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Modelling of shaped charges

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Ordnance, Munitions and Explosives (Safety)

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- the thesis submitted has not been previously submitted to this university or any other.
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Abstract

This assignment explores the world of explosive dynamics and engineering, with a specific focus on the research and development of an Explosives Formed Penetrator (EFP) also known as a shaped charge. The emphasis is on the significance of modelling and critical analysis, investigating vital components like the robust steel casing, High Explosive (HE) charge, and the intricately designed conical liner. Computer-Aided Engineering (CAE) modelling and critical assessment of these elements hold not only academic importance but are also essential in practical fields such as defence and explosives engineering. Beyond theoretical understanding, the study finds practical relevance in sectors such as defence, explosives engineering, and oil and gas. Shaped charges play pivotal roles in penetrating armoured structures, enhancing oil well productivity, and facilitating controlled demolitions. By unravelling the complexities of these devices, the study contributes to advancements in **fields critical to technological and industrial landscapes**. The assignment provides detailed insights into material properties crucial for precise Abaqus simulations, introduces the Johnson-Cook damage model, and explores the role of the Mie-Gruneisen Equation in simulating explosive dynamics. The methodology involves transitioning from 2D to 3D modelling in Abaqus, and the discussion covers key findings from both simulations, addressing the limitations and advantages of each approach. The exploration of an optimized jet-shaped charge design and its implications for real-world applications adds depth to the investigation into shaped charge technology.

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List of Abbreviations

LSC	Linear Shaped Charge
EFP	Explosively Formed Penetrator
TNT	Trinitrotoluene
HE	High Explosive
CAE	Computer Aided Engineering
JWL	Jones-Wilkins-Lee
EoS	Equation of State

1. Introduction

1.1 Overview of Assignment

This assignment delves into the realm of explosive dynamics and engineering by researching and designing an Explosives Formed Penetrator (EFP), commonly known as a shaped charge. Focus will be on the essential elements of modelling and critical analysis as prescribed in the module's learning objectives. The aim is to untangle the complexities inherent in shaped charge devices, comprised of a sturdy steel casing, a powerful High Explosive (HE) charge, and a thoughtfully designed conical liner. Proficiency in modelling and critically assessing these components is not merely an academic endeavour but also a vital requirement in practical fields like defence and explosives engineering. This introduction charts our course, underscoring the importance of refining these skills and providing a sneak peek into the captivating realm of shaped charge technology.

1.2 Significance of Modelling and Critical Analysis

In the world of engineering, systems are often complex and multifaceted. Having the ability to design and create an accurate Computer Aided Engineered (CAE) model allows engineers to break down the complex systems and processes into manageable components whilst gaining an understanding of them within the system, enabling them to comprehend how various elements correlate together.

CAE also equips engineers with the necessary tools making them able to predict the behaviour of their systems under different conditions. Whether designing structures, analysing fluid dynamics, or simulating electrical circuits, the predictive power of models aids in foreseeing potential challenges and optimizing designs before implementation.

A big part of being an engineer is problem solving and sometimes the ability to rigorously evaluate a model is limited, mostly by resource restraints and the complexity of the system. CAEs ability to critically analyse a model is invaluable as it sharpens the engineers ability and allows them to intricately simulate their models when faced with real-world engineering challenges to identify potential flaws and limitations in their model.

1.3 Introduction to Shaped Charge Device

Comprising of three components, the device concludes of a robust steel casing, a formidable high explosive charge, and a strategically shaped conical liner. The steel casing provides structural integrity, the HE charges imparts the necessary force, and the conical liner plays a pivotal role in directing the explosive energy.

The significance of studying shaped charge devices extends far beyond the confines of theoretical understanding. This investigation holds relevance in practical applications, particularly within industries such as defence, explosives engineering, and oil and gas. Shaped charges find their utility in penetrating armoured structures, enhancing oil well productivity through perforation, and executing controlled demolitions. By unravelling the intricacies of these devices, we not only gain insights into explosive dynamics but also contribute to advancements in fields critical to our technological and industrial landscape.

EFPs, commonly employed as "roadside bombs," contribute to a significant number of annual fatalities. These devices generate a shock wave through the detonation of HE, capable of distorting ductile metal liners. This characteristic makes EFPs effective in overcoming armour, masonry, and concrete targets. The projectiles ejected from EFPs can attain velocities exceeding 1000 m/s, resulting in considerable kinetic energy.



Figure 1 - Aftermath of roadside bomb attack, Baghdad 2007, killing U.S. troops – Sourced from Iraqnam Blogspot

2. Literature Review

Cylindrical explosive device featuring a hollow cavity at one end and a detonator at the opposite end is termed a hollow charge. The geometric shape of the hollow cavity, which can range from a hemisphere to a cone, focuses the energy of the detonation products generated at the opposite end of the cylinder. This concentration of force, when directed at a metal plate, results in a more profound cavity compared to a solid explosive cylinder, even when the latter contains a greater quantity of explosive material. This phenomenon is referred to as the Munroe effect in the U.S. and Britain and as the von Foerster or Neumann effect in Europe [1].

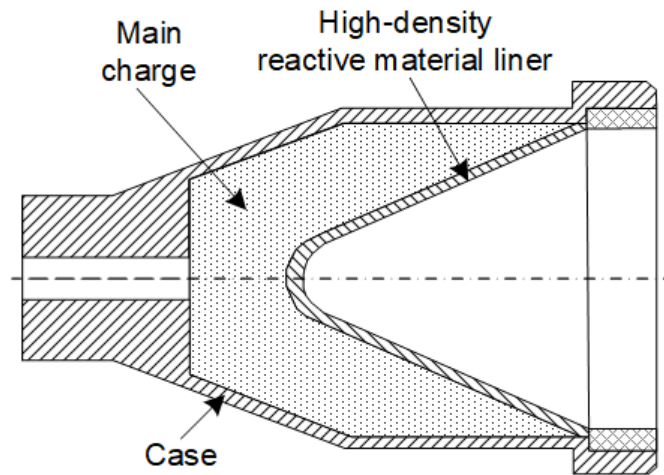


Figure 2 - Diagram of high-density reactive material liner shaped charge [1]

If the hollow cavity is lined with a thin layer of metal, glass, ceramic, or similar material, the liner transforms into a jet when the explosive charge detonates. Upon initiation, a spherical shock wave begins from the initiation point, moving at an extremely high velocity, typically around 8 km/s. As the detonation wave envelops the lined cavity, the material undergoes acceleration under high detonation pressure, collapsing the cone. This collapse induces violent distortions in the liner material over very brief time intervals at strain rates of 10^6 sec^{-1} . Maximum strains exceeding 10 are readily achievable due to the presence of large hydrodynamic pressures (peaking at approximately 200 GPa and decaying to an average of around 20 GPa).

The collapse of the conical liner forces a portion of the material to flow in the form of a jet, where the tip velocity can surpass 10 km/s. The energetic jet, upon striking a metal plate, forms a deep cavity surpassing that caused by a hollow charge without a liner. The metal plate experiences peak pressures of 100-200 GPa, decaying to an average of 10-20 GPa. Average temperatures range from 20-50% of the melt temperature, and average strains commonly fall between 0.1 and 0.5. Localized temperatures and strains at the jet tip may be even higher. The penetration process occurs at strain rates of 10^6 sec^{-1} . The cavity produced in the metal plate during this jet-target interaction is attributed not so much to a thermal effect but to the lateral displacement of armour due to the tremendous pressures generated. The target material is essentially pushed aside, and the penetration is accompanied by no change in target mass, neglecting any impact ejecta or spall from the rear surface of the target.

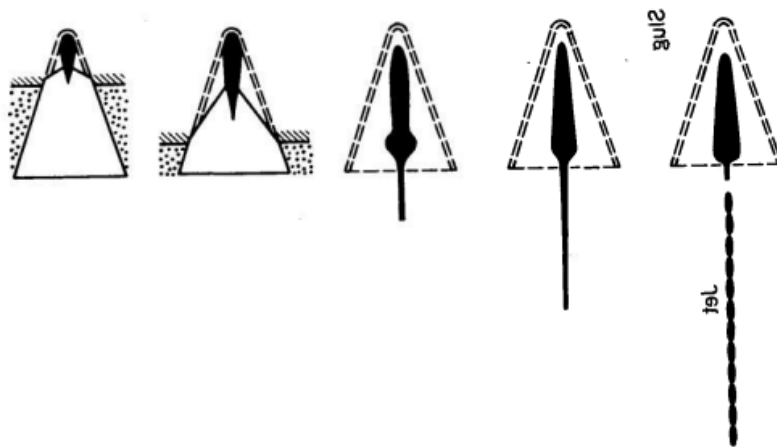


Figure 3 - The Collapse of a Shaped Charge with a Conical Liner – Sourced from Walters and Zukas 1989

3. Material Properties

Different materials were selected to model the EFP to allow for the study of the different configurations. These include Copper (Cu) for the Liner, Aluminium (Al), Steel Alloy, for the Casing, then TNT and Composition B¹ for the HE. The materials were selected using MatWeb [1].

	TNT	PBX-9404	HMX	FH-5
Density, ρ_0 (kg/m ³)	1630	1840	1891	1600
Detonation velocity, D (m/s)	6930	8800	9110	7930
Pressure at CJ state, p_{CJ} (GPa)	21.0	37.0	42.0	24.96
Specific detonation heat, E_0 (GPa)	7.0	10.2	10.5	8.7
R_1	4.15	4.60	4.2	4.2750
R_2	0.95	1.30	1.0	0.3175
ω	0.3	0.38	0.30	0.2178
A (GPa)	371.21	852.40	778.28	573.43
B (GPa)	3.2306	18.020	7.0714	0.96006
C (GPa)	1.0453	1.2070	0.6430	0.82373

Figure 4 - Detonation properties and the JWL parameters for four explosives

¹ Composition B is the common name for the widely used high explosive shell and bomb filling which is a melt-cast blend of RDX (cyclotrimethylenetrinitramine) and TNT (trinitrotoluene). Typically, Composition B consists of RDX (59.5 %, by mass), TNT (39.5 %) and Desensitising Wax (1%).

3.1 Overview of Material Properties

Material properties are integral to Abaqus simulations, particularly when modelling the intricate dynamics of shaped charges. These properties serve as the foundation for representing how materials respond under diverse loading conditions. In the realm of shaped charges, accurate representation of material behaviour is paramount, and material properties play a pivotal role in achieving this accuracy. Constitutive models employed in Abaqus rely on these properties to simulate the nonlinear and time-dependent responses of materials, allowing users to choose models that best capture the deformation and failure characteristics of each shaped charge component.

Shaped charges, by nature, undergo dynamic loading during detonation. To simulate this accurately, material properties such as dynamic yield strength, density, and strain-rate dependence become critical. These parameters enable the simulation to mirror the dynamic response of materials subjected to explosive conditions. Moreover, material properties related to failure, including fracture toughness and ductility, are crucial for modelling potential failure modes and damage during the simulation [2].

Shaped charge simulations often encompass coupled physics, such as fluid-structure interaction. Here, material properties come into play to model how materials interact with one another, allowing for a comprehensive representation of interactions between explosive materials, liners, and the surrounding medium. The accurate representation of thermal effects is another facet where material properties shine. Properties such as thermal conductivity, specific heat, and thermal expansion contribute to modelling the temperature changes generated by explosive detonation.

In essence, the accuracy of Abaqus simulation results hinges on the judicious selection and input of material properties. These properties form the basis for capturing the intricacies of shaped charge behaviour, ensuring that the simulation aligns closely with the real-world performance of these explosive devices. Researchers and engineers must choose and input realistic material data to guarantee reliability of their shaped charge simulations.

3.2 Johnson Cook Damage Model

The Johnson-Cook damage model becomes particularly pertinent at this part when configuring Abaqus for the shaped charge simulations where materials may undergo severe deformation, fracture, or fragmentation during detonation. By accounting for these damage mechanisms, the model contributes to a more accurate depiction of the shaped charge's performance, providing insights into potential failure modes and structural integrity. Researchers and engineers can leverage the Johnson-Cook damage model in conjunction with other material properties to enhance the overall accuracy of their simulations, ensuring a more realistic understanding of shaped charge dynamics and aiding in the design and optimization of these critical explosive devices [3].

$$\sigma = [A + B \cdot (\epsilon_p^*)^n] \cdot \left[1 + C \cdot \ln \left(\frac{\dot{\epsilon}_p}{\dot{\epsilon}_0} \right) \right] \cdot \left[1 - \left(\frac{T - T_0}{T_m - T_0} \right)^m \right]$$

Equation 1 - Johnson Cook **Damage Model** equation

- σ is the equivalent stress,
- $A, B, n, C,$ and m are material constants,
- ϵ_p^* is the effective plastic strain,
- $\dot{\epsilon}_p$ is the plastic strain rate,
- T is the temperature,
- T_0 is the reference temperature,
- T_m is the melting temperature.

3.3 Hooke's Law

Hooke's Law is a foundational principle in mechanics, expressing the linear relationship between stress (σ) and strain (ϵ) in elastic materials. In the context of Abaqus shaped charge simulations, this law is crucial for defining material properties like the elastic modulus (E). Abaqus uses finite element analysis to numerically solve equations derived from Hooke's Law, facilitating the simulation of complex interactions and deformations during the detonation/explosive process. It's important to recognize that Hooke's Law applies within the elastic limit of materials, and in dynamic events like shaped charge explosions, additional considerations may be necessary for accurate modelling beyond the elastic range [1].

$$\sigma = E \cdot \epsilon$$

Equation 2 - Hooke's Law equation

- σ is stress (Pa)
- ϵ is strain = $\frac{\Delta L}{L_0}$
- E is the modulus of elasticity (Pa)

3.4 Equation of State (EoS)

The EoS characterizes material responses under diverse thermodynamic conditions like pressure, volume, and temperature. This mathematical model helps to precisely simulate materials, including the liner and explosive components, react to high pressure situations. Various EOS options, such as the Mie-Gruneisen and JWL equations, cater to shock loading and explosive material behaviours, respectively. Abaqus provides specialized material models for metals and plastics, allowing for the incorporation of tabular data or experimental findings but materials have been sourced elsewhere [5].

3.4.1 Jones-Wilkins-Lee (JWL) Equation

The JWL equation is a model for simulating explosive materials. Equation 3 shows the pressure-volume-internal energy relationship during detonation. In the context of shaped charges, this equation is particularly effective in capturing the rapid volume changes and high pressures experienced during detonation. Implementation in Abaqus involves calibrating material parameters like A , B , C , and V_0 based on experimental data, ensuring accurate representation of the specific explosive material. Detailed instructions for implementation can be found in the Abaqus documentation and material modelling guidelines, and it's crucial to validate simulation results against experimental data if available [6].

$$P(V, U) = A + B \left(\frac{V_0}{V} - 1 \right) + \frac{1}{2} C \left(\frac{V_0}{V} - 1 \right)^2 + F(U)$$

Equation 3 - JWL equation

- P is the pressure, V is the volume, and U is the internal energy.
- A , B , C , V_0 , and $F(U)$ are material parameters.
- The internal energy (U) is related to the volume (V) through $U = \frac{1}{2} A (V_0 - V)^2$.

3.4.2 Mie-Gruneisen Equation

The Mie-Gruneisen Equation is a mathematical model employed in the simulation of explosive dynamics and shaped charges. It characterizes material responses under diverse thermodynamic conditions, including pressure, volume, and temperature. Specifically, this equation is crucial for accurately simulating how materials, such as liners and explosive components in shaped charges, react to high-pressure scenarios during detonation. Abaqus, the simulation software, incorporates specialized material models for metals and plastics, utilizing the Mie-Gruneisen Equation to ensure precise representation of material behaviours in dynamic and explosive conditions [7].

$$P(V, U) = A + B\left(\frac{V_0}{V} - 1\right) + \frac{1}{2}C\left(\frac{V_0}{V} - 1\right)^2 + F(U)$$

Equation 4 - Mie-Gruneisen Equation

- P is the pressure.
- V is the volume.
- U is the internal energy.
- A, B, C, V_0 , and $F(U)$ are material parameters.

3.5 Tensors Notation

Tensor notation is a crucial mathematical tool for describing how materials behave under different conditions. Tensors, mathematical entities extending beyond scalars and vectors, are key in capturing the anisotropic and directional properties of materials during explosive events. Abaqus relies heavily on tensor notation to define and manipulate parameters like stress, strain, and material properties.

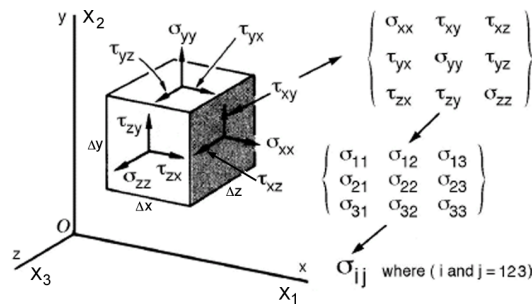


Figure 5 - Tensors Notation - Sourced College of Engineering, Virginia Tech

Stress and strain tensors play a critical role in shaping charge simulations by detailing how materials deform under external forces. The Deformation Gradient Tensor² provides insights into local material deformation, especially crucial in understanding events like the collapse of the liner and jet formation [2]. Rotation

² "The deformation gradient F is the fundamental measure of deformation in continuum mechanics. It is the second order tensor which maps line elements in the reference configuration into line elements (consisting of the same material particles) in the current configuration."

tensors guide the simulation of material movements, and tensor notation helps address symmetry conditions and accommodate material anisotropy. In summary, tensor notation in Abaqus for shaped charges is an essential framework, ensuring precise simulations of complex material behaviours.

4. Methodology

4.1 Modelling Approach

Abaqus is employed to model various components of the shaped charge, starting in the “Part” section, the casing, followed by the liner and the HE is sketched. Ensuring a faithful representation of the physical shaped charge geometries is crucial for obtaining accurate simulation results.

Material properties must be applied to the geometries of the Shaped Charge. The liner material considers constitutive models, such as elastic-plastic or rate-dependent properties. This involves specifying parameters like Young's modulus, Poisson's ratio, yield strength, and incorporating strain-rate sensitivity using experimental data or material testing results.

Similarly, for the casing material, the material properties should be defined by selecting a model that aligns with the casing's behaviour under the loading conditions in the simulation. This includes inputting parameters such as elastic constants, plasticity parameters and strain-rate sensitivity.

Regarding the HE component, which involves complex behaviours related to shock physics, Abaqus offers various material models, including the JWL equation of state. Defining explosive properties like density, detonation velocity, and parameters specific to the chosen explosive model is crucial. When simulating the detonation of a HE, it is crucial to carefully consider initiation and propagation conditions. The detonation point within a shaped charge is a pivotal location where the rapid release of explosive energy takes place, resulting in the formation of a focused jet that plays a critical role in effectively penetrating target materials. When the HE is detonated, it propagates a wave that spreads through the material in conical form. If the detonation point is placed in the middle of the

HE, a wave will be propagated in both directions towards the casing as well as the liner. During the setup of the simulation different detonation points were tested.

In the assembly section, components are constrained to create a cohesive model for simulation. Once assembled, loading conditions and boundary constraints must be specified in the “Step” section of Abaqus. Constraints are applied to the shaped charge to ground it and make it rigid. Boundary conditions can differ between 2D and 3D simulations because the physical nature and behaviour of the structures. Boundary conditions are imposed on the segmented face of the Shaped Charge 3D model to prevent the outward propagation of the HE. This segmented face effectively serves as a solid barrier, mimicking a 360-degree interaction, where the HE interacts against it as if the explosive force extends throughout the entire circumference.

A mesh must be assigned/generated on the geometry to enable a detailed representation of the structure. Emphasis should be placed on ensuring high mesh quality and making thoughtful selections of element types to accurately capture the physics of the simulation. Furthermore, it is advisable to implement a finer mesh in regions where significant deformation or stress gradients are anticipated.

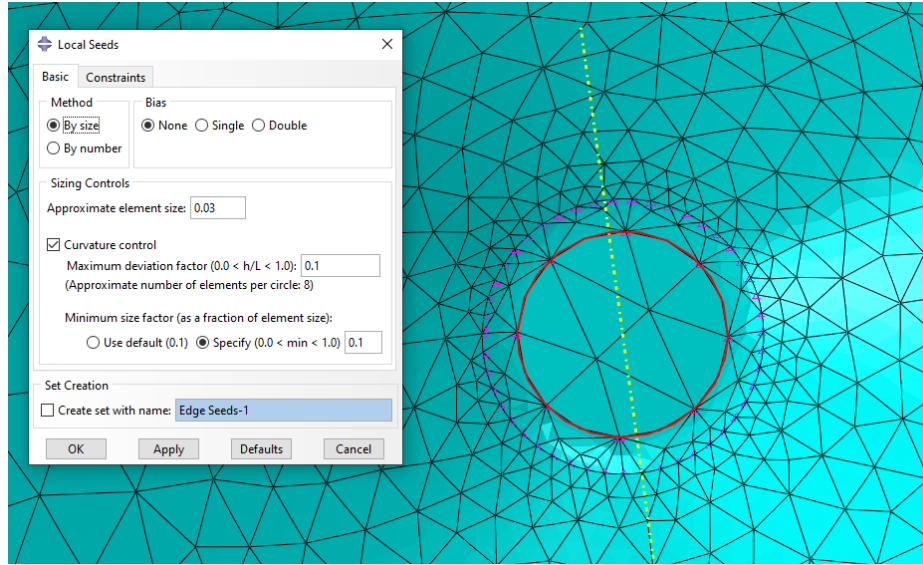


Figure 6 - Mesh using seed edge tool

The intricate geometry of shaped charges poses challenges for meshing in Abaqus. To optimize the mesh for the specific environment, manual adjustments need to be made, using the “Seed Edges” tool, placing additional nodes along selected edges. This is necessary to allow for a coarser representation that aligns with the intricacies of the shaped charge design. This meticulous approach to meshing enhances the precision and reliability of the physical behaviour in the simulation results, contributing to a more comprehensive understanding of the shaped charge behaviour under various conditions [9].

4.2 Steps in 2D Axisymmetric Model

Sketched Liner, Casing and HE. 1st sketch [Fig. 6] was incorrect as liner did not connect to the Casing properly. Many different variations of Shaped Charge were simulated to see differences [Fig. 6-8].

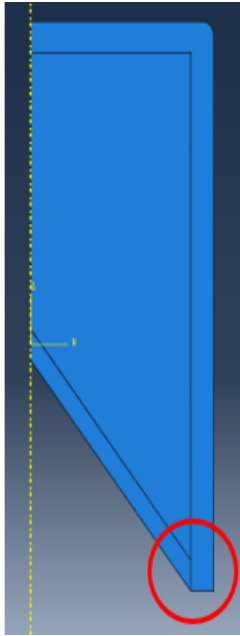


Figure 7 - 2D sketch (1)

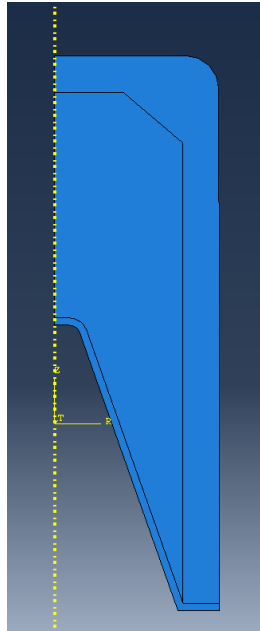


Figure 8 - 2D sketch (2)

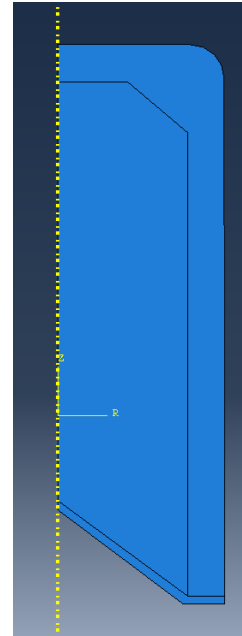


Figure 9 - 2D sketch (3)

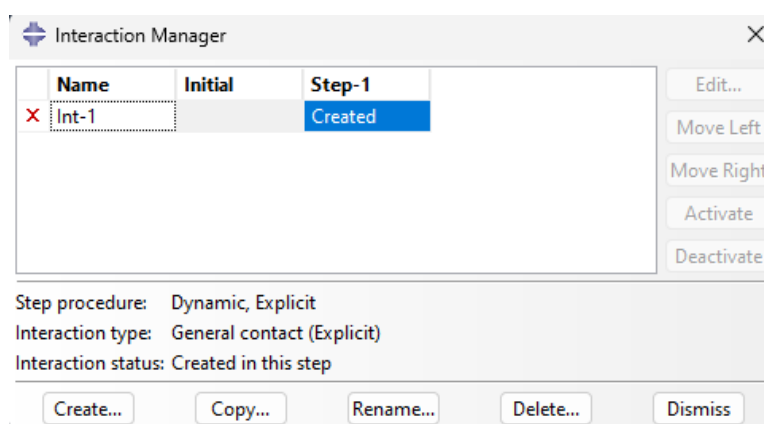


Figure 10 - Screenshot of Interaction Manager in Abaqus

4.3 Transition to 3D Model

Initially, the model is created and validated in 2D, covering aspects like defining geometry, material properties, meshing, and loading conditions. Once the 2D model is confirmed, the transition to 3D takes place by utilizing Abaqus' revolving feature, introducing a 3rd dimension to the previously flat (2D) geometry. This shift could involve adjustments to material properties, especially if there is a modification in element types but this was not necessary for this job. The transition includes generating an appropriate 3D mesh, considering element types, sizes, and refinement in critical zones [4. Methodology]. Boundary conditions and loading conditions from the 2D model are then transferred and adapted to accommodate the 3D geometry. The 3D simulation is submitted for analysis, and Abaqus solves the three-dimensional equations [3. Material Properties] based on specified input conditions. The results become more realistic with this job.

5. Results - 2D Axisymmetric Model

5.1 Presentation of Results

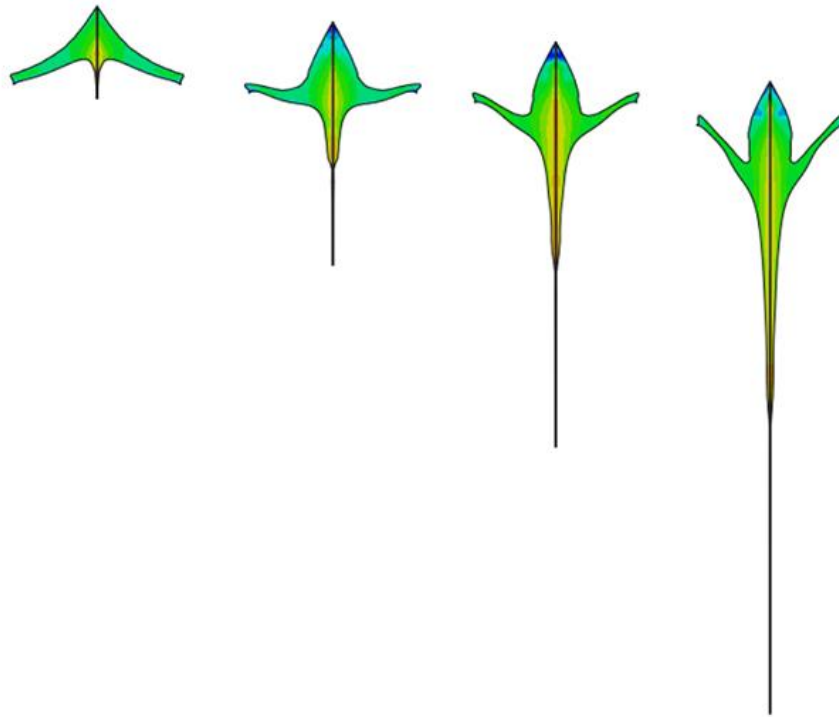


Figure 11 - Screenshots of jet using Display Group feature on Abaqus which is a user-defined collection of entities, such as nodes, elements, surfaces, or assemblies, that are grouped together for display purposes.

5.2 Discussion of Key Findings 2D

The simulation models the initiation and detonation of the explosive material, which then leads to a nice collapse of the liner. The liner's collapse generates a shockwave, transforming it into a focused, high-velocity jet.

Simulating the shaped charge in 2D within Abaqus presents inherent constraints in comparison to 3D simulations, especially concerning the jet's behaviour. The 2D model confines the analysis to two dimensions, overlooking critical out-of-plane information. The three-dimensional dynamics and interactions of the shaped charge jet may not be fully captured within a 2D simulation. While symmetry conditions are frequently employed in 2D to reduce computational costs, assumptions of symmetry may not accurately represent asymmetrical effects or non-symmetric interactions between the jet and surrounding structures.

Meshing challenges also arise in 2D simulations, where achieving accuracy may require a finer mesh, thereby increasing computational requirement. Certain phenomena related to jet behaviour, such as lateral spreading or interactions with nearby structures in three dimensions, cannot be faithfully modelled in 2D. Consequently, the realism of the results may be compromised, limiting the understanding of phenomena like jet penetration and target interactions.

Despite these constraints, 2D simulations can still offer valuable insights, particularly when computational resources are limited, providing a rapid assessment of shaped charge behaviour. However, for a comprehensive and realistic depiction of the shaped charge and its jet behaviour, a 3D simulation is generally favoured.

When visualising the job, the Max Principal option is selected. This stress analysis represents the highest normal stress on a specific plane within a material. According to the maximum principal stress theory, failure occurs if this maximum stress exceeds a critical value. This theory is used to predict material failure under different loading conditions, with the maximum principal stress acting as a key criterion. In engineering simulations, software like Abaqus employs these principles to analyse stress distributions and predict potential failure locations based on criteria such as the maximum principal stress.

6. Results - 3D Model

6.1 Presentation of 3D Model Results

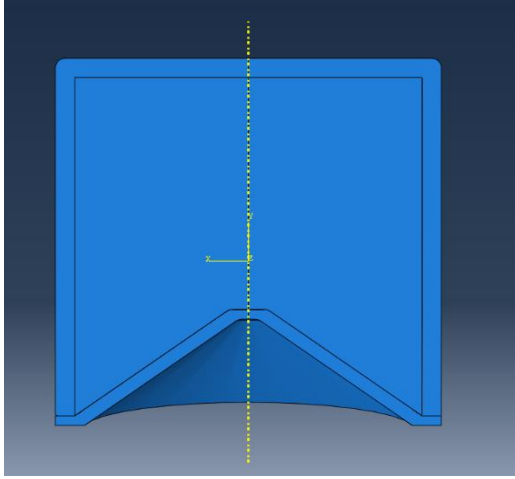


Figure 12 - 3D model 1

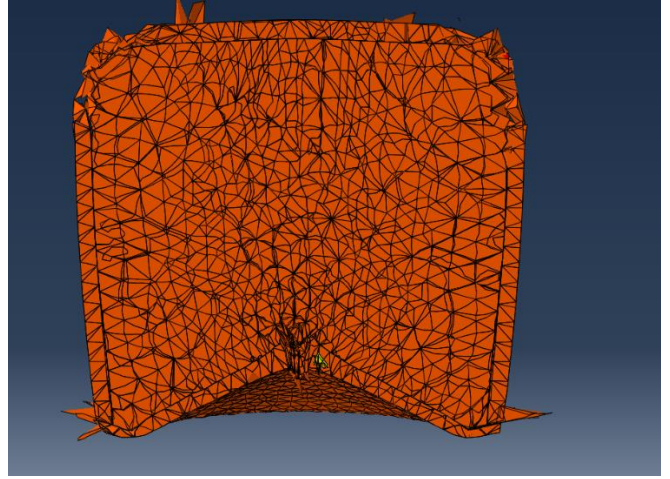


Figure 13 - 3D model (1) job result

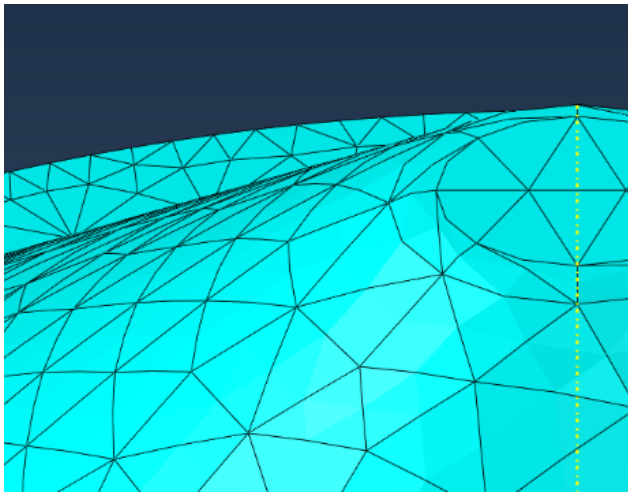


Figure 14 - Meshing on top of Liner - model 1

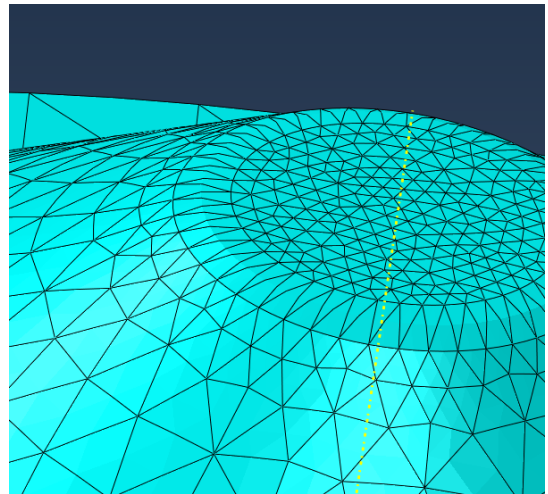


Figure 15 - Coarser mesh on top of Liner – model

1

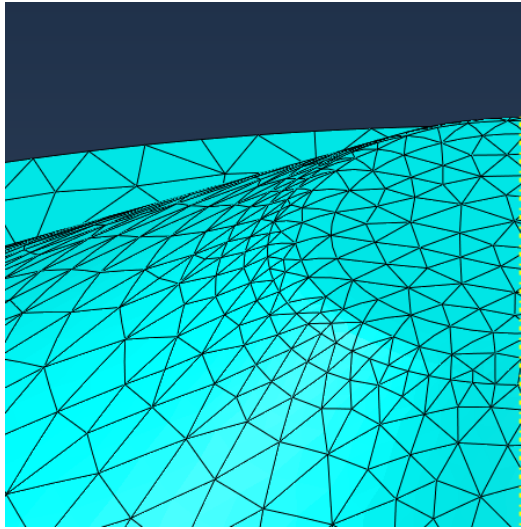


Figure 16 - Meshing on outside of liner.
Changed to 4mm 0.002 - model 1

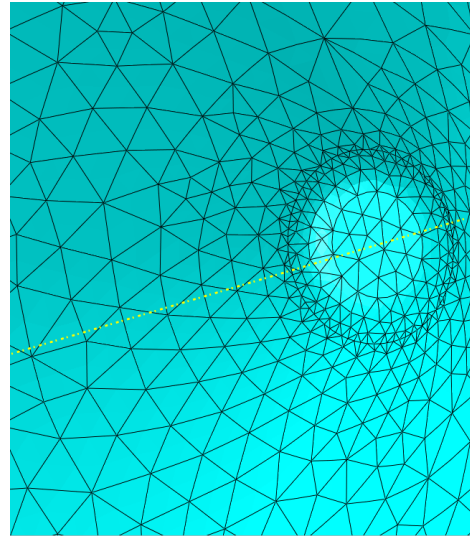


Figure 17 – Coarser mesh on inside of Liner - model
1

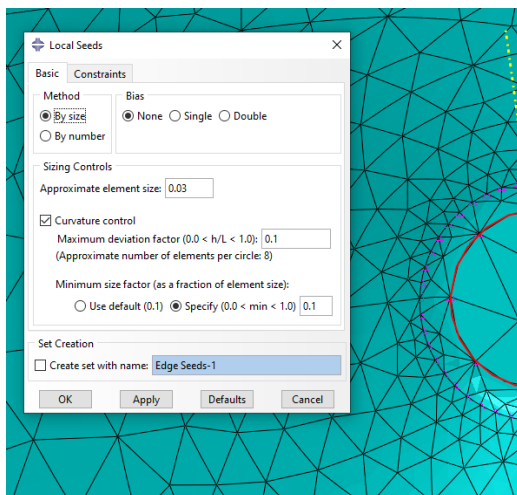


Figure 18 - HE inside 0.03 - model 1

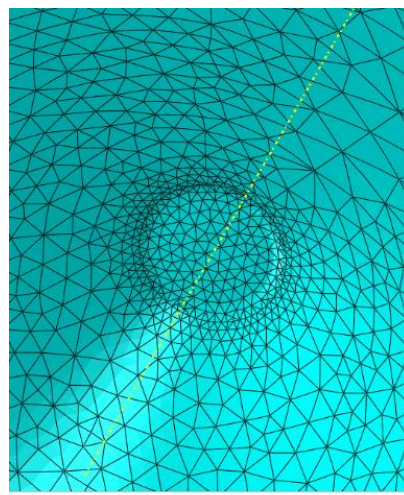


Figure 19 - HE insider, custom Local Seed applied
- model 1

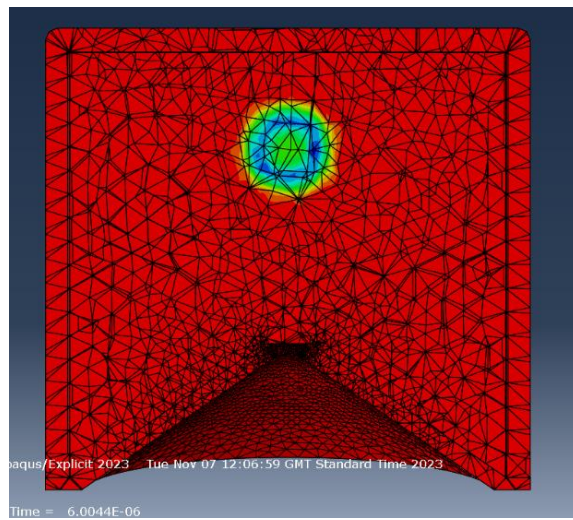


Figure 20 - Detonation point centralised & lowered - model 1

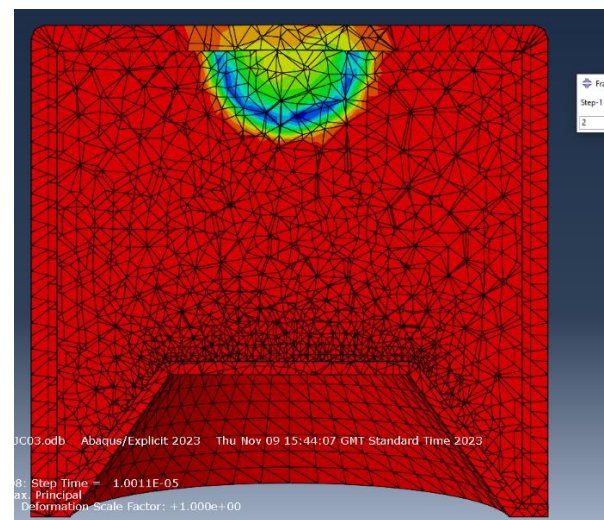


Figure 21 - Detonation point moved to top of HE - model 2

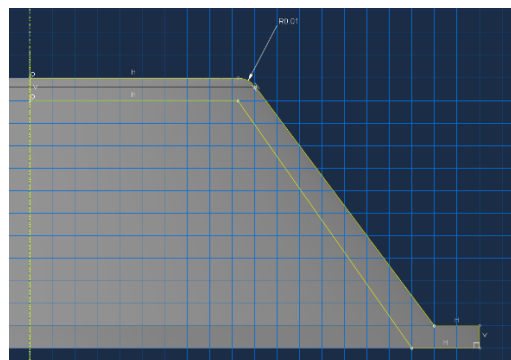


Figure 22 - Change of sketch to have larger liner surface area - model 2

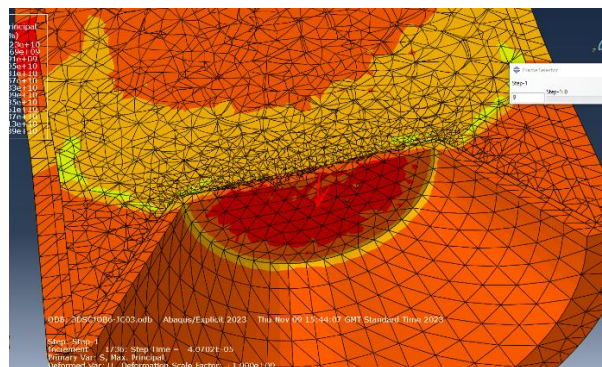


Figure 23 - Representation of the distribution of stress values throughout the mode - model 2

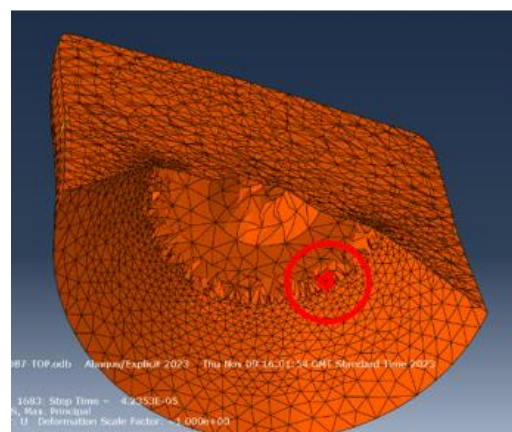


Figure 24 - Failure point highlighted (error) - model 2

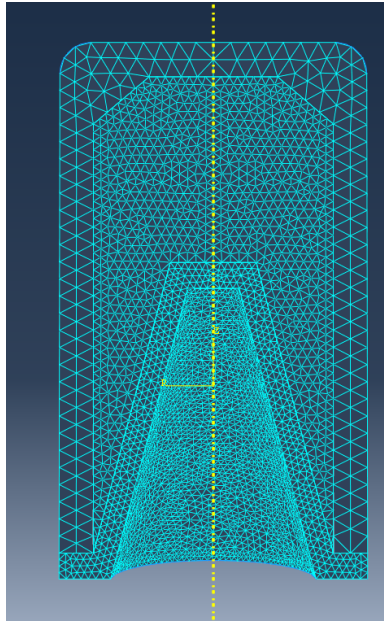


Figure 25 - Reconfiguration of liner showing meshing – model 3

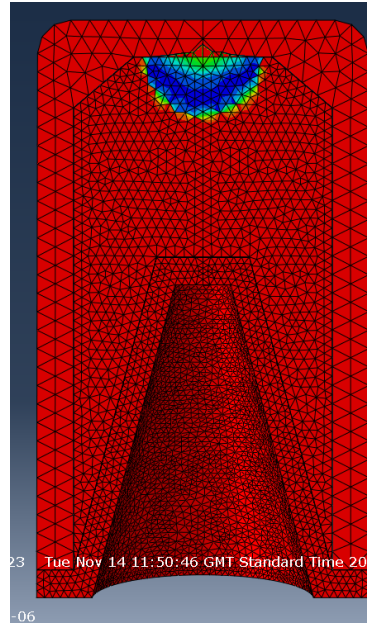


Figure 26 - New configuration of liner with detonation wave start model 3

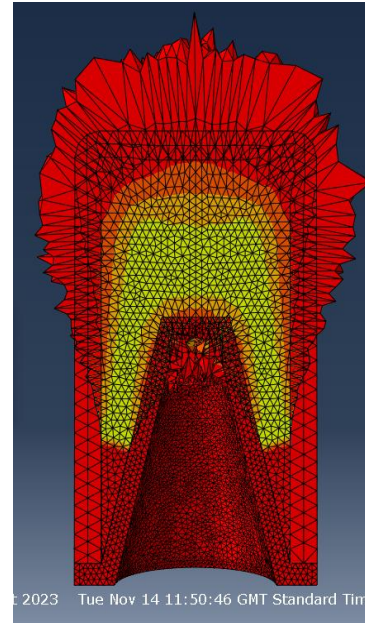


Figure 27 - Further stage of detonation – Failure due to no constraints applied – model 3

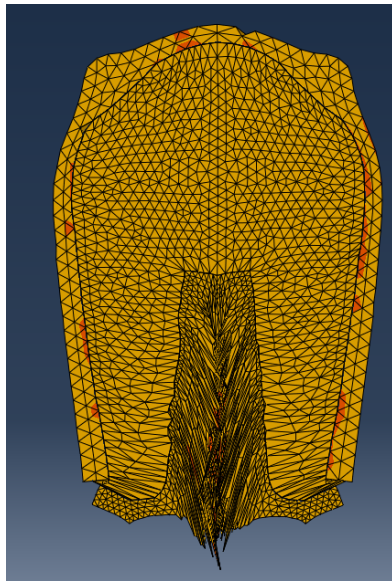


Figure 28 - Constraints applied – model

3

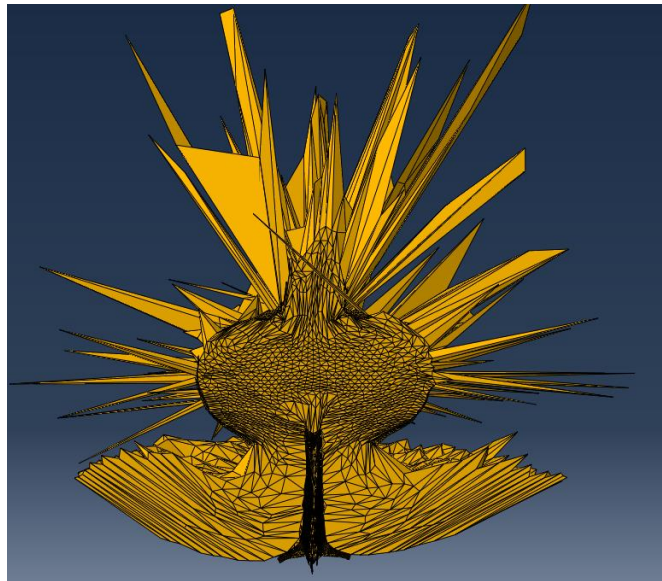


Figure 29 - Blast and start of formation of jet – model 3

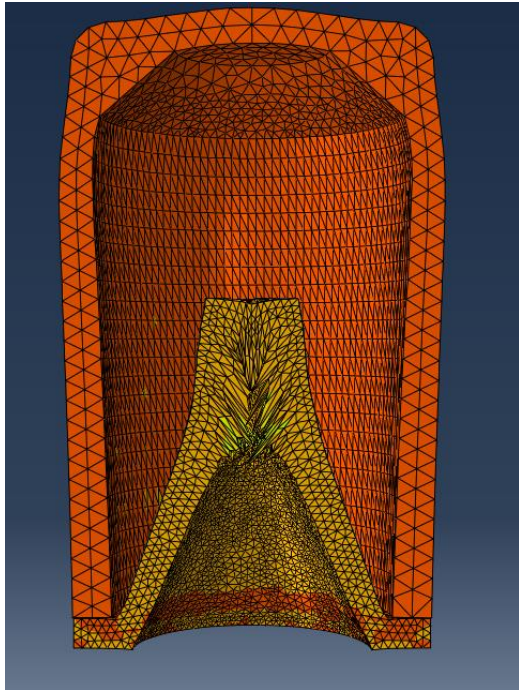


**Figure 30 - HE unselected from visualisation
– model 3**



**Figure 31 - Formation of jet - Can see Liner is
not constrained to Casing and follows the jet**



**Figure 32 - Further formation of jet. Good
blast**

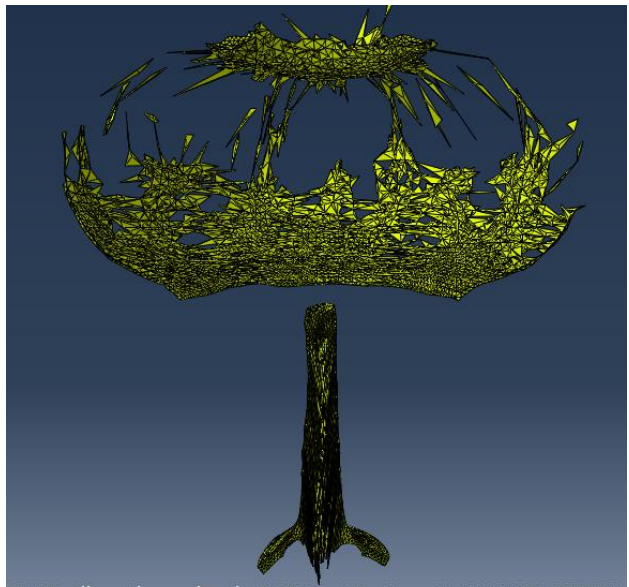


Figure 33 - Unusual result due to constraint issue

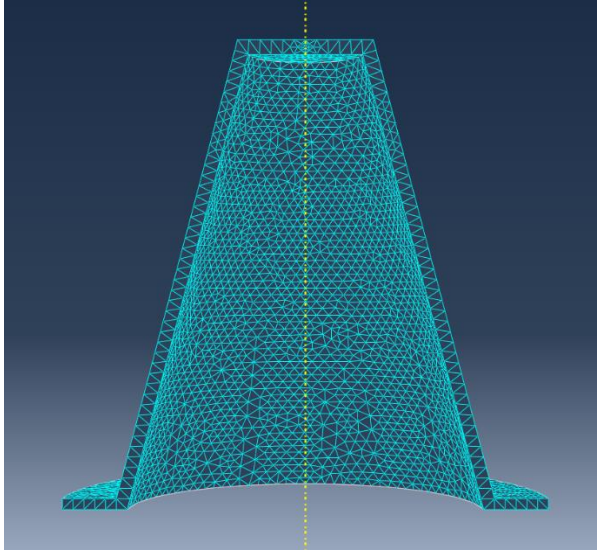


Figure 34 - Liner made thinner should be 2-4% of cone diameter – model 3.1

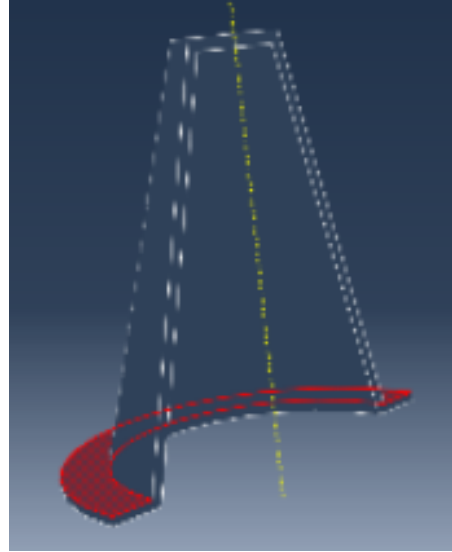


Figure 35 - Constraints shown – model 3

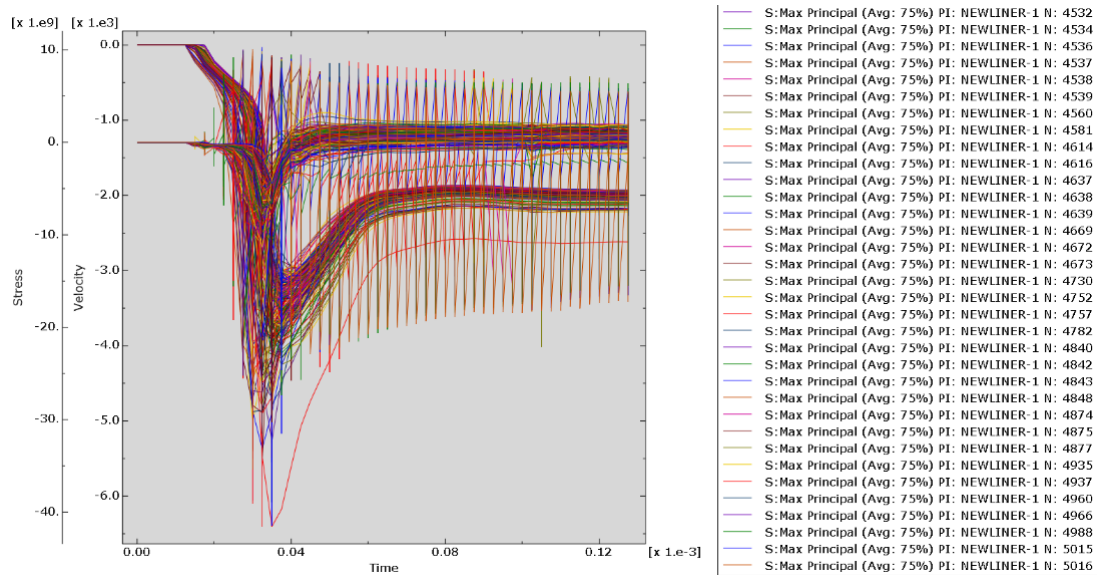


Figure 36 - Max principal turned on should be off. Interested in analysing and visualizing other parameters, such as strain, velocity.

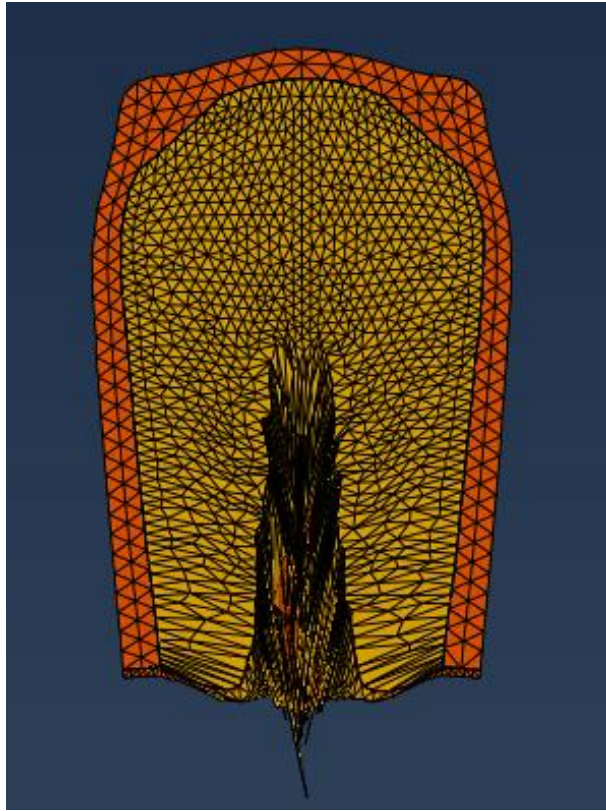


Figure 37 - Model 3.1 - Collapse of liner

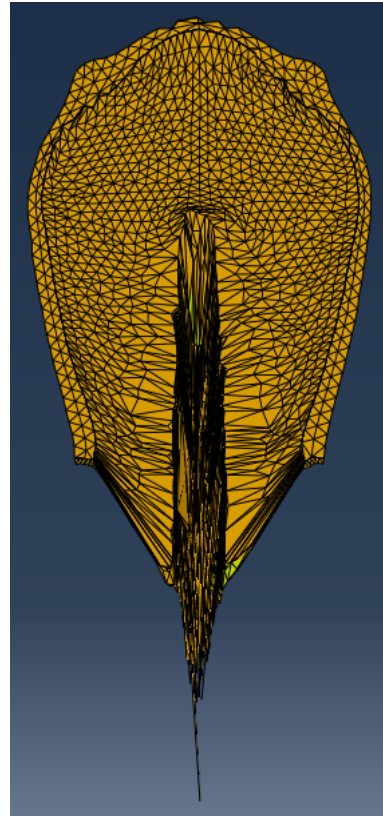


Figure 38 - Great result with optimized jet formation

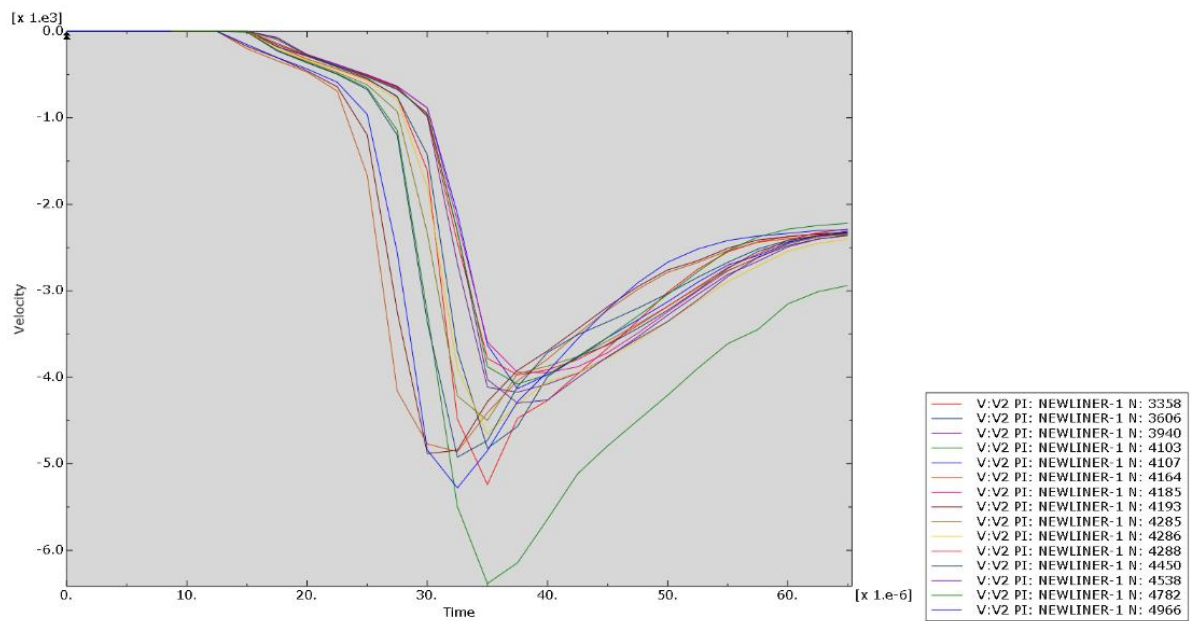


Figure 39 - Velocity time graph - model 3.1

6.2 Discussion of Key Findings 3D

In the process of meshing [Fig. 13-18] within the liner, a mesh size of 0.003 has been applied. Initial attempts were made to set both the inner and outer circles to 0.001; however, this resulted in mesh stretching. To rectify this, the outer circle mesh size was adjusted to 0.001, while the inner circle retained a mesh size of 0.003. This configuration ensures a coarse mesh without the undesired stretching phenomenon.

[Fig. 16] The liner mesh utilizes a 0.003 nominal size. Initial attempts with both inner and outer circles set at 0.001 led to undesired stretching. The revised configuration employs 0.001 for the outer circle and maintains 0.003 for the inner circle. Achieving a coarse yet non-stretched mesh for improved accuracy and stability.

The detonation point [Fig. 19-20] was repositioned to a more centralized location. In the previous configuration, the detonation point was situated at the top, and an additional detonation point was present off to the right. The current adjustment resulted in an earlier abortion compared to the preceding simulation.

The common error of incorrectly placing the detonation point too high above and outside the designated area of the shaped charge introduced significant simulation issues. This misalignment resulted in the explosive effects not directly impacting the shaped charge components, leading to inaccurate and irrelevant results.

In the Abaqus simulation for the shaped charge, the analysis primarily involves direct stress, principal stress, and shear stresses, while intentionally excluding von Mises stress. Von Mises stress is a metric designed for assessing material yielding or fracturing, particularly in ductile materials like metals. The von Mises yield criterion states that if the von Mises stress under load equals or surpasses the yield limit of the material under simple tension, the material will yield [1].

The decision to omit von Mises stress is motivated by the distinctive characteristics of the materials and the complexity of the shaped charge simulation. Shaped charges often feature non-uniform loading conditions and

materials with diverse mechanical properties, making direct stress, principal stress, and shear stresses more suitable for capturing the nuanced material behaviour. By focusing on these stress components, the simulation aims to provide a more accurate and tailored analysis of the dynamic response of the shaped charge under various conditions.

The technical modification involved altering the sketch of the liner and high explosive (HE) [Fig. 21] to reduce pointed features and increase the overall surface area. Despite these changes, the simulation job exhibited a comparable runtime and encountered an error at the identical stage of the simulation process. Further analysis is required to pinpoint the root cause of the recurring error, as the adjustments to the geometrical features did not yield the anticipated effect on the simulation outcome.

7. Discussion - Analysis of 2D and 3D Model Outcomes

The velocity-time graph [Fig.37] served as a crucial tool for examining the dynamic progression of the jet over time. This graphical representation offers vital insights into various aspects of the jet's behaviour, starting with its initiation and subsequent acceleration phase, characterized by distinct patterns on the velocity-time curve. The highest velocity point, a significant feature on the graph, provides a measurable parameter for evaluating the jet's penetration capabilities and kinetic energy. Post-peak, the graph reveals the steady-state or deceleration phase, offering essential information about the sustained motion of the jet. Anomalies or fluctuations in the velocity-time profile can indicate instabilities, impacting assessments of jet stability. The velocity-time graphs purpose is not only to comprehend the inherent characteristics of the jet but also to investigate the effects of design alterations on its performance. This visualization proves valuable in optimizing shaped charge designs and validating simulation results against experimental data, contributing to a more thorough understanding of the dynamic behaviour of shaped charge jets [4].

The jet has a velocity of 3 kilometres per second (3 km/s) [Fig.37]. This is a widely recognized jet velocity as significant and falls within the common range of velocities attained by shaped charges across different applications. The efficacy of a shaped charge is contingent upon its capability to produce a high-velocity metal jet that can effectively penetrate the targeted material. With a speed of 3 km/s, the velocity is considerable and proves effective for a diverse set of applications, encompassing both military and industrial contexts [5].

The discussion of the research findings on EFPs/shaped charges reveals insightful observations into the strengths and limitations of different simulation approaches. The comparison between 2D and 3D simulations acknowledges the computational efficiency of 2D models but highlights their inherent constraints, emphasizing the shift to 3D for a more realistic representation of shaped charge dynamics. The challenges associated with meshing, particularly the consideration of mesh size, are effectively addressed, showcasing an understanding of its impact on simulation accuracy. The repositioning of the

detonation point is scrutinized for its effects on simulation outcomes, shedding light on the sensitivity of shaped charge simulations to geometric parameters. The discussion briefly touches on the Johnson-Cook damage model and the EoS, suggesting a need for a more in-depth analysis of their influence on simulation accuracy. The exclusion of von Mises stress is acknowledged, but a more comprehensive discussion of its relevance and potential impact on failure predictions is warranted.

8. Conclusion

In conclusion, this assignment has provided a comprehensive exploration of explosive dynamics and engineering, with a specific focus on the design and simulation of EFPs or shaped charges. The significance of accurate modelling and critical analysis in engineering applications, especially in defence, explosives engineering, and other practical fields, has been emphasized throughout.

The literature review delves into the theoretical aspects of shaped charges, explaining the Munroe effect, hollow charge geometry, and the dynamics of the conical liner. Material properties, essential for Abaqus simulations, have been highlighted, with a special focus on the Johnson-Cook damage model, Hooke's Law, EoS, and the Jones-Wilkins-Lee (JWL) and Mie-Gruneisen equations.

The methodology section outlines the modelling approach using Abaqus, starting with a 2D axisymmetric model and transitioning to a more realistic 3D model. Results from both 2D and 3D simulations are presented and discussed, underlining the constraints and advantages of each approach. The impact of meshing choices, detonation point positioning, and geometric modifications on simulation outcomes are thoroughly examined.

The assignment not only demonstrates a deep understanding of shaped charge technology but also underscores the complexities and challenges in simulating such dynamic events. It emphasizes the importance of meticulous material selection, accurate modelling, and critical analysis for obtaining reliable and meaningful simulation results.

In the realm of shaped charge simulations, this assignment contributes valuable insights, and its methodology, findings, and discussions pave the way for further refinement and advancement in the understanding and application of explosive dynamics in engineering.

9. References

- [1 “MatWeb,” MatWeb, [Online]. Available:
] <https://www.matweb.com/index.aspx>. [Accessed 2023].
- [2 K. S. T. H. a. C. L. Xiangshang Li, “Dynamic Effect of Shaped Charge Blasting
] and Its Application in Coal Seam Permeability Enhancement,” American
Chemical Society, 2022.
- [3 X. Wang, “International Journal of Impact Engineering - Validation of
] Johnson-Cook plasticity and damage model using impact experiment,” United
Technologies Research Center, 411 Silver Lane, East Hartford, CT 06108,
USA, 2013.
- [4 Nuclear-Power, “Hooke’s law,” [Online]. Available: [https://www.nuclear-
\] power.com/nuclear-engineering/materials-science/material-
properties/strength/hookes-law/](https://www.nuclear-power.com/nuclear-engineering/materials-science/material-properties/strength/hookes-law/). [Accessed 2023].
- [5 R. L. Doney, “Effects of equations of state and constitutive models on
] simulating copper shaped charge jets in ALEGRA,” rmy Research Laboratory
& Sandia National Laboratories, MD, 21005, USA, 2020.
- [6 M. J. SZUCK, “SIMULATION OF MICRO-SHAPED CHARGE
] EXPERIMENTS AND,” University of Illinois at Urbana-Champaign, Illinois ,
2011.
- [7 C. Poole, “Penetration of a Shaped Charge,” University of Oxford, Oxford,
] 2005.
- [8 Kelly, “Solid Mechanics Part III,” University of Auckland, Auckland.
]
- [9 A. Massobrio, “What Is Meshing: Unlocking the Power of 3D Geometry,”
] Neaural Concept, 2020. [Online]. Available:

<https://www.neuralconcept.com/post/what-is-meshing-unlocking-the-power-of-3d-geometry>. [Accessed 2023].

[1] Simscale, "What is von Mises Stress?," 11 August 2023. [Online]. Available: 0] <https://www.simscale.com/docs/simwiki/fea-finite-element-analysis/what-is-von-mises-stress/>. [Accessed December 2023].

[1] M. Held, "Wayback Machine," *Journal of Battlefield Technology*, vol. 4, no. 1] 3, 2011.

[1] A. Doig, "Some metallurgical aspects of shaped charge liners," *ournal of* 2] *Battlefield Technology*, 1998.

[1] H. O. AGU, "THE EFFECT OF 3D PRINTED MATERIAL PROPERTIES ON 3] SHAPED," CRANFIELD UNIVERSITY, Cranfield, 2019.

[1] B. Trowbridge, "War cries and clashing steel: the Battle of Agincourt," 27 4] October 2015. [Online]. Available: <https://blog.nationalarchives.gov.uk/war-cries-clashing-steel-battle-agincourt/#:~:text=English%20archers%20marching%20within%20range,caused%20by%20earlier%20wet%20weather..> [Accessed November 2023].

[1] King John, "The Longbow and its Impact on the Battle of Agincourt," 2 July 5] 2015. [Online]. Available: <https://kingjohnshouse.org.uk/the-longbow-and-its-impact-on-the-battle-of-agincourt/>. [Accessed November 2023].

[1] C. Oord, "'Mad' Jack Churchill – The Only Man to Dispatch a German Soldier 6] With a Longbow in WW2," 9 December 2018. [Online]. Available: <https://www.warhistoryonline.com/instant-articles/jack-churchill-carry-a-sword.html>. [Accessed November 2023].

[1] J. Owen, *Winning World War II Behind Enemy Lines*, Ballantine Books, 2015. 7]

[1] Reuters, "False claim: "Middle finger" gesture derives from English soldiers 8] at the Battle of Agincourt in 1415," 14 May 2020. [Online]. Available:

<https://www.reuters.com/article/idUSKBN22Q2MU/>. [Accessed November 2023].

[1 E. Castelow, "The Longbow," Historic UK, 4 March 2016. [Online]. Available:
9] <https://www.historic-uk.com/HistoryUK/HistoryofEngland/The-Longbow/>.
[Accessed 2023 October 2023].

[2 Longbow Archers, "Arrowheads," Longbow Archers, 2016. [Online].
0] Available: <https://www.longbow-archers.com/arrowheads.html>. [Accessed
November 2023].

[2 Country Life, "How the English won the day at the Battle of Agincourt,"
1] Country Life, 25 October 2017. [Online]. Available:
[https://www.countrylife.co.uk/out-and-about/bring-me-my-bow-of-burning-
gold-a-day-in-the-life-of-an-english-archer-
167183#:~:text=After%20three%20hours%20of%20inactivity,two%20sheav
es%20of%2024%20arrows..](https://www.countrylife.co.uk/out-and-about/bring-me-my-bow-of-burning-gold-a-day-in-the-life-of-an-english-archer-167183#:~:text=After%20three%20hours%20of%20inactivity,two%20sheaves%20of%2024%20arrows..) [Accessed November 2023].

[2 A. Curry, in *Agincourt: A New History*, The History Press, 2006, p. 129.
2]

[2 A. Curry, *The Battle of Agincourt: Sources and Interpretations*, Rochester:
3] Boydell & Brewer Ltd, 2000.

[2 T. Sutherland, *The Battle of Agincourt: An Alternative Location?*, 2005.
4]

10. Bibliography

THE EFFECT OF 3D PRINTED MATERIAL PROPERTIES ON SHAPED

CHARGE LINER PERFORMANCE [13] - Interesting read

I was unable to get velocity time graph for my 2D simulation due to no access.