

DYNAMIC STRESS-STRAIN INVESTIGATION

Investigating the stress properties of selected
ballistic impacts using simulation software.

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Physics

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Abstract

The purpose of this investigation was to use a multi-physics simulation package (ABAQUS) to accurately model a number of ballistic impacts and draw conclusions using established theories in mechanical physics. Three simulations were run involving a high-velocity projectile striking an aluminium plate. The investigation found that the impact between a ballistic projectile and an armour plate invokes high stresses across the plate, but that the plate ultimately fails at the back face, where the tension can hit several giga-pascals of pressure. Shear stresses are also present, but ultimately failure occurs, if at all, due to the magnitude and duration of the tension felt across the plate on impact. The investigation highlighted a number of advantages to using simulation software to carry out these kinds of trials as opposed to a live firing, as well as a handful of drawbacks.

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Introduction

Advantages of Multiphysics Simulation Software

Ballistic trials are expensive, heavily regulated and time consuming. The average trial can take months to prepare, weeks to complete and millions to fund. The associated risk of going ahead with an expensive trial which may not work as intended is sometimes simply too large. The emergence of multi-physics simulation packages has given rise to the possibility of accurately simulating ballistic impacts at a fraction of the cost, and time, of a full trial. Modelling such as this can be used both as

an alternative to a physical trial, or as a justification for having or not having a trial, in which the software can be used to back-up or disprove a hypothesis and determine the next steps in the process.

Mechanical Properties of Materials

The mechanical properties of materials are the key determining factor in how they are used. One of the key properties is stress. Materials undergo two different forms of stress – direct stress and shear stress. Direct stress refers to tension and compression, the pulling and pushing forces that impart pressure on to an object. Tension can cause the brittle failure of materials, causing the object to snap, crack or break apart. Compression, whilst an incredibly strong force, does not usually cause the failure of an object. Shear stresses refer to the pressure created by sliding forces, such as those brought about by the movement of tectonic plates. Failure that is attributable to the shear stresses accumulated on an object is called ductile failure.

Materials all have a pair of mechanical properties known as the ultimate tensile strength (UTS) and maximum shear strength (MSS). Typically, the value of the shear strength is just under 60% of the material's ultimate tensile strength, and both values refer to the specific level of stress above which brittle or ductile failure will occur. These values are important to this investigation as they can be referred to when analysing the results to determine whether or not direct or sheer stresses (or both) are the main cause of failure. All values of UTS used in this investigation are taken using source data, whilst MSS is found using the mathematical extrapolation of $MSS = (60\% \text{ of UTS}) - 25$ [1].

Creating the Material Properties for the Aluminium Plate

Using the model guide provided to start the investigation, the first task was to set up the armour plate that would be the target for all future simulations.

1. Firstly, on ABAQUS, the plate was assigned a new 'section', labelled 'plate section'.
2. A new material was created in ABAQUS. This material was called labelled 'aluminium' and given mechanical properties in line with those of aluminium. Table 1 shows the figures used in this investigation.

Assigned Properties of Aluminium	
Density ¹ (kg/m ³)	2699
Modulus of Elasticity ¹ (GPa)	68
Poisson's Ratio ¹	0.36
Melting Point ¹ (K)	933
Ultimate Tensile Strength ² (Pa)	9×10^7
Maximum Shear Strength (Pa)	5.4×10^7
Yield Stress, A ³ (Pa)	1.67×10^7
Hardening Constant, B ³ (Pa)	5.96×10^7
Strain Rate, C ³	0.001
Thermal Softening Exponent, M ³	0.859
Hardening Exponent, N ³	0.551
Johnson-Cook Damage Parameter D1 ³	0.0261
Johnson-Cook Damage Parameter D2 ³	0.263

¹ Information taken from MatWeb [2]

² Information taken from AmesWeb [3]

³ Information taken from journal article 'Investigation on high-velocity impact performance of multi-layered alumina ceramic armours with polymeric interlayers' [4]

Johnson-Cook Damage Parameter D3³	-0.349
Johnson-Cook Damage Parameter D4³	0.247
Johnson-Cook Damage Parameter D5³	16.8

Table 1: List of mechanical information for aluminium that was used in all simulations.

The information from Table 1 was loaded on to the material properties for ‘aluminium’ as defined in the program, and this formed the basis for every simulation carried out – whereby the same specification aluminium plate was hit.

Simple Impact involving a Steel Bullet

Methodology

The aim of this part of the investigation was to run a simple collision between a steel bullet and an aluminium armour plate to get a clearer picture of how the simulations work, and to look at the stresses in operation during the collision.

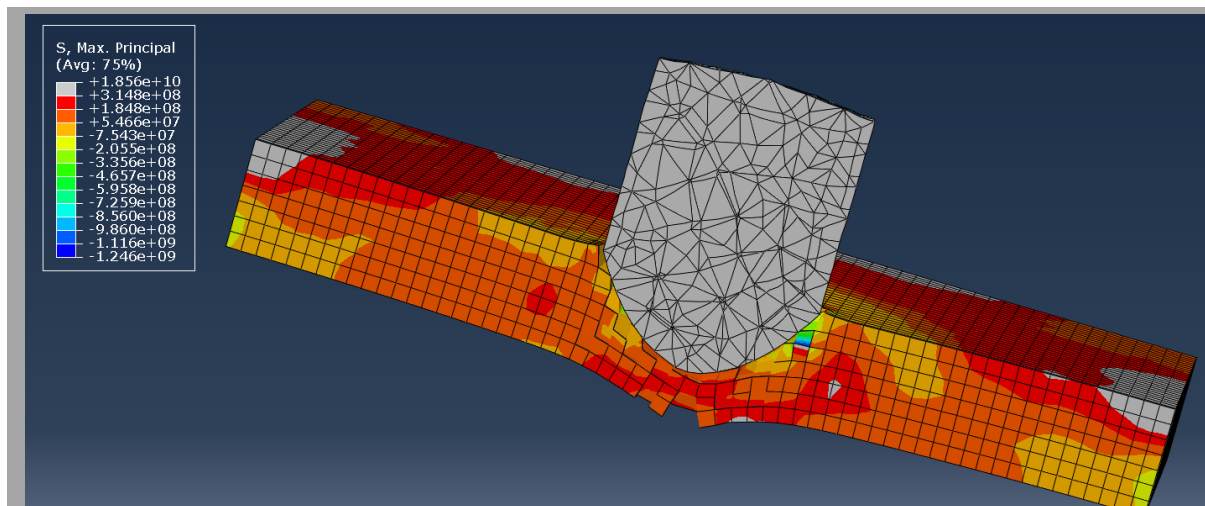
The projectile was assigned a new section called ‘bullet_section’, and was assigned the material ‘steel’, which had been created for the simulation. This was a simple collision, which assumed that the bullet was a uniformly hard object that was not subject to damage parameters. Table 2 describes the values attributed to the steel material.

Assigned Properties of Steel	
Density⁴ (kg/m³)	7872
Modulus of Elasticity⁴ (GPa)	200
Poisson’s Ratio⁴	0.29

Table 2: List of properties used to describe the steel bullet in the first simulation.

Once ready, the job was launched and submitted, and the simulation was run, over a simulated time period of 1×10^{-3} seconds and across 20 discrete ‘steps’.

Observations



⁴ Information taken from MatWeb [5]

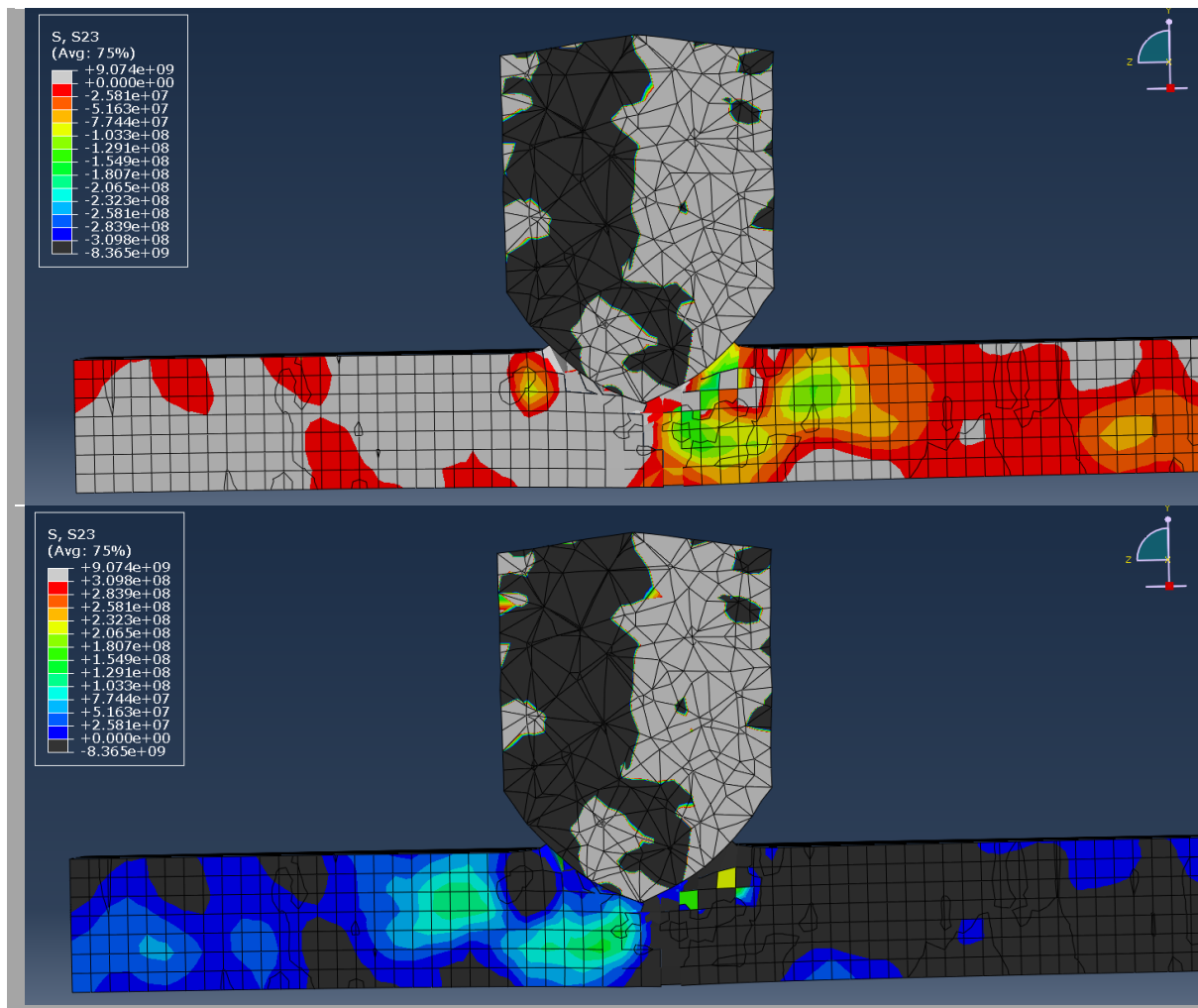


Figure 1: Comparisons of direct and shear stresses at first point of contact between bullet and plate.

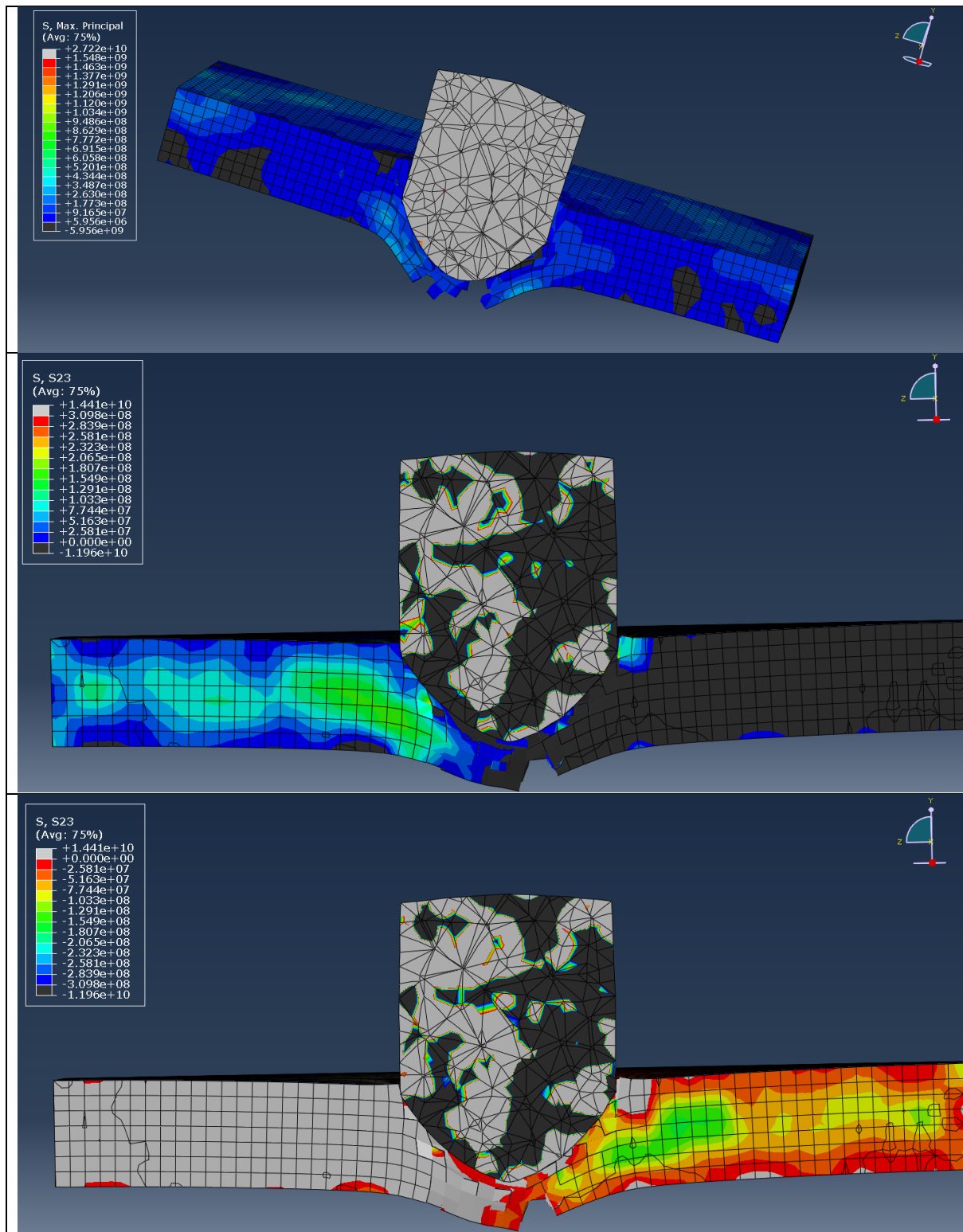


Figure 2: Comparison of direct and shear stresses as failure of the back face of the plate begins.

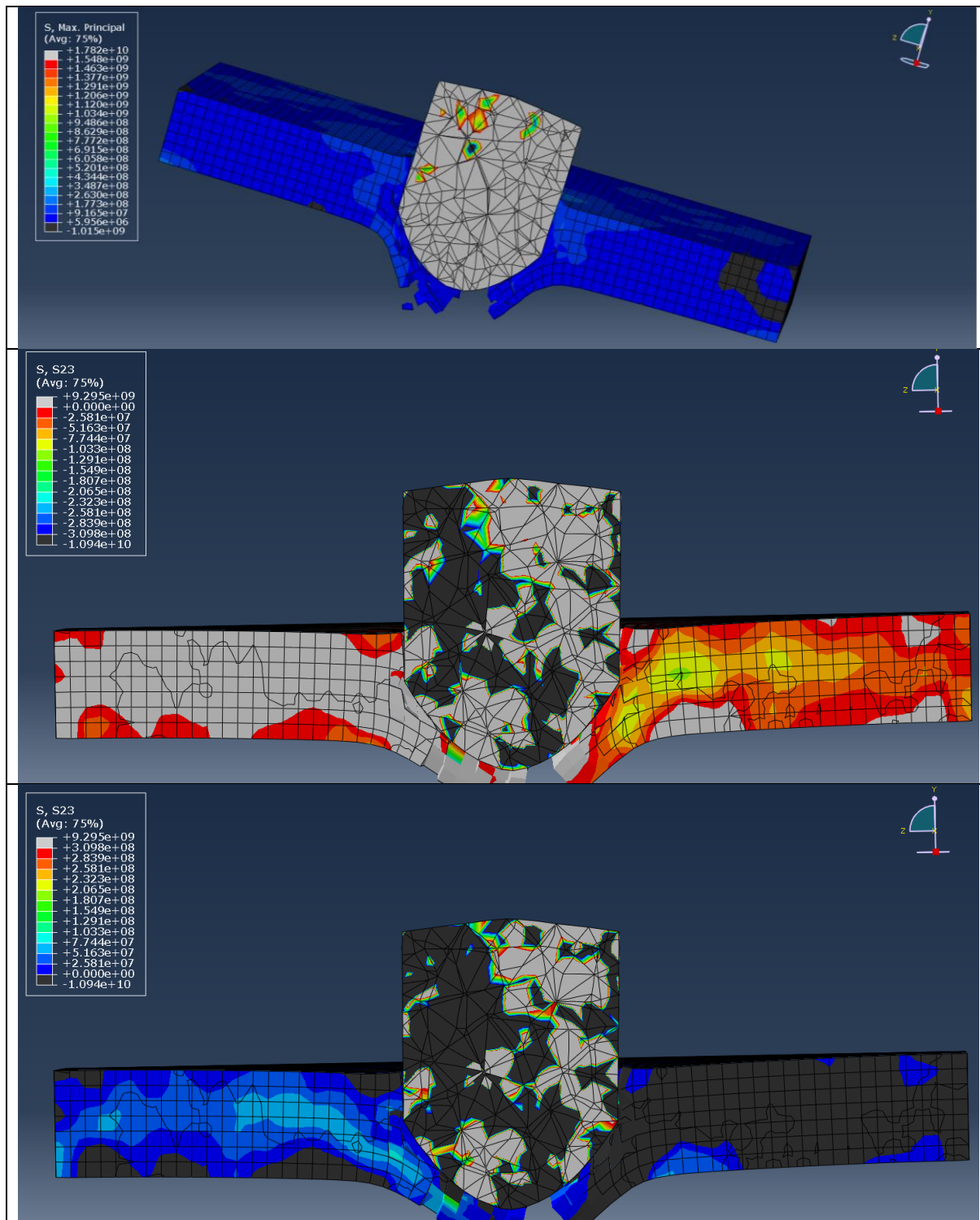


Figure 3: Comparison of direct and shear stresses as the bullet comes to a stop inside the projectile. Failure has reached a maximum and stresses are falling.

Analysis

Figures 1,2 and 3 describe the evolution of stresses as the bullet collides with the plate. From figure 1, it is already possible to predict that the tensile stress imparted on to the back face will cause the failure of the plate. There is a large area around the back face of the plate where the maximum tension acting at that point is well above the UTS of aluminium, peaking at above 184MPa, which is over double the UTS of aluminium (90MPa) as determined from [2].

Whilst figure 1 does also show that there are notable shear stresses on impact, which would cause ductile failure of the plate, the maximum absolute shear stress recorded was around 128MPa, higher than the material's MSS [2], but over a much smaller area than the large potential tensile failure zone.

Figure 2, taken from step 5/20, shows the back face failing. There is noticeable **spooling**, and the tensile stresses at the incident point remain well above the UTS of aluminium – ranging between 95 and 348MPa. In this range, continued failure of the back face is probable. Shear stresses at this point remain high, but have fallen significantly to around 51MPa in the immediate vicinity of the bullet, lower than aluminium's MSS and indicating that any prospect of ductile failure has diminished. At this stage, stresses have propagated across the material, which will cause notable vibrating across the plate.

The resistance placed on the bullet by the plate has caused a major slowdown in the bullet. By figure three, the bullet has settled inside the plate and come to a stop. Once the shear stresses on the plate dropped below that of the MSS of aluminium, the plate was able to slow the bullet to a stop and prevent it from travelling through. At this stage, the tensile stress acting on the back face in the incident area has dropped to between 59 and 90MPa, below the UTS of aluminium, so it would not be expected to see further brittle failure along the back face of the plate. There remains a residual shear stress propagation throughout the material, which has dropped well below the USS of aluminium, and will not cause further ductile failure of the plate.

Complex Impact involving a Steel Bullet

Methodology

In the second simulation, damage values were added to the steel bullet to add further mechanical realism. The steel bullet was, given the full Johnson-Cook damage and plasticity values to more accurately map the damage inflicted on to the bullet during the collision with the plate. Values for the aluminium plate remained unchanged from the first simulation.

Table 3 summarises the new plasticity and damage values assigned to the bullet ahead of the second simulation.

Newly Assigned Plasticity and Damage Properties of Steel	
Melting Point⁵ (K)	1723.15
Ultimate Tensile Strength⁵ (Pa)	50x10 ⁷
Maximum Shear Strength⁵ (Pa)	33x10 ⁷
Yield Stress, A⁵ (Pa)	35x10 ⁷
Hardening Constant, B⁵ (Pa)	27.5x10 ⁷
Strain Rate, C⁵	0.022
Thermal Softening Exponent, M⁵	1
Hardening Exponent, N⁵	0.36
Johnson-Cook Damage Parameter D1⁵	0.8
Johnson-Cook Damage Parameter D2⁵	2.1
Johnson-Cook Damage Parameter D3⁵	-0.5
Johnson-Cook Damage Parameter D4⁵	0.0002
Johnson-Cook Damage Parameter D5⁵	0.61

⁵ Information taken from PhD thesis 'Simulation of ballistic impacts on armoured civil vehicles' [6]

Table 3: Summary of the additional plasticity and damage values added to the steel bullet ahead of the second simulation on ABAQUS.

Once the new values were added to the steel bullet, the second simulation was sent for running, once again over a period of 1×10^{-3} seconds.

Observations

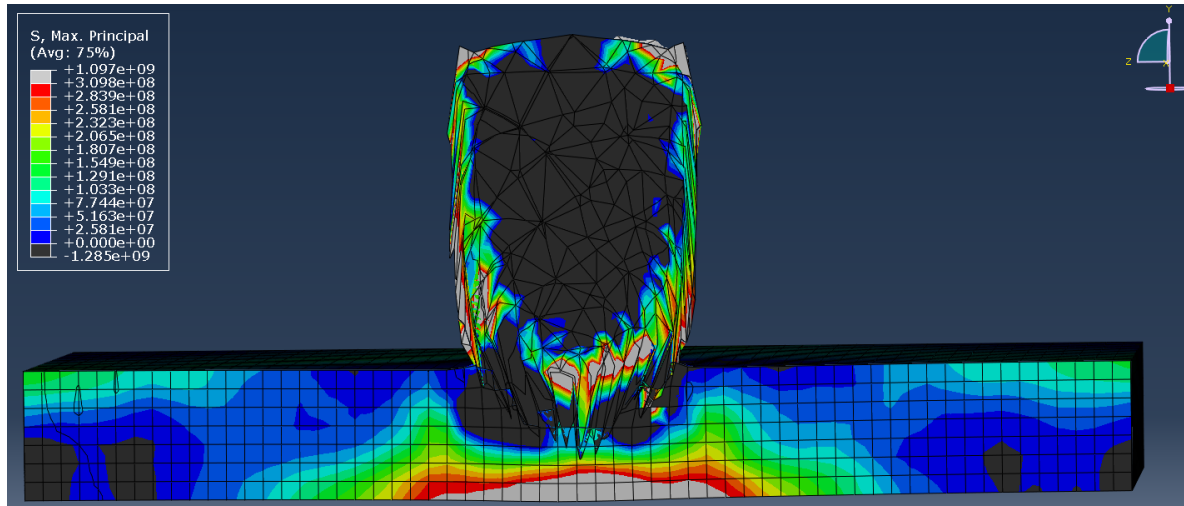


Figure 4: Demonstration of the maximum stresses acting on the aluminium plate at the first point of impact.

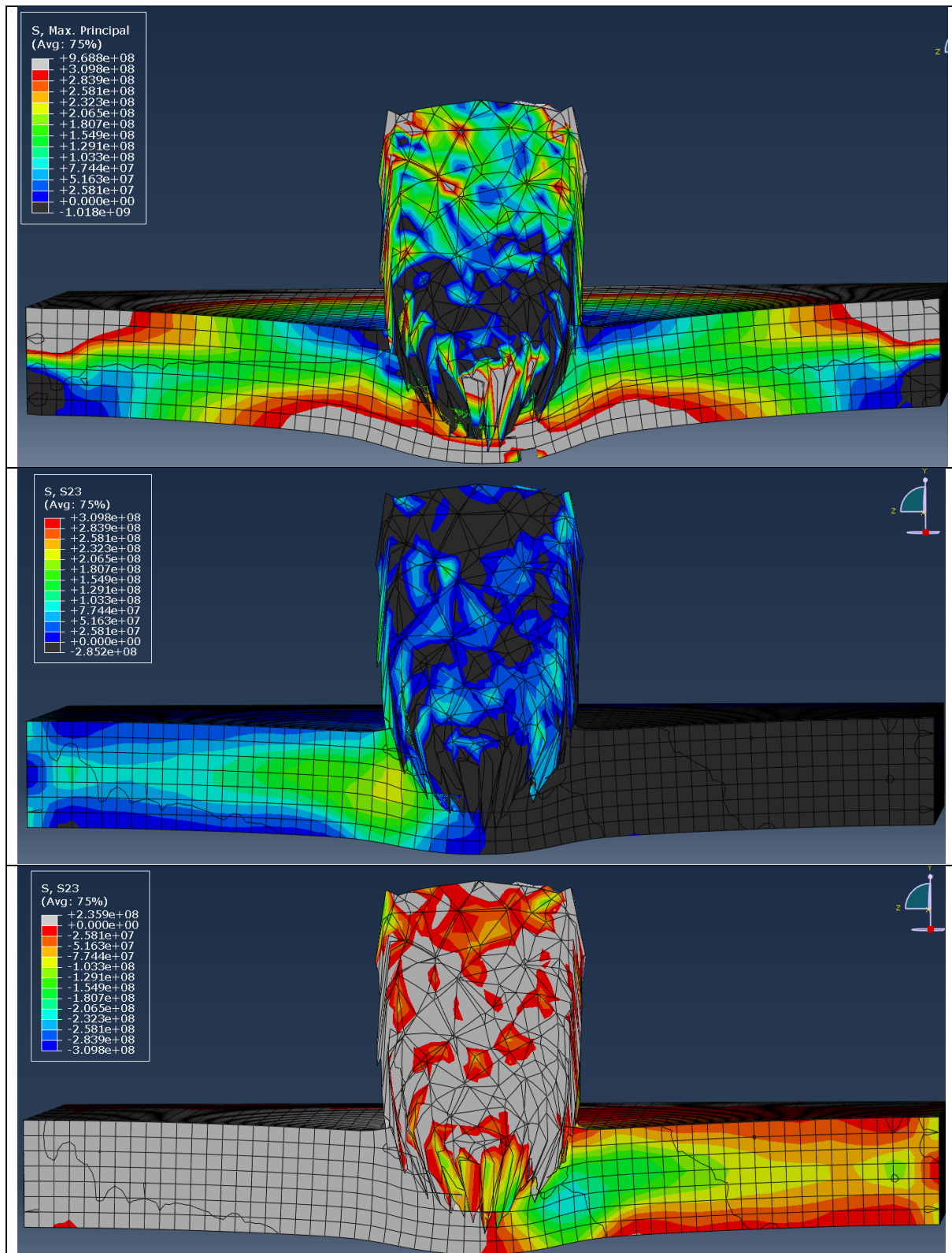


Figure 5: Comparison of direct and shear stresses acting on the aluminium plate and steel bullet shortly after impact.

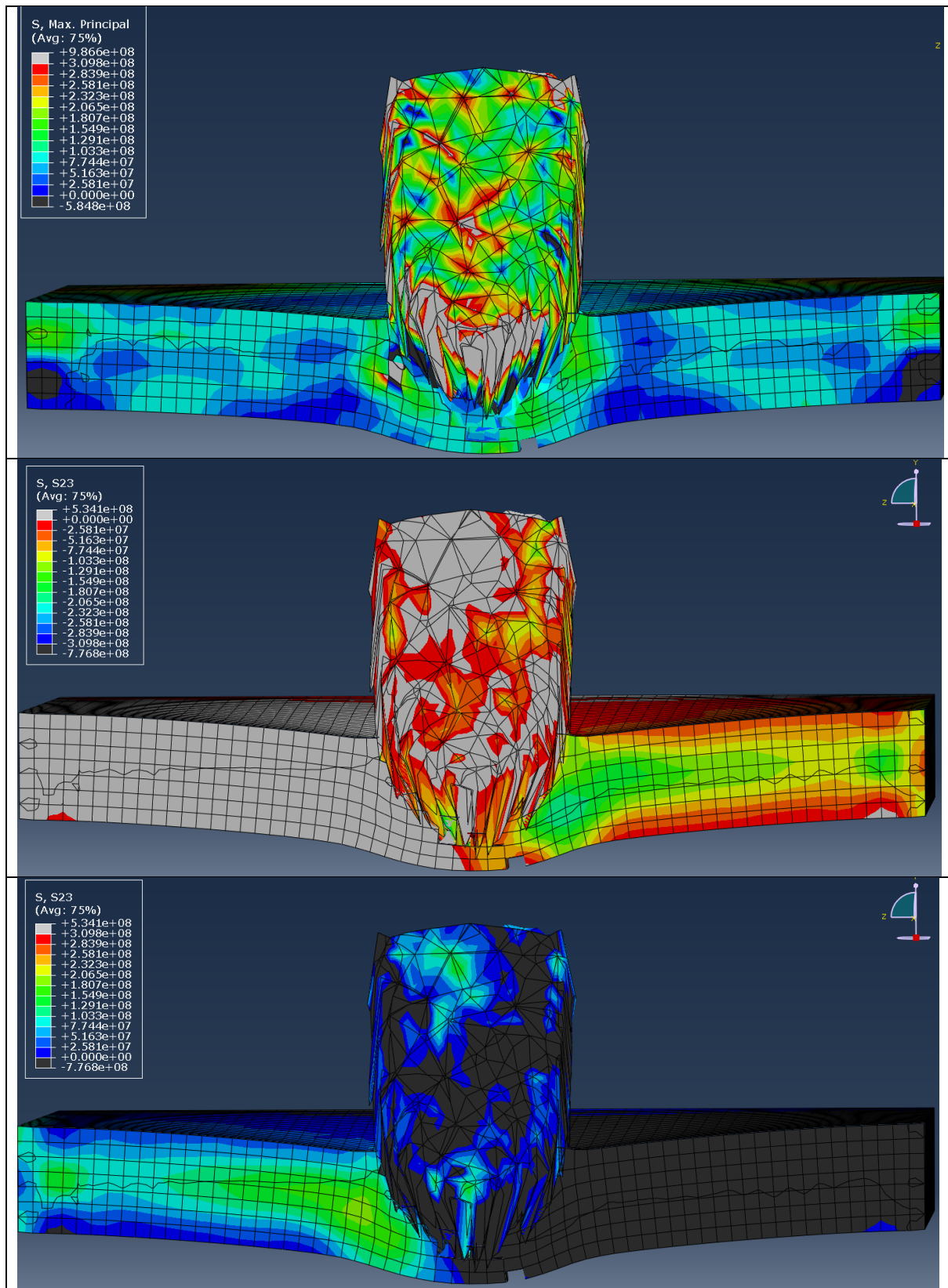


Figure 6: Comparison of direct and shear stresses as spooling begins at the back face of the aluminium plate.

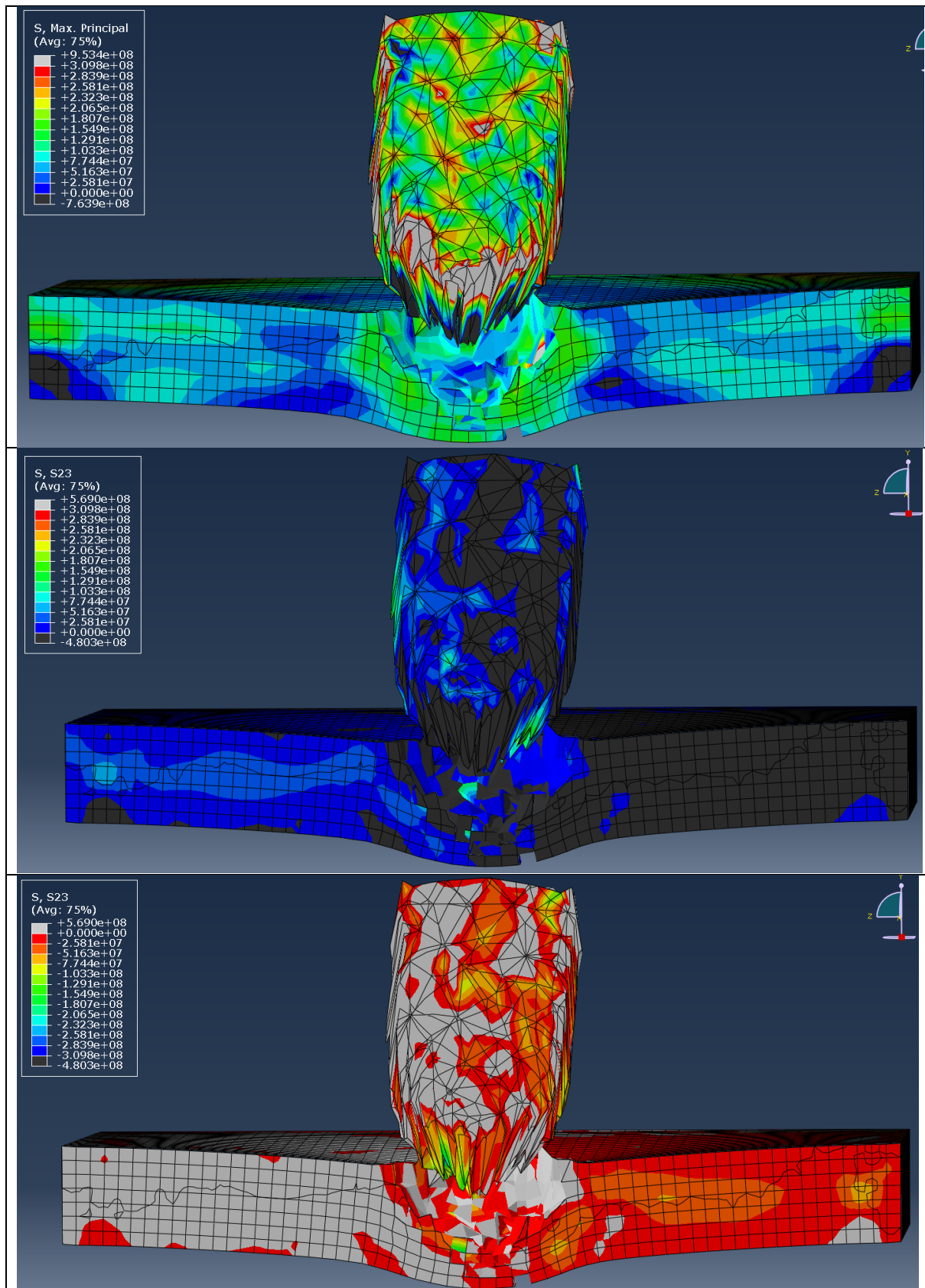


Figure 7: Comparison of direct and *sheer* stresses acting on the aluminium plate and steel bullet as the bullet comes to rest and begins to be bounced out of the plate.

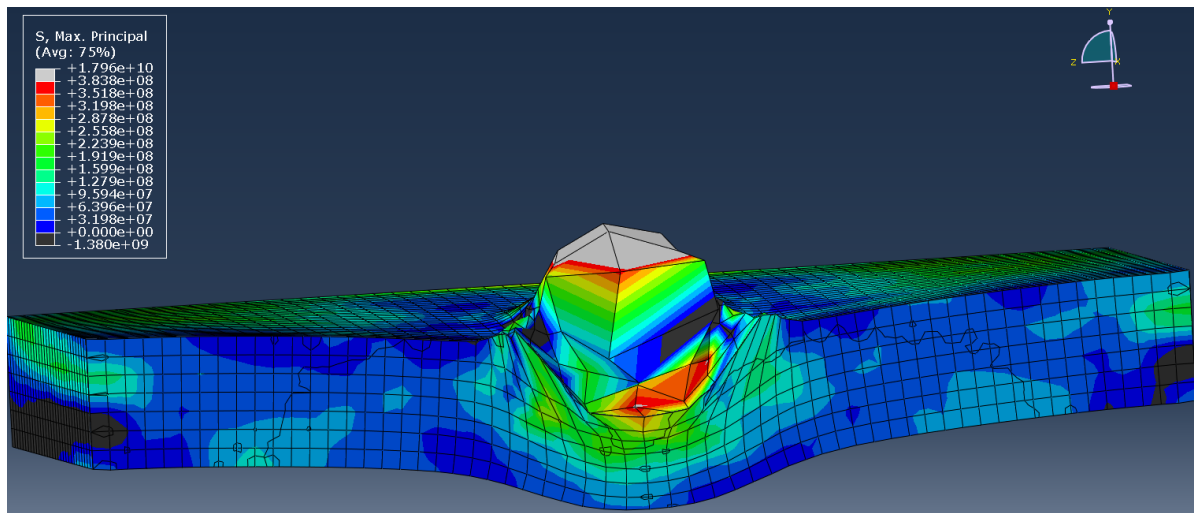


Figure 8: Final damage done to the aluminium plate after the steel bullet has been fully bounced out of the aluminium plate.

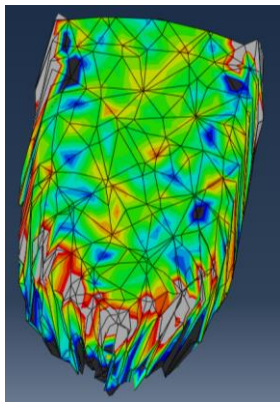


Figure 9: Visible damage inflicted on the steel bullet during impact with the target plate.

Analysis

Immediately upon contact, figure 4 highlights massive tension levels imparted upon the back face of the target. At this stage, direct tension at the back face of the plate peaks at over 310 MPa, far exceeding the UTS of aluminium from table 1. The notable difference in the second simulation is the speed at which the tension across the target drops off due to the damage now being inflicted back on to the projectile. Figure 4 shows that the steel bullet has been deformed significantly by the high-speed impact, a phenomenon that was not observed in the first simulation in which the bullet was treated as rigid and not subject to the effects of damage. The scale of the inflicted damage is shown clearly in figure 9.

Figure 5 demonstrates the massive stresses being imparted on to the plate. The first signs of spooling at the back face can be seen. This is, in the main, caused directly by tensile forces, and is backed up by the images, which show continued tensile stresses over 300 MPa, overpowering the UTS of the target plate. Absolute sheer stresses, whilst large, are lower, with the peak absolute sheer stress imparted in this time period being just under 200 MPa. This value still well exceeds aluminium's MSS, but is acting over a minute area relative to tension. There are large areas of the plate where the shear stresses acting are of a magnitude equivalent to or lower than the MSS of aluminium.

Spooling is less severe than in the first simulation, as shown in figure 6, by which point the bullet has reached its maximum penetration point before being bounced out in figure 7. The tension acting at the back face of the plate has fallen significantly, with the majority of the plate feeling a tension below 100MPa and falling. Shear stresses in Figure 6 have also lessened notably, down from around 200MPa previously to under 50MPa. Given the fact that the stresses of both natures will still be falling rapidly from this point, it can be seen why no further spooling occurs. The effect of adding damage values and reducing the rigidity of the incoming projectile has directly and negatively impacted the ability of the bullet to penetrate the target.

Figure 8 shows the final damage done to the target plate at the end of 1×10^{-3} seconds, by which point the bullet has been bounced out of the plate and away from the target. It can be seen that, whilst notable damage has been done, spooling in this simulation compared to the first is minimal, and full failure of the aluminium plate has not been achieved.

The notable difference in results comparing the first and second simulations demonstrates that it is possible for small differences in approach for the same impact can drastically alter the results. The results of the first two simulations suggest that steel bullets, in less than ideal conditions, may lack the penetrative ability required to consistently destroy armoured targets in combat scenarios.

Complex Impact involving a Tungsten Carbide Bullet

Methodology

Tungsten carbide as a material in the manufacture of armour and armour defeating projectiles is a more novel idea.

Tungsten carbide (WC) is heavier, denser, and harder than steel, and provides a possible option for penetrative rounds. The third simulation aimed to use the abilities of ABAQUS prove the viability of using WC for armour-defeating projectiles, without the need to conduct an expensive or time-consuming firing trial.

To run this simulation, a literature search was required to find valid values for WC in the same vain as was done for the second simulation with the steel projectile, including all plasticity and Johnson-Cook damage values. Table 4 shows the values used in the simulation.

Assigned Properties of Tungsten Carbide (WC)	
Density ⁶ (kg/m ³)	15700
Modulus of Elasticity ⁶ (GPa)	696
Poisson's Ratio ⁷	0.2
Melting Point ⁷ (K)	3143
Ultimate Tensile Strength ⁶ (Pa)	34.4×10^7
Maximum Shear Strength ⁶ (Pa)	22.7×10^7
Yield Stress, A ⁸ (Pa)	3×10^9
Hardening Constant, B ⁸ (Pa)	89×10^9
Strain Rate, C ⁸	0.00
Thermal Softening Exponent, M ⁸	1
Hardening Exponent, N ⁸	0.65

⁶ Information taken from MatWeb [7]

⁷ Information taken from AZOM Materials Database [8]

⁸ Information taken from journal article 'Modelling the 14.5 mm BS41 projectile for ballistic impact computations' [9]

Johnson-Cook Damage Parameter D1 ⁸	0.00
Johnson-Cook Damage Parameter D2 ⁸	0.0019
Johnson-Cook Damage Parameter D3 ⁸	-3.0
Johnson-Cook Damage Parameter D4 ⁸	0.00
Johnson-Cook Damage Parameter D5 ⁸	0.00

Observations

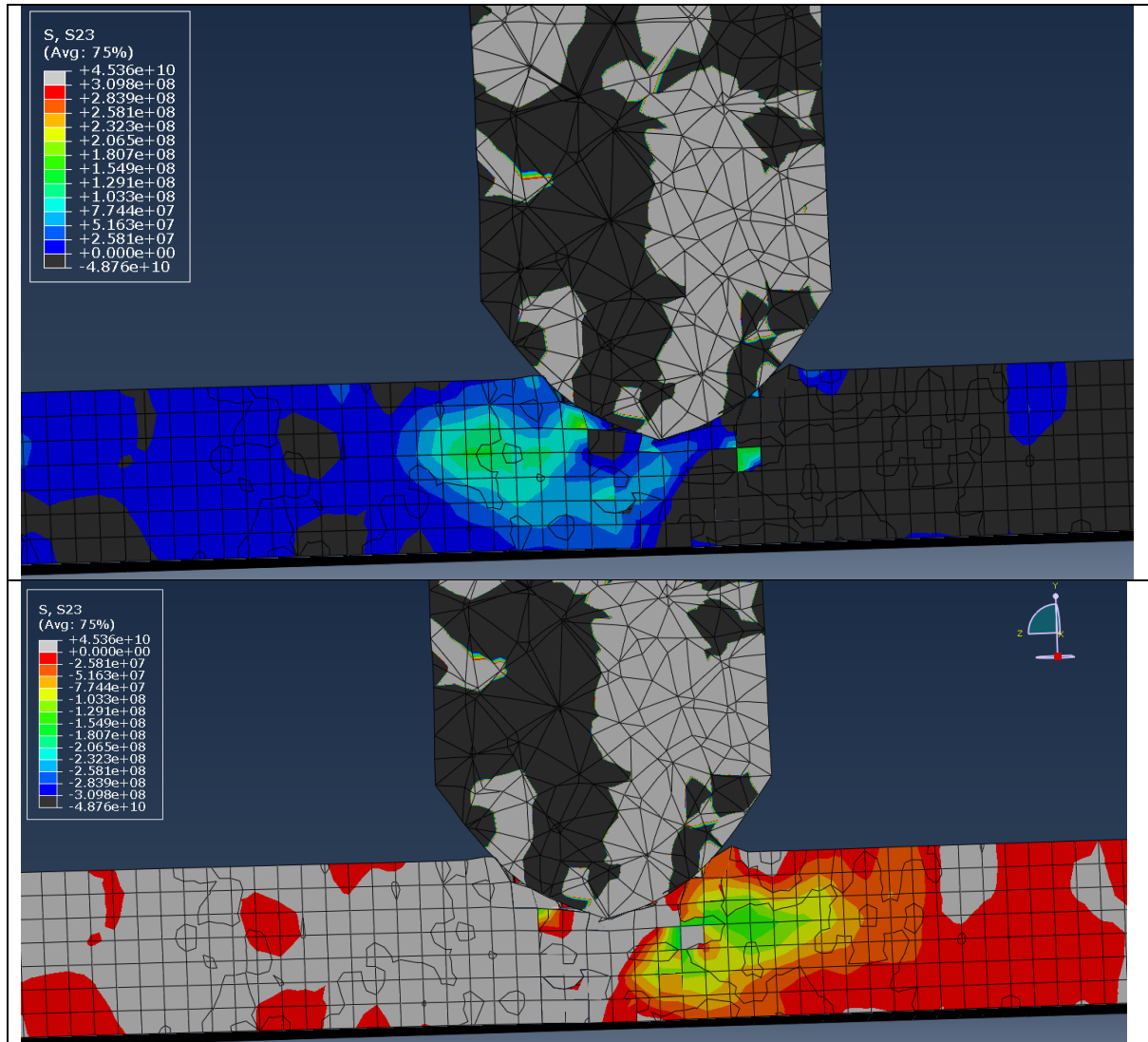


Figure 10: Representation of shear stresses acting on the plate at the moment of impact between the projectile and its target.

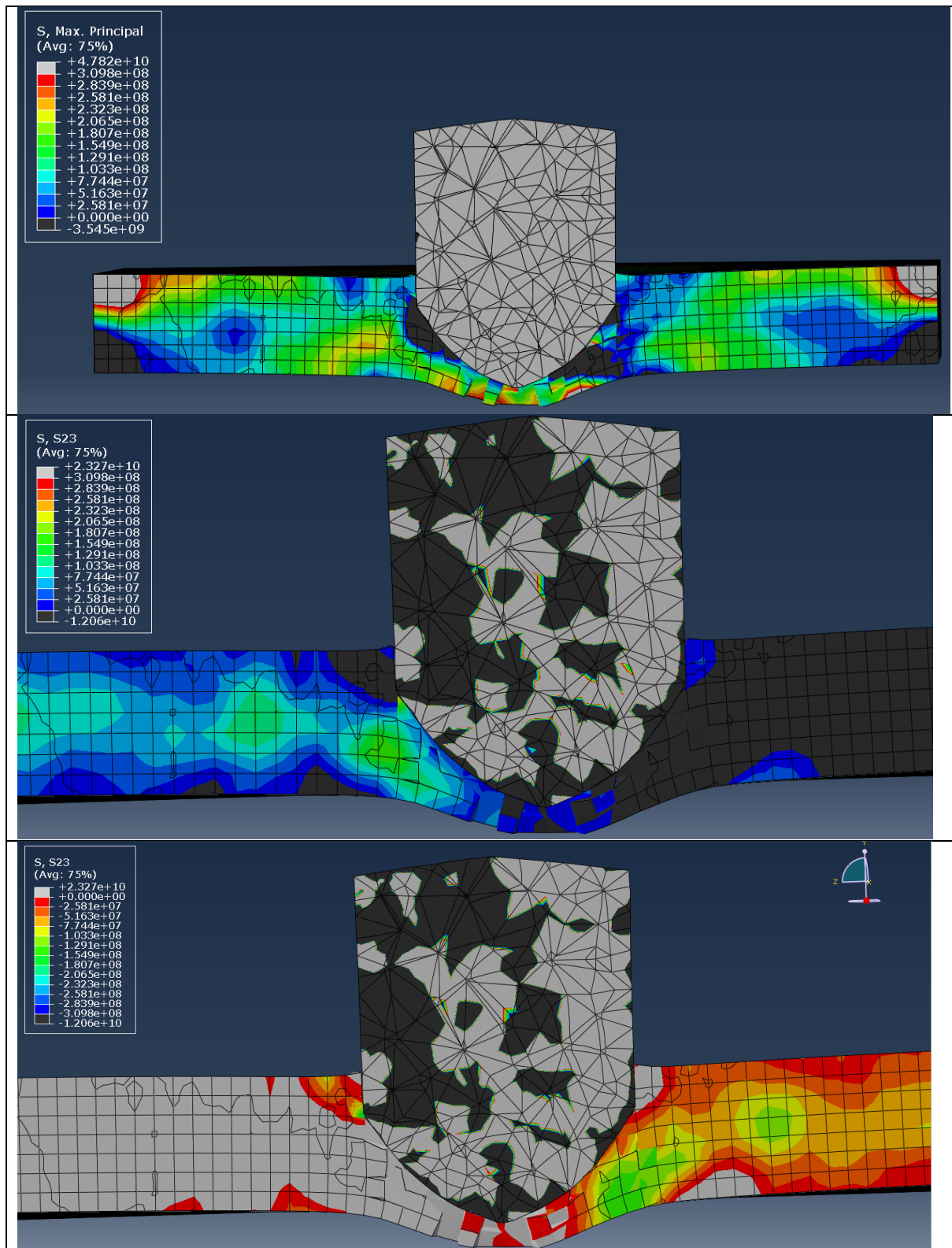


Figure 11: Comparison of direct and shear stresses as fracture begins at the back face of the target plate.

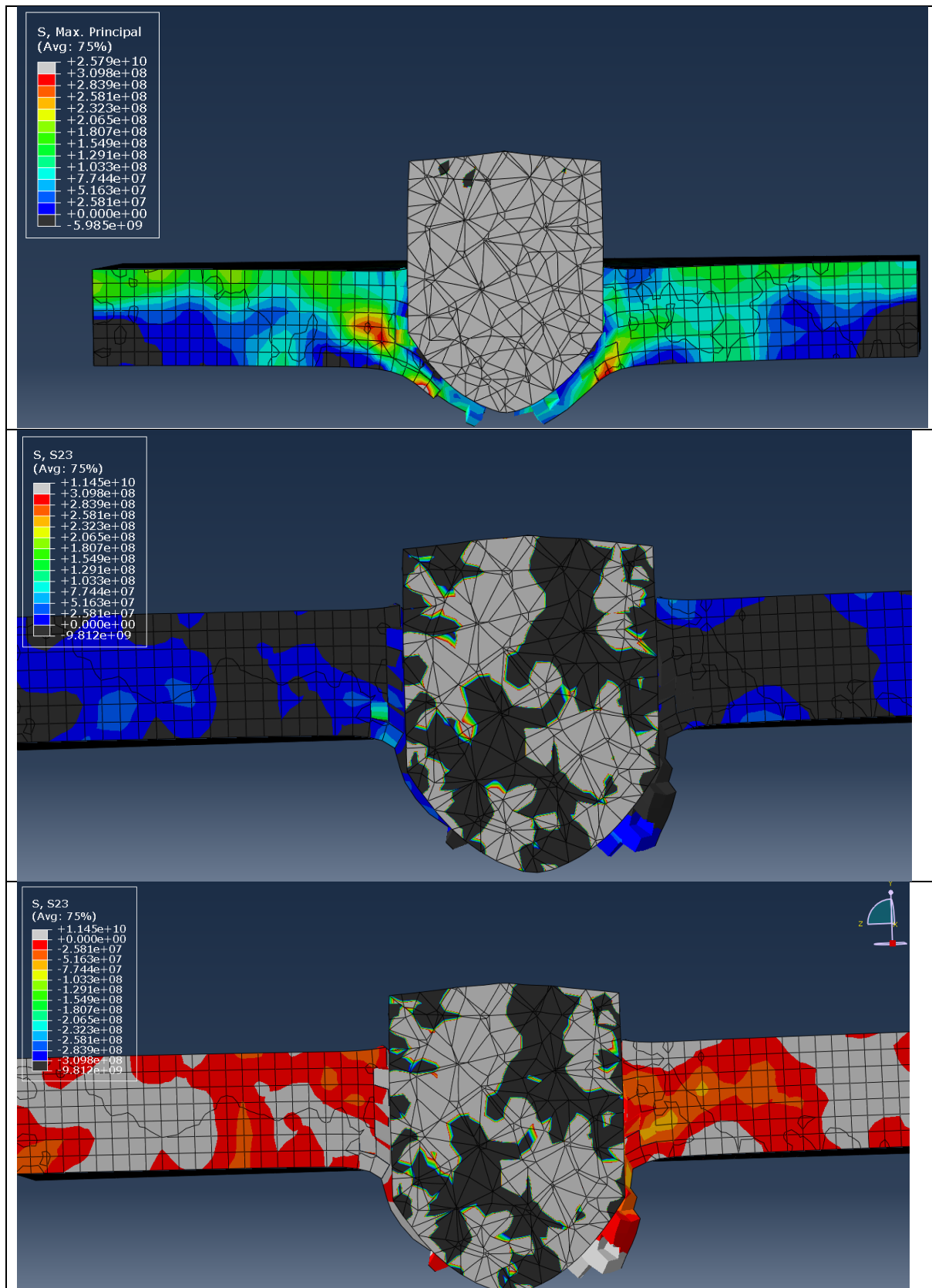


Figure 12: Comparison of direct and shear stresses imparted on to the target plate as complete failure of the plate's back face begins.

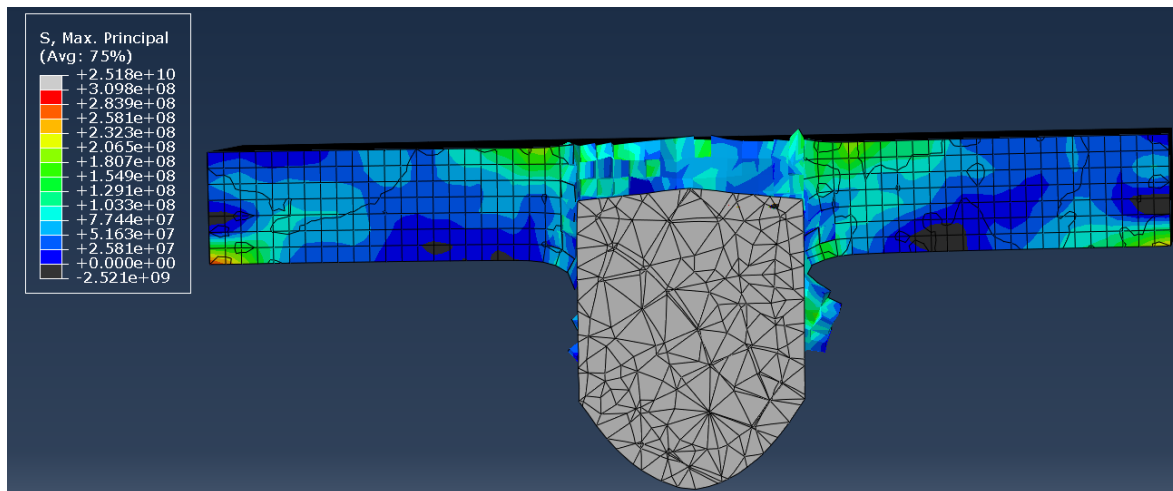


Figure 13: Screenshot showing the tungsten carbide bullet fully shattering the back face of the aluminium plate and penetrating the plate fully.

Analysis

The increased hardness and density of tungsten carbide has a significant impact on the penetration ability of the projectile compared with the first and second simulations, both using a steel projectile.

Figure 10 shows the shear stresses immediately upon contact between the projectile and target. The absolute shear stresses at this point show a concentrated area of shear stress well above the 62MPa value of aluminium's MSS, where the shear stresses acting on the plate are up to and around, and in limited areas above 100MPa. This persists throughout the duration of the collision but, as with previous simulations, the area of effect is smaller considerably than the vast area of high tension that is exerted on the back face of the target plate.

Figure 11 shows this. As the bullet penetrates the plate at speed, there is a huge area of tension across the back face of the aluminium target. More or less the entire back face is subjected to a tensile force of over 100MPa, enough to induce brittle failure. There is a small area of the back face where the tension has grown to such an extent that pressure on the back face has reached over 300 MPa. Spooling has already begun, and this is the fastest point at which spooling has been shown to occur (Step 3/20). The value of shear stress at this stage is also remains high, with areas of the plate still experiencing shearing at a pressure of over 100MPa. There is evidence that the plate is undergoing a sustained period of brittle and ductile failure, although the magnitude of tensile stress exerted on the plate means that it is direct stress that has more of an impact on the overall failure of the plate, as is backed up in figure 12.

Figure 12 is taken in step 7. By this time, it's clear that complete penetration of the aluminium target is going to occur. Shear stresses have decreased considerably to around or below 50MPa, but many areas of the back face are still subject to tensile forces of over 100MPa, which is causing continued and sustained shattering of the back face. Figure 13 shows the bullet making its way through the aluminium plate in its entirety with relative ease.

Conclusion

This investigation in to the failure dynamics of an aluminium target plate when subjected to a high-speed ballistic collision has provided an insight in to the advantages and drawbacks of using multi-physics software to carry out tests that would otherwise require a physical trial. Using ABAQUS has allowed conclusions and analysis to be drawn with respect to comparing the ability of two bullets of

different materials to penetrate a target plate. The results were clear, and matched up with pre-existing materials theory, showing that harder, more dense materials have a greater capability to cause a target to fail. This could be displayed clearly without the need for a trial, which is expensive, time-consuming, and an inherently riskier method of gathering results.

The obvious drawback to the investigation, is that the results produced are as meaningful as the competency of the user. In a more detailed investigation with more time to learn the features, it could have been possible to create a finer mesh to map the collision, create a NATO specification projectile or plate, and look at things such as impact velocities, composite materials and novel technologies. All of these things could be achievable in the software, but not with the level of knowledge of the system, or amount of time, provided.

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Further Reading

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