

Experimental Investigation of Shear and Tension Stress Effects in Aluminium Plates Subjected to
High-Velocity Projectile Impacts

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I. Contents

1. Introduction.....	3
2. Literature review	3
3. Stress and strain	5
4. Johnson-Cook damage model	6
5. Methodology	7
6. Simulation results.....	9
7. Practical application.....	17
8. Conclusion	17
9. Appendix.....	19
10. Bibliography	21

1. Introduction

1.1. Understanding the behaviour of materials under high-velocity impact is crucial in designing protective equipment and ensuring the safety of personnel. Simulation applications such as Abaqus have become increasingly popular in analysing such events, providing a cost-effective and safe way of evaluating the performance of different materials and designs.

1.2. This report investigates the effectiveness of aluminium body armour in protecting against different types of projectiles by simulating the ballistic impact on an aluminium plate using the Johnson-Cook damage model in Abaqus. The study focuses on two bullet materials, steel and tungsten carbide, then compares the resulting shear stress and tension in the aluminium plate.

2. Literature review

2.1. Studies have shown that parameters such as Young's modulus and bullet material strongly influence the behaviour of materials under impact. For instance, [1] demonstrated that the density and hardness of bullet material significantly affect the penetration and deformation of target material. In addition, [2] investigated the dynamic deformation of steel plates, finding Johnson-Cook plasticity model played a critical role in determining the material's behaviour under impact.

- 2.2. The difference in material properties, such as young's modulus, between the aluminium plate and the bullets will affect the deformation severity of the plate. Young's modulus is a measure of elasticity and its resistance to deformation under stress [3]. The aluminium plate, being a relatively soft material, is expected to deform more easily when subjected to high-velocity impacts. Therefore, the differences in material property between the bullets and the aluminium plate are expected to cause deformation of the plate when impacted as both bullets are harder material.
- 2.3. As previously noted, tungsten carbide is denser and harder than steel [4], which implies that it will exert greater force ($F=ma$) on the plate during impact, causing more deformation and penetration. Conversely, the steel bullet may cause less deformation in the plate due to lower density and hardness.
- 2.4. We expect that the simulations will confirm these predictions and demonstrate the importance of considering the properties of both the target material and the bullet material in predicting the behaviour of materials under ballistic impact.

3. Stress and strain

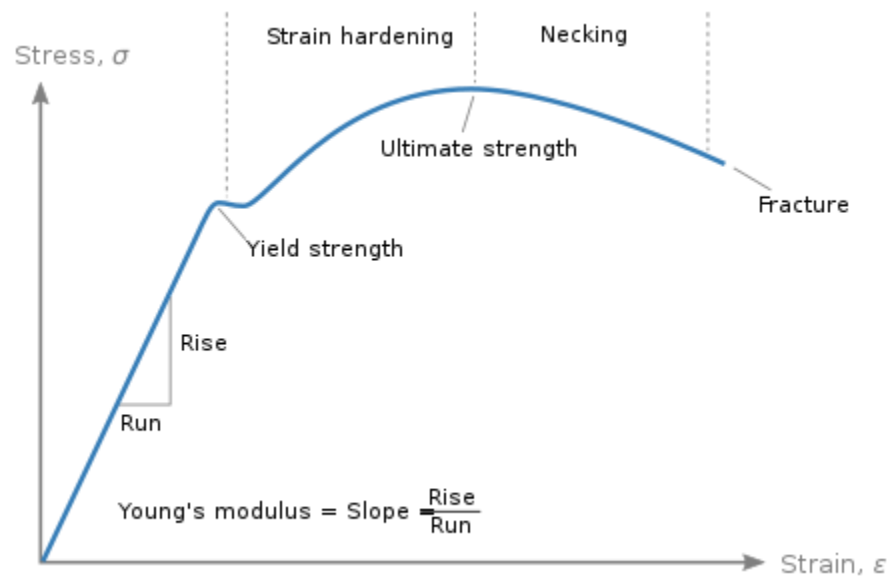


Figure 1 – stress-strain curve [5]

3.1. A stress-strain curve shows the relationship between applied stress and resulting deformation in a material. The regions: starting with the elastic region, stress and strain are proportional. The slope of this region is the Young's Modulus ($E = \sigma/\epsilon$). The yield strength is the where the material starts to deform plastically and will not return to its original shape when stress is removed. finally, the material enters the plastic region, where it undergoes significant deformation and may exhibit necking. The ultimate strength is the maximum stress the material can withstand before fracturing [6]. The simulations are expected to operate within the yield strength and fracture point throughout [5].

3.2.Tension stress-strain: a material is pulled apart or stretched. This type of stress occurs along the axis of the force and causes the material to plastically deform [7].

3.3.Shear stress-strain: a material is subjected to a force that causes it to slide or deform along its cross-section [8]. This type of stress is perpendicular to the axis of the force and causes the material to bend or distort.

3.4.When a bullet hits the plate, both shear stress and tension stress will be generated in the plate. The magnitude of each stress depends on various factors such as the bullet's velocity, the plate's thickness, and the material properties of both the bullet and the plate [9]. In general, tension stress tends to have a larger effect than shear stress when a bullet hits a plate, as the force acting is resisted centrally by the plate at impact.

4. Johnson-Cook damage model

4.1.The Johnson-Cook model incorporates the strain rate, temperature and strain. Along with the material properties, yield stress and the hardening coefficient. It also includes a damage parameter that accounts for the accumulation of microstructural damage within the material [10].

5. Methodology

5.1. To simulate the impact of a bullet on a metal plate using Abaqus, a finite element model was created. The geometry and boundary conditions of the model were defined based on the material properties of the metal plate, including the density, Young's modulus, Poisson's ratio, and yield strength. The material properties were implemented into a Johnson-Cook damage model.

(all material properties denoted in the **appendix**)

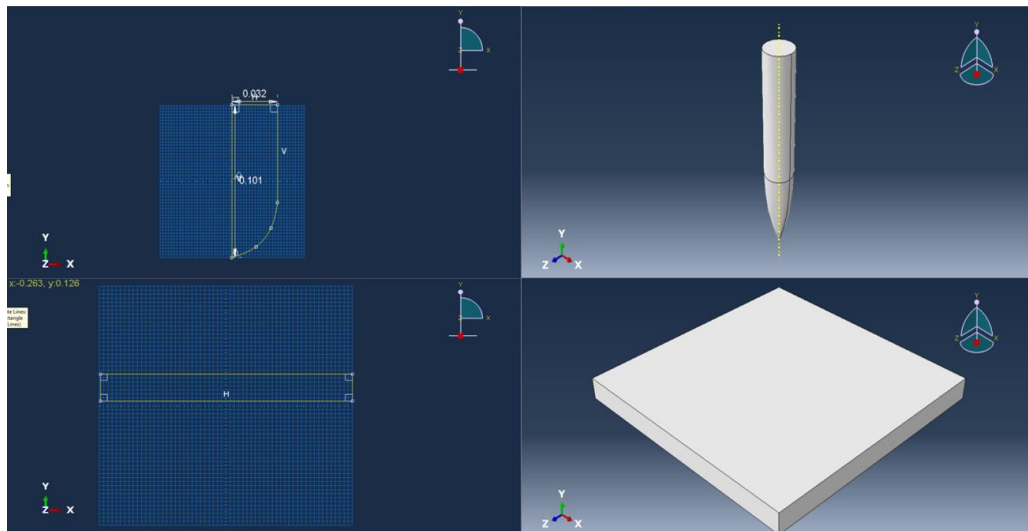


Figure 2 – creating parts and dimensions

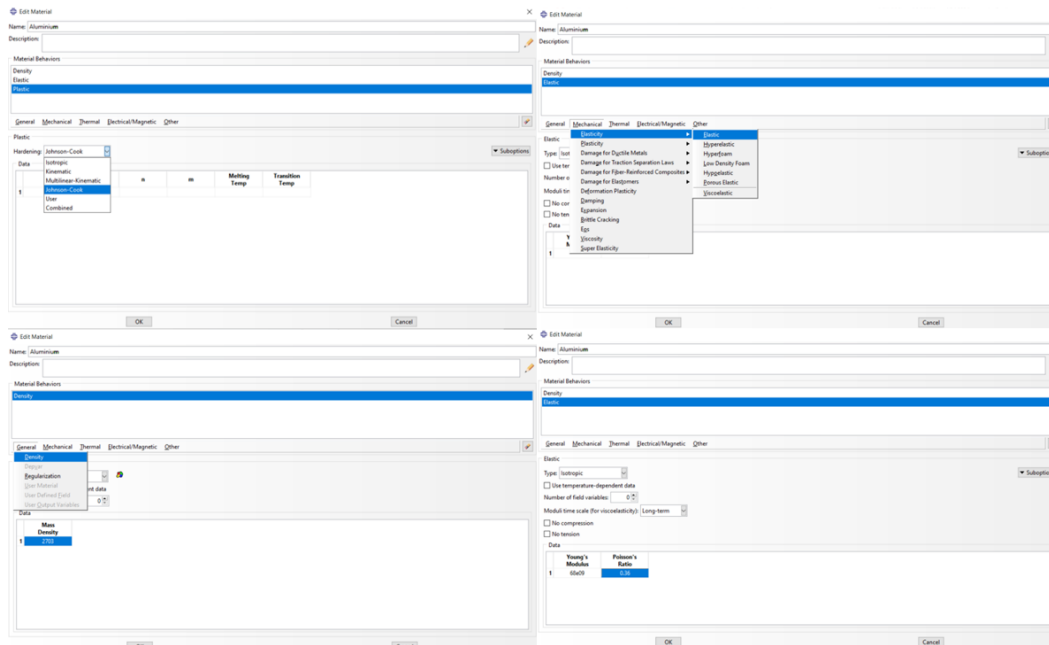


Figure 3 – implementing material properties

5.2. The model was meshed with uniform elements across the plate and the bullet to reduce the risk of simulation failure. The contact between the bullet and the metal plate was defined as surface-to-surface, specifying the friction and contact behaviour between the two surfaces, as along with any initial separation or penetration between them. The bullet was simulated centrally on X-Y to the plate and the direction of bullet travel was perpendicular to the Z axis of the plate with a velocity of 1200m/s.

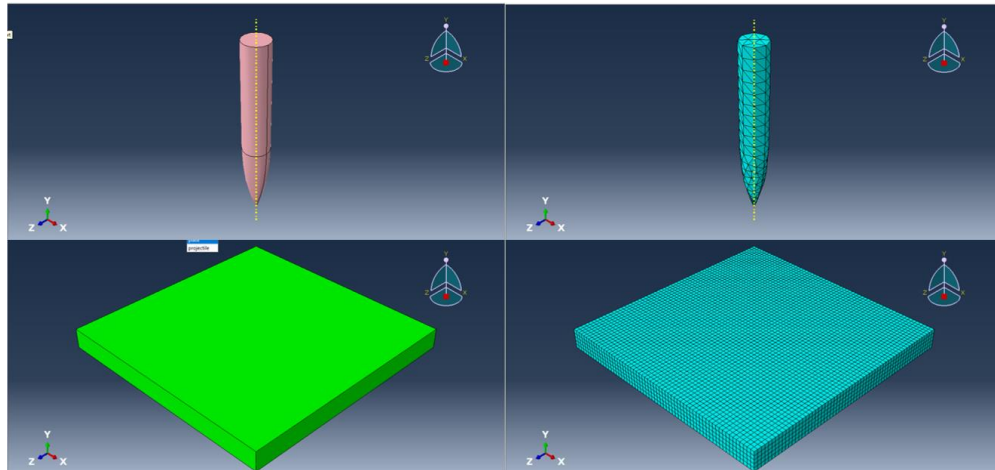


Figure 4 – part meshing

5.3. Multiple simulations were run by changing the material properties of the bullet while keeping the static values the same. The increments between each simulation movement were kept as compact as possible to allow for more steps to be evaluated when the bullet and plate were interacting.

6. Simulation results

6.1. Steel bullet

6.1.1. Initial impact

Initial impact max principal (tension) stress:

Initial impact S23 shear plane:

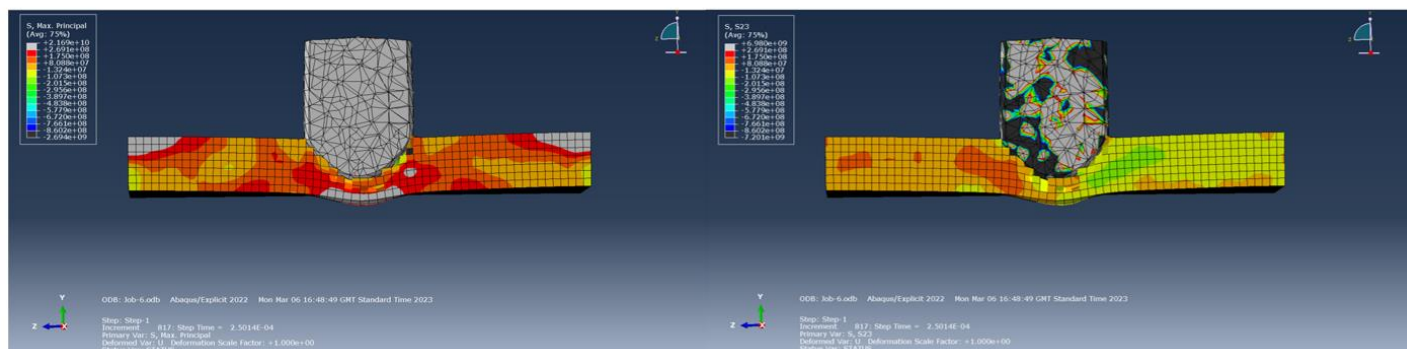


Figure 5 – Initial impact of steel bullet S23 shear and max principal tension side by side

6.1.2. At initial impact the tension acting on the plate hit is focused opposite to the bullet entry, resulting in plastic deformation at the opposite to entry. This behaviour is expected because the bullet's impact generates high-pressure waves that propagate through the plate, leading to stress concentrations in central partitions and outer edges. The focused tension acting opposite to the bullet entry is due to the reflection of the pressure waves at the back surface of the plate, which generates an opposing force.

6.1.3. Significant shear stresses are also transferred in the material. The shear stresses are mirrored either side of the bullet entry point with opposing magnitudes. This indicates that the bullet is deflecting, causing increased shear stress on one side of the impact than the other.

Max principle:

23:

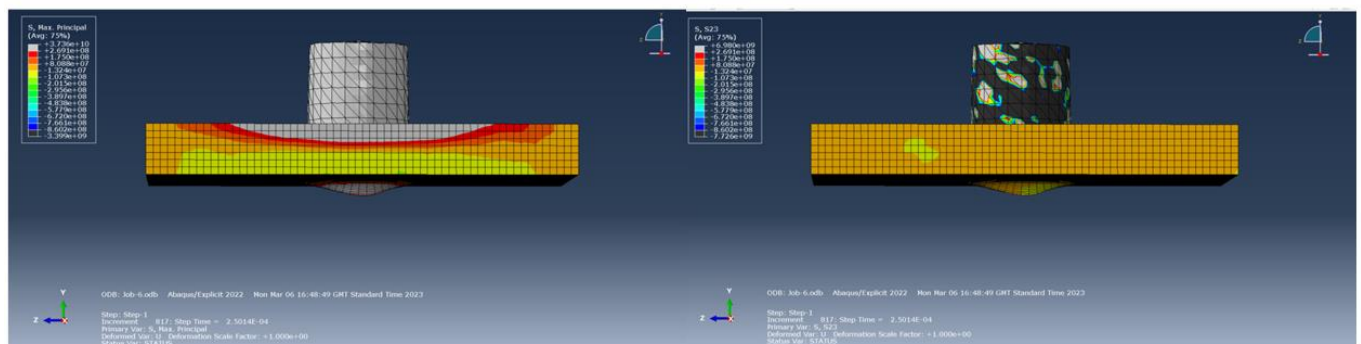


Figure 6 – steel bullet edge of plate at initial impact

6.1.4. The magnitude of the max principal tension is significantly larger than the shear stress acting on the plate because generated force was causing deformation through Z axis. The shear stress is lesser as there is less sliding force acting on the plate as the forces are applied centrally. This can be seen in **figure 6** as the tension wave is prominent across the whole plate, whereas the shear stress wave is acting primarily through the centre line of the z-axis.

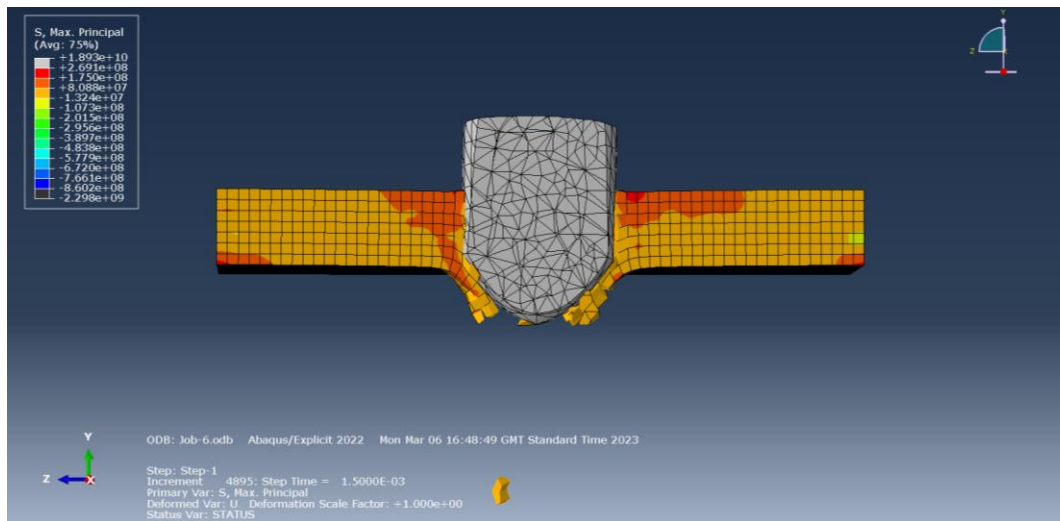


Figure 7 – steel bullet coming to rest

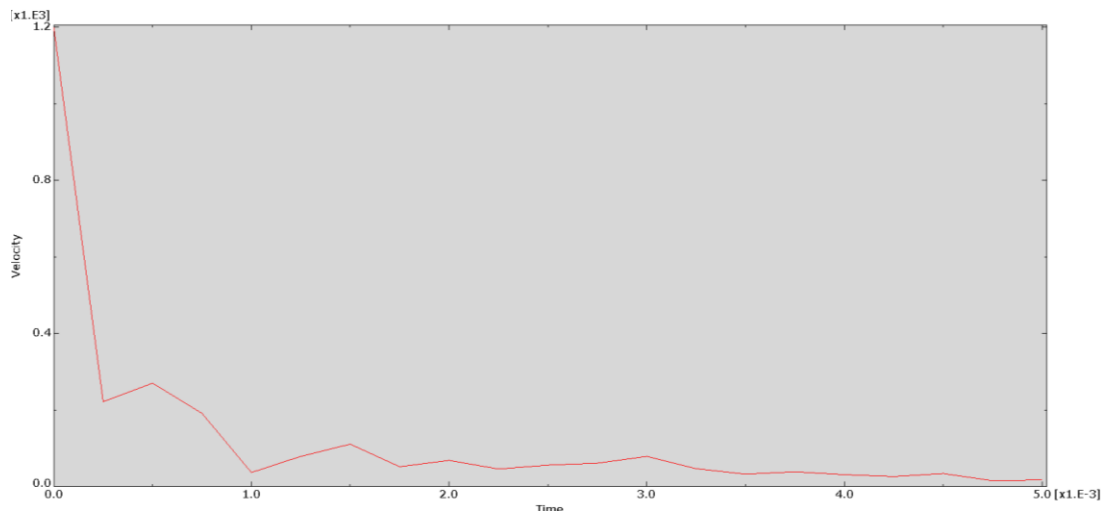


Figure 8 – steel bullet velocity over time

6.1.5. The steel bullet loses velocity over time as the resistive force from the plate become equal to what the bullet is exerting onto the plate.

6.2. Tungsten carbide bullet

6.2.1. Initial impact

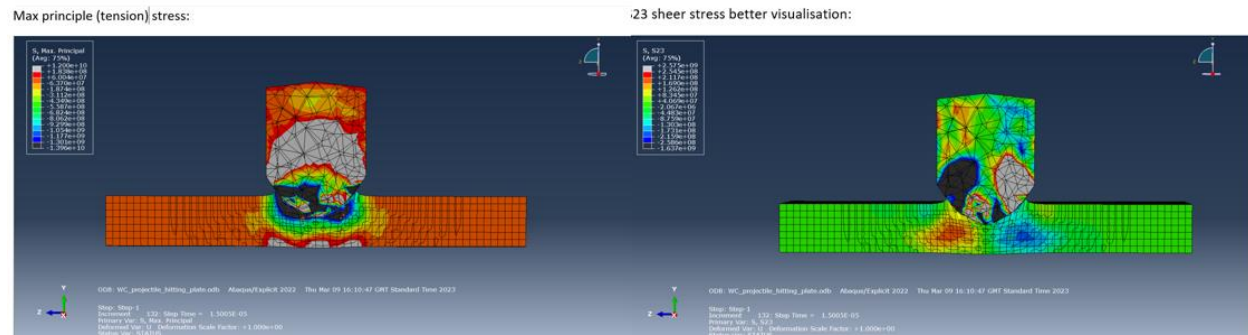


Figure 9 - Initial impact of steel bullet S23 shear and max principal tension side by side

6.2.2. The same stress wave forms can be observed on the plate as 5.2.2. & 5.2.3.

with an increase in the magnitude of the tension stress.

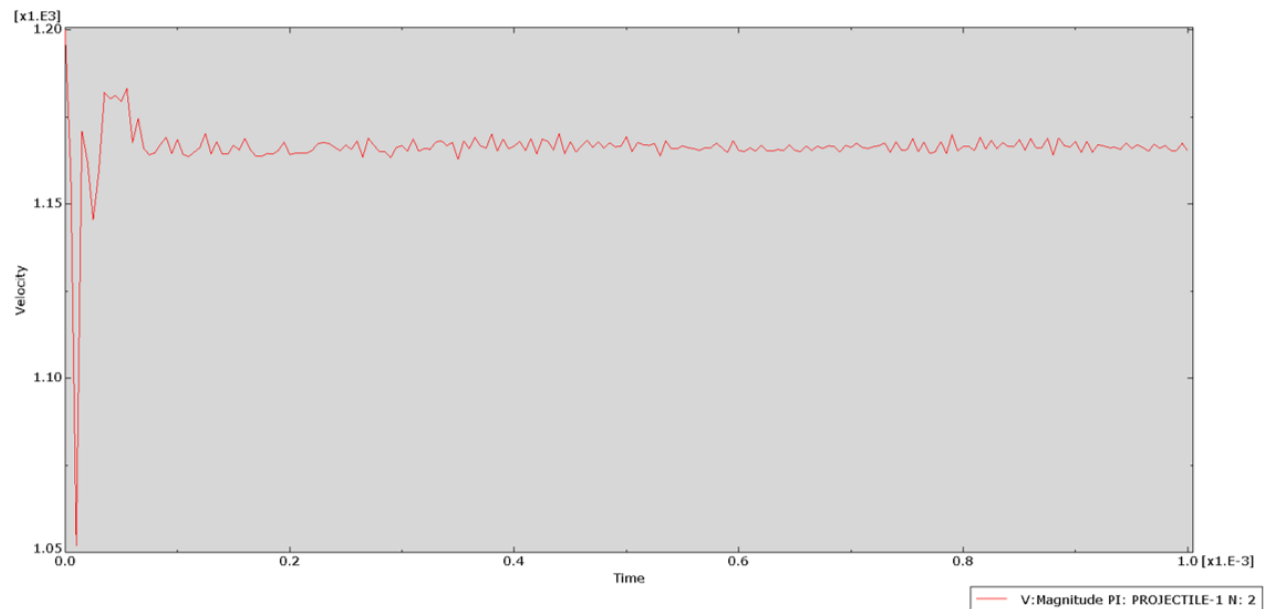


Figure 10 – Tungsten carbide bullet velocity over time

6.2.3. The velocity significantly drops at impact onto the plate but once the plate begins to fragment as per **figure 11**, The velocity spikes to then become continuous, showing stress-strain fracture is reached.

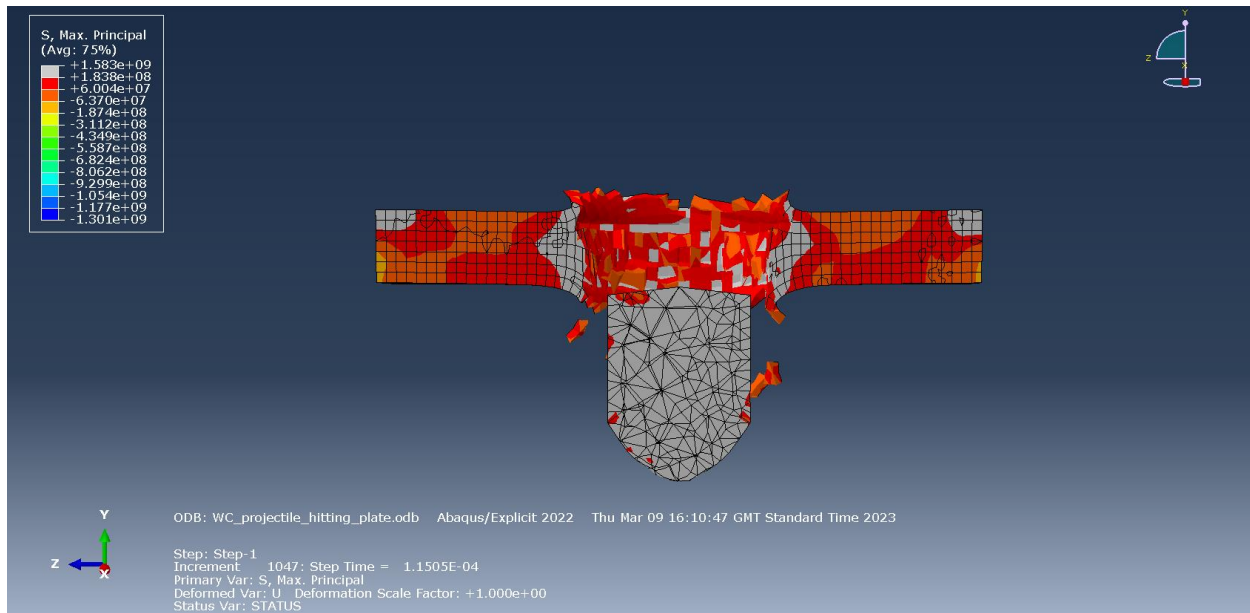


Figure 11 – tungsten bullet exiting plate

6.3. Comparison between steel bullet and tungsten bullet

Steel bullet at rest

Tungsten bullet exiting plate

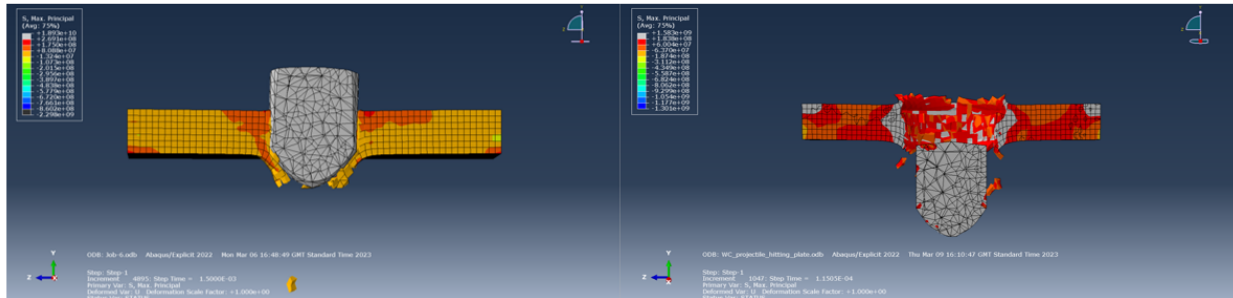


Figure 12 – both bullets final interaction with plate

- 6.3.1. As shown by **figures 5 & 9**, the reaction of the aluminium plate at initial impact for both bullet materials are very similar in tension and shear stresses, however, at a larger magnitude with the tungsten bullet. Showcased by the initial velocity drops in both bullets as the aluminium plate resists the forces applied by both plates (“newtons third law: each action has an equal and opposite reaction” [11] overcoming the opposing force is the failure of the aluminium). The difference is the tungsten bullet causes catastrophic structural failure where the resistive forces in the plate are overcome by the tungsten bullet and not by the steel bullet.
- 6.3.2. This simulation found the maximum principal tension acting on the plates was larger than the s23 shear in both cases. This showcases that the aluminium plate is more susceptible to failure due to tension stress-strain than shear stress-strain and can be seen in **figure 6** where tension waves affect the entire plate where shear is focal.
- 6.3.3. Overall, the tungsten bullet caused a larger reaction on the aluminium plate through plastic deformation, tension and shear stress, and final velocity due to greater property values, primarily density.

7. Practical application

7.1. Commonly, small arms munitions are Full Metal Jacket, a soft metal core with an outer shell made up of harder material such as steel, brass or tungsten [12]. The above simulations show that aluminium may not be practicable for direct personal protective equipment such as body armour, as this has been optimised significantly using steel composites [13]. However, due to aluminium's lighter weight compared to steel plating it could be used on vehicular applications where thicker layering can be applied and has been used within this application but could take wider presidents for weight reduction [14].

8. Conclusion

8.1. The simulation conducted to investigate the impact of tungsten and steel bullets on an aluminium plate has provided valuable insights into the behaviour of materials under high-velocity impacts. While both bullets caused similar initial reactions on the plate in terms of tension and shear stresses, the tungsten bullet caused a larger reaction due to its greater material properties, including density, Young's modulus, and Johnson-Cook damage values. This resulted in catastrophic structural failure that was not observed with the steel bullet.

8.2. Analysis of the stress waves generated in the aluminium plate revealed that the maximum principal tension stress acting on the plate was larger than the s23 shear stress in both cases. This suggests that aluminium is more susceptible to failure due to

tension stress than shear stress. **Figure 5** further corroborated this finding, as it showed that tension stress waves affected the entire plate, whereas shear stresses did not.

8.3. Results suggest aluminium may not be practical for direct personal protective equipment, such as body armour, as it has already been optimized significantly using steel composites. However, its use in vehicular applications, where thicker layering can be applied, could be explored further. While aluminium is lighter than steel, it is essential to evaluate its suitability in vehicular applications to ensure that it provides adequate protection against high-velocity impacts.

8.4. Future research could focus on exploring the impact of different bullet shapes, velocities, and angles of incidence on aluminium plates. This could lead to a better understanding of the behaviour of materials under high-velocity impacts and aid the development of more effective protective armour.

Word count excluding figure, references and bibliography: 1742.

9. Appendix

9.1. Material values:

9.1.1. Tungsten carbide

Parameters	Values and Units
Young's modulus	2.1×10^5 MPa
Poisson's coefficient	0.296
Yield stress (A)	455.0 MPa
Hardening coefficient (B)	2475.0 MPa
Hardening exponent (n)	0.9
Strain rate coefficient C	0.0235
Thermal softening exponent (m)	1.0
Melt temperature T_{melt}	1728 K
Transition temperature T_{trans}	293 K
Parameters	Tungsten Alloy
Damage Constant, D_1	0
Damage Constant, D_2	0.33
Damage Constant, D_3	-1.5
Damage Constant, D_4	0
Damage Constant, D_5	0

Figure 13 – WC material values [15]

9.1.2. Steel bullet

- density $\rho = 7.7 \div 8.1$ [kg/dm³]
- elastic modulus $E=190\div 210$ [GPa]
- Poisson's ratio $\nu = 0.27 \div 0.30$
- Thermal conductivity $\kappa = 11.2 \div 48.3$ [W/mK]
- Thermal expansion $\alpha = 9 \div 27$ [10⁻⁶ / K]

Parameters	MP800HY
A (MPa)	785
B (MPa)	610
n	0.508
C	0.010769
m	1.2–3.0

Figure 14 – Steel material values [16]

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