

ACDB4007 L4 OME PHYSICS REPT

by Bud Bhudoye

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ACRONYMS

NATO	North Atlantic Treaty Organisation
CCF	Combined Cadet Force
CSBTR L144A1	Cadet Small Bore Target Rifle L144A1

FIGURES

Fig. (1)	POISSON'S RATIO VISUAL REPRESENTATION
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1. SECTION 01 – ABSTRACT / EXECUTIVE SUMMARY

The aim of this physics simulation is to analyse the effects of ballistic impact and stress-strain rates, through computational modelling of a projectile, when striking a target. The projectile is to be of an aerodynamically ballistic shape, in motion, while the target will be flat, and stationary. Both the projectile and the target will be created as three dimensional objects, with a given mass and material properties. Both the projectile and the target will be created as models in the Abaqus programme.

Using Abaqus to create a set of models, assign both dimensions and material properties, allows lab-based multi-physics simulation testing of the impact of the projectile as it is propelled at a series of given velocities, towards the target.

The lab-based coursework was carried out between May and July 2023. The main tasks were to create the models, establish an impact of one on the other, and analyse the stress and strain values demonstrated by the impact.

In order to emulate the damage caused, and stress and strain values, the plate was given to be aluminium, and comparative in size to a standard target plate, and larger in mass and dimensions to the smaller projectile.

In an attempt to simulate, and be realistically similar to that of an aerodynamic, rifle-fired, Steel-bodied bullet, impacting into the plate, the projectile was therefore modelled on scaled-up, approximated external dimensions, from those of a NATO Standard 7.62mm x 51mm Ball Round [1], due to the requirement to ensure proportions including a rounded tip and boat-tail, giving a more realistically aerodynamic projectile, and also due to the practical experience of having observed fall of shot of this calibre of rifle-fired rounds, into similar target plates.

The given values for material properties are described later in this report.

2. SECTION 02 – INTRODUCTION

Abaqus is an engineering physics modelling programme [7], which amongst other powerful simulation models, allows for the creation of impact strike simulation, with the input of variables, such as material properties, trajectory, velocity and impact of one object, or in this case a projectile, model on another, and the demonstration of stress and strain properties. In this course-work study, and report, a projectile travelling at a given speed, and the stress / strain demonstrated on a static target object. Once models and material properties are established and analysed, the speed of the projectile will be varied, to compare both the stress and strain on the target, and on the projectile. For this report, the only variable will be the speed of the projectile. The target will remain stationary. This will allow the level of penetration of the projectile, and deformation of both projectile and target to be analysed.

For this report the focus is on the principles of describing the motion of an object subject to Lagrangian mechanics, which describes the state of motion for a particle through kinetic and potential energy [8]. The Lagrangian mechanic is also used to describe a path of an object, in this case the projectile, on a defined path through space [8].

The hypothesis of the report is that the aerodynamic nature of the ballistic projectile in flight, should penetrate an aluminium target – as this is the design of the projectile, or indeed a bullet.

FURTHER DEFINITIONS & EQUATIONS USED IN ABAQUS

- **Johnson-Cook Plasticity model:** Briefly, a type of Mises model of plasticity, suitable for high strain-rate deformation. This can be applied to many materials such as metals used in the Report. Is also applied to the progressive damage and failure rates, such as those modelled in Abaqus [9]. This is considered to be the most accurate model for rates of high-strain scenarios such as a high velocity impact of a projectile upon a target [9].
- **Young's Modulus:** Used to describe how a material will deform and stretch under stress and strain, and where it's breaking point will be. In this Report, leading to penetration of a projectile through a static target plate [10]

$$E = \frac{\sigma}{\epsilon} = \frac{F/A}{dl/l}$$

(E) = property of material, describing how easily the material will stretch and deform, Defined as the ratio of tensile stress (σ) to tensile strain (ϵ).

Where stress is the amount of force applied, per units of area ($\sigma = F/A$)

And strain is extension p/unit (l), so ($\epsilon = dl/l$), where dl = change in length.

Other stress forces to be considered: Tensile Force



Compressive Force



Shear Force



- **Poisson's Ratio:** Describes the transverse strain, normal to the applied load, relative to the axial strain in the direction of the applied load [11]



Figure 01 [11]

Metal	Poisson's Ratio - μ -
Aluminum	0.33
Aluminum Bronze	0.30
Beryllium	0.024 - 0.03
Blackheart Cast Iron	0.26
Bronze	0.34
Copper	0.36
Gold	0.42
Lead	0.40 - 0.45
Magnesium	0.35
Mild Steel	0.3
Molybdenum	0.32
Naval Brass	0.34
Nickel	0.31
Phosphor Bronze	0.33
Platinum	0.39
Plutonium	0.15 - 0.21
Silver	0.37
Stainless Steel 304L	0.3
Tantalum	0.35
Thorium	0.27
Tin	0.33
Titanium	0.3
Tungsten	0.28
Uranium	0.21
Wrought Iron	0.3
Zinc	0.25

Figure 02 [11] – Poisson's Ratio of metals

- **Strain:** Deformation of a material due to stresses induced on it. Stresses can be various, as shown above. When taken with Young's Modulus, also above, this can demonstrate where the "bending" strain will end, and the material will "break".
- **Gravity:** A given value of 9.81 m/s²
- **Brittle Material:** Ordinarily a strong material, that will hold it's integrity, until a breaking point
- **Ductile Material:** Ordinarily ductile materials have a greater elastic property, and will bend a greater deal, before breaking

3. SECTION 03 – METHODOLOGY

For the purpose of this Report, the material properties were set, and the projectile velocity was varied, to establish the differing penetration effects.

The variety of velocities is to establish differentiations in potential propellant, weapon systems or types of ammunition.

These are described below - Velocities used in simulations, named as "Load" in Abaqus:

190m/s - Muzzle velocity of Scorpion Air Rifle [3]

370 m/s - Muzzle velocity of Small-Bore Rifle (CSBTR L144A1) [3]

800 m/s - Initial velocity, to demonstrate Penetration from standard rifle muzzle velocity (lower approximation of L81A2 CTR – actual 870ms) [3]

1500 m/s - Increased velocity to demonstrate higher penetration stresses, similar to lower threshold of hyper-sonic velocity missiles

2530 m/s - Fragment impact testing for Insensitive Munitions (IM) (UN Series 7 type (I) test prescription fragment impact velocity 2530 ± 90 m/s, in alignment with standard Method 1 from AOP-4496 [2]

Dimensions used in Abaqus models:

Plate - 0.3m² x 0.035m (Aluminium material properties)

See Appendix A, for images of Plate/Target

Represents: Standard 1x foot square target plate

Projectile: - 0.052m Length
- 0.006m Radius (Steel material properties)

See Appendix A, for images of Projectile

Note: Modelled on approx. basic external anatomy of a NATO Standard 7.62mm x 51 Ball Round [1]

The material properties were assigned in Abaqus, as Aluminium for the Plate/Target, and Steel for the projectile.

For the stress-strain model problems and materials in Abaqus, an Explicit Solver was used.

Extremely small time-steps were used, as the velocities selected for testing were increasingly high. Step time: 40000^{-05} Increment: 2000

Young's Modulus and Poisson's ratio were entered in Abaqus to represent the elastic behaviour of the aluminium plate.

Johnson-Cook Plasticity model parameters were entered into Abaqus to simulate the plastic behaviour.

Materials chosen for the Target Plate and Projectile:

Target Plate – Aluminium. Aluminium was chosen for the Plate, as this is a realistic representation of the types of target plate often used by the British Military, for ballistic testing, such as fall of shot, and explosive and fragmentation testing. It also a highly ductile metal [12]. Aluminium plate model plasticity and damage were entered into Abaqus values using the dialogue box for constants.

Projectile – Steel. Steel was selected for the purpose of this Report, as it is typical of a standard NATO bullet. Steel has a reliable state of tensile strength (see below), and this is the reason it is often used in the manufacture of bullets. Steel core bullets will often deform upon impact with a target, but will maintain a high level of ductile stability, and often only deform upon impact with a target of much greater tensile strength. Steel plate model plasticity and damage were entered into Abaqus values using the dialogue box for material constants.

Johnson - Cook Plasticity Material Model					
Bullet Component	A [MPa]	B [MPa]	n	m	C
7.62x39mm MSC-core	234.4	413.8	0.25	1.03	0.00333
7.62x39mm MSC-jacket	448.2	303.4	0.15	1.03	0.00333
Lead-filler	10.3	41.3	0.21	1.03	0.00333

Johnson - Cook Dynamic Failure Model					
Bullet component	d ₁	d ₂	d ₃	d ₄	d ₅
Steel core	5.625	0.3	-7.2	-0.0123	0
7.62x39mm MSC-jacket	2.25	0.0005	-3.6	-0.0123	0
Lead filler	0.25	0	0	0	0

Figure 03 [13] Steel core bullet, failure models

The models were created in Abaqus, by entering the dimensions, and allocating the radius through 360 degrees, for the projectile, and by depth of plate, for the target plate.

Both models, or objects, were then allocated the material qualities of Steel and Aluminium, respectively, by entering the values into the values box of each. Both objects were meshed and nodes allocated for simulation of impact. Both objects' material values were given as constants.

The simulation is a two-part simulation, to demonstrate a collision. The trajectory is a direct path, with the projectile impacting the target from a 90° right-angle. This is to fully record the impact and stress-strain properties on both projectile and target, rather than an oblique angle, as an oblique angle impact would also subject the projectile to axial and radial forces [1], which would directly affect the results, and may lessen the penetration and damage caused on one, or both objects.

The variable, for the purpose of this report was the projectile velocity, as mentioned in the Section above.

good discussion of methodology

4. SECTION 04 – RESULTS

The results of the Abaqus simulated impact at each velocity of projectile are shown in the graph below.

Velocity: 190 m/s
370 m/s
800 m/s
1500 m/s
2530 m/s

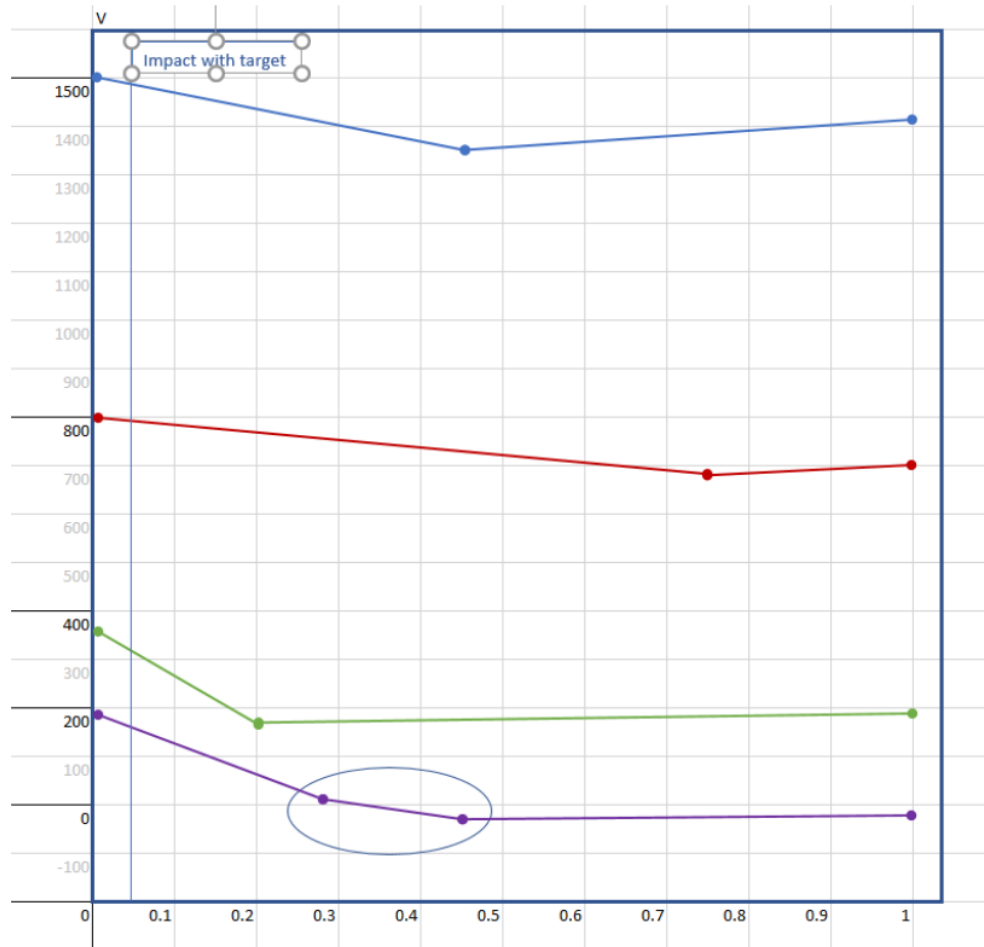


Figure 03 – Graph showing speeds of projectile at moment of impact at end of simulation

NOTES: While the initial simulation was set to 800m/s, for the purpose of the report, a variety of realistic projectile velocities were introduced, to the load, based on the weapon systems and impact testing listed in Methodology.

Time scale is simply listed as 00 to 01, representing 0% to 100% of simulation time, or conclusion of simulation. This was agreed to be the best way to show results, as the lower

velocities would have to be shown as a magnitude of x10 shorter than the higher velocities, if shown in actual time, having finished the collision in a much shorter scale of time. The more important conclusion is the velocity over the duration of the collision.

good explanation of results visualisation

The data has been simplified to 3x key data points, in the graph, with each point referencing a chosen point on the projectile model, at each velocity. The results show the start Velocity, the Velocity following impact (point of impact shown by blue line), and final Velocity.

The lower Velocity of 190 m/s shows 4x data points, as this seemed to show an anomalous data point, where the projectile slowed to less than zero m/s, following impact.

Good determination of anomalous data

The higher Velocity of 2530 m/s would not complete the Simulation, in Abaqus, in the given time allowed for course-work to be completed. It has been listed for completeness.

IMAGES (ALSO SHOWN IN MORE DETAIL IN APPENDICES)

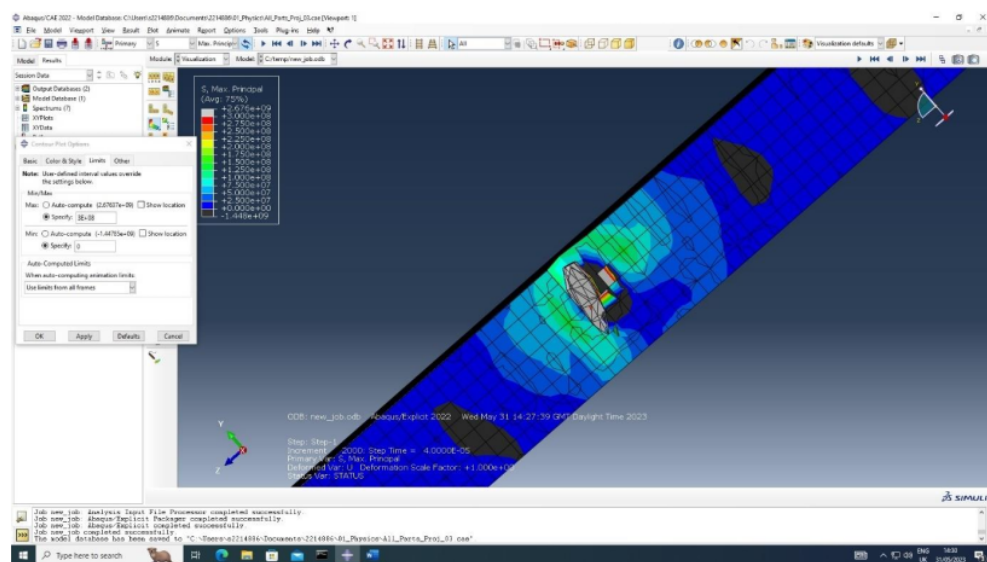


Figure 04: (Image 01) 20230531 7.62mm representative round (Steel), Plate (Aluminium) 800ms CROSS SECTION

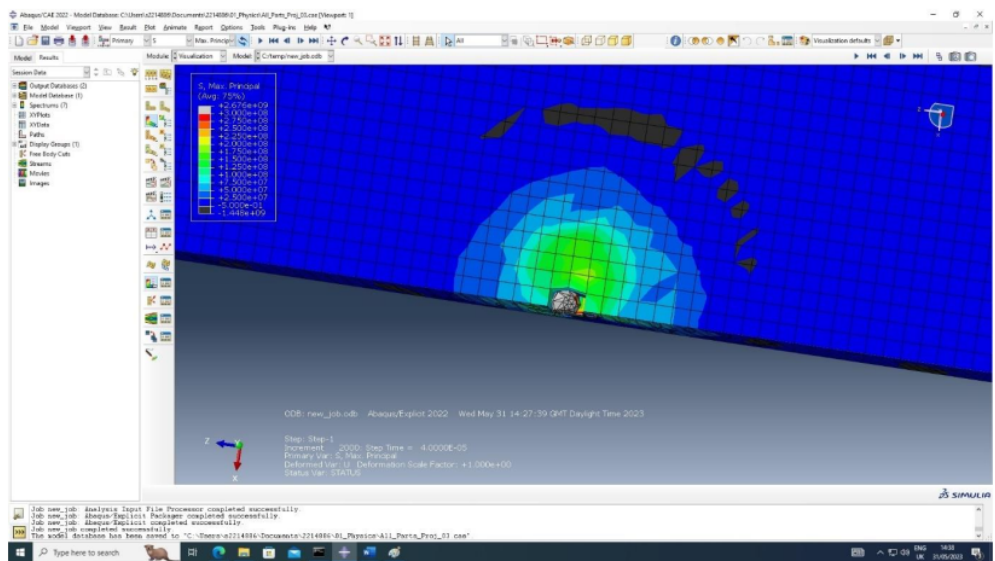


Figure 05: (Image 03) 20230531 7.62mm representative round (Steel), Plate (Aluminium) 800ms CROSS SECTION, TOP DOWN SHOWING RIPPLES OF STRESS in PLATE

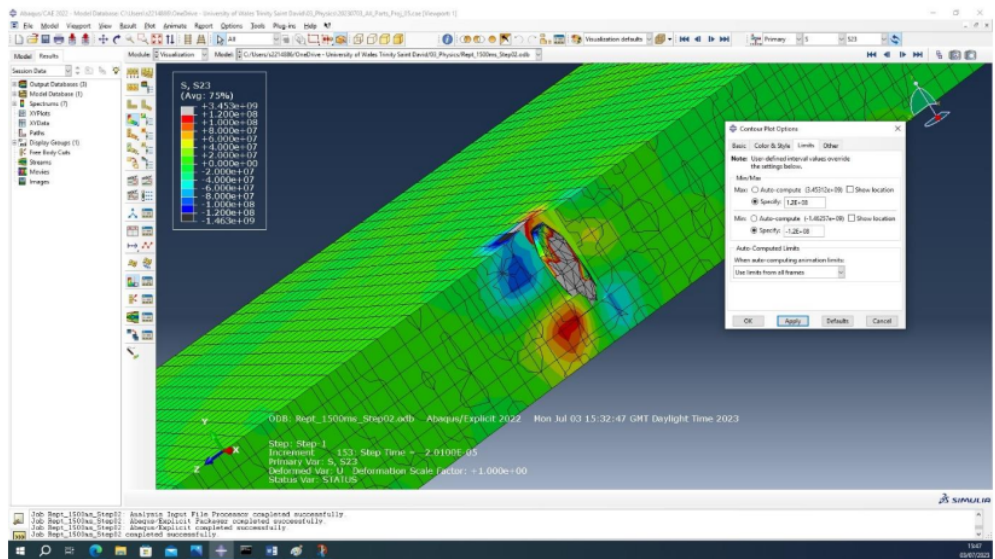


Figure 06: (Image 17) 20230703 7.62mm representative round (Steel), Plate (Aluminium) 1500ms - CROSS SECTION, SHOWING **SHEAR STRESS** in PLATE AND ROUND

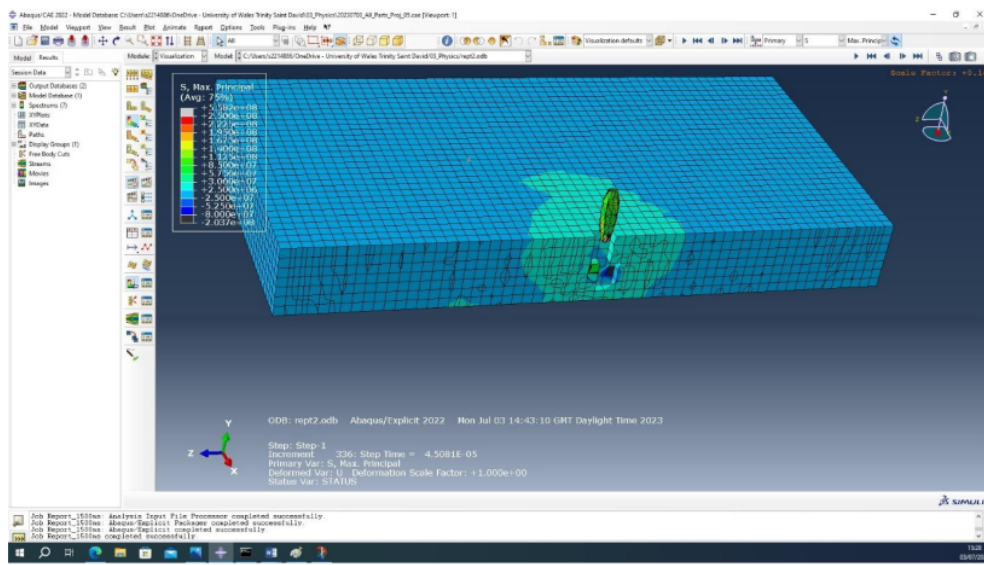


Figure 07: (Image 18) 20230703 7.62mm representative round (Steel), Plate (Aluminium) **1500ms** - CROSS SECTION, SHOWING **TENSILE STRESS** in PLATE, RIPPLES OF STRESS in PLATE

The key information to be taken from the stress data demonstrated in the simulations is that the projectile will penetrate the target even at lower velocities.

Where compared the shear stress and deformation of the target plate, around the projectile, as the model penetrates, shown in fig. 07 above, is approx. between $3,000\text{e}-07$ to $2,500\text{e}+06$, where this strain is spread over a large area around the projectile impact. In fig. 06 above, the tensile stresses are localised, and more concentrated with extremes of approx. $1200\text{e}+08$, in small areas, as the projectile penetrates the target, and lower concentrated stresses of $4,000\text{e}+08$ to $8,000\text{e}+08$. The tensile stress appears in "clusters", with a large area surrounding the impact showing little to no change in shear stress.

good discussion of stress results

I will assume the commas are equivalent to decimal places for the benefit of the doubt

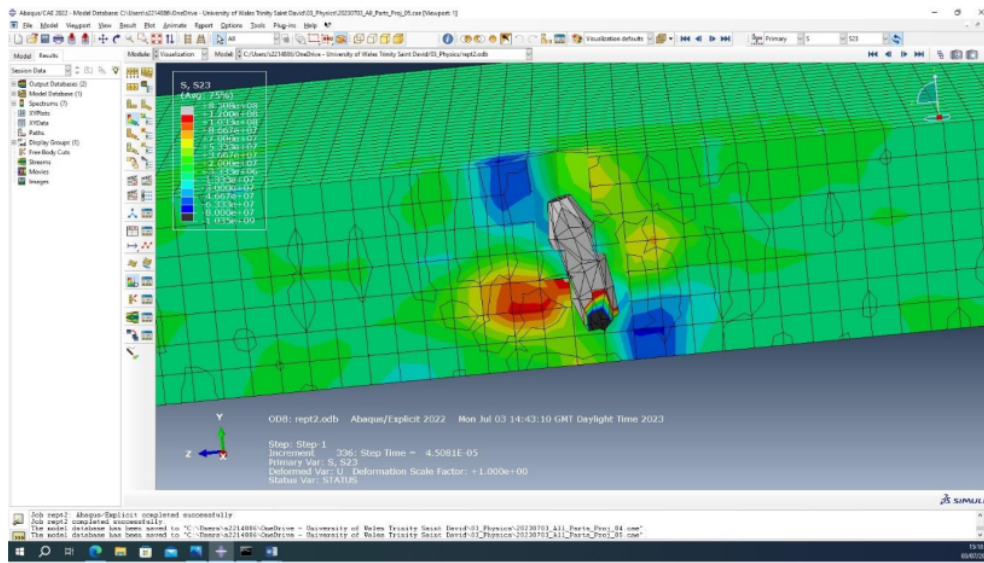


Figure 08 (Image 15) 20230703 7.62mm representative round (Steel), Plate (Aluminium) 800ms - CROSS SECTION, SHOWING **SHEAR STRESS** in PLATE

Comparatively, in Fig. 08, above, measuring the variation in shear stress at a projectile velocity of 800m/s, similar clusters of stress appear with extremes of 1,200e+08 to 6,333e+07, in the target plate.

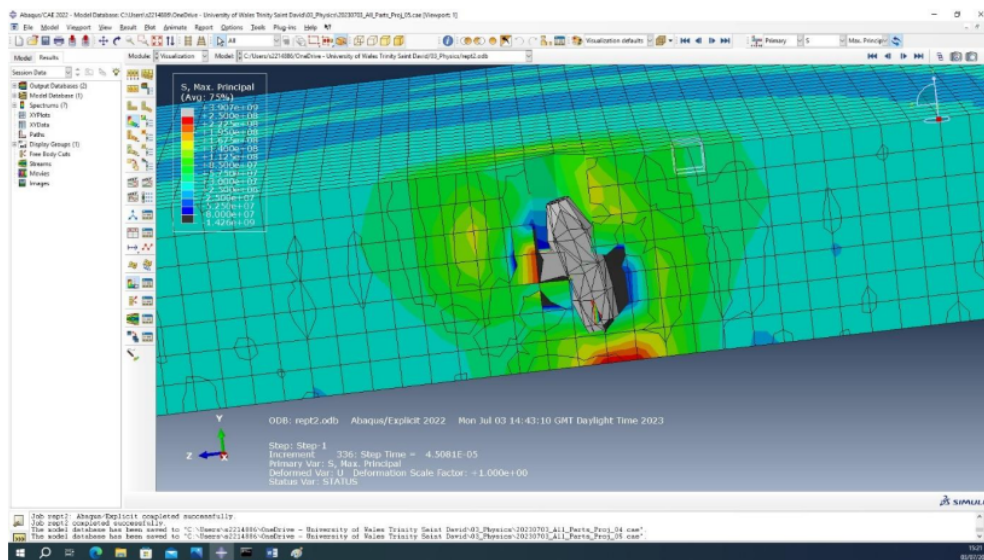


Figure 09 (Image 16) 20230703 7.62mm representative round (Steel), Plate (Aluminium) 800ms - CROSS SECTION, SHOWING **TENSILE STRESS** in PLATE

When the tensile stresses at the lower velocity of 800m/s are considered, in Fig. 09 above, it shows the stress dissipating in waves away from the impact site. This is to be expected, flowing outwards in a capillary wave deformation. It would appear in both cases that the shear stress is dominant to the tensile stress, in concentrated areas, where the tensile stress flows outward and is absorbed by the surrounding material.

The lower and higher velocities appear to have a similar effect on the target plate, and projectile. This is due to the ductile properties of aluminium in the target, and the more dense, stronger, but brittle projectile.

This is evident in the ductile failure of the target plate, not brittle failure or fragmenting [1], allowing the projectile to penetrate through, with no deformation of the projectile. A wider projectile, of a similar material property, would possibly have shown pettling, or spalling in the target plate. Ductile failure demonstrates that the projectile is successful in it's intended use.

5. SECTION 05 – CONCLUSION

The objective of this course-work and report was to create and model a simulation of an impact of a projectile on a stationary target. The data generated on the material stress and strain would then be analysed

In summary, the results and data produced re-enforce the reasoning and design of modern ballistic projectiles. In reality, a steel core, or entirely steel material projectile, when fired towards a static aluminium target, will result in deformation of the target, by the projectile, and in sufficient velocities will cause the projectile to entirely penetrate the target.

The results clearly show that the projectile will penetrate the target at even the lowest variable of the velocity used, in 190m/s, and that at greater velocities, up to 1,500m/s as successfully simulated, the target will not stop the projectile.

The hypothesis that the projectile design, as an aerodynamically efficient, ballistic round, or bullet, is a successful, and proven design for overmatching and penetrating the target, is correct.

EVALUATION

The simulation could be improved with more time spent in increasing the limits of the velocity. It could be simulated down to the lesser required velocity limit, to prevent penetration of the target. Increasing the velocity further than the upper limits simulated, 1,500 m/s would prove little, as it could be hypothesised that ductile failure of the target material will most often occur. More nodes placed in proximity to the impact area could provide a higher amount of detail in the stress-strain figures generated, but this would likely not change the outcome of the simulation. Some simplification of the materials used could be argued to also simplify the results generated. For example, the standard NATO 7.62mm round / model simulated, features a steel core and copper outer jacket [1], which may effect material property stress, in that copper is a more ductile material, but it is unlikely that this detail would have affected the overall outcome of the simulation.

More time spent on computer modelling could have also improved the accuracy of results.

If re-creating the simulation, variations in the material properties could be introduced to confirm at what point the target would prevent penetration of the projectile, even at greater velocities. Variation of the shape of the projectile model could also provide damage and stresses other than ductile failure. Spalling, or fragmentation could be created if using a more brittle material value for the target, or a more ductile material for the projectile model.

APPENDICES

APPENDIX A1 – ABAQUS IMAGES

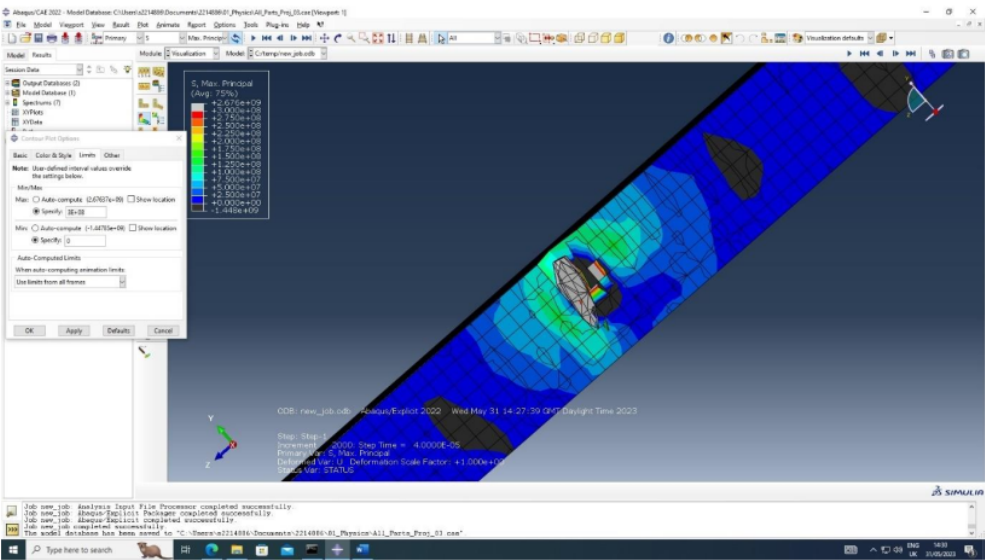


Image 01: 20230531 7.62mm representative round (Steel), Plate (Aluminium) 800ms CROSS SECTION

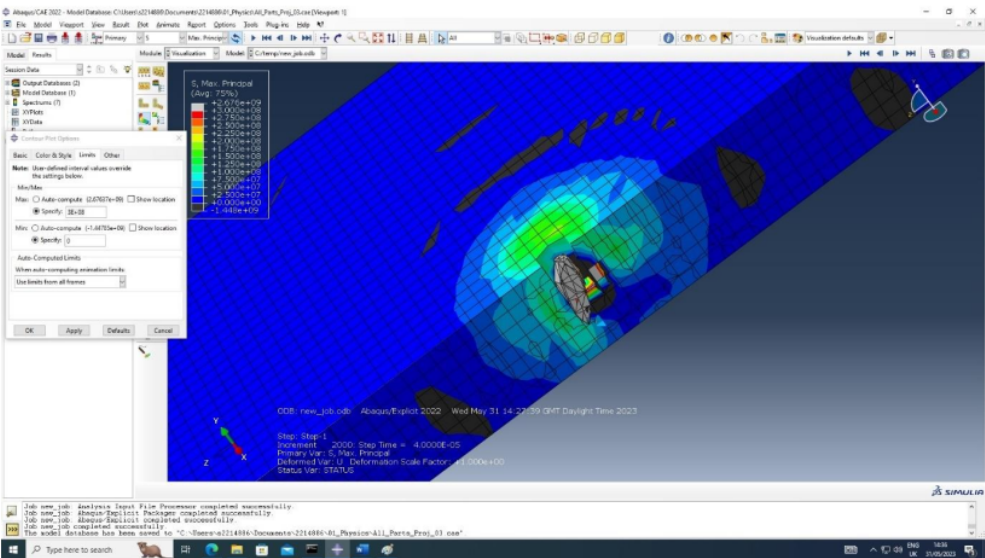
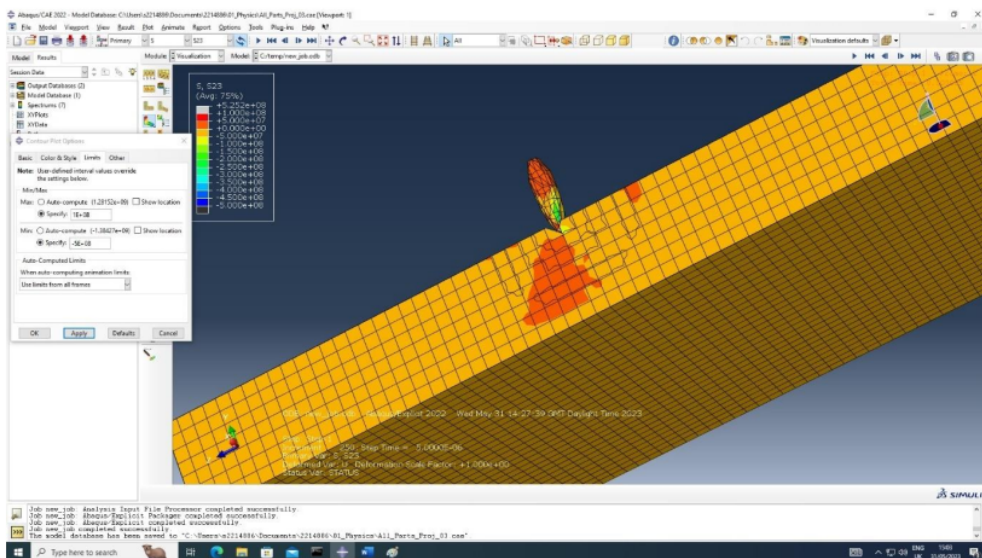
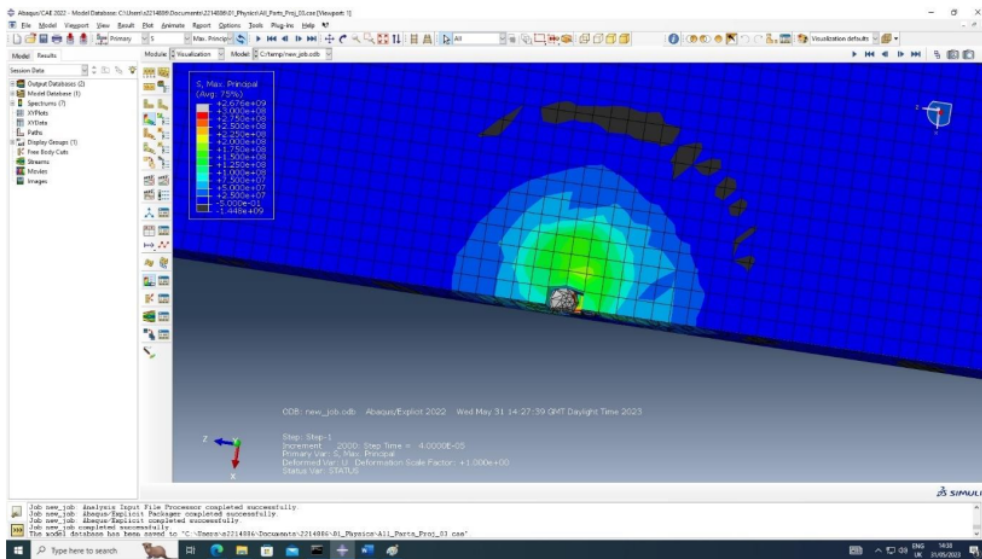


Image 02: 20230531 7.62mm representative round (Steel), Plate (Aluminium) 800ms CROSS SECTION, SHOWING RIPPLES OF STRESS IN PLATE



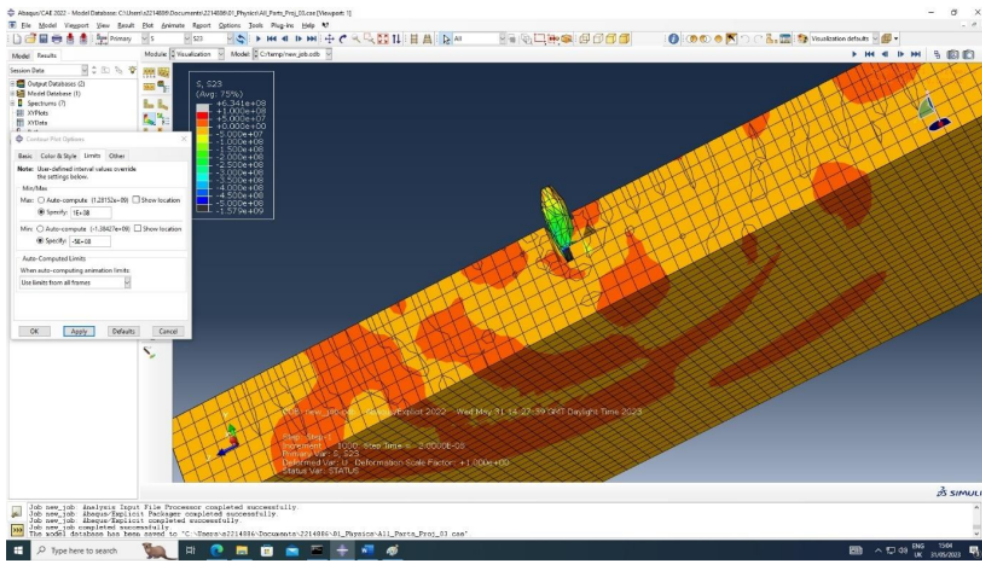


Image 05: 20230531 7.62mm representative round (Steel), Plate (Aluminium) 800ms CROSS SECTION, SHOWING RIPPLES OF STRESS in PLATE

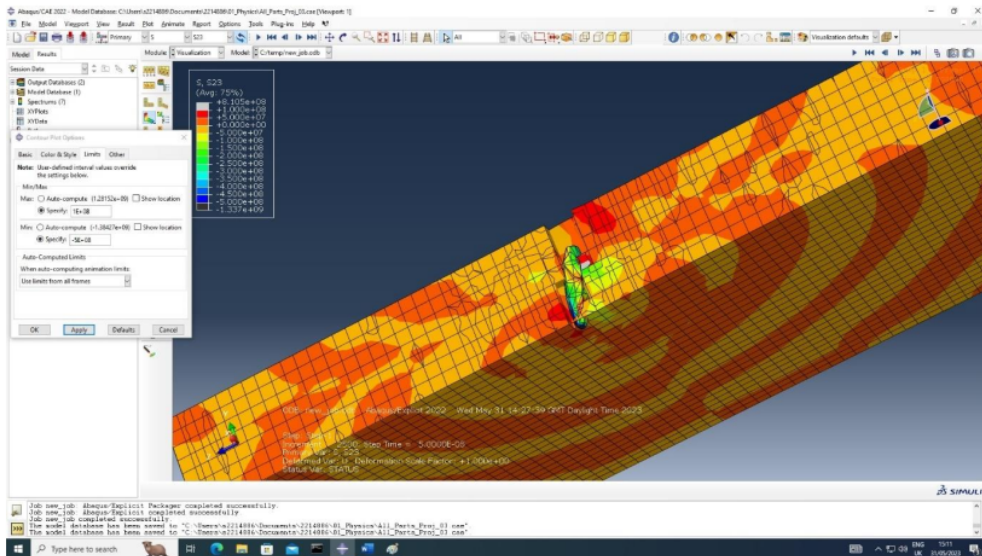


Image 06: 20230531 7.62mm representative round (Steel), Plate (Aluminium) 800ms CROSS SECTION, SHOWING RIPPLES OF STRESS in PLATE

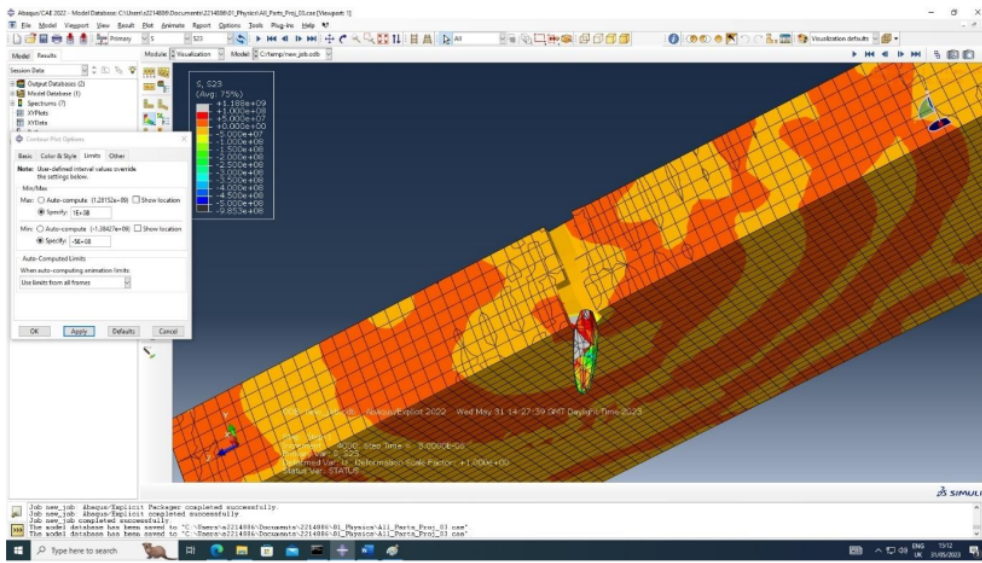


Image 07: 20230531 7.62mm representative round (Steel), Plate (Aluminium) 800ms CROSS SECTION, SHOWING RIPPLES OF STRESS in PLATE, ROUND EXITS PLATE

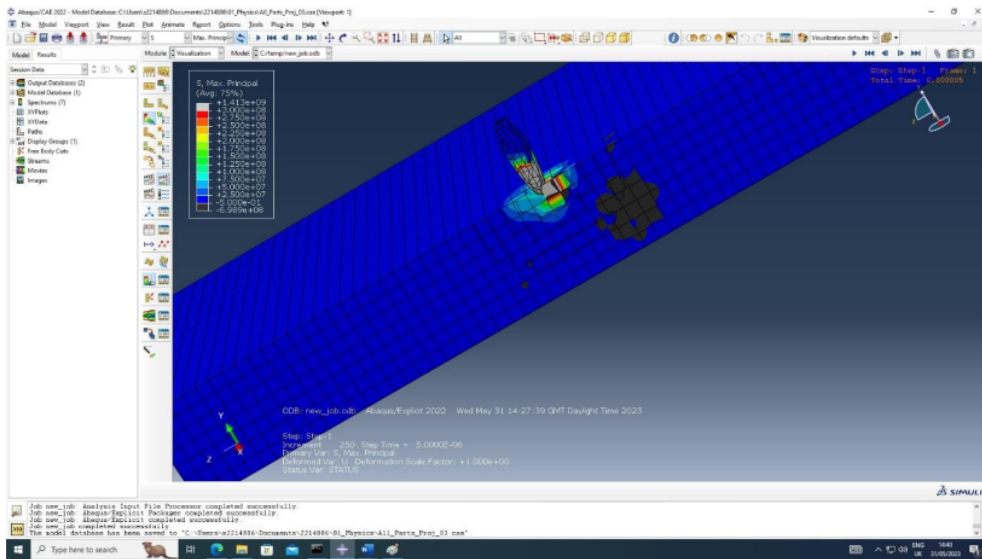


Image 08: 20230531 7.62mm representative round (Steel), Plate (Aluminium) 800ms - CROSS SECTION, SHOWING STRESS in PLATE

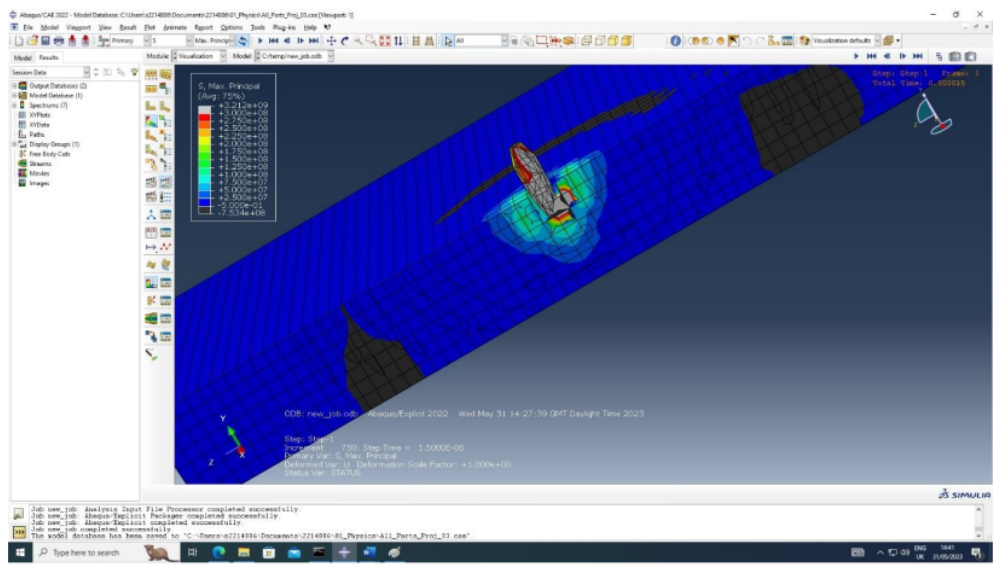


Image 09: 20230531 7.62mm representative round (Steel), Plate (Aluminium) 800ms
- CROSS SECTION, SHOWING STRESS in PLATE

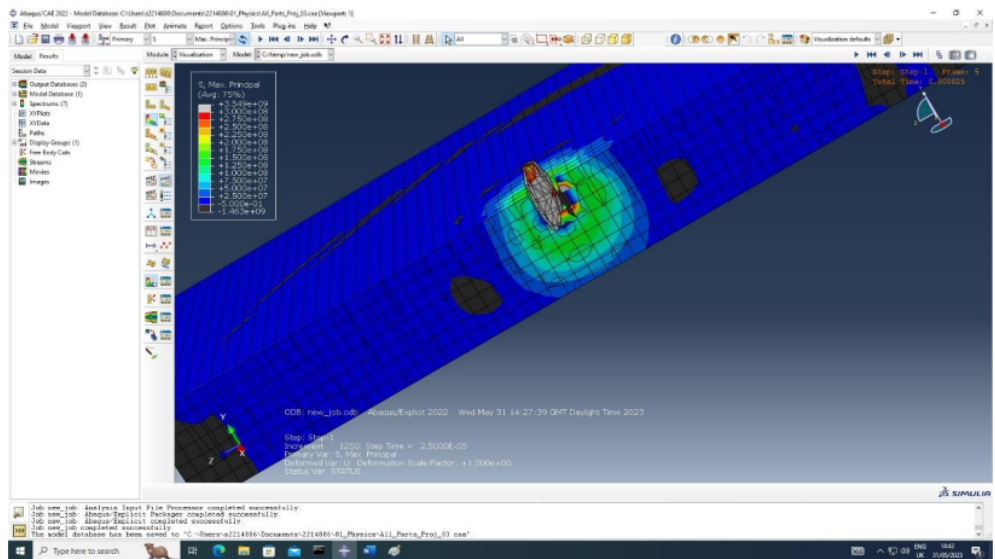


Image 10: 20230531 7.62mm representative round (Steel), Plate (Aluminium) 800ms
- CROSS SECTION, SHOWING STRESS in PLATE AND ROUND

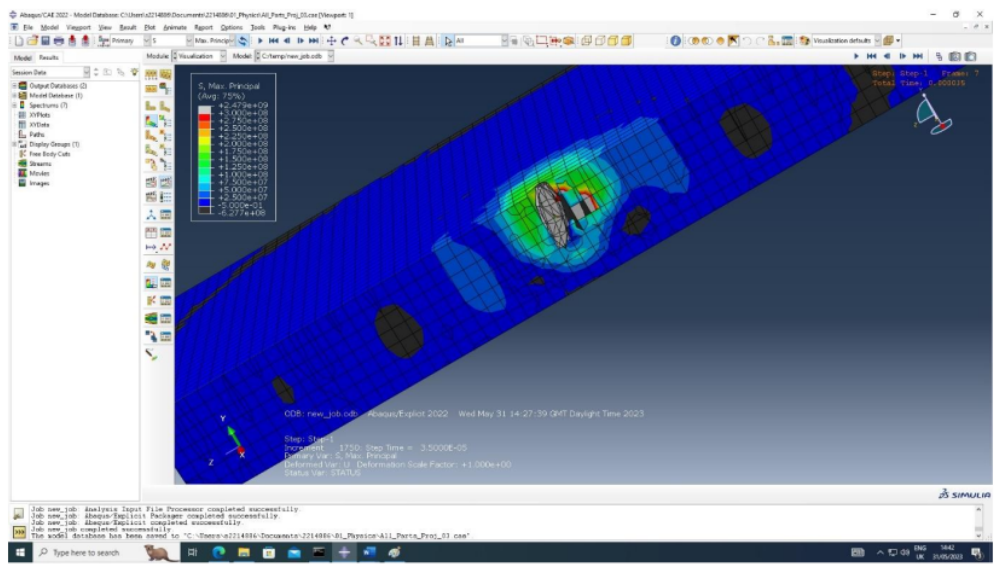


Image 11: 20230531 7.62mm representative round (Steel), Plate (Aluminium) 800ms - CROSS SECTION, SHOWING STRESS in PLATE

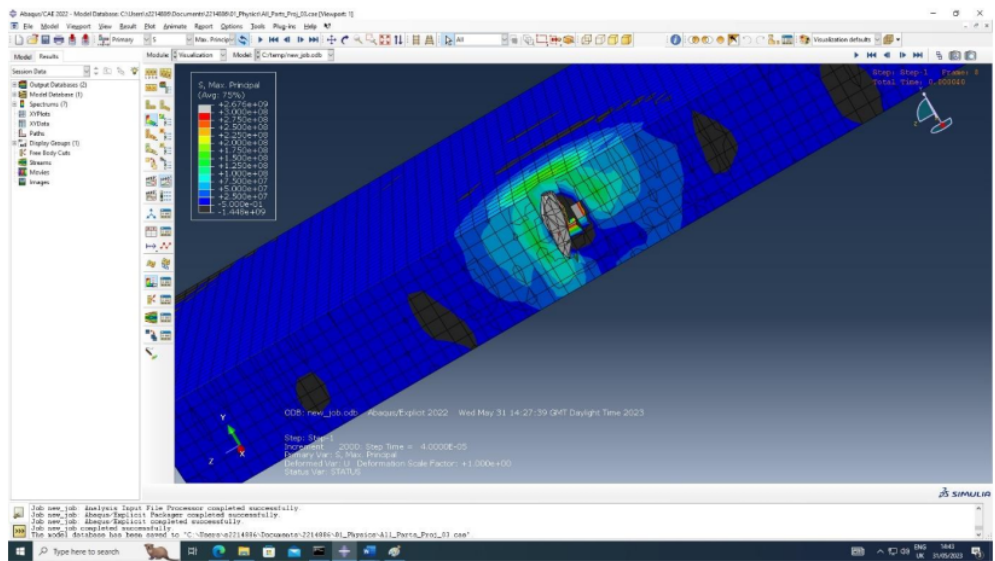


Image 12: 20230531 7.62mm representative round (Steel), Plate (Aluminium) 800ms - CROSS SECTION, SHOWING STRESS in PLATE

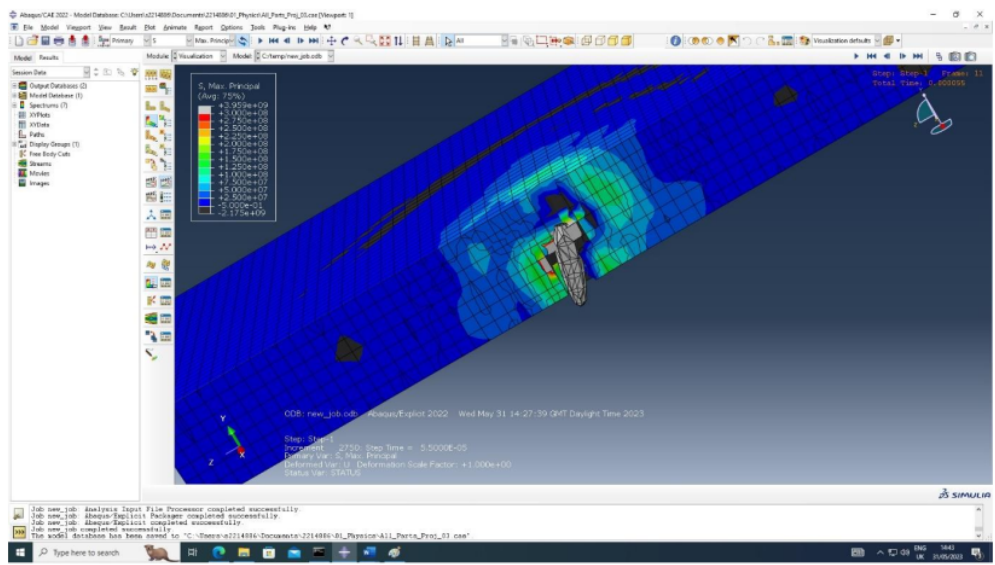


Image 13: 20230531 7.62mm representative round (Steel), Plate (Aluminium) 800ms
- CROSS SECTION, SHOWING STRESS in PLATE

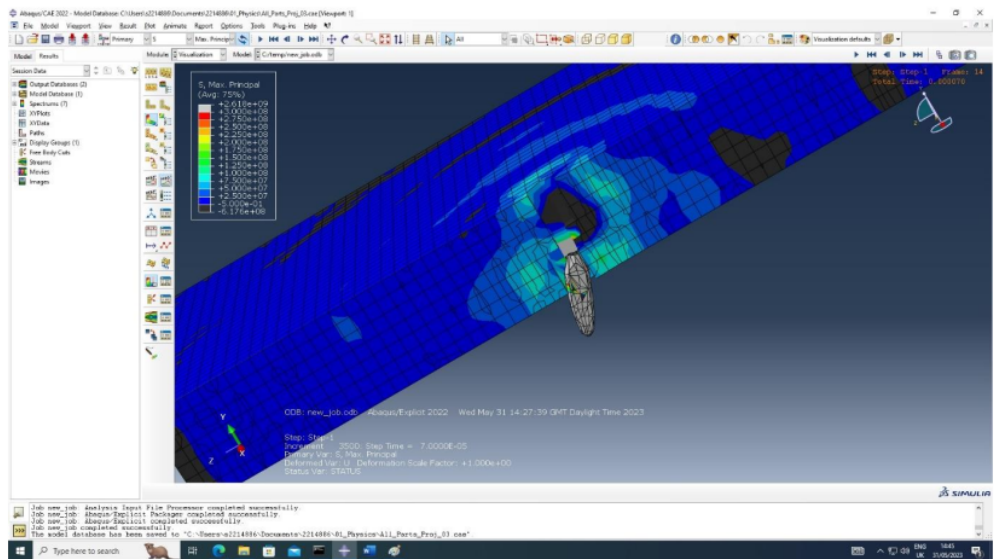


Image 14: 20230531 7.62mm representative round (Steel), Plate (Aluminium) 800ms
- CROSS SECTION, SHOWING STRESS in PLATE, ROUND EXITS PLATE

APPENDIX A2 – SHEAR STRESS AND TENSILE STRESS IMAGES

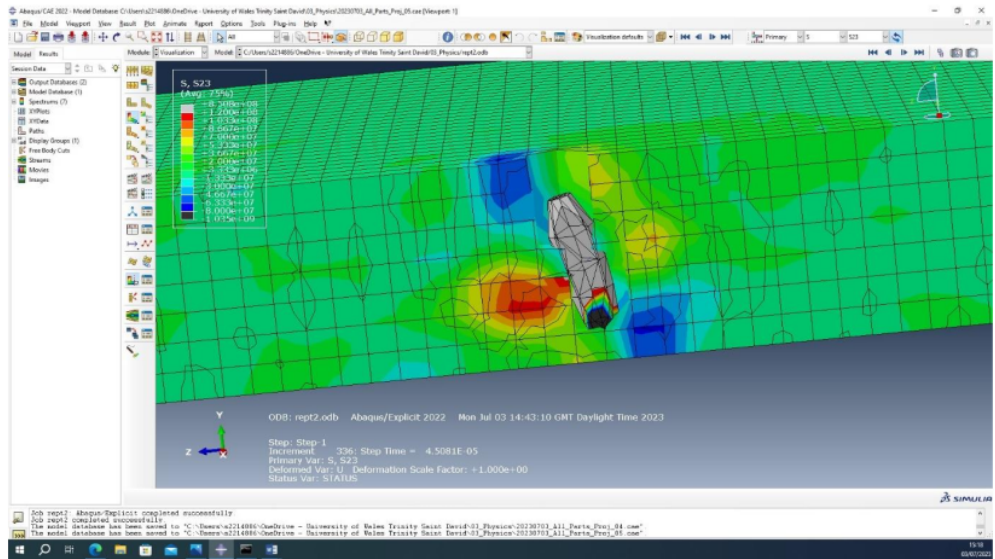


Image 15: 20230703 7.62mm representative round (Steel), Plate (Aluminium) 800ms - CROSS SECTION, SHOWING **SHEAR STRESS** in PLATE

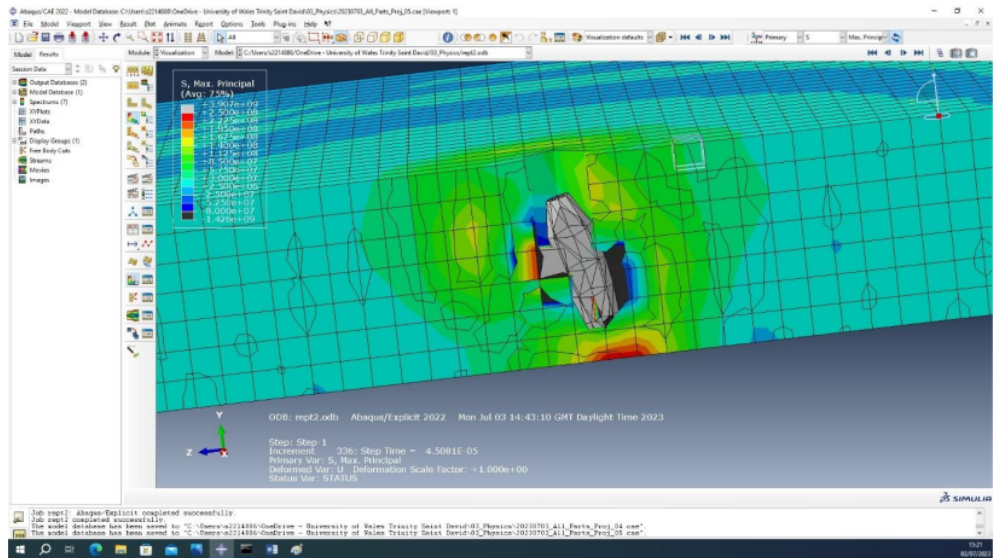


Image 16: 20230703 7.62mm representative round (Steel), Plate (Aluminium) 800ms - CROSS SECTION, SHOWING **TENSILE STRESS** in PLATE

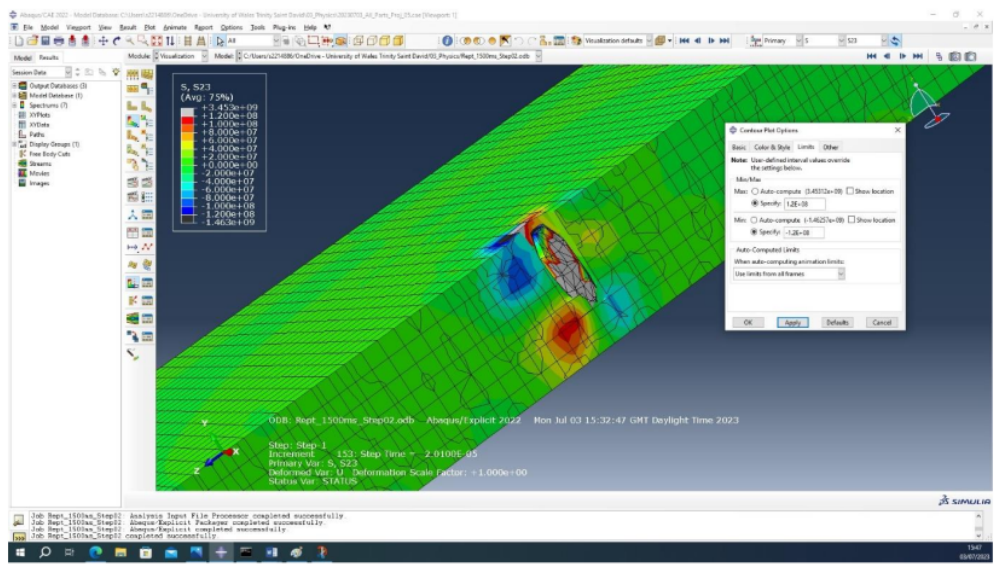


Image 17: 20230703 7.62mm representative round (Steel), Plate (Aluminium)
1500ms - CROSS SECTION, SHOWING **SHEAR STRESS** in PLATE AND ROUND

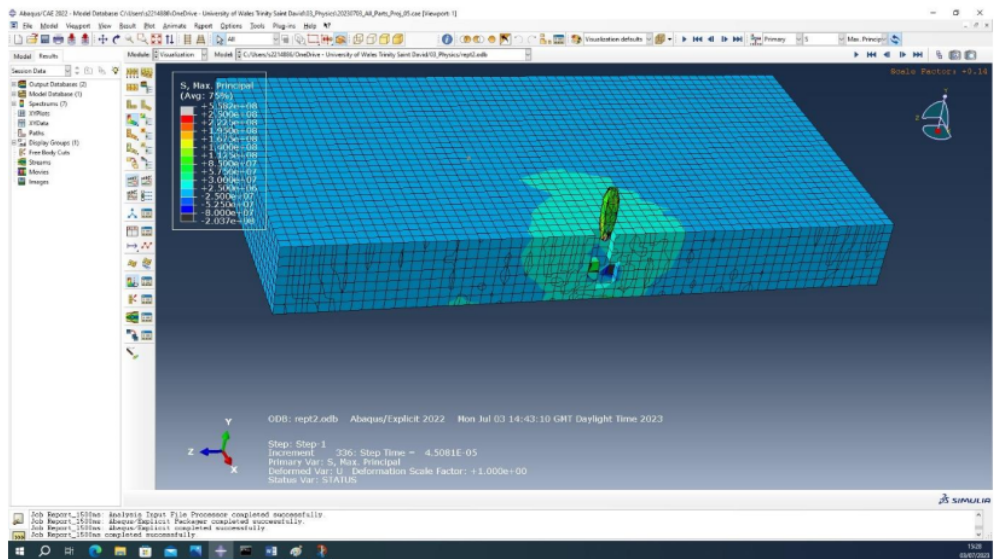
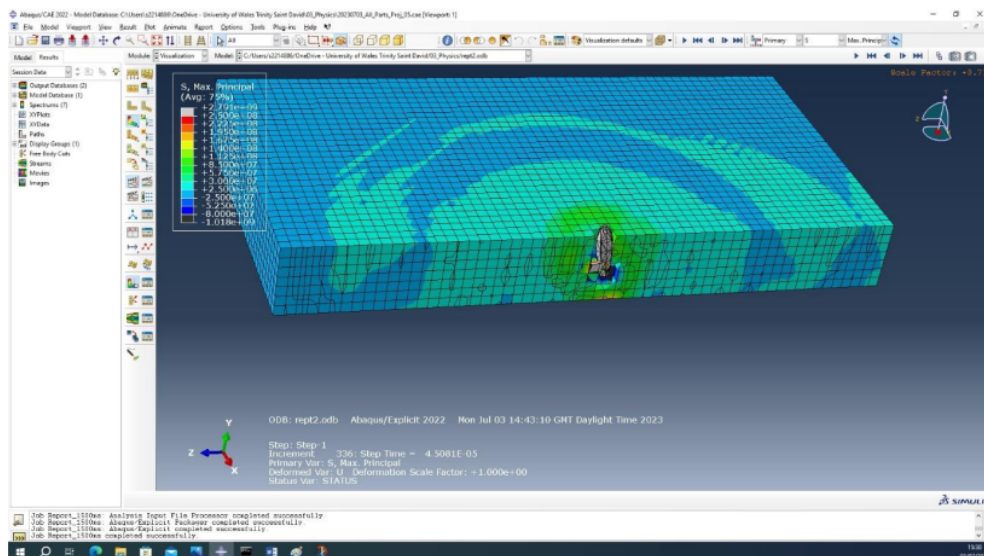
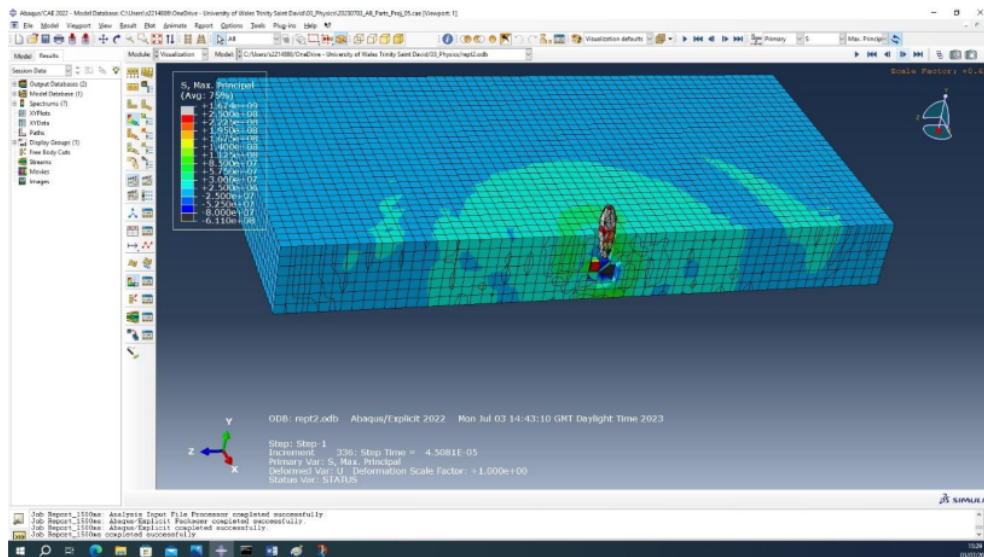
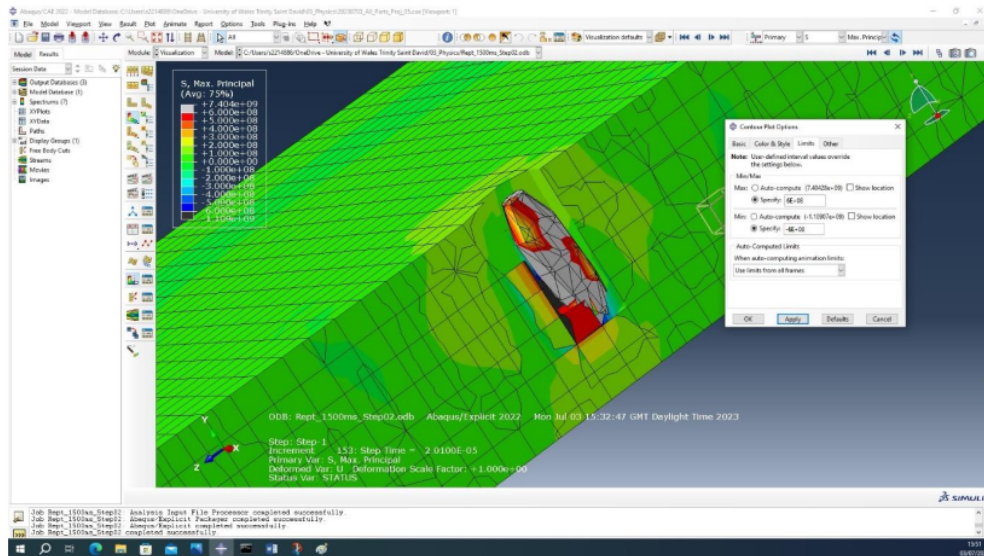
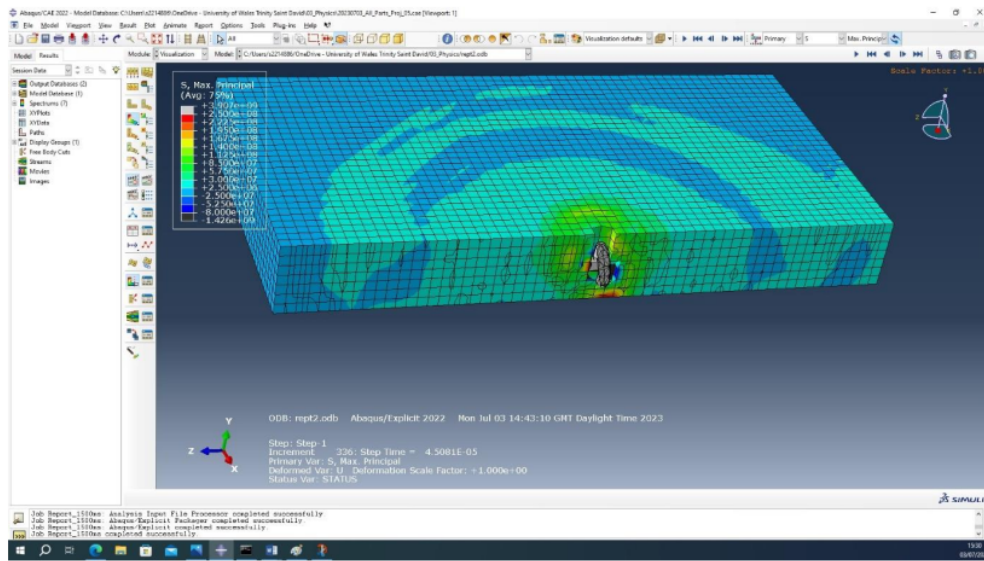


Image 18: 20230703 7.62mm representative round (Steel), Plate (Aluminium)
1500ms - CROSS SECTION, SHOWING **TENSILE STRESS** in PLATE, RIPPLES
OF STRESS in PLATE





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