



Thomas James Cresswell

Physics Lab Report – Finite Element Analysis of a steel projectile
into an Inconel 718 plate.

University of Wales Trinity Saint David
Ordnance Munitions and Explosives Professional

BEng
Academic Year: 2024 - 2029

Supervisor: Prof Kelvin Donne
May 2025

Academic integrity declaration

I declare that:

- the thesis submitted has been written by me alone.
- the thesis submitted has not been previously submitted to this university or any other.
- that all content, including primary and/or secondary data, is true to the best of my knowledge.
- that all quotations and references have been duly acknowledged according to the requirements of academic research.

I understand that to knowingly submit work in violation of the above statement will be considered by examiners as academic misconduct

Table of contents

1.	Introduction	1
1.1.	Purpose of modelling.....	1
1.2.	Finite Element Analysis (FEA)	1
1.3.	Johnson-Cook damage model	1
2.	Setup of Abacus CAE for FEA.....	2
2.1.	Production of threat	2
2.1.1.	Properties of threat	2
2.2.	Production of armour plate	2
2.2.1.	Properties of armour plate	2
3.	Results.....	3
3.1.	800ms ⁻¹ threat.....	3
3.2.	1600ms ⁻¹ threat	6
4.	Discussion	10
4.1.	Relevance to OME	10
4.1.1.	Kinetic penetrator modelling.....	10
4.1.2.	Shaped charge FEA modelling	10
4.2.	Velocity graph analysis	10
4.3.	Armour plate damage comparison and analysis.....	11
5.	Limitations	12
5.1.	Limitation of Johnson-Cook.....	12
5.2.	Limitations of Abacus CAE.....	12
6.	References.....	13

List of Figures

Figure 1 - Johnson-Cook flow stress equation [1]	1
Figure 2 - 800ms ⁻¹ initial contact.....	3
Figure 3 - 800ms ⁻¹ initial damage.....	3
Figure 4 - 800ms ⁻¹ resultant damage pre-bounce	4
Figure 5 - 800ms ⁻¹ resultant damage post-bounce	4
Figure 6 - 800ms ⁻¹ final deflection	5
Figure 7 - 800ms ⁻¹ backplate analysis	5
Figure 8 - 1600ms ⁻¹ initial contact	6
Figure 9 - 1600ms ⁻¹ initial damage	6
Figure 10 - 1600ms ⁻¹ pre penetration, both side and backplate view	7
Figure 11 - 1600ms ⁻¹ mid penetration part 1	8
Figure 12 - 1600ms ⁻¹ mid penetration part 2	9
Figure 13 - 800ms ⁻¹ velocity graph	10
Figure 14 - 1600ms ⁻¹ velocity graph.....	11

List of Tables

Table 1 - Properties of ARMOX 440T for FEA simulation [2] [3]	2
Table 2 - Johnson-Cook plasticity and failure parameters for Inconel-718 [4] [5] [6]	2

List of Abbreviations

FEA	Finite Element Analysis
OME	Ordnance, Munitions & Explosives

1. Introduction

1.1. Purpose of modelling

The purpose of the simulation exercise is to determine the mode of failure, if present, for an armoured plate made of Inconel 718 against a steel bullet. This report will detail the methodology followed as well as an analysis of the damage to the plate.

1.2. Finite Element Analysis (FEA)

The FEA package in use for this exercise is Abacus from Dassault Systems. This modelling will use the Lagrange model. This will generate a grid mesh of nodes within the threat and the armour plate on which to model the interaction between them.

In this analysis, both S23 (shear stress in XY plane) and max principle (tensile/compressive stress) will be assessed.

1.3. Johnson-Cook damage model

The Johnson-Cook damage model is used to calculate the deformation of the armour plate as the threat contacts and in some cases penetrates. The equation for the flow stress within the Johnson-Cook model is as follows:

$$\sigma = (a + b\varepsilon_p^n) \left(1 + c \ln \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right) (1 - T^{*m})$$

Figure 1 - Johnson-Cook flow stress equation [1]

The equation considers the strain rate, plastic deformation and temperature of the material as well as yield stress and hardening of the material under load [1]. The Johnson-Cook model also accounts for the thermal softening of a material.

2. Setup of Abacus CAE for FEA

2.1. Production of threat

2.1.1. Properties of threat

Steel is a typical material for armour piercing projectiles used by armed forces all over the world. ARMOX 440T was chosen for its hardness and potential application to perform a similar role for the simulation. Some generic steel properties were also used to complete an estimated profile of the material.

The parameters used for the Steel projectile were:

A (MPa)	B (MPa)	n	C	m	ϵ' (s ⁻¹)	Poisson's Ratio	Density (kg/m ³)	Melt Point (°C)	Trans Point (°C)	YM (GPa)
1100	1550	0.584	0.0140	1.4	1.0	0.27	7850	1450	-40	210

Table 1 - Properties of ARMOX 440T for FEA simulation [2] [3]

2.2. Production of armour plate

2.2.1. Properties of armour plate

Inconel 718 is a Nickel-Chromium alloy which is typically used in applications which require corrosion resistance, weldability and toughness. It is not currently used in armour applications which was determined to be worth simulating.

The parameters used for Inconel 718 were:

Johnson-Cook plasticity parameters					
A (MPa)	B (MPa)	n	C	m	ϵ' (s ⁻¹)
860	1100	0.5	0.0082	1.05	1.0
Johnson-Cook failure parameters					
D ₁	D ₂	D ₃	D ₄	D ₅	
0.04	0.75	-1.45	0.04	0.89	
Density (kg/m ³)	Melt Point (°C)	Transition Point (°C)	Poisson's Ratio	YM (GPa)	Poisson's Ratio
8220	1593	25	0.284	200	0.284

Table 2 - Johnson-Cook plasticity and failure parameters for Inconel-718 [4] [5] [6]

3. Results

3.1. 800ms⁻¹ threat

The 800ms⁻¹ projectile was evaluated first against the plate.

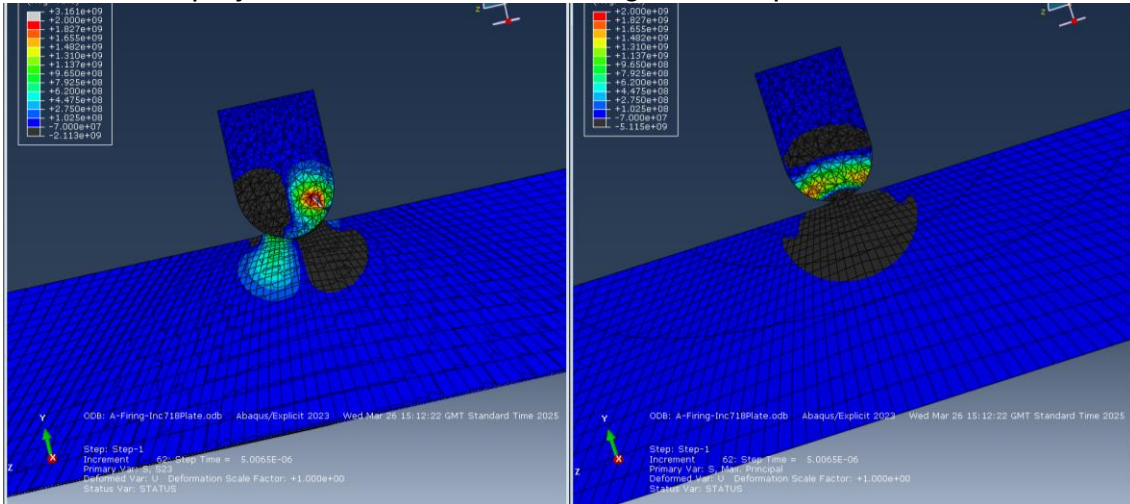


Figure 2 - 800ms⁻¹ initial contact

In the above image, the initial contact of projectile 1 was observed. The left image displays the S23 stress, and the right image displays max principal stress. A partially mirrored shear stress cone can be observed from initial contact with a maximum stress of 2.11e9 Pa. Compressive stress in the right image is at a maximum of 5.12e9 Pa so Currently, the compressive stress is the greatest.

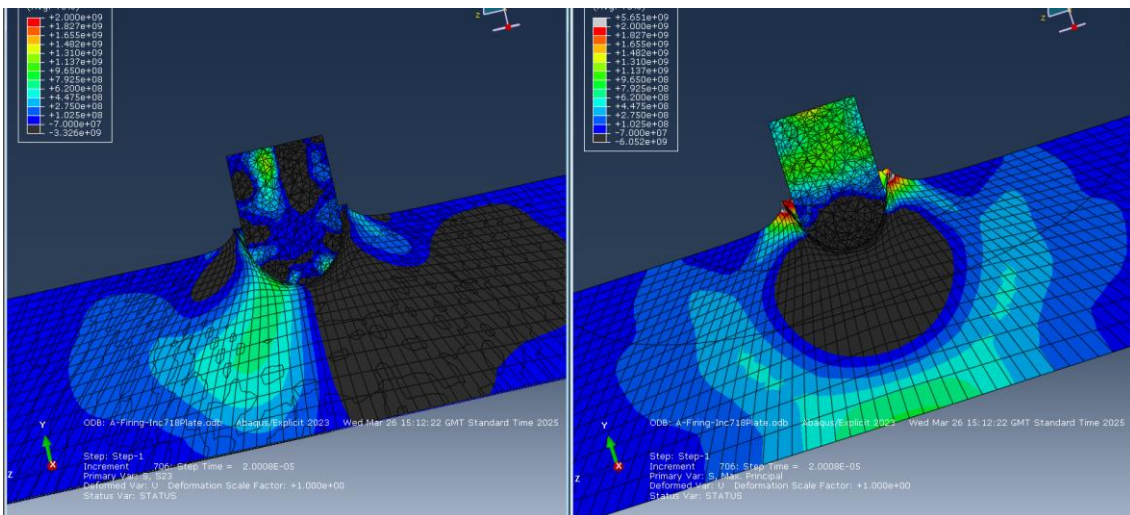


Figure 3 - 800ms⁻¹ initial damage

In the initial damage of projectile 1's simulation, a large compression wave can be observed along with an extension of the shear stress cone. A reflection of the compression wave can also be observed at the base of the right image. Compressive stress is still greater than shear stress, 6.05e9 Pa compressive, 3.33e9 Pa shear stress (in mirrored direction). The projectile has begun to penetrate the plate leaving a curved deformation of the plate due to the tensile stress of the projectile's entry pushing the walls apart from one another as the compression wave moves throughout the plate.

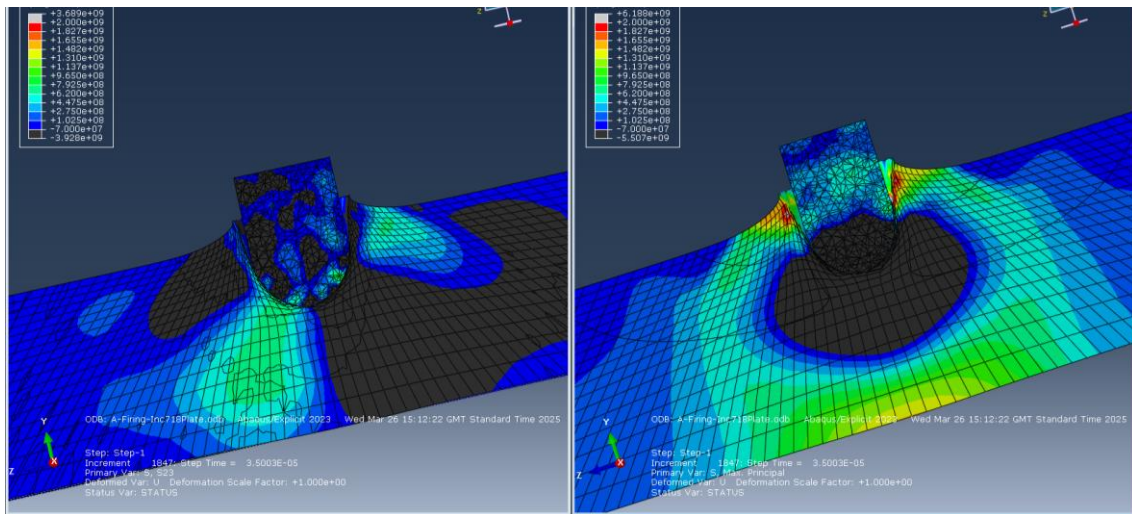


Figure 4 - 800ms⁻¹ resultant damage pre-bounce

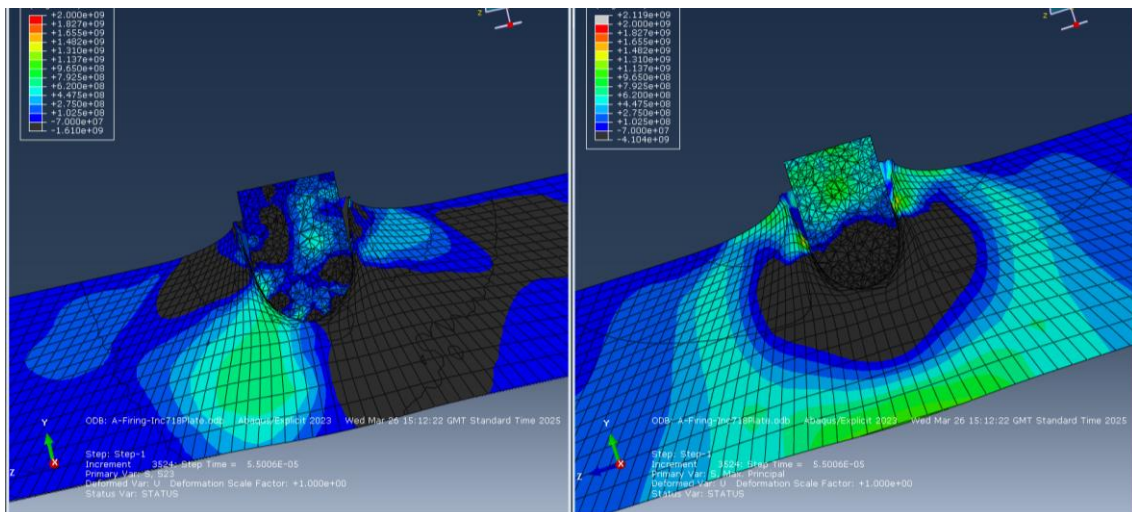


Figure 5 - 800ms⁻¹ resultant damage post-bounce

In figure 4 and 5 the final transfer of the projectiles kinetic energy can be observed. The projectile managed to penetrate approximately 40% of the plates thickness. The maximum compressive stress (4.1e9 Pa) remained higher than the maximum shear stress (6.2e9 Pa). This energy was not enough to allow continuation through the plate and the reflected force from the plate overcame the force being applied by the projectile.

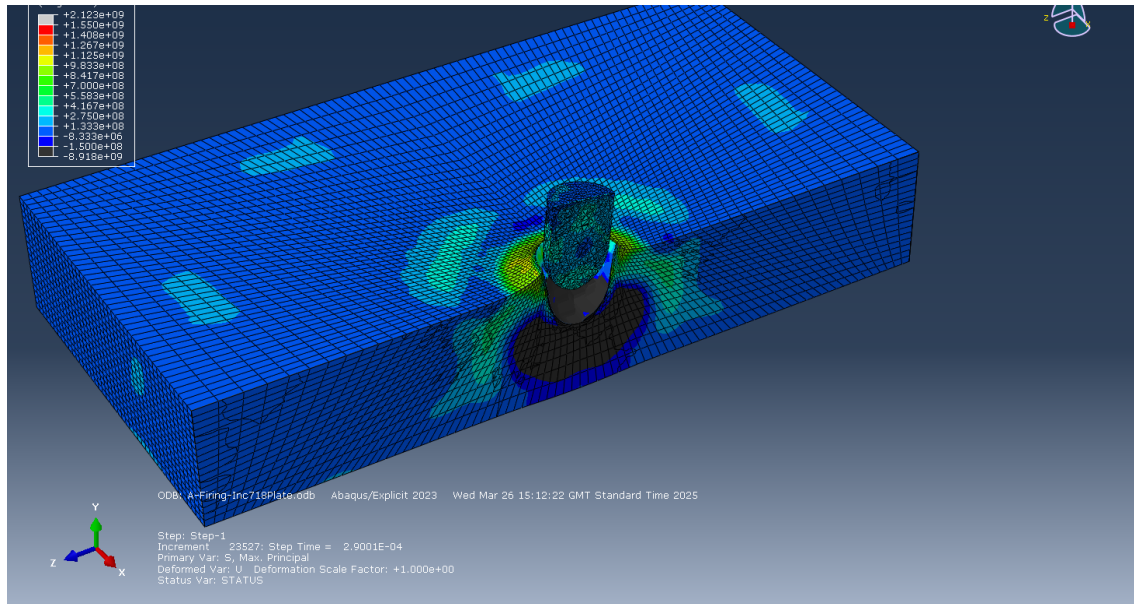


Figure 6 - 800ms^{-1} final deflection

Projectile 1 did not manage to penetrate the plate. A rebound was modelled and resulted in no additional damage to the plate.

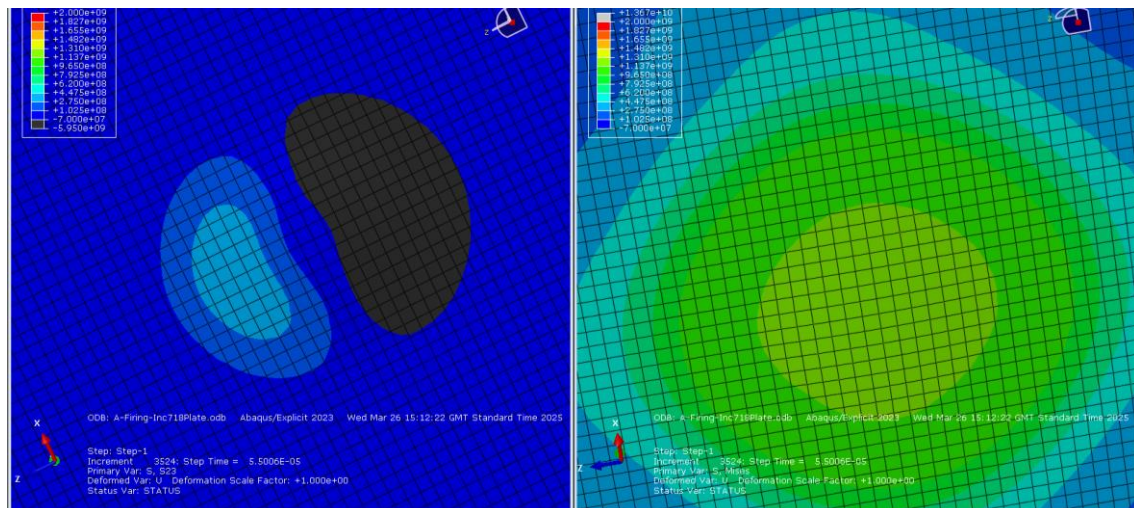


Figure 7 - 800ms^{-1} backplate analysis

The maximum stress to the backplate sat at $2.67\text{e}9$ Pa for shear and $1.24\text{e}9$ Pa for tensile stress. The imprint of a bullseye fracture can be seen with the generated stress however there was not enough stress, and therefore kinetic energy, present to materialise the damage. Notably, the stress faced by the backplate is dominated by shear stress whereas before the compressive stresses were greater. This would suggest that the cause of plate failure would be shear on penetration.

3.2. 1600ms⁻¹ threat

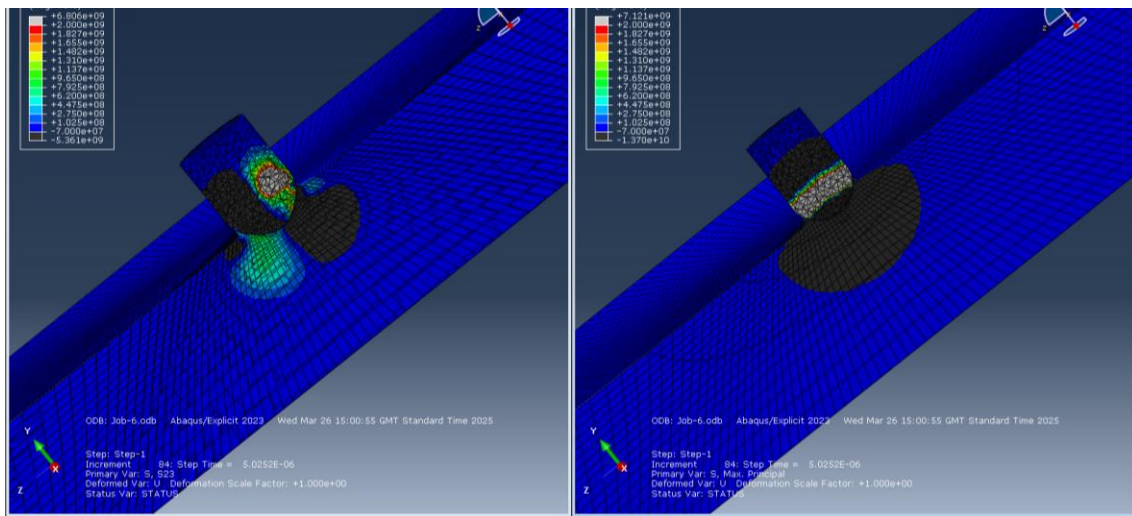


Figure 8 - 1600ms⁻¹ initial contact

In the initial contact of projectile 2, a strong compressive wave of 1.37×10^{10} Pa is generated by the projectile. Shear stress is also high at 5.36×10^9 Pa. Following a similar pattern, the compressive stress is higher than shear. Some tensile failure of the plate can already be observed around the tip of the projectile.

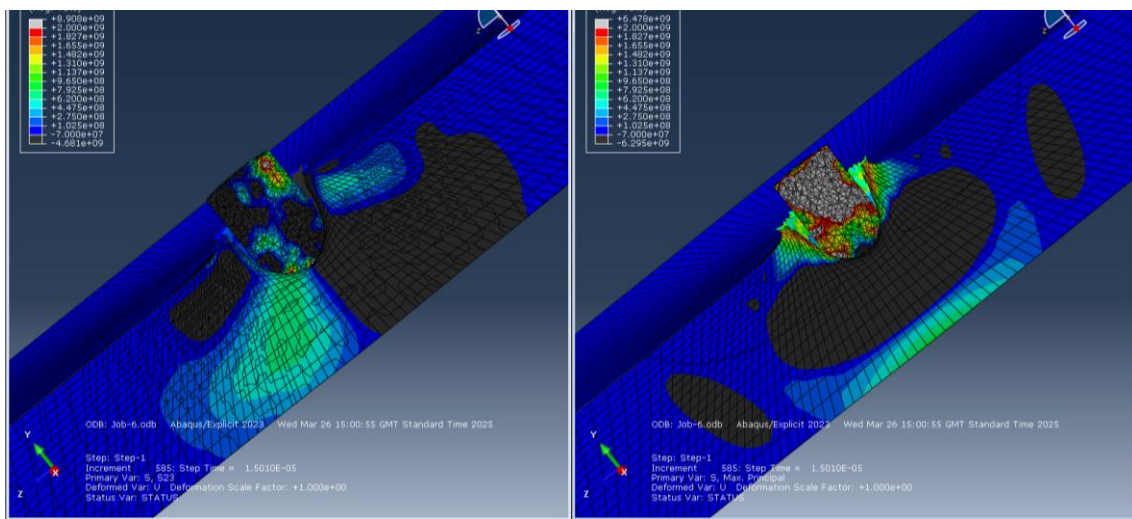


Figure 9 - 1600ms⁻¹ initial damage

As the projectile progresses into the plate, shear stress cones of approximately 7×10^8 Pa can be seen on either side of the projectile's path through the plate. The compression wave has expanded, and a reflection wave can be seen starting to propagate. Compressive stresses of 6.3×10^9 can be observed in the space ahead of the projectile. Shear stress is building up in the impact side of the plate.

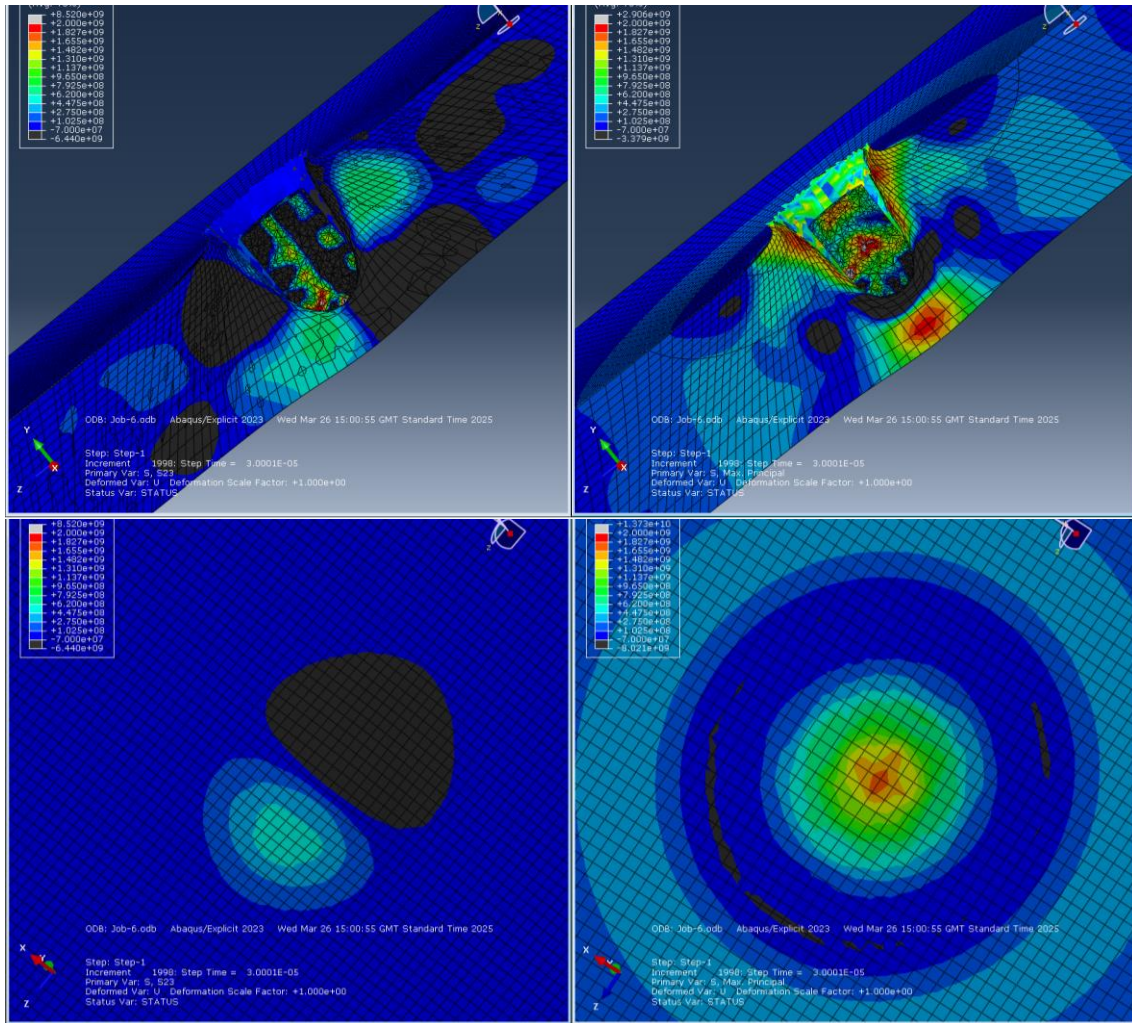


Figure 10 - 1600ms^{-1} pre penetration, both side and backplate view

At the start of the penetration of the backplate, a distinct bullseye fracture can be seen in the formation of the tensile stress in its centre (see bottom right image of figure 10). This area has a tensile stress of approximately $1.9\text{e}9$ as the plate is being pushed apart by the compressive stress wave's reflection. Compressive stress has reduced to $3.37\text{e}9$ as the energy is being transferred to the separation of the plate. Shear cones are still present through to the backplate and peat at approximately $5\text{e}8$ Pa. The cones facing away from the projectile back towards the initial surface have fully formed.

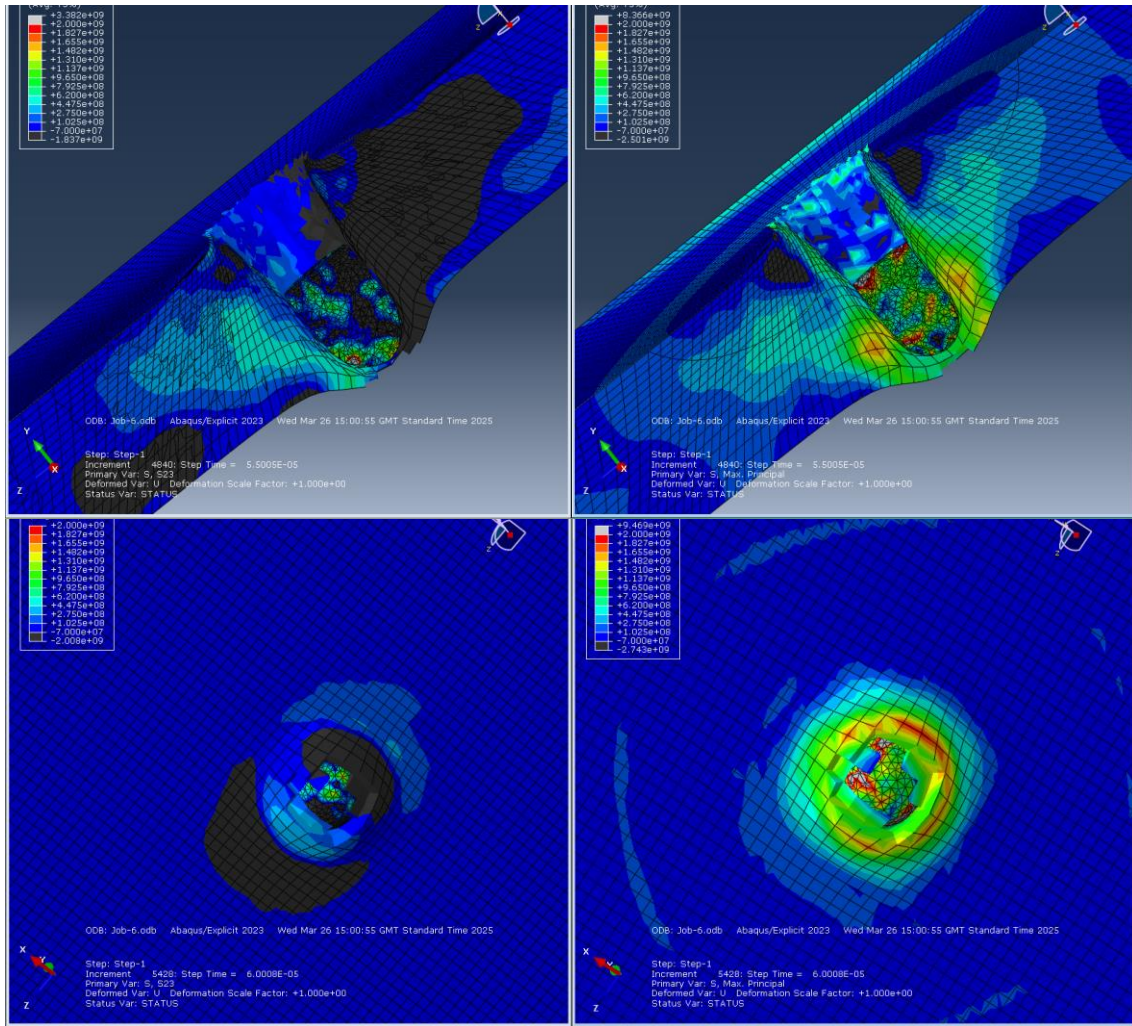


Figure 11 - 1600ms⁻¹ mid penetration part 1

In figure 11, the armour plate has now failed. The tensile stresses caused by the compression waves reflection have now separated the plate completely. Tensile stresses of 1.83e9 Pa can be observed. The failure of the backplate also produced spalling but due to the settings in Abaqus, the spall was deleted. The compression wave has been transferred mostly into the tensile stresses at this point of penetration. Shear stress can also be seen in magnitude of 2e9 Pa.

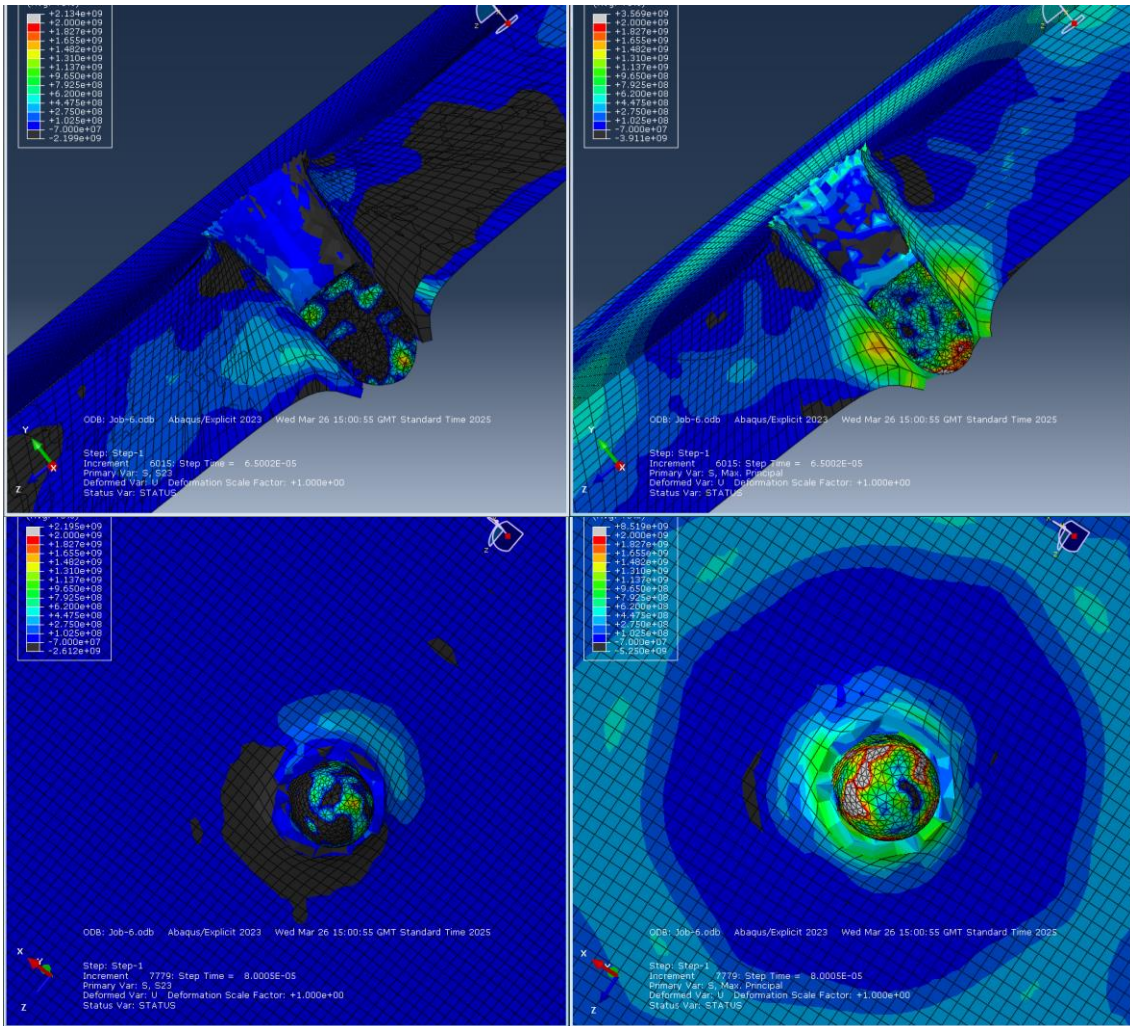


Figure 12 - 1600ms^{-1} mid penetration part 2

As observed in figure 11, similar patterns are seen in figure 12. The shear stress exceeds the compressive and tensile stresses at the point of failure in the material.

4. Discussion

4.1. Relevance to OME

4.1.1. Kinetic penetrator modelling

Kinetic penetrator FEA modelling has wide use within defence and OME engineering. Typically, it is used in the verification of new ammunition with a threat in mind. A mock up of the armour scheme that is intended to be defeated will be produced, a projectile will then be modelled and developed based off repeat simulations simulating firing of the munition at a range of angles and speeds based of variation from prior testing. This simulation work reduces the cost of the validation as if the model is proven, it can be taken as the equivalent of firing some of the munitions when used for evidence to bring it into service.

4.1.2. Shaped charge FEA modelling

Shaped charge FEA modelling can be used for a similar purpose as described in 4.1.1. It also has uses in the development of explosive reactive armour. An example of FEA modelling of shaped charges is a journal entry by J.F. Molinari. In this journal entry, they modelled a typical shaped charge and managed to produce a range of informative images and graphs. This modelling proved the use of Lagrange, the FEA mesh method used in this experiment, for use with shaped charge explosives [7].

4.2. Velocity graph analysis

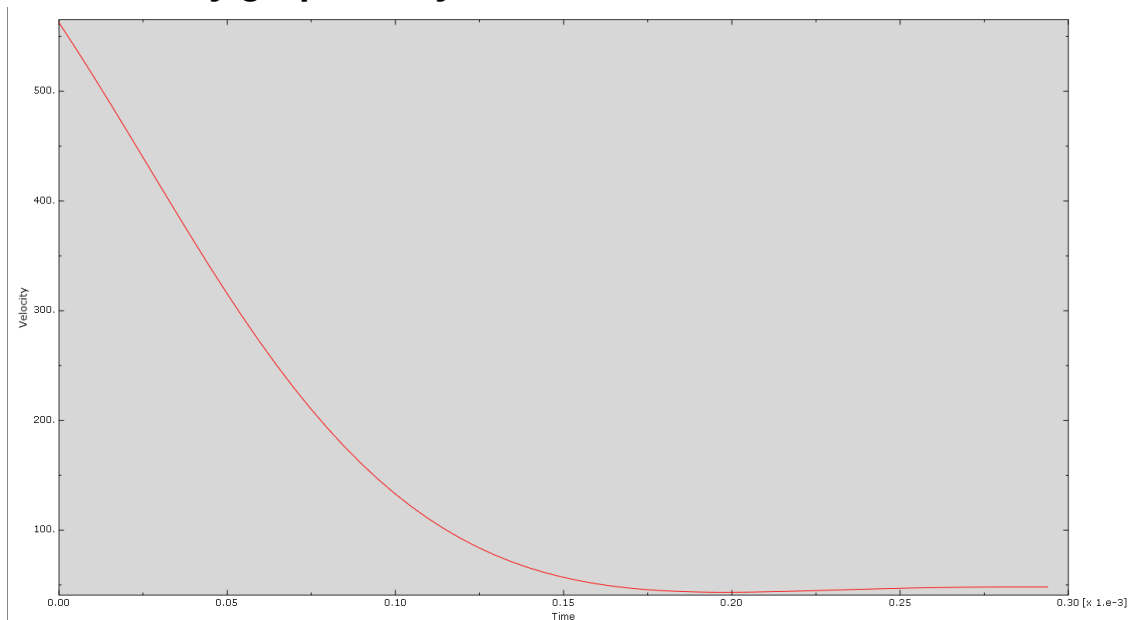


Figure 13 - 800ms^{-1} velocity graph

As the projectile passes through the plate, the kinetic energy is transferred to the plate in the stresses that get applied. The 800ms^{-1} projectile's velocity eventually reaches 0ms^{-1} where it fails to penetrate – threat defeat. The rise in velocity after the defeat is the rebound of the projectile from the impact in the plate due to the reflected stresses and forces.

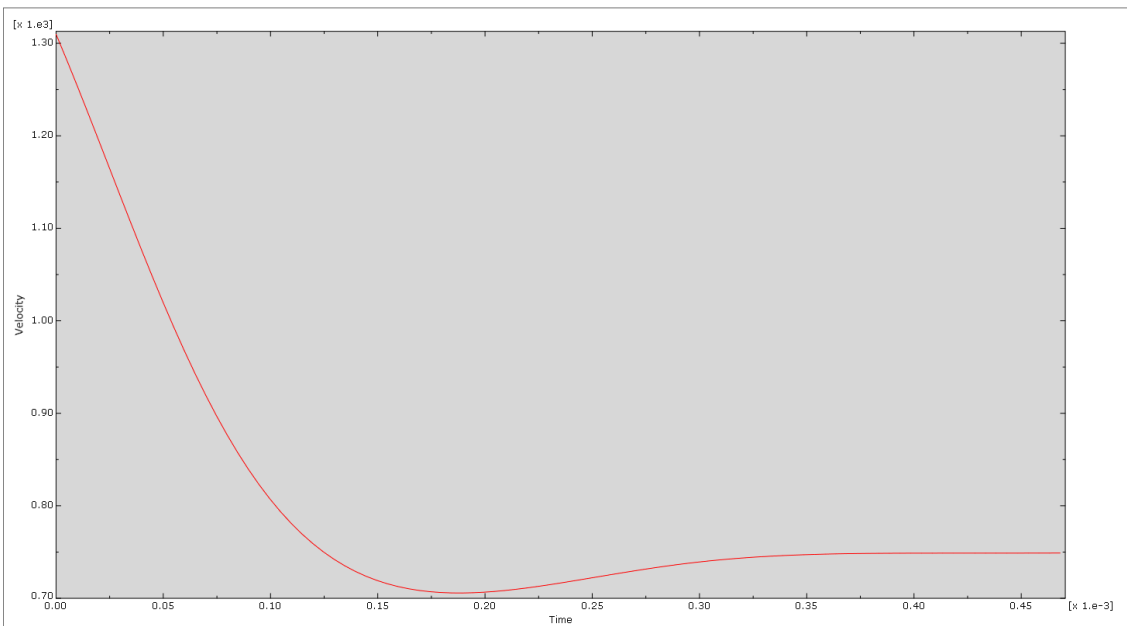


Figure 14 - 1600ms⁻¹ velocity graph

As the projectile passes through the plate, the kinetic energy is transferred to the plate in the stresses that get applied, this causes a slowing down of the projectile as the energy is transferred and partially reflected. The projectile eventually reaches full penetration at approximately 0.18ms into the simulation. Once the projectile has passed through the plate, the friction and opposing forces no longer affect it allowing it to speed up to approximately 760ms⁻¹ post penetration – threat win.

4.3. Armour plate damage comparison and analysis

The significant difference in performance between the two projectiles is due to the velocity's effect on the kinetic energy: $KE = 0.5mv^2$. Since the mass is the same, doubling the velocity does not double the energy. Instead, the energy of the projectile increases by a factor of 4. This significant difference in kinetic energy is reflected in the forces being applied to the armour plate in the damage analysis.

The initial contact of the two projectiles shows the increase in energy, the stresses seen on the 1600ms⁻¹ impact were 5.36 GPa shear stress, 13.7 GPa compressive compared to 2.11 GPa shear and 5.12 GPa compressive.

During the failure of the plate, a compressive wave pushing through the plate, transferring into a tensile stress in the reflected wave from the backplate of the plate. This is combined with a shear stress cone which ultimately causes the failure of the plate. The projectile induces the sliding stresses as it penetrates the plate and transfers the energy into stress on the material.

5. Limitations

5.1. Limitation of Johnson-Cook

- Johnson-Cook is limited in the assumption that the material has the same properties throughout, typically with armour, it used a rolled material which will be harder towards the outside and therefore not truly uniform in properties.

5.2. Limitations of Abacus CAE

- Limited to 250,000 nodes – reduced accuracy of simulation due to larger nodes in both.
- Unable to use Johnson-Cook damage on both projectile and armour plate with model.
- Pointed projectiles cause issues with the program as it is unable to determine the damage accurately.

6. References

- [1] S. Dasanayaka, "Introduction to the Johnson-Cook Material Model," ALGO Engineering, 31 Jan 2023. [Online]. Available: <https://algoeng.com/introduction-to-the-johnson-cook-material-model/>. [Accessed 13 05 2025].
- [2] SSAB, "Armox® 440T," SSAB, 2025. [Online]. Available: <https://www.ssab.com/en/brands-and-products/armox/product-offer/armox-440t>. [Accessed 16 05 2025].
- [3] K. S. Prasad and N. Bhatnagar, "Finite Element Simulation of Armour Steel used for Blast Protection," *Procedia Structural Integrity*, vol. 14, no. 1, pp. 514-520, 2019.
- [4] H. Farahani, M. Ketabchi and S. Zanageneh, "Determination of Johnson-Cook plasticity model parameters for Inconel 718," *Journal of Materials Engineering and Performance*, vol. 28, no. 11, pp. 5284-5293, 2017.
- [5] I. u. Haq, G. Weiguo, M. Arif and M. Z. Sheikh, "Study of Various Conical Projectiles Penetration into Inconel -718 Target," *Loading and Environmental effects on Structural Integrity*, vol. 13, no. 1, pp. 1955-1960, 2018.
- [6] A. Iturbe, E. Giraud, E. Hormaetxe, A. Garay, K. Ostolaza and P. J. Arrazola, "Mechanical characterization and modelling of Inconel 718 material behavior for machining process assessment," *Materials Science & Engineering A*, vol. 682, no. 1, pp. 441-453, 2017.
- [7] J. Molinari, "Finite element simulation of shaped charges," *Finite Elements in Analysis and Design*, vol. 38, no. 1, p. 921 – 936, 2002.

- [8] A. Banerjee, S. Dhar, S. Acharyya, D. Datta and N. Nayak, "Determination of Johnson cook material and failure model constants and numerical modelling of Charpy impact test of armour steel," *Materials Science and Engineering*, vol. 640, no. 1, pp. 200-209, 2015.

