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Design of Shaped Charges

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1. Introduction

A shaped charge, previously known as a hollow charge, is a cylindrical shape filled with explosive, with a detonator and a hollow cavity [1]. It is used for penetrating targets (armour, etc.) in military capacities [2]. The hollow cavity (liner) can be any axisymmetric shape, such as a cone (most popular), hemisphere or pyramid. Intense, localised shock waves and forces are created at the initiation of the explosive and directed towards the liner [2]. This causes high detonation pressures and very high strain rates, resulting in the liner collapsing in the form of a jet. This jet tip can reach speeds of more than 10 km/s, whereas the slower 'slug' will be around 2 km/s, as seen in Figure 2. This velocity gradient along the jet results in the jet stretching, and it consequently breaking due to the severe elongation, this is known as the Munroe or Neumann effect [2].

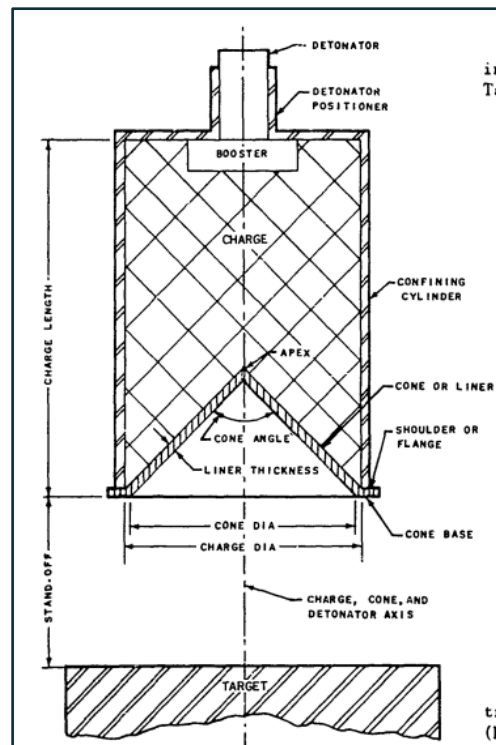


Figure 1 Schematic of a shaped charge [3].

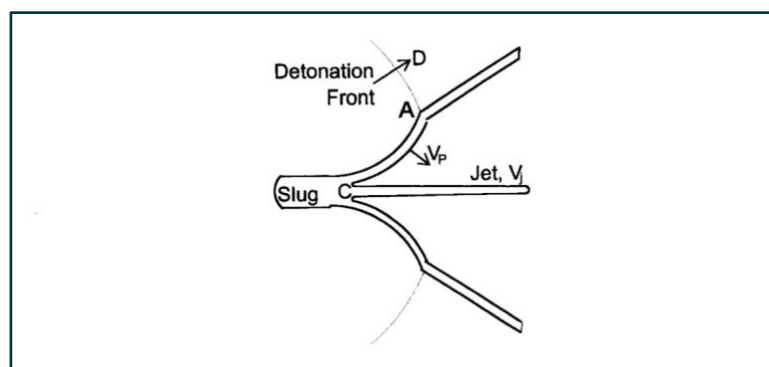


Figure 2 Collapse of a shaped charge liner [4].

The performance of a shaped charge is highly dependent on certain jet tip characteristics, such as velocity and stability, with velocity being the main factor in penetration ability and the elongation of the jet defining its effectiveness over distance [4]. Velocity and elongation can both be influenced by things such as liner material, liner angle, thickness or the detonation behaviour of an explosive [4]. Liner material, for example, plays a critical role as it defines the high-strain-rate deformation behaviour of the collapse [5].

Numerical modelling has become a common approach for accurate analysis of shaped charges. Finite Element Analysis (FEA), such as an explicit dynamic solver, is able to investigate detailed jet formations, material deformation and shock propagation.

This study investigates the influence of liner material on shaped charge performance by performing comparative numerical analysis of two designs in 2D and 3D. Design 1 comprises of a copper liner and Design 2 comprises of an aluminium liner. Copper is commonly used in shaped charges due to its very good ductility and high density, both of which promote a good jet formation. Aluminium has a lower density and different deformation characteristics to copper, which may result in jet formation and velocity variations. As these two liners will be analysed under identical geometry, boundary and load conditions, the differing of the jet formation can be evaluated accurately.

The modelling is conducted on ABAQUS using a Lagrangian finite element framework with an explicit dynamic solver. The Jones-Wilkins-Lee (JWL) equation of state is used to model the detonation products of the explosive, and the Mie-Grüneisen equation of state (EOS) and the Johnson-Cook (JC) plasticity model are used to model the strain rate and deformation of the liner and case. Outputs analysed include velocity, pressure and strain distributions and time data such as jet velocity progression and strain evolution.

2. Literature Review

2.1.Fundamentals of Shaped Charges

Shaped charges utilise the focusing of detonation energy to generate a high-velocity jet capable of penetrating targets. Used extensively in WWII when mining companies and explosives developers created lined cavity shaped charges for use by the military [6]. It generally works by a detonation of an explosive around a hollow cavity, which is most commonly lined with copper, aluminium or steel, and this collapses due to extreme pressure and forms a jet [4], [7]. The liner collapses due to undergoing extreme plastic deformation, and it therefore inverts, producing a very high velocity jet and a slower moving slug [6]. The jet is formed from the inner 'point' of the liner and the outer point, which has more mass but lower velocities, creates the slug [6]. Effective penetration of the target is in the jet's ability to stay continuous and not break up [6]. The jet tip will be travelling considerably faster than the trailing material, and this gradient leads to jet elongation over time and results in separation from the slower material behind it.

The performance of shaped charges are therefore dependent on geometric, explosive, and material parameters that influence the jet formation, behaviour and penetration effectiveness [8]. The angle of the cone liner (apex) is a crucial geometric parameter due to the fact it controls the direction of the liner flow of the jet formation and the velocity [9]. Zhang et al [9] showed that decreasing the liner angle increases the jet tip velocity as it is able to direct more liner material to the apex centre. There is, however, a trade-off of velocity and penetration effectiveness when you get to very small cone angles, as it reduces the mass of the jet [7]. The quality and formation of the jet are also strongly dependent on the axisymmetric geometry of the liner, as that controls the uniformity of the collapse, along with the uniformity of the pressure wave generated by the explosive [8]. Irregularities with the liner shape or asymmetry can lead to jet deflection or dispersion and therefore reduce the penetration capabilities of the jet, and this is why axisymmetric configuration is often studied to ensure consistent jet formation [8], [10].

Liner thickness is also a key parameter affecting jet formation and liner collapsing [9]. Both studies on the liner thickness [9], [11] determined that thinner liners mean a considerable increase in jet length and velocities. Therefore, an assumption can be made that the penetration depth also increases with decreasing liner thickness [11].

Liner material also greatly affects the jet formation and its penetration ability, as it is governed by high strain rate deformation, and therefore the liner material must have high density, good ductility and high sound speeds [12]. Materials must have enough ductility to undergo large plastic strains without fracturing, or else early failure can disrupt the jet [12]. This is why copper is most often used as liners in shaped charges, as it exhibits good density, excellent ductility and its properties provide good processing capabilities [12]. Density is an important factor in jet penetration because the square root of the liner's density is directionally proportional to its penetration [13].

$$P = L \times \sqrt{\frac{\lambda \times \rho_{liner}}{\rho_{target}}} \quad [14]$$

$$\therefore$$

$$P \propto \sqrt{\rho_{liner}} \quad [15]$$

Where P is penetration, L is jet length, λ is a constant between 1 and 2 and ρ is density.

There have been many studies on the best material to be used in shaped charge liners, and these have include materials such as molybdenum, tantalum, tungsten and uranium, where copper, molybdenum and tungsten showed the best properties for shaped charge liners [16]. Another study showed that silver, zirconium, depleted uranium and titanium produced a very good jet with a longer breakup time than copper and concluded they displayed a better penetration at longer stand-off distances [17]. Depleted Uranium's use in liners has since been abandoned however, due to its radiation and toxicity hazards.

The properties of the explosive are also vital in obtaining the detonation velocity and pressures needed for effective liner collapse. It was shown in [9] that explosion detonation velocity and jet tip velocity increase proportionally to each other. However, if the detonation velocity increases too high, then the jet tip velocity decreases [9].

2.2. Material Models used in Shape Charge Modelling

Accurate numerical modelling of shaped charges requires suitable models that can represent material behaviour under extreme pressures and high-strain-rate conditions [5].

The JC model is widely used for modelling penetration and impact problems [18]. The JC model is used in this study to model the flow stress behaviour of a ductile material, in this case, the copper liner. The JC model can accurately predict the behaviour of materials, such as strain rates, deformation and flow behaviours [19]. The JC model signifies the stress and strain interactions of the material, and the flow stress equation is shown below:

$$\sigma = (A + B^n)(1 + C \ln \dot{\epsilon}^*)(1 - T^{*m}) \quad [19]$$

Where σ is equivalent stress, ϵ is equivalent plastic strain, and the JC constants are: A – yield stress, B – strain hardening, C – strengthening factor of strain rate and m – thermal softening coefficient.

The JC damage model is also used to predict ductile material failure behaviour. The model states that the stress triaxiality ratio, strain rate and temperature are all relied upon by the fracture strain. The JC damage model is shown below:

$$\left[D^1 + D^2 \exp(D^3 \left(\frac{\sigma_m}{\sigma_{eq}} \right)) \right] [1 + D^4 \ln(\dot{\epsilon}_p^*)] [1 + D^5 T^*] \quad [20]$$

Where D^1 to D^5 are the damage constants, σ_{eq} is equivalent stress, and σ_m is mean stress.

Shaped charge liners often experience very high strain rates during collapse, and therefore, the J-C model is well-suited to this application [21]. It enables very good predictions of large plastic deformations, which is vital in modelling liner flow and jet formations.

The Mie–Grüneisen EOS is used to represent the volumetric response of metals (in this case, the liner) under shock loading [5]. It allows accurate modelling of compressibility and shock wave propagation within the liner during the detonation loading [22]. This is shown in the equation:

$$u_s = C_0 + Su_p \quad [20]$$

This shows the relation of linear shock velocity with material particle velocity. Where C_0 is the intercept of the $U_s - U_p$ curve (elastic bulk wave velocity) and S is the coefficient slope of the $U_s - U_p$ curve. From this, the Mie–Grüneisen EOS model expresses compressed materials pressure as:

$$p = \frac{\rho_0 C_0^2 \mu \left[1 + \left(1 - \frac{\gamma_0}{2} \right) \mu - \left(\frac{\alpha}{2} \right) \mu^2 \right]}{[1 - (S-1)\mu]^2 + \gamma_0 E_{int}} \quad [20]$$

Using both the J-C model and the Mie–Grüneisen EOS together when modelling allows plastic deformation and pressure-dependent volumetric responses in materials under extreme loads to be represented properly for shaped charges [5].

The detonation behaviours of High Explosive (HE) are commonly defined by using the JWL EOS [23]. It is related to the Mie–Grüneisen equation as it has the Grüneisen coefficient and a constant specific heat [24]. The JWL EOS is often used for HE and, therefore, shaped charges, as it can capture the pressure loading and volume from the rapid expansion of the detonation gases [25]. The JWL equation below shows the pressure produced by the detonation process:

$$P = A \left(1 - \frac{\omega}{R_1 V} \right) e^{-R_1 V} + B \left(1 - \frac{\omega}{R_2 V} \right) e^{-R_2 V} + \frac{\omega E^0}{V} \quad [9]$$

These material models are commonly used within explicit dynamic finite element analysis to simulate high-pressure detonations and high-strain-rate conditions [9], [21]. JWL can model the pressure generated by the detonation and ultimately cause the liner collapse, while Mie–Grüneisen EOS and JC work cohesively to model material flow behaviour and deformation.

2.3. Numerical Modelling Approaches

Numerical modelling is extensively used in the analysis of shape charge systems [9], [11], [26]. Explicit dynamic finite element methods are commonly used due to the nonlinear behaviour of shaped charges and are excellent at solving problems involving high strain rates, complex interactions and large deformations.

Numerical modelling techniques used in shape charges are often Eulerian or Lagrangian, where the differences are whether the material flows through a fixed mesh or the mesh is the deformation of the solid [27]. Lagrangian modelling is the most common approach in shape charges, as the mesh deforms with the material and is therefore able to model the plasticity and strain hardening of the liner accurately [26]. There are however, some limitations to this method in that large deformations of the mesh can cause finite elements to become severely distorted, and these are likely to arise in the jet formation [27]. The Eulerian method can manage large deformations as the mesh remains fixed in space while the material flows through it, but has limitations of its own in that managing

these large deformations can come at the cost of the resolution of flow details or precision definition [28].

Mesh discretisation plays a large role in accuracy, stability and convergence of FEA simulations, especially when there is large deformation or high strain rate load [29]. Finer meshes generally improve results but also increase computational cost, whilst coarser meshes may lead to inaccurate predictions [30], [31]. Incorrectly refining the mesh can lead to poor representation of stress and strain gradients and, therefore, could lead to solution inaccuracy [32]. Shaped charge jets have regions experiencing severe deformation, and therefore require finer meshes in these regions [26]. The liner apex, for example, experiences large pressure and strain gradients when collapsing [26]. Gradual meshes are commonly used in FEA to minimise abrupt changes in element size, create reliable results and reduce computational time [33]. Gradual meshes help in minimising excessive element distortion and inaccuracies in stress wave propagation [29].

3. Numerical Methodology

3.1. Geometry and Design

A shaped charge was designed to investigate the influence of liner material on jet formation behaviour. Two 2D axisymmetric models were designed, consisting of a HE fill, liner/cone, and a case. The geometries of both models are identical, just the liner material varied (copper and aluminium). The geometry is shown in Figures 3 and 4 below.

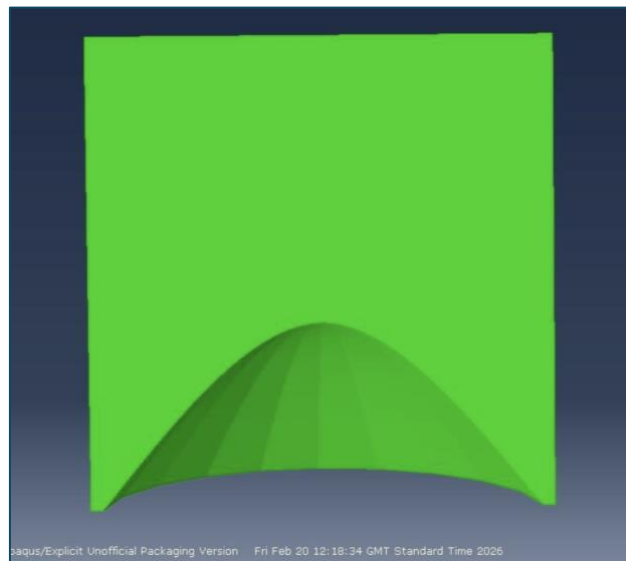


Figure 3 Basic geometry of the shaped charge.

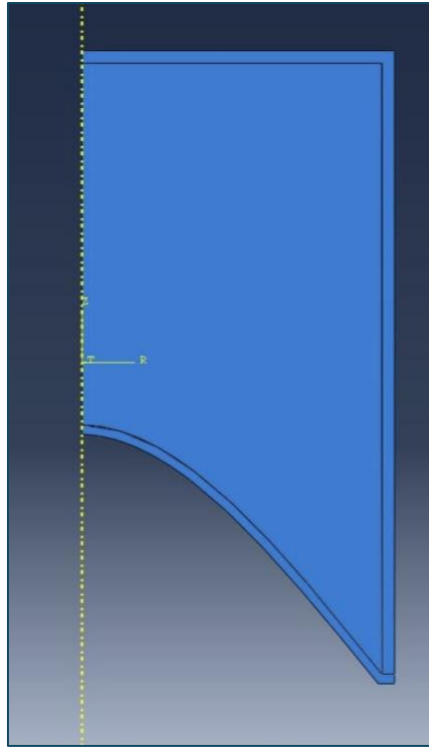


Figure 4 Geometry of shaped charge showing case, HE fill and liner geometry.

A conical liner was used due to its widespread use in shaped charge applications and its known ability to produce a high-velocity jet during collapse [4], [5]. The liner thickness was 0.0015 m, and the dimensions can be seen in Figure 5 where the units are metres.

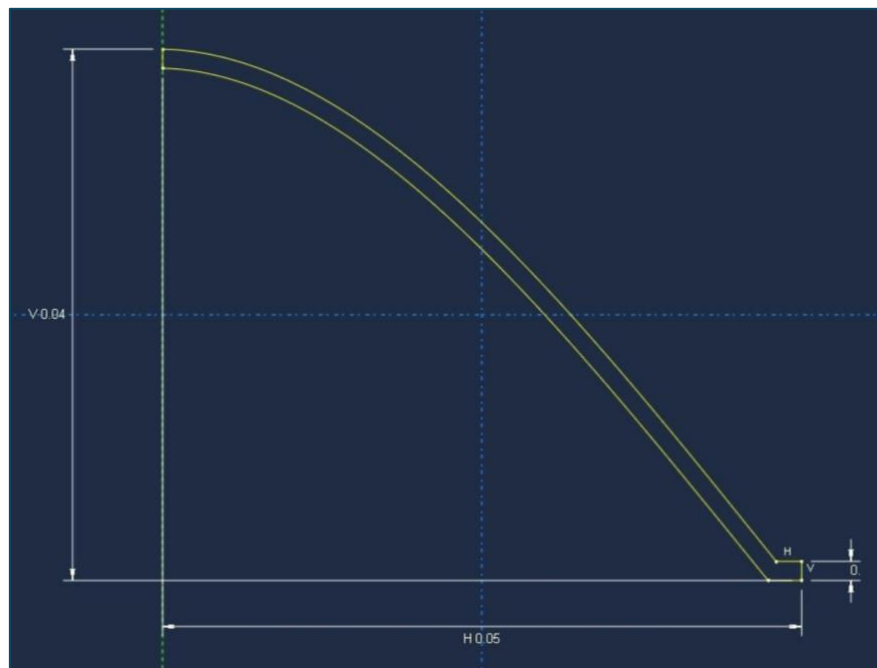


Figure 5 Sketch of the liner with dimensions.

The case was included to provide confinement of the explosive and direct the detonation energy to the liner. The case was 0.02 m thick, and the dimensions can be seen in Figure 6 below.

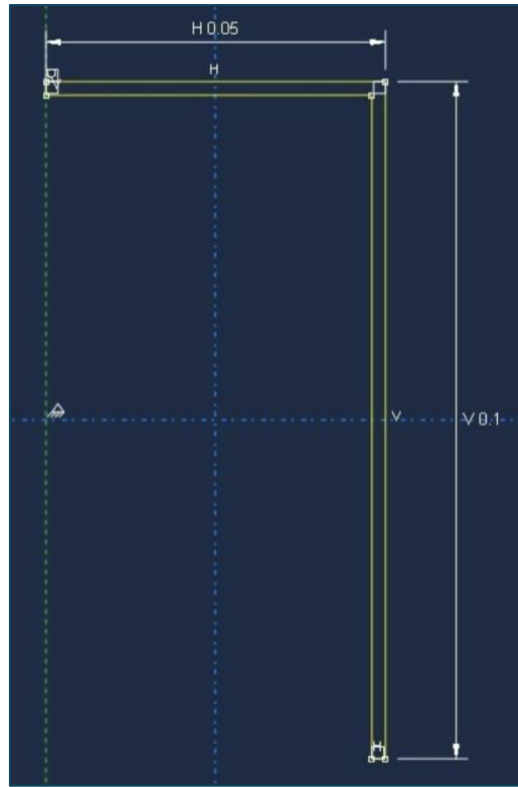


Figure 6 Sketch of the case with dimensions.

3.2. Material Models and Properties

3.2.1. Liner Properties

Both 2D liners were modelled using the JC model combined with the Mie–Grüneisen EOS. The JC model was selected due to it considering strain hardening, strain-rate sensitivity and thermal softening effects under high strain rate loading conditions. This was critical in this study due to the liner experiencing extremely large plastic deformation when it collapses and formed the jet. The Mie–Grüneisen EOS is used to capture the shock wave propagation through the liner, as it is excellent at capturing compressibility behaviours of metallic materials. OFHC copper and Aluminium 5083-H116 were selected for this study due to both being a popular choice in shaped charge liners, but also, they should produce comparable results from their differing densities and deformation behaviour. Copper is commonly used due to its high density and ductility, which promotes a coherent and high-velocity jet. Aluminium should offer a good comparison as it has a lower density and reduced mass. All parameters for the liners in this study are shown in Table 1 below.

Table 1 Parameters for the liner materials.

Parameters		Unit	OFHC Copper		Aluminium 5083-H116	
Density, ρ_0		g/cm ³	8.96	[34]	2.66	[35]
Shear Modulus, G		GPa	46	[34]	26.4	[36]
Mie-Gruneisen	C_0	m/s	3940	[34]	5340	[36]
	S		1.49	[34]	1.4	[36]
	Gruneisen Coefficient, Γ_0		1.99	[34]	1.97	[36]
Johnson-Cook	A	MPa	90	[36]	167	[37]
	B	MPa	292	[34]	596	[37]
	n		0.31	[34]	0.551	[37]
	m		1.09	[34]	0.859	[37]
	C		0.025	[34]	0.001	[37]
	θ_{melt}	K	1356	[34]	883	[35]
	$\theta_{\text{transition}}$	K	293		293	
	ε_0	1/s	1		1	

3.2.2. HE Fill Properties

The behaviour of the HE fill was modelled using the JWL EOS. The JWL was selected due to its widespread use in explosive simulations and its reliability in accurately representing the rapid expansion of detonation gases. Octol was selected as the HE fill in this study, and its parameters can be seen in Table 2 below.

Table 2 Parameters for the HE fill.

Parameter	Unit	Octol	
Density, ρ_0	g/cm ³	1.82	[34]
Detonation Wave Speed	ms ⁻¹	8480	[34]
A	GPa	748.6	[34]
B	GPa	13.38	[34]
R1		4.5	[34]
R2		1.2	[34]
ω		0.38	[34]
Detonation Energy Density	JKg ⁻¹	5769230	
Internal Energy, E_0	GJ/m ³	10.5	[34]

$$\text{Detonation Energy Density} = \frac{\text{Internal Energy}}{\text{Density}}$$

$$\text{Detonation Energy Density} = \frac{10.5}{1820} = 5769230 \text{ JKg}^{-1}$$

3.2.3. Case Properties

The case was modelled with the JC model combined with the JC damage model, which enabled it to show plastic deformation and failure under loading. The case, however, was not the primary focus of this study as and was only present to direct and contain the HE fill. As a result, these simple parameters seen in Table 3 were deemed suitable.

Table 3 Parameters for the case.

Parameters		Unit	Ti-6Al-4V
Density, ρ_0		g/cm ³	44.28 [20]
Young's Modulus, E		GPa	114 [38]
Poisson's Ratio, ν			0.33 [20]
Johnson-Cook	A	MPa	1098 [20]
	B	MPa	1092 [20]
	n		0.93 [20]
	m		1.1 [20]
	C		0.014 [20]
	θ_{melt}	K	1878 [20]
	$\theta_{\text{transition}}$	K	293
	ϵ_0	1/s	1
Johnson-Cook Damage	d_1		-0.09 [20]
	d_2		0.27 [20]
	d_3		0.48 [20]
	d_4		0.014 [20]
	d_5		3.87 [20]
	Reference Strain Rate		1

3.3. Meshing and Element Types

Mesh discretisation was a critical aspect of the numerical modelling process due to the extreme deformation and large strain rates that happen with shaped charge jet formations. The 2 and 3D models both had a gradual mesh applied, with a finer mesh applied to regions that were expected to experience high deformation, such as the liner apex. This can be seen in Figures 7 and 8 for 2D and Figures 9 and 10 for the 3D model.

The initial study was a 2D axisymmetric simulation using triangle elements as they conform well to complex geometries. The 3D model of the copper liner utilised tetrahedral elements, which accommodated for the more complex meshing of 3D geometries. Quadratic elements were originally selected for the 3D model however, this was later changed to linear as quadratic elements resulted in an excessive node count and the simulation aborting due to excessive distortion.

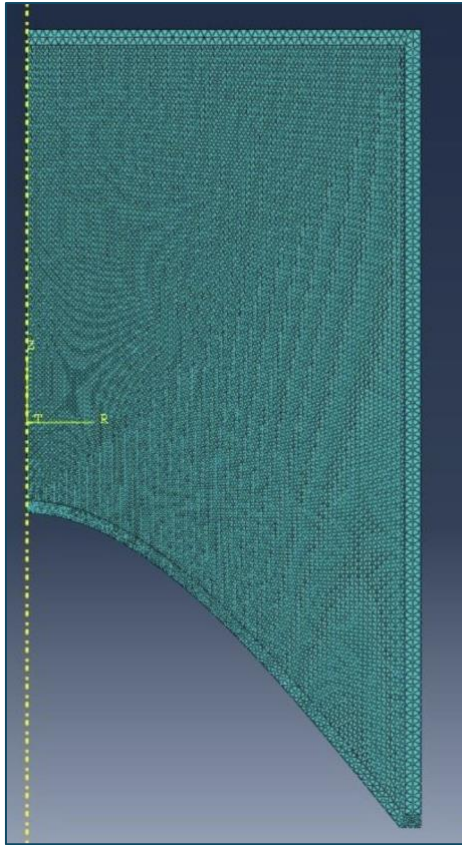


Figure 7 2D mesh of shaped charge.

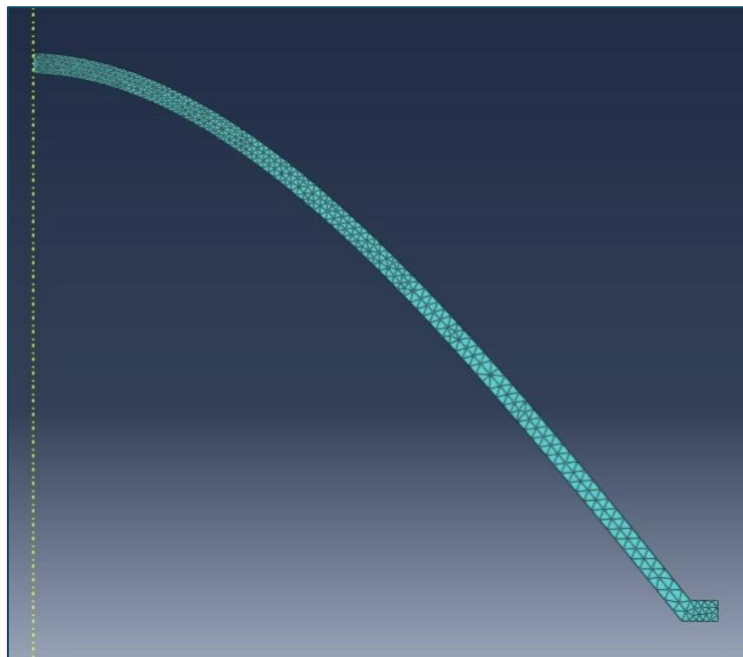


Figure 8 2D liner gradual mesh.

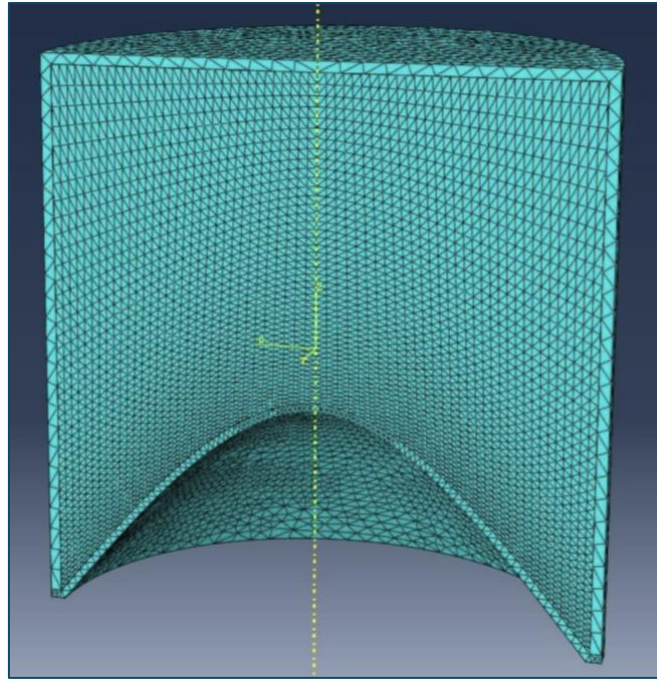


Figure 9 3D mesh of shaped charge.

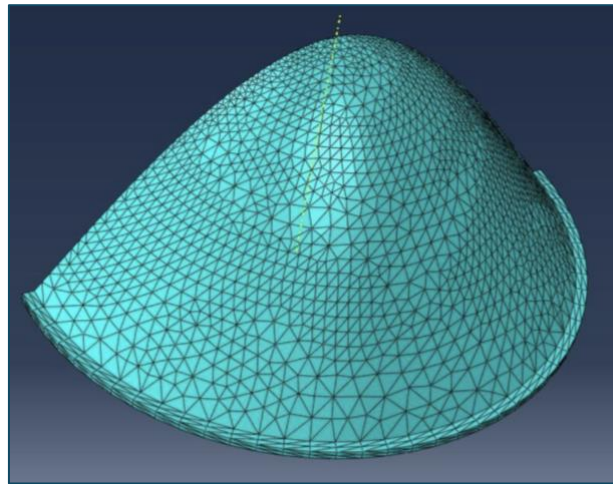


Figure 10 3D gradual mesh of the liner.

3.4. Boundary Conditions

Axisymmetric boundary conditions were applied to the 2D models along the axis of symmetry as seen in Figure 11. This allowed for rigid body motion while also allowing the deformation of the liner. Surface-to-surface contact interactions were made between the liner and the case to enable the transmission of pressure and deformation, which would result in the collapse of the liner.

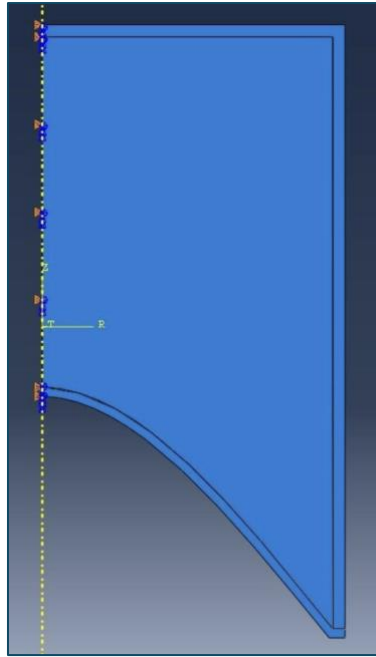


Figure 11 Axisymmetric boundary conditions of the 2D model.

For the 3D model, a Z symmetry boundary condition was applied which was applied across the whole 'cross-sectional face' as seen in Figure 12.

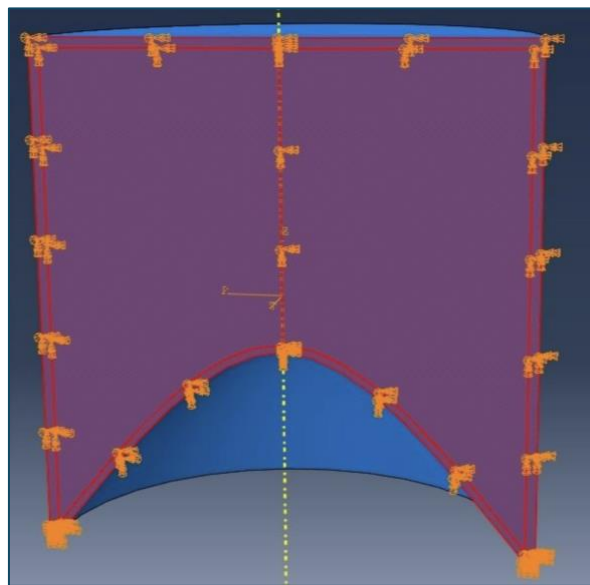


Figure 12 Symmetric boundary conditions of the 3D model.

3.5.Numerical Approach

Both simulations were modelled using an explicit dynamic finite element approach, as this would best capture the explosive loading and large deformations of a shape charge. A Lagrangian model was adopted, which allowed the mesh to deform with the material and would allow for good deformation behaviour results. This could, however, result in severe mesh distortion from extreme mesh deformation. To improve numerical stability, the bulk viscosity parameters within the explicit dynamic step were adjusted to values 1 and 10. This increases the viscosity and reduces excessive numerical oscillations and therefore improves solution stability. Care was taken not to increase the viscosity so much that it would reduce solution accuracy by dampening the physical response.

4. 2D Modelling

4.1.Copper Liner

4.1.1. Velocity

The velocity contours in Figures 13 to 15 show a progressive collapse of the conical liner and the formation of a high velocity jet. As seen in Figure 15 the highest velocity magnitudes were concentrated at the tip and reached values of around 8000 m/s, whilst the slug had lower velocities of around 3 m/s.

The copper liner produced a long and coherent jet structure, which indicates stable material flow during collapse. The high density and ductility of the copper ensured a good and continuous jet with little fragmentation throughout the simulation. Element distortion and extreme deformation lead to small irregularities later in the simulation.

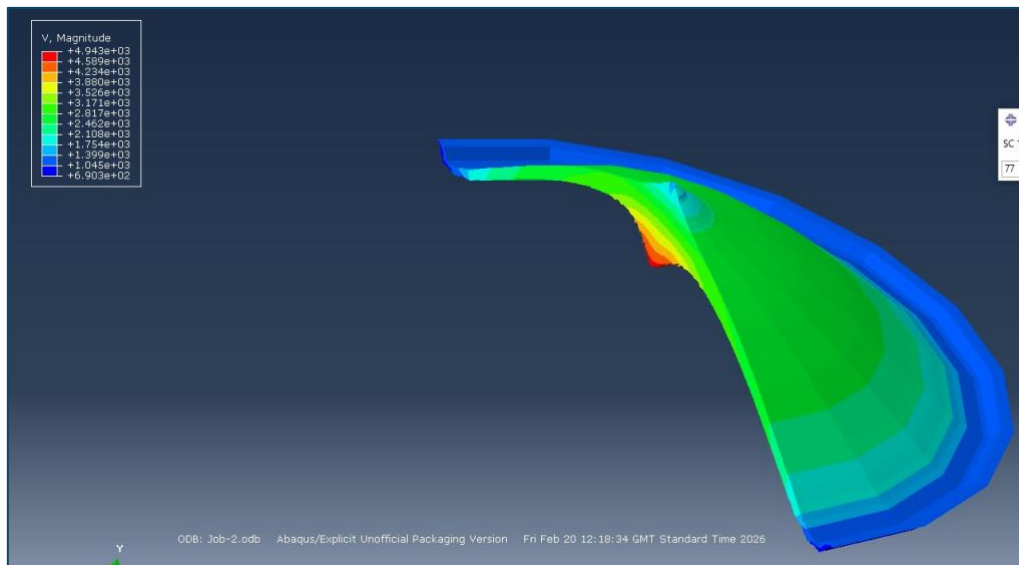


Figure 13 Velocity contour of the 2D copper liner.

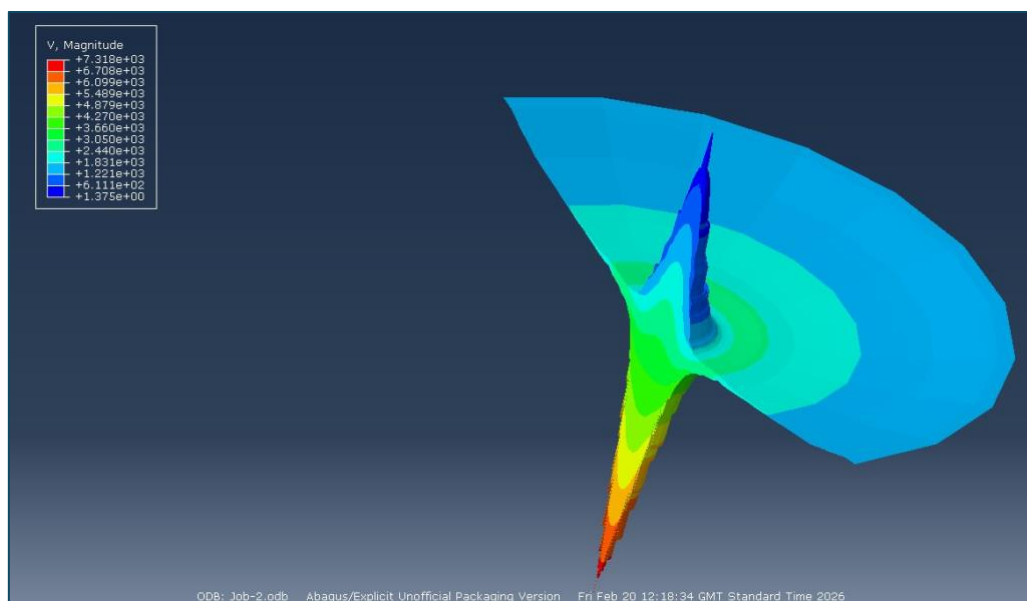


Figure 14 Velocity contour of the 2D copper liner 2.

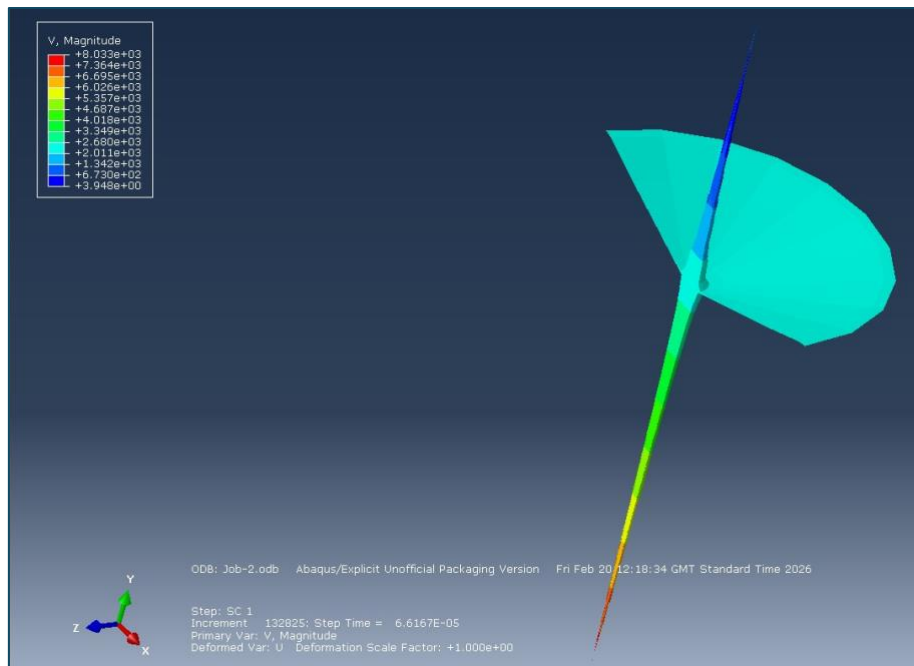


Figure 15 Velocity contour of the 2D copper liner 3.

4.1.2. Pressure

The pressure contours in Figures 16-18 show the spread of the detonation wave through the explosive and the transfer of pressure onto the copper liner during collapse. High-pressure regions were concentrated along the collapsing liner surface, with peak pressures of 3×10^{10} Pa occurring near the liner as the detonation wave made contact. The contour images demonstrate relatively symmetric pressure loading across the liner surface, contributing to the formation of a stable and coherent jet. Pressure magnitudes gradually reduced as the jet formed and the explosive gases expanded, indicating dissipation of the detonation energy throughout the simulation.

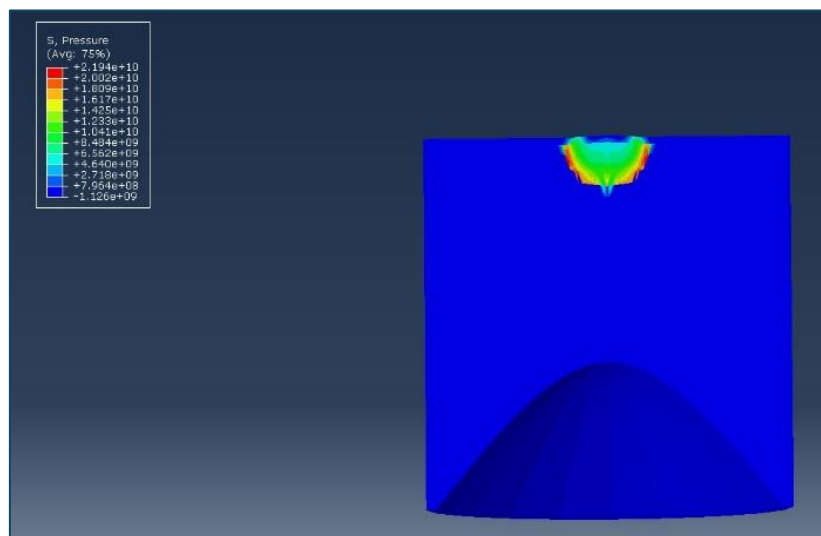


Figure 16 Pressure contour of the 2D Octol fill.

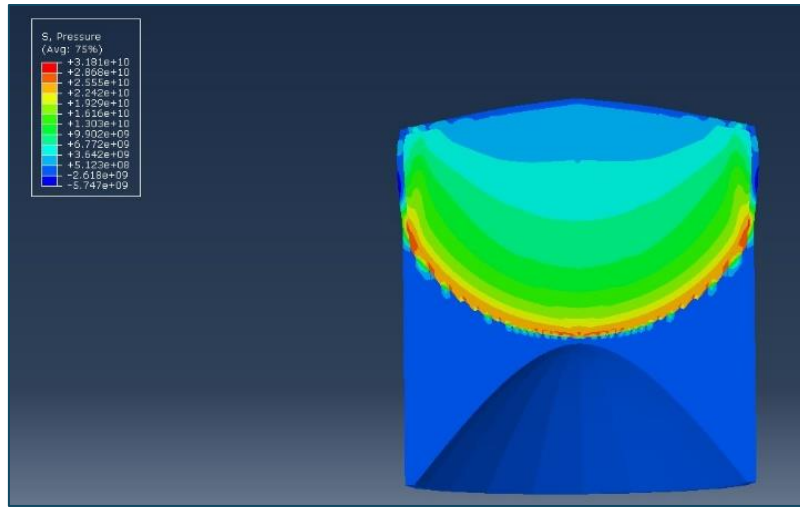


Figure 17 Pressure contour of the 2D Octol fill 2.

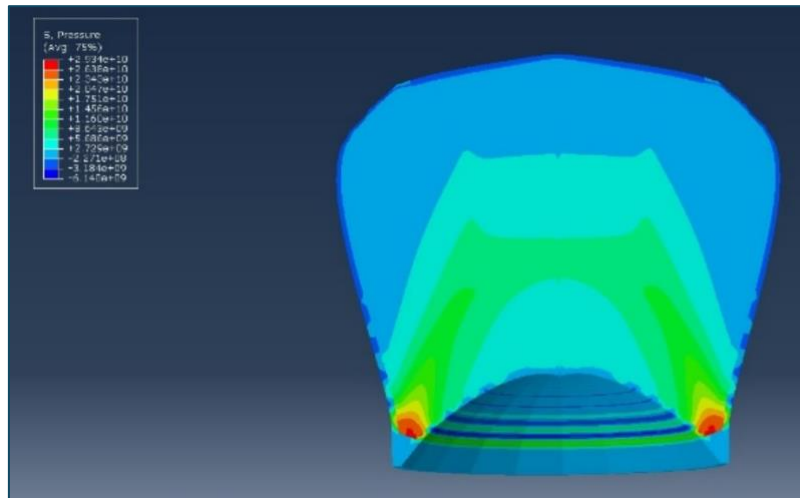


Figure 18 Pressure contour of the 2D Octol fill 3.

4.1.3. Strain

The strain contours in Figures 19 to 21 show that deformation begins at the apex of the liner, and as the liner continues to deform, strain becomes concentrated in the jet formation region. The magnified image of the jet in Figure 22 shows there is clear localisation in the middle of the jet, and therefore that region experiences significant stretching as the jet pulls away and moves away from the slower slug. A maximum value of 6 for strain represents extremely severe deformation. In the real world, failure, fracture, or necking would be expected at this level and therefore, the high strain in the middle of the jet suggests that it would be very susceptible to this.

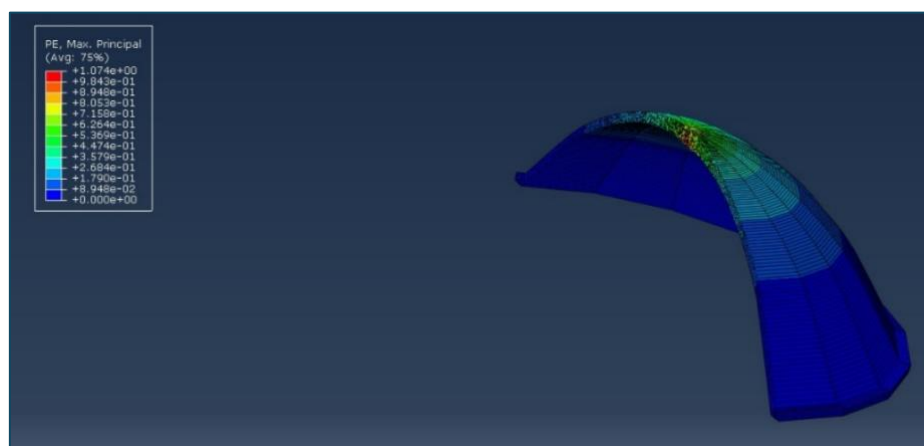


Figure 19 Strain contour of 2D copper liner.

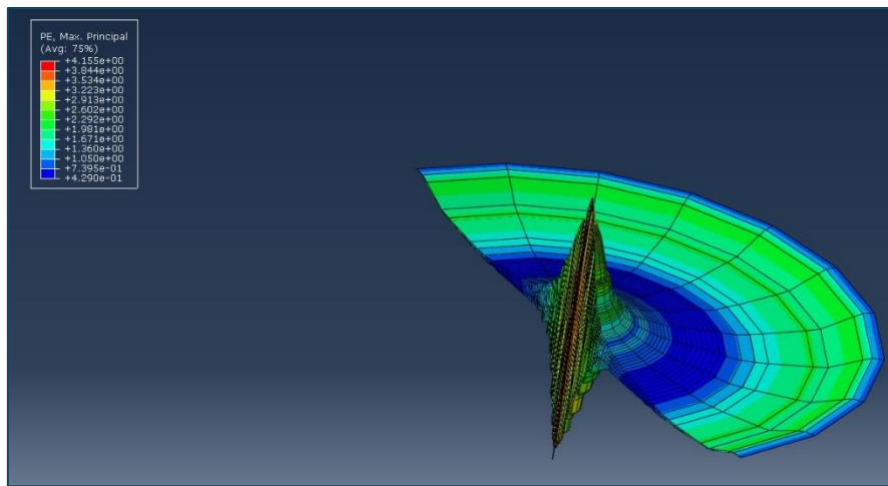


Figure 20 Strain contour of 2D copper liner 2.

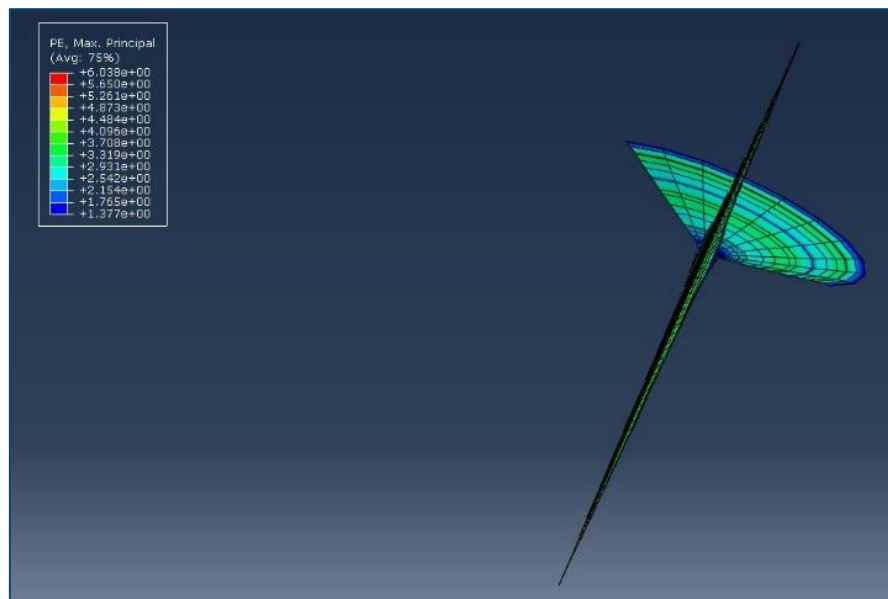


Figure 21 Strain contour of 2D copper liner 3.

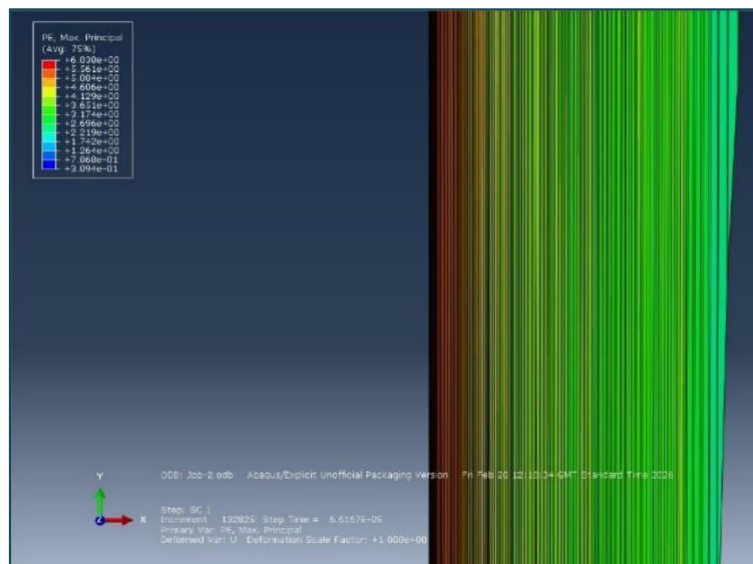


Figure 22 Magnified strain contour of the jet.

4.1.4. Velocity vs Time Graph

Figure 23 shows the acceleration behaviour of nodes taken from the tip, middle section and slug of the copper liner. The tip nodes reach the high velocities of 7000-8000 m/s, increasing rapidly from detonation. This confirms that the copper liner is successful in forming a high-velocity jet as the tip travels significantly faster than the rest of the liner. The middle and slug jet nodes reach around 4500 m/s and 3000 m/s, respectively. This clear velocity separation is to be expected in shape charge jet formations. This graph therefore supports the contour images showing strong acceleration and high velocities of the liner. Oscillations in the early part of the node accelerations are likely due to rapid shock loading and local deformation as the liner collapses.

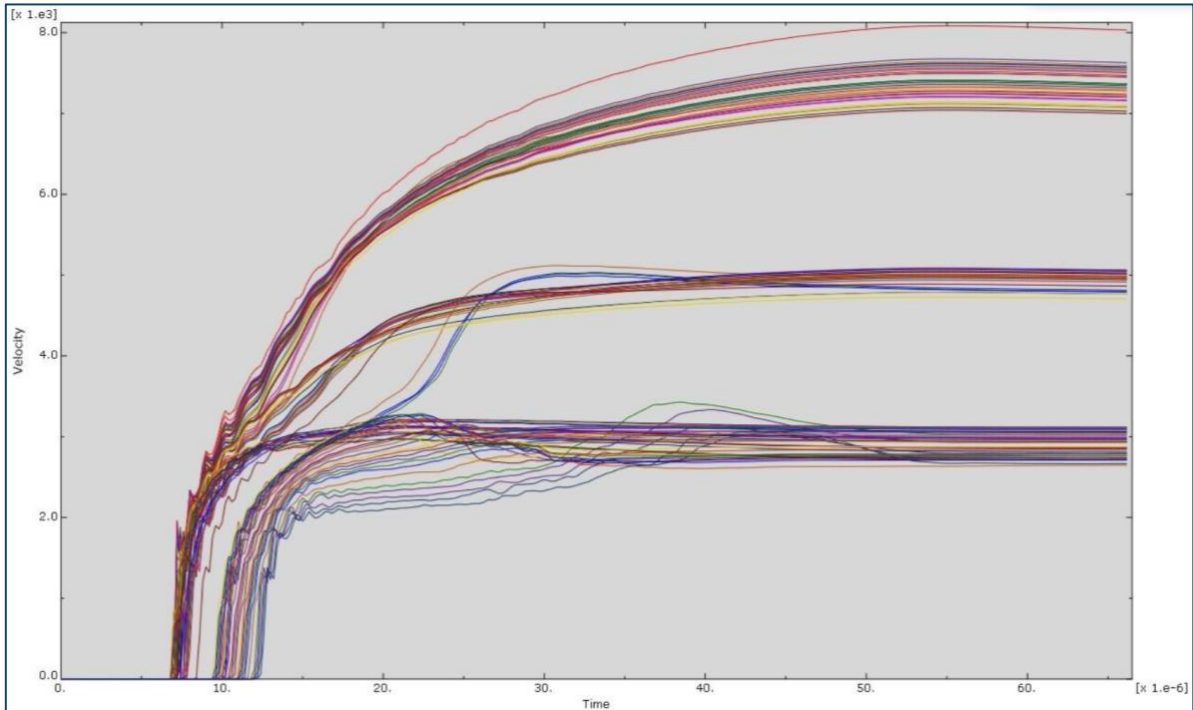


Figure 23 Velocity vs time graph of the 2D copper liner.

4.1.5. Strain vs Time Graph

The strain vs time graph in Figure 24 also shows nodes from the tip, middle and slug of the jet, meaning the deformation behaviour of different areas could be compared. The graph shows that the strain is not uniform throughout the liner after collapse. Nodes within the stretched jet region experience the highest strain values, whereas nodes in the slug remain lower. This is expected due to the jet tip accelerating away from the slower slug material, causing the jet to stretch. The higher values of 5-6 are extreme deformation, and as stated before, this in the real world would have led to fracture long before this point. As the contour images show no failure regions, these strain rates can be used to identify likely failure areas rather than showing where fracturing occurs.

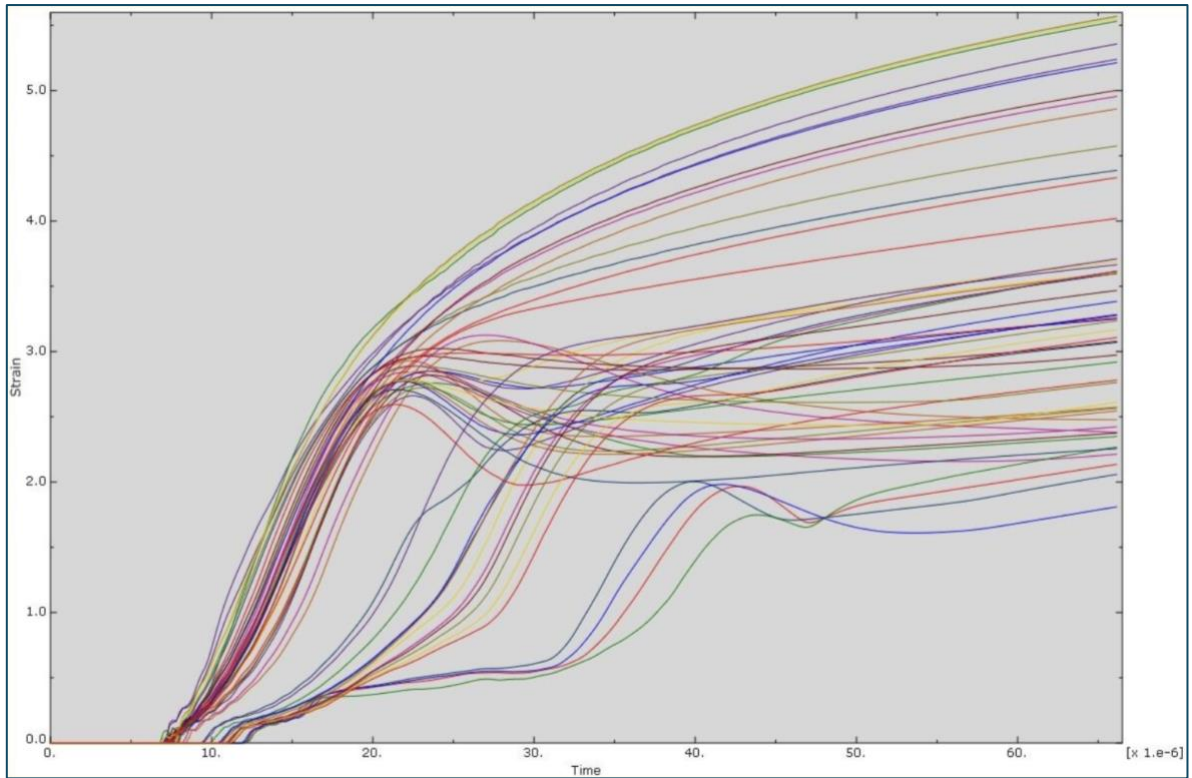


Figure 24 Strain vs time graph of the copper liner.

4.2. Aluminium Liner

4.2.1. Velocity

The aluminium liner images show rapid collapse of the liner and formation of a jet from the apex region. The highest velocities are concentrated in the jet, with peak contour values reaching approximately 6000-7000 m/s. The aluminium jet is wide and not very defined which suggests a less coherent jet formation. This is likely linked to aluminium having a lower density, which allows rapid acceleration but produces a lower-momentum jet. Overall, the aluminium liner successfully forms a high-speed jet, but not as successfully as the copper liner.

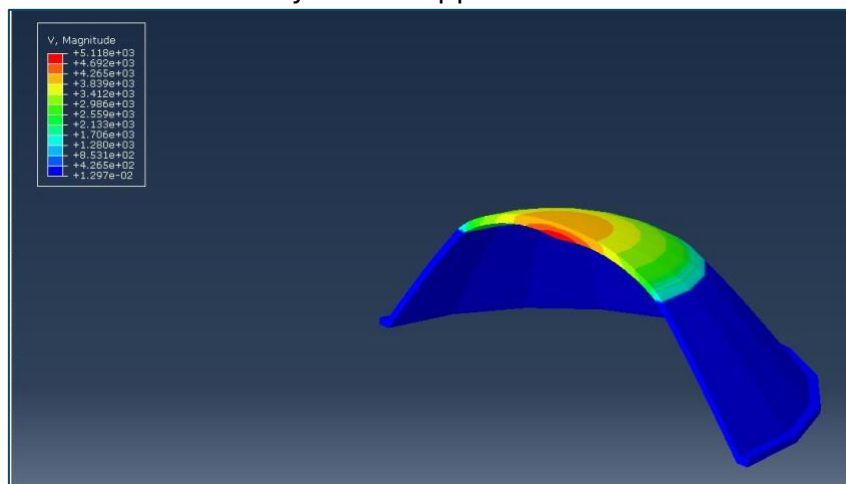


Figure 25 Velocity contour of the 2D aluminium liner.

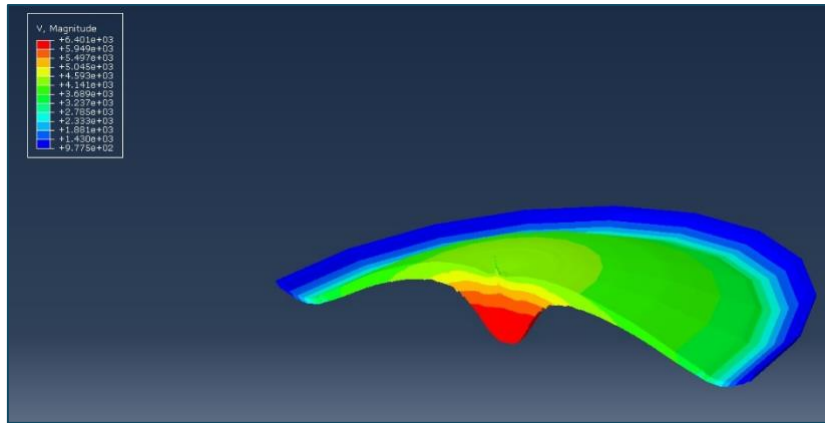


Figure 26 Velocity contour of the 2D aluminium liner 2.

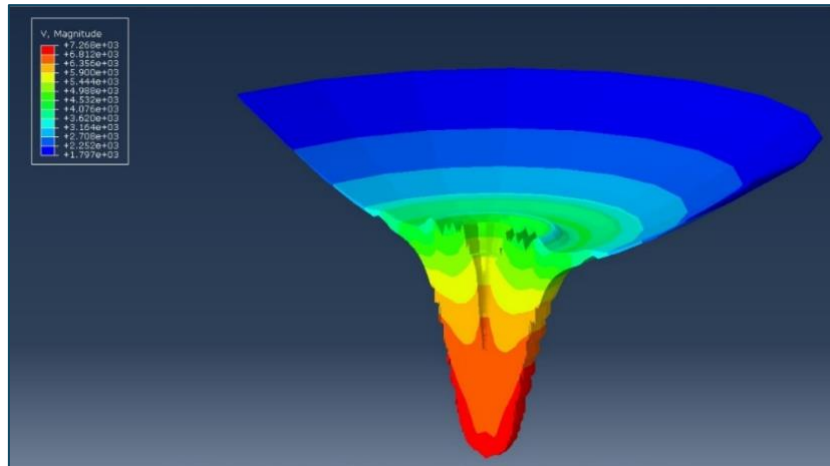


Figure 27 Velocity contour of the 2D aluminium liner 3.

4.2.2. Strain

The strain contours in Figures 28-30 show that, like the copper liner, deformation is concentrated in the liner as it collapses. The highest strain values occur around the jet formation region and along the stretched jet, shown in Figure 30. This indicates that the aluminium liner is undergoing significant elongation and thinning as the faster-moving jet material pulls away from the slower rear material. In reality, this level of deformation would indicate a high risk of necking or fracture. The irregular strain distribution and jagged deformation also suggest that the aluminium jet is less stable and more prone to localised distortion than the copper liner.

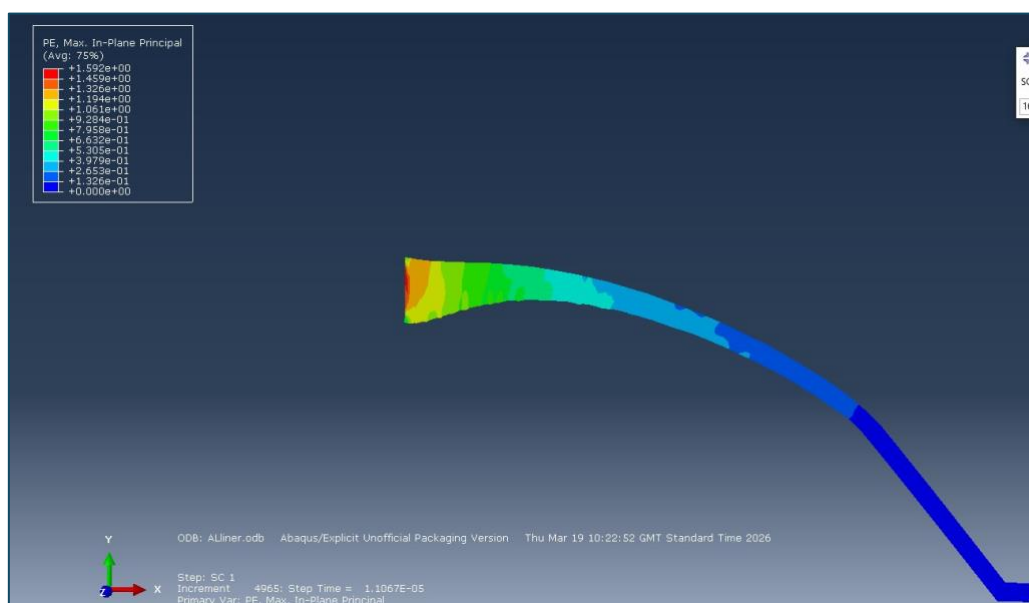


Figure 28 Strain contour of the 2D aluminium liner.

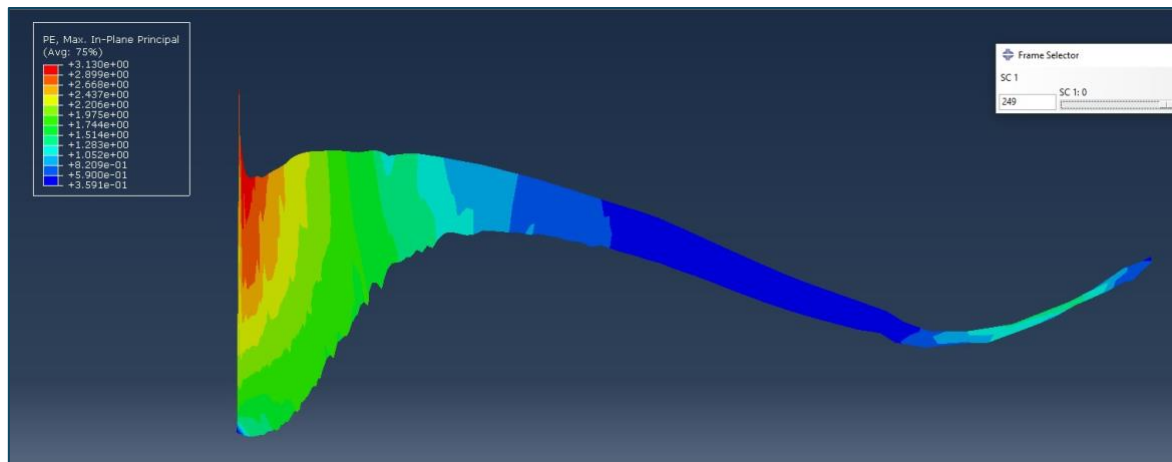


Figure 29 Strain contour of the 2D aluminium liner 2.

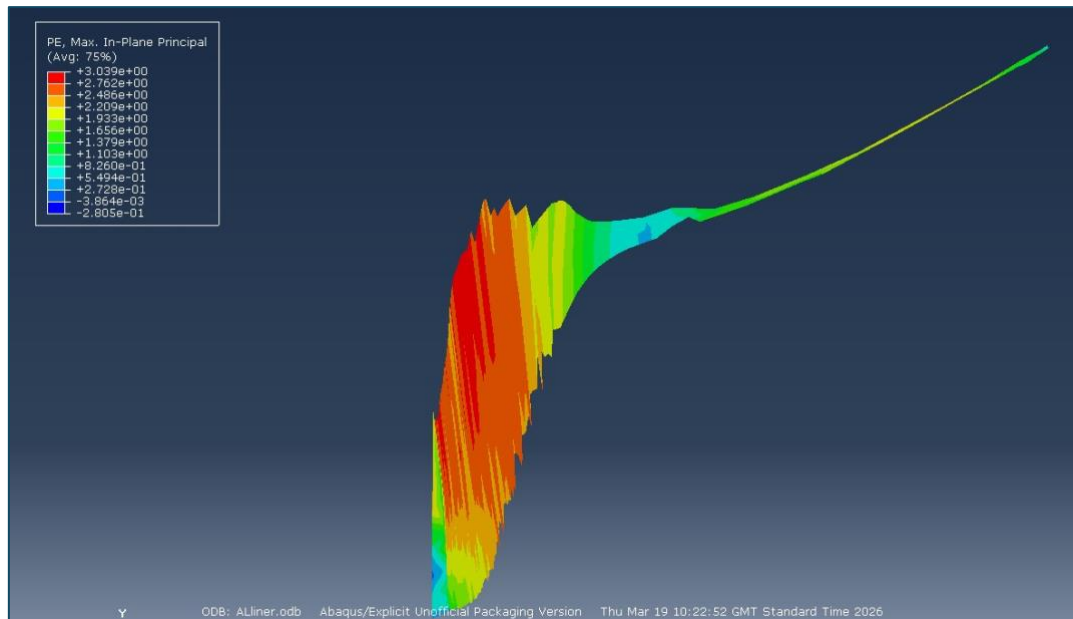


Figure 30 Strain contour of the 2D aluminium liner 3.

4.2.3. Velocity vs Time Graph

Figure 31 shows the velocity vs time graph of the aluminium liner. It contains nodes from the jet tip and slug region. The curves show rapid acceleration after detonation as the liner begins to collapse. There is large oscillations in the tip nodes, which is likely caused by sudden shock loading and rapid deformation. The curves of the tip and slug converge around 20×10^{-6} s, which is not expected, as the jet tip is meant to be faster. This could be due to aluminium's lower density causing the liner to accelerate rapidly, the jet and slug might not have had enough time to separate yet, or the nodes selected may not have been slug nodes.

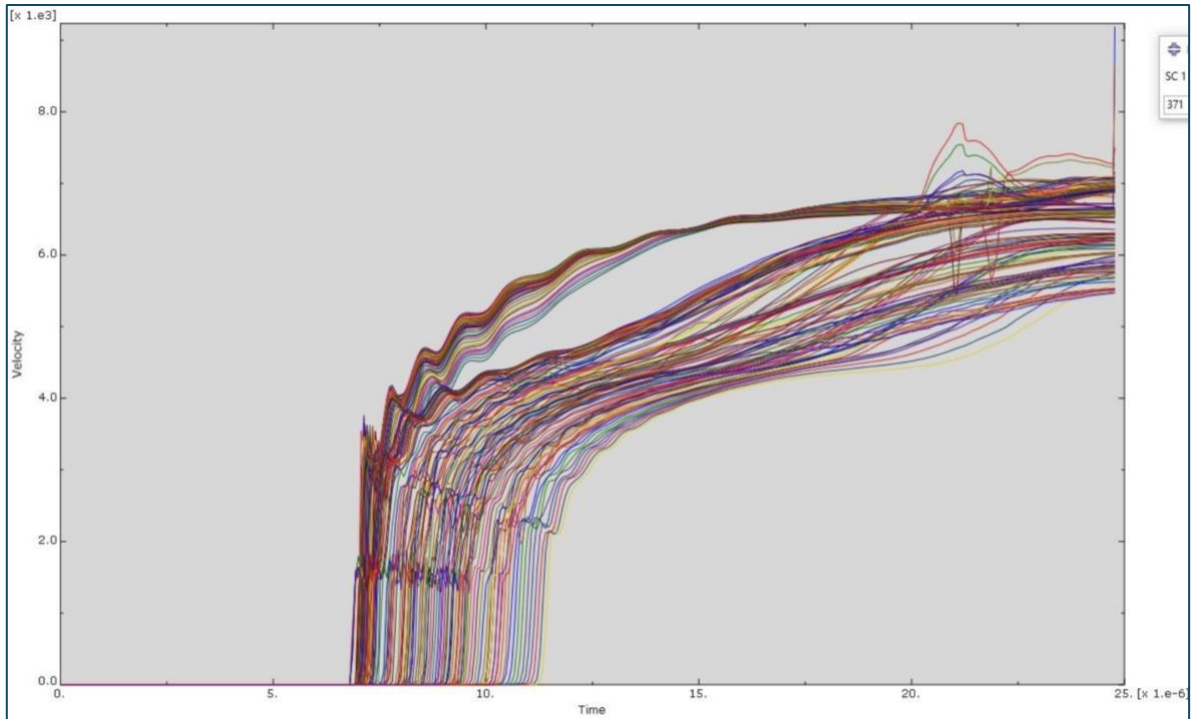


Figure 31 Velocity vs Time graph of the aluminium liner.

4.2.4. Strain vs Time Graph

The graph in Figure 32 includes nodes taken from the jet tip and slug, but they do not seem to separate into distinct tip and slug groups. This may be because the selected slug nodes were located close to the collapsing liner region and were therefore accelerated and stretched with the jet rather than representing the slower rear slug. The general messiness of the graph could be due to the aluminium liner undergoing rapid deformation under shock loading much quicker than the copper. Mesh distortion could also contribute to the curve behaviour.

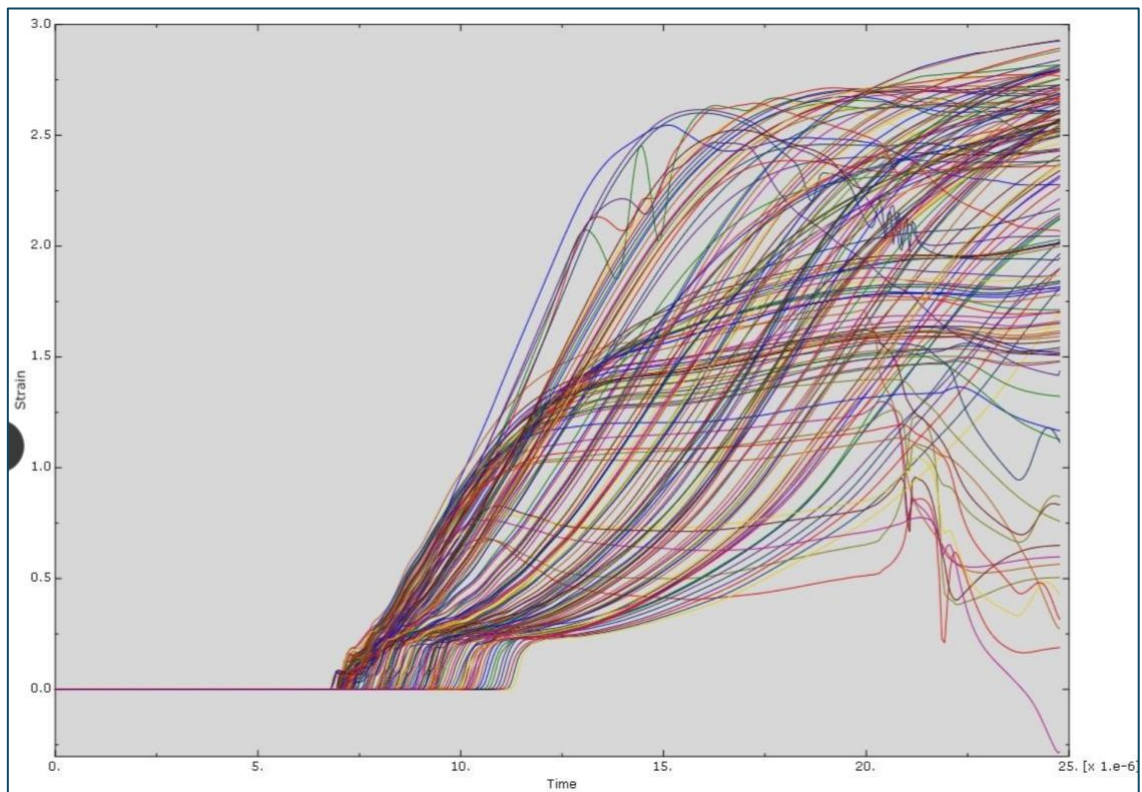


Figure 32 Strain vs time graph of the aluminium liner.

4.3.2D Design Comparison

Both 2D models show that both copper and aluminium liners successfully collapse under explosive loading, and both formed high velocity jets. However, the two materials produced noticeably different jet behaviour. The copper jet generated a narrow, long jet with a clear velocity difference between the jet tip and slug. This indicates a stable jet development. In contrast, the aluminium liner, whilst it did produce a high velocity jet, the jet was wider and less defined. There was also uncertain tip and slug distinctions and more oscillation. This could be due to not correctly identifying slug nodes or nodes that were closer to the collapsing liner, or the fact that aluminium has a lower density, which allows for rapid acceleration but produces a lower momentum jet.

The strain results also showed differences between the two designs. The copper liner reached higher strain values of approximately 6.0, suggesting severe jet stretching and possible fracture-prone regions. The aluminium liner reached lower peak strain values of around 3.0 but showed a more irregular strain distribution and a less stable deformation pattern. Overall, the copper liner was selected as the better design because it produced a more coherent, focused jet with clearer jet-tip and slug behaviour, making it more suitable for the 3D model.

5. 3D Modelling

5.1.3D Velocity

The 3D velocity contours in Figures 33 to 35 show that the copper liner collapses and forms a high velocity jet largely matching the 2D simulation. Like the 2D simulation, the high velocities are at the jet tip, and the slower velocities are in the slug region. The velocity vs time graph in Figure 36 shows two distinct groupings of the tip and slug velocities. The faster tip velocities of around 6000-7500 m/s and the slower slug velocities of around 3000 m/s are consistent with the 2D copper results and support the conclusion that copper makes a coherent jet structure.

The 3D velocity contours, however, display more severe irregular deformation around the edges of the liner than the 2D model. This is to be expected as the 3D model is more computationally demanding and uses the tetrahedral mesh, which is more prone to distortion from extreme deformation than the triangular mesh.

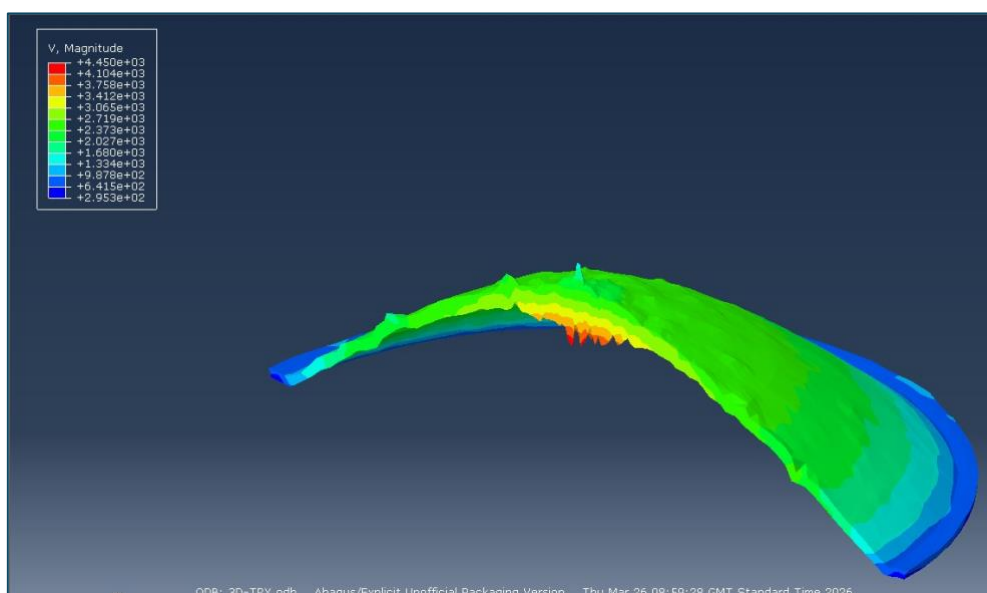


Figure 33 Velocity contour of the 3D copper liner.

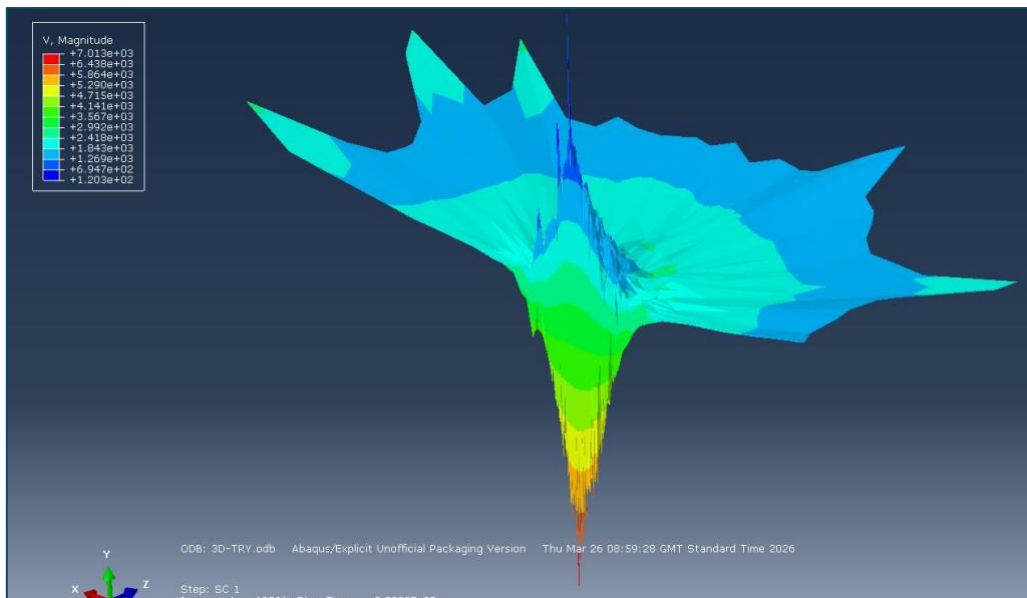


Figure 34 Velocity contour of the 3D copper liner 2.

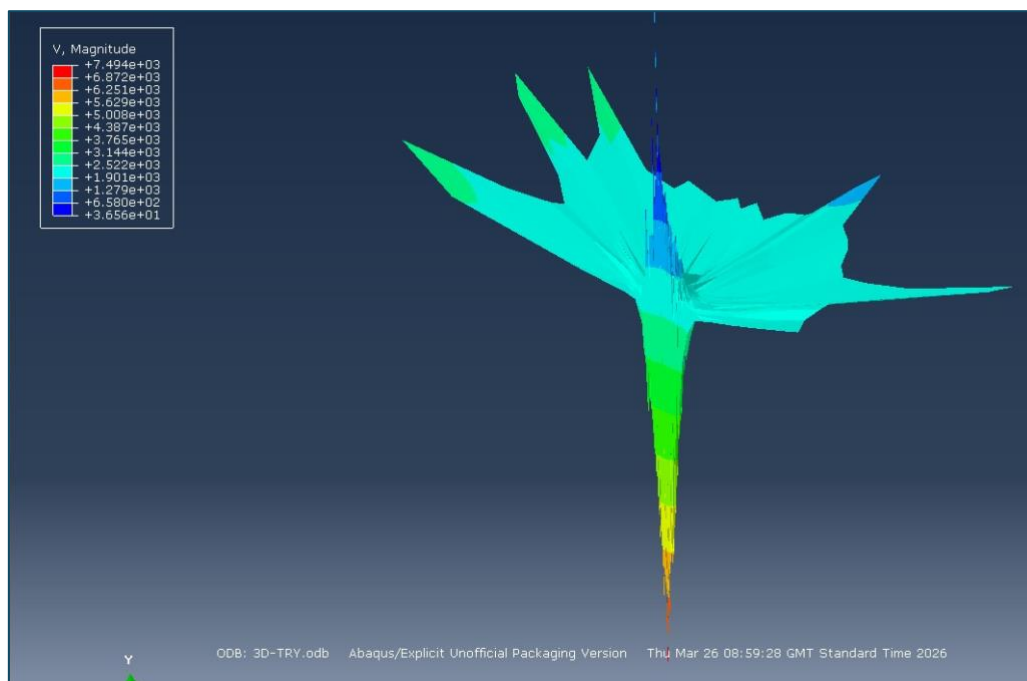


Figure 35 Velocity contour of the 3D copper liner 3.

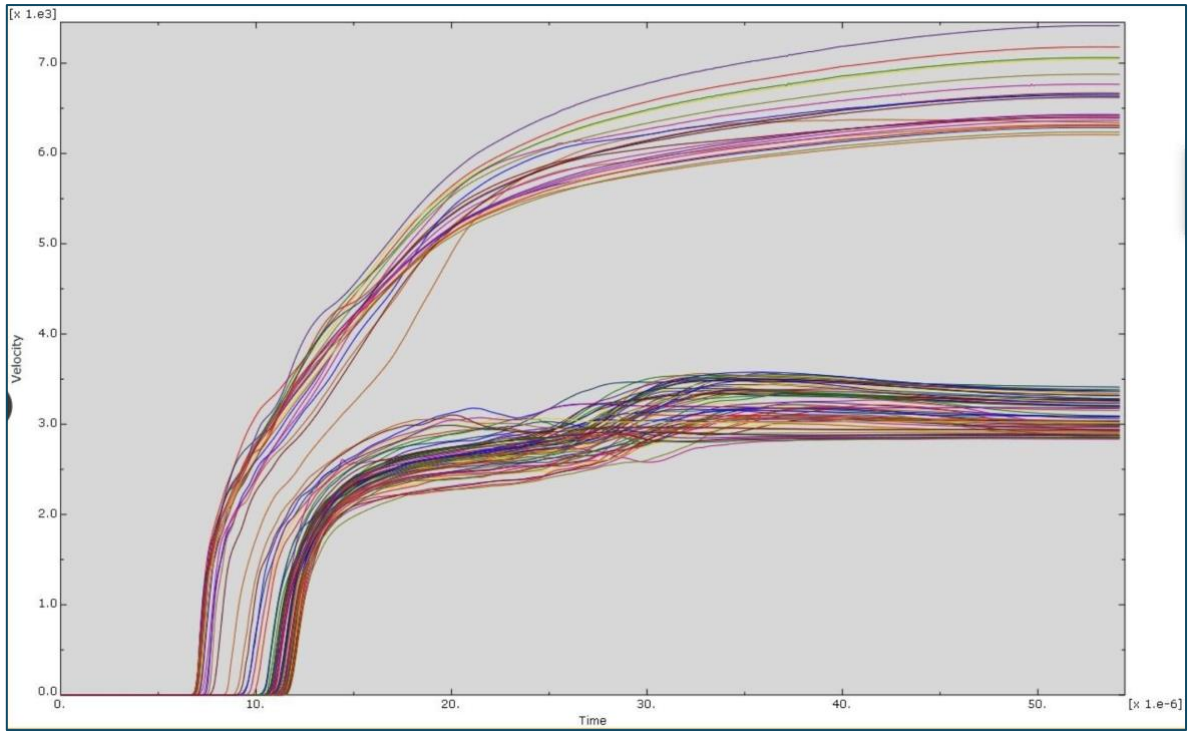


Figure 36 Velocity vs time graph of the 3D copper liner.

5.2. 3D Pressure

The 3D pressure contours in Figures 37 to 39 show the detonation pressure developing within the explosive and transferring onto the copper liner. The pressure distribution is symmetric across the model, suggesting that the applied symmetry boundary condition and loading produced a stable overall collapse pattern. Peak pressures are shown to be around 3×10^{10} Pa, which is consistent with the very high pressure expected during explosive detonation and the 2D simulation results. However, compared with the 2D model, the 3D contours appear more jagged. This is likely due to the tetrahedral mesh and the increased complexity of the full spatial model. Overall, the pressure results show that the explosive loading was successfully transferred to the liner and was sufficient to drive collapse and jet formation.

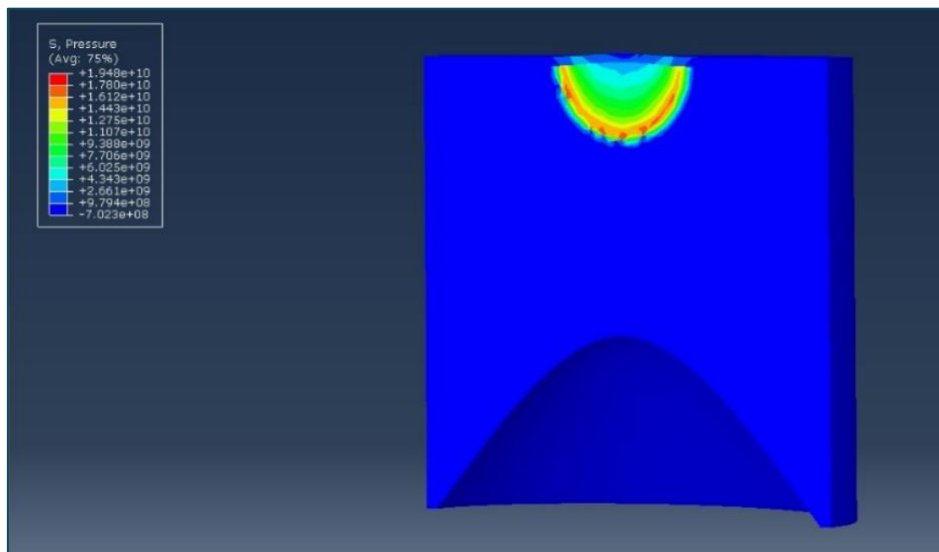


Figure 37 Pressure contour of the 3D Octol.

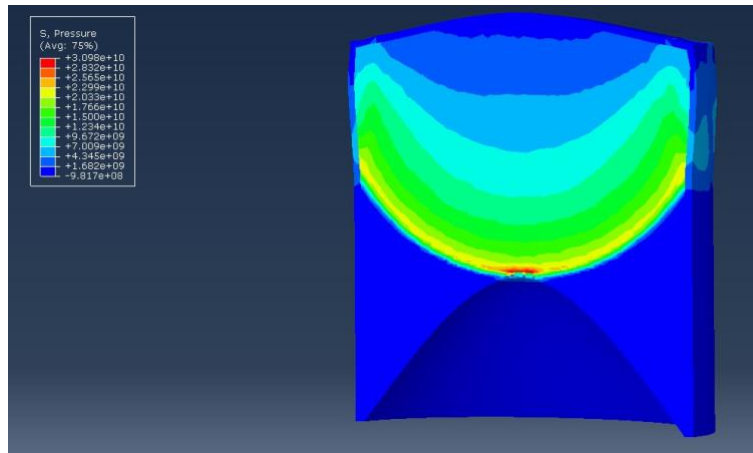


Figure 38 Pressure contour of the 3D Octol 2.

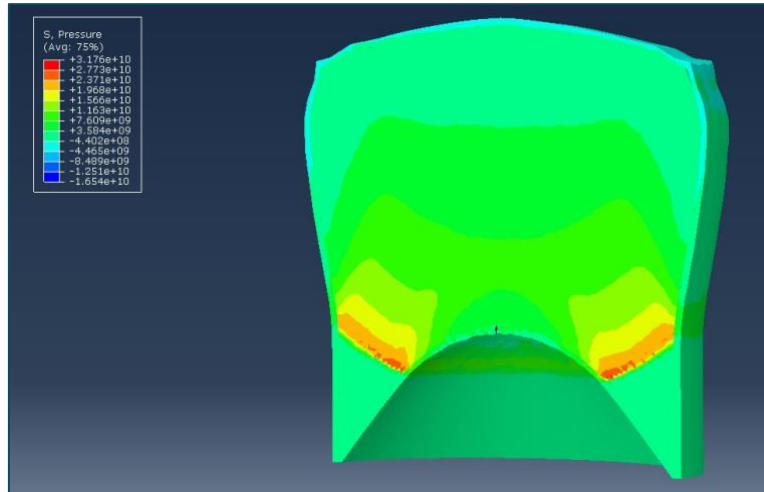


Figure 39 Pressure contour of the 3D Octol 3.

5.3. 3D Strain

The strain contours in Figures 40 to 42 concur with the 2D results that the strain becomes highly localised as the copper liner collapses and stretches into the jet. The highest values are along the middle of the jet as it pulled into its elongated form. Like the 2D images, the magnified jet of Figure 43 shows that there is a strong strain concentration through the centre of the jet and therefore indicates severe stretching and thinning. The strain vs time graph in Figure 44, like the 2D graph, includes nodes from the tip, middle and slug of the jet. The curves show a rapid increase in strain and, overall, extremely large deformation. The max strain value of 4.5 in this graph is lower than the 2D model of 6. This could be due to the 3D model allowing deformation to spread in an additional spatial direction. The 2D model being axisymmetric only allows material to flow in a path down the axis and therefore creates a narrower region, producing high strain rates. The 3D model has more freedom to deform in more directions and therefore distributes strain over a larger area and reduces peak strain.

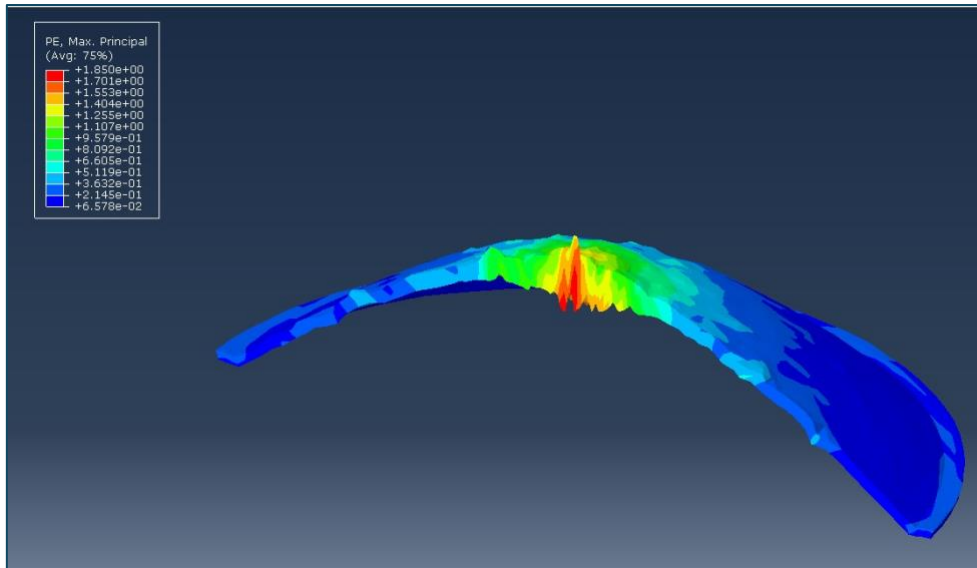


Figure 40 Strain contour of the 3D copper liner.

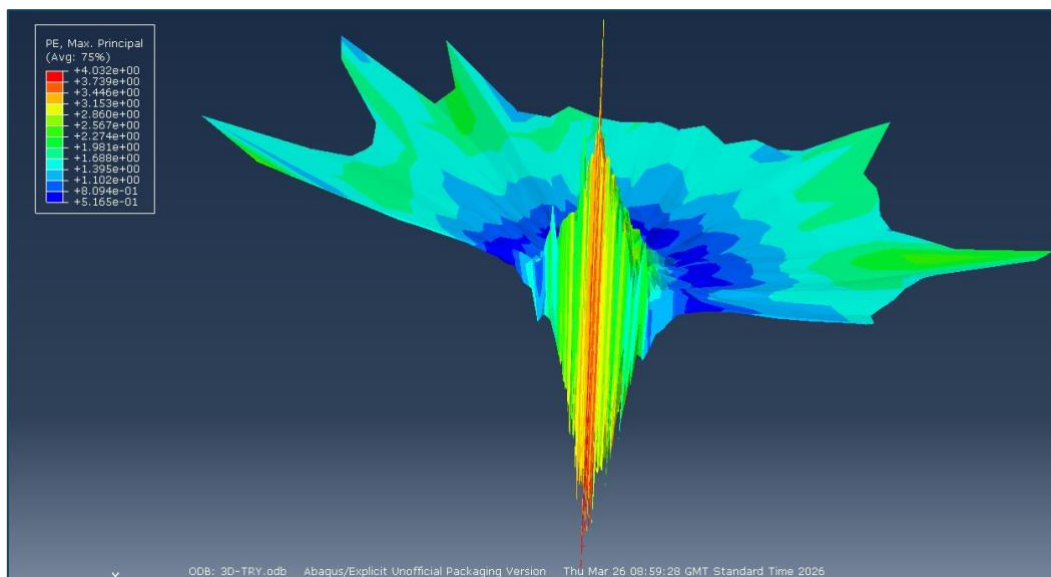


Figure 41 Strain contour of the 3D copper liner 2.

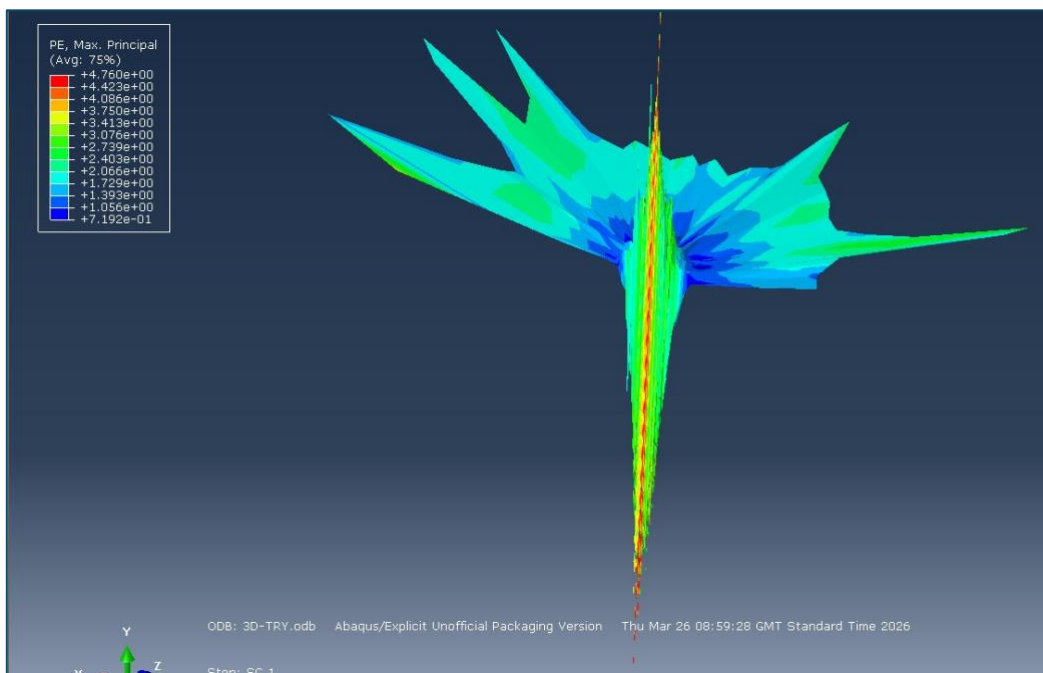


Figure 42 Strain contour of the 3D copper liner 3.

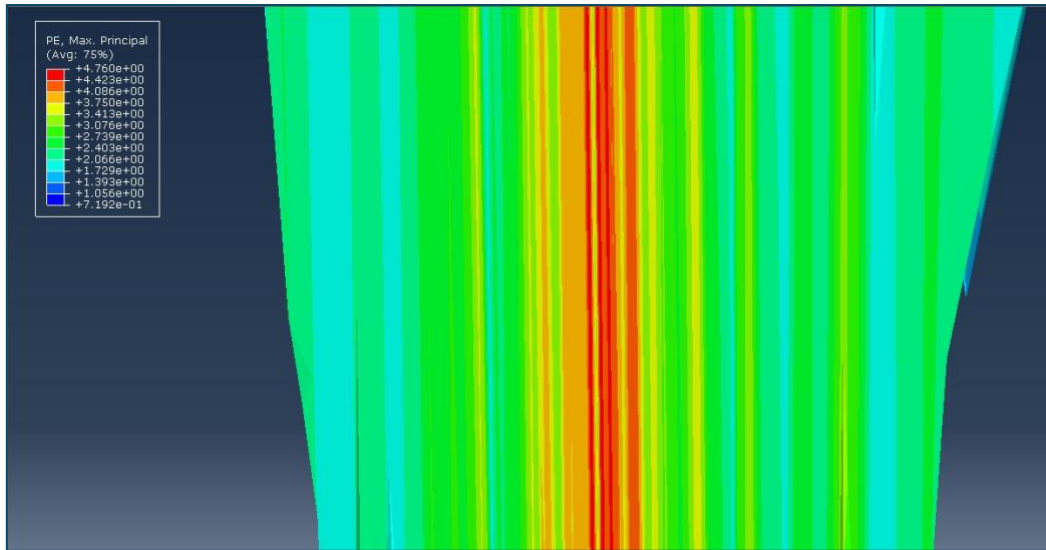


Figure 43 Magnified strain contour of 3D copper jet.

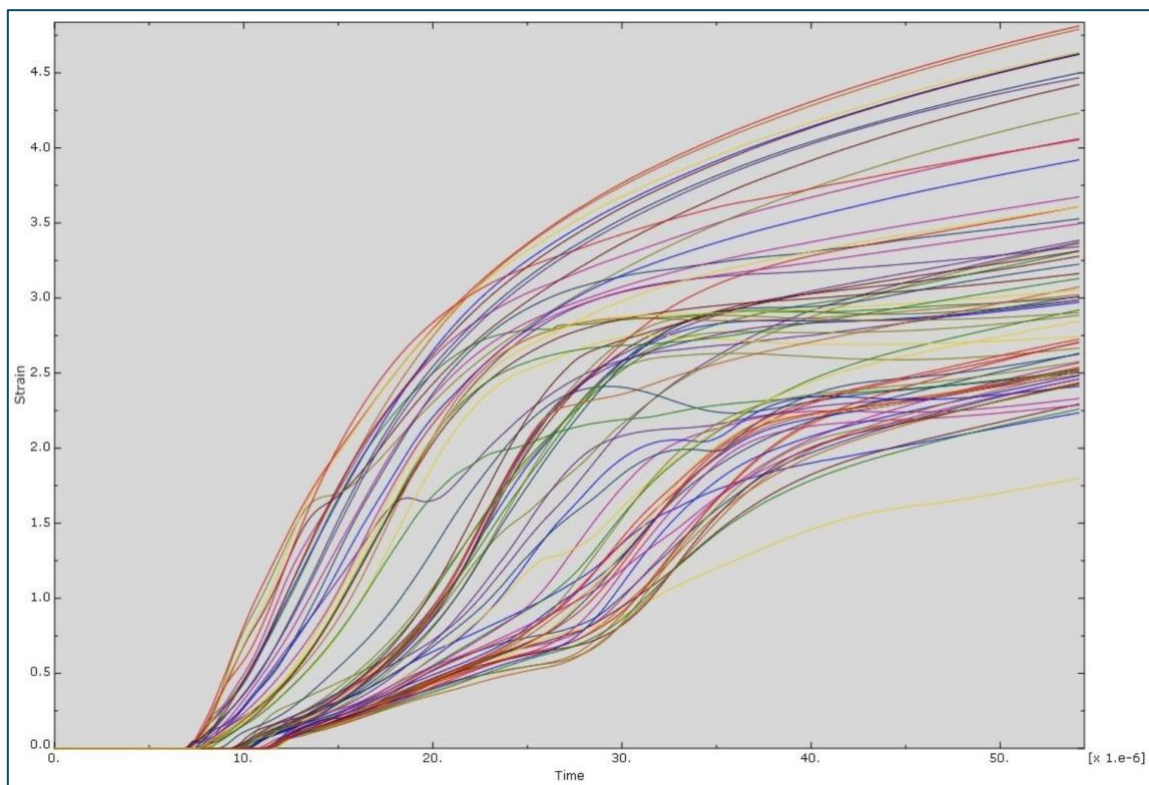


Figure 44 Strain vs time graph of the 3D copper liner.

5.4. 3D Limitations

During the 3D simulation, leakage of the HE fill was observed as the liner detached from the case and therefore gaps developed. This can be seen in Figures 45 and 46 where the case is included. A contact interaction was not defined in the 3D model, and therefore, it could be the reason for this. The severe deformation that was occurring could have also caused the Lagrangian mesh to distort significantly, allowing the liner and case to separate rather than remain in contact during the collapse stages. This leakage could have affected the accuracy of the model as it could have reduced the efficiency of the pressure transfer to the liner. This could partly explain the lower strain values seen in the 3D model compared to the 2D model.

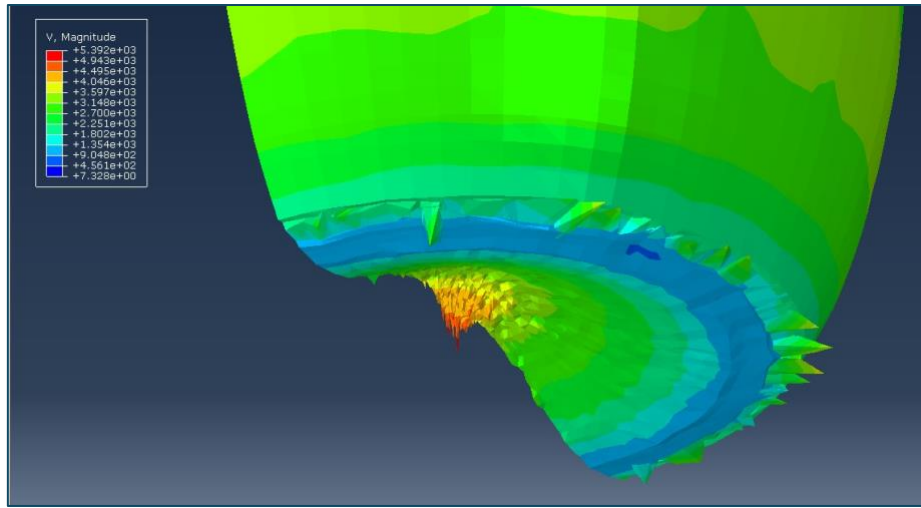


Figure 45 HE leak of the 3D model.

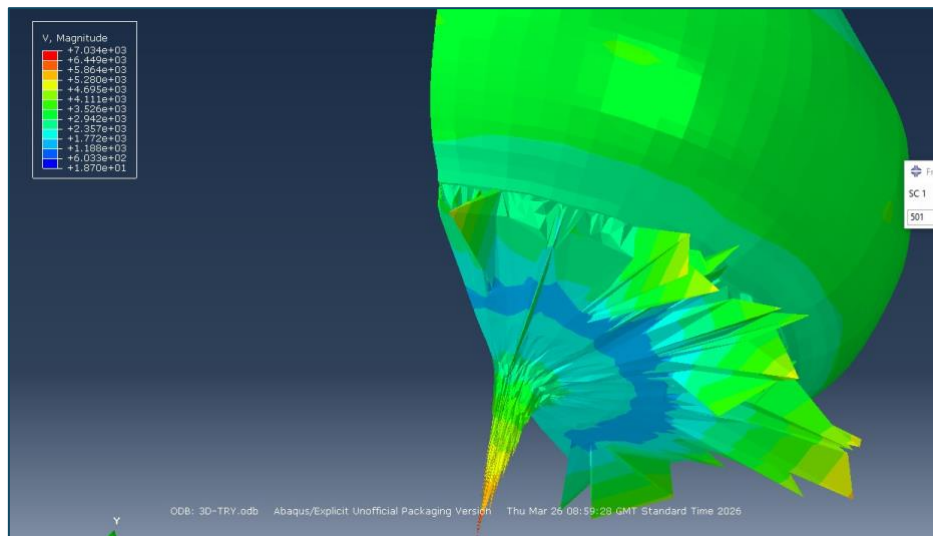


Figure 46 HE leak of the 3D model.

6. Conclusion

This study investigated shape charge behaviour using two 2D liner designs made of copper and aluminium, followed by a 3D model of the copper design. The simulations used velocity, pressure and strain results to assess jet formation, liner collapse and deformation behaviour.

Both materials produced high-velocity jets however, the copper liner was able to produce the most coherent and focused jet. The copper results showed clearer separation between the jet tip, middle and slower slug, making it a stronger design for further 3D modelling. The aluminium liner also reached high velocities, but the jet appeared less stable. The strain results indicated that both liners experienced severe plastic deformation with collectively high values in the centre of the tip. However, as a fracture model was not included in the liner parameters, the simulations might not be indicative of real-world situations and should therefore be treated as potential indicators of values and behaviours.

The 3D results largely supported the 2D results but also highlighted limitations such as mesh distortion, HE leakage and computational cost. Future improvements to this study could be using an Eulerian approach to help with element distortion, using Smoothed Particle Hydrodynamics, which handles deformation better than Lagrangian, adding JC damage to the liner for better liner modelling, improving contact definitions in the 3D model between the liner and case and performing a mesh sensitivity study to obtain more accurate results.

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