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Modelling of Shaped Charges

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Abstract

The shaped charge is a vital tool in applications requiring precise penetration capabilities, with usage spanning military and industrial domains. This report investigates the principles and modelling of shaped charges, focusing on their computational analysis through 2D and 3D simulations. A comprehensive literature review examines the theoretical and material models underlying the behaviour of shaped charges, including the effects of ballistics, blast waves, shock mechanics and penetration capabilities. Two distinct 2D designs are modelled and critically analysed, leading to the selection of an optimal configuration for subsequent 3D modelling. Using ABAQUS Finite Element Analysis (FEA) software, this study evaluates key parameters such as dimensions, meshing strategies such as adaptive, control parameters and smooth particle hydrodynamic conversion to understand the jet formation process and its dependencies. Simulation results reveal critical insights into the performance of the designs and are complemented by evidence-based recommendations for model refinement and validation. This research highlights the importance of computational tools in advancing the understanding and design of shaped charges while suggesting avenues for future experimental verification.

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Introduction

The shaped charge has long been recognised as a cornerstone technology in applications that require precision and penetration, ranging from military ordnance to industrial cutting and demolition. At its core, the shaped charge operates by focusing explosive energy into a high-speed jet, capable of penetrating materials far thicker than the charge's own dimensions. The complexity of its behaviour, governed by phenomena such as shock wave propagation, jet formation, and material deformation, necessitating a thorough understanding of the underlying mechanics and engineering science.

This report explores the theoretical principles and computational modelling of shaped charges, emphasising the use of ABAQUS Finite Element Analysis (FEA) software to design and analyse specific configurations. The study begins with a literature review, providing a foundation for understanding the material models, structural mechanics, and dynamic effects relevant to shaped charges. Following this, two different 2D designs are modelled and analysed to identify the most effective configuration using velocity graphs, range of stresses and penetrative power. The selected design is then extended into a 3D model to capture additional complexities, such as asymmetry and energy dissipation, which cannot be addressed in 2D simulations.

Key aspects of the modelling process, including geometry, material definitions, meshing techniques, and boundary conditions, are examined in detail. The simulation results are explored to evaluate the performance of the designs, with a focus on jet formation, velocity distribution, and the effects of dimensionality on the results. Finally, recommendations are provided for improving the models and validating them against experimental benchmarks, highlighting the potential for further advancements in shaped charge design.

1 Overview of Shaped Charges

A shaped charge is a specialised explosive device engineered to direct its energy into a concentrated, high-velocity jet capable of penetrating materials far thicker than the charge itself. Its distinctive design features a hollow cavity, typically conical or hemispherical in shape, which is lined with a material such as metal although alternatives like ceramics or composites are sometimes employed depending on the application. If this cavity is unlined, it is typically referred to as a "hollow charge". This configuration allows for the rapid deformation and acceleration of the liner material upon detonation, producing the jet responsible for the charge's extraordinary penetrative capability (as illustrated in Figure 1-1). This section provides a foundational overview of shaped charges, emphasising their design principles and versatility in material selection.

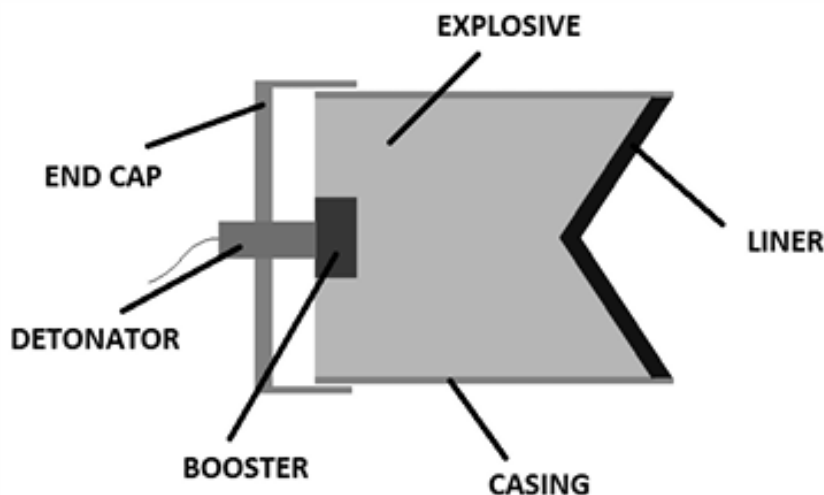


Figure 1-1 Configuration of A Shape Charge [1]

The shape and material of this liner play a crucial role in the behaviour of the charge upon detonation. Common liner shapes include conical, hemispherical, and parabolic geometries, each producing different effects when the explosive is triggered. For instance, a conical liner focuses the explosion into a high-speed jet capable of penetrating armour, while a "bow-shaped" liner forms what's known as an Explosively Formed Penetrator (EFP) are designed to optimise explosive force for specific applications, such as piercing solid targets or delivering high-impact force over a distance [1].

1.1 Applications of Shaped Charges

A shaped charge detonates on impact, liquefying metal, which melts the target which in a military applications this would be tank armour. the explosive energy compresses and directs this liner into a narrow, high-velocity jet that has a high temperature plasma (about 20,000 °C). The jet reaches a density several times that of steel, and the armour becomes plastic and yields whilst the jet torch assists by melting and burning the armour metal [1]. A portion of the liner flows into a compact slug, the large mass at the rear of the jet, this can be seen in Figure 1-2.

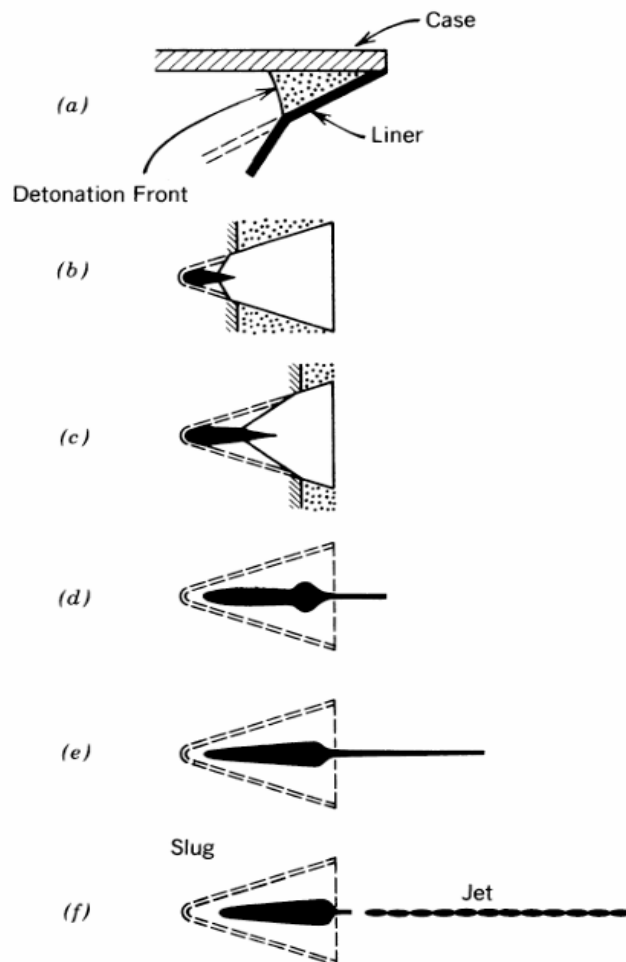


Figure 1-2 The collapse of a shaped charge with a conical liner [3].

2 Fundamentals of Shaped Charge Jet Formation

2.1 Steady State Hydrodynamic Theory

Preliminary jet formation theory was advocated by Birkhoff (1943, 1947) and George (1945). George and Birkhoff proved earlier jet formation theories invalid and discredited them using radiographs. Earlier theories claimed that the penetrating jet were due to either a focusing of the gases detonating, or shock waves interacting, the spallation of the liner material, or a combination of effects, including the theory that jets of gas (from the detonation products) break through the metallic liner and carry fragments resulting from the rupture and erosion of the liner [1]. It was later proved collision results in liner material under tremendous pressure being extruded along the axis of symmetry, as described. This extruded material (the jet). When the generated pressures exceed the yield strength of the liner material, the liner behaves as an inviscid, incompressible fluid [1].

2.2 Rankine-Hugoniot

For successful jet formation in the detonation process conditions are crucial, the Hugoniot relations, describe the conditions across a shock front propagating through a material. They are derived from the fundamental conservation laws of mass, momentum, and energy. The term "Hugoniot" often refers to all possible shocked states that a material can reach through a single shock compression, plotted in a thermodynamic state space, mathematically expressed below [3].

Mass:

Equation 1 Rankine-Hugoniot

Momentum:

$$p_1 u_1 = p_2 u_2$$

Energy:³

$$P_1 + p_1 u_1^2 = P_2 u_2^2$$

$$\left(\frac{1}{2} u_1^2 + h_1 \right) = p^2 u_2 \left(\frac{1}{2} u_2^2 = h_2 \right)$$

Where,

- ρ Mass density²
- T Absolute Temperature²
- S Entropy per-unit-mass
- u Internal energy per-unit-mass
- P Pressure²
- M Mach number V/a
 - V speed of flow
 - a speed of sound

The equations describe the relationships between the physical properties in the two possible states of a moving compressible gas for which mass, momentum and energies are conserved [5].

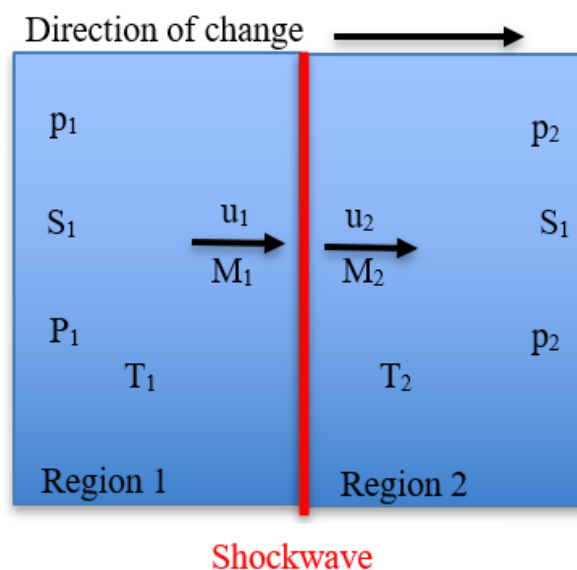


Figure 2-1 Notation of shock wave

The jet formation process is highly dependent on the material properties of the liner and explosive, as well as the charge's geometry, all of which are analysed through the Rankine-Hugoniot framework. The "limit" in Rankine-Hugoniot typically refers to the constraints imposed by material properties, such as the maximum compressibility or yield strength, under extreme pressures [6].

2.3 The Munroe Effect

The Munroe Effect is the foundational principle behind shaped charges, named after Charles E. Munroe, who first observed it in the 19th century. It describes the focusing of the explosive gases (detonation products) by the hollow or concave cavity, resulting in a concentrated, intense force capable of producing deeper penetration in a target compared to a charge without a cavity [1]. Because of this principle, two designs were chosen for analysis, each featuring differently shaped liners: one conical and one trumpet-shaped, to evaluate their uniquely shaped cavities and how these differences differentiate behavioural characteristics.

2.4 Equations of State (EOS)

The Jones-Wilkins-Lee EOS conditions are closely tied to Mie-Grüneisen EOS. These equations describe the relationship between pressure, volume, and energy in the detonation products, helping to predict detonation velocities and pressures.

Equation of state are commonly used to model of elastic-plastic behaviour typically in incremental form, employing a von Mises yield criterion and providing thermal softening, some form of hardening, and effects of strain rate [1]. To be specific JWL values are only valid when the charge is large and Mie-Grüneisen when the charge is slower than the sonic velocity in that which is modeled [7].

2.5 Gurney Theory

The Gurney model is used to estimate the kinetic energy imparted to metal fragments and expanding product gases during an explosive detonation. It calculates the energy available for accelerating the metal by comparing the internal energy of the explosive's expanded products with its unreacted state, ignoring wave dynamics. The model assumes all fragments are ejected at the same initial velocity, with the gaseous product velocity linearly increasing from the explosive's centre to match the metal's velocity at break-up. It provides a quantitative prediction of fragment velocity or impulse across various loading conditions and geometries [7].

2.6 Chapman-Jouguet (CJ)

During detonation, a shock wave compresses the explosive from its initial density, pressure, and temperature (P_0 , P_0 , T_0) to higher values (P_1 , P_1 , T_1), initiating chemical reactions. Once detonation is complete, the explosive's density, pressure, and temperature (P_2 , P_2 , T_2) correspond to the detonation product's state on the shock adiabetic curve, expanding isentropically into the surroundings. The Rayleigh line, representing the relationship between these states, is defined by the detonation velocity, with the Chapman-Jouguet (C-J) point marking the end of chemical reactions where the Rayleigh line tangentially intersects the adiabetic shock curve (illustrated in Figure 2-2), [7].

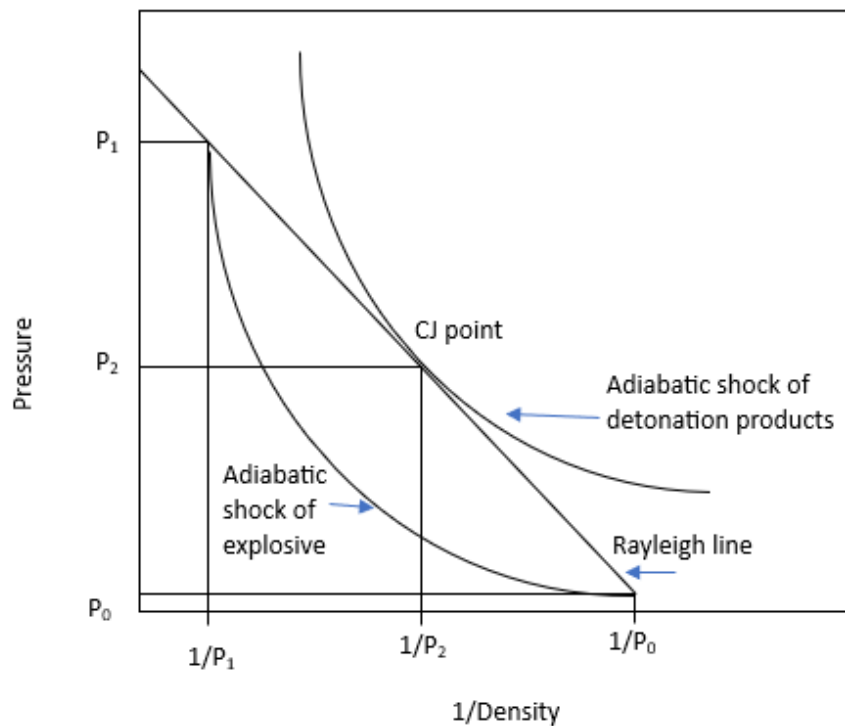


Figure 2-2 Adiabatic Shock of the Explosive and its Detonation Products in the Case of Steady State Detonation [7]

3 Modelling and Simulation of Shaped Charge Jets

Using the ABAQUS Software Application, two 2D simulations of shaped charges were conducted to analyse jet formation and penetration dynamics. The simulations were oriented within the X and Y planes to model cross-sectional interactions, focusing on the detonation effects during liner collapse and jet velocity in a two-dimensional framework. This setup allowed for accurate 2D analysis of material deformation and shock propagation along the orthogonal axes, providing insights into the behaviour of the charge under controlled conditions. Before modelling one 3D design under similar analysis.

3.1 Shape Charge Configuration Material Parameters

All designs were three-part constructed, Low Carbon Steel casing, TNT explosive material and OFHC Copper liner, exact parameters can be found in Tables 4-6

Table 1 Material Properties of TNT High Explosive [4]

Material Properties of TNT									
JWL EOS							Density (Kg/m ³)		
Detonation Wave Speed (m/s)	A	B	Omega	R1	R2	Detonation Energy Dens (Pa)	Pre-deton Bulk Modulus (Pa)		
6930	3.74E+11	3.74E+09	0.33	406	1.05	6.06E+06	0	1800	

Table 2 Material Properties of OFHC Copper Liner [5]

Material Properties of Copper															
Johnson-Cook Constants (Plasticity Model)						Density (Kg/m ³)	Shear Modulus (GP. Mie-Grüneisen (EOS)				EOS				
A (MPa)	B (MPa)	n	C	M			A (MPa)	B (MPa)	n		D (x10 ⁻³) p	$\dot{\epsilon}_{ref}$ (s ⁻¹)	C (m/s)	S	
90	292	0.31	0.025	1.09		8960	47.7	250	100	0.24	500	2	1	3933	1.52

Table 3 Material Properties of Low Carbon Steel Casing [6]

Material Properties of Low Carbon Steel

Johnson Cook Parameters								Younges Modulus (GPa)	Density (Kg/m ³)	Poisson's Ratio
A (GPa)	B (GPa)	C	m	n	$\dot{\epsilon}_0$ (s ⁻¹)	T _m (°C)	T _r (°C)			
175	380	0.06	0.55	0.32	1	1536	25	E = 208	p = 7800	v = 0.29

3.2 Target Material Properties

A target was modelled using the parameters below, (Table 6). This was later introduced to the simulations to accurately assess the penetrative power and behaviours of each shaped charge design.

Table 4 Material Properties of CP-Titanium Target [6]

Material Properties of CP- Titanium

Johnson Cook Damage Parameters					Younges Modulus (GPa)	Density (Kg/m ³)	Poisson's Ratio
D1	D2	D3	D4	D5			
0.021	0.132	-1.1	0.0238	3.451	E = 163	p = 4510	v = 0.3

4 Computational Approach for 2D Designs

Designs One and Two both terminated due to excessive element distortion; however, valuable data was still successfully captured before the simulation aborted.

4.1 Design One Conical Liner Configuration & Meshing

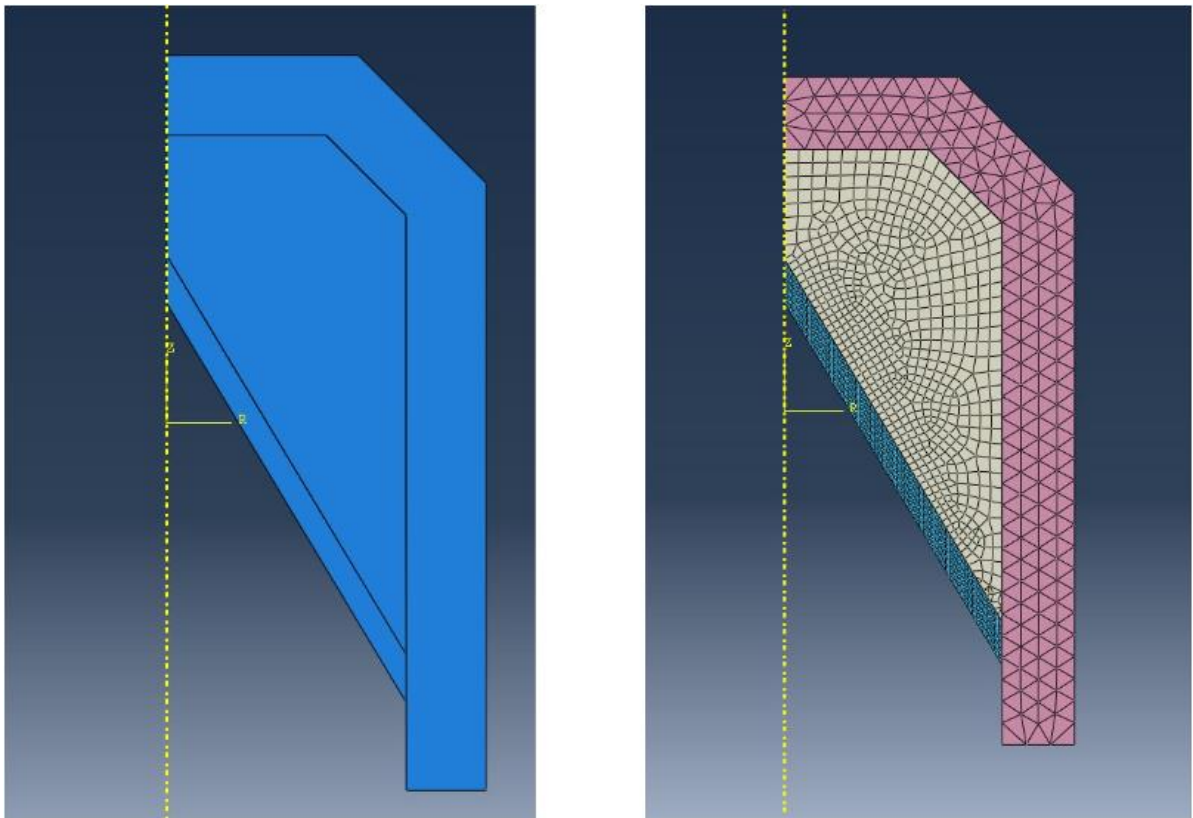


Figure 4-1 Design One Conical Liner Configuration

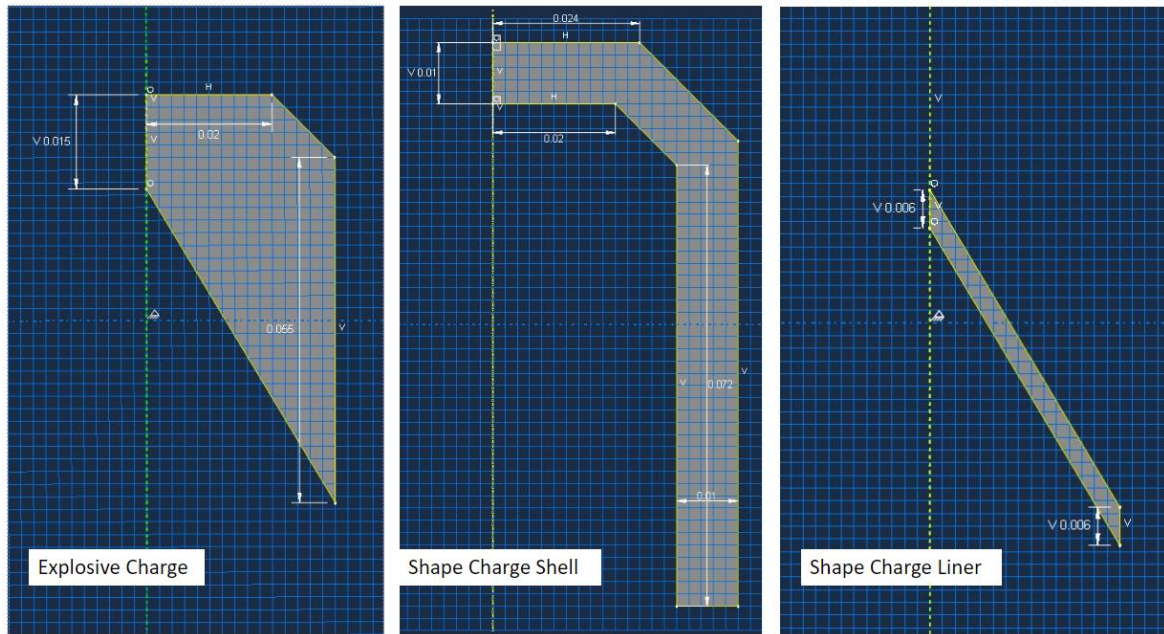


Figure 4-2 Design One Conical Liner Geometry

To achieve the mesh configuration, the geometry was partitioned into multiple regions to allow tailored meshing strategies for different areas of the model. A combination of tetrahedral (TET) and hexahedral (HEX) meshes were later introduced. TET elements were applied to complex regions for their flexibility, while HEX elements were used in structured areas to enhance computational efficiency and accuracy. Local mesh sizes were refined in critical regions, such as the liner's apex, to capture detailed behaviour, while coarser meshes were applied in less critical zones to reduce computational challenges such as the 250,000-node licensing limit. Element controls were assigned to ensure high quality mesh generation, minimising distortion and maintaining element integrity. Smooth transitions between mesh densities and types were carefully managed

to avoid numerical instabilities, providing an optimised balance between precision and computational efficiency.

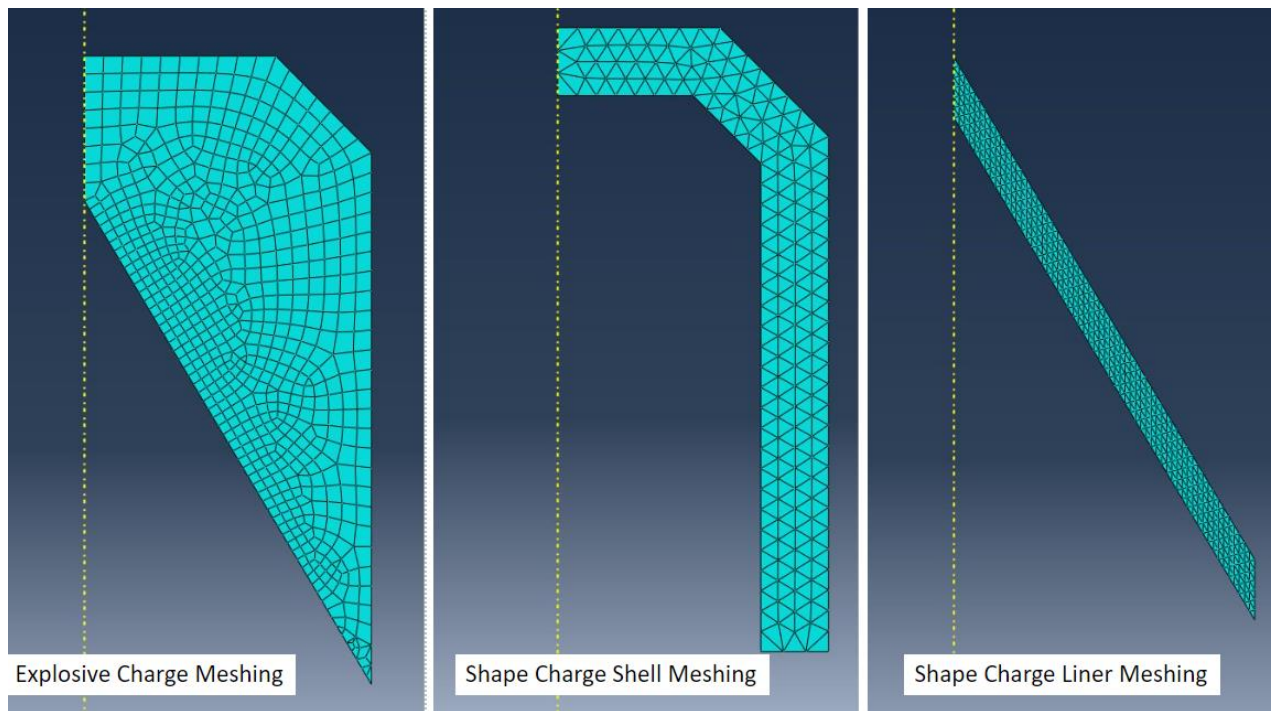


Figure 4-3 - Design One Conical Liner Meshing

4.2 Design Two Trumpet Liner Configuration & Meshing

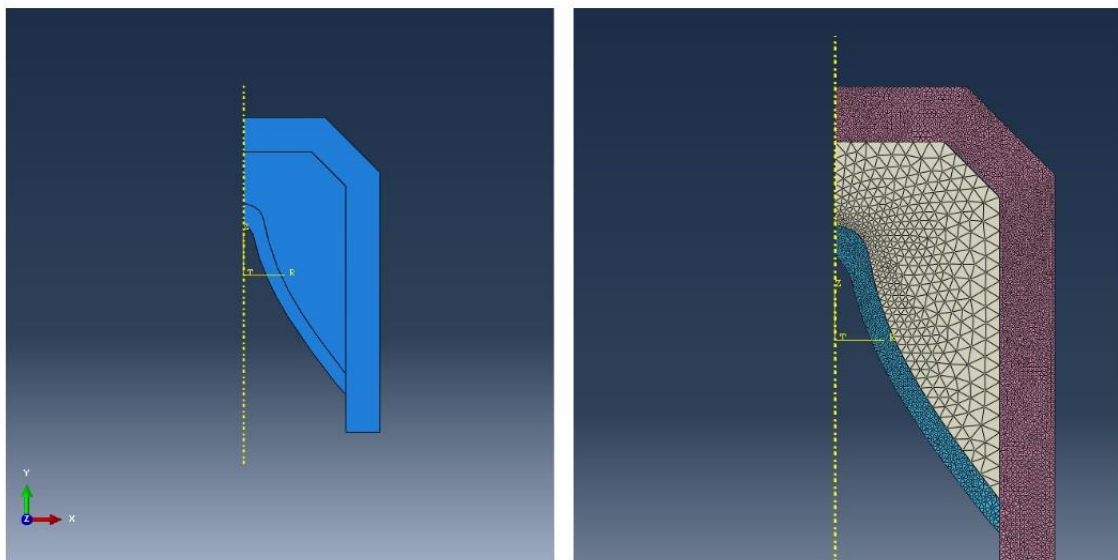


Figure 4-4 Design Two Trumpet Liner Configuration

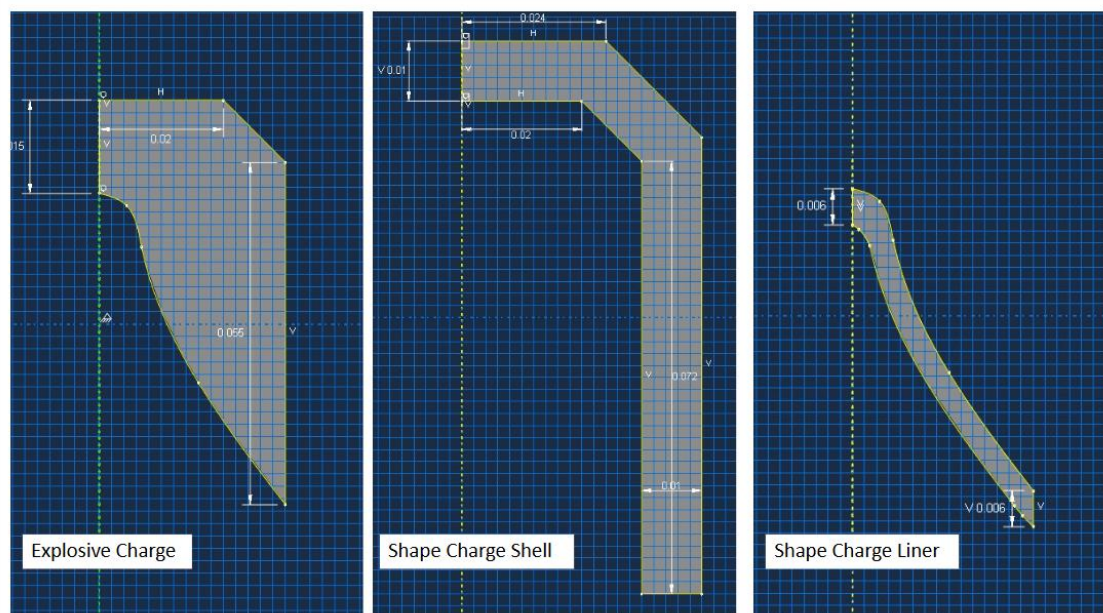


Figure 4-5 Design Two Trumpet Liner Geometry

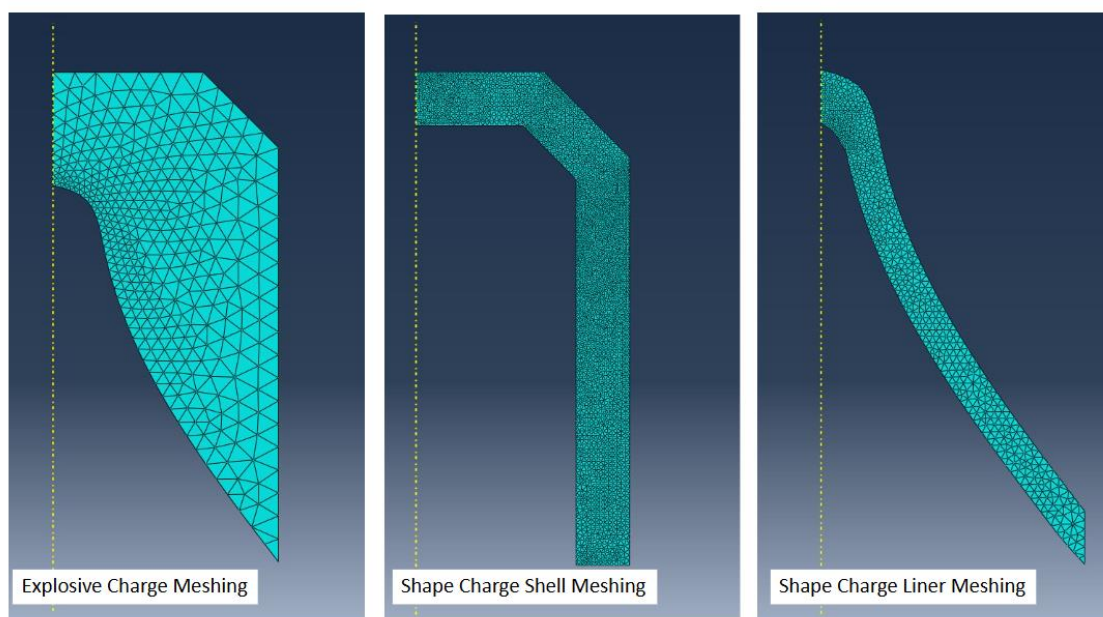


Figure 4-6 Design Two Trumpet Liner Meshing

4.3 Pressure Distribution For Conical and Trumpet Designs

Figure 4-7 and Figure 4-8 illustrates the pressure distribution throughout the detonation process within both the conical and trumpet, copper liner design.

Figure 4-7, and Figure 4-8, section A present the shaped charge before detonation, with low-pressure regions represented in blue. Once detonation is initiated, seen in section B of these figures the pressure spikes near the apex of the liner, shown in red, with these high-pressure areas measuring approximately 9.057GPa. This red area indicates the high-pressure shock front propagating through the TNT, transforming the explosive material into gas and releasing energy to begin deforming the liner.

Section C, the high-pressure region expands, causing the liner to start collapsing inward, being an essential step in forming the high-velocity jet characteristic of shaped charges, during this phase the shock wave propagates and interacts with the liner, the pressure intensifies further, reaching approximately 28.8GPa. This increase reflects how the shock wave compresses the liner material, concentrating the pressure and accelerating the liner inward to form a focused, high-speed jet.

Section D, At this stage, tremendous pressure on the copper liner resulted in the liner collapsing along the axis of symmetry. This pressure far exceeds the yield strength of the copper liner, behaving perhaps as an inviscid, incompressible fluid. The cone collapses progressively from apex to base under point initiation of the high explosive [7].

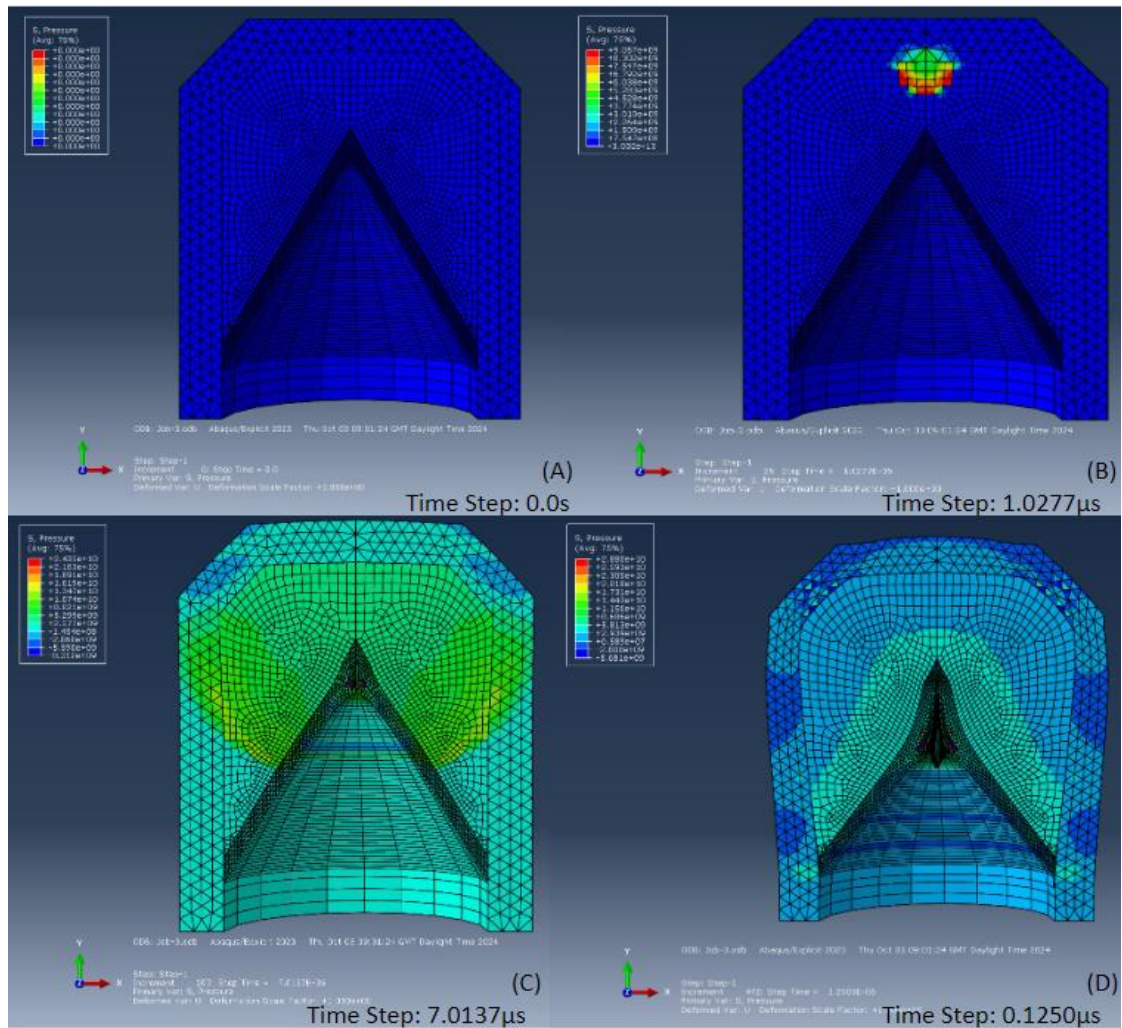


Figure 4-7 - Design One Conical Liner Pressure Distribution

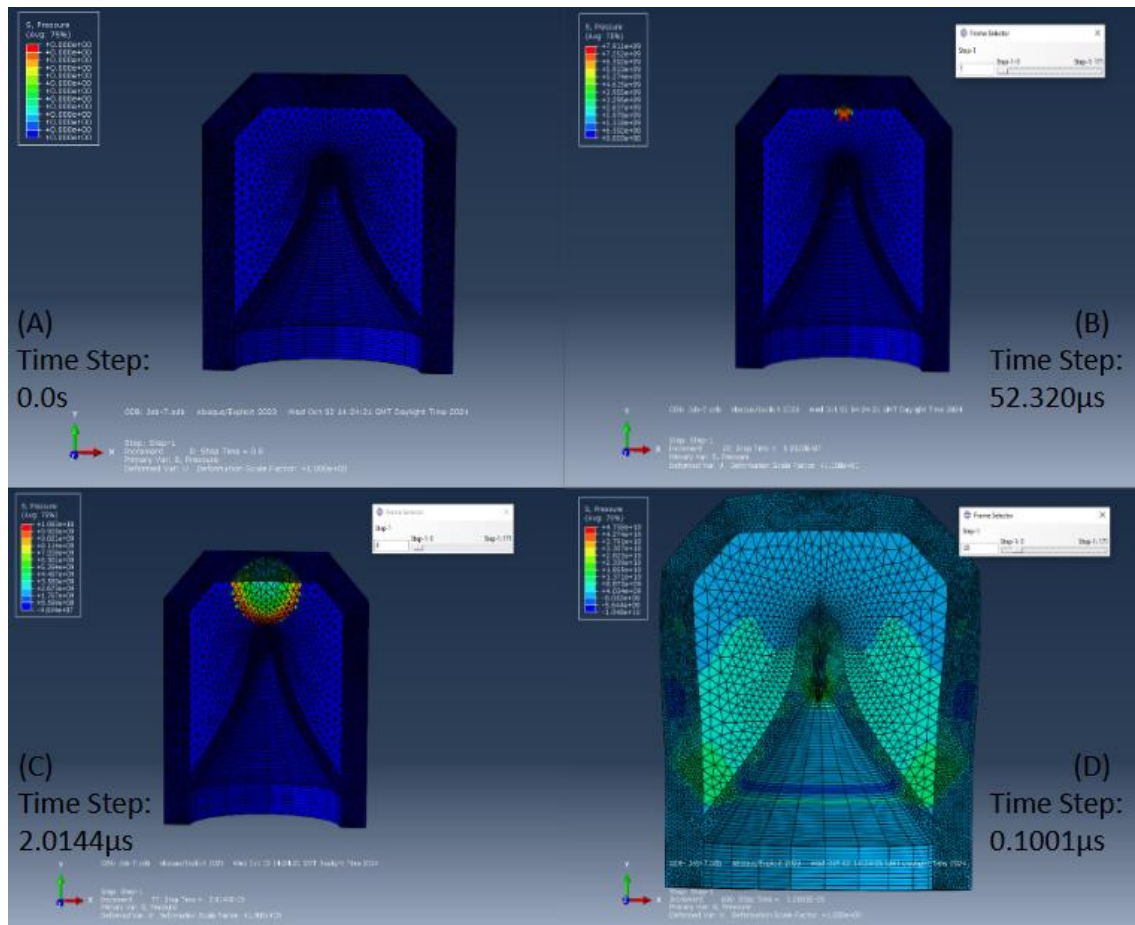


Figure 4-8 Design Two Trumpet Liner Pressure Distribution

Overall, both designs exhibit similar detonation properties. However, in Sequence 2, the trumpet design shows a high-pressure region that expands while remaining concentrated around the apex for a longer duration. This sustained concentration intensifies pressure along the liner's inner walls. The progression of the pressure wave in Sequence 2 displays a distinct spread pattern compared to Sequence 1, which uses a conical liner.

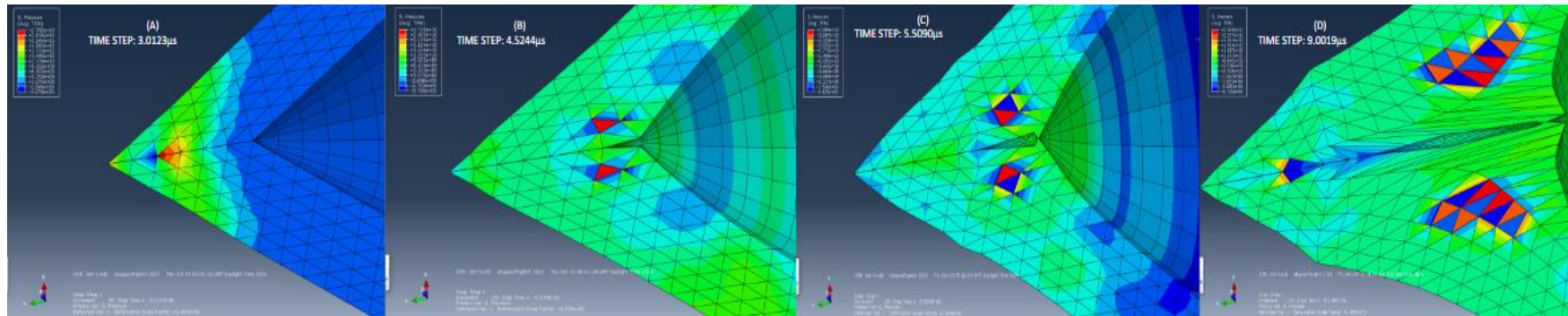


Figure 4-9 Design One Conical Liner Apex Pressure Deformation

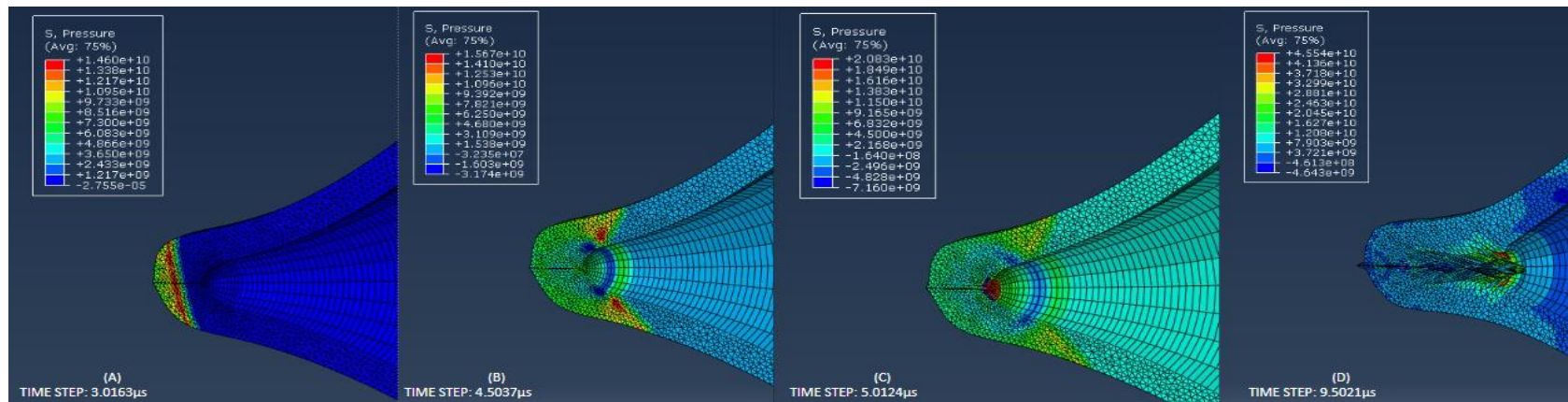


Figure 4-10 Design Two Trumpet Liner Apex Pressure Deformation

Close-up view of the pressure wave collapsing at the apex, highlighting visible deformation and distortion in the elements and nodes.

4.4 Principle Stress for Both Conical and Trumpet Designs

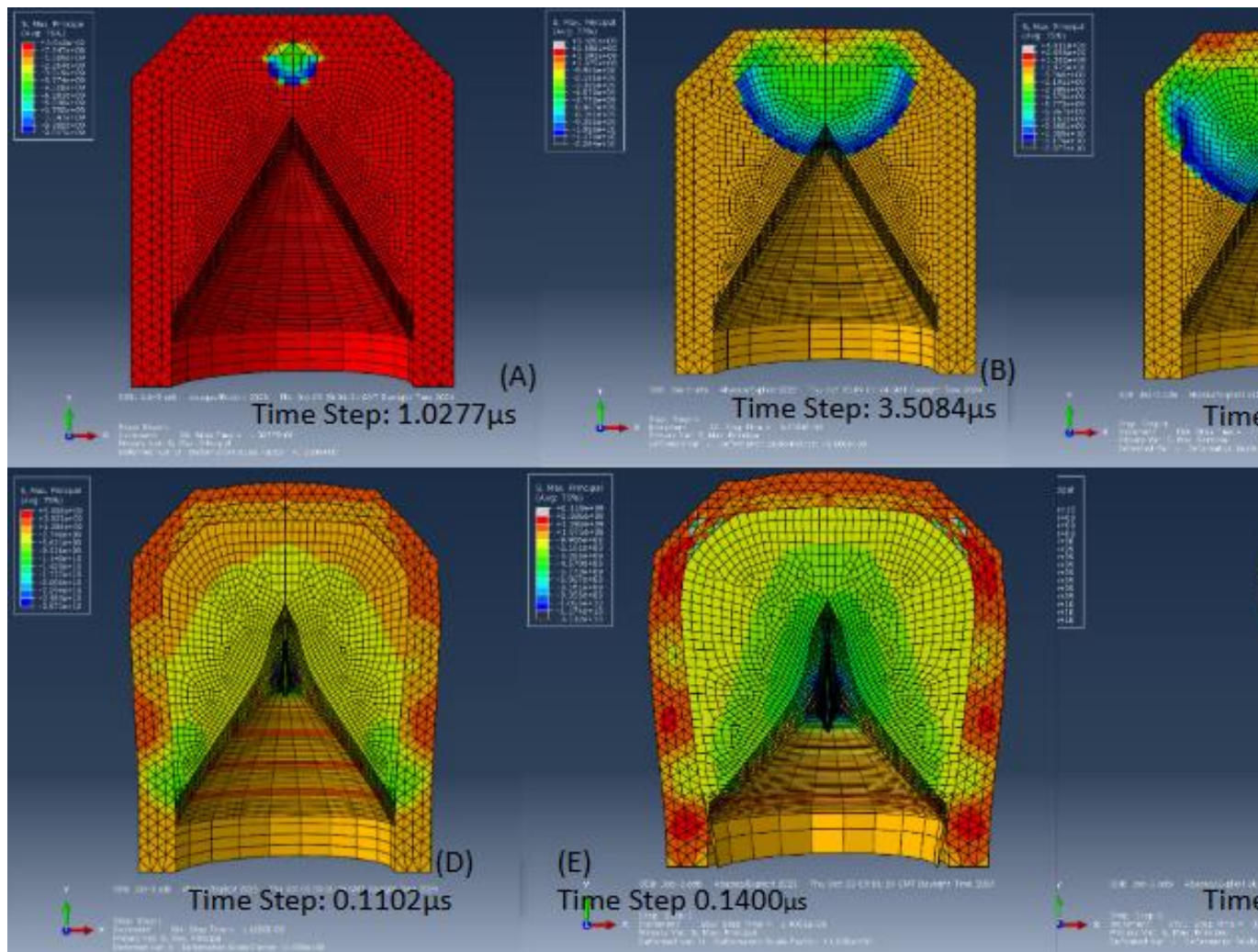


Figure 4-11 below gives visual aid to the principle stresses present as the pressure wave propagates through Design Ones shape charge, Negative values such as $-3.112 \times 10^{10} \text{ Pa}$ and positive approximate value, $6.118 \times 10^9 \text{ Pa}$ In frame (E), provides insight into the behaviours present in the creation of the high velocity jet.

- **Blue or green:** In this analysis these colours indicate lower principal stress values in the negative region, meaning these areas experience less critical stress, and typically undergo compression.
- **Yellow to red:** These warmer colours represent higher principal stress levels within the positive value region, highlighting areas where the material is most stressed and therefore more vulnerable to failure, tensile stress can be observed here.

These colour representations are also applicable to Section (D) of Design Two Figure 4-12. Positive values reach around $1.627 \times 10^{10} \text{Pa}$ and negative values extend to approximately $-6.340 \times 10^{10} \text{Pa}$. Additionally, the positive values are shown in shades including grey, while negative values are depicted with black. Design Two's pressure range is more extensive compared to Design One, in frame (E). Section (D) was selected to match a similar time step to Design One, providing insight into the differing pressure behaviours and their impact on high-velocity jet formation.

4.4.1 Conical Liner Range of Principle Stress

The disparity between the maximum tensile and minimum compressive stresses could indicate areas of complex loading, such as bending or combined axial and bending forces.

Design One:

Equation 2 Design One Principal Stress Range

$$6.118 \times 10^9 \text{Pa} - (-3.112 \times 10^{10} \text{Pa}) = 3.723 \times 10^{10} \text{Pa}$$

Design Two:

Equation 3 Design Two Principal Stress Range

$$1.627 \times 10^{10} \text{Pa} - (-6.340 \times 10^{10} \text{Pa}) = 7.967 \times 10^{10} \text{Pa}$$

The principle stress ranges calculated for each design reveal significant differences, Design Two exhibits a much larger range suggesting the shape charge is experiencing significant cyclic stress or fluctuating stresses, tensile and compressive forces are acting with a large difference in magnitude. Differences become apparent in the visual time-step analysis for each design, at a comparable time step, such as $0.1 \mu\text{s}$ for both Design One and Two, the

intensified pressure distribution in Design Two leads to a quicker collapse of the liner and faster jet formation. This rapid sequence of events indicates that the larger pressure differential is accelerating the liner collapse, which contributes to the earlier and potentially more powerful jet formation observed.

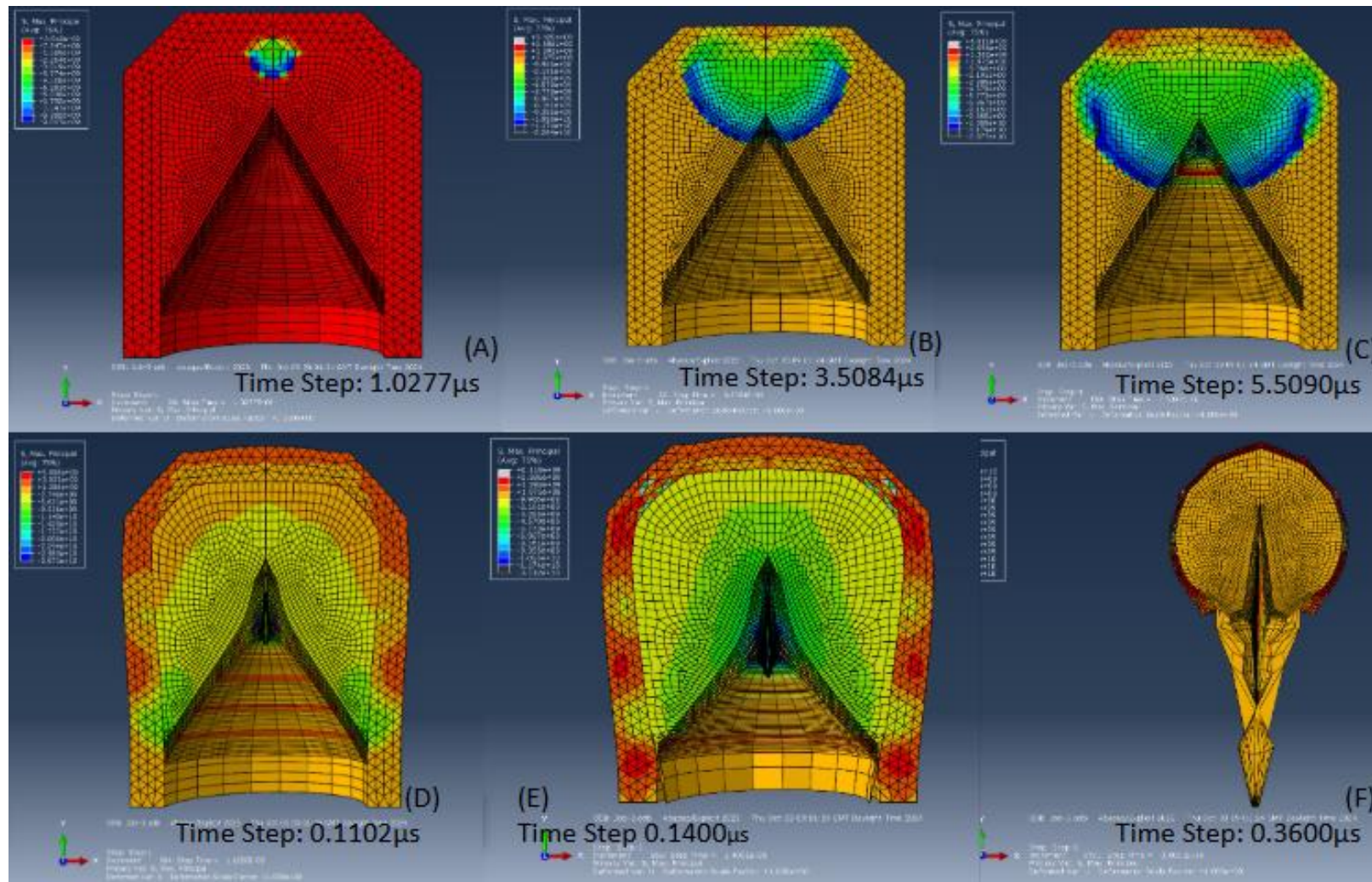


Figure 4-11 Design One Conical Liner Shape Charge Principal Stresses

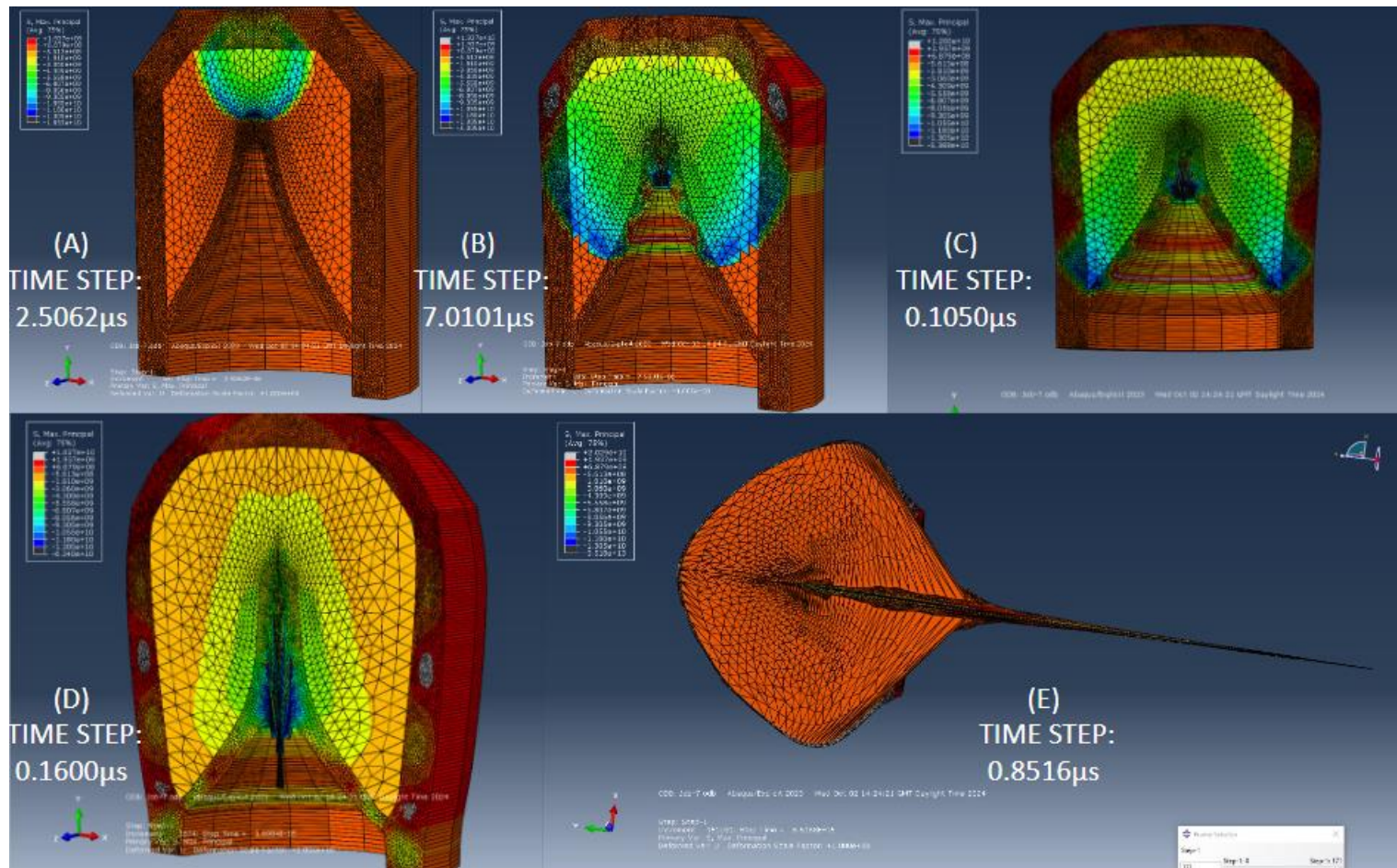


Figure 4-12 Design Two Trumpet Liner Shape Charge Principal Stresses

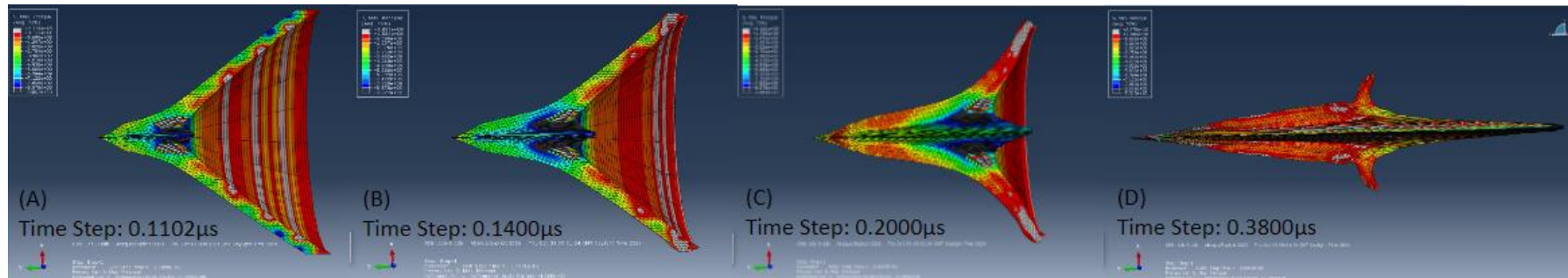


Figure 4-13 Design One Principal Stresses Conical Liner Collapse

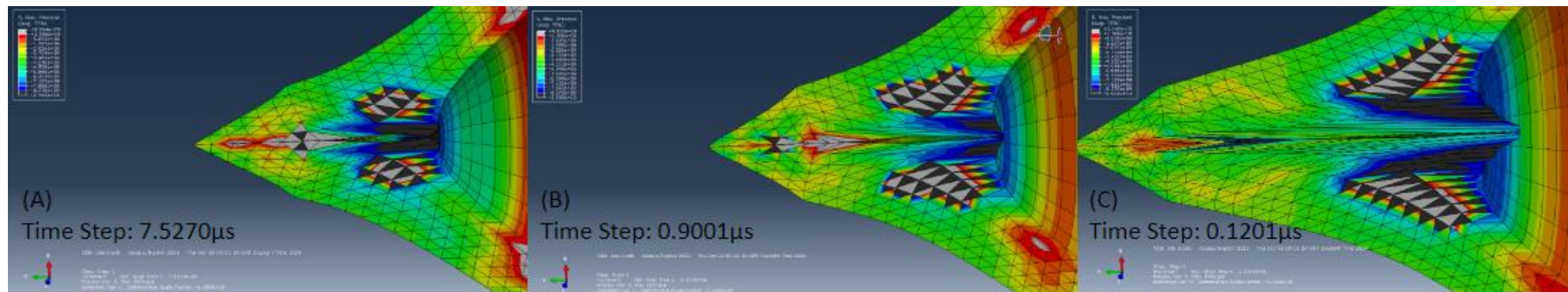


Figure 4-14 Design One Principal Stresses On Apex Of Conical Liner Jet Formation

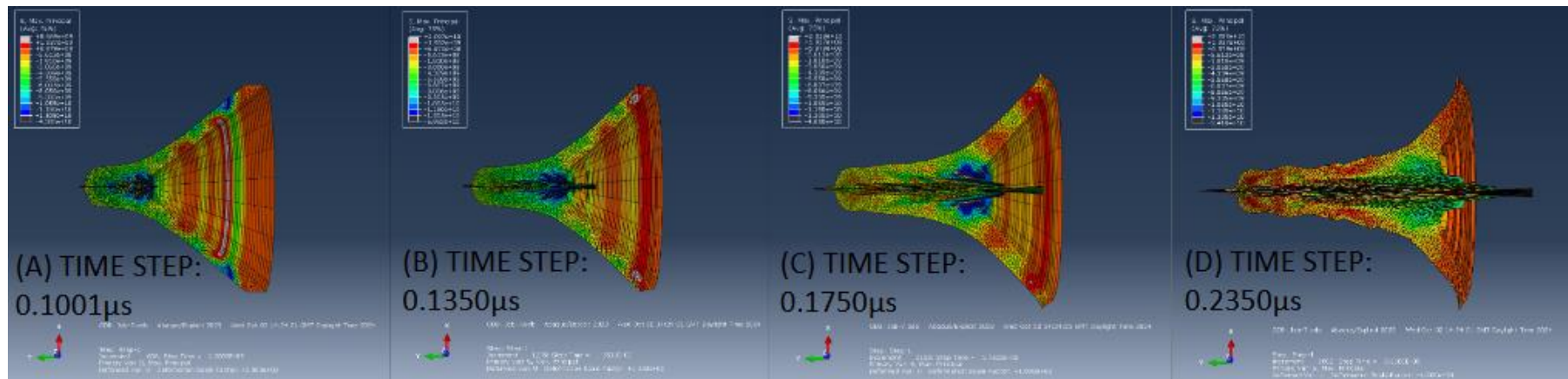


Figure 4-15 Design Two Principal Stresses Trumpet Liner Collapse

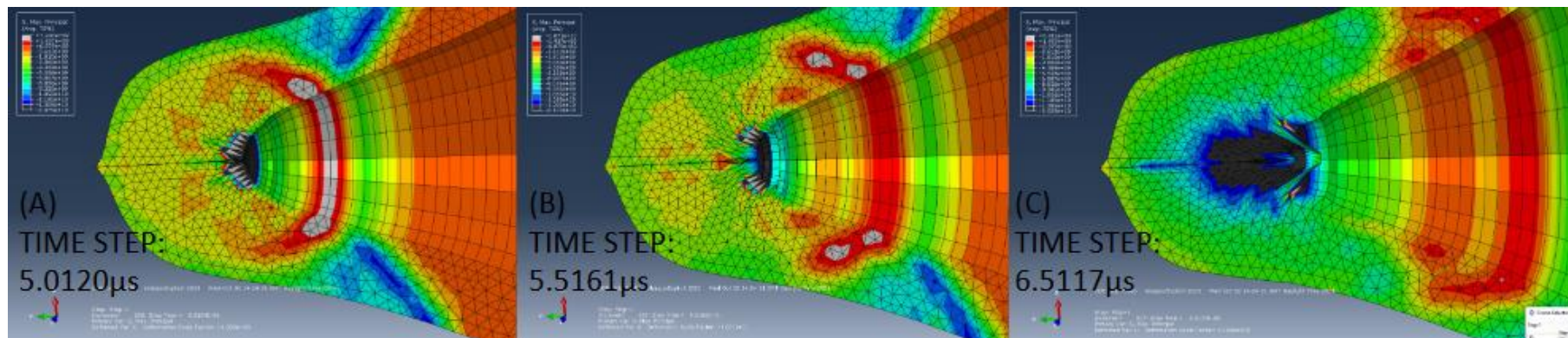


Figure 4-16 Design Two Principal Stresses On Apex Of Trumpet Liner Jet Formation

FiguresFigure 4-13,Figure 4-14,Figure 4-15,Figure 4-16, show the evolution of the simulation over microseconds. The sequential images demonstrate how the stress and pressure changes over time. As they progress, the images reveal the liner's inward collapse under intense compressive forces, forming a high-velocity jet. This time-dependent visualisation provides insight into both the magnitude and direction of stresses, as well as the concentrated zones of maximum pressure that drive jet formation.

Figure 4-17 and Figure 4-8 are visual representations of the stress distribution within each design of shaped charge jet.

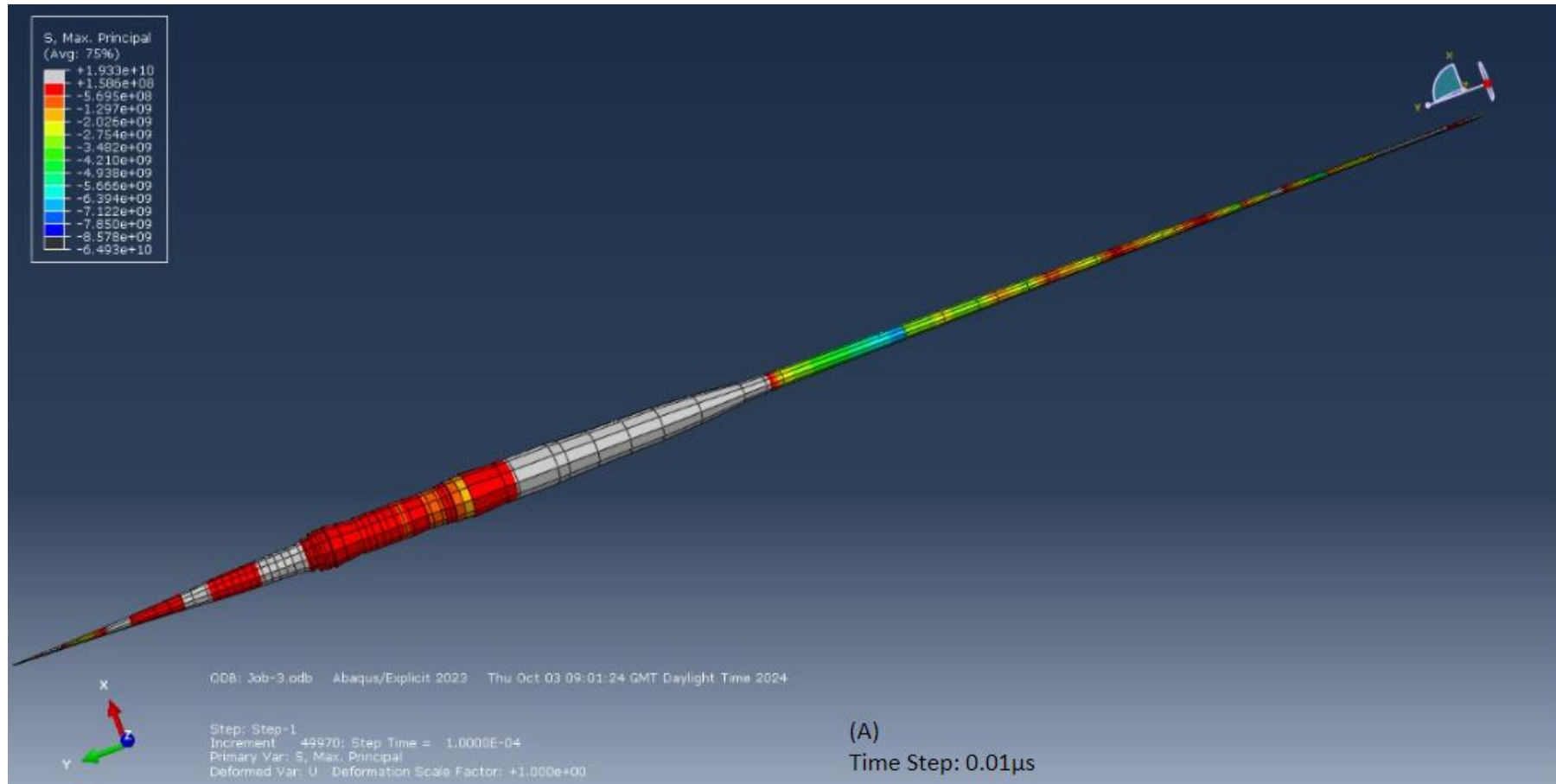


Figure 4-17 Conical Liner Shape Charge Jet

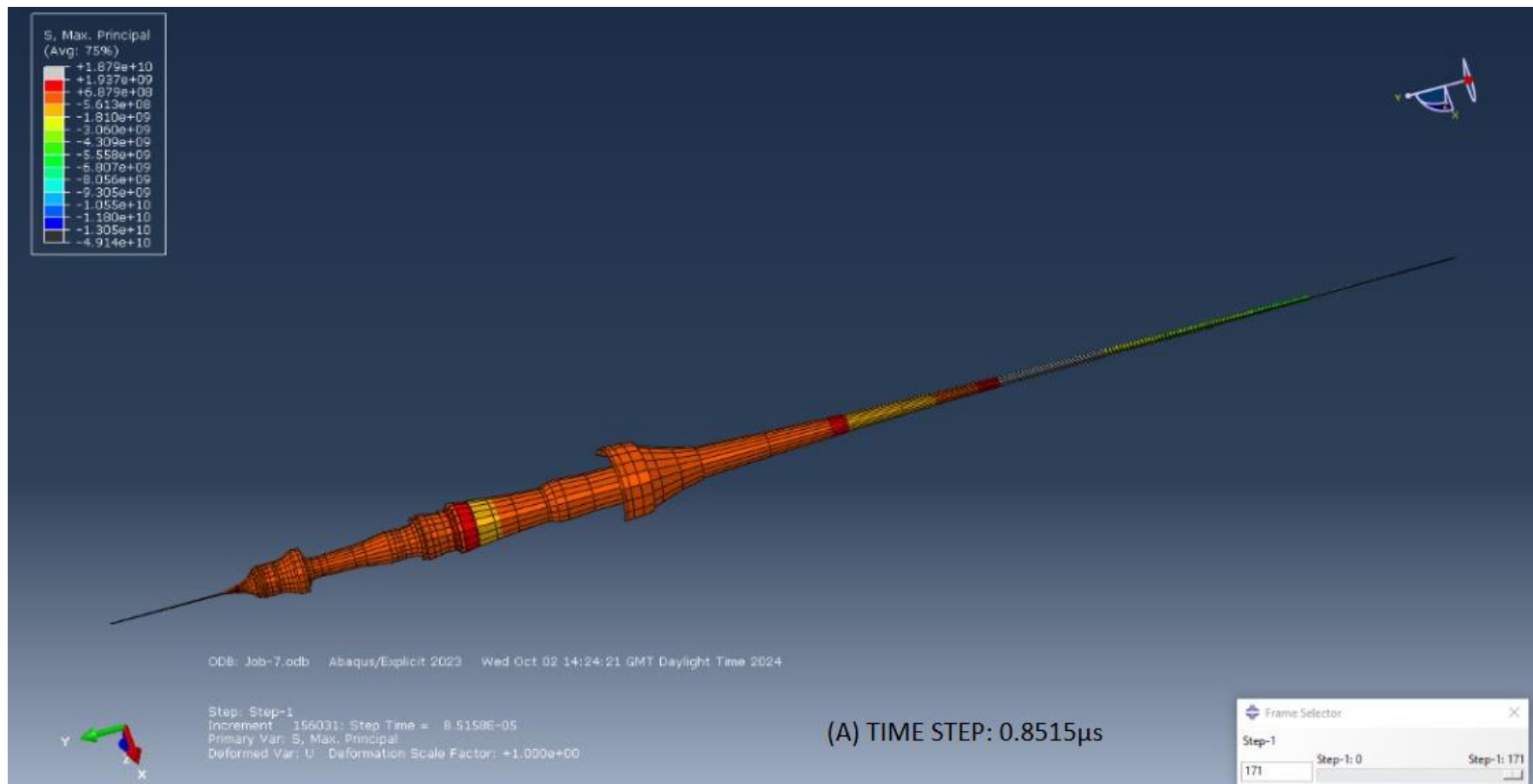


Figure 4-18 Trumpet Liner Shape Charge Jet

In Figures, Figure 4-19 Figure 4-20 The high-pressure shock wave induced stresses that surpass both the yield and ultimate tensile strength of the liner material. When these stresses exceed the material's yield limit, the liner begins to deform plastically, meaning it permanently changes shape. When further exceeding the ultimate tensile strength, the liner material essentially flows, as it can no longer withstand the forces and begins to behave like a highly viscous liquid, the jet can be observed here.

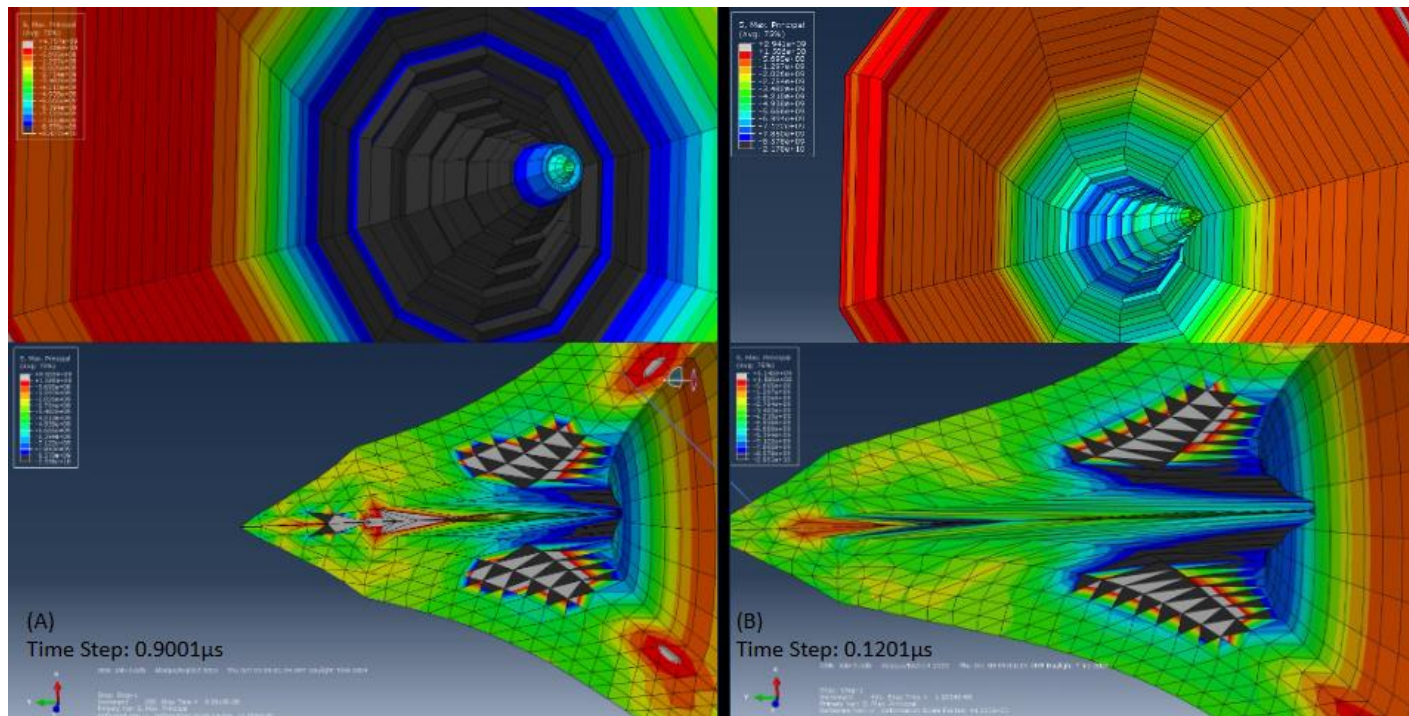


Figure 4-19 Design One Conical Liner Excessive Stress, Jet Formation

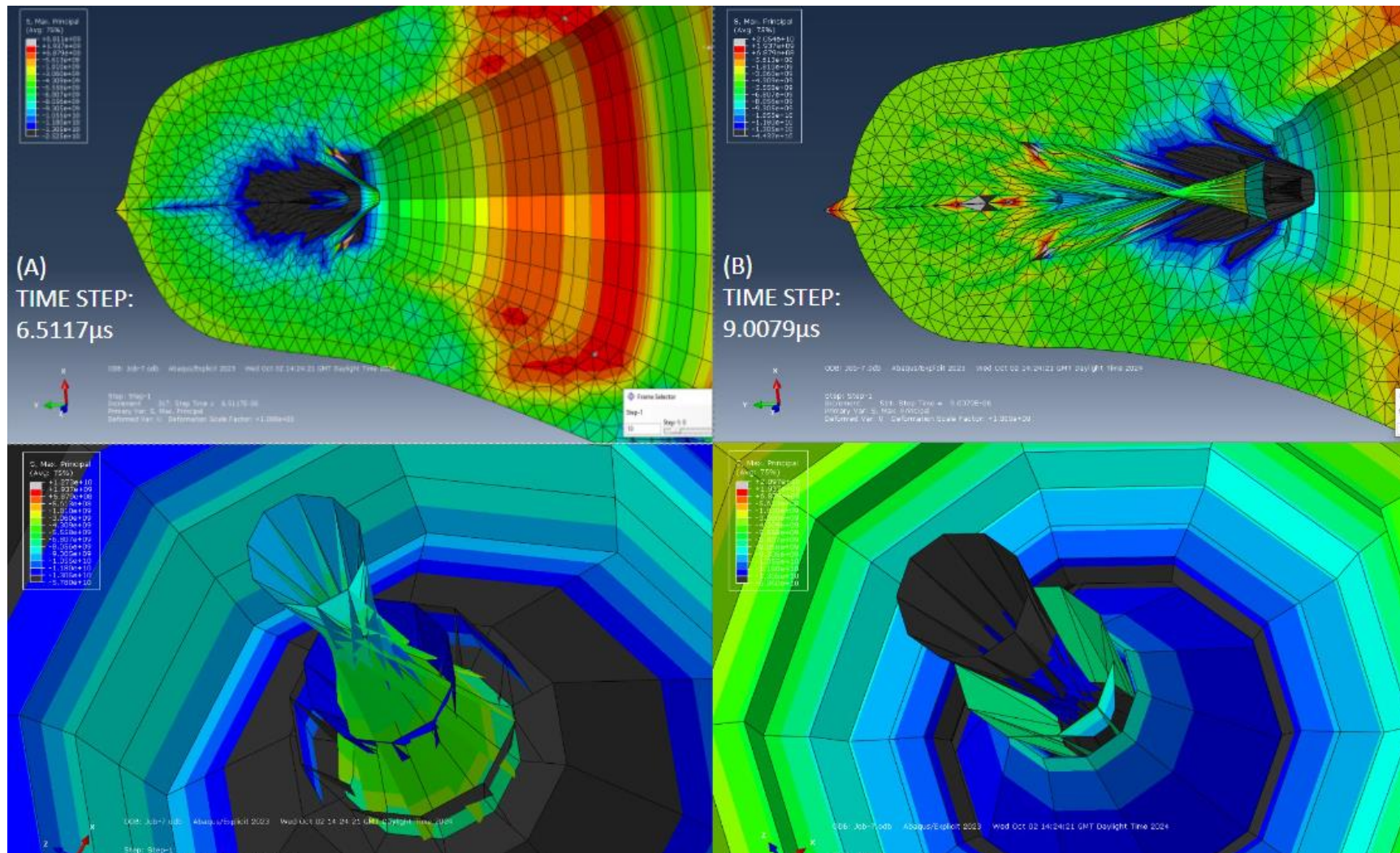


Figure 4-20 Design Two Trumpet Liner Excessive Stress, Jet Formation

4.5 Velocity Graphs for Both Conical and Trumpet Deigns

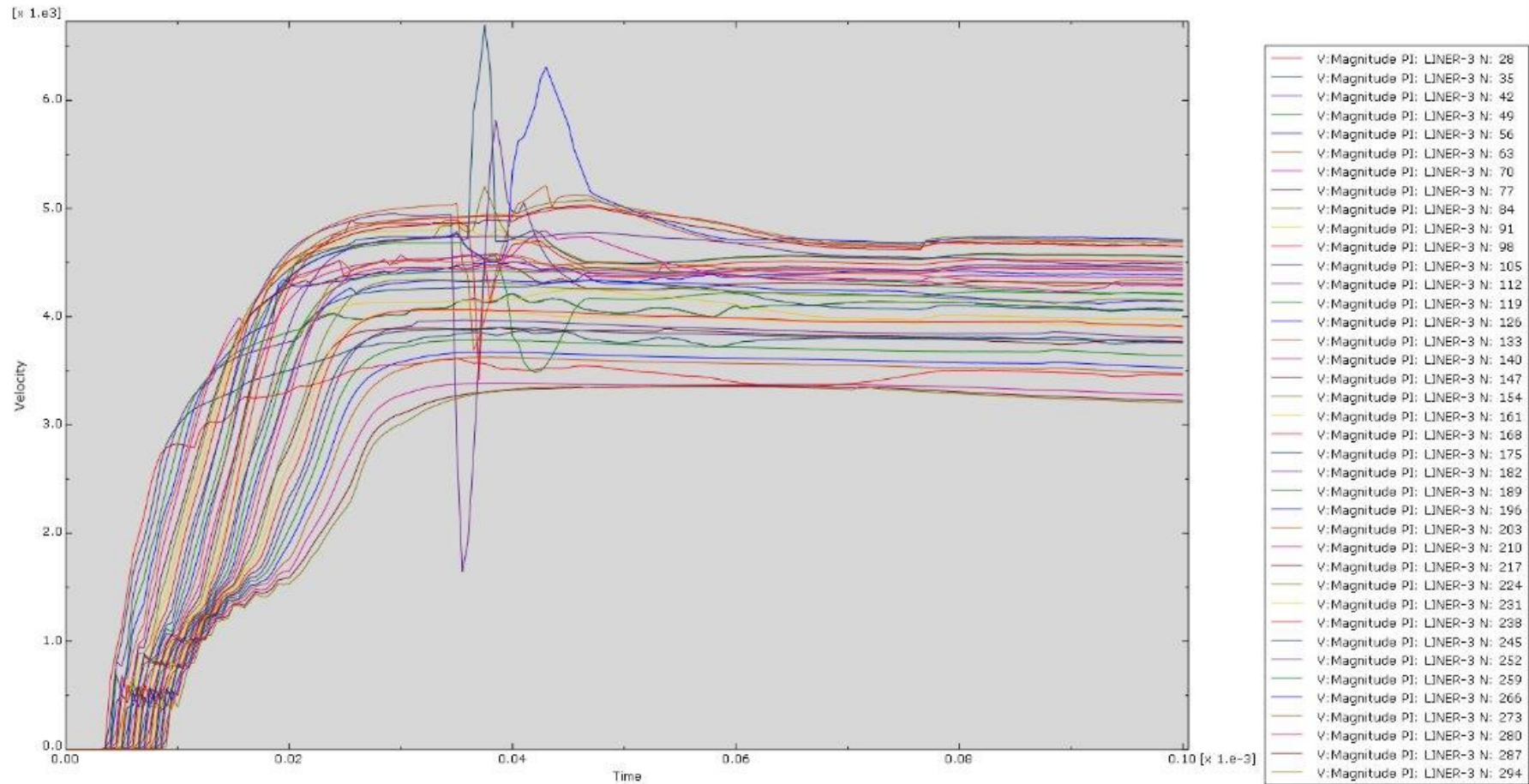


Figure 4-21 Design One Conical Liner Velocity Graph

A selection of nodes seen in Figure 4-22 were Initially captured from the Apex of the Conical liner design. The data recorded shows a rapid rise in velocity this is coherent with the initial impact of the explosive detonation. The nodes undergo an acceleration phase where the liner is pushed inward by the high-pressure shock wave. Around 0.02 milliseconds, velocities appear to stabilise, but there are fluctuations across different nodes, suggesting that not all parts of the apex are experiencing uniform acceleration. These fluctuations are a result from slight differences in pressure distribution. After the initial spike, most nodes show a relatively steady velocity of 4.5km s^{-1} , indicating the liner's consistent inward movement. This plateau is characteristic of the high-speed jet formation phase in shaped charges, where the liner is collapsing towards the axis.

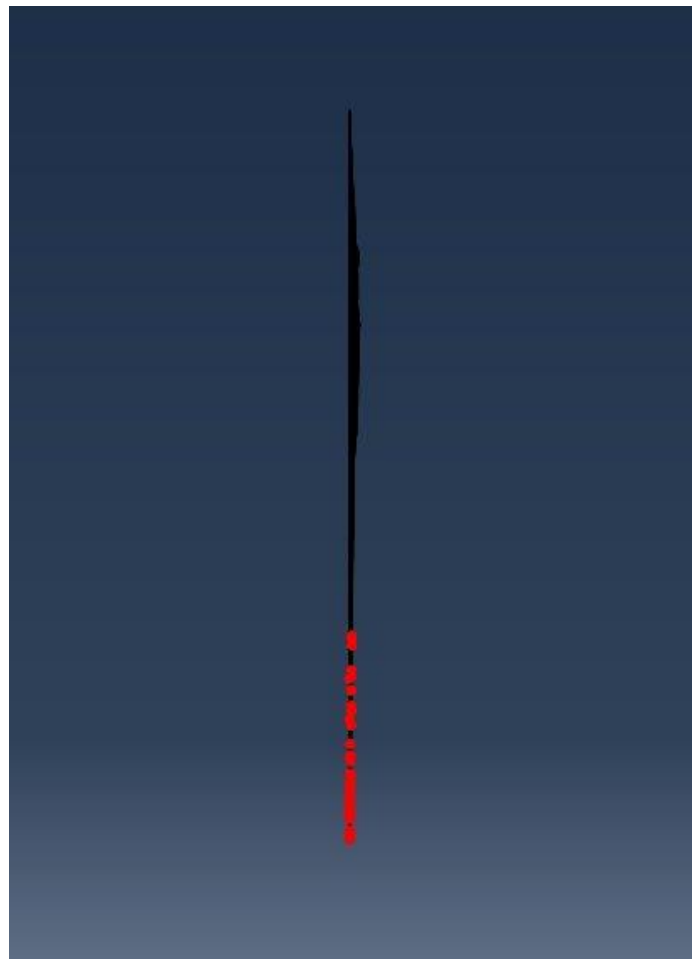


Figure 4-22 Design One Velocity Graph, Node Selection

The graph shows that some nodes highlighted in Figure 4-23, reach higher peak velocities than others, suggesting localised variations in stress and deformation rates. This could be due to non-uniformities in material properties or small asymmetries in the charge design.

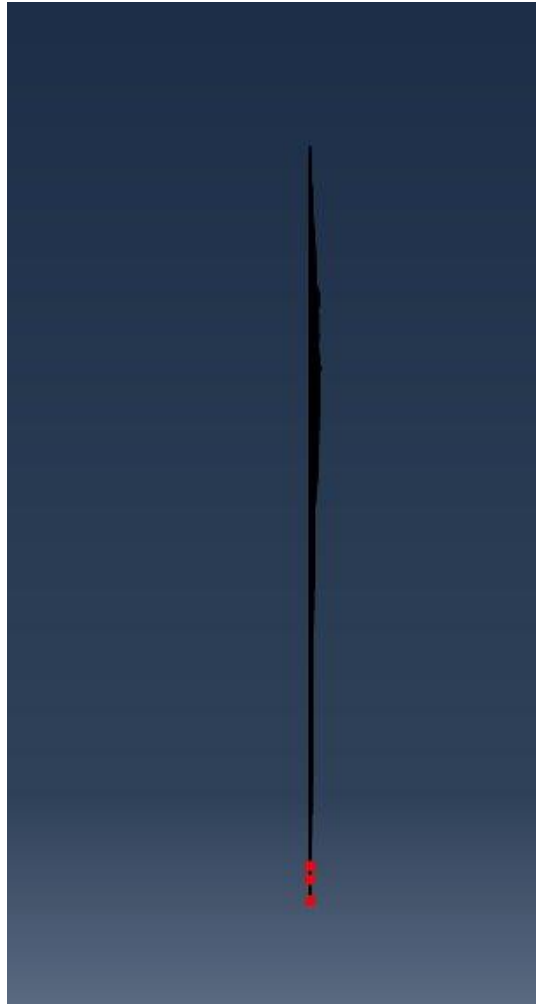


Figure 4-23 Design One Velocity Graph Highly Distorted Nodes

To get a more accurate result we can discount the highly distorted nodes to get a refined velocity graph seen in the below Figure 4-24.

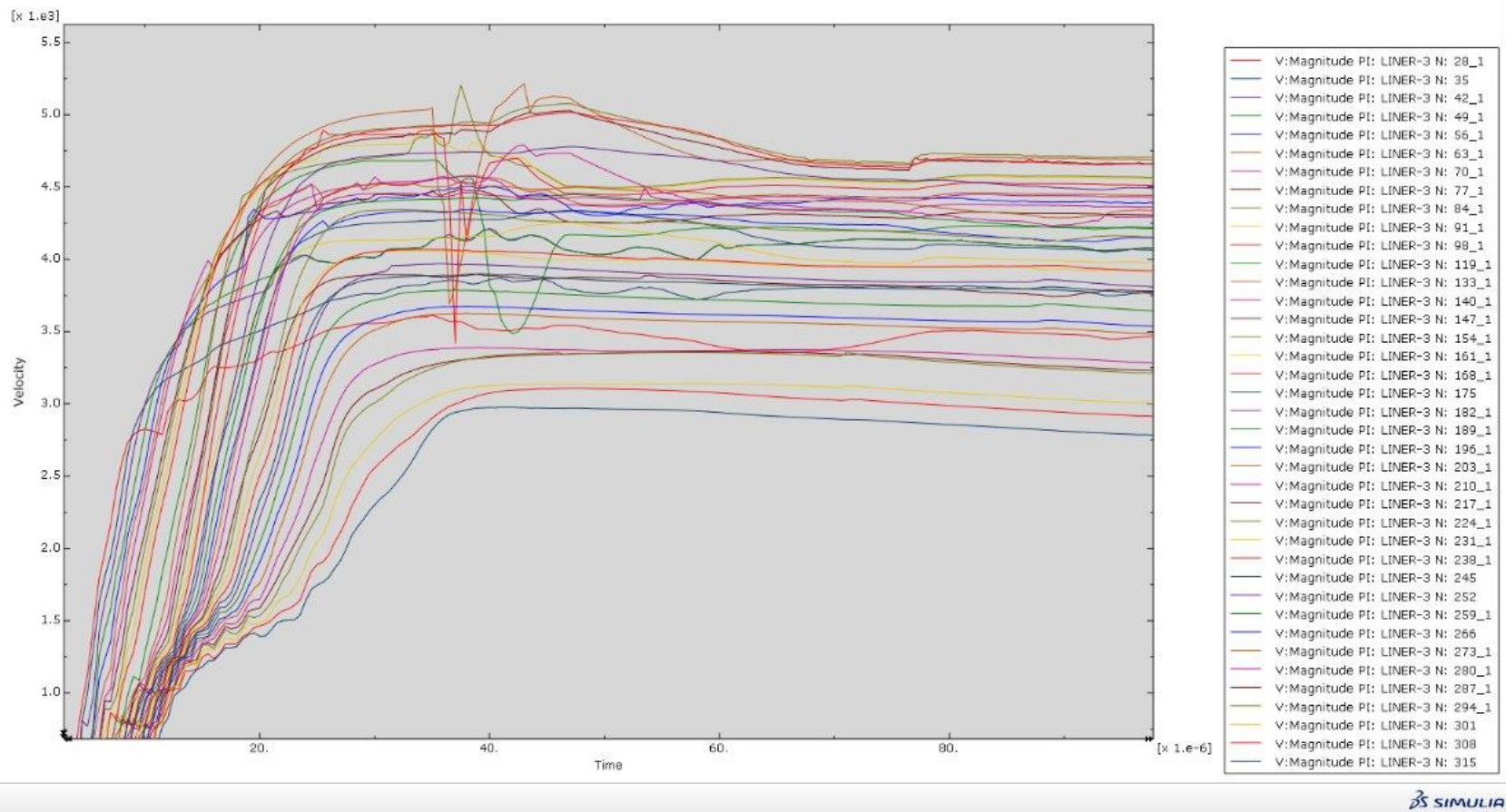


Figure 4-24 Design One Conical Liner Refined Velocity Graph

Design Two exhibits similar velocity characteristics to Design One. Figure 4-25 Nodes from the trumpet liner were plotted in Figure 4-26, initially producing irregular data due to a distorted element, as shown in Figure 4-27. After refining the graph (Figure 4-24), the data shows a rapid velocity increase as the liner is pushed inward by the shock wave, peaking around 0.02 milliseconds. At this point, velocities stabilise near 4.5 km/s^{-1} , with minor fluctuations across nodes due to pressure variations. Most nodes maintain this velocity after the initial spike, indicating consistent liner movement.

The main difference between them is Design Two experiences a more intense initial velocity and greater instability compared to Design One.



Figure 4-25 Design Two Velocity Trumpet Liner Graph, Node Selection

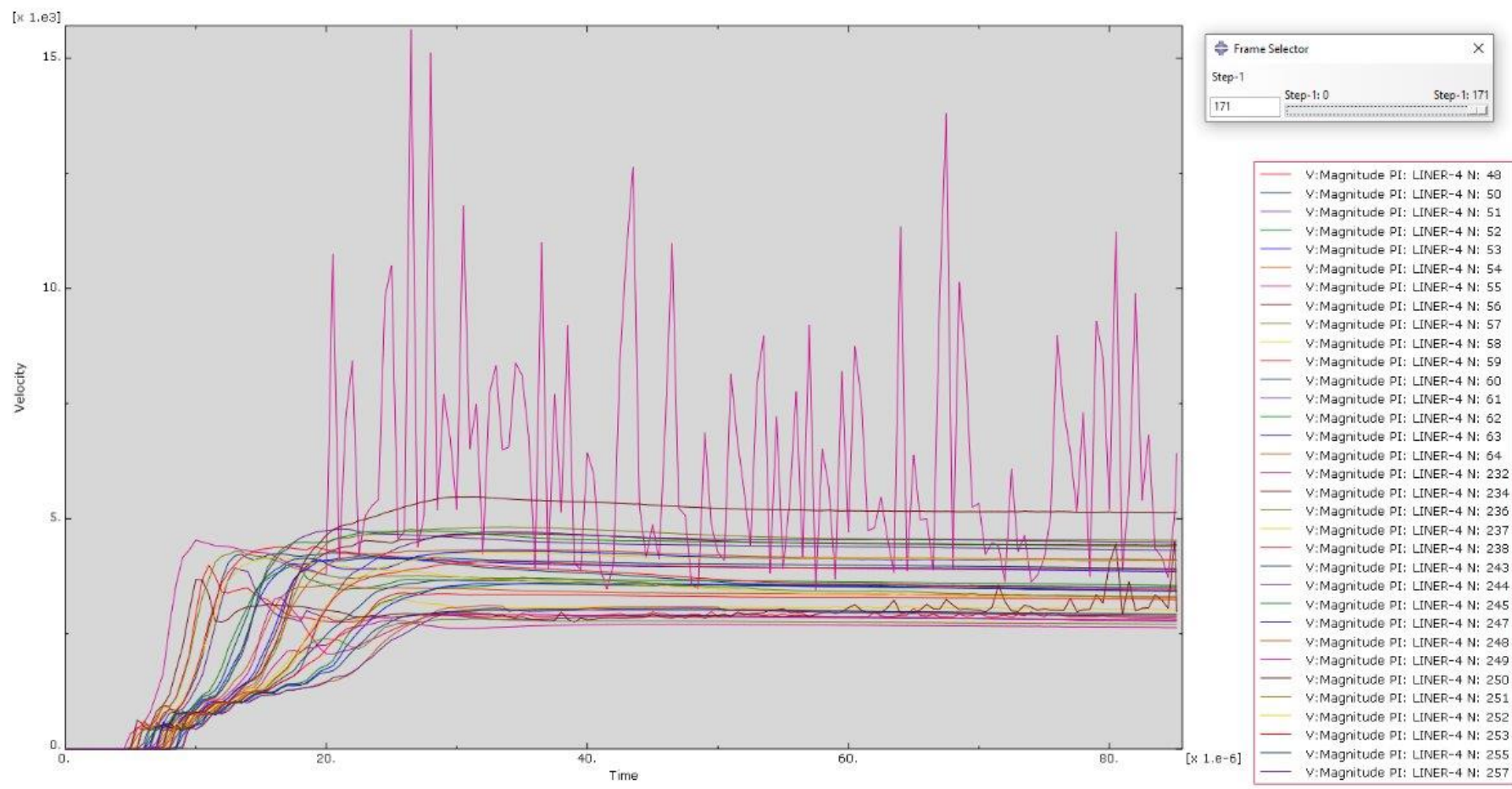


Figure 4-26 Design Two Trumpet Liner Velocity Graph



Figure 4-27 Design Two Trumpet Liner Velocity Graph Highly Distorted Nodes

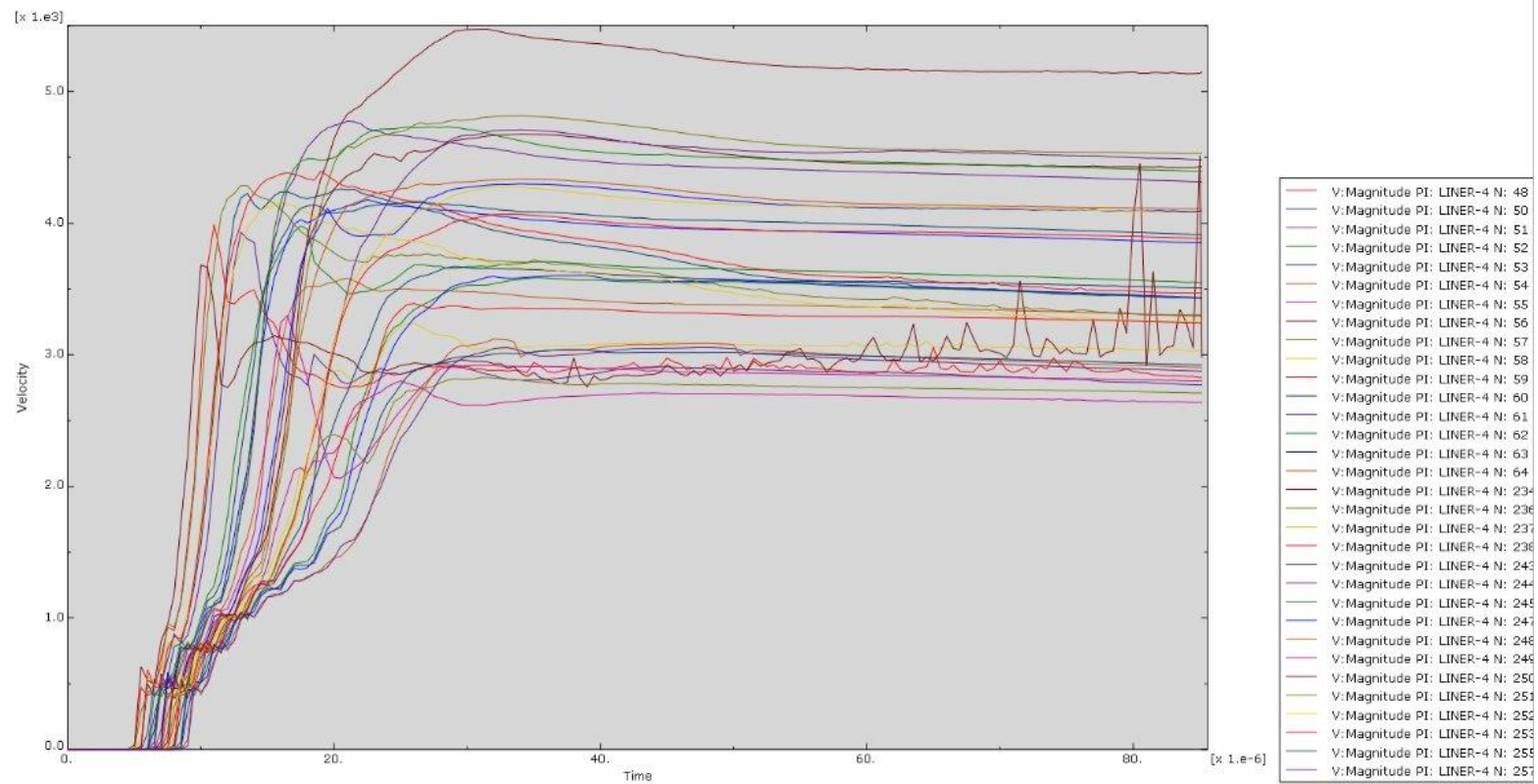


Figure 4-28 Design Two Trumpet Liner Refined Velocity Graph

4.6 Testing 2D Designs Penetrative Power (Added Target)

Both Designs had a target introduced to the run to look at the efficiency of the shape charges application, to a real world scenario, allowing the behaviours to be understood. Given material properties stayed consistent in both designs, both can analyse the interactions based on material densities and mechanical properties.

Seen in tables 5 and 6, copper has a density of approximately double that of titanium. Normally, when a shaped charge jet (in this case, copper) impacts a less dense material (titanium), it would be expected that the copper jet penetrates the titanium with relative ease due to the high energy focused at the jet's tip. The higher density of copper gives it significant inertia, which helps to maintain the momentum needed to drive through the titanium.

However when a shaped charge impacts a target and reaches high enough pressure for both the liner (copper) and target (titanium) to behave like fluids, the dynamics of density and momentum transfer change significantly. Both materials are in a "liquid-like" phase at the point of contact, this alters the effective density in terms of how momentum and energy are transferred. Materials are no longer governed by their original solid densities alone. Instead, they behave more like highly pressurised fluids with densities that can shift depending on the specific equation of state (EOS) applied in the model. The EOS accounts for variations in density, pressure, and internal energy under the extreme conditions of the impact, so the density isn't simply "doubled" or fixed it becomes a function of the conditions at each moment during the impact.

The liquid-like behaviour also implies that the interaction will depend heavily on the relative compressibility of the two materials. Since copper and titanium respond differently to pressure, their effective densities (and therefore the flow dynamics) are influenced by how each material compresses and moves under the given EOS. This can lead to an increased or decreased effective density during the interaction, depending on the specific conditions simulated.

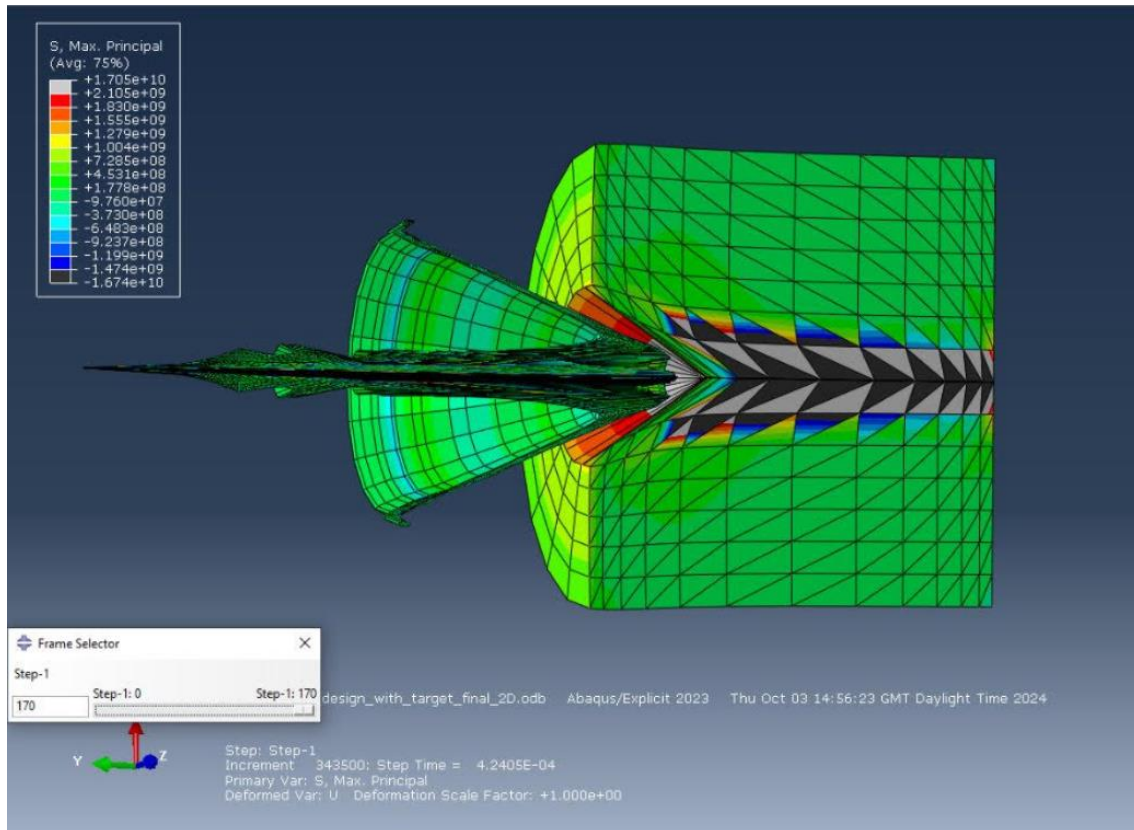


Figure 4-29 Design One Conical Liner Penetrating Target

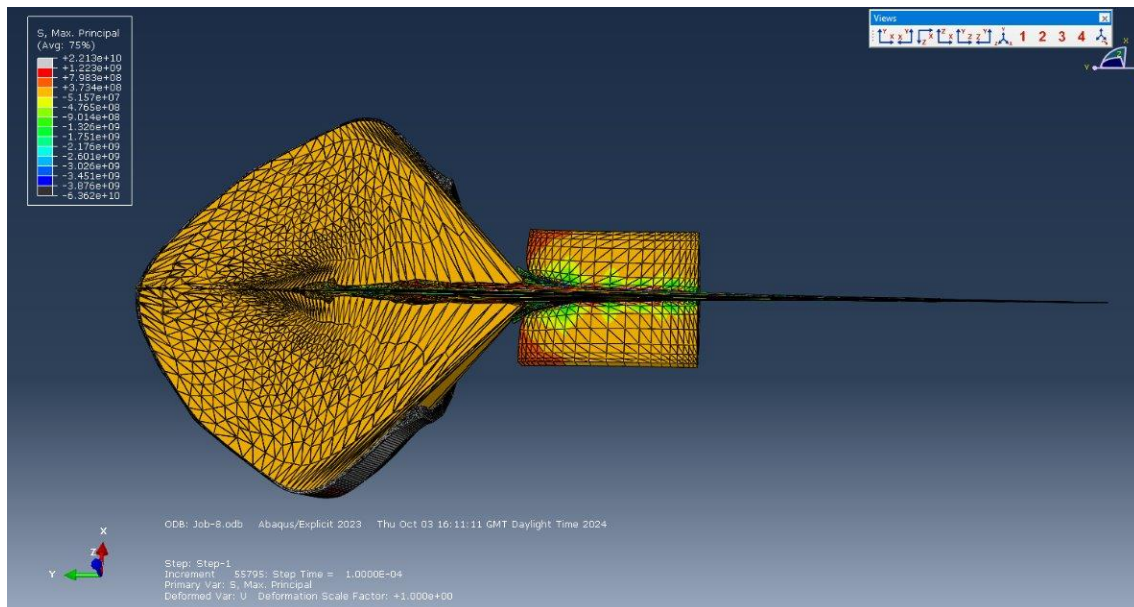


Figure 4-30 Design Two Trumpet Liner Penetrating Target

Both Designs had a cone diameter of 0.06m, using this a stand-off distance of 0.06m was determined to be appropriate.

Design one, conical liner is observed to perforate the target due to reduction in penetration effectiveness, like a less focused jet, which, combined with the high density of copper, may result in some degree of "bounce-back." Seen in Figure 4-29.

Design two trumpet liner (illustrated in Figure 4-30), results in smoother jet formation and a visual deeper penetration in the target where the jet remains coherent, as the liquid-like jet and target may minimise shock reflections and energy dissipation that occur in solid-to-solid impacts. This effect could stem from the inability of the jet to maintain its velocity and shape upon contact, dissipating its energy before reaching full penetration.

Because of the previous velocity graphs showing very similar behaviours, it was felt an anomaly was present, because of this changes were made to the trumpet liner design to get more accurate outputs.

4.7 Refined 2D Design Trumpet Liner

Because of the penetrative powers observed in the Trumpet liner, it was decided to add surface to surface boundary conditions to the model, to re-run and obtain more concise results.

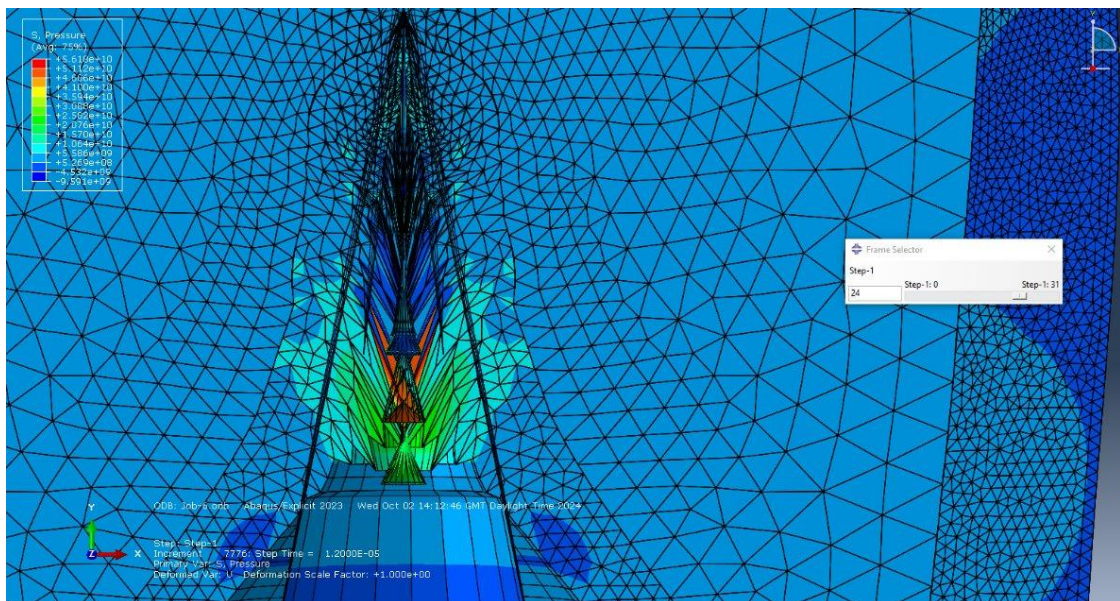


Figure 4-31 Trumpet Liner Apex With Surface-To-Surface Boundary Conditions

Figure 4-31 shows Surface-to-surface boundary conditions restricting the relative movement of nodes on one surface in relation to another. In addition, they're also ensuring the accurate transfer of forces such as pressure distribution and contribute to maintaining the stability of the simulation.

However with refined boundary conditions, the trumpet liner aborted due to excessively distorted elements before a defined jet could be identified and results could be obtained. This concept was then taken into the 3D design to adapt with adaptive meshing along with other controls later discussed.

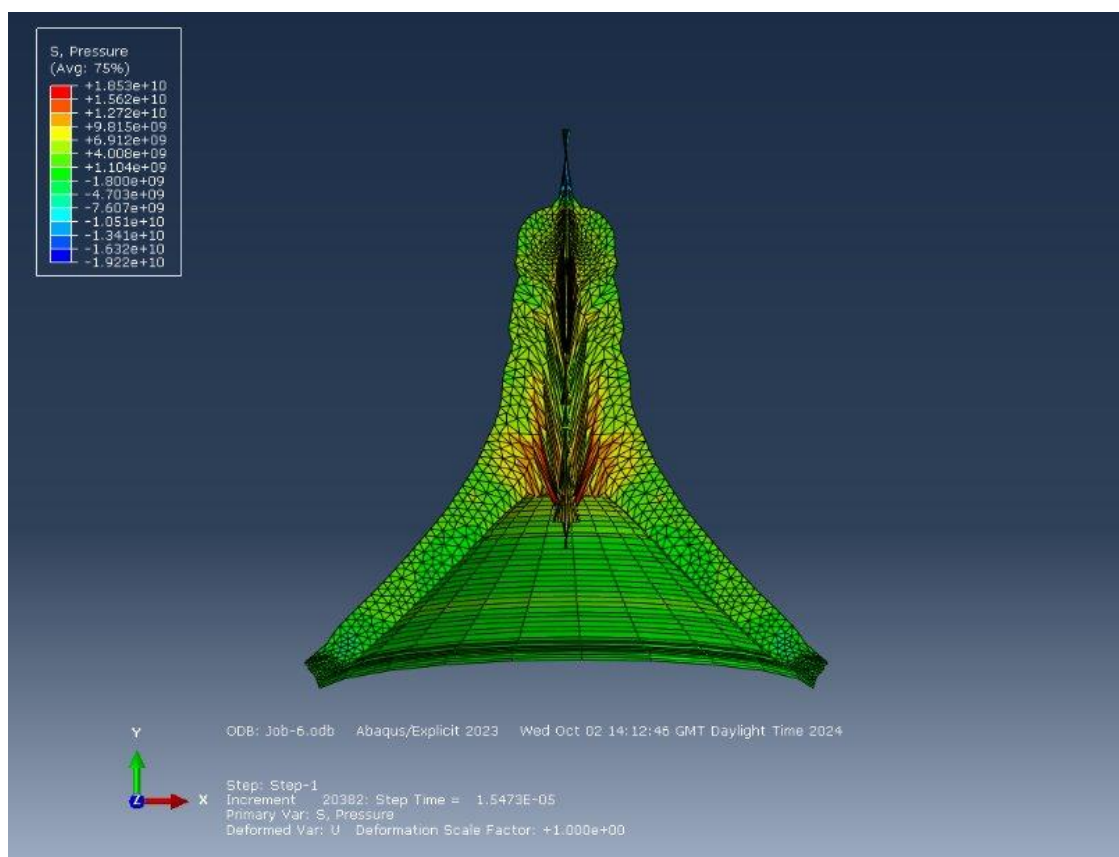


Figure 4-32 Trumpet Liner with Added Boundary Conditions

5 Trumpet Liner 3D Design

Run 1: The simulation was aborted prematurely as the liner deformation could not progress due to extreme element distortion. This occurred because the initial mesh lacked the resolution and adaptability to accommodate the severe deformations during collapse.

Outcome: No meaningful results were obtained, highlighting the need for improved mesh controls.

Run 2: To address the premature termination, adaptive meshing was introduced one time step before excessively distorted elements aborted the simulation. Lagrangian Eulerian adaptive meshing, refined the mesh as the deformation progressed, helping mitigate distortion [10]. While this allowed the simulation to run further, significant mesh distortion at the later stages resulted in a collapsed, disfigured mesh that severely crossed the plane of symmetry.

Outcome: The simulation ran longer, but further adjustments to mesh controls were required to avoid excessive element distortion. Results can be seen in Figure 5-1.

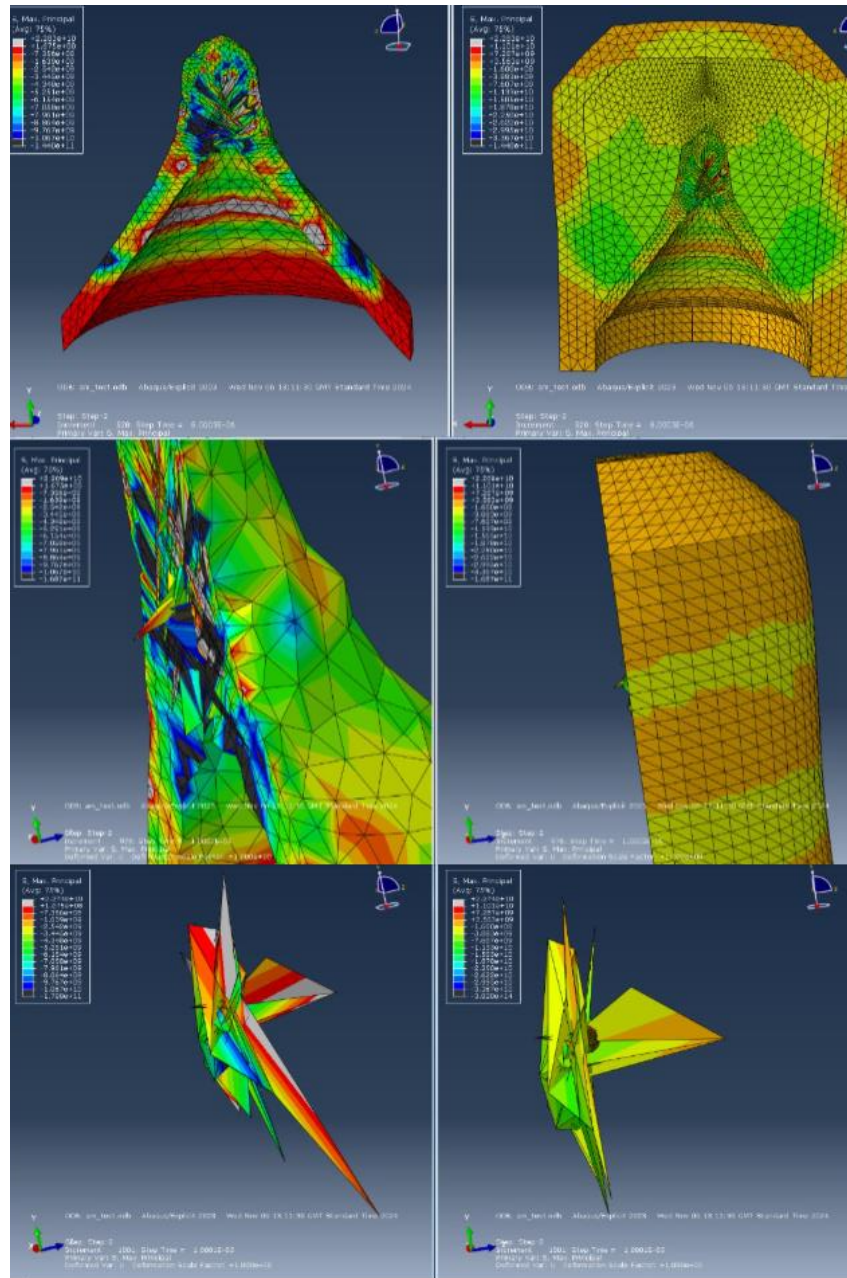


Figure 5-1 Trumpet Liner 3D Design, Run 2 Results

Run 3: Adaptive meshing controls were optimised by enabling boundary region smoothing and curvature refinement. These settings help the mesh adapt more effectively in areas of high deformation by smoothing element transitions and improving accuracy near curved regions. Additionally, surface-to-surface contact was replaced with general contact. Surface-to-surface contact formulations caused errors with adaptive meshing due to incompatibilities, whereas general contact provided a more robust solution.

Outcome: The mesh was better able to handle deformations, reducing distortions, but instability still occurred late in the simulation causing early abortion. . Results can be seen in Figure 5-2.

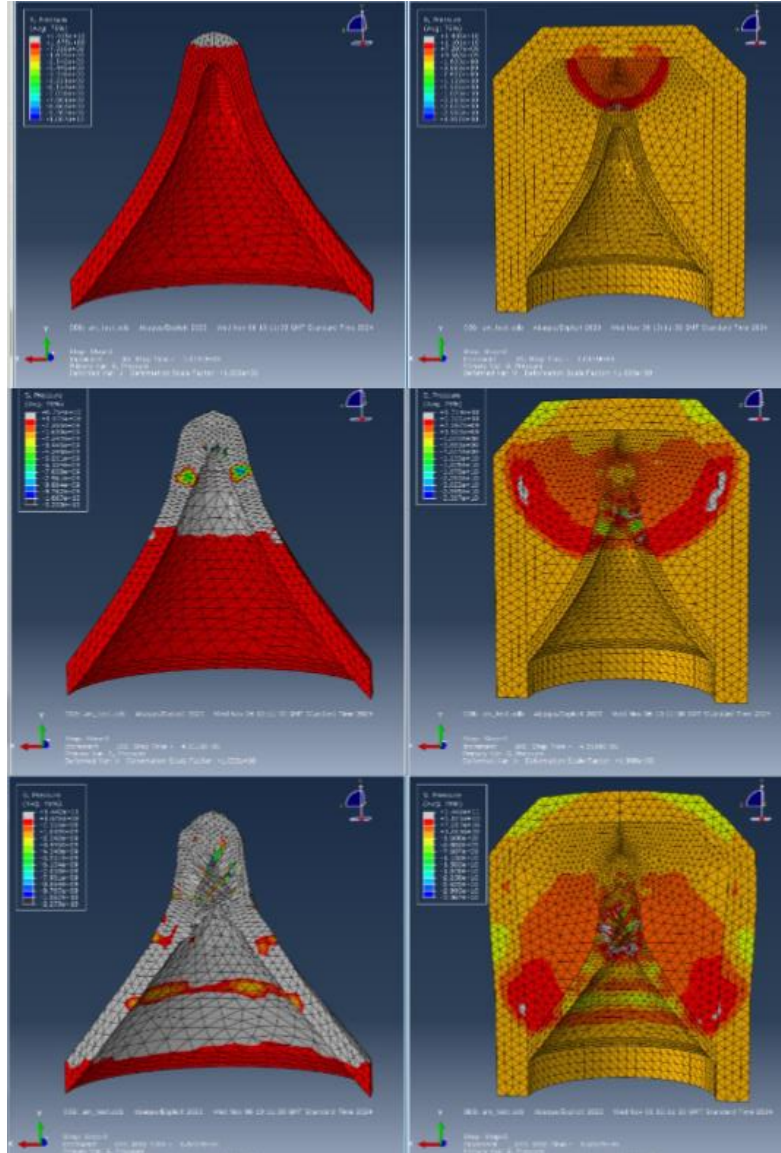


Figure 5-2 Trumpet Liner 3D Design, Run 3 Results

Run 4: To enhance stability, hourglass control were applied to specific partitions of the liner geometry. Hourglass controls suppress non-physical, zero-energy deformation modes that can occur in reduced-integration elements under extreme loading. Additionally, the mesh element type was changed from

tetrahedral (TET) to hexahedral (HEX) elements, as HEX elements offer reduced susceptibility to distortion compared to TET elements.

Outcome: The simulation stability improved, running further and providing a cleaner deformation profile to analyse the hydrodynamic instabilities such as Rayleigh–Taylor (RT) a naturally occurring phenomena within engineering applications [7]. This occurs when a denser fluid or material (the high-pressure shock wave) accelerates a lighter material (such as the liner or surrounding air), causing surface ripples. This run later aborted prematurely before a shape jet could form fully due to excessively distorted nodes. Results can be seen in Figure 5-3.

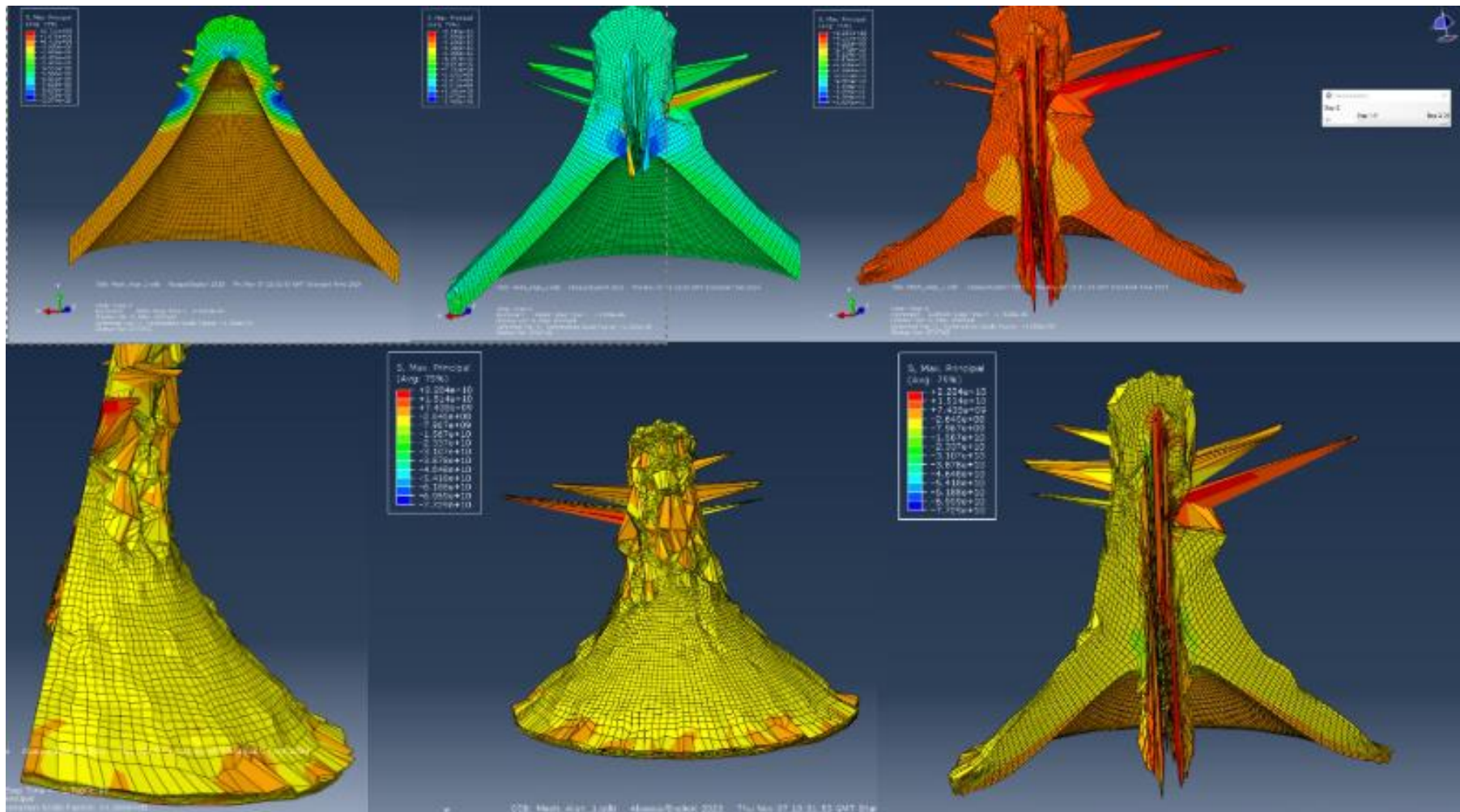


Figure 5-3 Trumpet Liner 3D Design, Run 4 Results

Run 5: To further refine the mesh, the frequency sweep for adaptive meshing was increased to 1,000,000, and the remeshing sweeps per increment were raised to 100,000. These adjustments allowed the mesh to update more frequently, ensuring finer resolution during rapid deformation phases. In regions experiencing excessive mesh distortion causing the run to abort, the Smoothed Particle Hydrodynamics (SPH) method was implemented. SPH is a mesh-free method that converts distorted elements into particles, which can continue to deform without the constraints of a traditional mesh. This was done by accessing the element type within ABAQUS and manually editing the element library, geometric order, the element controls and re-coding the input file to trigger SPH conversion for highly distorted regions, as seen below in Figure 5-4 [11].

Criterion: Time

Setting "Time" as the conversion criterion meant elements will transition from Finite Element (FE) to Smoothed Particle Hydrodynamics (SPH) at a specified simulation time. Ensuring a controlled conversion where extreme deformations began (e.g., liner collapse). By timing the transition, it prevents premature SPH conversion, which can cause instability.

Threshold: 1E-05

The threshold defines the criteria for triggering the conversion. This is a small value, that ensures elements convert as soon as time limits exceed the set condition.

PPD (Particles Per Direction): 1

PPD determined the resolution of SPH particles within each element. The value 1 corresponds to a lower particle density per element. PPD reduced avoids overloading the computational solver. It's often a starting point to test SPH implementation. although can lead to less accurate particle representation.

Kernel: Cubic

The cubic smoothing kernel defines how particle interactions are smoothed over a given range, to ensure smooth interpolation of physical quantities like velocity and pressure across particles.

Hourglass Control: Stiffness-viscous Weight Factor = 0.5

Hourglass control stops elements from behaving like jelly, where they deform unrealistically without any real stiffness or resistance. This keeps the simulation stable and ensures the deformations and results are physically correct.

Why it was added: In SPH conversion, hourglass control ensures that residual mesh-based instabilities (pre-conversion) do not propagate.

Max Degradation and Linear Kinematic Conversion

Max Degradation: prevents further degradation of elements after they have converted into SPH particles.

Linear Kinematic Conversion: Ensures that the velocity and deformation continuity between FE elements and SPH particles remains consistent during the transition. This is done by maintaining numerical stability and physical accuracy during conversion. Resulting in seamless transfer of momentum and strain fields when switching from FE to SPH.

However, the SPH implementation failed, as indicated by the error message:

"The smoothing length is too large for several PC3D elements, which indicates the particle distribution is strongly non-uniform".

The error suggests that the particle distribution was inconsistent, likely due to highly distorted parent elements or poor aspect ratios in the original mesh. Abaqus recommended using a uniform background grid for FE-to-SPH conversion to ensure more uniform particle distribution.

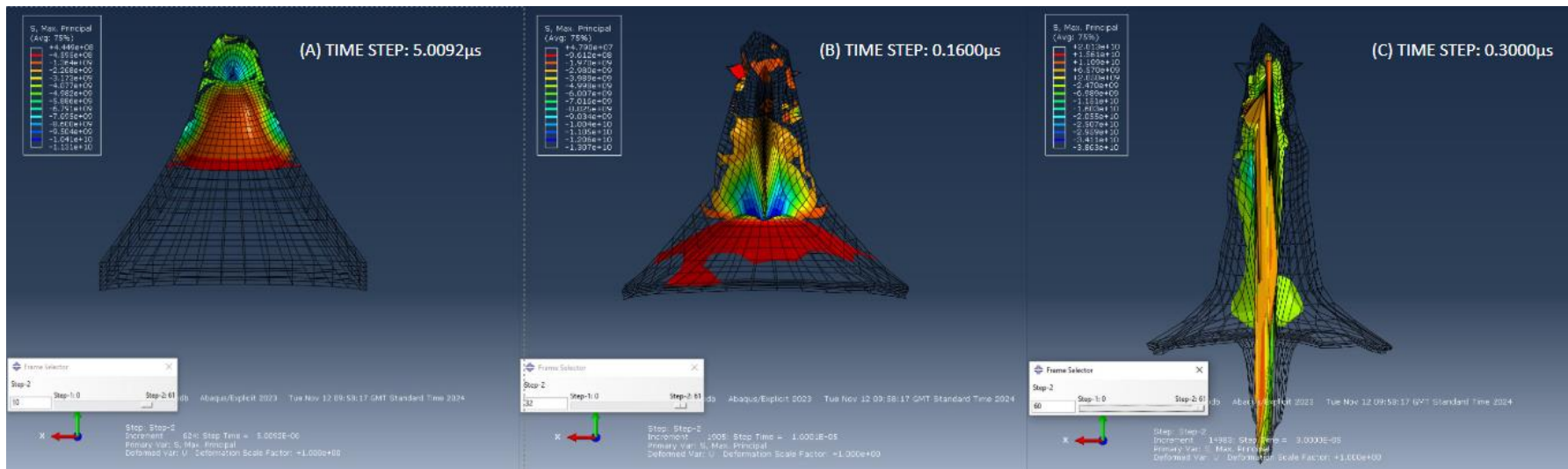


Figure 5-4 Trumpet Liner 3D Design, Run 2 Results Max Principal Stresses

When applying the colour range of stress and strain previously expressed on page 24 it is clear this simulation is having the same forces act upon the shape charge. Using the range calculated from Design Two from the 2D simulations we can calculate from the same timestep B in Figure 6-4 and compare the ranges from Equations 3 and 4 to see how modelling the same design in 2D and 3D translates.

Equation 4 Principal Stress Range 3D Design

$$4.790 \times 10^{10} \text{Pa} - (-1.307 \times 10^{10} \text{Pa}) = 6.097 \times 10^{10} \text{Pa}$$

While the simulations for both designs could not be completed in their entirety, the initial stages of the simulations provide accurate and reliable data for comparison. The stress ranges calculated at the beginning of the simulation highlight key differences between the 2D and 3D models. The 2D simulation of both designs shows a higher stress range ($7.967 \times 10^{10} \text{Pa}$) which is likely due to the exaggerated stress gradients inherent in the 2D approximation. In contrast, the 3D simulation predicts a lower and more realistic stress range ($6.097 \times 10^{10} \text{Pa}$) as it captures the true spatial distribution of stresses and out-of-plane effects. These early results indicate that the conical the trumpet liner (Design 2) benefits from smoother stress distribution, consistent with its geometry. Despite the simulations being incomplete, the early-stage data remain valid and offer meaningful insights into the behaviour and performance of both designs under initial loading conditions.

The velocity (Seen in Figure 5-5), is significantly reduced in the 3D model compared to the 2D models, with maximum values around $3.0 \times 10^3 \text{m/s}$, compared to the 2D model having $5.0 \times 10^3 \text{m/s}$. The 3D model shows a wider range of velocities, showing significant variability present among the nodes indicated by the spread of lines. 2D appeared to have a more stable velocity distribution with less variation between nodes.

The results recorded could have been due to the liner collapse in 3D, introducing asymmetries due to the additional degrees of freedom. leading to more non-uniform collapse dynamics, resulting in a broader spread of velocity profiles. Some nodes might even experience localised effects like shear or rotation, causing more variation.

Whereas the 2D axisymmetric model eliminates certain complexities, leading to more uniform collapse behaviours. Nodes follow more predictable paths, this was seen in the plane of symmetry, 2D could not exceed this limit and was only discovered as a computational restriction within the 3D models. These limitation result in less variation and a clearer grouping of velocities.

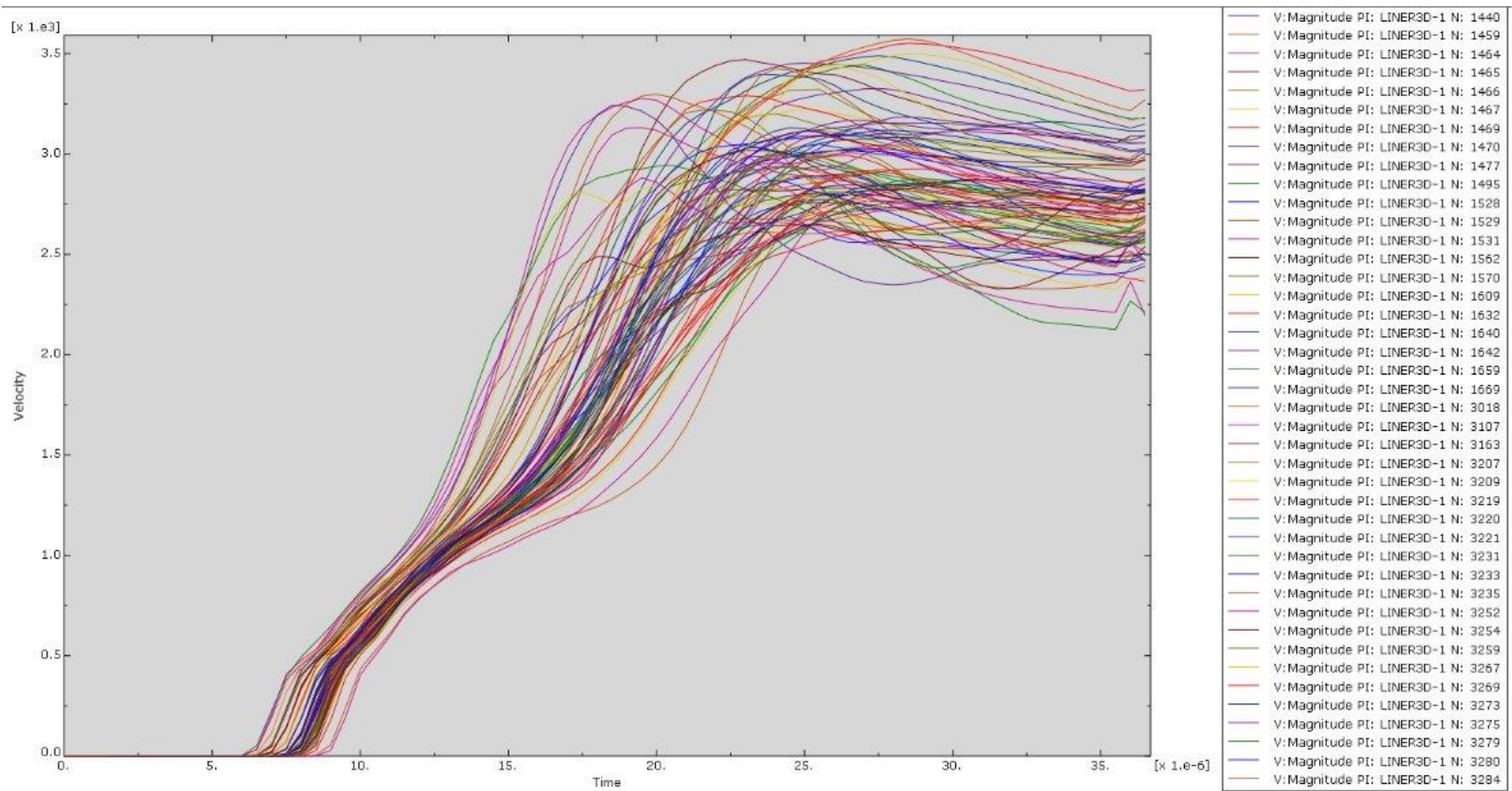


Figure 5-5 Final Run 3D Velocity Graph

6 Conclusion & Recommendations

The 3D simulation of a trumpet liner shape charge design performed successfully for an extended period without contact-related errors. The refined mesh and frequent remeshing significantly improved the accuracy of the results, particularly in regions experiencing large deformations. This allowed the simulation to advance beyond previously problematic deformation zones, providing more reliable results under extreme conditions. However, the SPH conversion failed, necessitating either further mesh refinement to mitigate non-uniformities or the adoption of a more robust conversion strategy incorporating background grids to enhance the simulation's stability and accuracy.

Time constraints limited the advancement of this simulated model. With more time, SPH could have been achieved other advances would have been research into the influence of liner geometry could have been conducted. It was evident that the distance between the detonation point and the liner apex was insufficient. Allowing more distance for the wave to propagate and build energy before impacting the liner might have produced a more effective shaped charge. Additionally, increasing the stand-off distance between the shaped charge and the target would likely have resulted in a more uniform shaped charge jet penetration. Following the successful implementation of SPH on this model, the subsequent steps would involve simulating a scenario using a titanium target to evaluate the penetrative power of the jet.

At Current, the Rankine-Hugoniot Limit has been reached for this simulation, Monroe Effect optimised, Steady State Hydrodynamic Theory has been observed, EOS data has been captured and Gurney Theory recognised and finally Chapman-Jouguet has been demonstrated within a successful literature review of simulated shape charge devices.

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