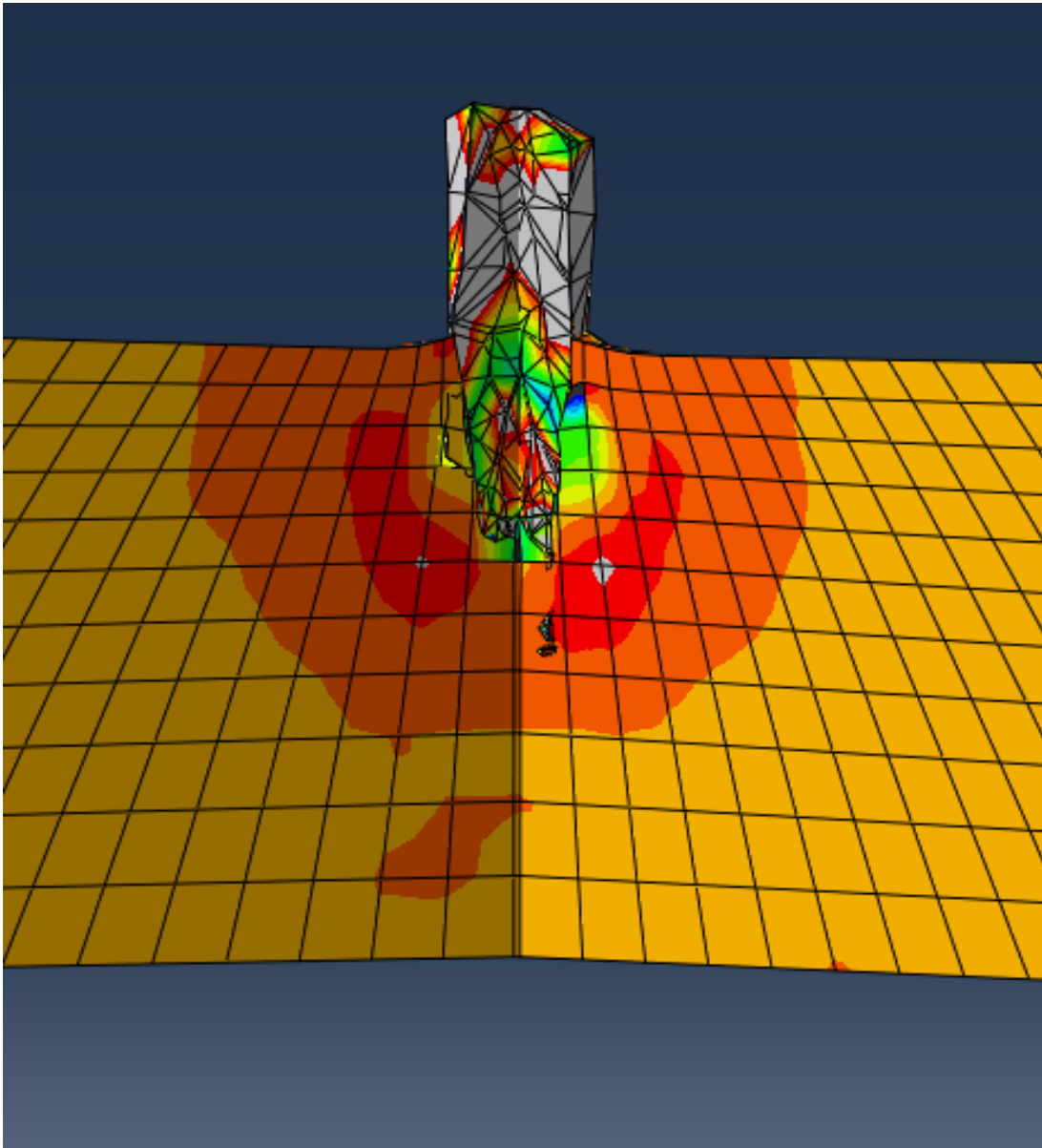




Dynamic Stress-Strain Investigation

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ABSTRACT

This assignment looks into how the change in velocity of a 7.62mm bullet between the velocities of 800m/s^{-1} and 1600m/s^{-1} has on an aluminum plate. This includes the formation of the Hertzian cone and other phenomena described below. This is an important consideration prior to the design and manufacture of new ammunition and weapon systems.

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Problem

High muzzle velocity weapons allow for engagement of targets and greater distances. However there is a very important tradeoff between mobility and effectiveness. The higher the muzzle velocity the larger the caliber of round and the heavier the weapon. The weapon must be capable of withstanding the increased forces related to the increase in velocity. To counter these forces manufactures often increases the sizes of pressure bearing components such as the barrel and chamber. Human factors must also be considered as there will be an increase in recoil which will have an unfavorable impact on the user. In addition if the lower muzzle velocity still defeats the target there is no advantage of overcomplicating the system. This report looks into the end effect on an aluminum plate of a steel 7.62mm bullet fired at an aluminum plate at 800m/s^{-1} , 1200m/s^{-1} and 1600m/s^{-1} .

ABAQUS model

This section describes in brief the construction of the model and how the simulation is constrained. Figure 1 and figure 2 show two different parts that are used for the simulation. Figure 3 shows how the plate is secured through the boundary condition manager. In order for the simulation to work correctly a certain number of nodes need to be selected that can be damaged shown in figure 4. This is classed as an interaction and what type of interaction must be chosen. In this example it is surface to surface contact (explicit) and kinematic contact method. Figures 5 and 6 show the mesh on both the plate and the projectile. Note the gradual mesh on the plate to allow the simulation to focus the workload. Figure 7 shows the tab from the material manager section. This is where both the steel and aluminum material properties and the Johnson- Cook damage data is entered.

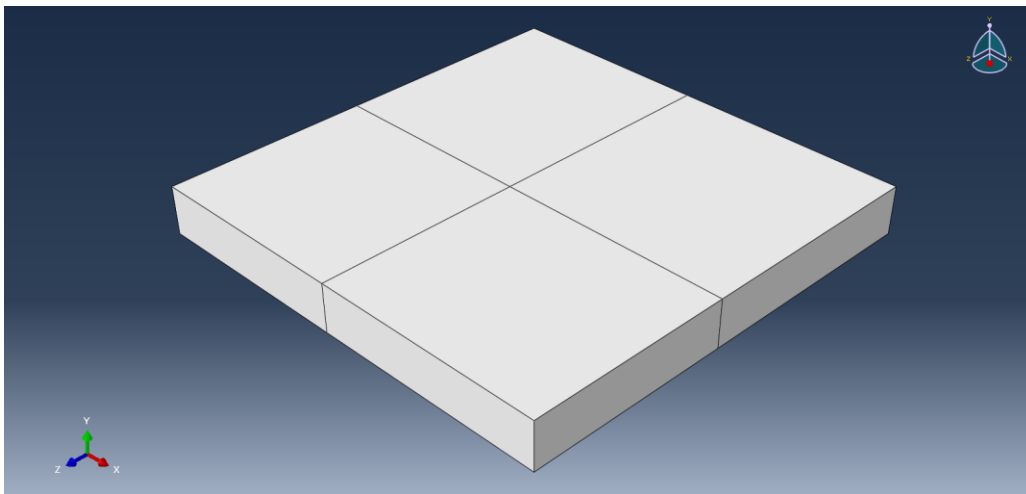


Figure 1- Aluminum plate

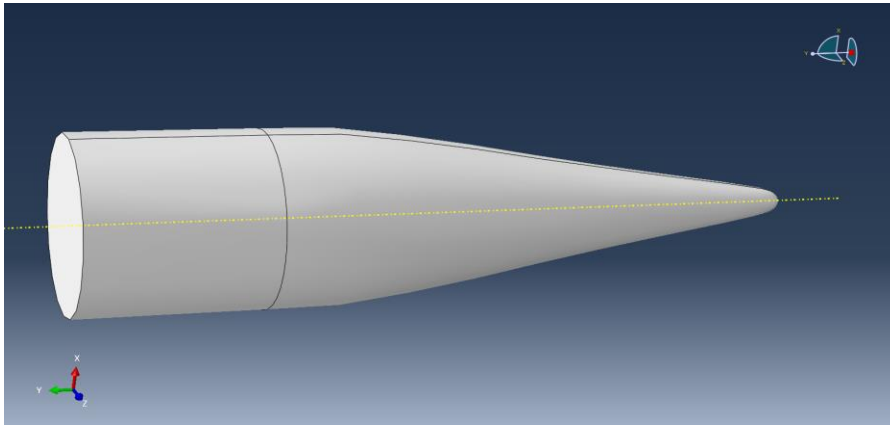


Figure 2- Steel projectile

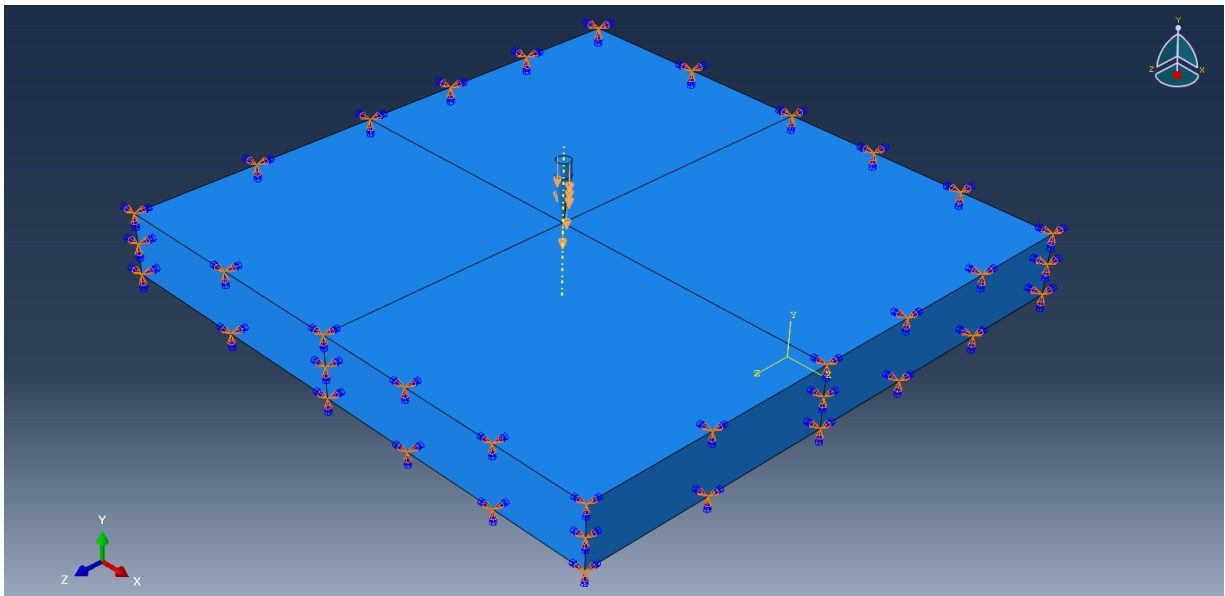


Figure 3- Plate secured on all sides

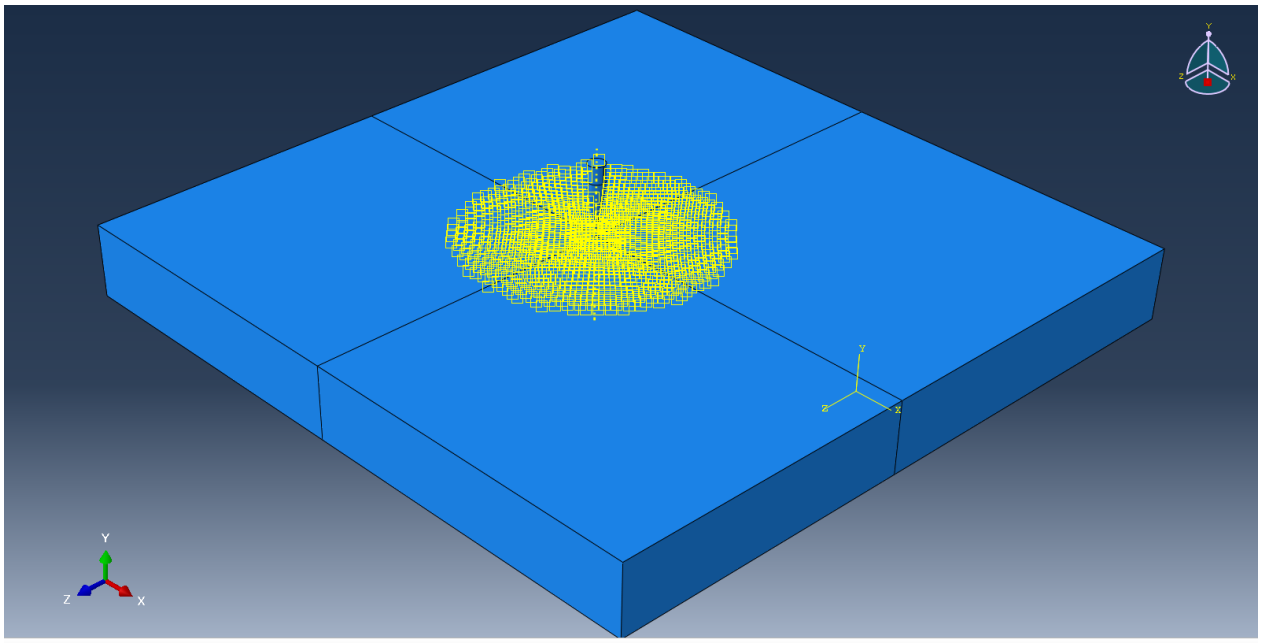


Figure 4- Plate with projectile and nodes to be hit/ impacted shown in yellow

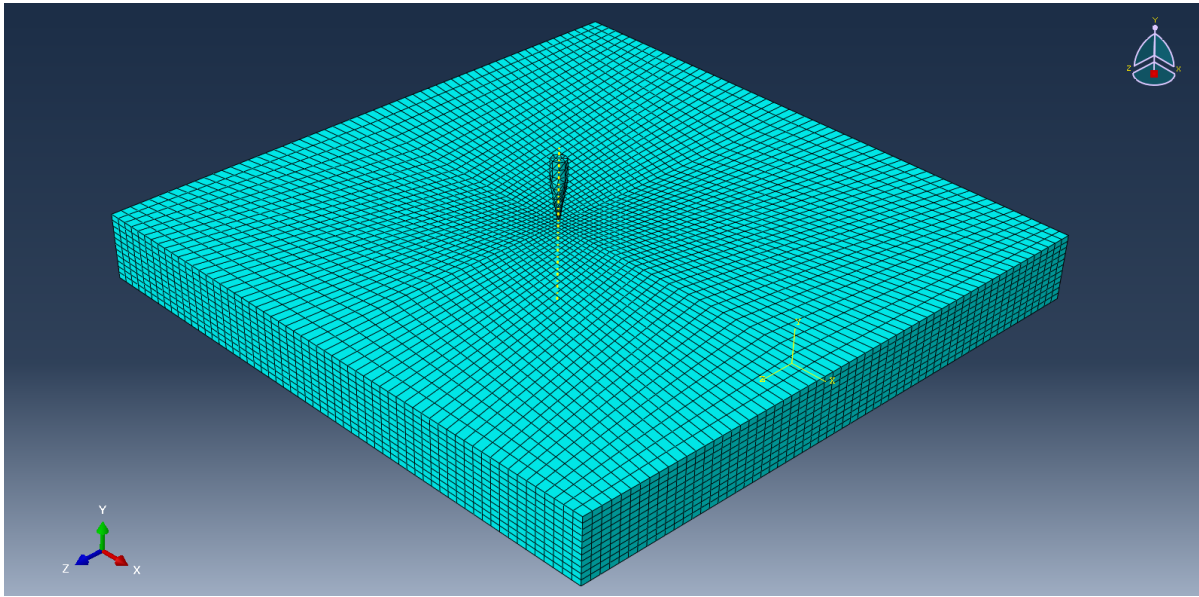


Figure 6- Mesh highlighted on the plate and projectile

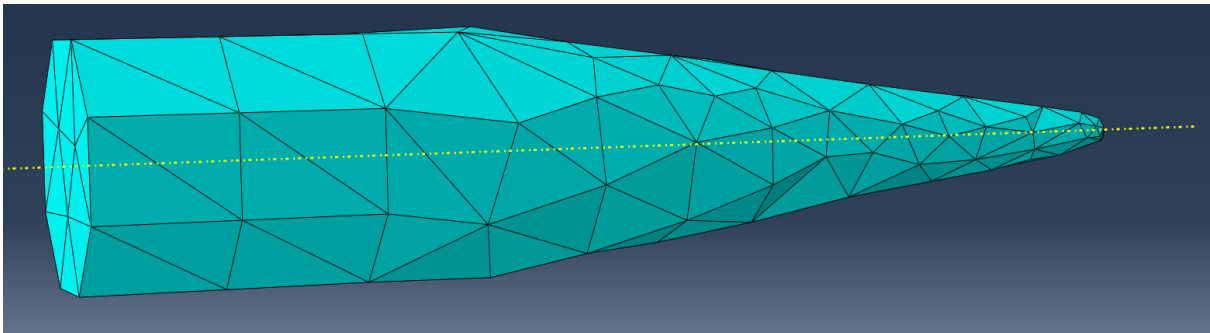


Figure 5- Projectile mesh

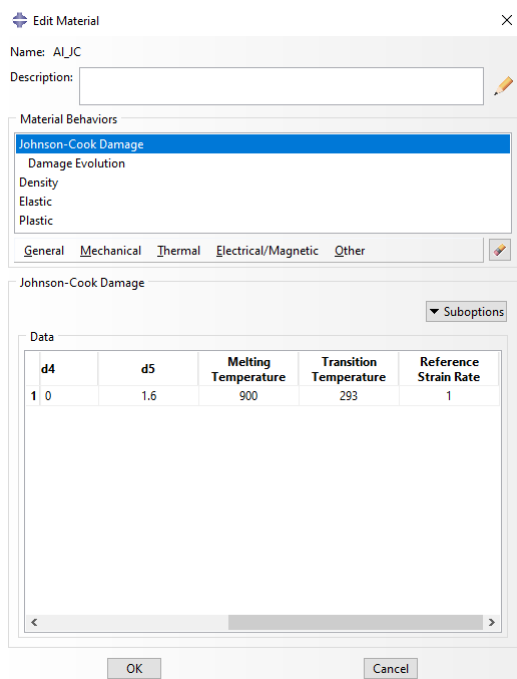


Figure 7- Material edit tab from material manager section

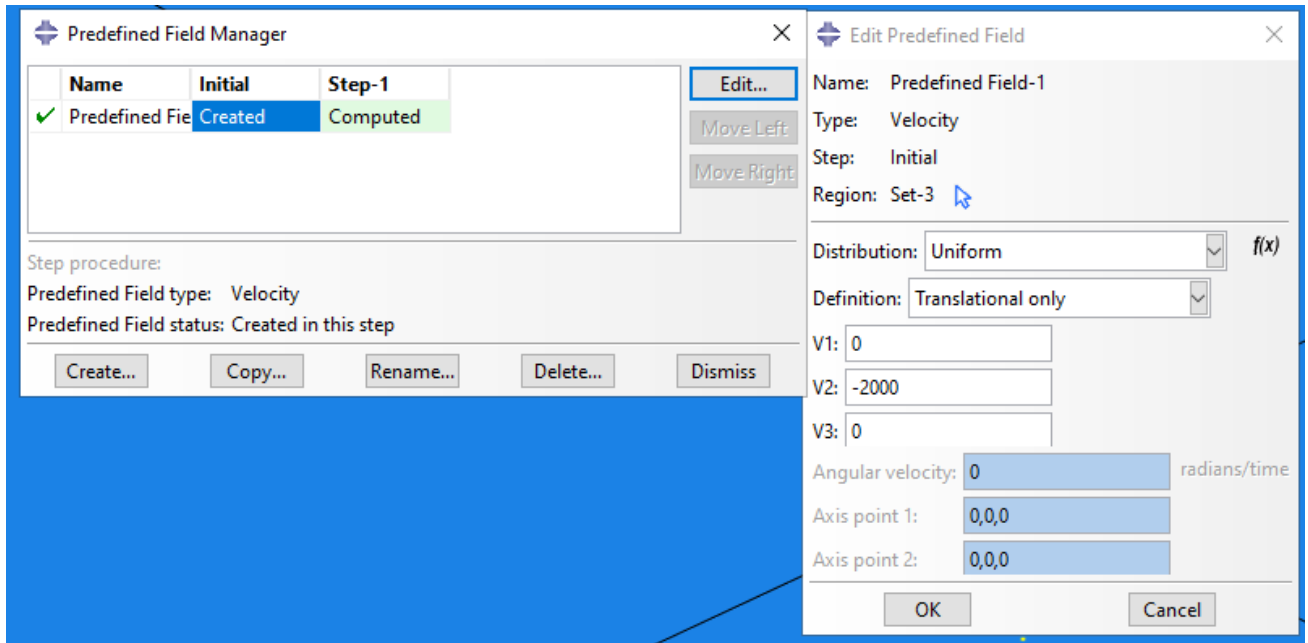


Figure 8- Predefined field tab from the predefined field manager section

Material models

The bullet is a simple steel construction. This is a common material for projectiles however modifications/ adaptations have been made over time, including steel jacket with a lead core and steel core with copper jacket often called copper washed. [1] These all have increased performance characteristics.

On this ABAQUS simulation the material damage for the projectile has not been enabled. This is due to the **large file sizes (over 100gb)**, the machine's capabilities and time allocated.

The aluminum target plate has the material properties of aluminum with the Johnson Cook damage.

“The Johnson-Cook (JC) (Johnson & Cook, 1985) constitutive model is the most widely used constitutive model in predicting the flow stress behavior because of its simplicity with fewer number of material constants. It is a temperature, strain, and strain-rate-dependent phenomenological model and is successfully used for a variety of materials with different ranges of deformation temperature and strain rates.” [2]

Table 2: Input parameters for the Johnson-Cook plasticity model, [5, 6, 7]

Material	A , [MPa]	B , [MPa]	n	θ_{melt} [K]	$\theta_{transition}$, [K]	m	C	$\dot{\epsilon}_0$, [1/s]
Aluminum 6061-T6	324.1	113.8	0.42	925	293.2	1.34	0.002	1.0
Steel 4340, C-30	792	510	0.26	1793	293.2	1.03	0.014	1.0

Figure 9- input parameters for the Johnson-Cook plasticity model [3]

Table 1. Material parameters for aluminum plate.

Modulus of elasticity	E (N/m²)	65.762×10^9
Poisson's ratio	ν	0.30
Density	ρ (kg/m ³)	2700
Yield stress constant	A (N/m ²)	148.361×10^6
Strain hardening constant	B (N/m ²)	345.513×10^6
	n	0.183
Viscous effect	C	0.001
Thermal softening constant	m	0.859
Reference strain rate		1,000 s ⁻¹
Melting temperature	θ_{melt} (K)	893
Transition temperature	$\theta_{transition}$ (K)	293
Fracture strain constant	D_1	0.071

	D_2	1.248
	D_3	-1.142
	D_4	0.0097
	D_5	0.0

Stress

“Stress, in physical sciences and engineering, force per unit area within materials that arises from externally applied forces, uneven heating, or permanent deformation and that permits an accurate description and prediction of elastic, plastic, and fluid behaviour. A stress is expressed as a quotient of a force divided by an area.” [4]

Strain

“Strain may be classified into three types; normal strain, shear strain and volumetric strain. The normal strain is the relative change in length whether shearing strain relative change in shape. The volumetric strain is defined by the relative change in volume.” [5]

ABAQUS Simulation

Plate

The plate is 300mm x 300mm x 35mm size with a node region to be hit located in the center. The elements that are of the most interest is located from the center point outwards. The plate has been split into four to allow for a progressive node region that changes as you get further away from the center but focusing efforts in the center. This hugely reduces processing times and allows the focus to be where the main damage is taking place. For the simulation the plate is fixed on all four sides this one of the constraints. Element deletion turned on due to the complexities of the simulation and to allow for analysis of the remaining damaged elements in the plate.

The plate material is aluminum as stated in the material model section with Johnson- Cook damage properties added. Hooke’s law applies to aluminum up to the proportionality limit. Once past this point stress is no longer proportional to the strain and the gradient will no longer equal the elastic modulus.

Projectile

The projectile resembles that of 7.62 x 51mm round to the best ability of the software and the time available. The 7.62 round is a commonly used NATO ammunition type and other countries have similar rounds. The 7.62 round is used for longer ranges and has a higher degree of armor penetration than smaller calibers. This is partly due to longer barrel weapons being used and the higher velocity the round reaches before impacting the target. This simulation analysis the effect the change in velocity has on the target plate. The average 7.62 round has a muzzle velocity of 850m/s [6]. The simulation starts at 800 m/s⁻¹ and rises to 1600 m/s⁻¹. This allows for comparison between higher muzzle velocity and the damage caused to the plate.

Hooke's law for steel is different to aluminum as described above. Steel "Steel displays linear-elastic behavior in most engineering applications; Hooke's law is valid for it throughout its elastic span" [7]

Images

The below images have been taken from the Abaqus simulation changing the velocity and the time stamp. Two different graphical outputs have been included Max principle stress and S23 for two different timings on all velocities. Max principle stress is often closely associated with Rankine's theory. "Rankine's Theory assumes that failure will occur when the maximum principal stress at any point reaches a value equal to the tensile stress in a simple tension specimen at failure. This theory does not take into account the effect of the other two principal stresses. Rankine's theory is satisfactory for brittle materials, and not applicable to ductile materials. This theory is also called the Maximum Stress Theory." [8] S23 figures show the shear stress experience by the plate. At 800m/s^{-1} the plate is experiencing

In a number of the max principle figures the shockwave moving through the material can be witnessed through the gradual change in colour working outwards from the impact point. High levels of tensile stress can be observed closest to the center. For a very brief period negative tensile stress which is known as compression is also detected immediately surrounding the projectile in the plate. Stress cracking or fracturing of the plate is also likely under the high stress loads experienced.

Figure 12 and 22 showing the Hertzian cone very clearly on the S23 plane this is both positive and negative as the shear stress forces are working in opposite directions. Figure 16 showing high tension zone between $1.815\text{E}+08$ – $2.599\text{E}+08$. This suggests that spalling could take place on the rear of the material prior to the projectile penetrating. This is important as even if the armour stops the projectile penetrating the behind armour effect could still be lethal however with the higher velocity the projectile has penetrated the plate so the behind armour effect would be significant.

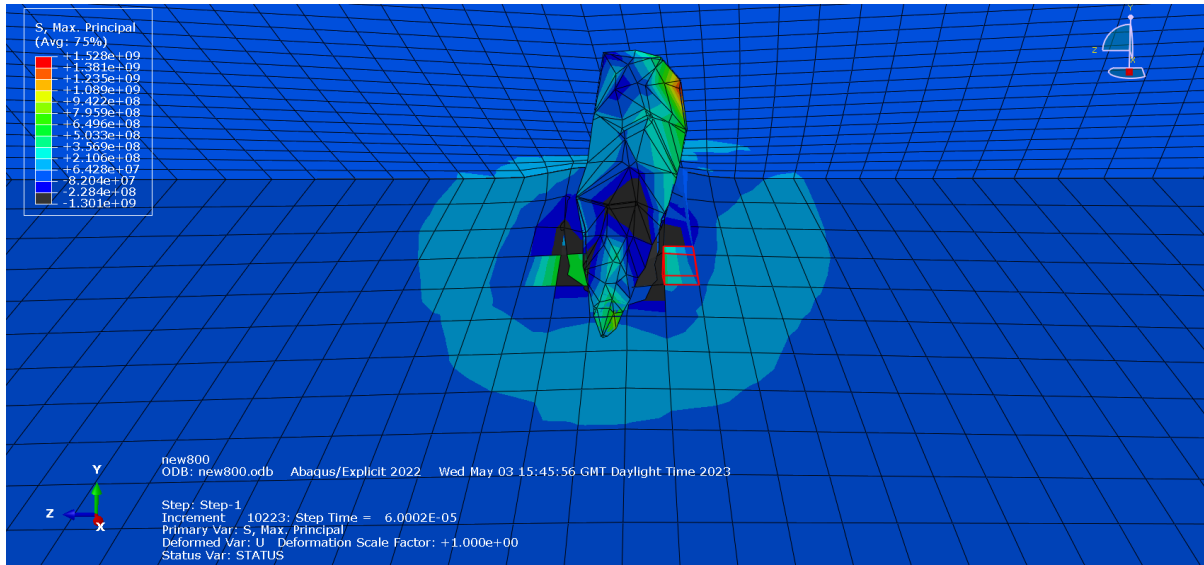


Figure 9- 800m/s⁻¹, Step 6000, Time 6.000E-05, max principle

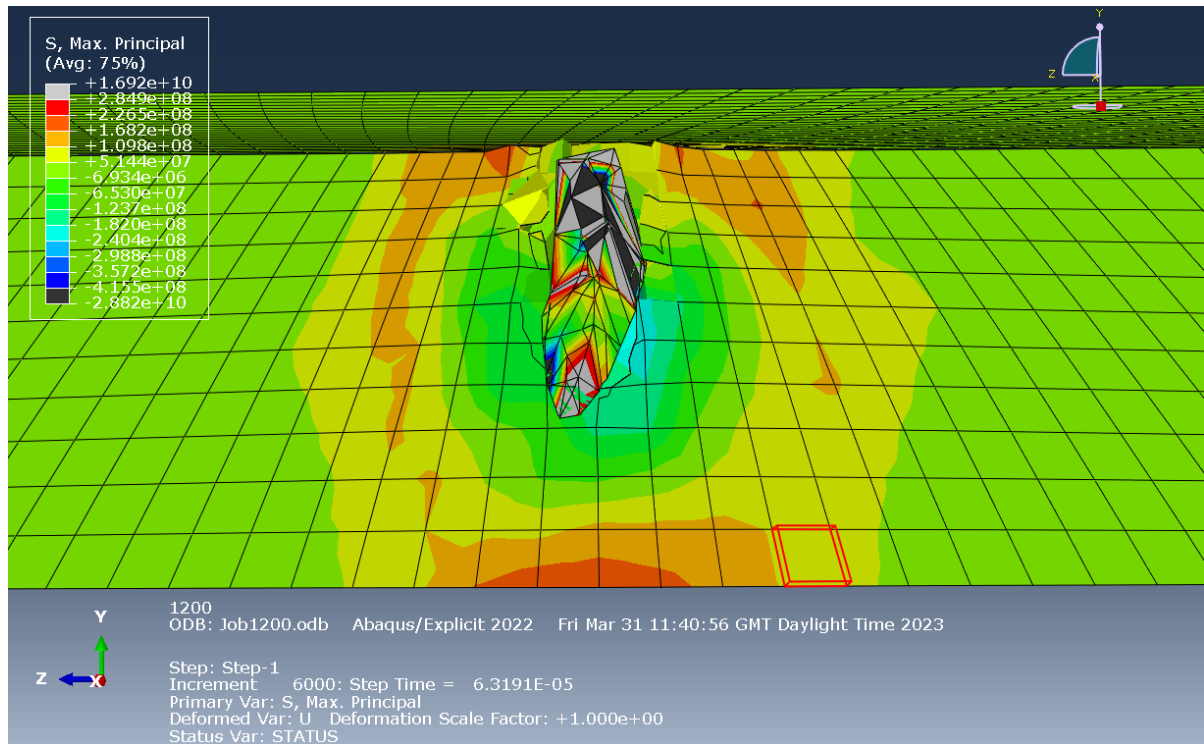


Figure 10- 1200m/s⁻¹, step 6000, time 6.3191E-05, max principle

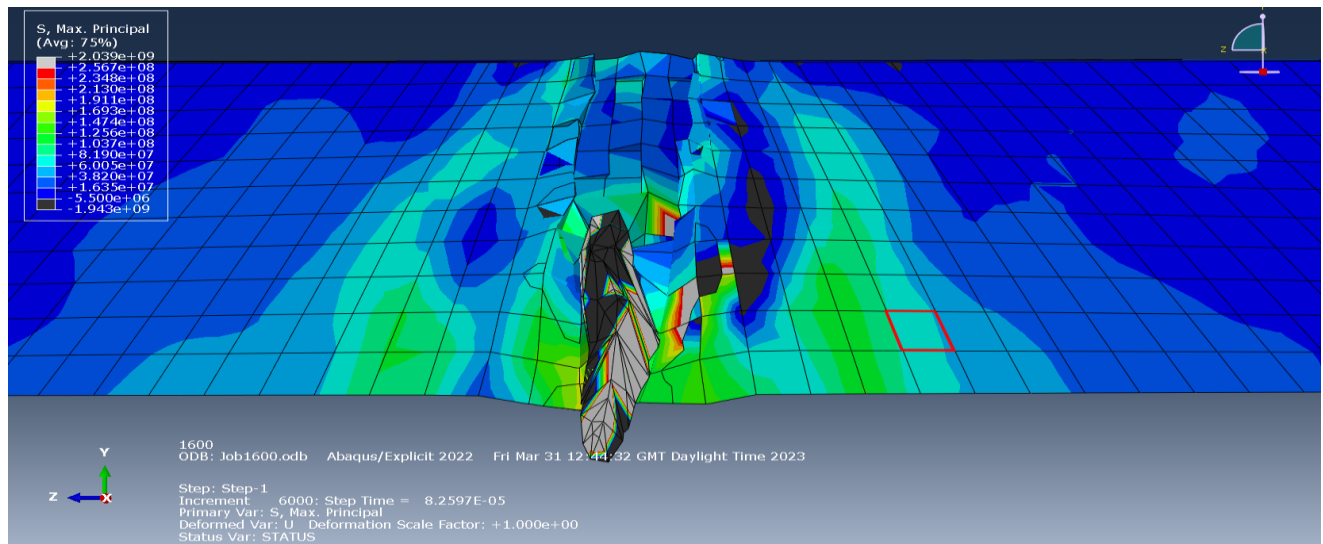


Figure 12- 1600m/s⁻¹, step 6000, time 8.2597E-05, max principle

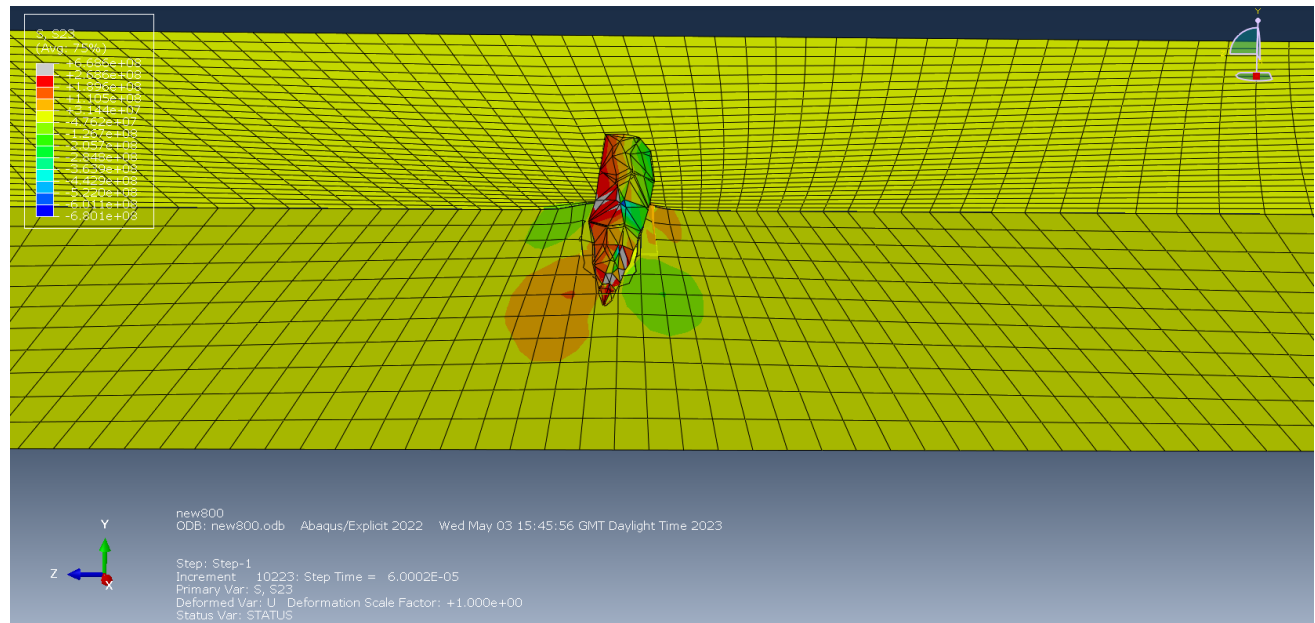


Figure 11- 800m/s⁻¹, Step 6000, Time 6.000E-05, S23

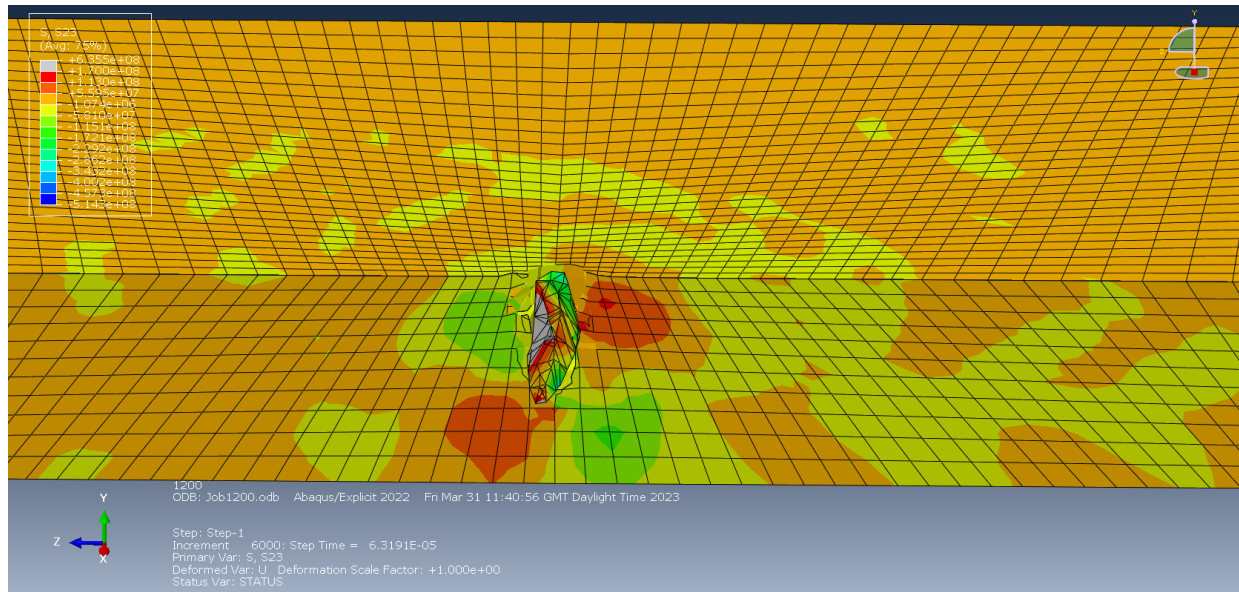


Figure 14- 1200m/s⁻¹, step 6000, time 6.3191E-05, S₂₃

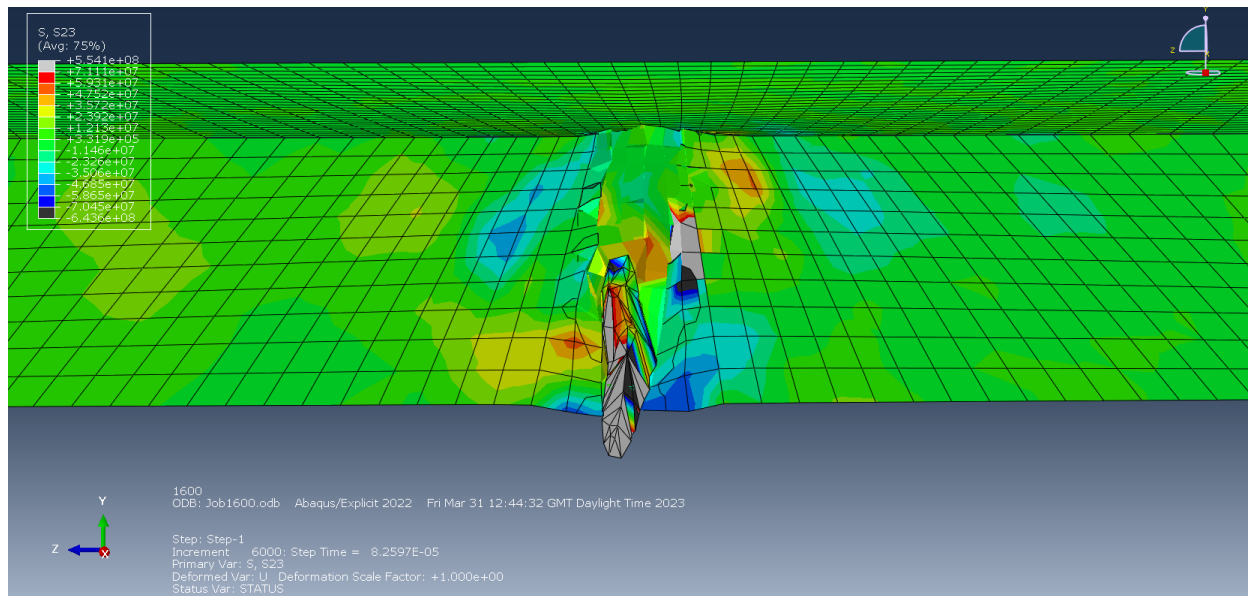


Figure 13- 1600m/s⁻¹, step 6000, time 8.2597E-05, S₂₃

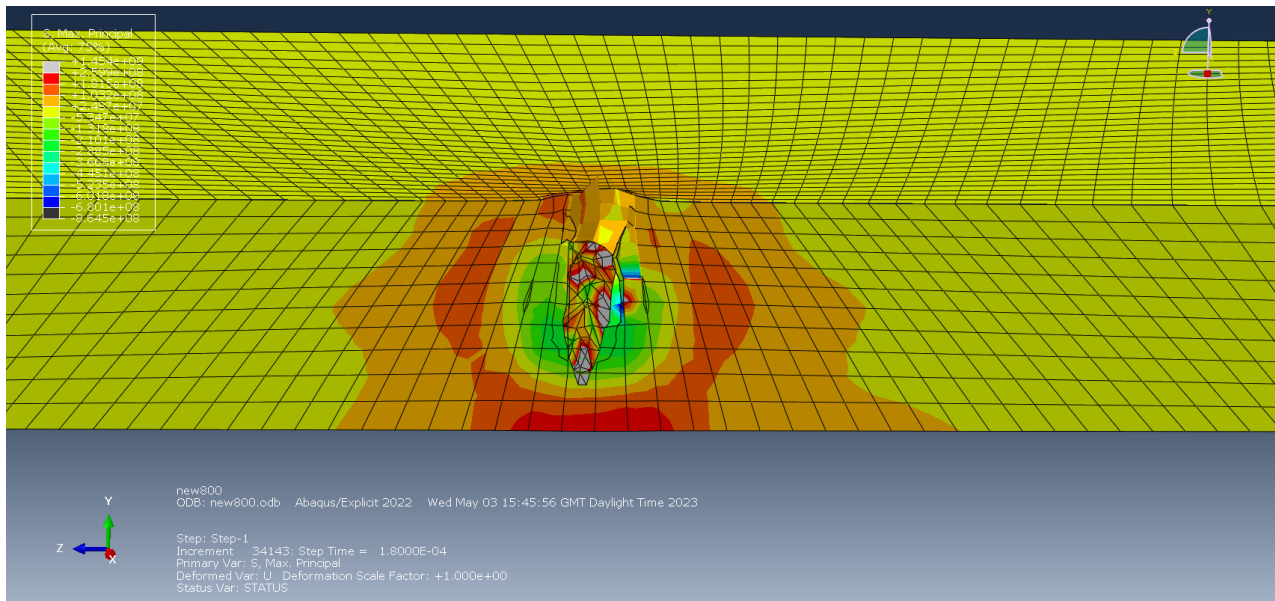
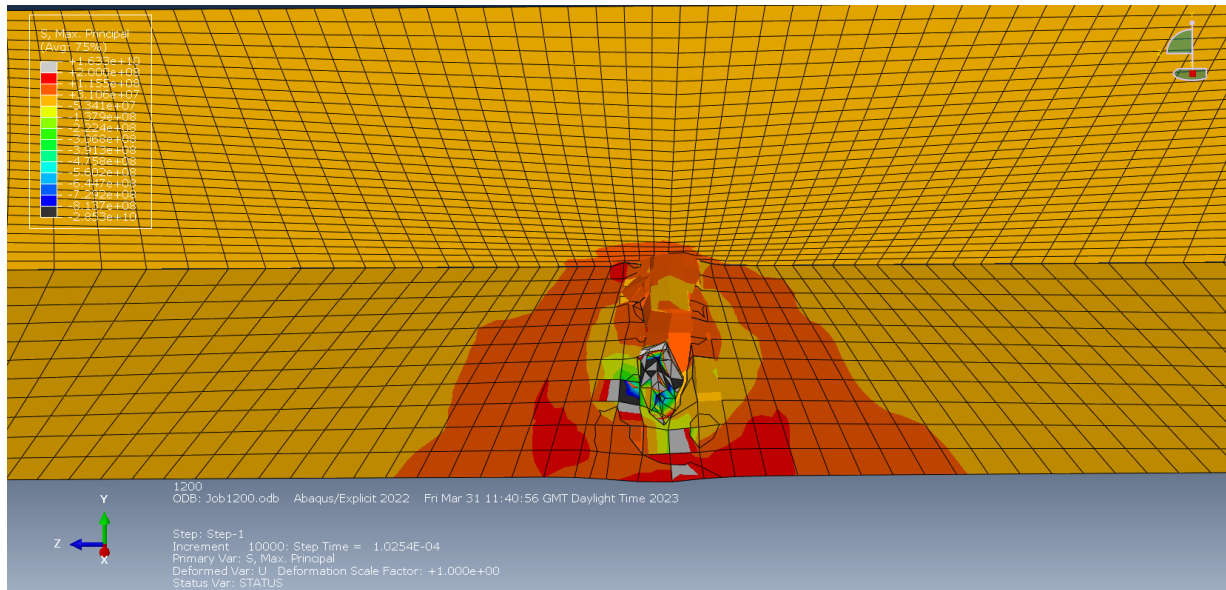
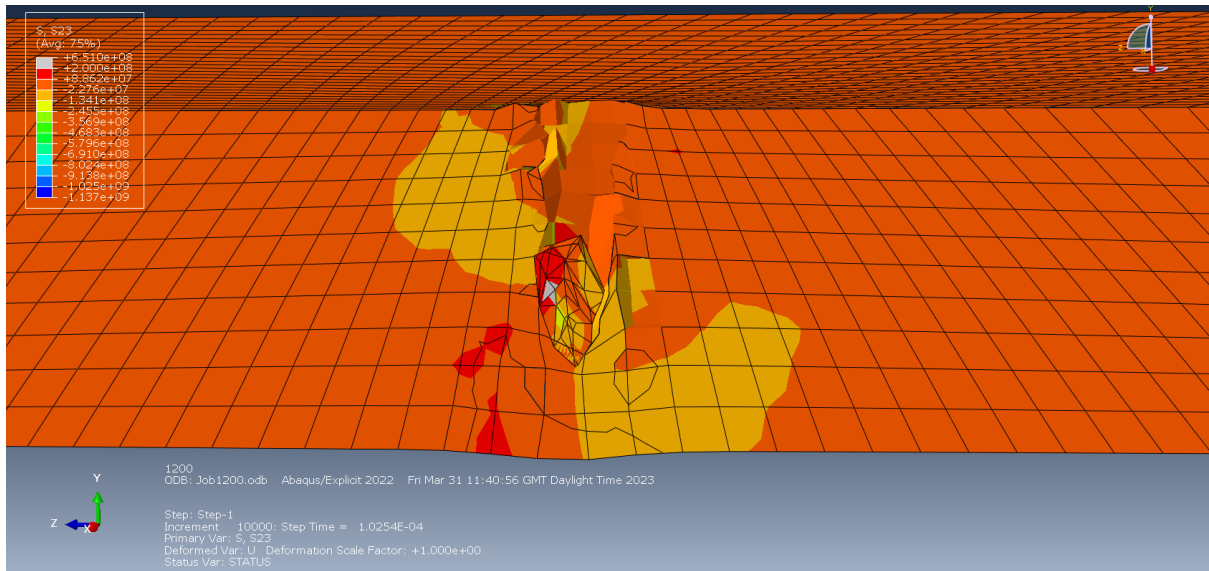
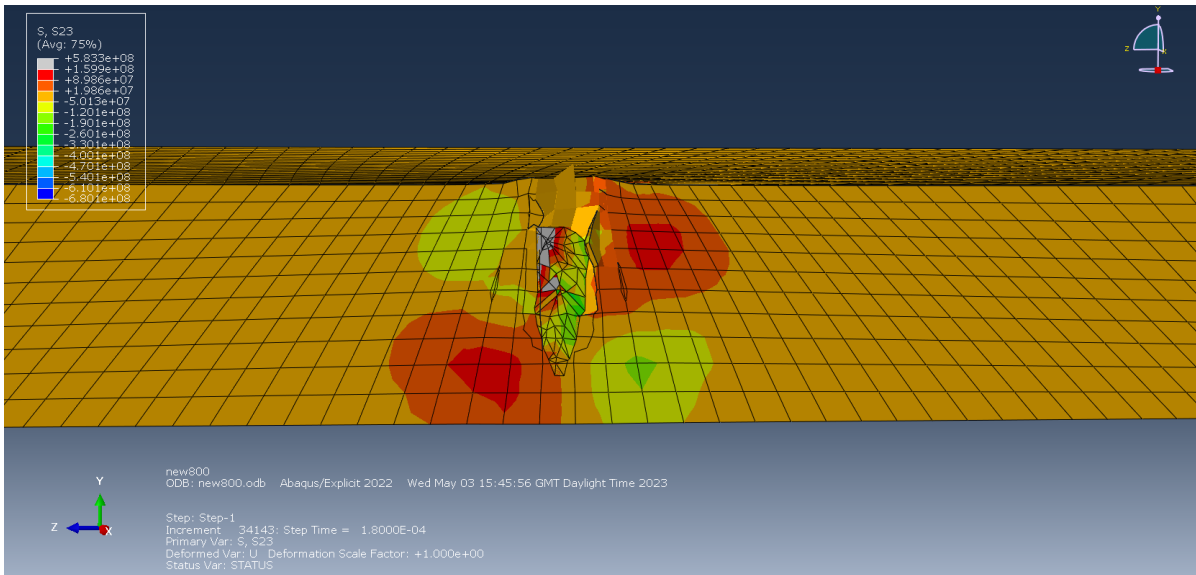


Figure 16- 800m/s^{-1} , step 18000, time $1.8\text{E}-04$, max principle



Figure 15- 800m/s^{-1} , step 18000, time $1.8\text{E}-04$, max principle, rear of plate





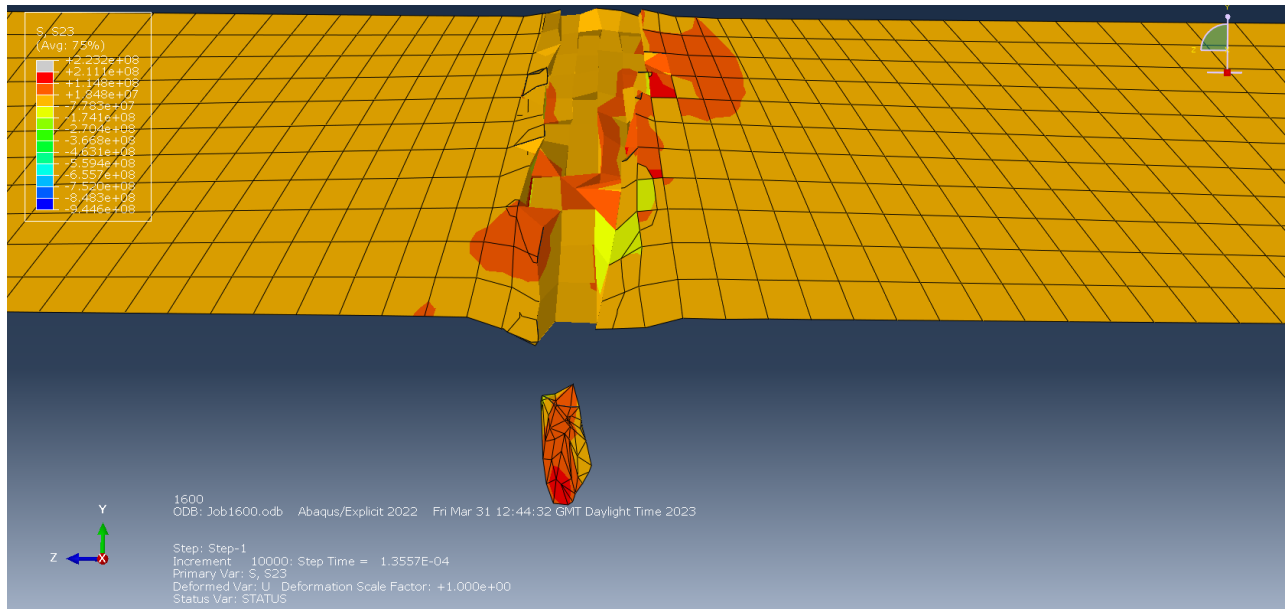


Figure 21- 1600m/s⁻¹, step 10000, time 1.3557E-04, S₂₃

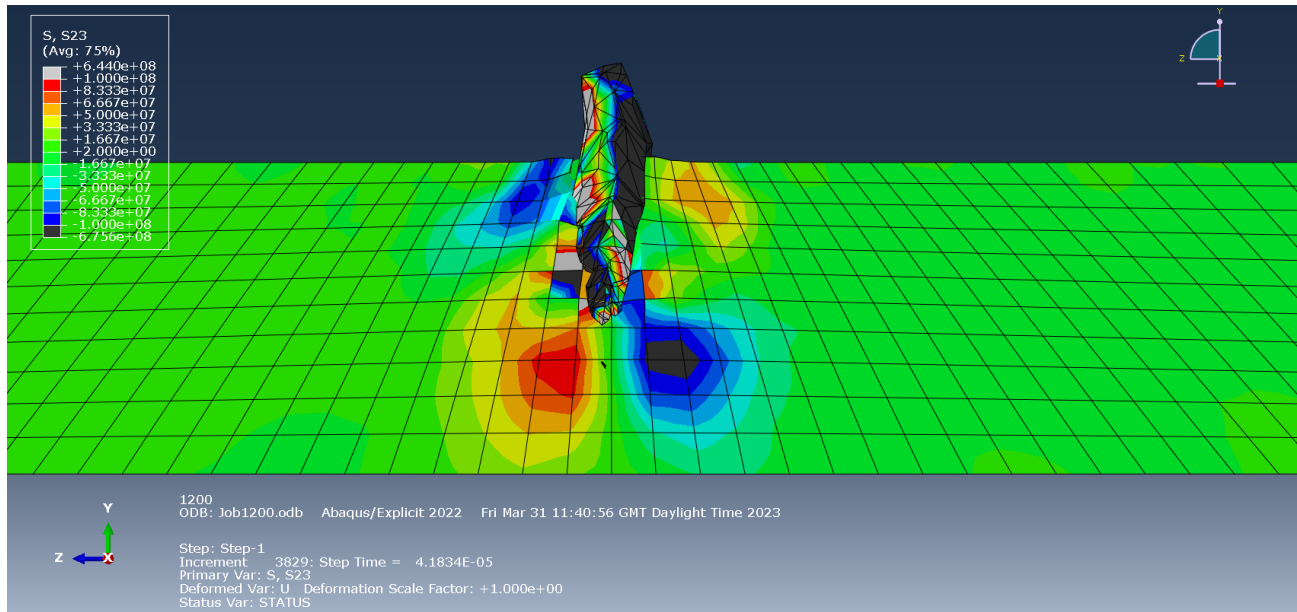


Figure 20-1200m/s⁻¹, step 3829, time 4.1834E-05, S₂₃ (Hertzian cone)

Limitations and approximations of simulation

Further work could be completed in many areas depending on time and available resources. Using student Abaqus limits the number of nodes available between the different packages. The average processing time of the simulation was on average around 3 hours.

Material specification from various online sources and the software manufacturer. There is some varying results between sources of data. Trusted sources must be used to ensure accurate and reliable results.

File storage limitations on PC/ OneDrive. Due to the large file sizes that the Abaqus software produces, storage has been in issue/ limitation as the university servers and hard drives in the computers that the software is run from are not of a large enough size to cope adequately.

Time management was important during this task as there was limited time that the simulation work could be completed as this needed specialist machines only available at certain times. This limited the complexity of what could be produced and simulated.

Conclusion, future work and recommendations

In conclusion this assignment implies that with an increase in muzzle velocity the greater the damage over a shorter period of time is experienced on the target. However as discussed there is not always a benefit to this. The high tensile stress zones experienced by the plate suggest that failure is highly likely even if the projectile does not penetrate the plate with significant behind armour effect.

In the future this work can be repeated with an increase in the number of nodes and decrease in mesh sizes which will increase accuracy however drastically increase calculation time and file sizes. As new target sets are produced and new weapons designed this model should be updated and re simulated.

It is recommended that future physical trials compliment the use of finite element analysis modeling ensuring that the researcher and user has trust in the results produced and that they are comparable.

References

- [1] STANDFAIR OPERATIONS, "7.62MMx39 Cartridge With Steel," April 2023. [Online]. Available: <https://www.standfairoperations.com/products/special-weapons-and-ammunitions/small-arms-ammunition/7-62mmx39-cartridge-with-steel/>.
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