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Design of Shaped Charges

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Abstract

This report presents the design and finite element analysis of shaped charges using ABAQUS. Two 2-dimensional axisymmetric simulations with differing shaped charge designs were compared. The 2D results demonstrated that the variable thickness conical liner produces a higher peak jet velocity and more favourable strain distribution and was therefore selected for 3D modelling. The 3D simulations presented many challenges due to excessive element distortion. The challenges were addressed using Smooth Particle Hydrodynamics, adaptive meshing and the adjustment of the linear bulk viscosity parameter. A mesh sensitivity study was conducted comparing the trade-off between mesh refinement and computational cost. The report concludes that 2D axisymmetric simulations are preferable over 3D simulations, and that Eulerian formulations should be used over Lagrangian ones for problems involving explosives.

1 Introduction

This report discusses the process of designing and modelling a shaped charge in ABAQUS, a finite element analysis software developed by Dassault Systèmes [1]. Two 2D shaped-charge designs will be compared using a simulation in section 4, and a design will then be selected and modelled in 3D. The 2D and 3D simulations will be compared to understand the benefits and drawbacks of modelling in 3 dimensions in section 5.

Additionally, a mesh sensitivity analysis has been performed and is outlined in section 6 of the report. The history and use of shaped charges will be discussed as well as the different approaches towards modelling problems in ABAQUS.

2 Background

2.1 Jet Formation Theory

The fundamental principle behind shaped charge jet formation is the Munroe effect. The Munroe effect describes that a hollow or lined cavity in an explosive, when detonated, focuses the explosive energy into a narrow, high-velocity jet [6]. As the detonation wave hits the liner, the liner begins to collapse and is accelerated downward into a thin jet which can travel at speeds between 7000 and 10,000 m/s. The velocity gradient across the jet causes it to stretch over time, eventually as the jet continues to stretch it will begin to break apart, this is known as particulation [7,8]. This is why the standoff distance, the distance between the shaped charge and the target is crucial in the usage of shaped charges, if the standoff distance is too far than the jet begins to particulate and can no longer deeply penetrate the target.

2.1.1 Shaped Charge use and History

Shaped charges are used for both military and civilian usage. For the military a shaped charge is used to defeat armoured targets such as tanks, one of the most notable shaped charge munitions is the RPGs (Rocket Propelled Grenade) HEAT (High Explosive Anti-Tank) grenade shown in figure 1.

Shaped charges are also used in the oil and the mining industries for blasting rocks and as cutting and perforating charges [10]. Shaped charges are also used for controlled demolition and underwater salvage operations. The versatility in the technology extends its use well beyond just the military.

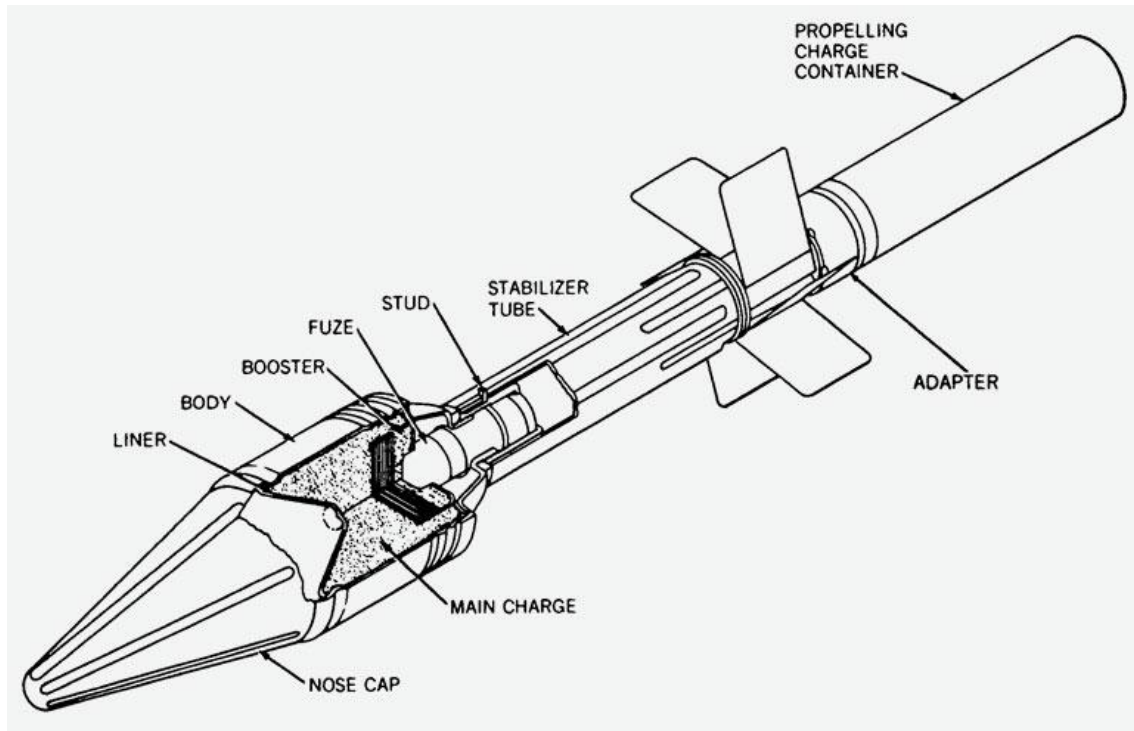


Figure 1 - A diagram of the RPG-2's HEAT grenade [9].

2.2 Modelling Approaches

2.2.1 Lagrangian

In a lagrangian mesh the mesh is attached to the material, therefore it moves with the material as it deforms. Each node in the mesh represents that point in the material throughout the entire simulation. It is an easy method to implement and can track material boundaries and interfaces precisely; however, elements can become extremely stretched and distorted, which reduces the accuracy of the simulation and can cause the simulation to abort.

This is also the default approach used in ABAQUS and will be the approach used for this test case.

2.2.2 Eulerian

In a Eulerian mesh the mesh is fixed in space and represents the area in which the simulation will be performed. Material flows through the mesh; this means that the mesh cannot distort. Eulerian meshes are very effective for simulations that involve fluid-like behaviour such as hydrodynamic problems like a shaped

charge. However, it is computationally more expensive per element than Lagrangian is, and it is harder to track material history through the simulation, as you can't pick and follow a specific section of the material throughout the simulation.

3 ABAQUS Model setup

3.1 Model Geometry

The two shaped charge designs will be a constant thickness conical liner and a variable thickness conical liner (Figure 2). The expectation is that the variable thickness conical liner will form a thinner jet with a higher velocity compared to the constant thickness conical liner. A thinner jet at higher velocity is more beneficial to penetrating armour as the jet can impart a similar amount of energy over a smaller area, potentially increasing the penetration depth of the jet.

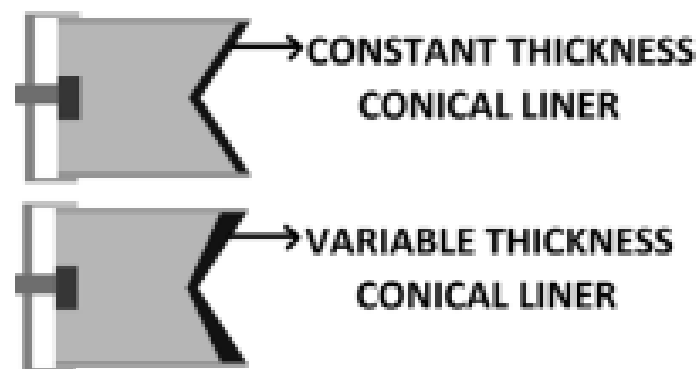


Figure 2 - Image taken from Saran's "Experimental investigations on aluminum shaped charge liners", showing the two different shaped charge designs used for the simulation [5].

The model will be designed to be axisymmetric; half of the liner will be modelled and then the results will be revolved 180° to show a sectioned conical liner. The axisymmetric design for the variable thickness conical liner is shown in figure 3.

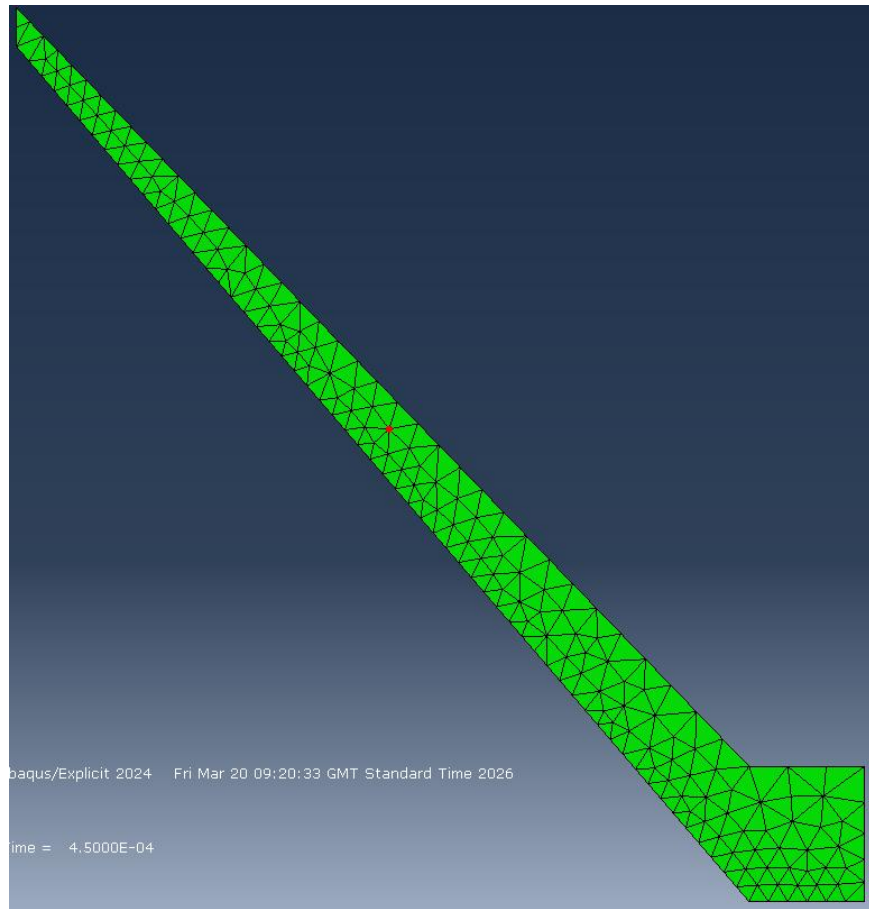


Figure 3 – The 2D axisymmetric design for the variable thickness liner.

The design of the mesh for the shaped charge has been made so that the nodes on the conical liner align with the explosive (figure 4). This is useful when modelling with a lagrangian approach as the mesh deforms with the material, the simulation will be able to handle the calculations better if the nodes are lined up. The mesh also varies in density across the liner; there is an input bias towards the tip of the cone. This is to improve the accuracy of the simulation within this region of the conical liner, as this is the first part of the jet formation this part of the cone undergoes the most deformation. The tip of the cone will invert and form the point of the jet, and this is the most crucial part of the model.

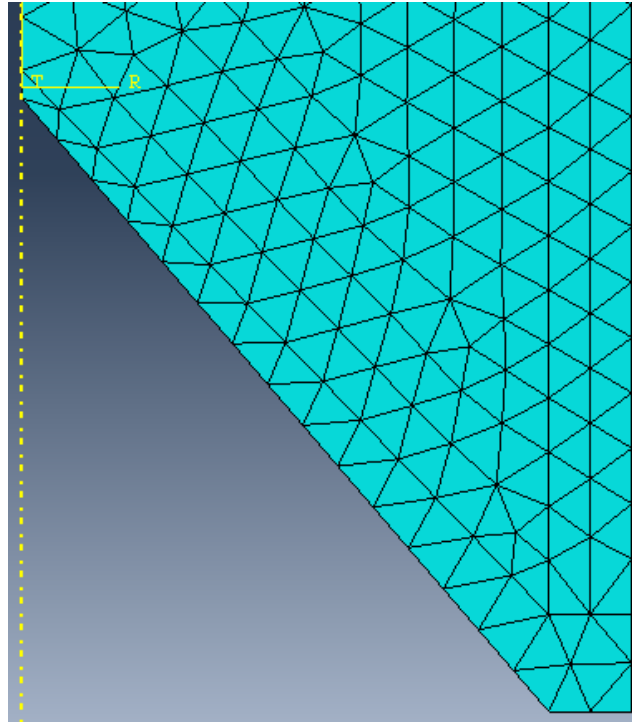


Figure 4 - A basic mesh applied to the liner and the explosive to show the alignment of the nodes in each part.

3.2 Model Materials

OFHC copper was selected for the cone material, this is because copper is a common material used for shaped charges due to its high ductility and it being well-characterised at high strain rates.

Aluminium 6061-T6 is a common material used for shaped charge casings, this is partly due to its low cost and machinability. Additionally, aluminium is a low-density metal that is ductile under high stress loads. This is useful for shaped charges as the casing needs to have minimal interference with the jet formation and these properties are all key in enabling this. As the jet begins to form the casing will rapidly expand and break apart, reducing the time the case can interfere with the cone.

3.2.1 Johnson Cook parameters for the casing and the liner

Table 1 - Johnson Cook parameters of OFHC Copper used for the liner [2].

<i>A (MPa)</i>	<i>B (MPa)</i>	<i>n</i>	<i>C</i>	<i>m</i>
90	292	0.31	0.025	1.09

Table 2 - Johnson Cook Parameters of Aluminium 6061-T6 used for the casing [3].

<i>A (MPa)</i>	<i>B (MPa)</i>	<i>n</i>	<i>C</i>	<i>m</i>
324	114	0.42	0.002	1.34

3.2.2 Elastic and Thermal Properties for Copper and Aluminium

Table 3 - The material properties used in the simulation for OFHC Copper and Al 6061-T6.

<i>Property</i>	<i>OFHC Copper</i>	<i>Al 6061-T6</i>
Density (kg/m ³)	8960	2703
Young's Modulus (GPa)	124	68.9
Poisson's Ratio	0.34	0.33
Melting point (K)	1356	925
Specific heat (J/kg·K)	383	896

3.2.3 Material properties for Trinitrotoluene (TNT)

TNT was selected as the material due to the number of sources available for it. Whilst it is not an explosive that you would typically find in a shaped charge it is frequently used in simulations and for research.

Originally the explosive used was Composition-B, a plastic explosive. However, the simulation struggled to model the explosive with these parameters, potentially due to the plasticity of the material.

Table 4 – The material properties used for TNT in the simulation [4].

<i>Density (kg/m³)</i>	<i>DWS</i>	<i>A (GPa)</i>	<i>B (GPa)</i>	<i>ω</i>	<i>R₁</i>	<i>R₂</i>	<i>Detonation Energy Density</i>
1600	8193	493.6	6.0	0.25	4.749	1.057	3.68x10 ⁶

4 2D Simulation Results and Analysis

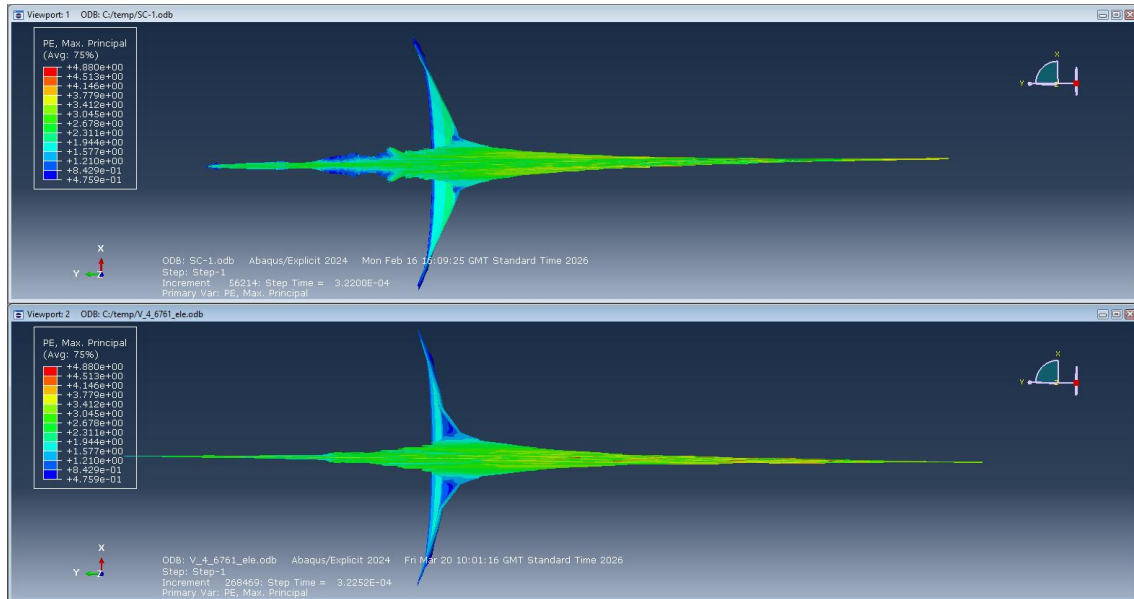


Figure 5 - A comparison in the plastic strain for the constant thickness (top) and the variable thickness (bottom) liners.

Figure 5 shows the plastic strain in the constant and variable thickness conical liners at the point at which the jet has fully formed. At this point the jet for the variable thickness liner is thinner and longer as expected. The strain is more present at the centre of the cone for the variable thickness liner than it is for the constant thickness liner. This is due to the outer edges of the cone being thicker and therefore requiring greater amounts of energy to deform, this shows that more of the energy output from the explosive goes into forming the jet and less goes into the outer part of the cone which does not contribute to the jet. The stress looks similar in both the variable and constant thickness liners, however the high stress area for the variable thickness liner is further along the jet body, this suggests a more uniform plastic deformation during the jet formation which is consistent with the design intent of variable thickness liners.

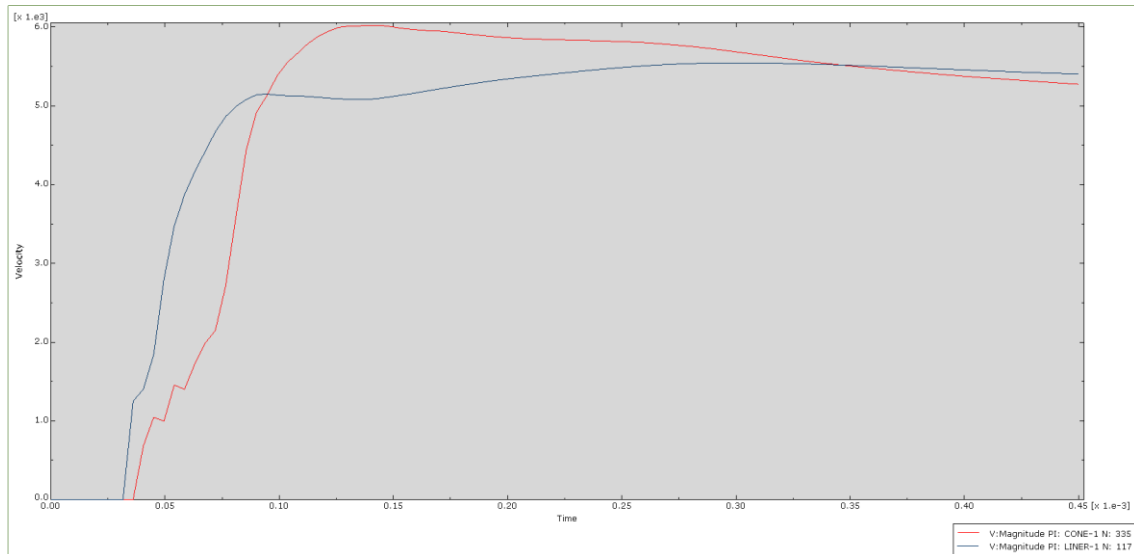


Figure 6 - Velocity plot for the constant thickness (blue) and the variable thickness (red) liners.

Variable thickness liners are designed so that the liner velocity varies along the length of the jet, this produces a more controlled velocity gradient. The velocity plots in figure 6 shows the variable thickness liner reaching a higher peak velocity, 6000m/s, than the constant thickness liner, 5000m/s.

Altogether the simulations show that the variable thickness liner shows more pronounced necking than the constant thickness liner. This is a slightly more volatile design as it shows a higher potential penetration, however if the standoff distance for the shaped charge was too far then the design increases the risk of the jet breaking apart mid-flight prior to penetration.

The bulbous rear section of the liner is more pronounced in the constant thickness liner, this portion of the liner does not contribute to penetration, therefore more material is wasted with this liner design than with the variable thickness liner design.

Overall, the variable thickness conical liner is a more efficient liner design than the constant thickness conical liner, reaching higher peak velocities and a better strain distribution. The main downsides the variable thickness liner has compared with the constant thickness liner is cost; this includes cost to manufacture due to added complexity and the additional computational cost with modelling a more

complex shaped charge design. It is for these reasons that the variable thickness liner has been chosen for the 3D simulation.

5 3D Simulation Results and Analysis

5.1 Simulation issues

To begin with the simulations predominantly failed due to excessive deformation of both the liner, the casing and the explosive at different points. The mesh density and bias were adjusted to try and get the simulation to run for longer, but the parts would still excessively deform before the simulations reached full jet formation.

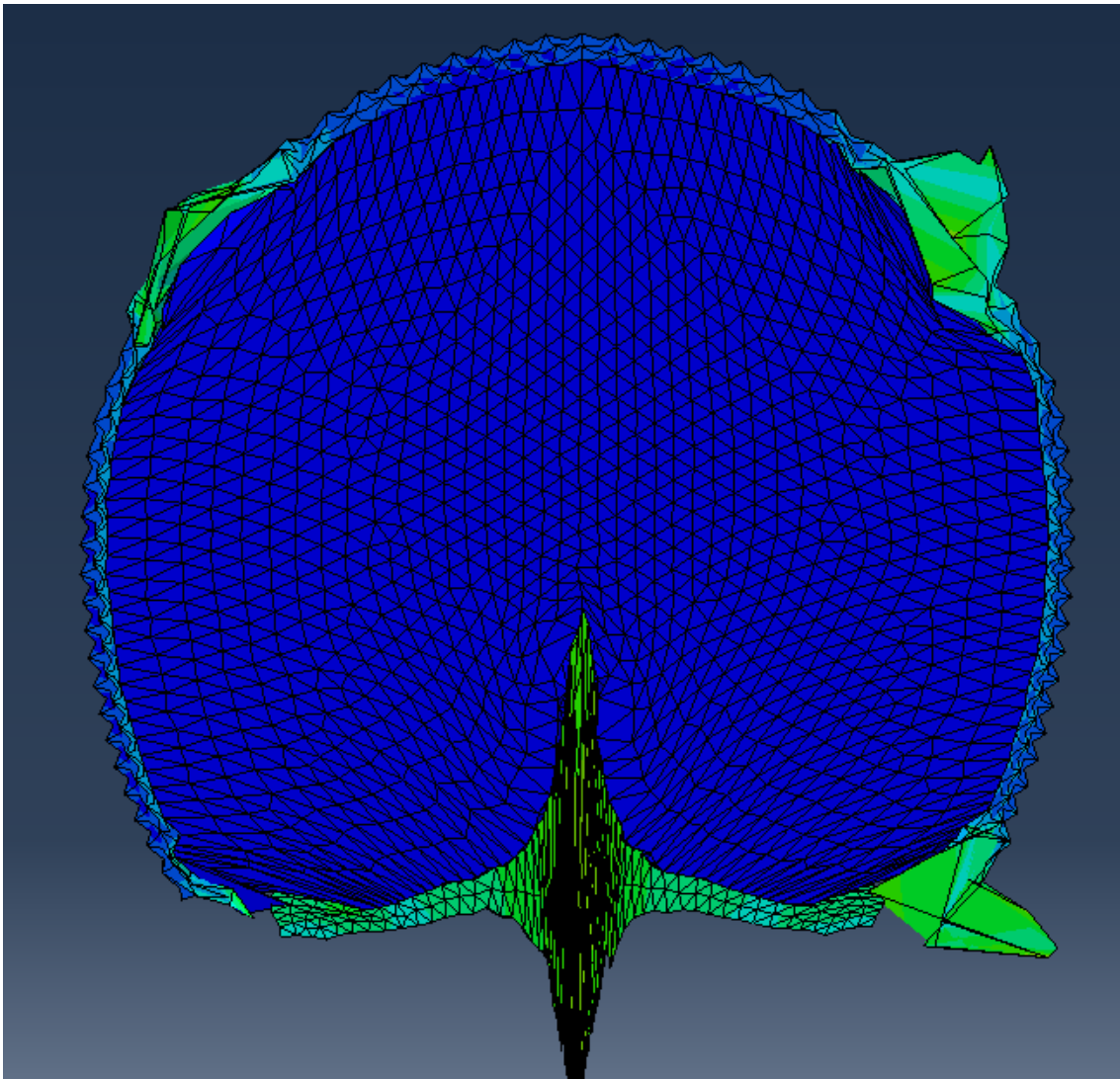


Figure 7 - Original 3D simulation showing excessive case distortion.

To try to fix this problem the first idea was to simplify the mesh to be as basic as reasonably practicable (Figure 8).

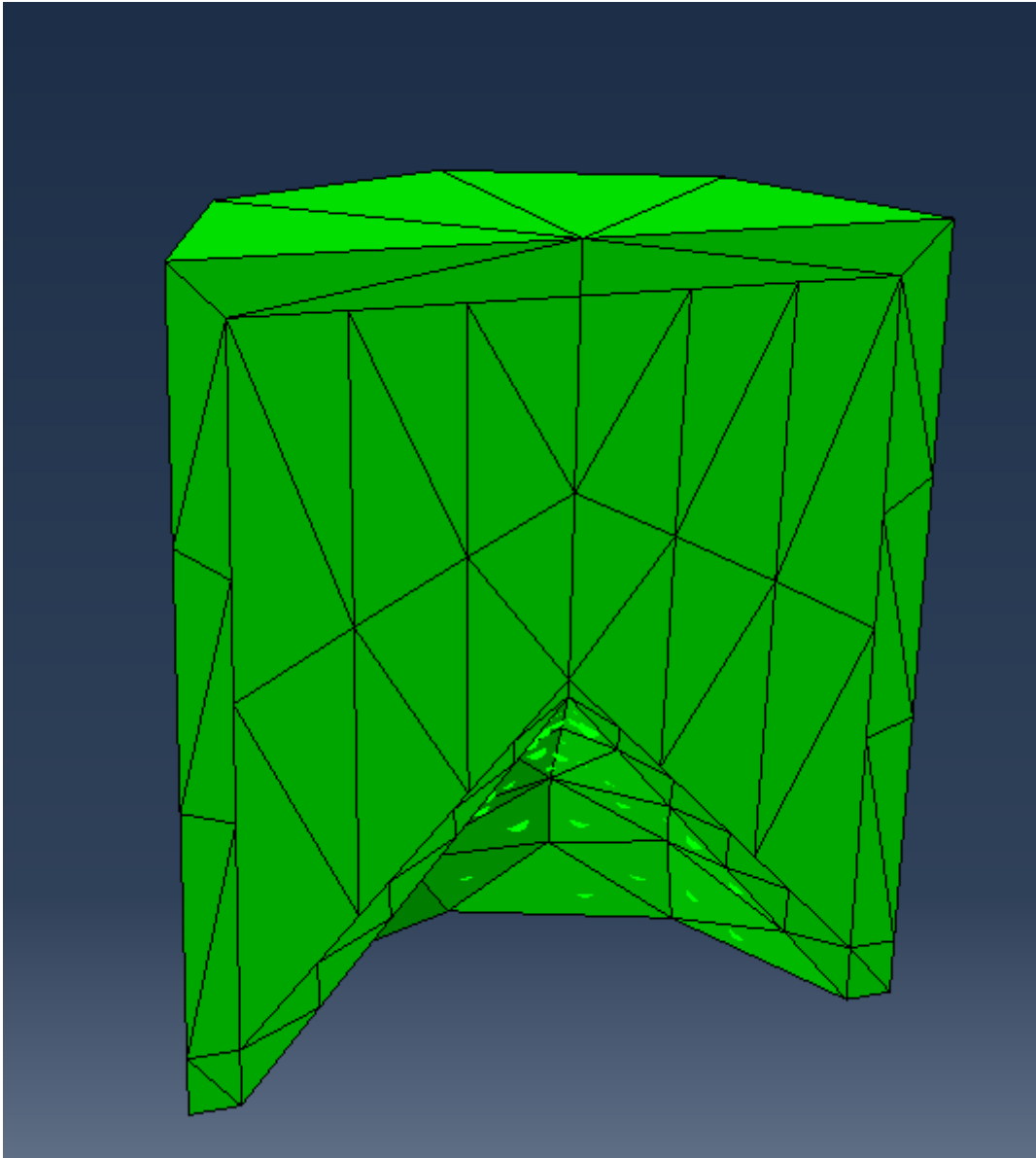


Figure 8 - 3D model with very basic mesh.

The mesh was uniform across each part of the shaped charge and was very coarse with no added bias. The results from this mesh (figure 9) did provide a simulation that ran for the whole duration without being aborted.

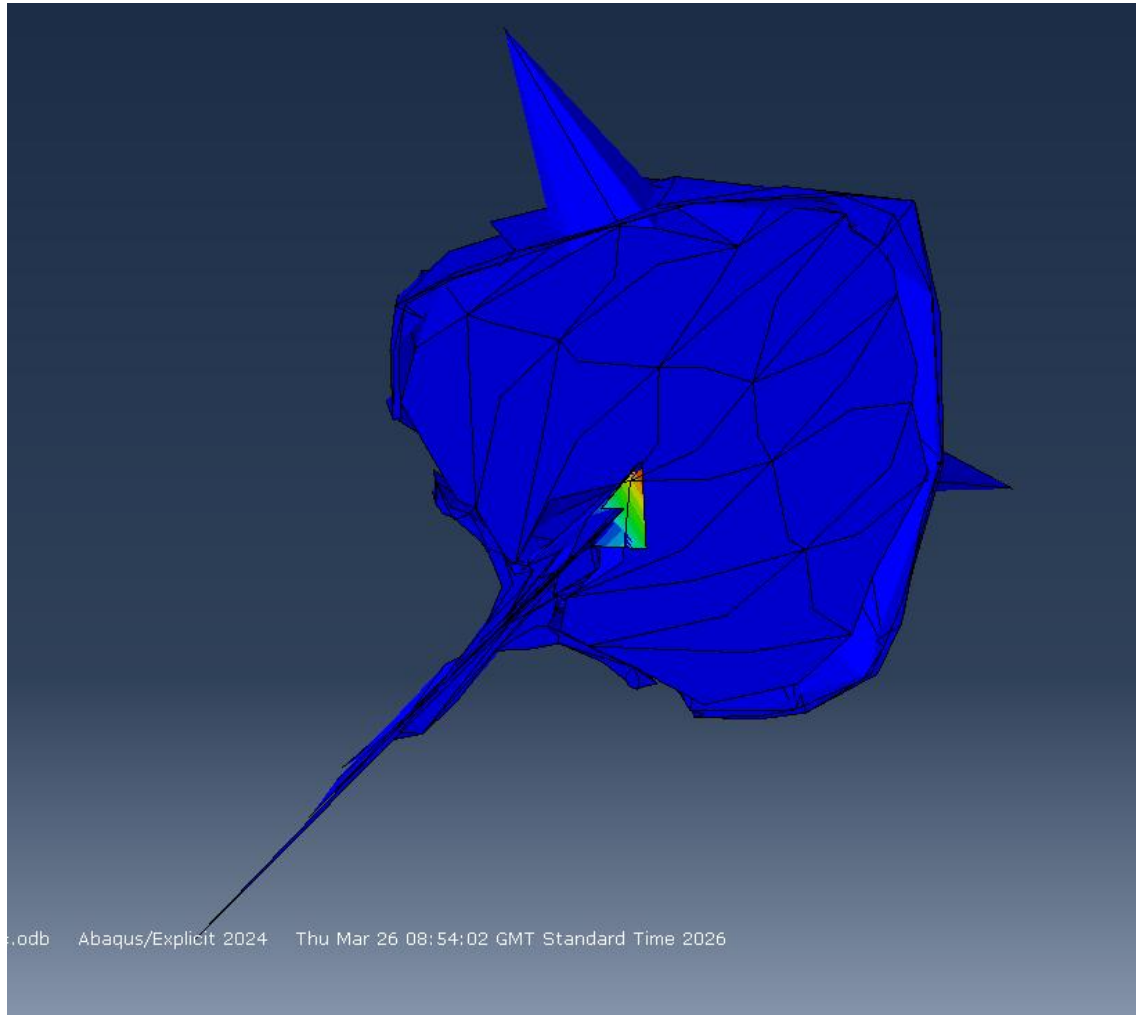


Figure 9 - Results from the coarse 3D mesh.

This simulation proved an effective method of diagnosing the issues with the design. Whilst a full simulation was achieved, the results were very faceted and abstract. This is an artefact from having too few elements, causing the curved surfaces to not be calculated correctly. The elements are very distorted and, in some cases, partially separated from one another. The jet formation is very thin and poorly resolved, showing no close resemblance to the 2D simulation whatsoever. This shows that whilst it is possible to get a full simulation with a coarse mesh, the results are far from accurate. The two main concerns from this

simulation are the excessive deformation of the explosive, as the explosive is shown protruding through the case, and the very high levels of stress shown at the point of the cone. These two areas will need some adjustment to produce a successful 3D simulation.

5.1.1 Smooth Particle Hydrodynamics

To achieve a simulation with a more accurate mesh, there needed to be a way of mitigating the excessive distortion issues that were being experienced in both the liner and the explosive.

One method of combatting these issues involves the usage of smooth particle hydrodynamics (SPH). During the simulation SPH can be used to convert elements into particles, this can be useful for extending the duration of a simulation before it gets aborted due to excessive distortion. Initially the conversion criteria were based on the max principal stress in the liner. From reviewing previous failed 3D simulations, you can retrieve information such as the stress and strain up to the point the simulation was aborted. By selecting the conversion to particle criteria to be equal to the principal stress in the part at the point of excessive distortion, then the simulation can keep running.

However, this led to a problem; the level of stress at which the liner begins to distort is lower than the stress experienced by the liner at the point at which the detonation front begins to interact with it (Figure 10). Due to this at the very start of the simulation, the entire liner would convert to particles, whilst this would achieve a full simulation the results would not be usable. This is due to the particles behaving differently to the elements, instead of forming a jet the particles would instead fire out with a shotgun like spread.

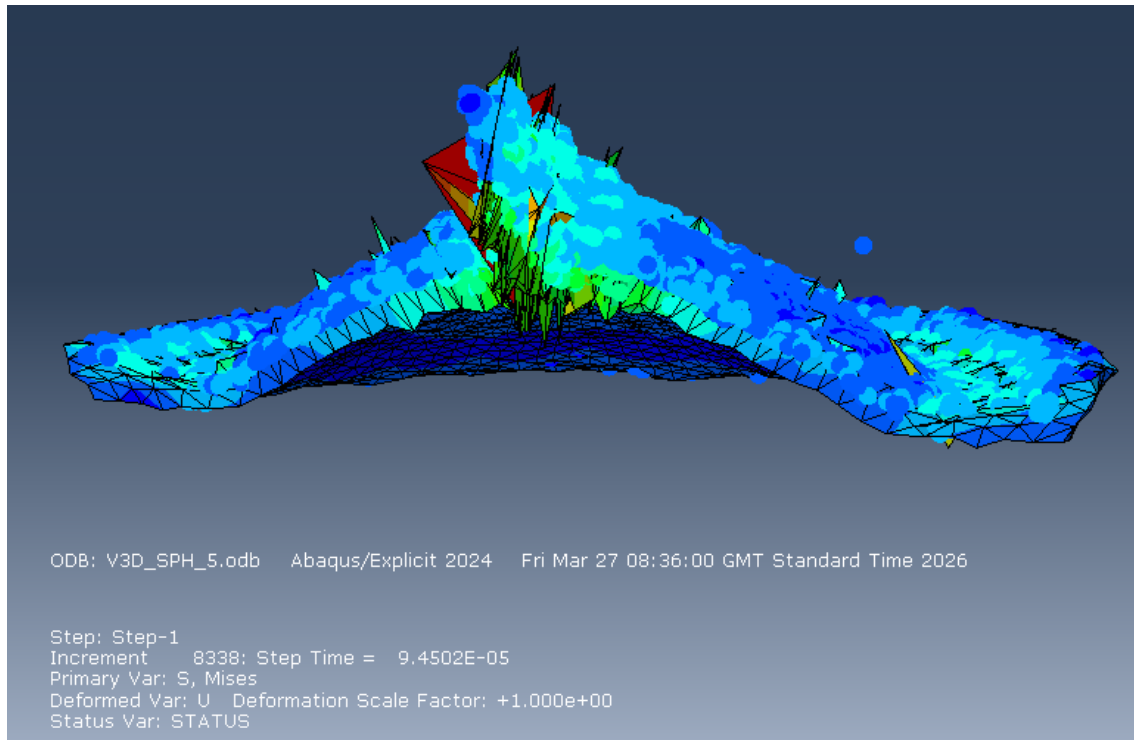


Figure 10 - 3D simulation using SPH with a stress-based criteria.

The next solution was to change the criteria from being stress based to being time based. With information taken from previously aborted simulations, a time could be selected which is just before the moment at which the liner would excessively distort. These settings are shown in figure 11.

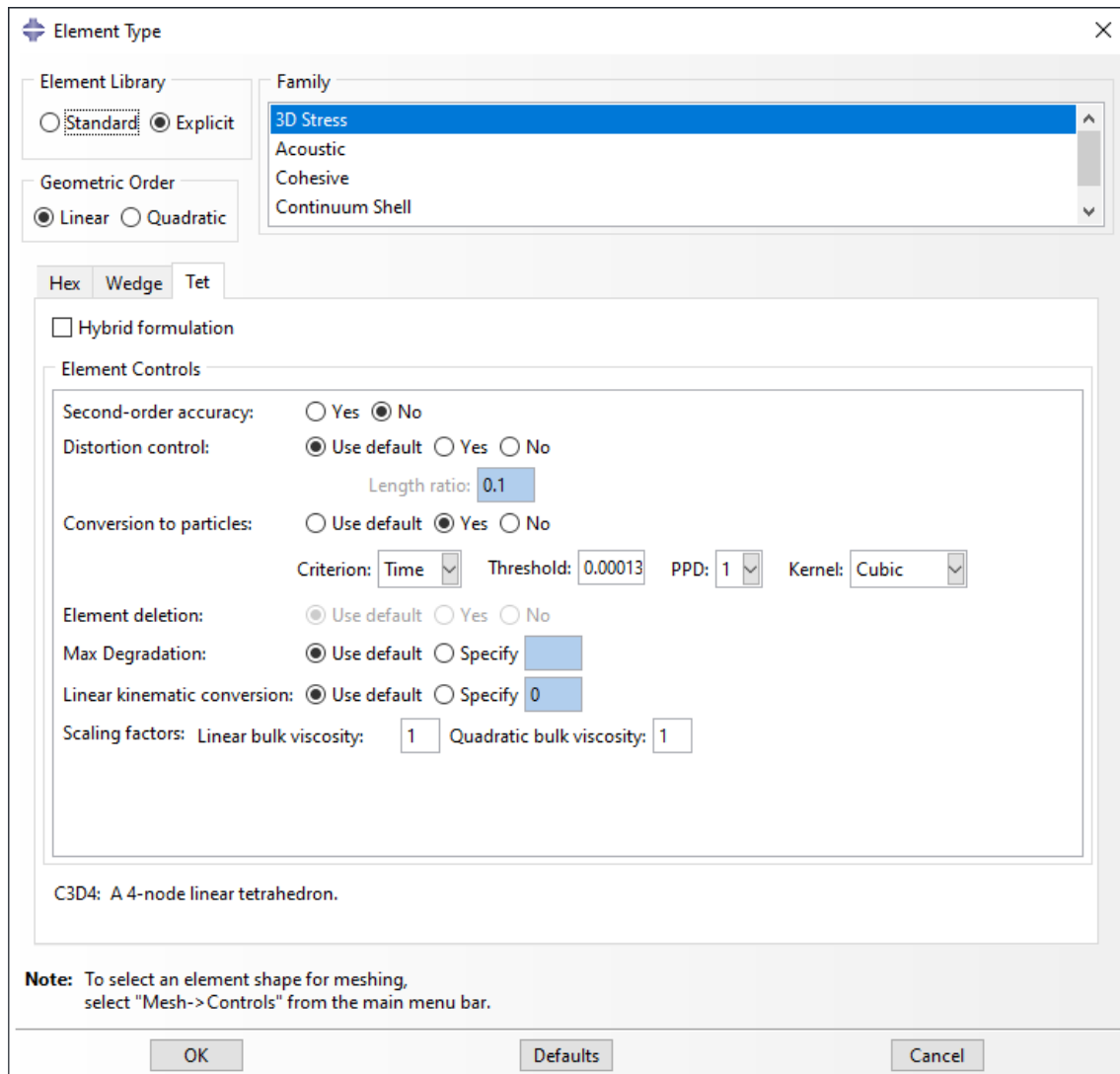


Figure 11 - Model settings used for converting elements to particles.

This provided a much better simulation, with the particles beginning to form a jet. However, this transformation still had to occur too early in the simulation to be able to acquire accurate and comparable results.

5.1.2 Adaptive Meshing and linear bulk viscosity

Due to the lack of success using SPH, it was removed. Instead, the linear bulk viscosity parameter was increased to 10, and adaptive meshing was applied to the model. Ideally the linear bulk viscosity parameter would be set between 0.6 and 1.2, however the struggles with the simulation combined with the lack of time meant that drastic measures had to be implemented to acquire a full simulation. The linear bulk viscosity parameter in ABAQUS acts as a dampener for the

simulation. When the parameter is too low it can cause oscillations in your model which shows as irregular stress patterns in the simulation (Figure 12).

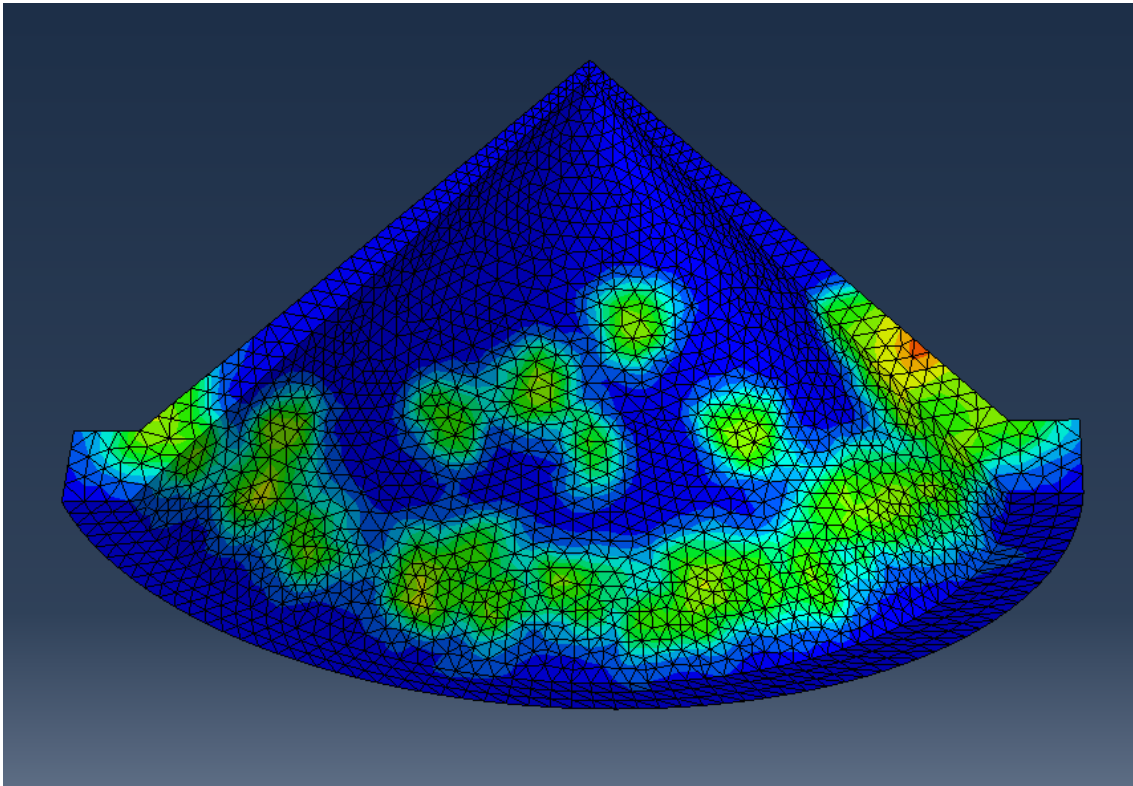


Figure 12 - Irregular stress pattern in the conical liner prior to being shocked by the explosive.

The linear bulk viscosity parameter helps fix this behaviour at the cost of artificially dampening the real physical behaviour in the simulation. This can cause the calculated stresses and velocities of the jet to be underpredicted.

Adaptive meshing was added to the simulation to aid with element distortion. Adaptive meshing rules allow the simulation to re-mesh the parts as the simulation is running, this prevents excessive distortion of parts as the nodes won't be separated too far from one another causing the simulation to be aborted.

5.2 2D and 3D results comparison

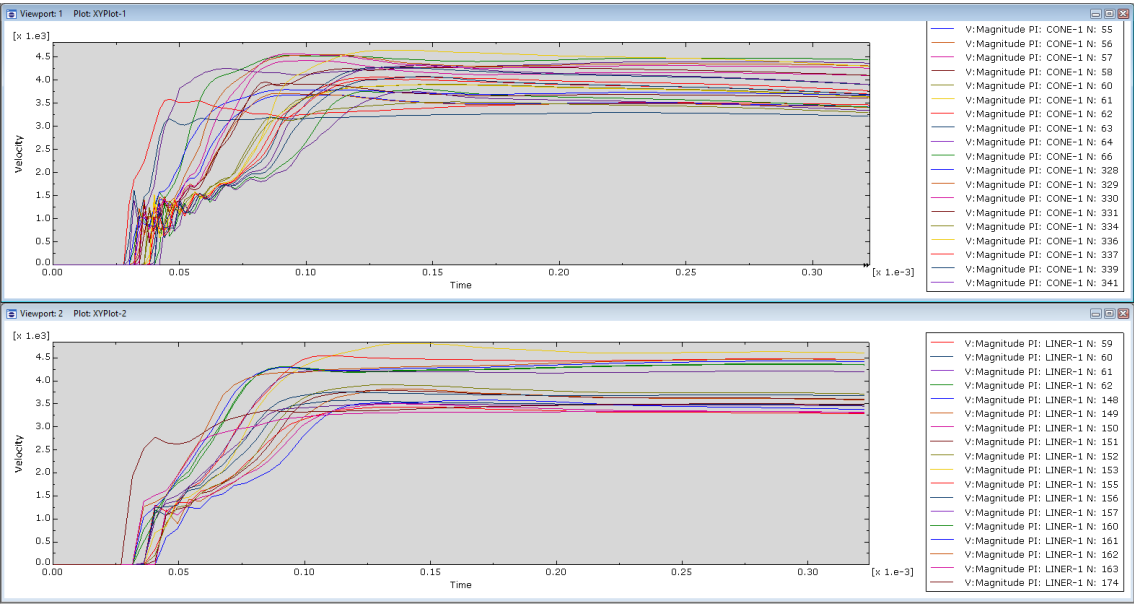


Figure 13 – Velocity plots for the 3D simulation (top) and the 2D simulation (bottom).

Figure 13 shows very similar results for the velocity of the jet for both 2D and 3D simulations, with both simulations showing the main body of the jet travelling between 3000 and 4500 m/s.

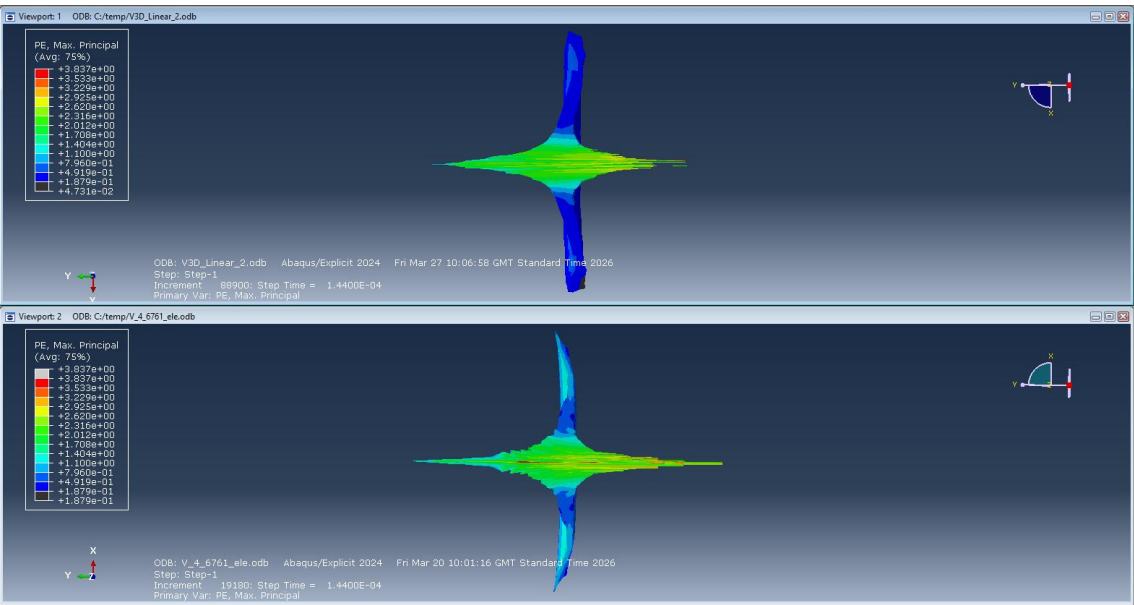


Figure 14 - Comparison in plastic strain between the 3D simulation (top) and the 2D simulation (bottom).

Figure 14 shows two differing results for the formation of the jet and the plastic strain in the material. The jet for the 3D simulation is much bulkier than the 2D simulation, this is potentially due to the linear bulk viscosity parameter used in the 3D simulation. This is a good representation of how this parameter can impact the results. It is worth noting that the 3D simulation failed to run for the entire duration, this is why a much earlier time step was selected, as the 3D simulation never achieved a full jet formation.

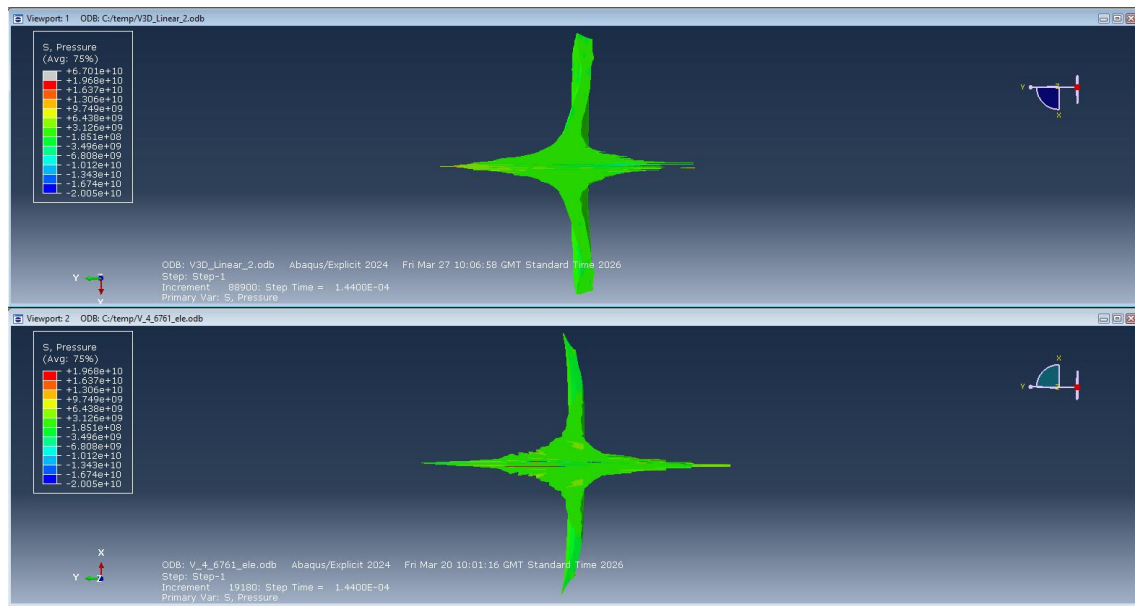


Figure 15 - Comparison of pressure in the liner between the 3D simulation (top) and the 2D simulation (bottom).

The pressure in both 2D and 3D liners are very similar, however the 2D simulation shows more variation and a higher pressure near the centre of the jet. The deformation of the outer area of the cone is notable different in the two simulations. At this time step the 2D simulation shows that the liner has already inverted across the entirety of the cone, however, the 3D simulation shows that the far edges of the cone have still not inverted.

6 Mesh Evaluation

The mesh density was evaluated to understand the computational costs of mesh density on the simulation. These results come from the 3D shaped charge simulation.

Table 5 – A table comparing the impact of mesh density on the simulation time, images of the mesh designs can be found in Figure 16.

<i>Mesh design</i>	<i>Nodes</i>	<i>Elements</i>	<i>Simulation Time (minutes)</i>	<i>Simulated Steps</i>
1	345	524	0.5	100/100
2	1782	3203	2	100/100
3	3611	6761	6	72/100
4	10798	20810	25	37/100

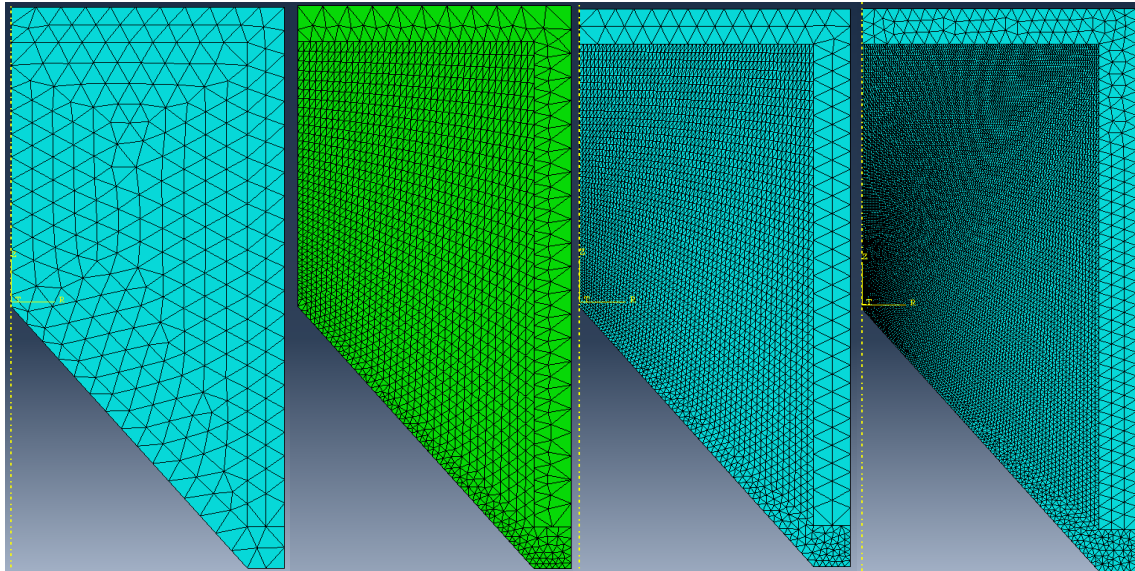


Figure 16 – An image displaying the differing mesh densities from designs 1, 2, 3 and 4 (left to right).

The coarser the mesh the greater the likelihood of completing the simulation, and the time to calculate the result is significantly shorter.

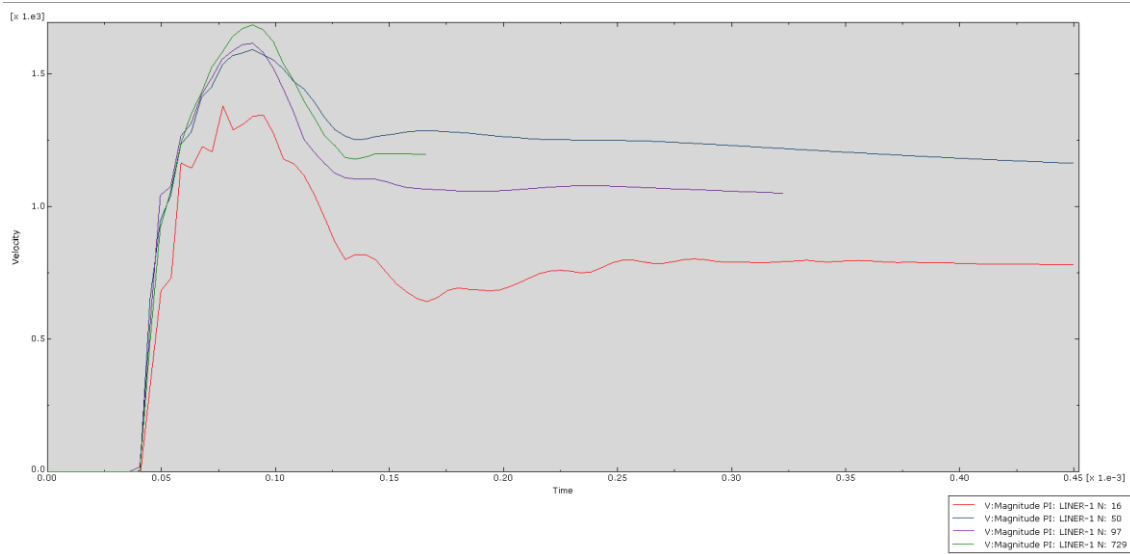


Figure 17 – Peak jet velocity results from simulations of varying mesh densities, from top to bottom: 3203 elements, 20810 elements, 6761 elements and 524 elements.

Figure 17 shows the impact that the mesh size has on the accuracy of the results. The coarse mesh shows the lowest peak velocity by far, approximately 750 m/s. The other results agree more closely on the peak velocity, around 1250 m/s, however due to the excessive distortion of the elements the finer meshes were unable to run a full simulation.

7 Conclusion

For symmetrical parts it is better to perform a 2D simulation than a 3D one. A 2D simulation has a lower computational cost and can provide similar if not better results, as you can revolve your result to create a pseudo 3D simulation.

For 3D simulations it seems to be better to perform a Eulerian simulation rather than a Lagrangian simulation for problems that involve extreme stress, such as those involving explosives. This is due to the mesh not moving for the Eulerian setups which prevents the excessive distortion issues that plagued the 3D simulations using a Lagrangian method. Lagrangian simulations are better for structural loading problems such as beam bending.

In future where possible 2D simulations should be performed in place of full 3D simulations, however in situations where a 2D simulation is not possible for the given problem, then an Eulerian simulation should be performed if the problem involves explosives.

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