

Computational modelling of a high-speed ballistic impact of a projectile onto a target plate

Abstract: The following report explores the use of a computational model and examines the ballistic impact of a steel projectile on an aluminium target plate, to discover and identify factors contributing towards failure of the target plate. Key areas of interest are the tensile stress and shear strain elements of the target plate are exposed to, and how these are affected by different velocities of a 7.62 x 51 mm Armour Piercing M2 projectile.

Introduction:

Armour Plating has numerous applications both in the civilian world and within the military environment.

Armour plating has numerous applications in the civilian arena, ranging from use in numerous industries providing security solutions and protection to high value targets, through to use in the aerospace industries [1], as well several **medical** applications. These uses have included production of bank safes, safe-rooms, armoured glass in vehicles, aircraft canopies & windows, alongside provision of defensive protection from threats to public figures and state officials across the world. Medical applications have included joint replacement and use in reconstructive and corrective surgeries.

Within the military environment armour plating has previously been (and continues to be) used to protect military vehicles from impacts caused by bullets, missiles, explosives, and shrapnel. protecting mission critical vehicles and equipment, armour plates are also used by ground troops providing crucial protection to similar threats.

There are numerous materials and armour solutions available. These range from ceramic and Kevlar-epoxy composites, through to monolithic steel plate & HMA (Homogenous Rolled Armour), through to light-weight alloys including titanium alloys (respectively Ti-6AL-V4) [2] and aluminium alloys [3] (respectively 5083, 6061, and 7039 within the United States).

1. Research

Research has been conducted into the ballistic resistance of monolithic, composite, ceramic and laminate composite plates, to reduce the overall weight of armour systems, whilst maintaining the integrity and resistance to ballistic impact [1]. There have been dramatic improvements in the field of body armour systems since the 1980s, with the introduction of the Small Arms Protective Insert (SAPI, ESAPI, and subsequent XSAPI) the weight of these systems has also increased [4].

Whilst the armour and protection deployed during the Afghanistan and Iraq conflicts, threats changed as the conflict progressed. It was alleged that armour piercing ammunition was found in both theatres [5], and there were implications in providing further enhanced protection for ground troops. Existing armours during the period from 2003 to 2014 provided some level of protection, however due to the changing nature of the battles being fought, troops, tactics and vehicles faced multiple threats which needed to be addressed.

Therefore, finding a solution to reducing weight of body armour plates, and identifying lighter weight armour materials would be a natural progression from existing protection deployed in theatres at this time.

Hardened steel plates, despite their heavy weights, are predominantly used for ballistic protection under rifle bullet threats. Although commercial monolithic steel plates could be manufactured to a large thickness, they may not meet the design needs of certain thickness and multiple thinner plates are used to meet design specifications. Additionally, multi-layer plates may provide flexibility to users in terms of maintenance and mobility [1].

There are materials which provide similar protective characteristics to hardened steel plates, which weigh less than steel, and less than the existing SAPI plates (including the three mentioned alternatives).

When a projectile impacts on a surface there are certain features which can be identified as characteristic of a ballistic, or high-speed impact. The projectile may cause *spalling* around the surface where it has struck the object. The impact may leave a *spall crater* and produce *fragmentation* from either the surface of the object, or from the projectile itself (depending on which is harder, what force is greater, etc). There is the possibility *scabbing* may occur behind the impact surface, which is characteristic of HESH (High Explosive Squash Head) ammunition [6] used by Anti-tank platoons by members of NATO. and *penetration/perforation* may take place [7].

Understanding how projectiles can impact and affect materials such as armour plates, what happens when they do, and what characteristic features to look at, are beneficial when looking at the computational model produced.

2. The Model

This report examines the effects that speed has on a steel projectile impacting on an aluminium plate. The two factors identified in APM2 munitions were the velocity of the projectile and the material it is made from.

Computational modelling

The programme used to complete the models was ABAQUS by Dassault Systèmes. This programme uses the Johnson Cook models to create the visual representation of the simulation. There are several component parts of the equation, which relate to the shear stress and fracture strain, combined with the plasticity and hardening of the materials used. This can also be used to compare the **shear stresses** that the materials are subject to, and the strain under which they fracture.

Shear stress can be explained as the force causing deformation of a material along a plane which is parallel to the force imposed [8].

Fracture Strain relates to the elasticity of an object or material. When an object is exposed to a force which pushes the material past its elastic limit, it will result in permanent deformation and fracture [9]. Hooke's Law applies to the materials involved, to the extent that when a force is applied to the object, it will extend some distance depending on the cross-sectional area and constants involved.

With regards to metals and metal alloys, these are expected to bend and deform, as they are **not typically elastic, whereas with rubbers, they would be expected to return to their original shape (or close to it)**.

With regards to the Johnson-Cook models, Young's Modulus refers to the ratio of tensile stress (σ) to tensile strain (ϵ).

The Johnson Cook Damage Model is explained below:

$$\bar{\epsilon}_f^{pl} = \left[d_1 + d_2 \exp\left(d_3 \frac{p}{q}\right) \right] \left[1 + d_4 \ln\left(\frac{\dot{\bar{\epsilon}}^{pl}}{\dot{\epsilon}_0}\right) \right] (1 + d_5 \hat{\theta})$$

The Johnson Cook Material Model can be found below:

$$\bar{\sigma} = (A + B\bar{\epsilon}^{-n}) \left[1 + C \ln \left(\frac{\dot{\bar{\epsilon}}}{\dot{\bar{\epsilon}}_0} \right) \right] \left(\frac{\dot{\bar{\epsilon}}}{\dot{\bar{\epsilon}}_0} \right)^{\alpha} (D - ET^*m)$$

Materials

Following research, it was determined to test a readily available and common munition against existing and known vehicle armour (Specifically AA5083-H116 Aluminium Plate).

Projectile

The steel projectile is based on the 7.62 x 51 Armour Piercing Round (APM2) hardened steel core round, used by NATO (North Atlantic Treaty Organisation) forces in numerous conflicts.

Armour plate –

The Aluminium plate is based on an AA5083-H116 Aluminium Plate, which was first developed during the Vietnam War as a solution to improve weight of armoured vehicles & enhance mobility and has been used in different types of vehicle armour since [10].

The Johnson Cook parameters for both the steel projectile and Aluminium Armour Plates, was located and input for each of the materials accordingly. The data and information can be found in Table 1 below:

Parameter	Symbol (Unit)	Aluminium	Steel [11]
		AA5083-H116	7.62 mm APM2
Johnson-Cook Model Density	Ro (kg/m ³)	2700	7850
Shear Modulus	G (Pa)	2.69 x 10 ¹⁰	8.18 x 10 ¹⁰
Young's (Elastic) Modulus	E (Pa)	70 x 10 ⁹	20.9 x 10 ¹⁰
Poisson's Ratio	PR	0.3	0.28
Yield Stress	A (Pa)	1.67 x 10 ⁸	7.92 x 10 ⁸
Hardening Constant	B (Pa)	5.96 x 10 ⁸	5.1 x 10 ⁸
Strain Rate Constant	C	0.001	0.014
Thermal Softening Exponent	M	0.859	1.03
Hardening Exponent	N	0.551	0.26
Melting Temperature	TM (K)	893	1790
Room Temperature	TR (K)	300	300
Ref: Strain Rate	EPSO (s ⁻¹)	1	1
Specific Heat	CP (Jkg ⁻¹ K ⁻¹)	910	477
Pressure Cut-off	PC (Pa)	-1.5 x 10 ⁹	-
Failure Parameter	D1	0.0261	0.05
Failure Parameter	D2	0.263	3.44
Failure Parameter	D3	-0.349	-2.12
Failure Parameter	D4	0.247	0.002
Failure Parameter	D5	16.8	0.61
Add erosion model			

Max Effective Strain at failure	EFPEPS	2	2.1
EOS ⁵ linear polynomial			
Bulk modulus	Cl (Pa)	5.83×10^{10}	1.59×10^{11}

Table 1.

3. - Construction:

The simulation was conducted using ABAQUS (2022). The model itself was constructed in stages as individual parts, and then assembled. Characteristics and sizing were attempted to be close to existing samples as possible.

Understanding Stress and strain in relation to the materials used in the model is crucial to understanding how they perform and what pressures they are put under. Using a computational model of this scenario helps us to understand how these materials will perform and predicts exactly how the materials will interact with each other.

3.1 - Plate:

The plate was constructed and meshed first. It was allocated the data related to AA5083-H116 Aluminium: dimensions were set at 100mm x 100mm, with a depth of 20mm. This is shown in figure 1.

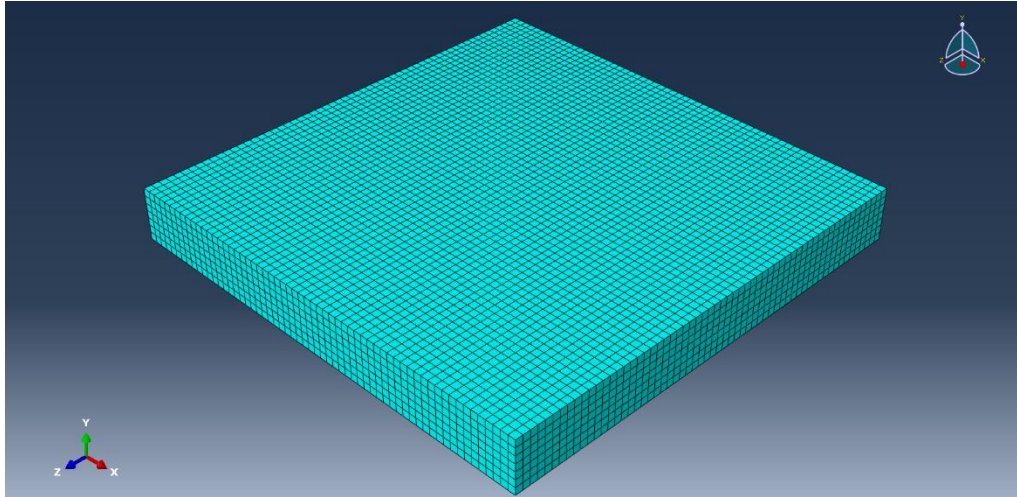


Figure 1.

3.2 - Projectile

The projectile was constructed and meshed. It was sized to simulate a 7.62mm APM2 projectile. It was allocated the properties of the steel core of the munition & meshed accordingly.

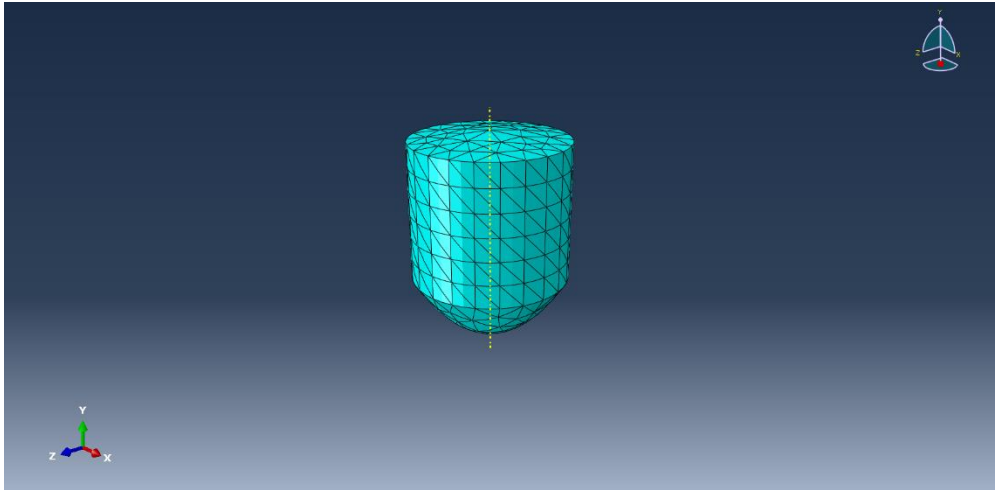


Figure 2.

3.3 - Assembly:

With the individual parts completed, the two parts were combined in the Assembly stage, resulting in the below configuration.

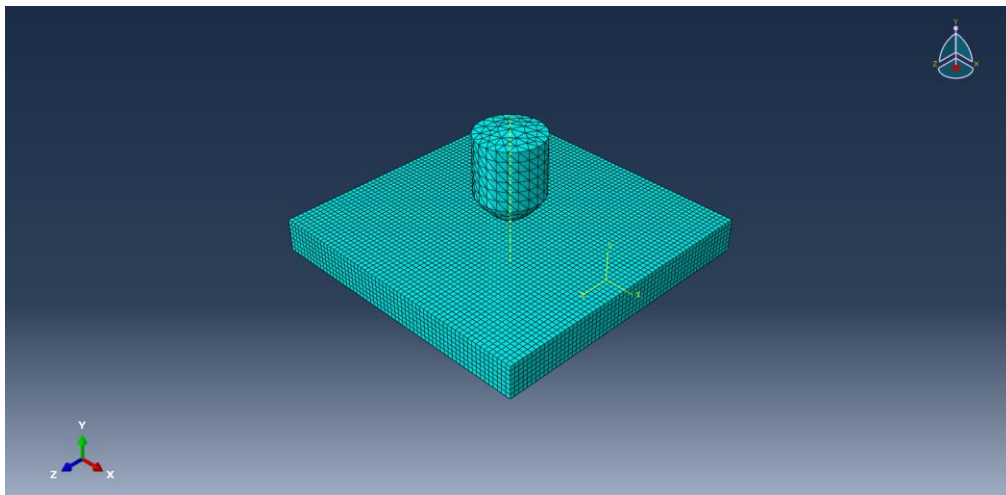


Figure 3.

4. Simulation

The simulation was run to examine the effect of velocity on the projectile and the armour plate. The velocities were chosen based on the standard velocity of the APM2 projectile, and lower speed to simulate a slower velocity projectile of the same material. The materials for both the projectile and the plate were constant, to assess how velocity would affect the tensile and shear stresses the plate was exposed to.

The simulation will examine *maximum principal tension stress*, and the *Shear Stresses* the plate is exposed to at the different velocities. Maximum principal stress can be used to identify areas where failure is likely to occur at perpendicular angles to the direction of stress applied [12]. Shear stress can be used to identify the areas in which the plate is likely to fail, due to the stress applied in the direction the projectile is travelling [8].

4.1 – Simulation run at 950 m/s (meters per second)

Max Principal Tension Stress

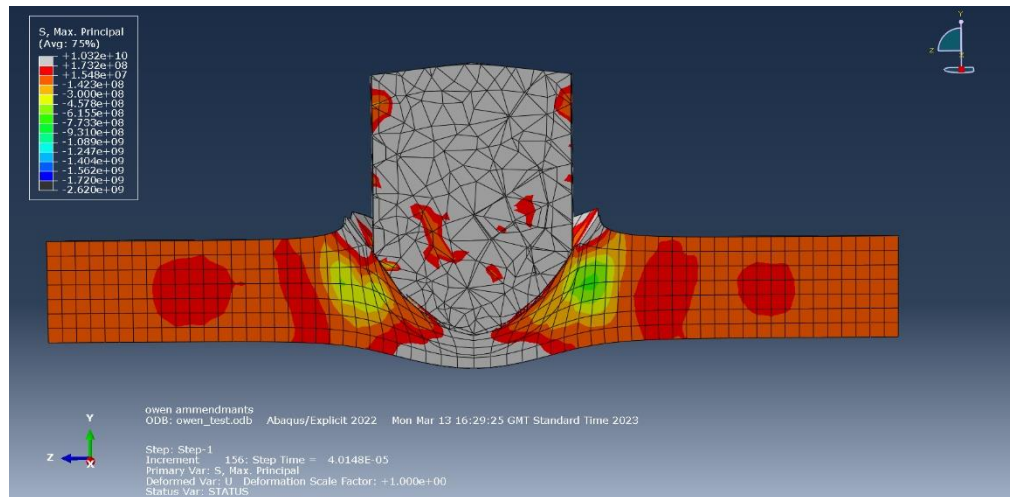


Figure 4.

In the cross section of the simulation, the light-grey areas denote areas under high stress tolerances and give a clear indication of the areas which are likely to fail.

S23 – Shear Stress

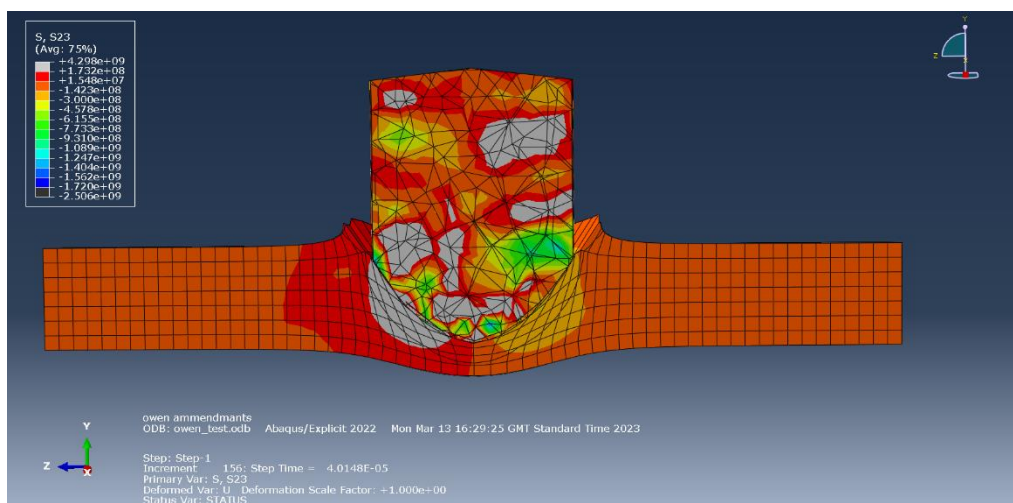


Figure 5.

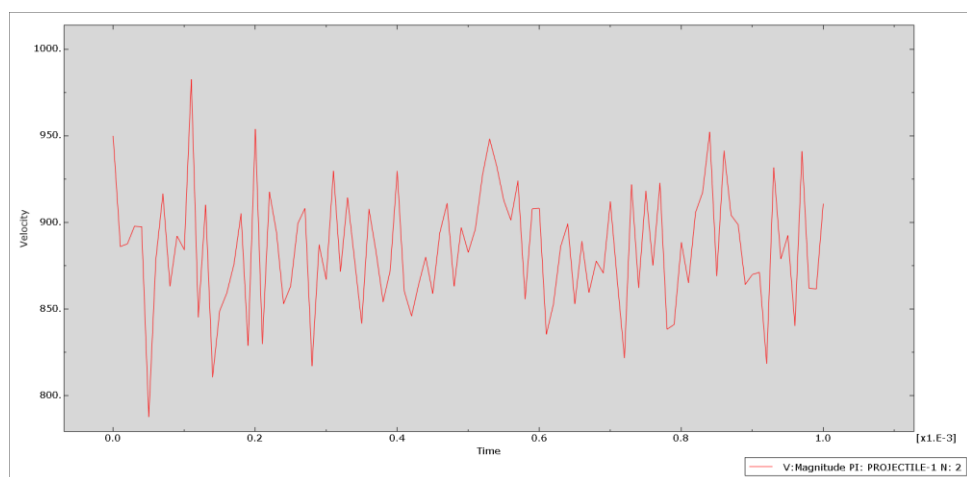
The Shear stress can be seen within the material of the plate in the light-grey area, indicating the point of highest values. Where the boundaries of the colour demarcation change, these can provide an insight as to where the plate is most likely to fail. Whilst the

values of shear stress are highest (where the projectile has impacted on the plate), the boundary between the red and orange colours indicate an area of interest.

If we were to overlay the images of the Max Principal Tension stress and the S23 stress, this can give an indication of where the plate is likely to fracture.

Velocity time Graph

Producing a velocity time graph we can understand how the plate affects the velocity of the projectile. From the velocity graph we are able to see that the projectile is affected to some degree. With an impact speed of 950 m/s, the plate reduces the velocity by approximately 50 m/s. This is expected due to the nature of the APM2 projectile having been designed as an armour defeating capability, intended to penetrate plate armour of this thickness.



Velocity graph 1.

Further images were captured relating to the Max Principal tension stress to illustrate how the plate reacts under the conditions it is exposed to.

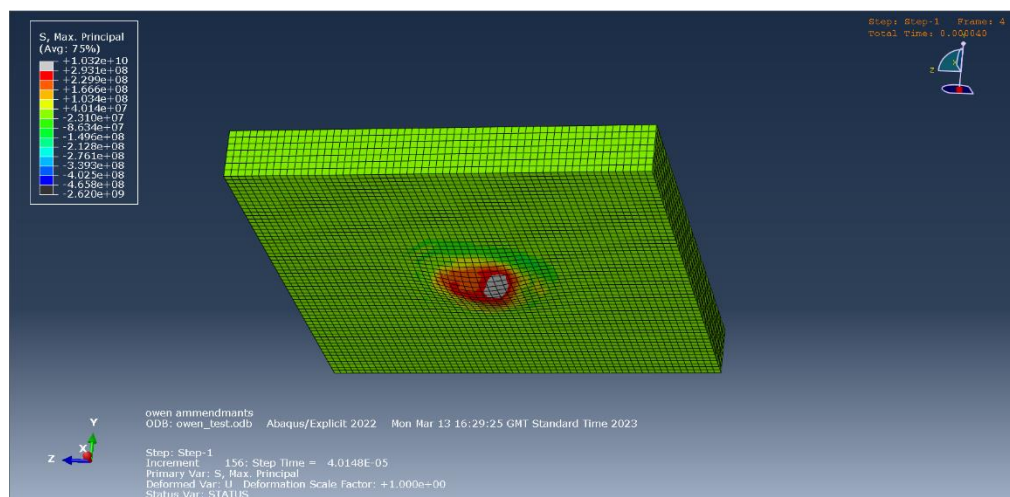


Figure 6.

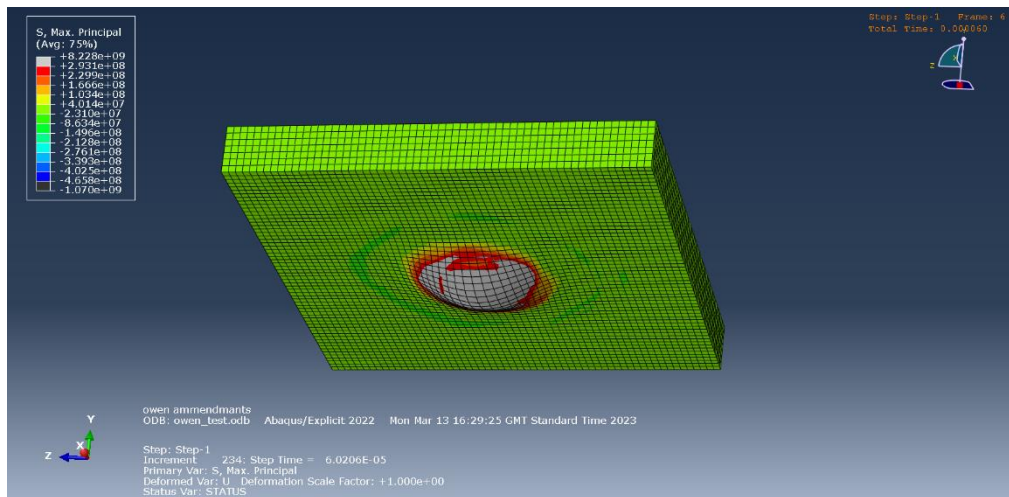


Figure 7.

From these images, we can see the distortion and elasticity of the aluminium through the different stages of the impact, with clear visual indication of high tensile stress areas being highlighted by the light-grey colour.

The images below provide further insight of how the plate is deformed, through to point of failure of the material, from a rear view perspective. It also provides further understanding of how the stresses are localised to the material surrounding the point of impact.

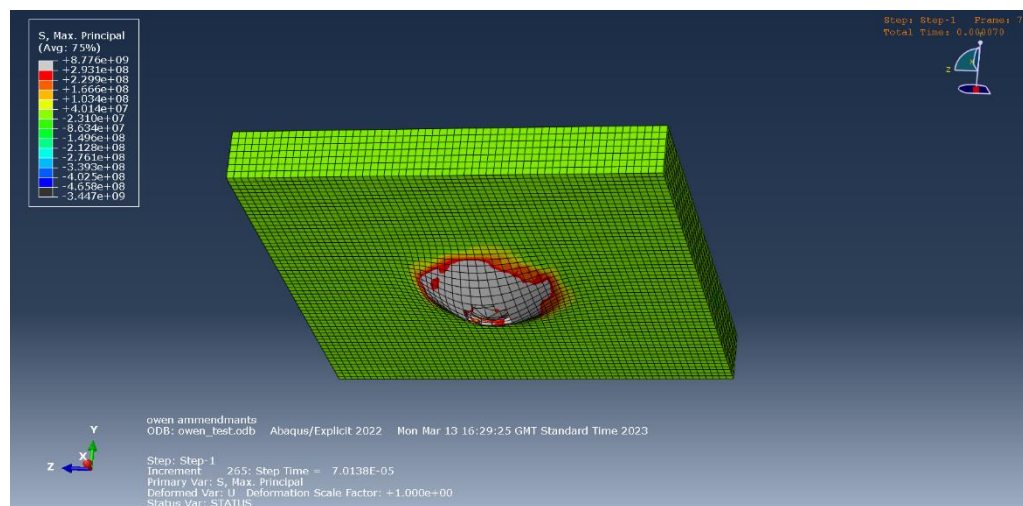


Figure 8.

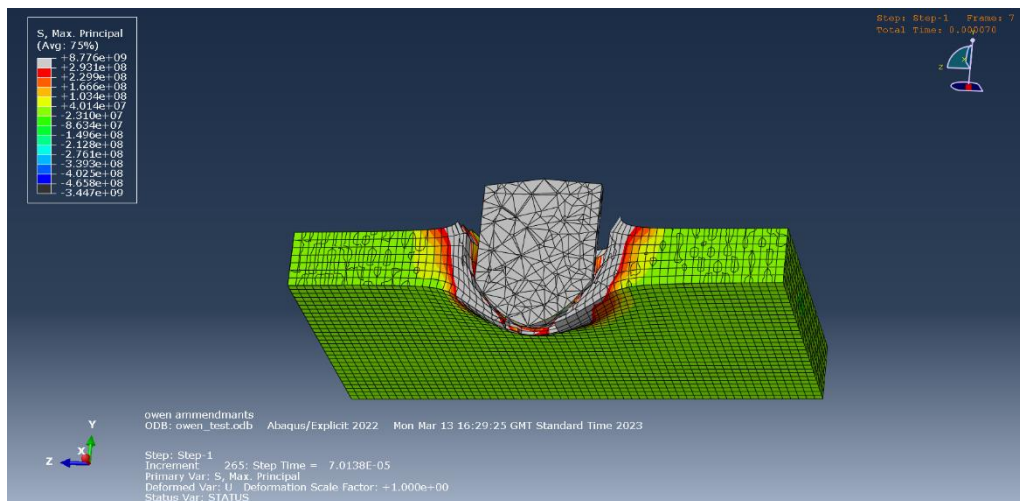


Figure 9.

Figures 10, 11 & figure 12 illustrate how the tensile stress is affected by the velocity of the projectile and the stress the armour plate is exposed to, from just after point of impact, through to the point of failure.

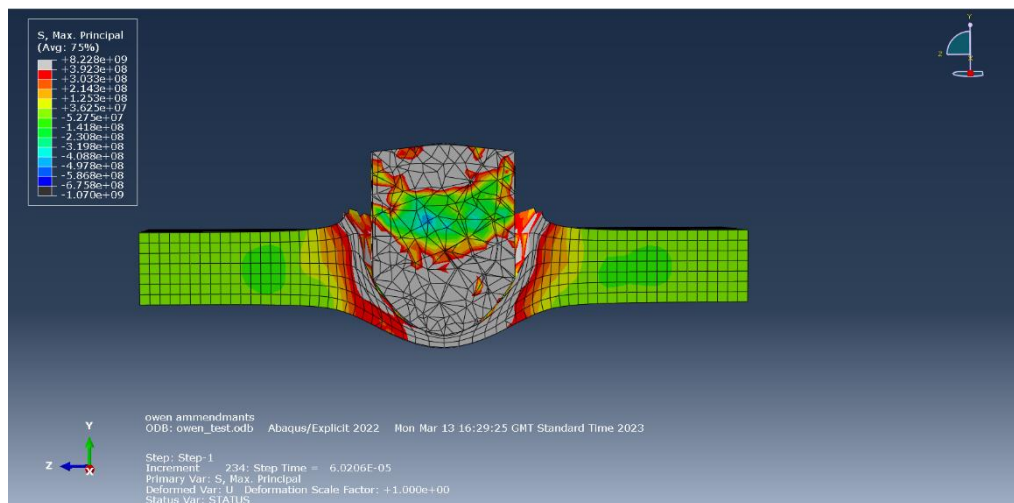


Figure 10.

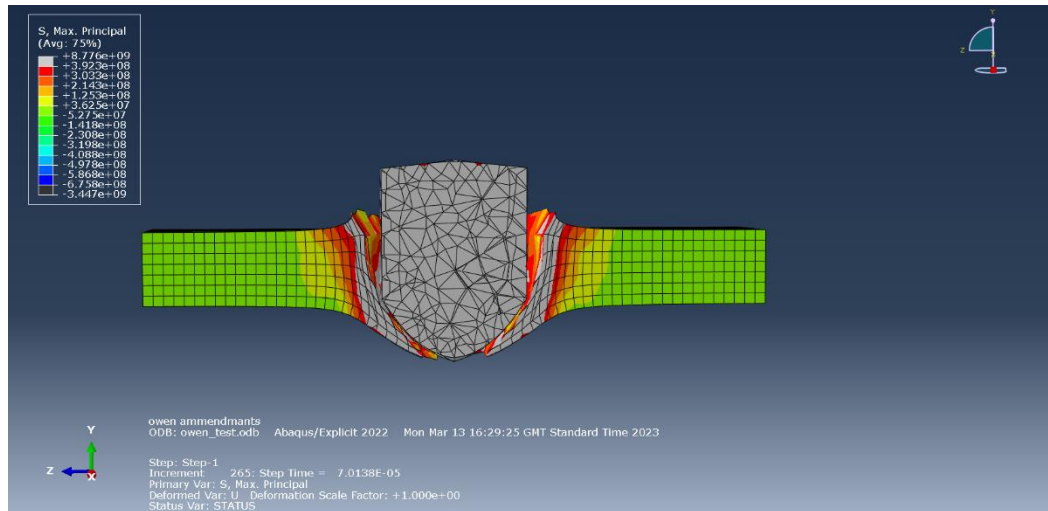


Figure 11.

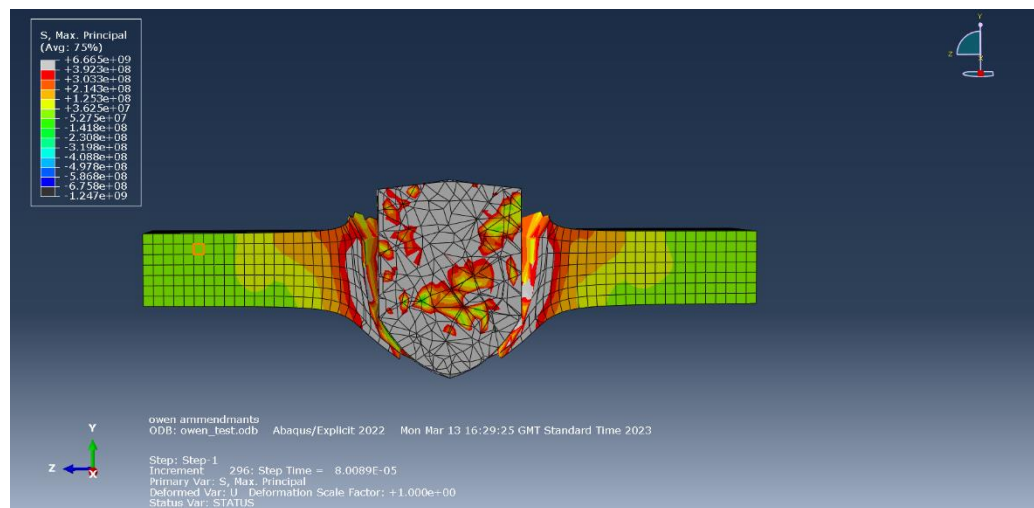


Figure 12.

4.2. - Simulation run at 450 m/s (meters per second)

The simulation was run again with a velocity of 450 m/s. Figure 13 shows the Max Principal Tension Stress and figure 14 illustrates the Shear Stress. Graph 2 shows the velocity of the projectile and how the velocity is affected by the impact with the armour plate.

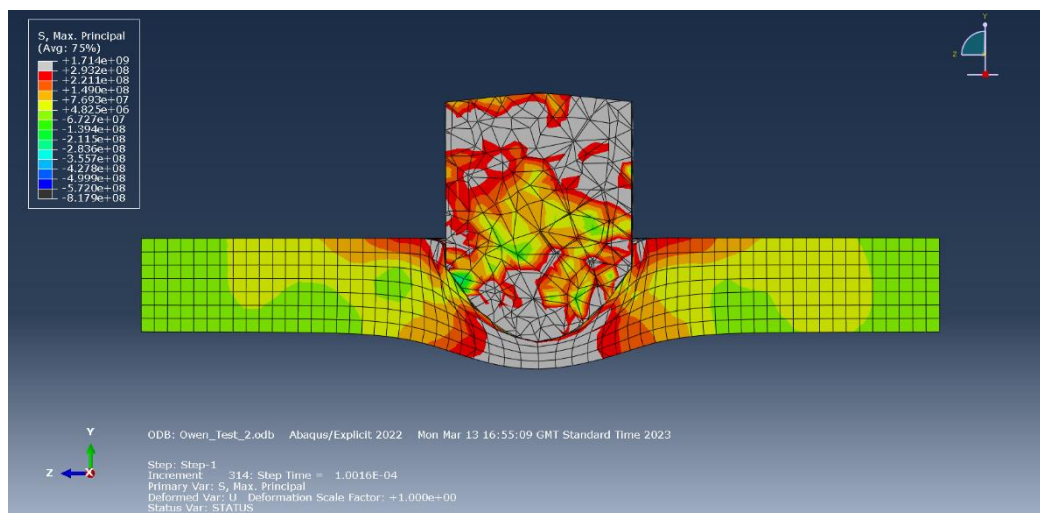
Max Principal Tension Stress:

Figure 13.

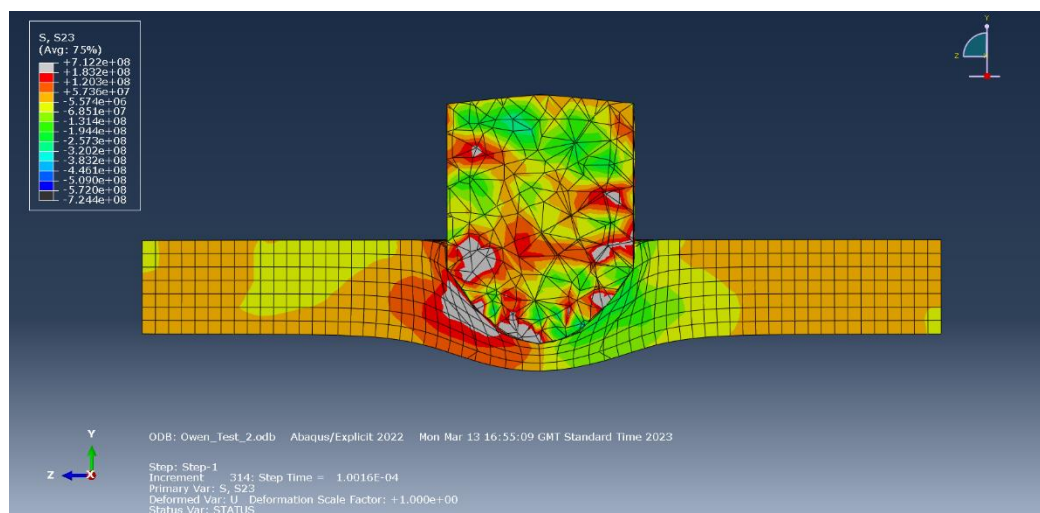
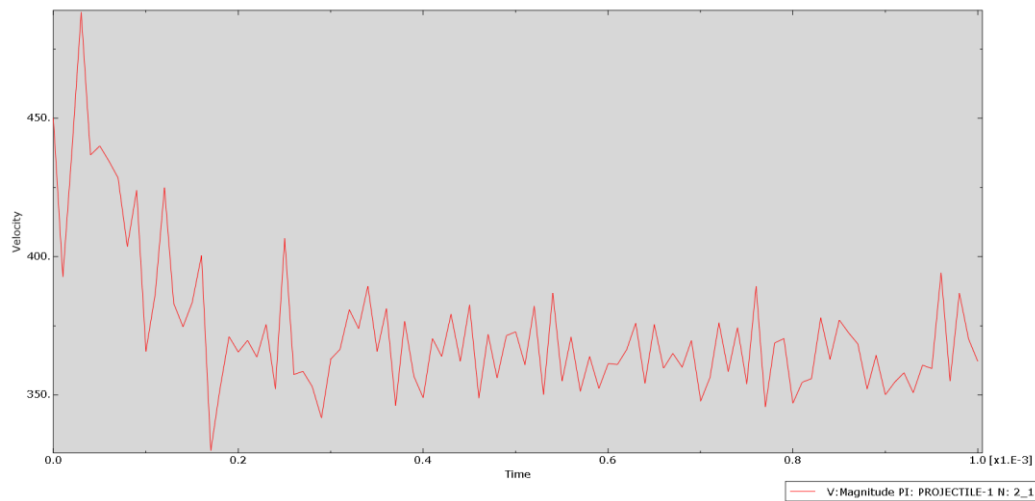
S23 – Shear Stress:

Figure 14.

Velocity Time Graph



Graph 2.

4.2.1 - Point of Failure –

Whilst the projectile is traveling at a lower velocity than the simulation in 4.1, the colour differentiation shows the areas of the armour plate under the relevant stress and strain values. The images in figures 15 and 16 provide further insight into how the plate reacts to the stress it is exposed to, again providing insight to likely points of failure. When these are combined with Figures 17 and 18, we can see where the material fractures, and where the point of failure is likely to be.

Max. Principle – TENSION

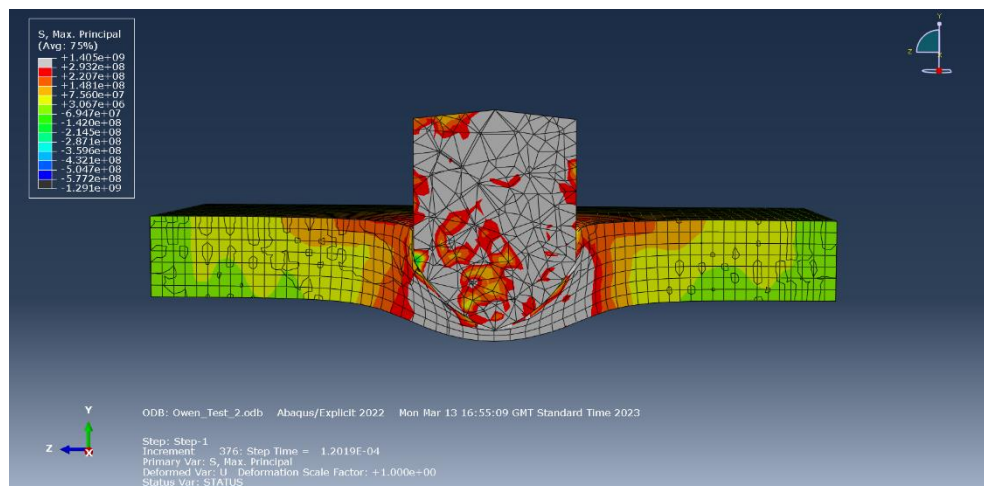


Figure 15.

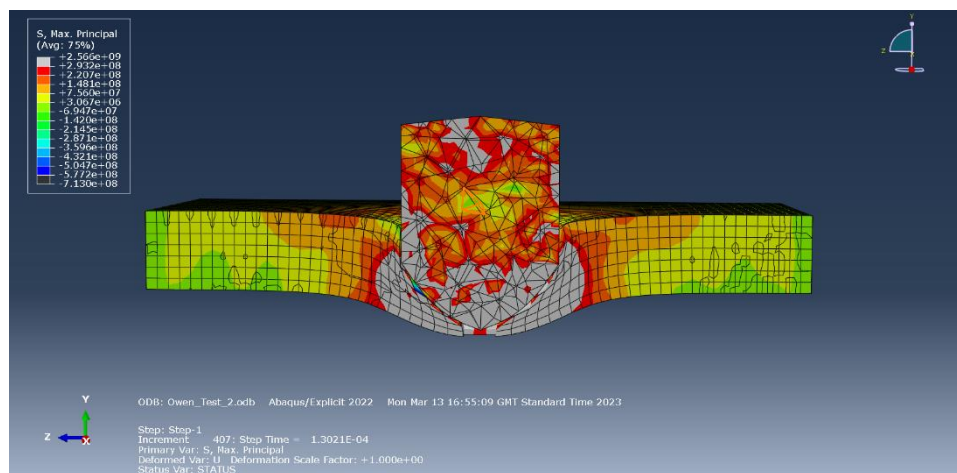


Figure 16.

S23 Shear Stress –

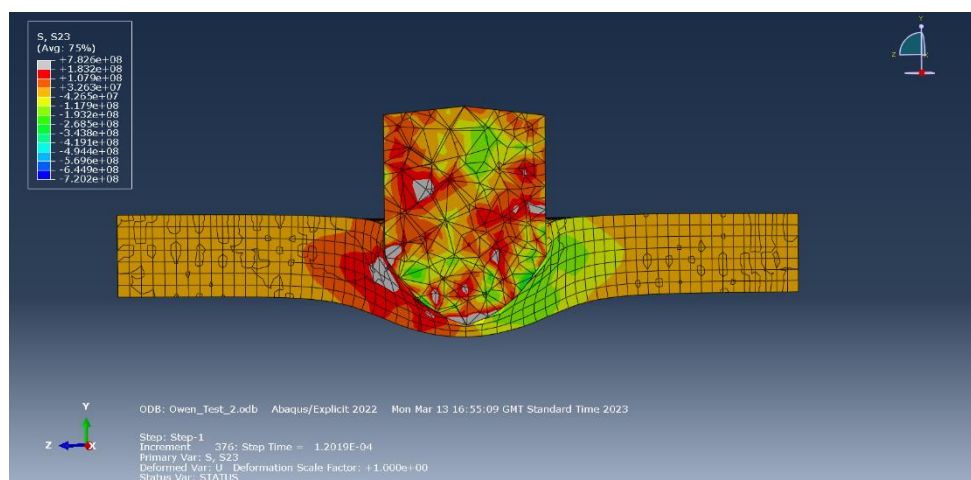


Figure 17.

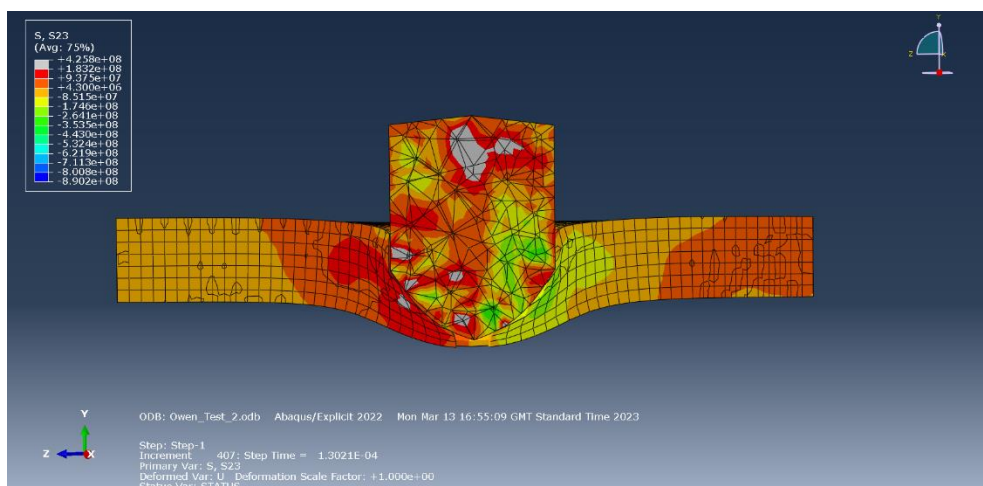


Figure 18.

4.3. – Nodal Evaluation –

The ABAQUS programme can also be used to identify specific nodes from the mesh on the model and show their associated stress and strain values. These can be used to identify areas of the model where failure is likely to occur. These can be seen in Figures 19-23 below.

This can be used to identify the points of highest stress and indicate where the most likely point of failure will be. For example, in this case the point of failure will likely be between the nodes indicated in figures 21 & 22, whereby the respective figures are 4.4738×10^8 Pascals and 4.43283×10^8 Pascals. This point of failure is corroborated by the images in figure 15 and figure 16.

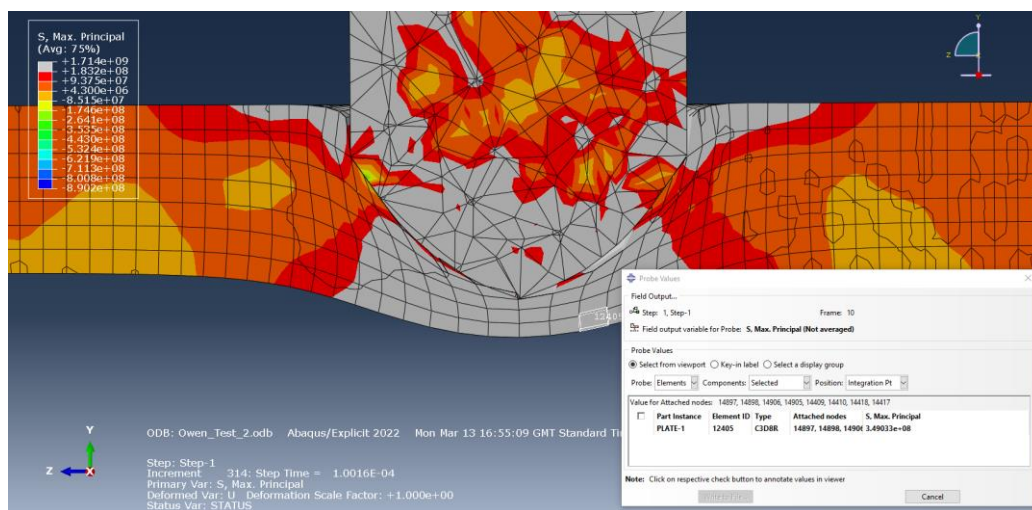


Figure 19.

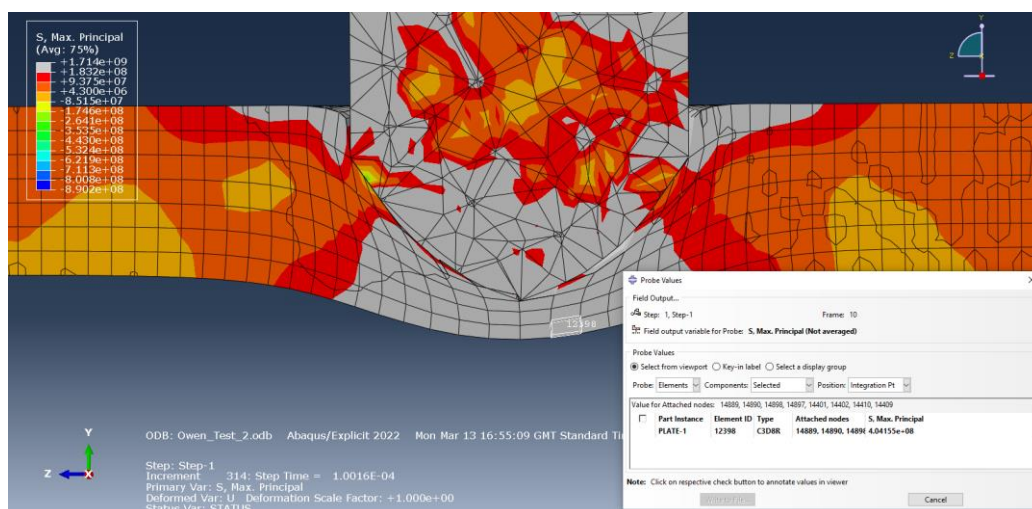


Figure 20.

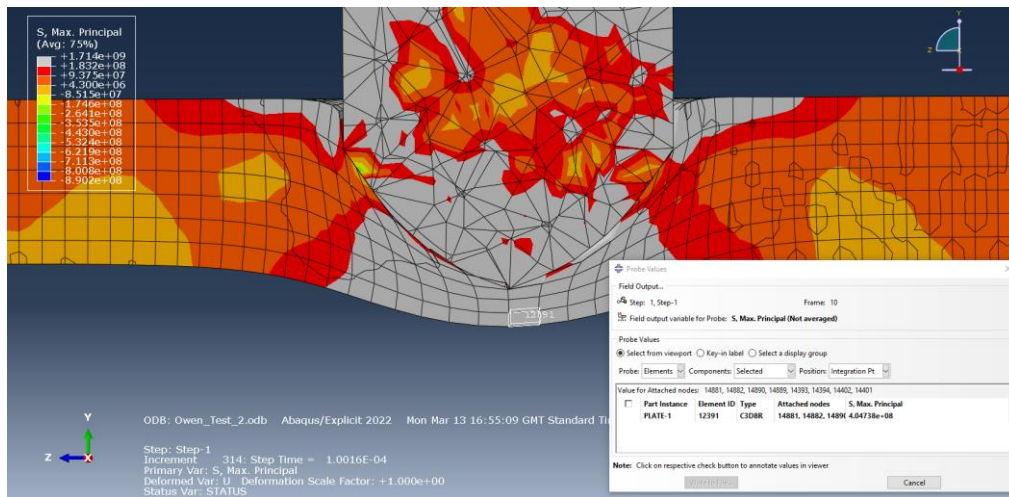


Figure 21.

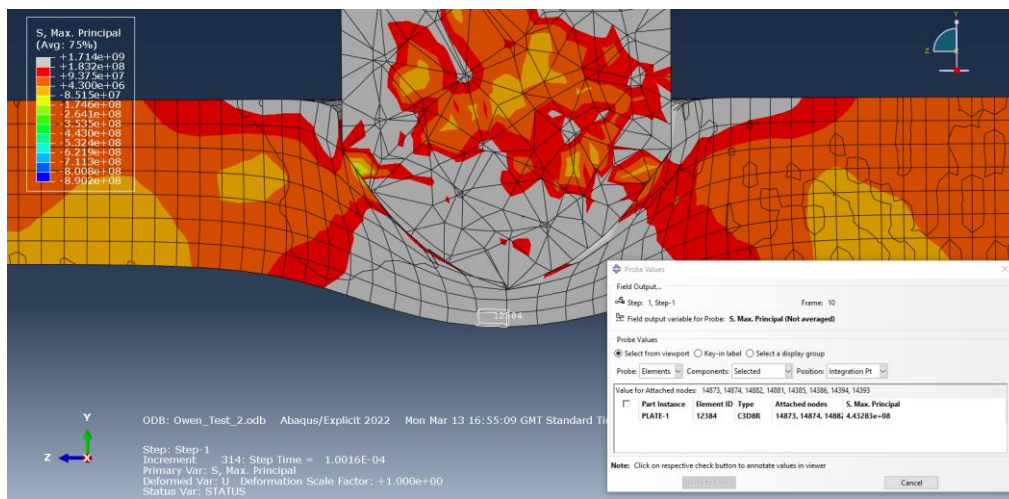


Figure 22.

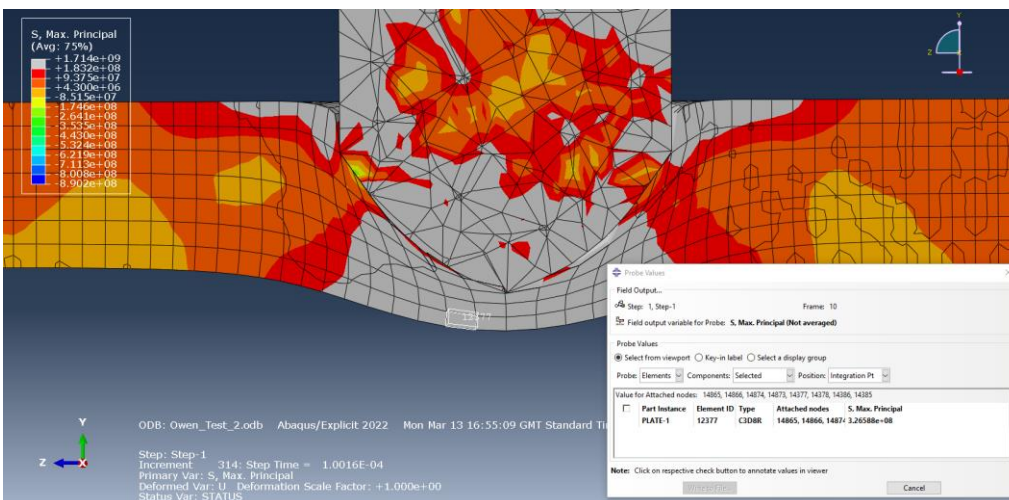


Figure 23.

5. – Conclusion –

The ABAQUS simulation provided a good quality visualisation of how a steel projectile impacted upon an aluminium armour plate. The **computational** model also showed the characteristics associated with a high speed impact, including spalling and associated fragmentation as a result.

The simulation of both the projectile and the armour plate would behave is clearly useful in understanding how the materials behave, along with providing information relating to the tensile stress and shear strain that the materials are subjected to.

Whilst there were limitations with the user's experience of ABAQUS as a programme, it is clear that there are benefits in using this programme to understand how specific materials act.

It has raised questions for further study as to what would happen if the plate was made of a different material (such as another aluminium alloy, or steel), how this would then act if exposed to similar impact. Other questions were also raised as to the shape of the projectile, along with size and material this is made from, and how the maximum **principles** of tensile stress and shear strain would be affected as a result.

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