altered at the bottom to account for the new liner shape. This is shown in Figure 5.

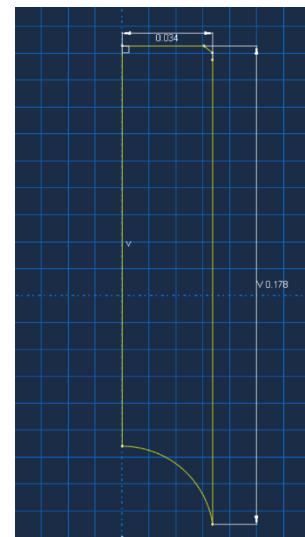
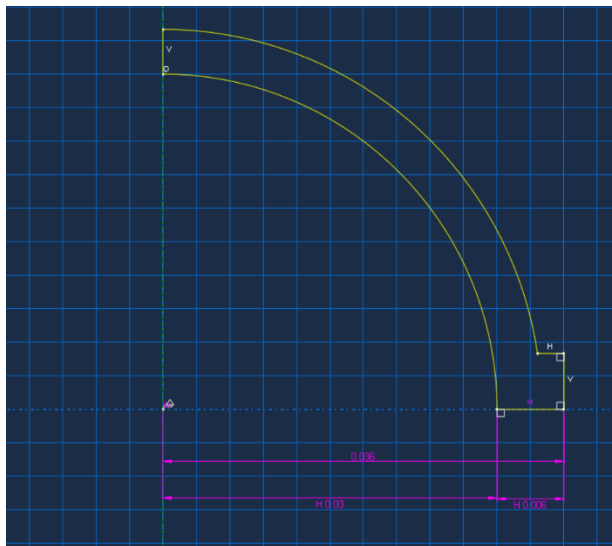


Figure 5: Sketches of the arced liner and main fill for the new charge design.

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As with the previous design, the individual parts were assembled, and assigned materials using the material editor, as shown in Figure 6.

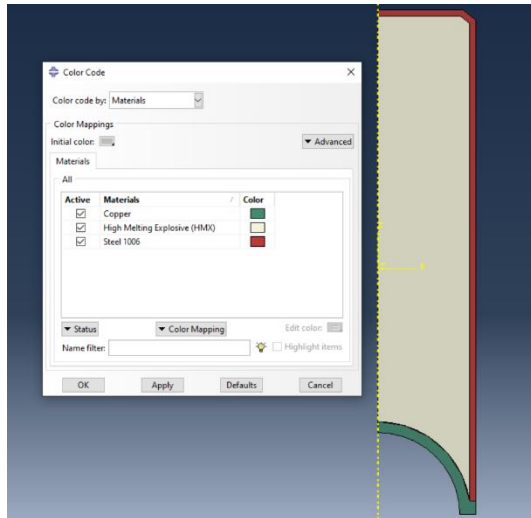


Figure 6: Charge shown with assigned materials and material properties.

Contact, interaction and step parameters were applied as per the controls established before the first design, and, to ensure as accurate a comparison as possible between the two designs, the mesh from the conical liner design was carried forward to the arc design, as per Figure 7.

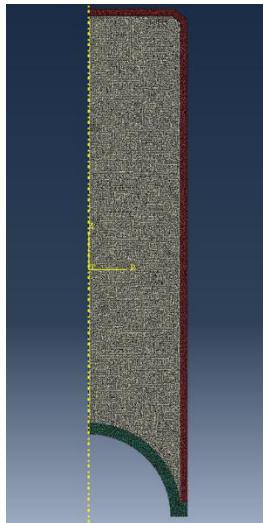


Figure 7: Mesh used for the arc liner simulation, with the same dimensions and parameters as for the conical liner.

Discussion of Results

In both designs, velocity was recorded at different locations along the metal jets formed from the explosion, with the fastest moving projectile taken forward to a full 3D analysis.

Conical Liner

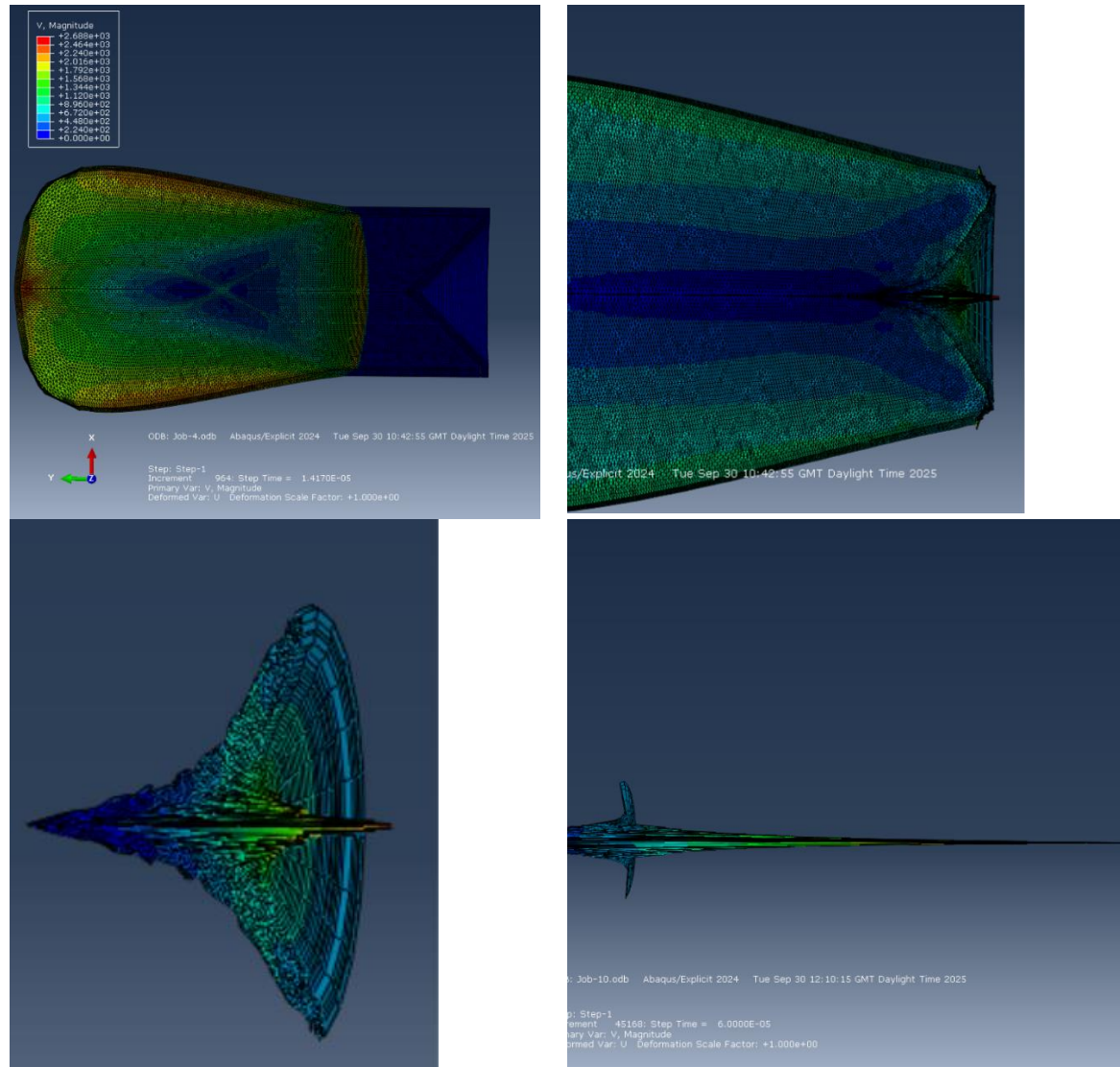


Figure 8: Evolution of the formation of copper jet from shaped charge explosion.

Figure 8 captures the evolution of the simulation from detonation to jet formation, beginning with the detonation shockwave passing through the fill, then reaching the liner and forming the beginnings of a jet as the conical liner turns inwards, before finally a long, high velocity copper jet is formed and sent off towards a hypothetical target.

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A series of measurements of jet velocity were taken throughout the simulation, beginning with the very tip of the jet at equal time intervals between 20 and 60 microseconds (μs). Figure 9 shows the velocity plot of the tip of the jet.

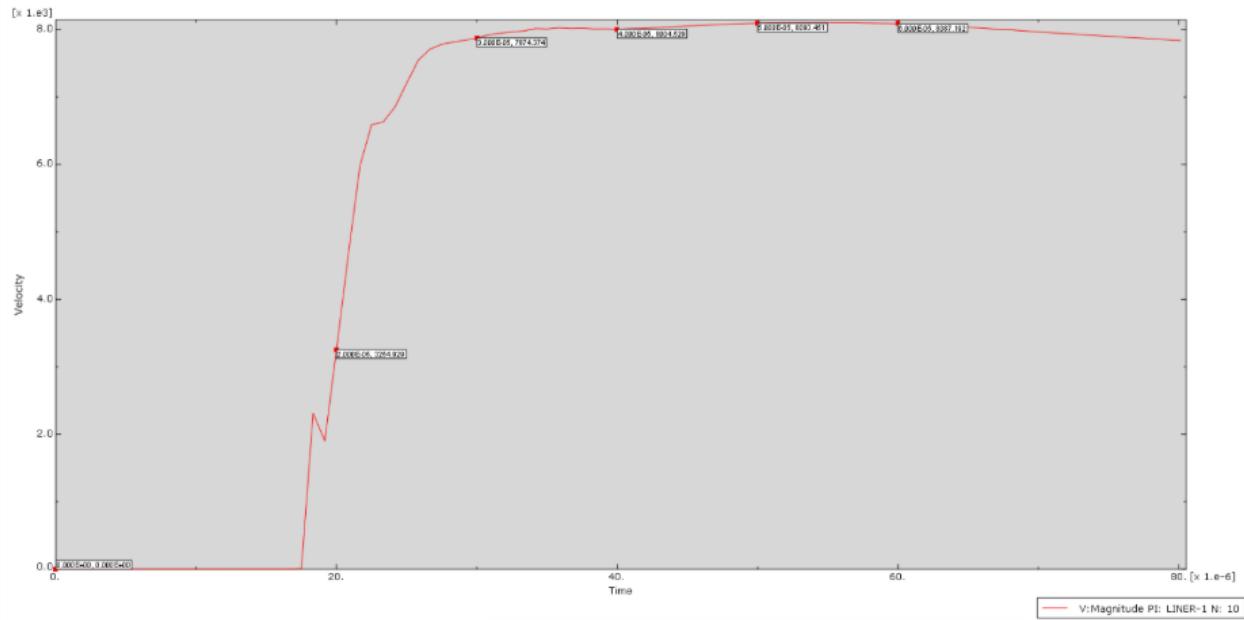


Figure 9: Velocity-Time plot of the tip of the jet.

From the point where the detonation wave reaches the liner, at around $17\mu\text{s}$, until a time just before $30\mu\text{s}$ after detonation, the tip of the jet undergoes a rapid acceleration, moving from stationary to a top speed of over 7km/s in just over ten millionths of a second. A probe of the plot determined during this time that the jet was travelling at 3255m/s at a time $20\mu\text{s}$ after detonation, and had reached a speed of 7874m/s by $30\mu\text{s}$ after detonation.

From 30 to $50\mu\text{s}$, acceleration continues but at a much slower rate, passing through 8km/s at $40\mu\text{s}$, reaching a speed of 8093m/s at $50\mu\text{s}$, before energy begins to dissipate and a very gradual deceleration process begins, at which point the speed of the jet has decreased slightly at the tip to 8087m/s .

Velocities were also taken at separate points along the jet at a time $60\mu\text{s}$, in the central region of the jet, and the rear portion of the jet. Figures 10 and 11 show the velocity-time plots for these regions.

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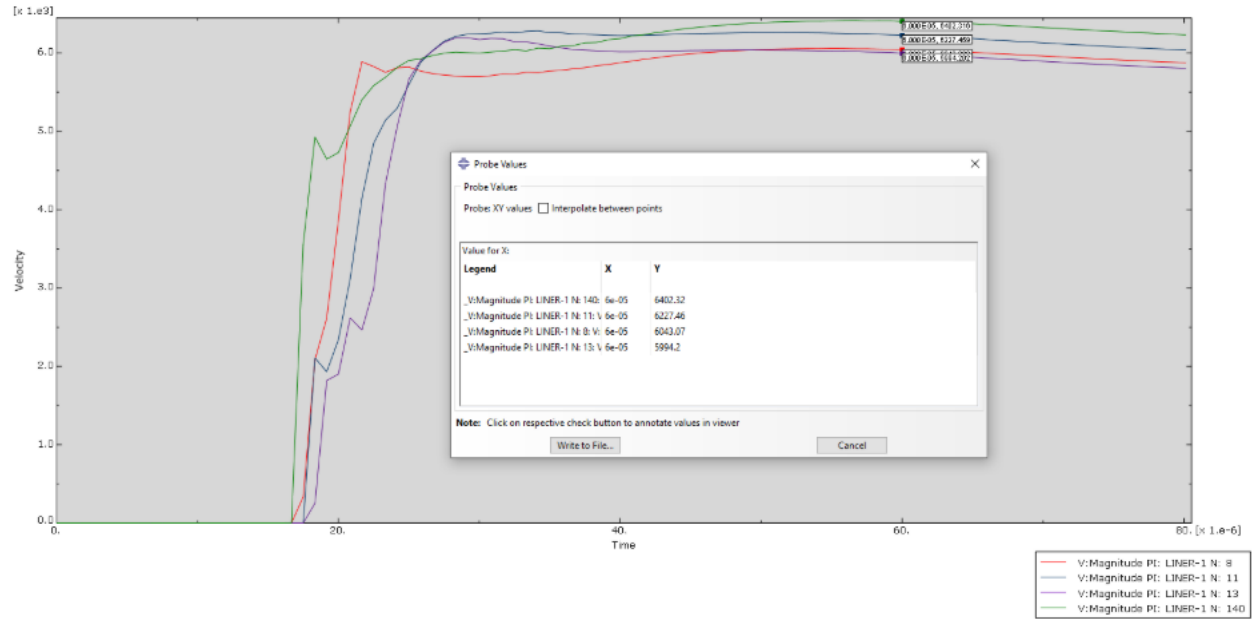


Figure 10: Velocity-time plot of nodes in the region at the centre of the jet.

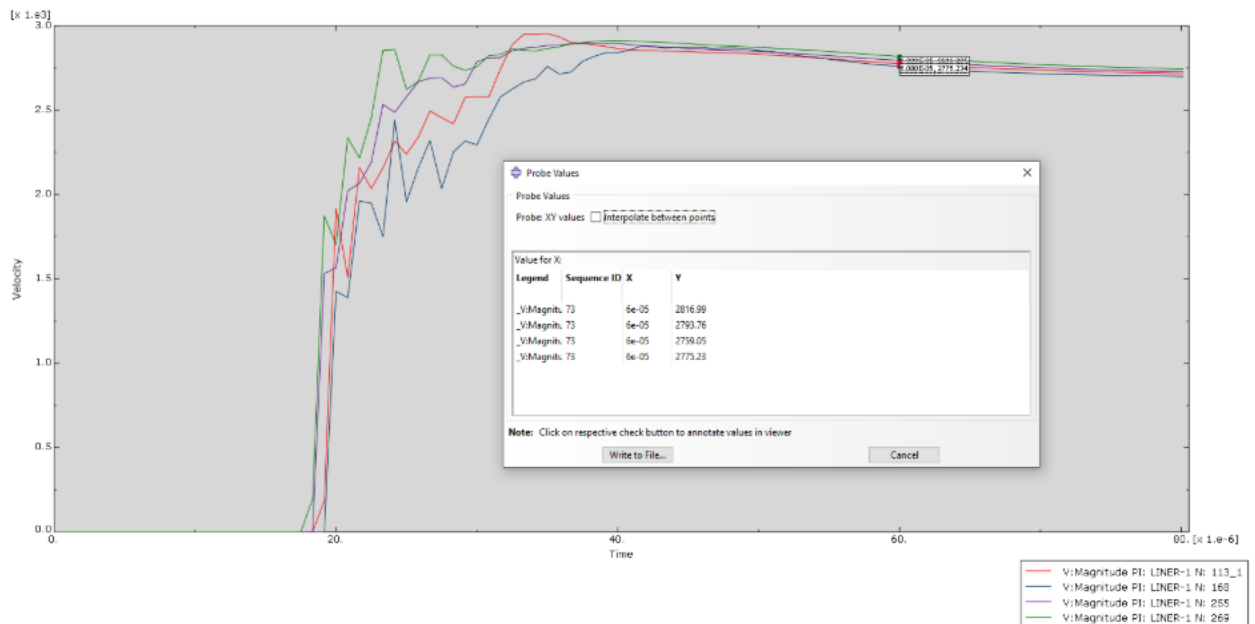


Figure 11: Velocity-time plot for nodes in the rear region of the jet.

Figure 10 shows that, at $60\mu\text{s}$, the central portion of the jet is moving between 5994m/s and 6408m/s , with the average velocity in the central region from the nodes probed being 6166m/s . Figure 11 shows that, at the same time, the rear region of the jet is moving at velocities between 2759m/s and 2817m/s , with an average velocity of 2786m/s .

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These results show that the jet produced during this detonation is moving at incredibly high speeds, and therefore is carrying huge amounts of kinetic energy, as the jet's kinetic energy is directly proportional to the square of its velocity. It is also very narrow in shape and so will hit the target over a very small surface area, increasing the pressure exerted on the target as the two are inversely proportional. The high pressure and energy with which the jet would impact the target means that it would have the ability to inflict significant damage upon it.

Arc Liner

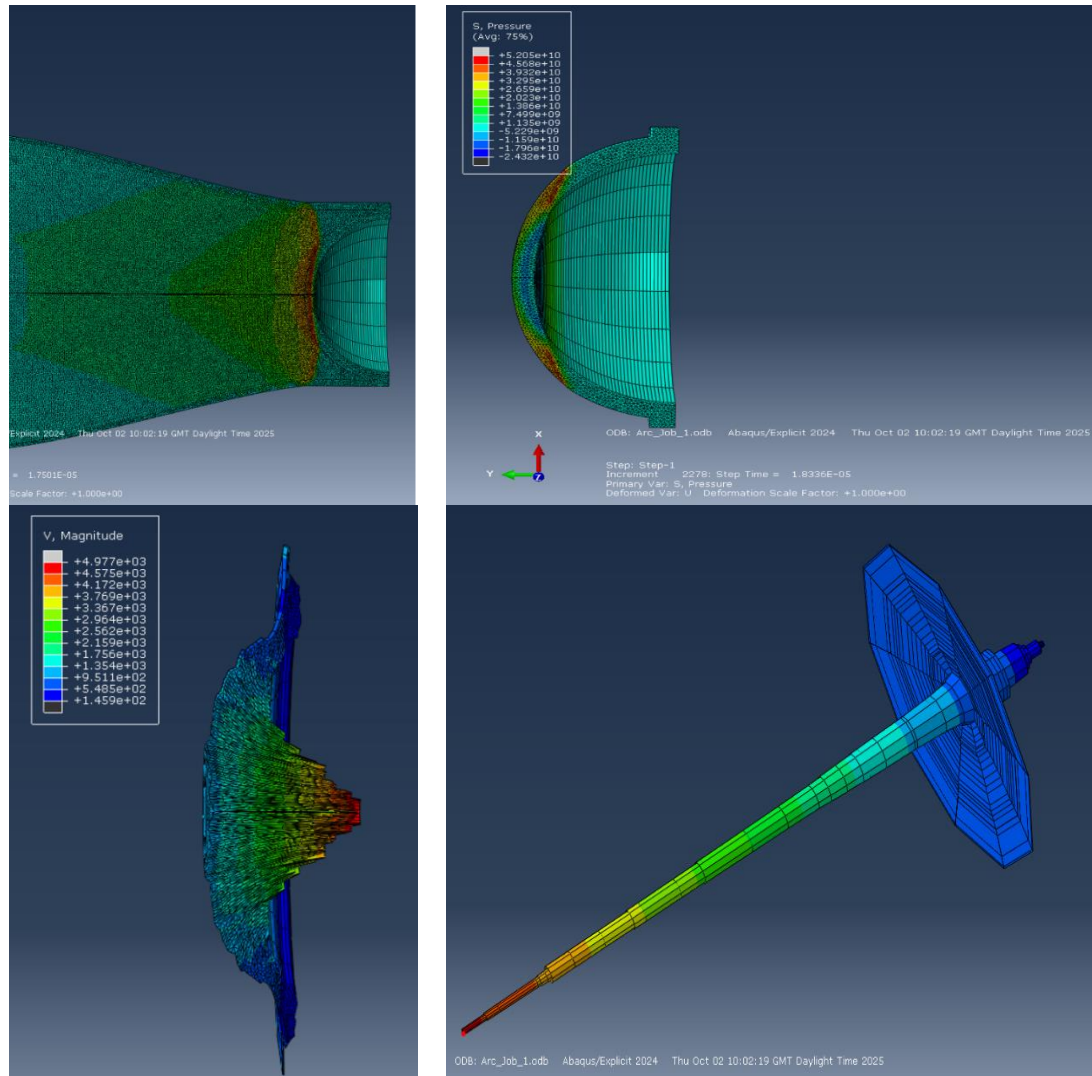


Figure 12: Evolution of jet formation in conical liner charge after detonation.

Figure 12 captures the stages of the second simulation from detonation to jet, beginning with the detonation shockwave moving through the fill, then reaching the liner and forming a jet as the arc turns inwards, before finally a long, high velocity jet is formed and sent towards the target. Initially, it had been anticipated that the arced liner might produce an

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explosively formed projectile in the form of a large metal slug type splinter fragment, rather than a full high-energy jet, but the simulations showed that the arc liner used was more than capable of functioning as a classic shaped-charge.

As with the conical liner simulation, velocity measurements were taken at the tip of the jet at the same time intervals. Figure 13 shows the velocity-time plot for this measurement.

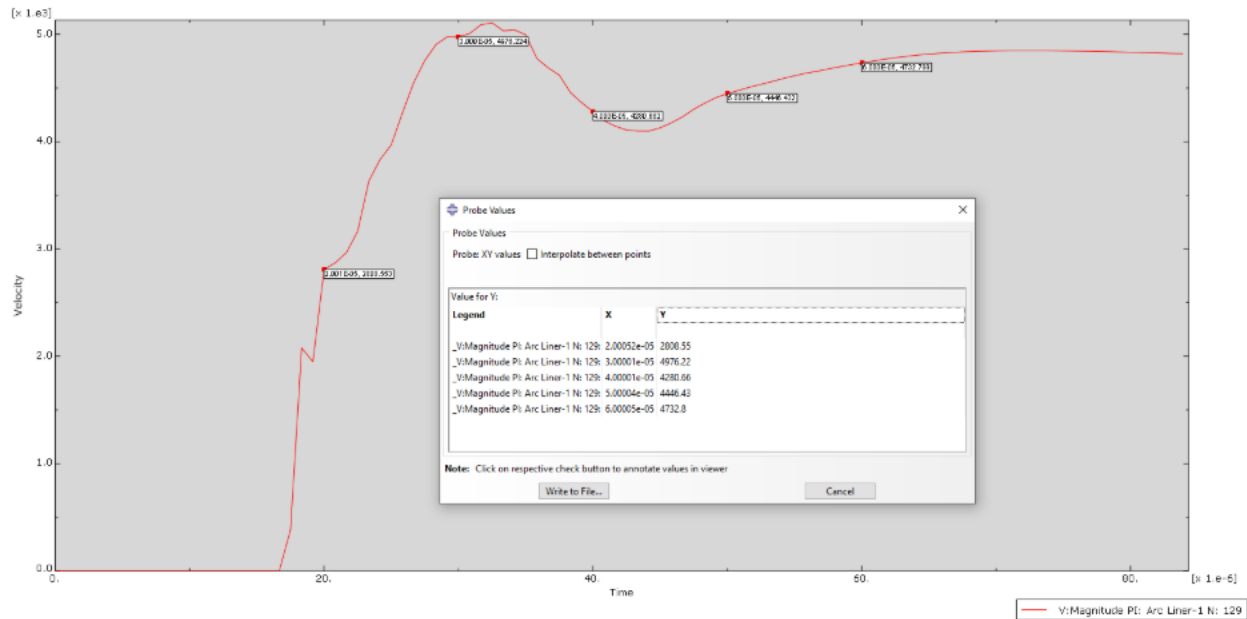


Figure 13: Velocity-time plot for the tip of the arc-liner formed jet.

The first thing that stands out about the graph is the sudden deceleration, and then gradual acceleration that takes place midway through the simulation. This was unexpected as it was anticipated that the graph would be similar in shape, if not in magnitude, to Figure 9. Basic understanding of projectile motion dictates that this is an anomalous reading as there is not additional force intentionally applied to the jet after the initial detonation that would cause such a sharp deceleration and then a new period of acceleration. A period of fault finding was unable to determine exactly what caused the reading, as it was not repeated in any other region of the jet.

Just as with the conical liner however, there is a rapid acceleration over a period of around $13\mu\text{s}$, from stationary to nearly 5km/s between $17\mu\text{s}$ and $30\mu\text{s}$. The highest speed recorded at any point is just over 5000m/s at $32\mu\text{s}$ after detonation. At $60\mu\text{s}$, when the plot recovers in line with the anticipated curve, the jet is moving at 4733m/s . Dissipation of energy begins at around $70\mu\text{s}$, slightly later than in the conical liner, but ultimately negligible in difference.

Simulations show that using an arced liner such as the one in this design would produce a viable shaped charge with the ability to act decisively against certain armour, with a narrow

jet moving at high velocity capable of acting at high pressure with immense kinetic energy. However, given that the jet is slightly wider than the jet produced by the cone liner – and that it is travelling with around 60% of the velocity of the cone jet, the kinetic energy per unit surface area exerted on a hypothetical target would be significantly lower in the cone liner.

Based on this, although both designs are viable in many target defeating applications, the increased penetrative ability of the conical liner meant that it was selected for the full 3D analysis.

3D Shaped Charge Design

Design and Setup

Assembly and Material Setup

To begin, the sketches from Figure 1 were re-used to create the sketch for the conical liner in 3D. Once completed and assembled into a single entity, all three parts were revolved around 180 degrees to create the 3D model, as shown in Figure 14.

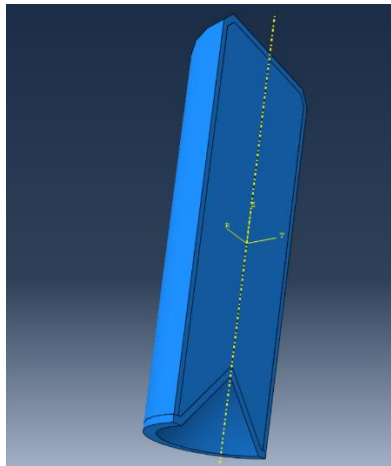


Figure 14: 3D assembly of the model.

The model was revolved around 180 degrees as opposed to 360 degrees because it would be easier to control and refine the inner mesh, and analyse what is happening inside the charge during the simulation being able to see straight in to it.

Figure 15 verifies the correct selection of material properties, in line with the 2D designs.

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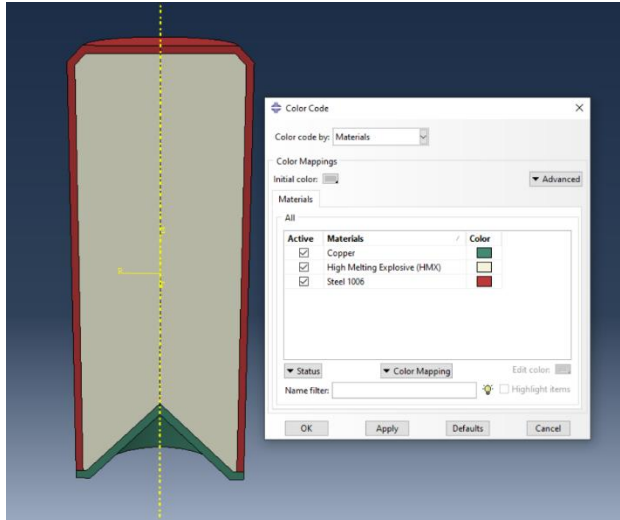


Figure 15: Material property assignment of the model.

Mesh Refinement

As a starting point, the mesh used was the same as had been used in the 2D designs for consistency, but this breached the 250,000 node limit – as the 3D design has orders of magnitude more nodes in it than either 2D design did.

The first mesh to produce results was a graduated mesh of 0.004m across the casing, reduced to 0.002m at the interface with the liner, which itself retained a mesh sizing of 0.00075m per node. In the casing the mesh gradually worked outwards from the intersection with the liner, where the element size was 0.00075m to match the interface, and this slowly increased outward to match the 0.004m size of the casing elements. This brought the node count down below the 250,000-limit imposed by the software, and prioritised finer meshing where the need for more detail was essential. However, the simulation routinely crashed after just 34 intervals due to excessive distortion and yielded no meaningful results. Figure 16 shows this mesh visually.

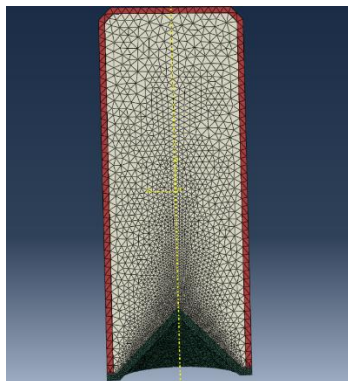


Figure 16: Graduated mesh used to get first simulations

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Figure 17 shows the point at which the simulation with the mesh shown in Figure 16 crashed, due to an error warning of excessive distortion of a single element around the area of the liner when impacted by the detonation wave.

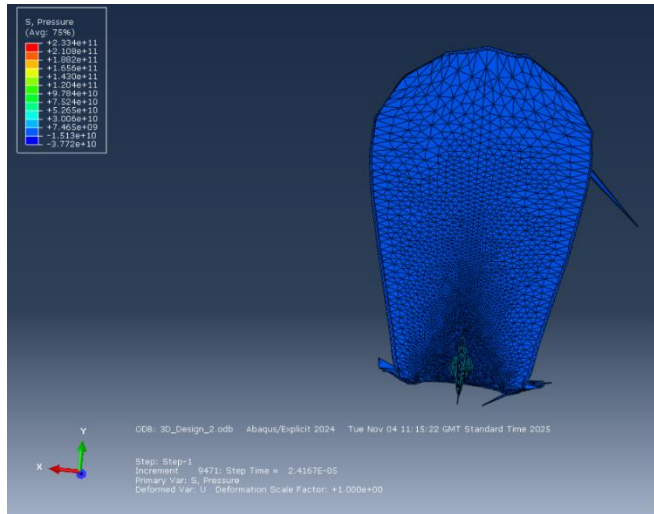


Figure 17: Crashing point of simulation with Figure 16 mesh.

In response to this, in an attempt to fault-fix, a new mesh was created (Figure 18), further refining the liner mesh and the mesh around the interface between fill and liner to 0.0004m, but this pushed the node count back over 250,000. To get around this, the mesh for the rest of the fill, and for the case, was significantly coarsened to 0.006m. A partition was inserted into centre line to bring the position at which the fill mesh coarsened closer to the interface. Running a simulation based on this still caused a crash, due to excessive distortion of a single element at the interface at the same point as in Figure 17.

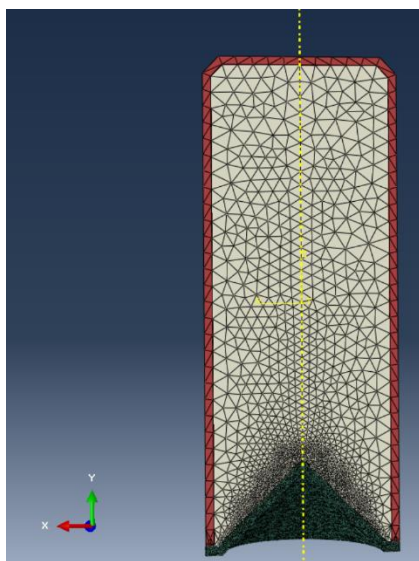


Figure 18: Second attempt at a working mesh.

Investigating the mesh determined that its graduation seemed perfectly adequate to produce working results, and that further refinement risked making the calculations around the liner take too long, and the mesh around the rest of the fill and casing become too coarse, so other ways to fix the simulation to produce results were considered.

Impact of the Addition of More Realistic Behaviours

To try and improve behaviour, Mie-Gruneisen equation of state (EPS) values for the copper liner were added to attempt to model the fluid-like behaviour of the liner more accurately when impacted upon by the shock wave.

The Mie-Gruneisen EOS is a thermodynamic equation that relates temperature, pressure and volume in solid materials under high stress and strain rates, particularly useful when looking at material behaviour under shock [12]. It was hoped that adding these values for the copper liner would better mirror the behaviour expected from the copper under the extreme pressure of a detonation wave, and better compute the distortion without crashing the program.

The material properties of copper for completing the Mie-Gruneisen EOS for it are listed in Table 4.

Material	Shear Modulus	C_0	s	λ_0
Copper	45GPa [13]	3933 m/s [14]	1.5 [14]	2.12 [14]

Table 4: Mie-Gruneisen EoS values for copper

Running the simulation again, on the mesh from Figure 18, using the Mie-Gruneisen EOS, produced a working simulation.

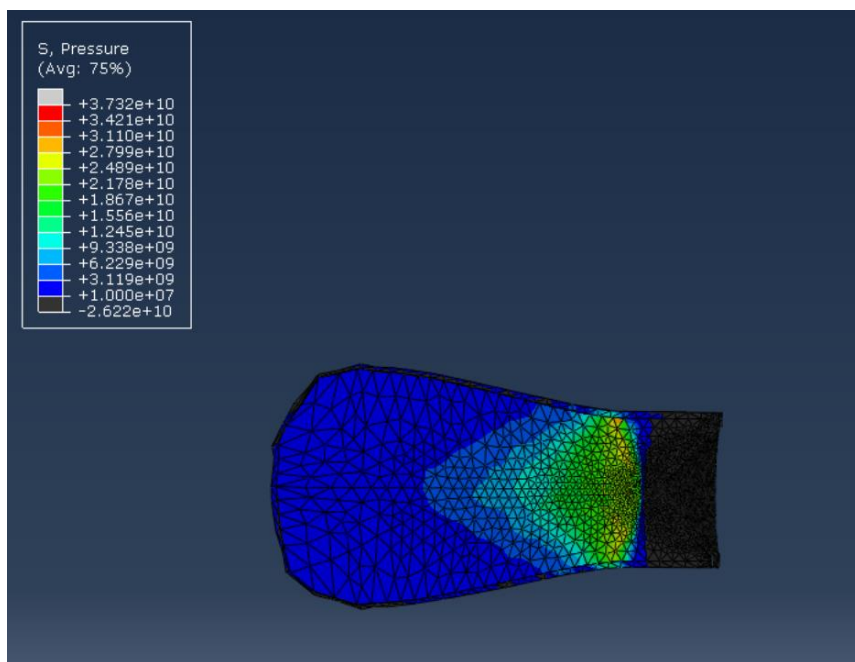
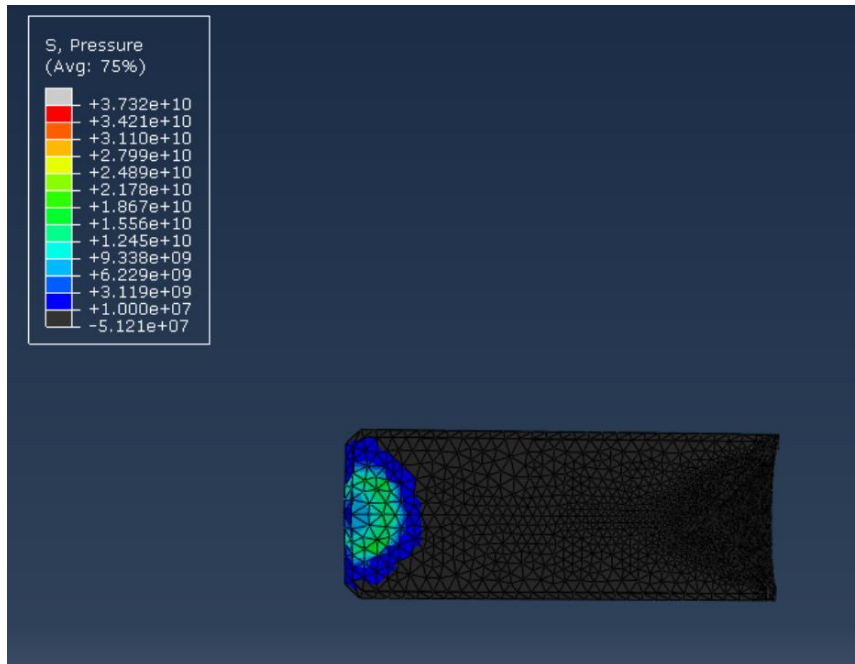
Discussion of Results

Velocity and Pressure Analysis

Figures 19 displays the evolution of the formation of the jet in the 3D model design, from the early shockwave beginning to move through the fill, through to the impact on the copper liner, and then through the jet formation. They also show the pressures acting at different times as the shockwave reaches the liner and forms the jet.

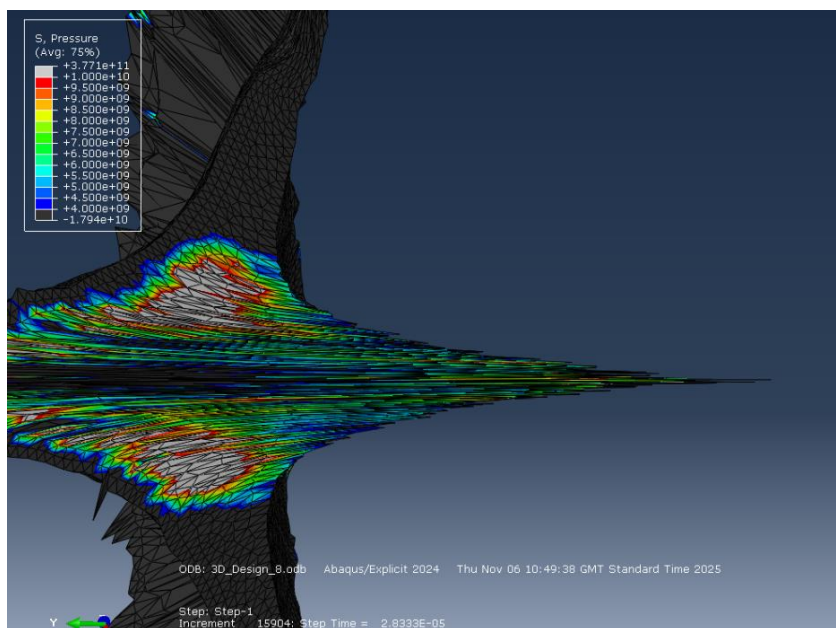
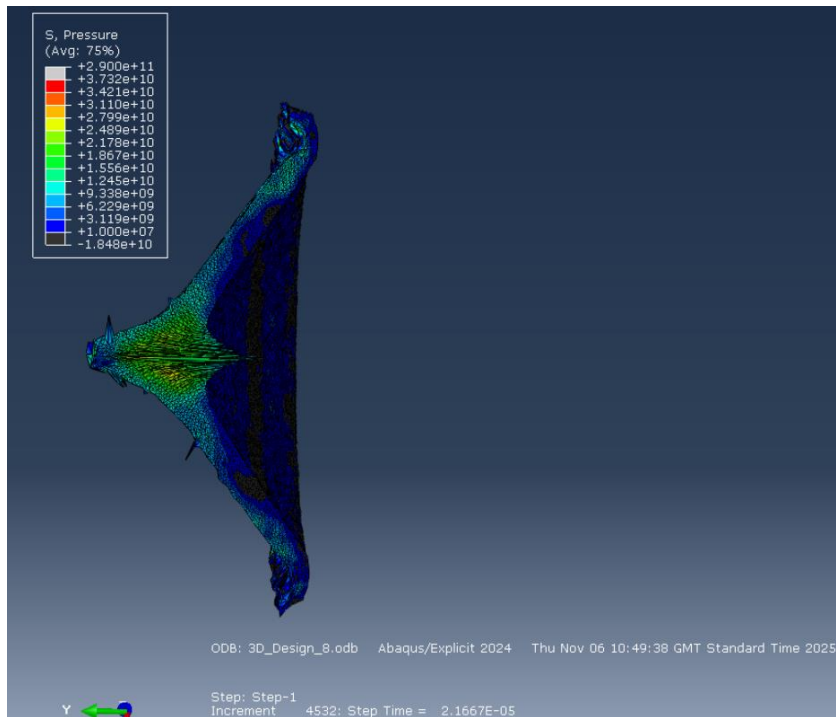
As the detonation wave moves through the charge there is a visible spike in pressure moving through the medium of more than 10GPa through, and at its peak approaching 30GPa. During early jet formation, the pressures acting throughout the liner material are between 4 and 10GPa and, at the point where the jet is near fully formed, pressures along the centre of the jet far exceed 10GPa, falling away on the sides as the tip of the jet continues to extend at high speeds.

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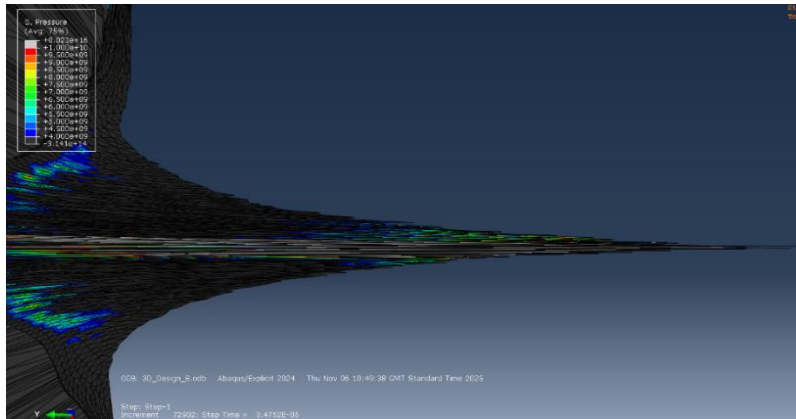


Figure 19 (A-E): Evolution of jet formation in 3D design including pressure values.

Figure 20 shows a combined velocity-time and pressure-time plot, with a probe at a time $30\mu\text{s}$ after detonation.

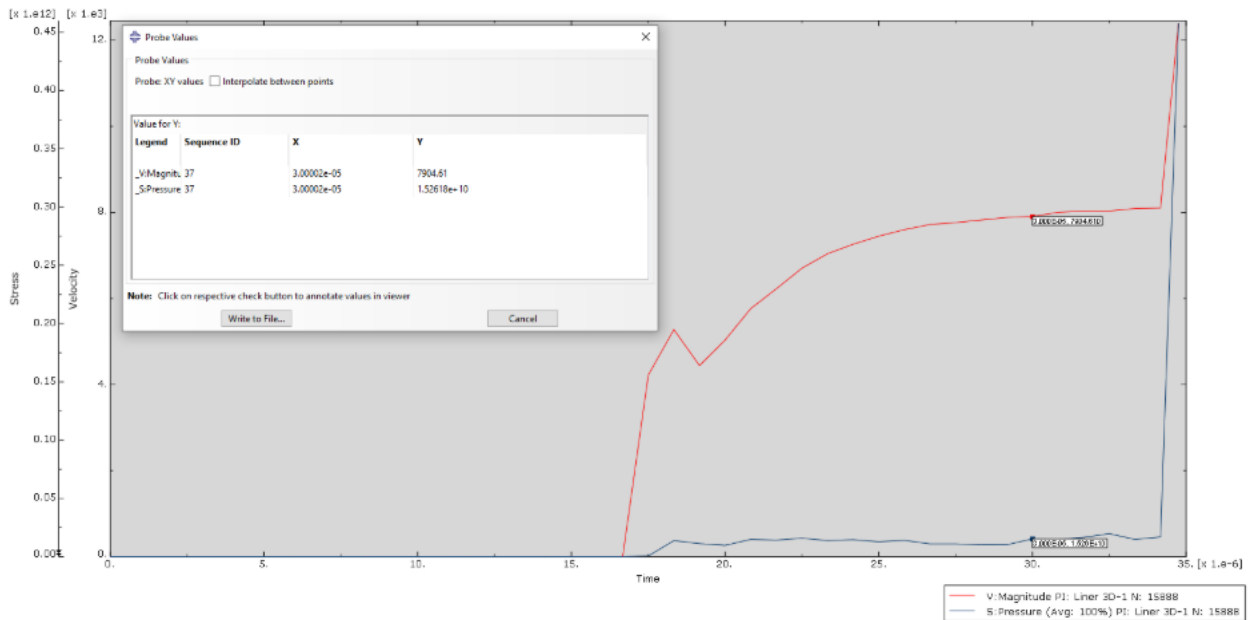


Figure 20: Velocity-time and pressure-time plots of the 3D simulation at the tip of the jet.

As can be seen from the probe of the plot, the velocity of the tip of the jet at $30\mu\text{s}$ is 7.9km/s and the pressure is over 15GPa . Comparatively, the velocities obtained from the 2D run with cone liner, and from the 3D run, suggests a good degree of precision and consistency. The 2D cone run displayed a velocity of 7.874km/s at 30microseconds at the tip of the jet, compared with a value of 7.904km/s at 30microseconds in the 3D run. This can be taken as a validation of the model's consistency and give weight to the other measurements taken in the 3D simulation.

Figure 21 shows another velocity and pressure-time plot of the central region of the jet, again probed at $30\mu\text{s}$ for results. In this region, the velocity sits between 5.2 and 5.35km/s, and the pressure varies between 3.3 and 7.6GPa.

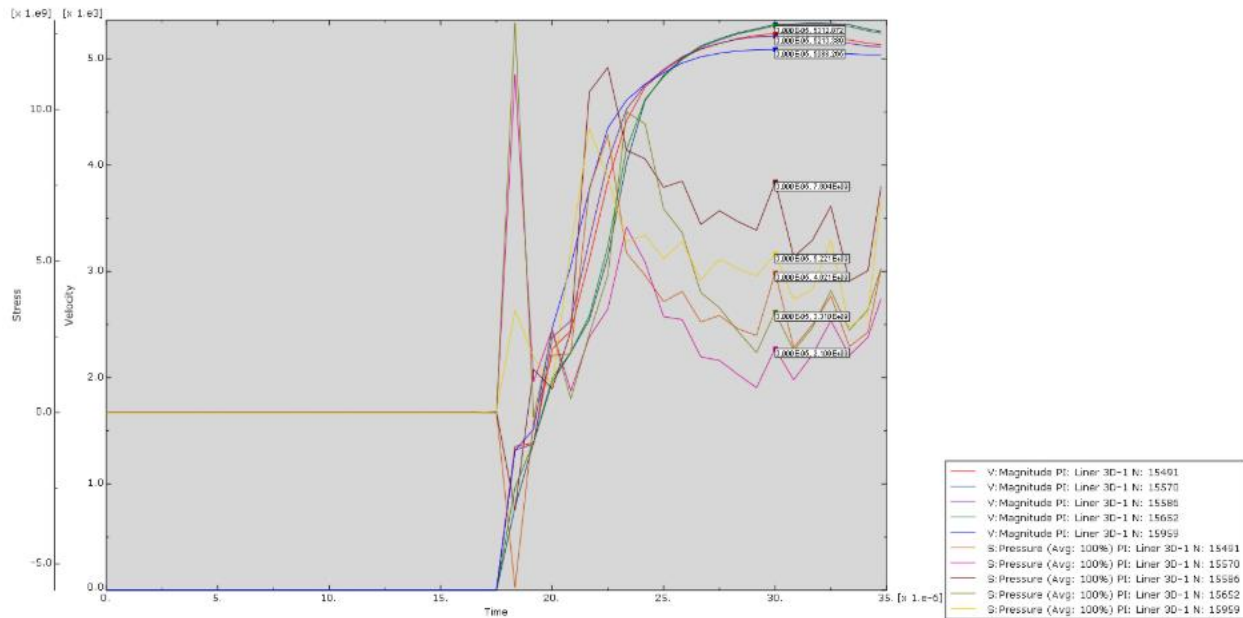


Figure 21: Velocity-time and pressure-time plots for central region of jet.

Stress Analysis

The primary factor behind the formation of a shaped-charge jet is stress, both the compressive stress of a detonation wave, which turns the liner inside out to form the jet, and the massive shear stresses that allow liner material to slide past one another to extend the jet outwards and create the long rod that will penetrate the target.

During the simulation, maximum principal direct stresses and Von-Mises stresses were observed to understand the forces driving formation.

At the first stage of formation, there is a major compressive wave through the top of the liner, with max principal direct stress of between -5 and -30GPa. The volume averaged shear stress at this stage is between 300 and 400MPa. As per table 2, the copper liner in this simulation has a yield strength of 90MPa, so the stresses at play are more than enough to cause significant and permanent plastic deformation in the copper. At the mid-point of formation, there is a significant area of compressive stress continuing to push through the jet, between -5 and -10GPa. There is also a continuing high shear stress working across the whole jet, as the internal shear stresses drive the tip of the jet away from the sides of the jet further. An average shear stress of 600-700MPa far exceeds the yield strength of copper, so the jet will continue to form past this point as rapid deformation continues. At the final frame

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of the simulation, there are still significant compressive stresses at play at the tip of the jet, but the power of the detonation wave is beginning to rapidly fall away, as shown by the broad range of values of maximum principal stress at the tip. The most substantial pressure being around -6GPa , and the rest falling well below this value. As the detonation wave reverberates through the material, an area of tensile stress has appeared in the centre of the liner material, ranging from around 100MPa up to more than 1GPa . Shear stresses continue to increase, showing that even at this stage the internal shear stress inside the jet are continuing to grow to between 700MPa - 1GPa , demonstrating that jet formation would have continued well after the crash point of this simulation, as the average parallel stresses across the tip of the jet far exceed the 90MPa yield strength of the liner.

Figures 22 and 23 demonstrate this evolution visually.

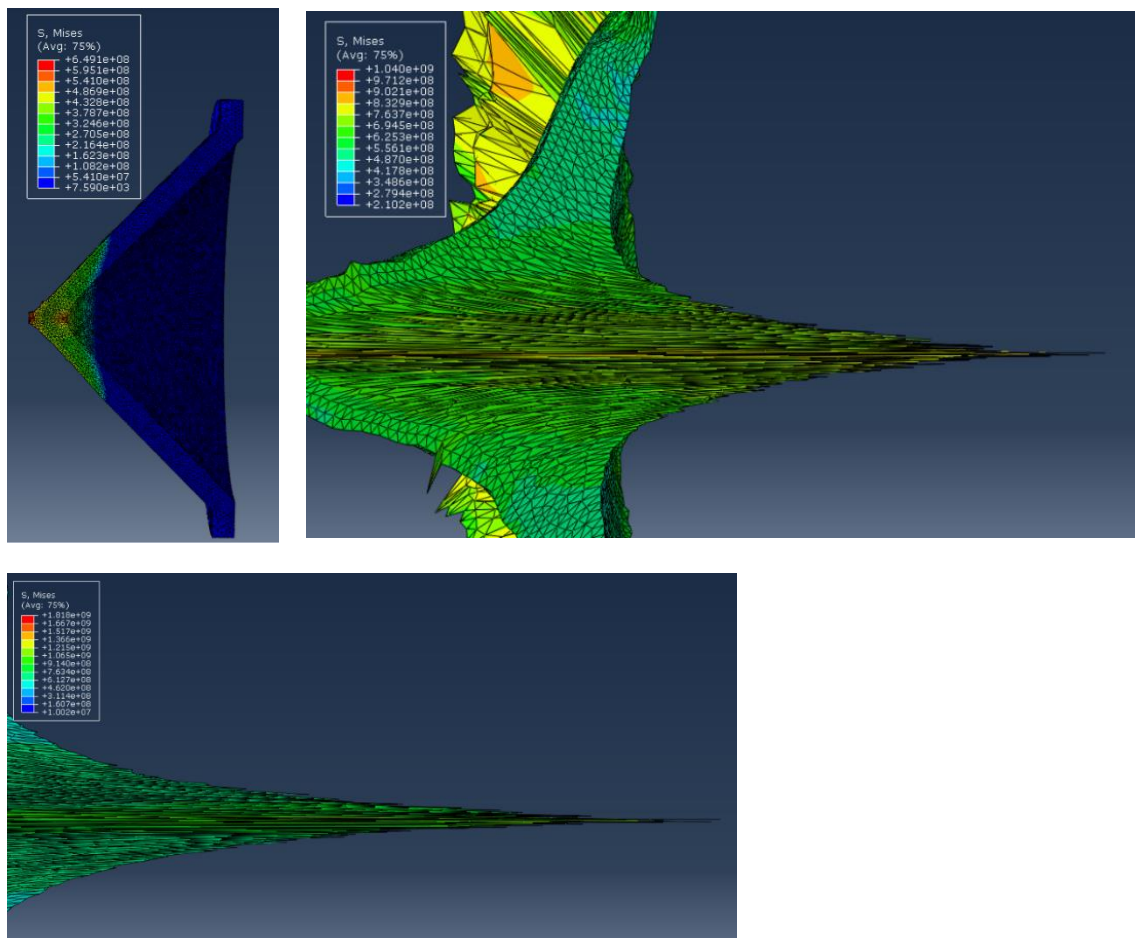


Figure 22 (A-C): Shear stress (Von-Mises) evolution of the charge formation.

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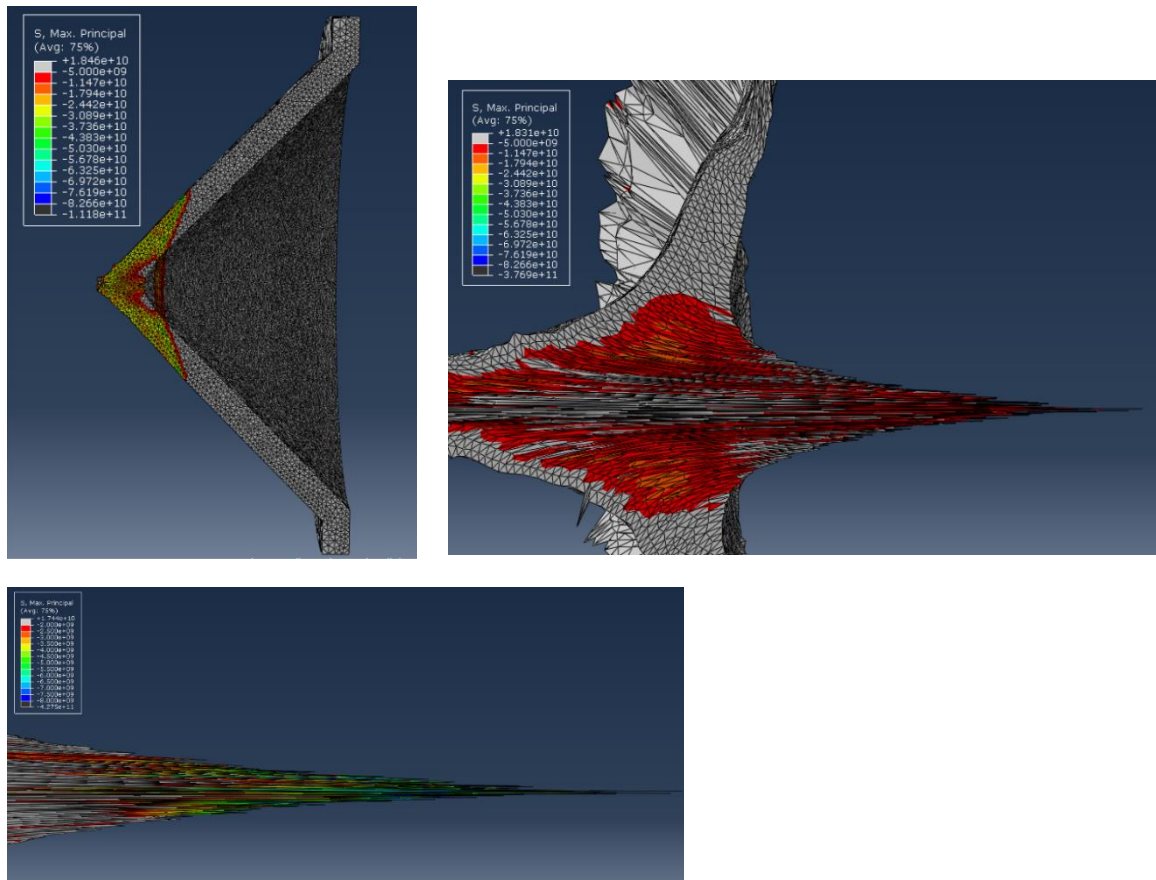


Figure 23 (A-C): Maximum principal stress evolution during charge formation.

This simulation crashed at around $35\mu\text{s}$, which is a shorter time period than both 2D simulations made it. For the benefit of consistency, it would have been ideal to have the simulation run beyond $60\mu\text{s}$ as the 2D designs did to obtain better results. To do so, distortion control was needed, which required use of more advanced features of the Abaqus software package.

Introduction of Smoothed Particle Hydrodynamics

One such method for controlling excessive distortion during high strain-rate impacts is smoothed particle hydrodynamics (SPH)

SPH is an alternative to traditional meshing methods whereby distortable elements are replaced with particles that do not distort in the same way, allowing for higher strain rates and fluid flow to be computed without overwhelming the solver [15].

To set up the simulation to use SPH, the step creation is split in to two parts, with the second part of the step set to invoke smoothed particles in the liner before the point of crashing. From previous run-throughs, it was shown that the 3D model crashes at $35\mu\text{s}$. To give

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enough leeway and avoid crashing, the simulation was set to turn to particles 10 μ s beforehand, at a time 25 μ s after detonation.

All other aspects of the model, including mesh, were left the same. This simulation completed the full 100 μ s time-step, the first simulation, including 2D designs, to manage to do so – showing clearly the benefits of SPH, but the solver took a massive amount of time to complete, taking over 24 hours of constant running to solve the simulation.

Figure 24 shows the results of the simulation at 60 μ s, the same point that the 2D designs had their velocities observed.

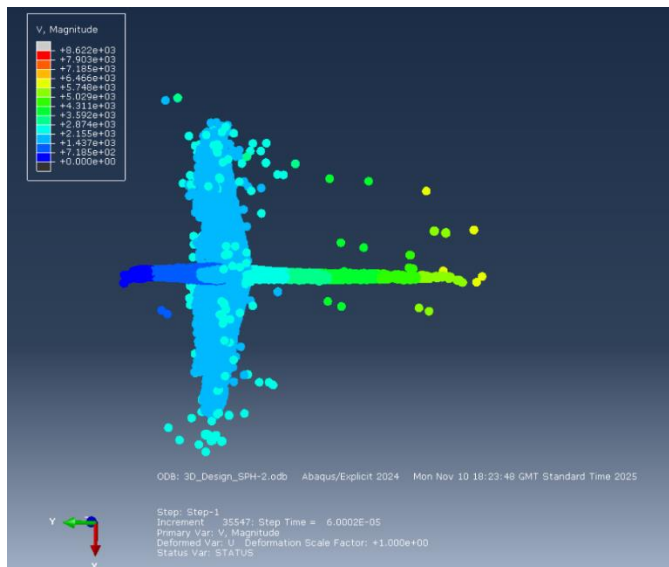


Figure 24: 3D model simulation at 60 microseconds using SPH.

Figure 25 shows the jet at the final frame of 100 μ s, showing the velocities in different places at the time.

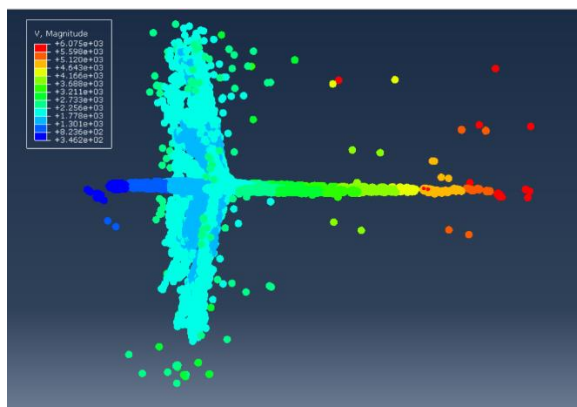


Figure 25: Jet at 100 microseconds with velocities displayed.

Velocity and Pressure Analysis

Figure 26 shows a plot of velocity-time and pressure-time for tip of the SPH jet at different time intervals

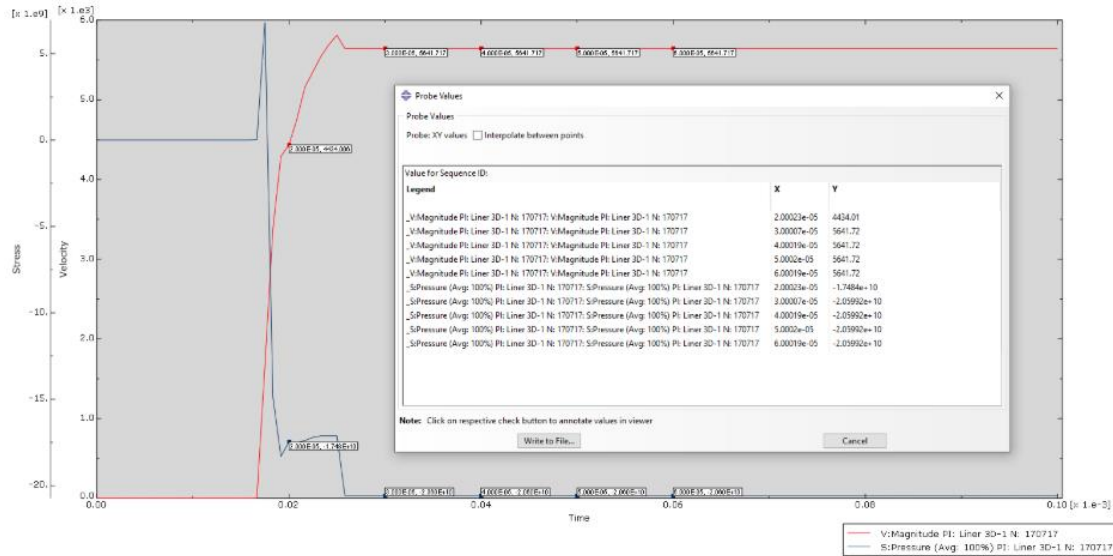


Figure 26: Velocity and pressure-time plots of tip of SPH jet.

The plot shows a rapid increase in velocity coupled with a rapid increase in compressive pressure as the detonation wave reaches the liner. In 3μs, the liner has accelerated from stationary to a velocity of 4434m/s, whilst the pressure accelerated to -17GPa in the same time. The velocity and pressure peak around 30μs, at 5461m/s and -20GPa, and remain constant thereafter, owing to the fact there are no forces such as friction or air resistance to slow the charge down as would exist in real life.

At a time of 60μs, the velocity and pressure were also measured in the central region of the jet, as displayed in Figure 27.

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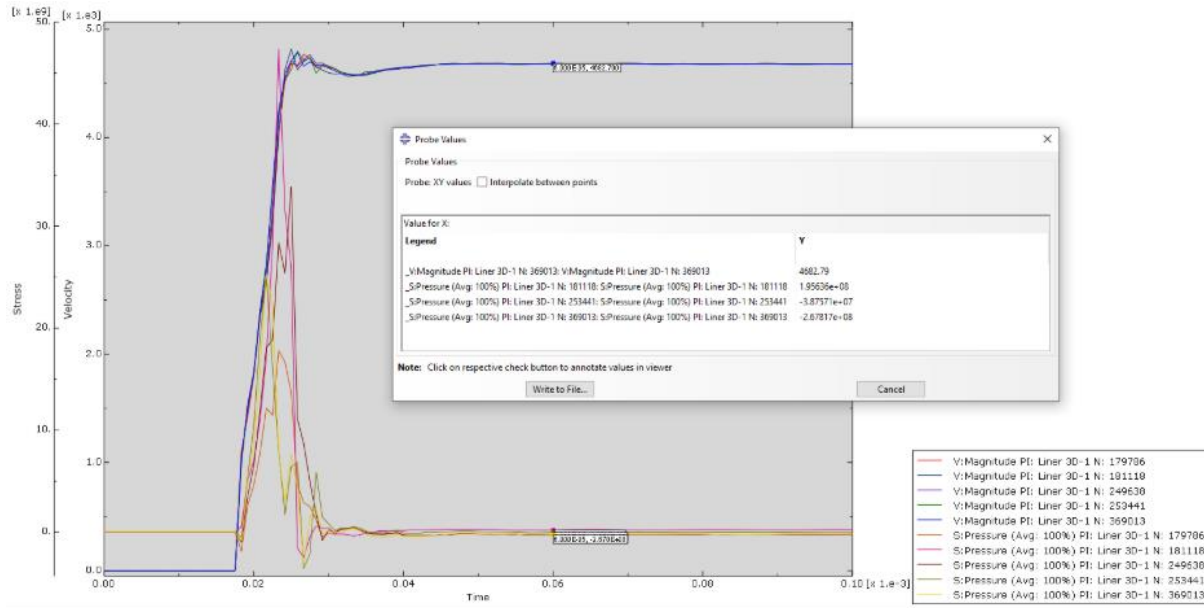


Figure 27: Velocity and pressure-time plots of central region of the jet

A probe of the plot in Figure 27 determined that the velocity of the centre portion of the jet is 4682m/s at 60 μ s, whilst the pressure varies wildly, between 200MPa and -260MPa.

The velocity of the charge post-detonation in the SPH model is noticeably slower than that of the regular 2D and 3D models, both of which had the jet travelling at nearly 8km/s at 60 μ s after detonation. This is likely due to the differences in the way the solver deals with particles relative to deformable tetrahedral elements.

Stress Analysis

As with the regular 3D model, the direct and shear stresses acting over the course of the simulation were analysed.

An average shear stress of 600-700MPa across the top of the liner when first impacted by the detonation wave (17 μ s), far exceeding the 90 MPa yield strength of the copper liner, causing large shear deformations to begin the formation of a jet in combination with the large compressive stress in areas above -10GPa acting from the blast wave. At a time 25 μ s, just before conversion to SPH takes place, there is a large average shear stress driving plastic shearing of the liner. The stress is more than 700MPa through the middle of the jet and at the tip, and lower around the edges. High compressive stresses continue to act on the liner, between 4 and 20GPa across the liner, higher at the back where the deep blue section is, and lowest around the red edges. The pressure straight through the centre is around 7GPa, with some variance.

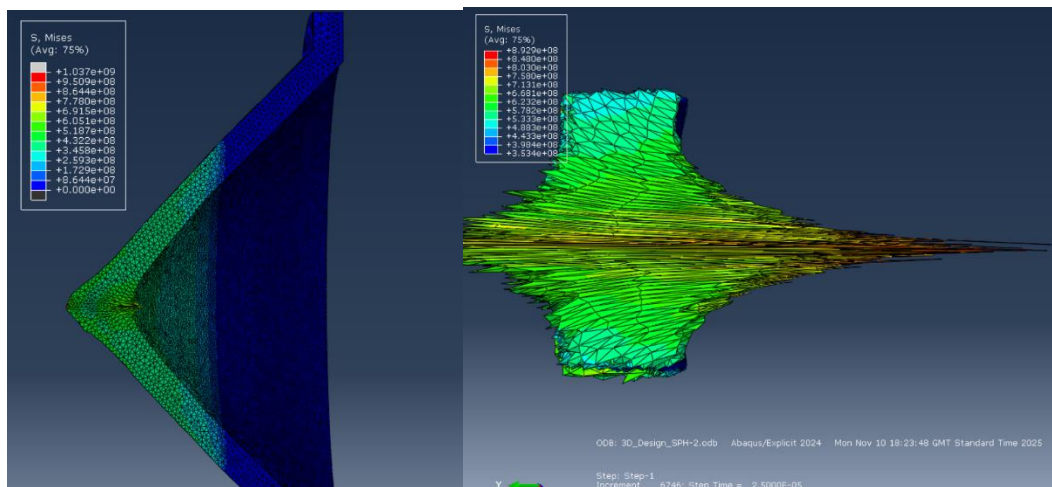
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At 40 μ s, there is still a large shearing stress average throughout the jet driving shearing plastic behaviours. Values of shear stress are highest through the central portion of the jet, between 640 and 940MPa, and fall away either side to around 500MPa on the edges. Stresses at this point in the normal direction have largely become positive, and vary wildly, as the remnants of the detonation wave reverberate through the jet. They have also fallen off considerably to between 80 and 490MPa, and acceleration of the jet has stopped.

At 60 μ s, maximum principal stress has fallen further, a fall from around 500MPa to 200-300MPa, with more regions appearing below this. Average shear stresses are decreasing but remain high, more than enough to ensure that jet formation through copper shearing continues – between 400 and 600 MPa for the most part throughout the jet, with small regions of variance.

By the end of the simulation, at 0.1ms, normal stresses are down to 0-300MPa, and acceleration has stopped completely. If air resistance had been factored in it would now be slowing down. Shear stresses remain largely unchanged but have decreased to around 400MPa. This means that the jet can continue to grow as shear stresses remain above the 90MPa yield of copper, but the process will likely not continue much further.

Figures 28 and 29 show this analysis visually.



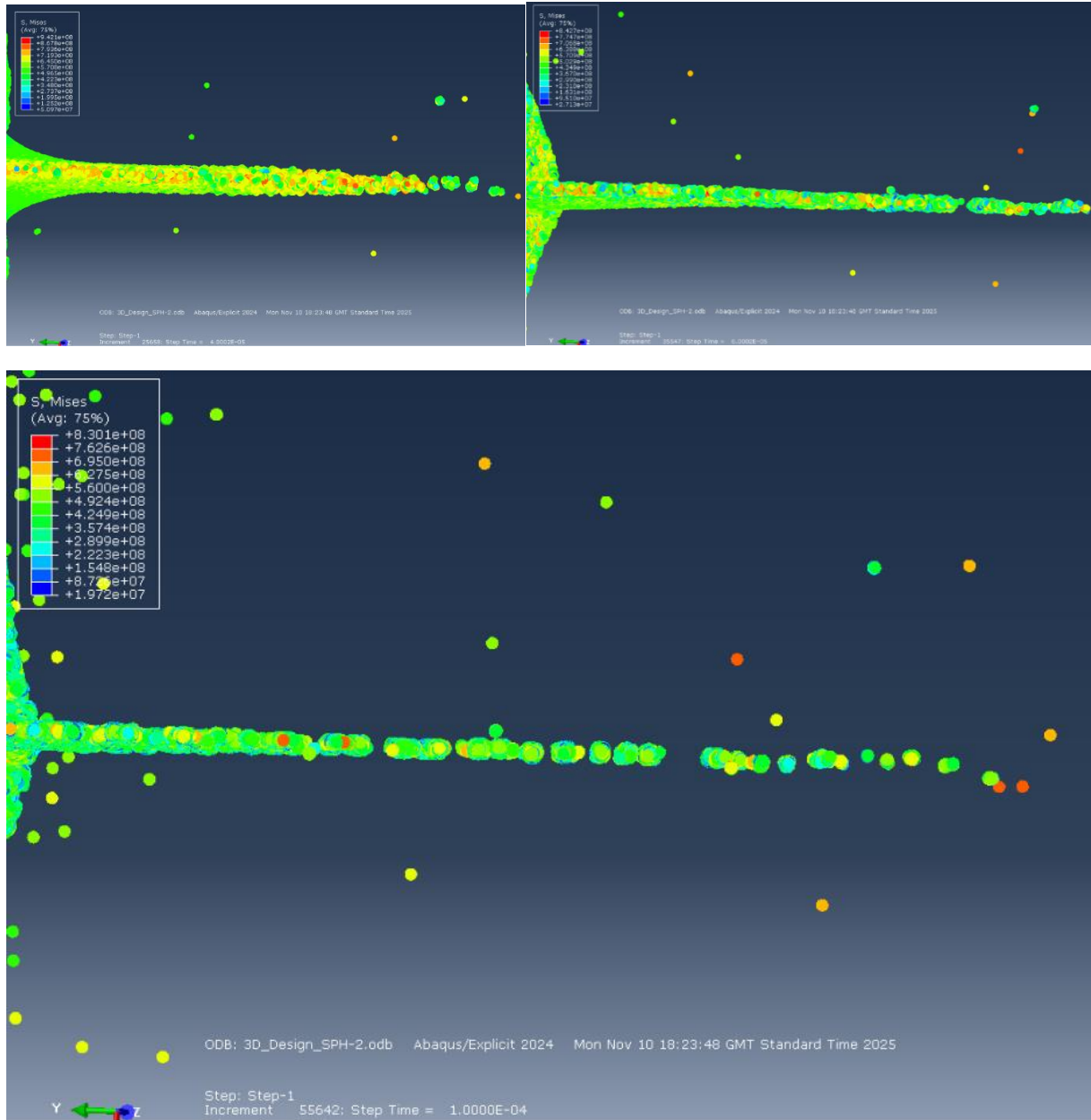
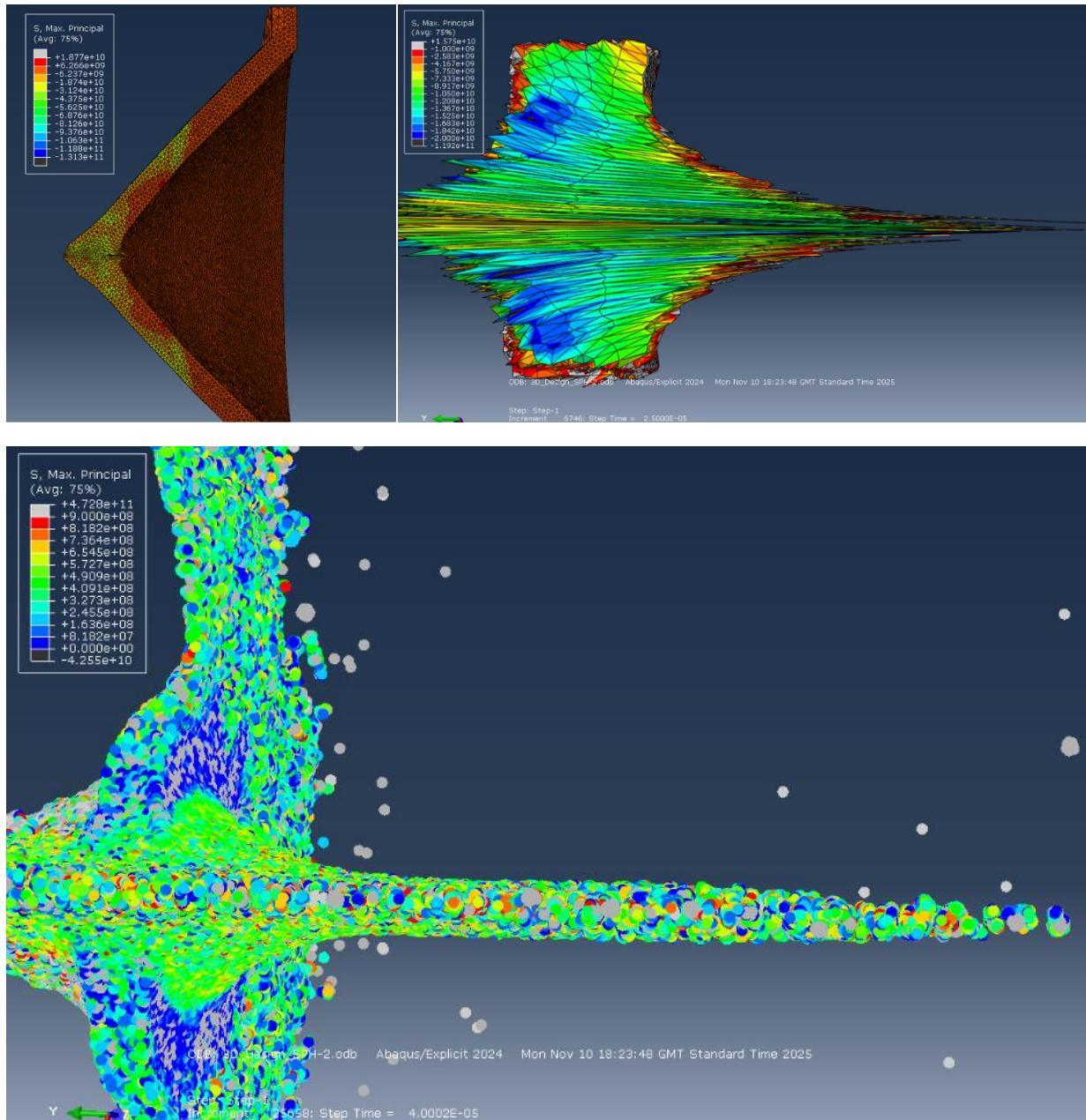
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Figure 28 (A-E): Evolution of Von-Mises shear stresses across the jet formation.

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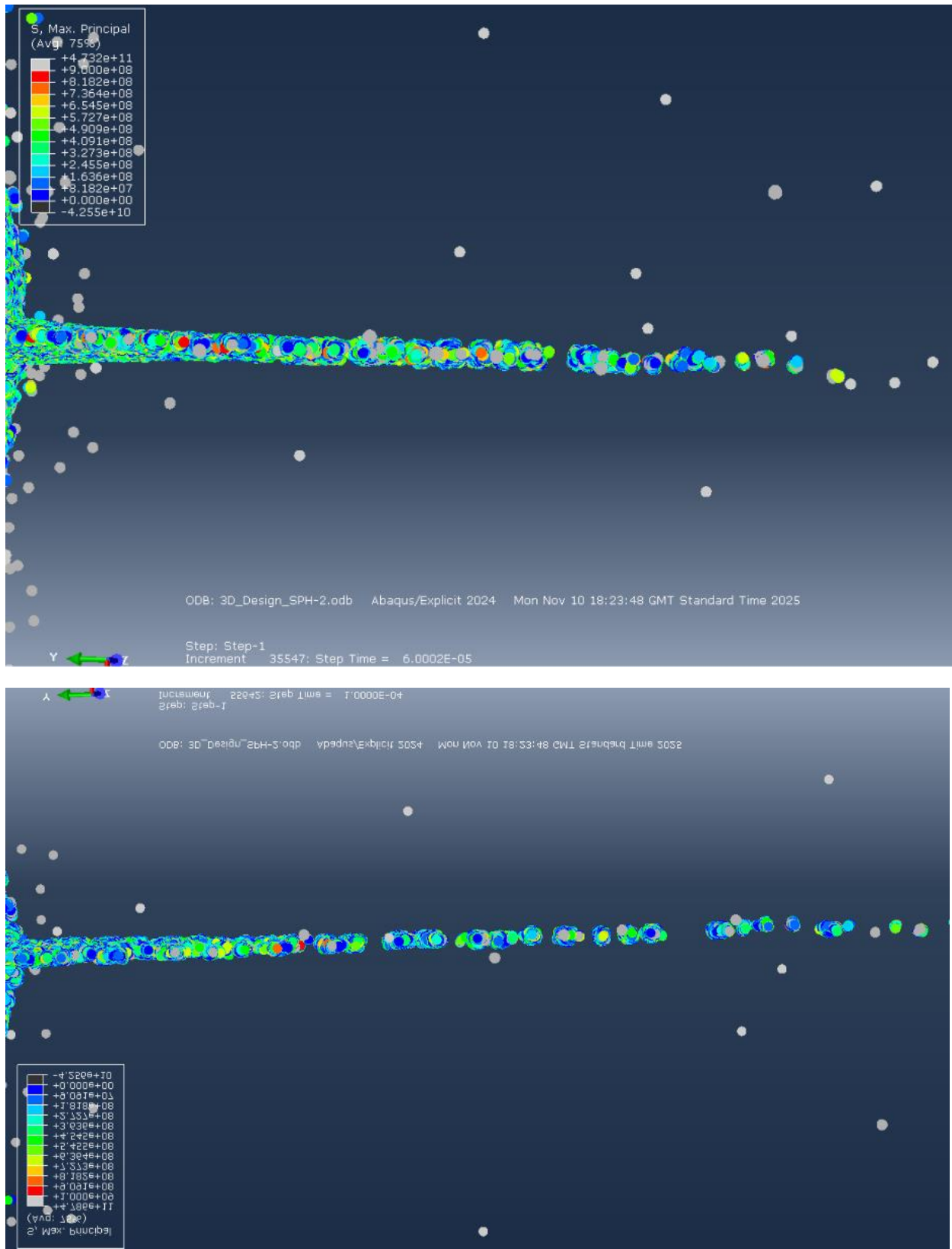


Figure 29 (A-E): Evolution of direct stresses during jet formation.

Conclusion

In conclusion, FEA software such as Abaqus are a useful tool for critical analysis of high strain-rate physics simulations such as the design and evaluation of shaped charges. The software has a selection of tools that make it viable as a means of running several test and evaluation cycles on different designs of shaped charges and analysing them to determine their viability. This has the ability to save money during the design and testing process of product design in these instances, where real-life manufacture and trials can be exceedingly expensive.

FEA software has a good understanding of the physics at play in these high-energy simulations, as well as having the ability to produce very detailed material databases which include equations of state such as JWL and Mie-Gruneisen, which are useful to help fine-tune the materials to make them behave more realistically under such high stress and strain conditions.

However, user ability is a key factor to consider when analysing results. Steps such as mesh refinement are hugely important. If the mesh is not good, nor will the results be. Understanding meshing, how meshing works, and how to adapt a mesh to get better and more valid results is vital – and only with an understanding of meshing can results taken from software such as Abaqus be deemed viable.

More advanced features, such as SPH, can overcome common problems with high-strain dynamic solutions where excessive distortion causes crashes to give longer, more meaningful results, but the results produced can be notably different from regular elements due to the different way they are calculated in the solver, so this is something that must be considered.

With more time, the opportunity to investigate adaptive meshing within the abaqus package would have enhance the report, but the tool could not be made to work in the limited time available, with no time left to carry out the required fault-finding.

However, overall, there can be no doubt about the long list of benefits to using modern FEA packages to conduct such high-energy simulations, and the future suggests that this will become a more and more common means of conducting design, test and evaluation where real-life trials comes at significant cost.

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- [15] MIT, “Smoothed particle hydrodynamics,” [Online]. Available: <https://abaqus-docs.mit.edu/2017/English/SIMACAEANLRefMap/simaanl-c-sphanalysis.htm>. [Accessed 19 December 2025].

Reading List

This section contains works read in conjunction with, and which helped shape the report but that were not directly used or cited in the report body.

- *Numerical Study and Theoretical Model of Shaped Charge Jet Penetrating Into Thick-Walled Target With Following Velocity*, International Journal of Aerospace Engineering - Bin Liang, Hengwei Xu, Xing Chen, Jian Zhang
- *Shaped Charge Design – Construction of a Minature Shaped Charge*, Karlstads University – Andreas Gustaffson
- *Modelling and analysis of a 66mm shaped charge*, International Journal of Impact Engineering - Kevin T. Miers, Nicholas R. Peterson, W. Lee Perry, Levi A. Lystrom, Justin C. Sweitzer, Stanley E. DeFisher
- *Modelling of shaped charge jet penetration depth: Analytical and numerical approach*, Scientific Technical Review – Predrag Elek, Dejan Jetvic, Milos Markovic, Radavan Djurovic
- *Numerical Simulation on Jet Formation of Shaped Charge with Different Liner Materials*, Defence Science Journal - Cheng Wang, Jianxu Ding, and Haitao Zhao
- *Investigation of Factors Affecting Shaped Charge Performance*, Ahmed Riad – 9th International Conference On Aerospace Sciences & Aviation Technology