

DYNAMIC STRESS-STRAIN INVESTIGATION

MODELLING AND ANALYSIS OF A TUNGSTEN-CARBIDE PENTRATOR IMPACTING AN ALUMINIUM
PLATE

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ABSTRACT

This report is investigating the high stress-strain environment of a target plate being impacted by a projectile. The projectile under investigation is the Tungsten-Carbide penetrator core from the U.S. Army Research Laboratory (ARL) 14.5mm BS41 Anti-Material cartridge, which itself is a reproduction Soviet designed BS 14.5x114mm armour-piercing incendiary anti-tank cartridge. The target plate is comprised of Aluminium 6061-T6 and was chosen due to its wide proliferation in general structural applications. An Abaqus model was created and simulations run for three impact velocities; 1000ms^{-1} , 343ms^{-1} and 450ms^{-1} .

PROJECTILE CHARACTERISTICS

DIMENSIONS

Dimensions of the projectile were taken from a characterization and modelling report that validated a new production run of the projectiles for use in ballistic acceptance testing of armour plates [1]. These dimensions and some material properties were corroborated by a second report qualifying these projectiles by the U.S. Army Research Laboratory [2].

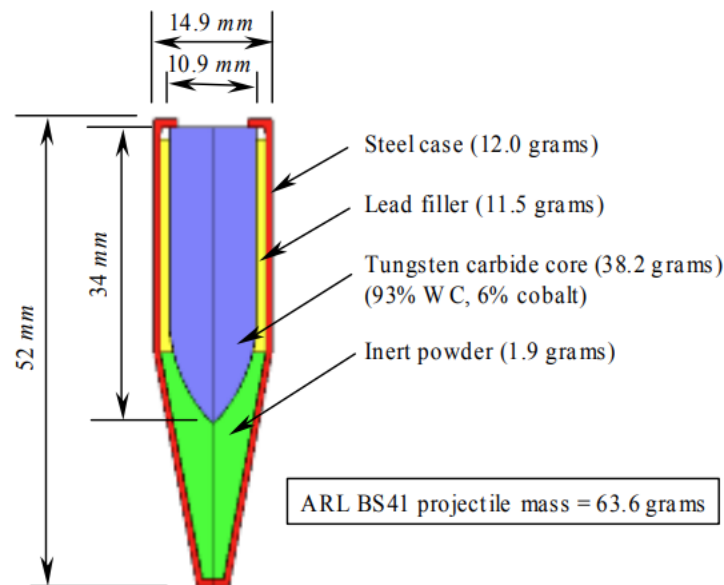


FIGURE 1 - SCHEMATIC OF ARL 14.5MM BS41 PROJECTILE TAKEN FROM LITERATURE [1]

For the purposes of this investigation, only the Tungsten-Carbide (WC) penetrator core was modelled, seen in Figure 1. This decision was made to reduce modelling time, including processing time, as the penetrator would be doing the vast majority of work in deforming the target plate due to its high strength and low ductility compared to the steel case and lead fillers comparatively smaller effect. Measurement data for the ogive radius of the core could not be found, so an approximation was made.

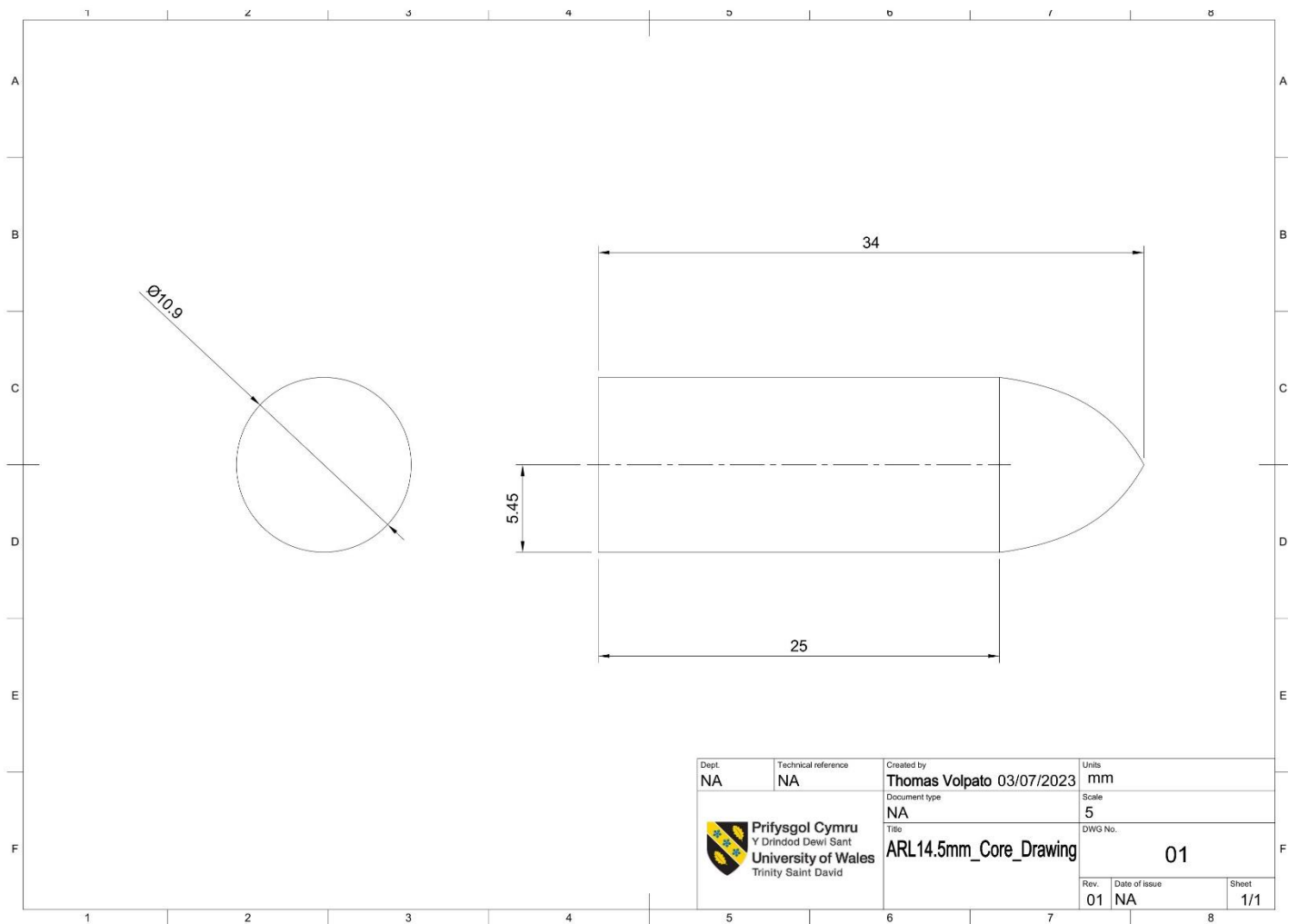


FIGURE 2 - SCHEMATIC OF ARL14.5MM BS41 WC CORE

MATERIAL PROPERTIES

The penetrator consists of 83% WC and 6% Co with a high Young's modulus of 620 GPa, (in comparison, Aluminium alloys have a Young's modulus of 70 GPa [3]) and a low Poisson's ratio of 0.215. The density of the core was 14770 kgm⁻³.

$$E = \frac{\sigma}{\varepsilon} = \frac{F/A}{\delta L/L}$$

EQUATION 1 - EQUATION FOR YOUNG'S MODULUS, INCLUDING STRESS & STRAIN

Young's modulus is a measure of stiffness in a material, calculated from stress over strain (Equation 1) and describes how much a material changes shape in the elastic region under loading.

Poisson's ratio describes the relationship between axial (Y-direction) strain and transverse (X-direction) strain. To frame the WC core's Poisson's ratio; Silicate glasses have a ratio between 0.2-0.276, Aluminium 6061-T6 is 0.33 and natural rubber is 0.499 [4].

IMPACT VELOCITIES

The model was simulated with the projectile moving at 1000ms^{-1} , 343ms^{-1} and 450ms^{-1} . 1000ms^{-1} is the muzzle velocity of the projectile from PTRD and PTRS Anti-Tank rifles [5]. 343ms^{-1} is the speed of sound at atmospheric pressure and 20°C [6]; and was chosen as a representative velocity that the projectile may reach at extended ranges or potentially after penetrating a previous target. Ballistic data is unavailable for the projectile in open source, therefore an investigation into penetration performance at set ranges, and thus velocity, was not possible. After running a series of simulations in 50ms^{-1} increments between 350 and 950ms^{-1} . 450ms^{-1} showed the greatest lateral deflection of the projectile and was selected for analysis.

TARGET PROPERTIES

The target is a $300\times 300\times 50\text{mm}$ Aluminium 6061-T6 plate. Aluminium 6061-T6 has desirable material properties that are well referenced; including the Johnson-Cook material properties [7]. It is used commonly in structural applications and was chosen due to its proliferation. Johnson-Cook material properties are experimentally derived parameters for use in the modelling of high strain rate environments such as ballistic impacts [8].

Density, ρ , [kgm^{-3}]	Specific Heat Capacity [$\text{Jkg}^{-1}\text{K}^{-1}$]						
2703	885.0						
A , [Mpa]	B , [Mpa]	n	Θ_{melt} , [K]	$\Theta_{\text{transition}}$, [K]	m	C	$\dot{\epsilon}$, [s^{-1}]
324.1	113.8	0.42	925	293.2	1.34	0.002	1
D_1	D_2	D_3	D_4	D_5			
-0.77	1.45	0.47	0.0	1.6			

TABLE 1 - JOHNSON-COOK MATERIAL PROPERTIES OF ALUMINIUM 6061-T6 [7]

MODEL

The projectile impact model was simulated in Abaqus, a finite element analysis software. Simply, the model is divided into small elements and partial differential equations involving the material properties response to loading can be solved and aggregated to analyse the system as a whole.

A model of the projectile and target parts were created using dimensions from the above sections; and in the assembly module, staged so that the projectile was centered on the target with a suitable y-axis offset and normal incidence. The parts were meshed utilizing explicit tetrahedral elements. Explicit solving is preferred for non-linear, dynamic events such as ballistic impacts; compared to standard which is used for static or linear dynamic events (i.e. loading of structural trusses in buildings) [9]. Default element deletion and hourglass control were enabled to remove excessively distorted elements during the simulation. Previous iterations did not use these settings and resulted in errors, terminating the simulations. Figure 3 shows the use of a virtual partition within the target plate to enable a finer mesh to be seeded where the projectile would impact.

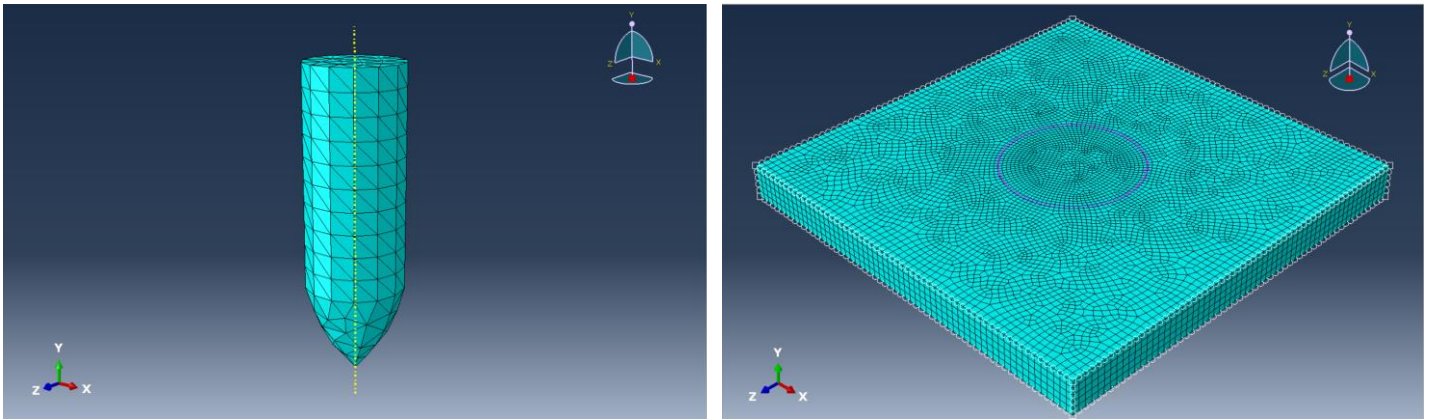


FIGURE 3 - TETRAHEDRAL MESHING OF PROJECTILE AND TARGET PLATE WITH PARTITION

The edges of the target plate were constrained in the load module using the encastre function. This constrains all structural degrees of freedom of the edges (X, Y, Z as well as U1, U2, U3 which define the rotation about the former axes). A predefined field of the selected velocities is then applied to the projectile as a negative value due to the direction of the axis and is described as V2; (the number referring to the axis involved, X=1, Y=2 and Z=3). Figure 4 also shows the interaction module; this defines what is to be solved in each step of the model. In this instance an explicit surface-to-surface contact is prescribed between the projectile and the center of the target from the initial step of the model.

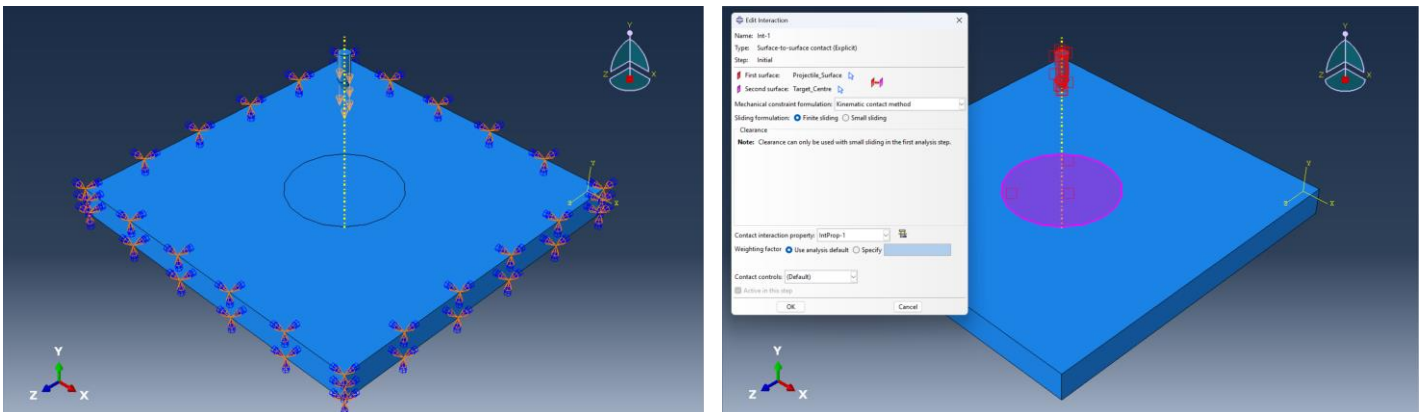


FIGURE 4 - INITIAL LOADING AND INTERACTION CONDITIONS OF MODEL

The end step (time-period of the model) was defined as 200 μs (0.0002) to allow for the projectile to fully penetrate the target plate.

RESULTS

SHEAR STRESS

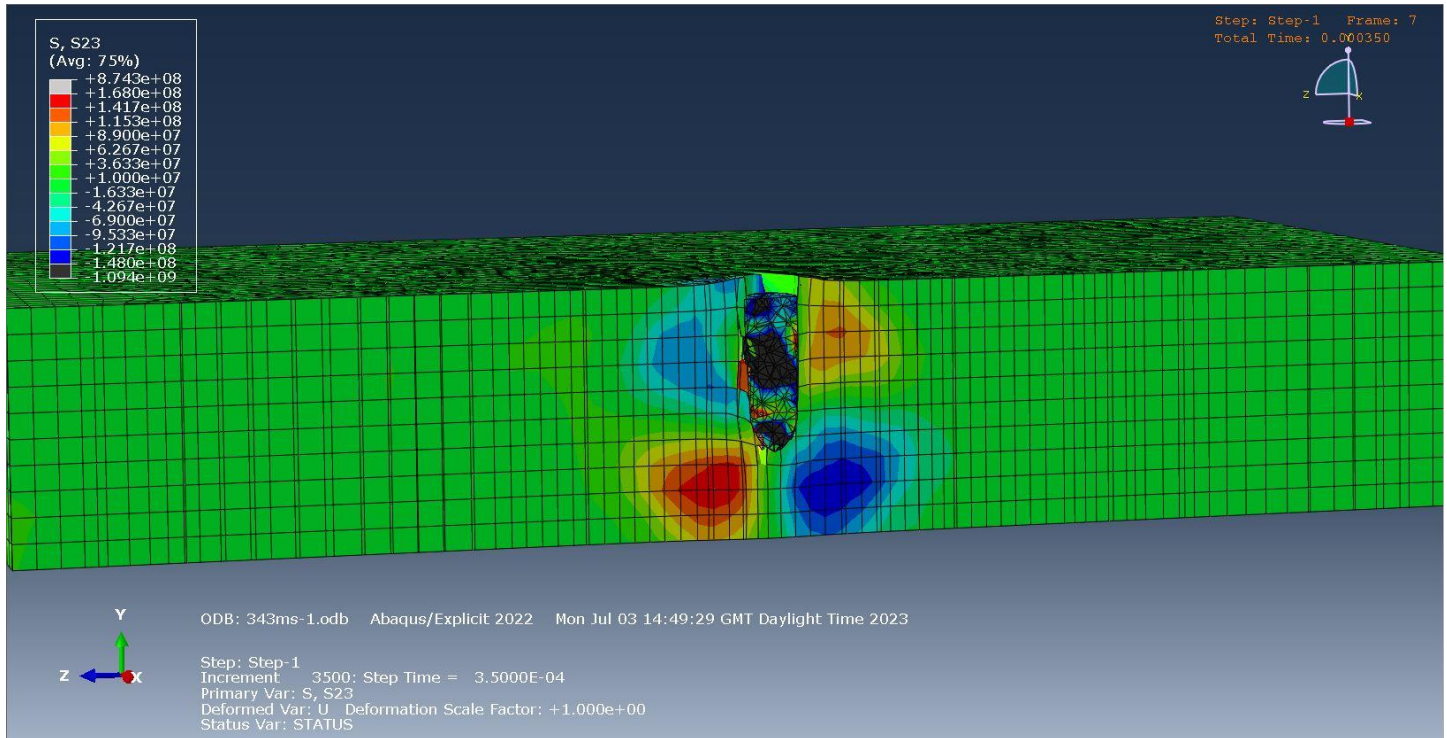


FIGURE 5 - 343MS-1 S23

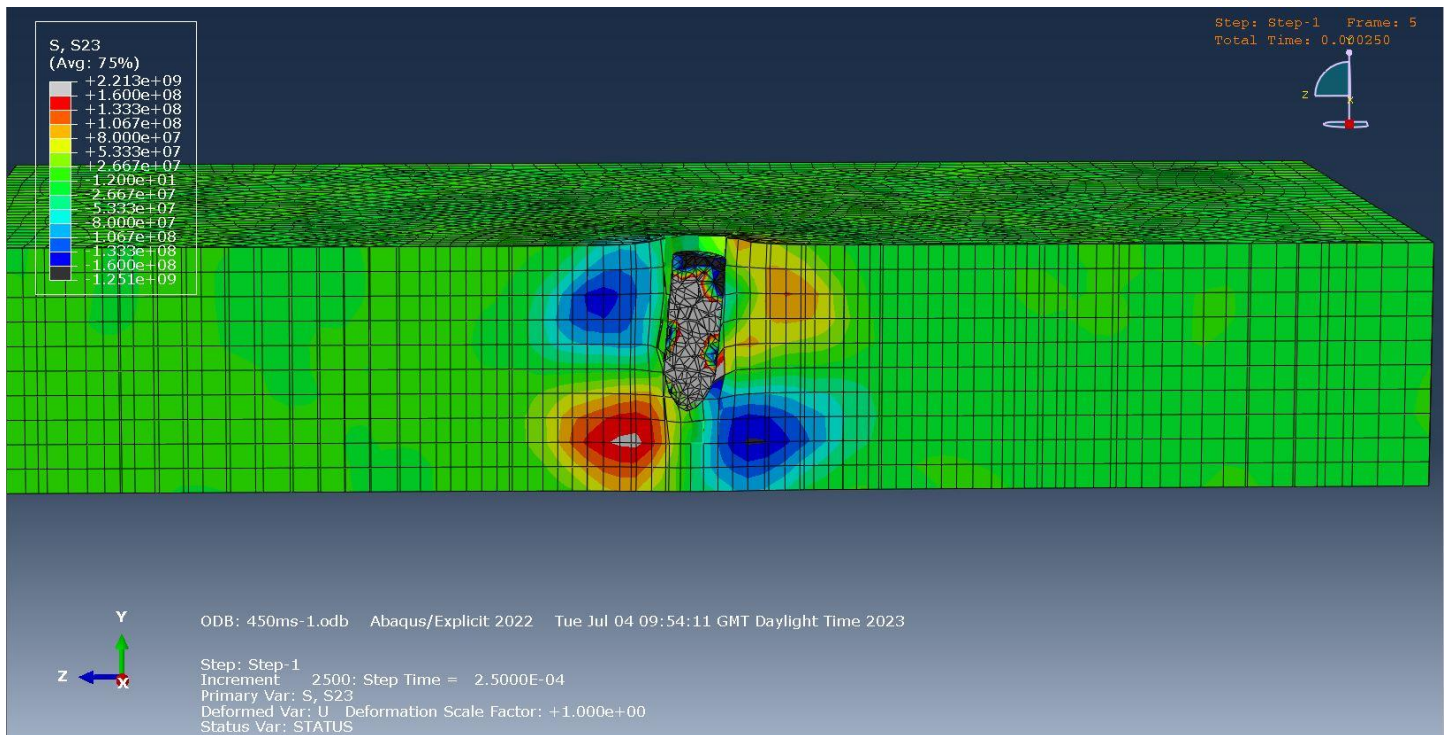


FIGURE 6 - 450MS-1 S23

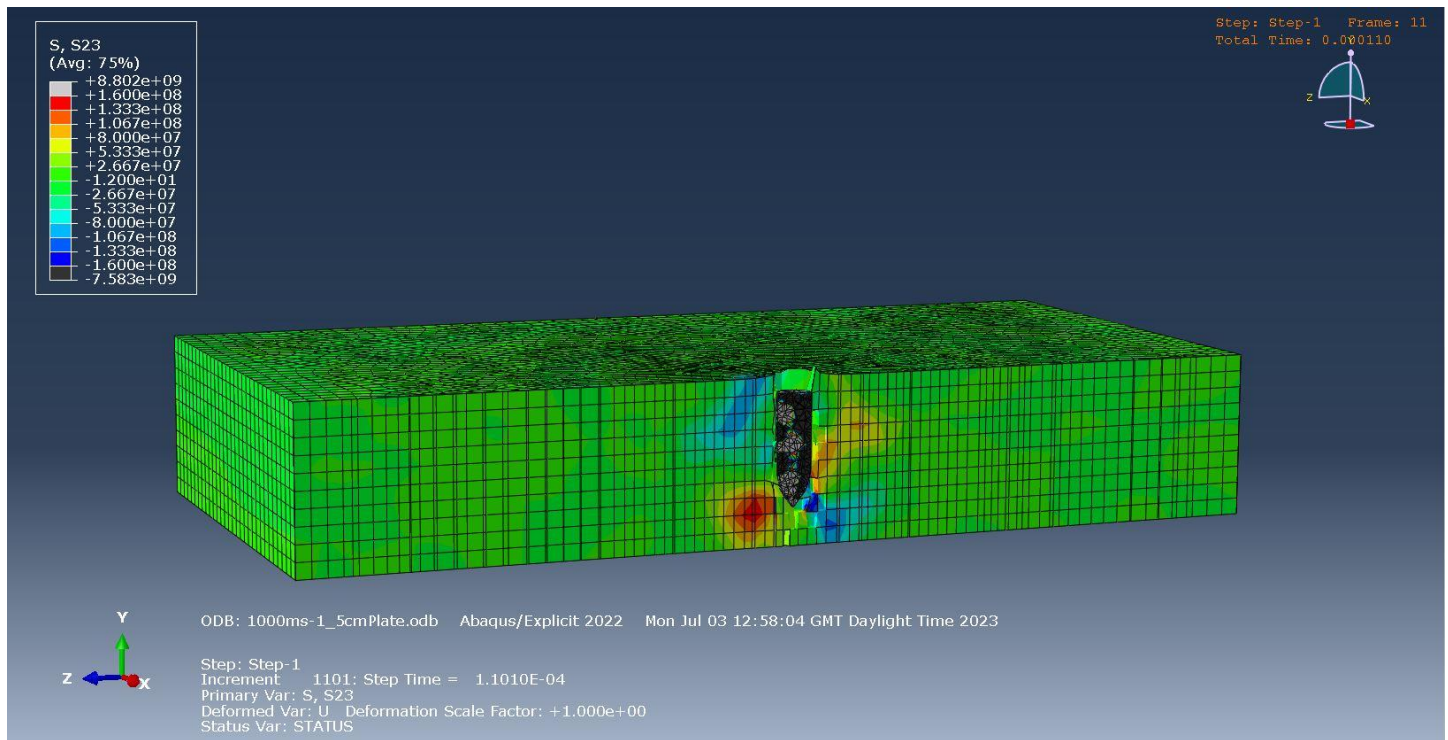


FIGURE 7 - 1000MS-1 S23

Projectile speed [ms-1]	Max positive shear stress [GPa]	Max negative shear stress [GPa]
343	0.1680	0.1480
450	2.213	1.251
1000	0.1600	0.1600

TABLE 2 - MAXIMUM POSITIVE AND NEGATIVE SHEAR STRESS VALUES OF TARGET PLATE AT EACH PROJECTILE VELOCITY

MAXIMUM STRESS

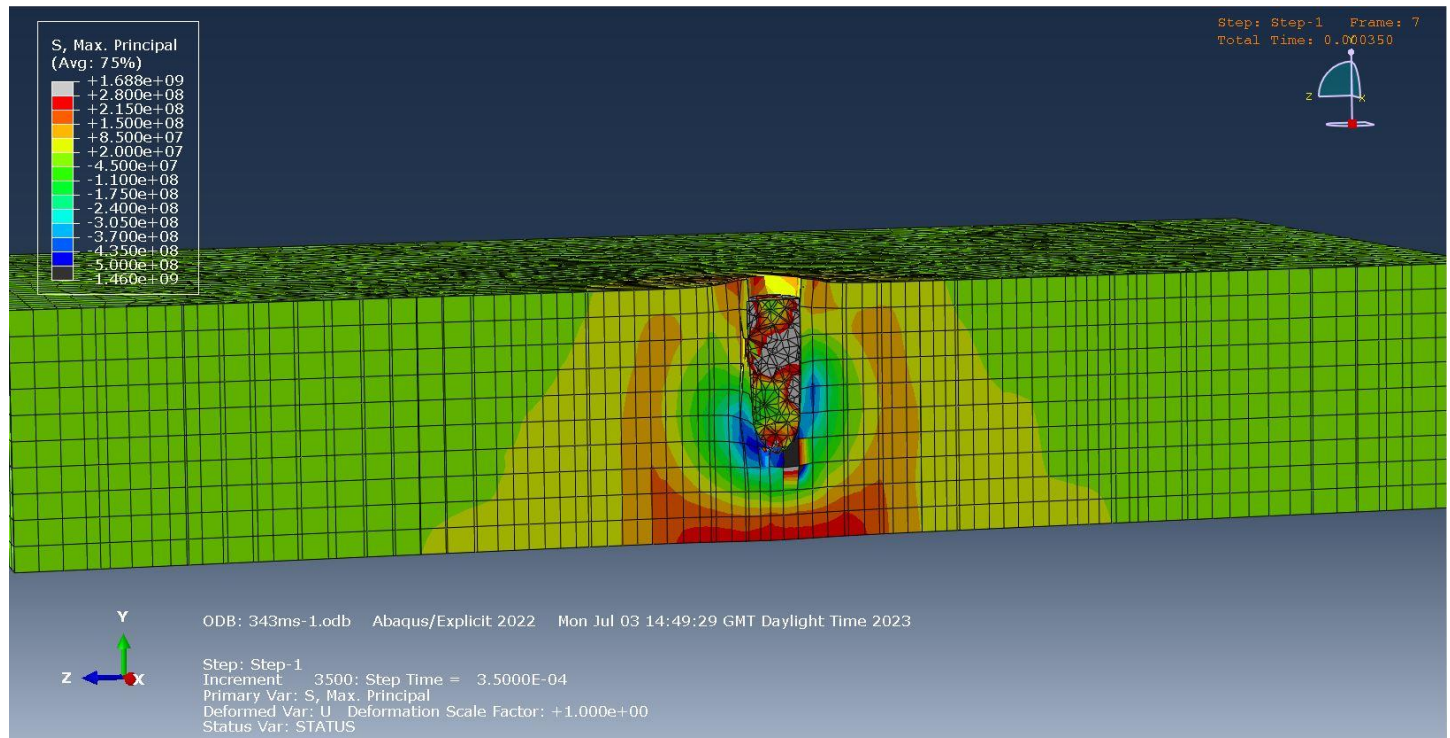


FIGURE 8 - 343MS-1 SMAX

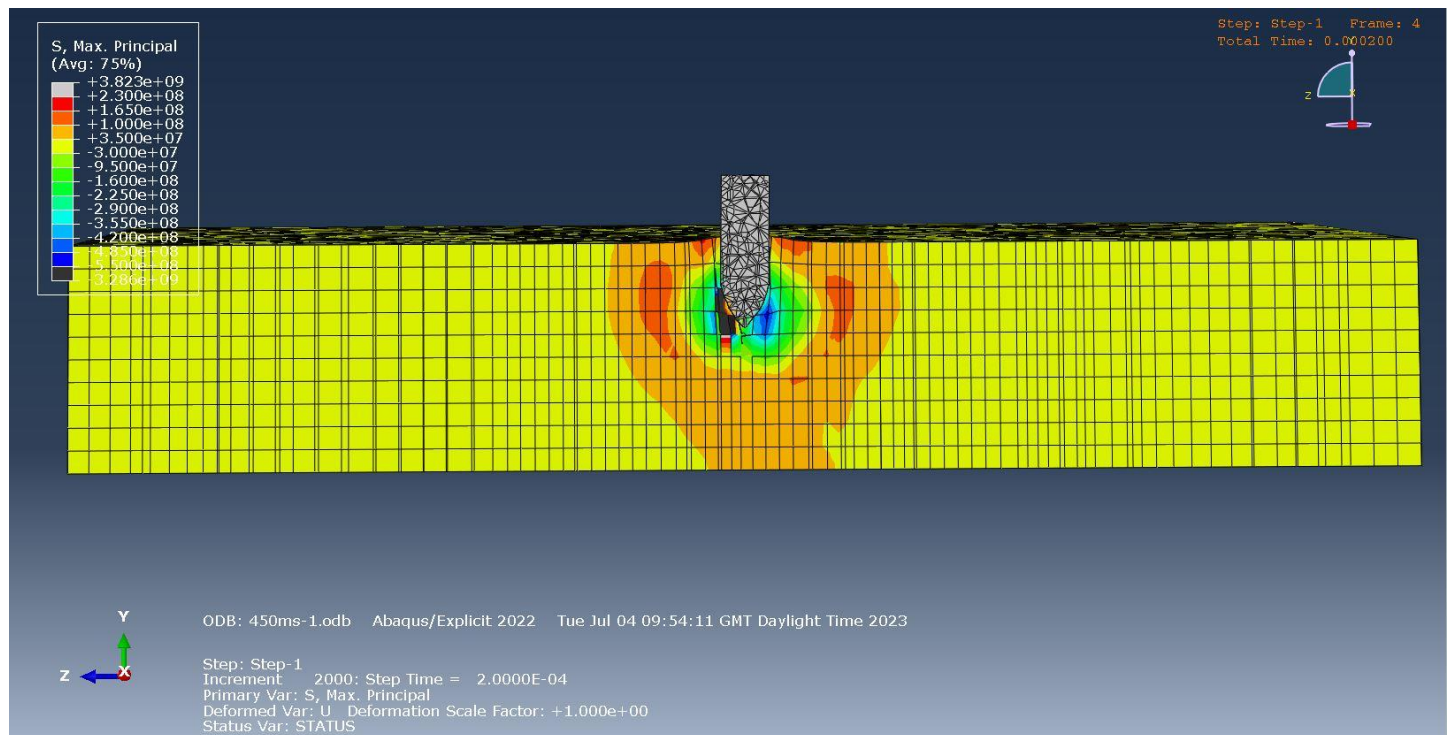


FIGURE 9 - 450MS-1 SMAX

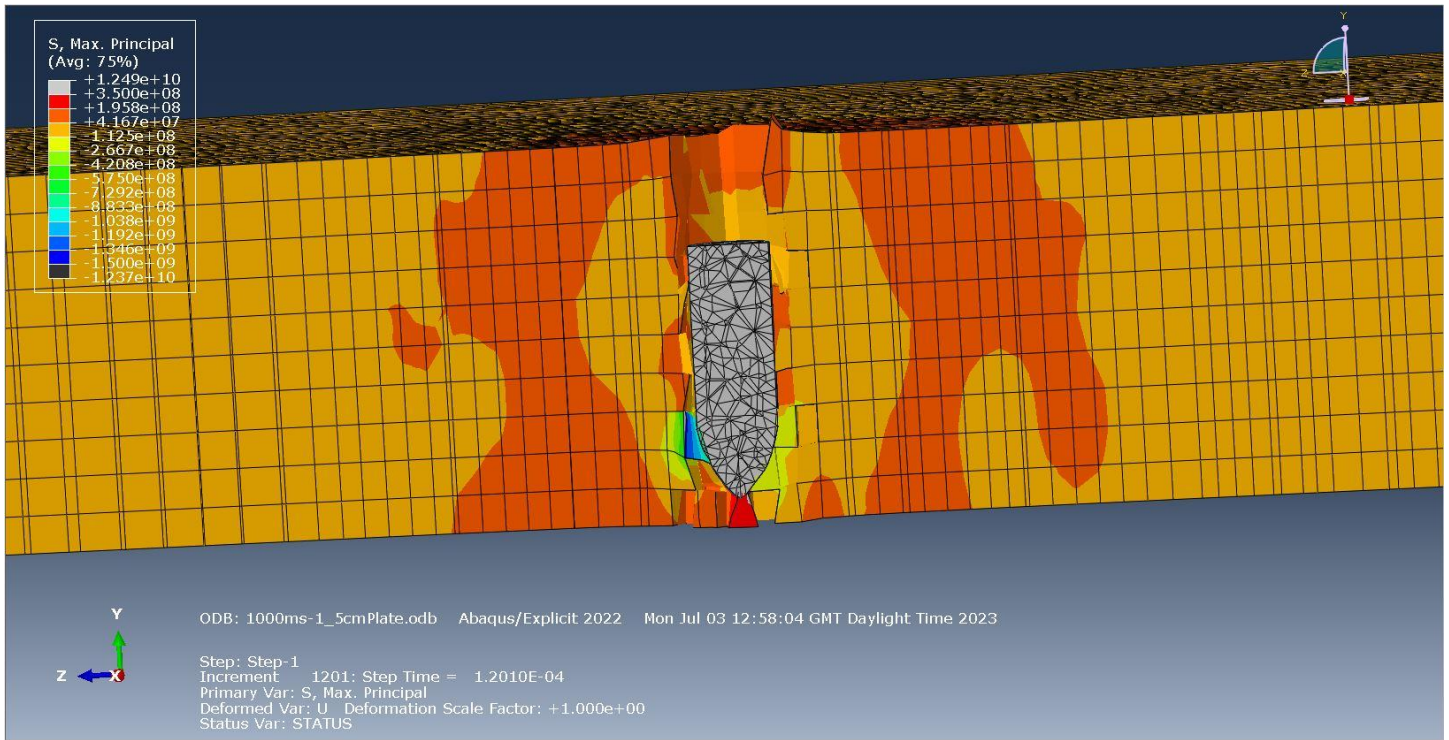


FIGURE 10 - 1000MS-1 SMAX

Projectile speed [ms^{-1}]	Max positive stress [GPa]	Max negative stress [GPa]
343	1.688	1.460
450	3.820	3.286
1000	0.3500	1.500

TABLE 3 - MAXIMUM POSITIVE AND NEGATIVE VALUES OF PRINCIPAL STRESS FOR EACH PROJECTILE VELOCITY

A full series of impact, mid-point and post impact screenshots of the simulation can be found in Appendix A – All simulation results. This includes top-down views of the plates in which you can see concentric waves of stress propagating through the plates such as in Figure 11.

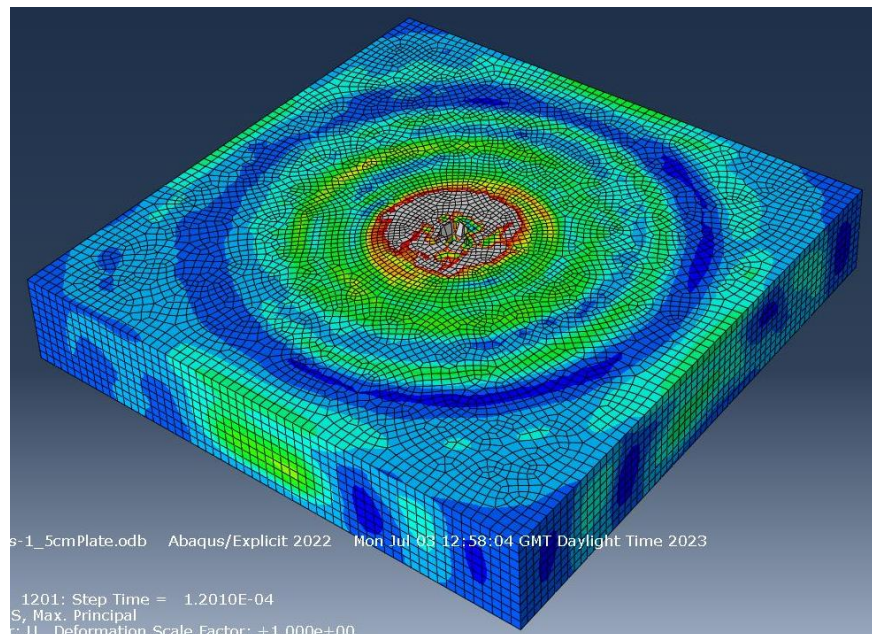


FIGURE 11 - SMAX WAVES IN 1000MAS-1 IMPACT

PROJECTILE VELOCITY AND KINETIC ENERGY

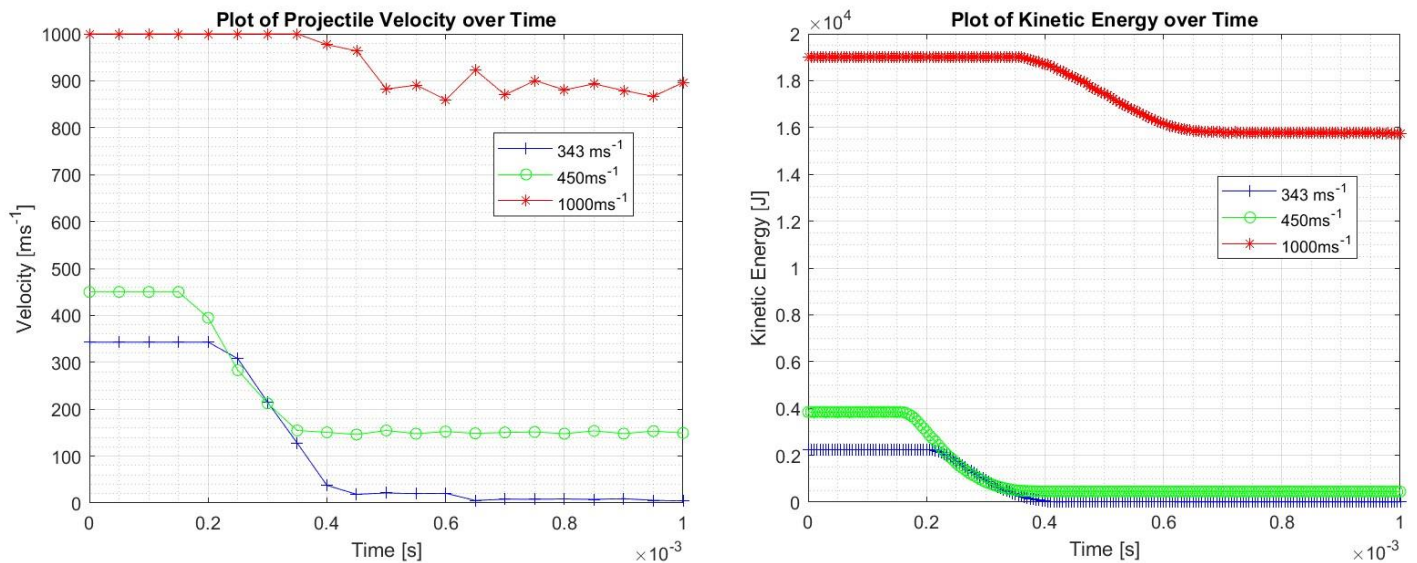


FIGURE 12 - PLOTS OF PROJECTILE VELOCITY AND KINETIC ENERGY OVER TIME

The plots in Figure 12 are not fully representative for the 1000ms^{-1} impact as the data was scaled with coding found in Appendix B – Matlab plotting script to align with the other velocities for ease of analysis. Unscaled plots can be found in Appendix C – Unscaled plots. An element in the centre of the projectile was selected for the data capture as there would not be erroneous results from the elements distorting on the surface of the projectile.

ANALYSIS

V1	V2	% Loss	KE1	KE2	% Loss
343	0	100%	2236.19	0	100%
450	150	67%	3848.98	455	88%
1000	880	12%	19007.3	15760	17%

TABLE 4 - PERCENTAGE LOSS OF VELOCITY AND KINETIC ENERGY OF THE PROJECTILE

As seen in Figure 12 - Plots of projectile velocity and kinetic energy over time, the 343 and 450 ms⁻¹ lose velocity and kinetic energy at similar rates (gradient of slope). This is due to the projectile's kinetic energy being "converted" (equaling) into the work done on the target elements; reaching the fracture point on the stress-strain curve of the elements requires the same amount of energy acting as a resistive force.

$$KE_{(before)} = \frac{1}{2}mv^2 = W_{(after)} = Fd$$

EQUATION 2 - CONSERVATION OF ENERGY FOR PROJECTILE IMPACT

From Table 2 and Table 3 it can be observed that the 450 ms⁻¹ impact exerts the greatest shear and max principal stress upon the target plate. The shear stress values align with the observation of the projectile deflection in the z-axis, caused by increased deformation (shear stress) within the elements. The increased deformation is the result of the strain rate sensitivity of the aluminium in which the strength of the material is dependent on the strain rate [10]. The aluminium experiences greater strain at 450ms⁻¹ due to the lower strain-rate.

Expanding on Table 4 and Equation 2 it can be observed that the 1000ms⁻¹ simulation has the lowest percentage loss of velocity and deceleration of the projectile. As $F = ma$ or $F = m(\frac{\Delta V}{t})$ this results in less force being imparted upon impact. The kinetic energy of the impact may also be dissipated by heating of the material or hydrodynamic effects such as shockwaves, thus leading to less energy contributing to deformation and therefore shear and principal stress.

The resisting deformation force of the aluminium within the 343ms⁻¹ impact was greater than the kinetic energy of the projectile ~25mm into penetrating the plate. Initially the projectile had enough energy to penetrate the material but the loss in KE was sufficient for the projectile to reach a zero velocity and be lodged in the target.

CONCLUSION

The high stress-strain environment of a target plate being impacted by a projectile was investigated by simulating a Tungsten-Carbide penetrator core impacting an aluminium 6061-T6 plate at three impact velocities; 1000ms⁻¹, 343 ms⁻¹ and 450 ms⁻¹.

The 343 ms⁻¹ showed the target plate requiring greater energy to deform than the projectile could supply. The 450 ms⁻¹ impact induced the greatest shear and principal stress within the target due to the increased contact time (impulse) and strain rate sensitivity of the material. The 1000 ms⁻¹ imparted the least energy to the plate and as such the least shear and principle stress. This is due to the high velocity increasing heating and shockwaves thus reducing the KE imparted into work done deforming the target material.

The results could be further improved by mesh convergence analysis, this looks to refining the mesh, and measuring the change in simulation results until a suitable convergence between processing time and accuracy is reached. The projectile model also disregards the steel case and lead filler surrounding the core; for more representative results, these components should be included. Further work could also be done by investigating more representative target materials and structures such as spaced armour or RHA. Simulating different target materials is subject to Johnson-Cook material properties being available. If experimental ballistic data is available the model could be modified to corroborate this (velocities, target penetration at various plate thicknesses etc).

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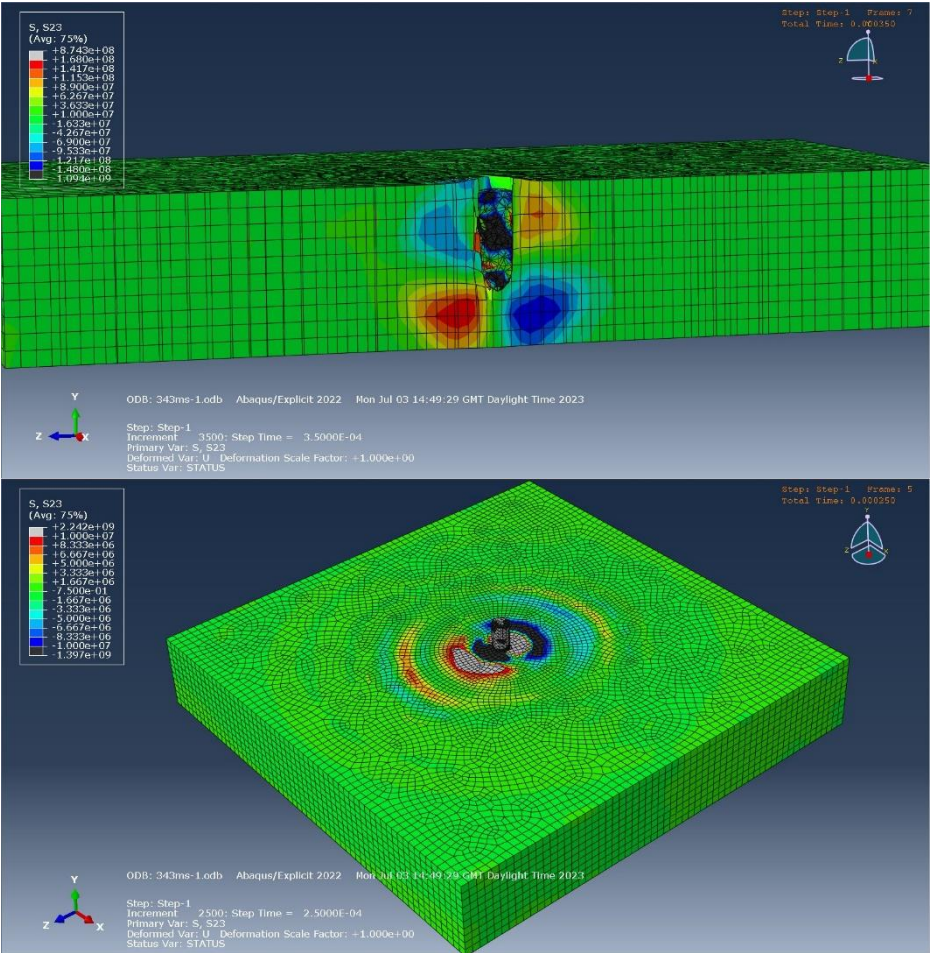
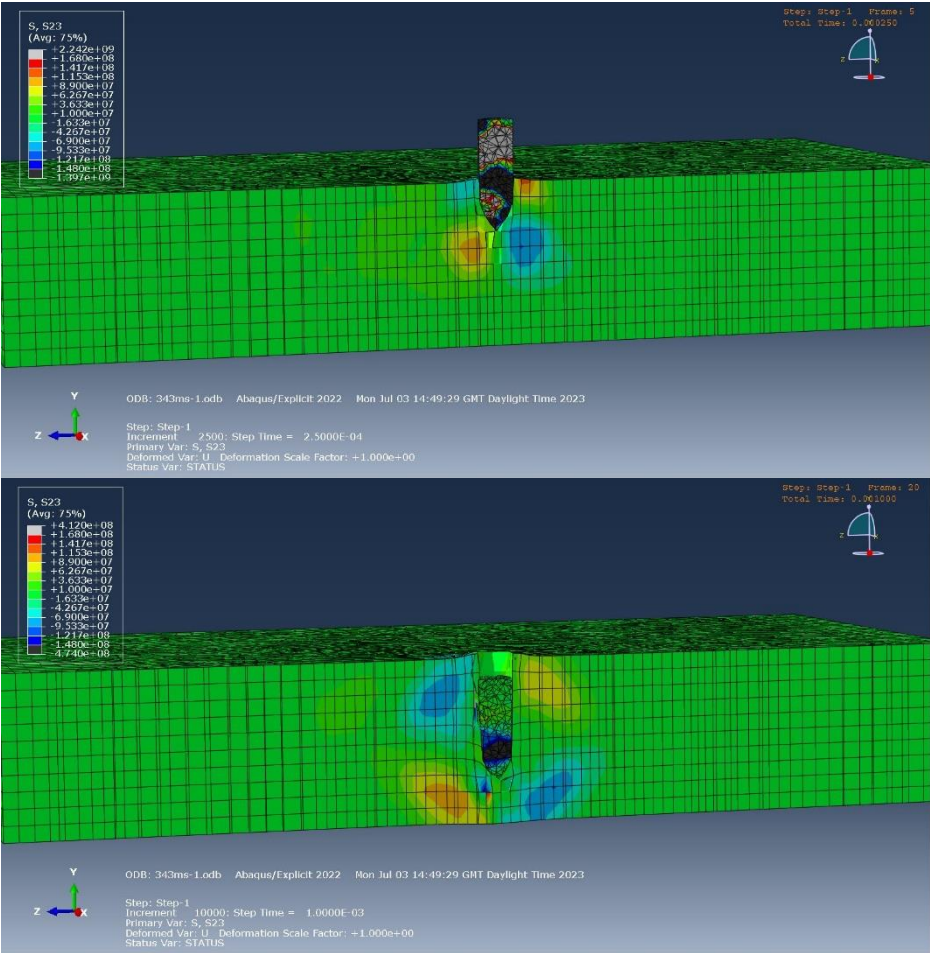
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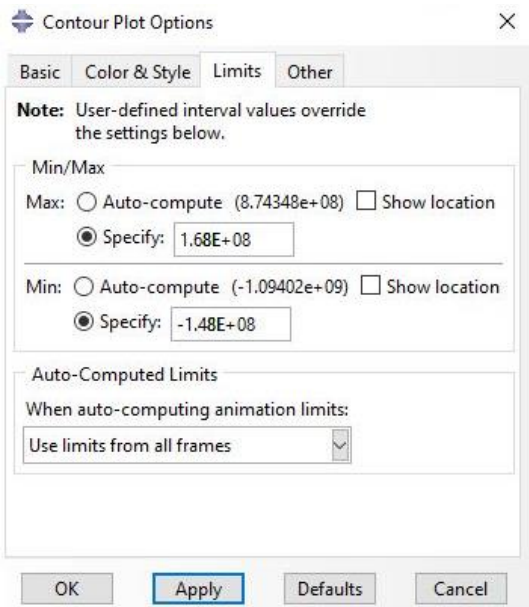
APPENDICES

APPENDIX A – ALL SIMULATION RESULTS

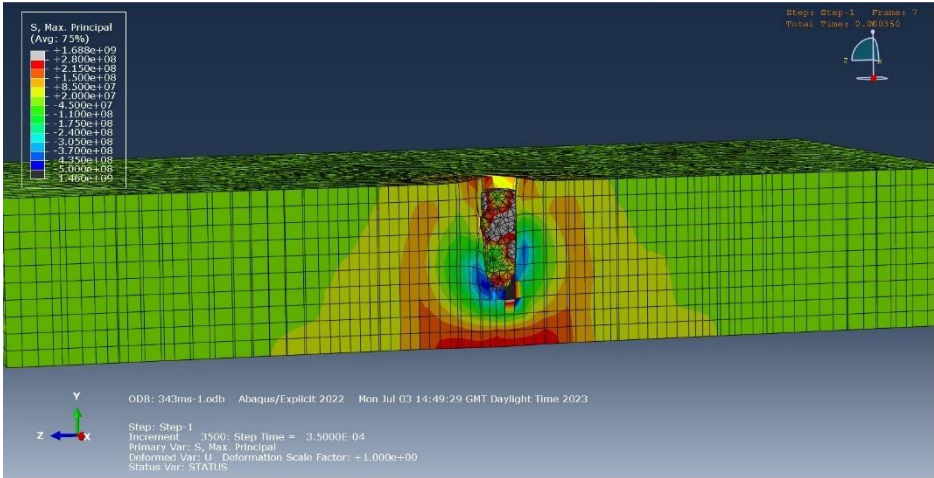
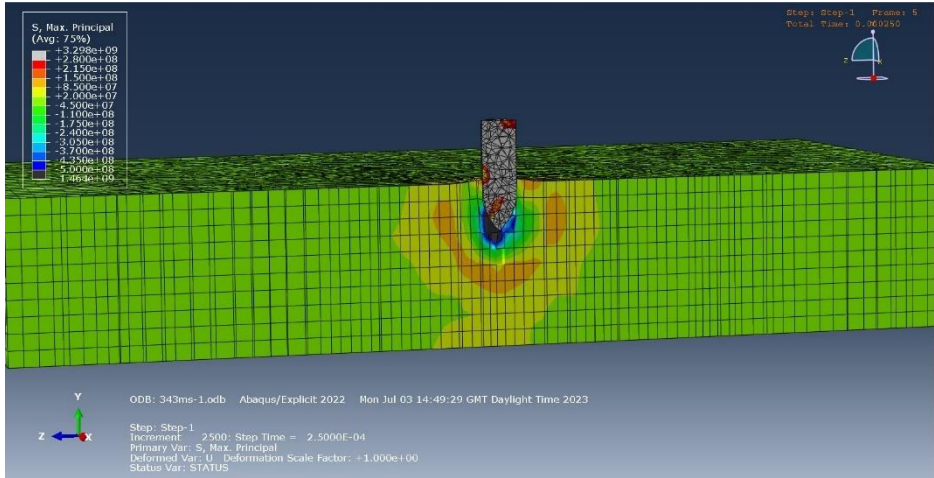
343MS⁻¹

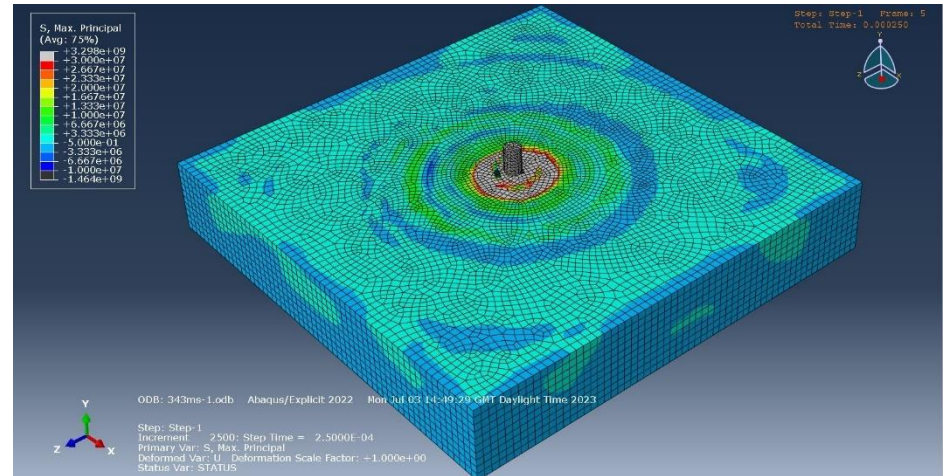
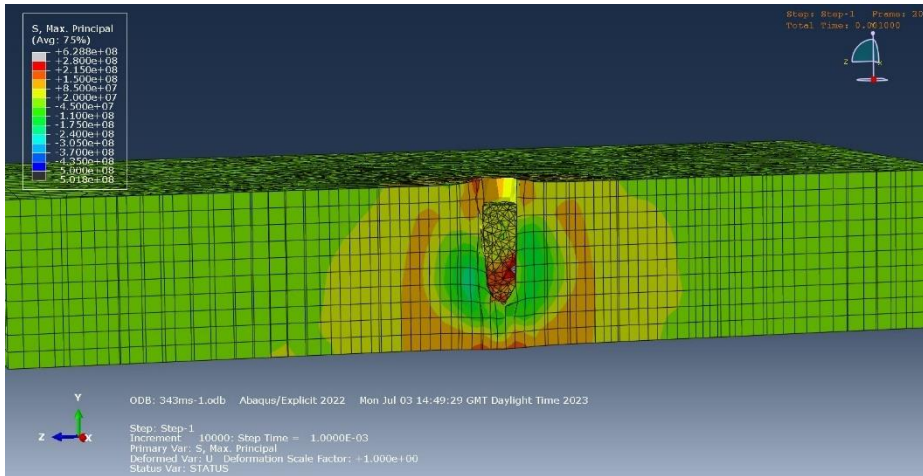
S23





SMAx





Contour Plot Options

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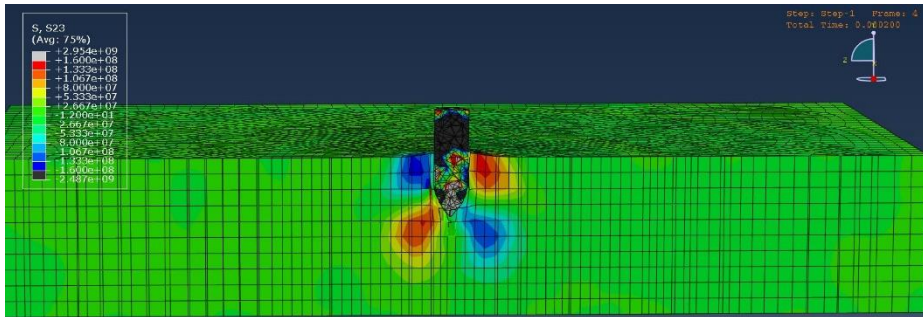
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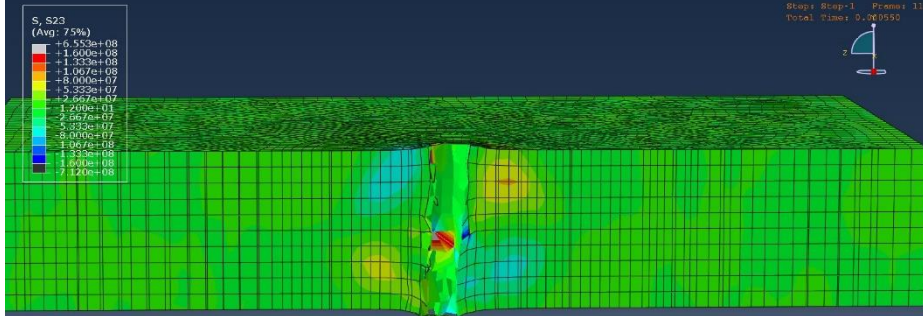
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450MS⁻¹



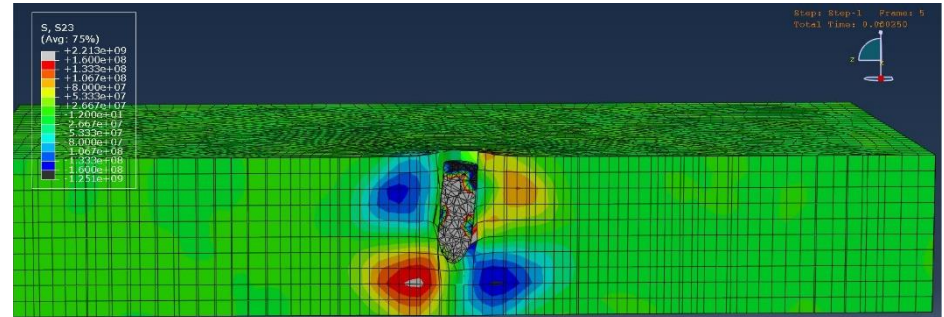
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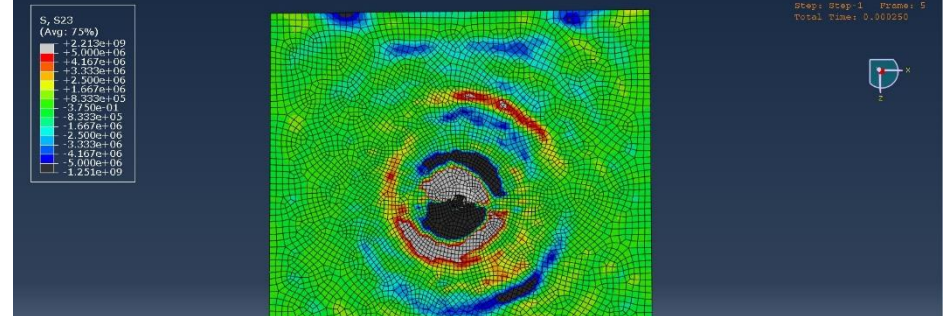
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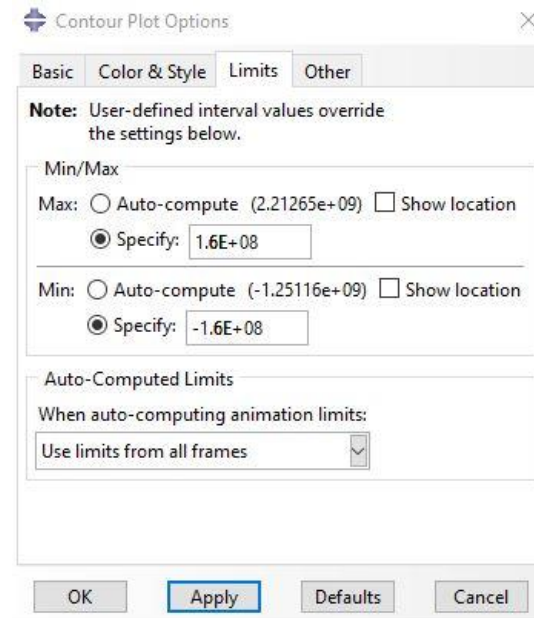
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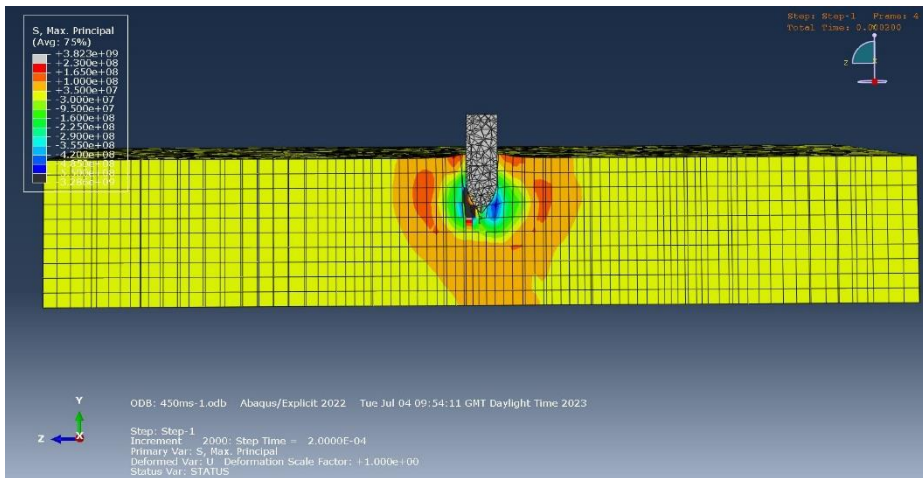


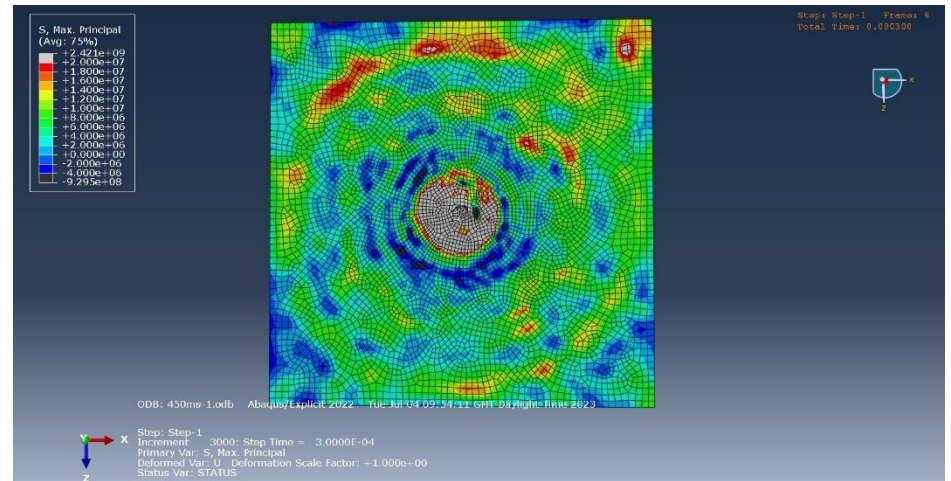
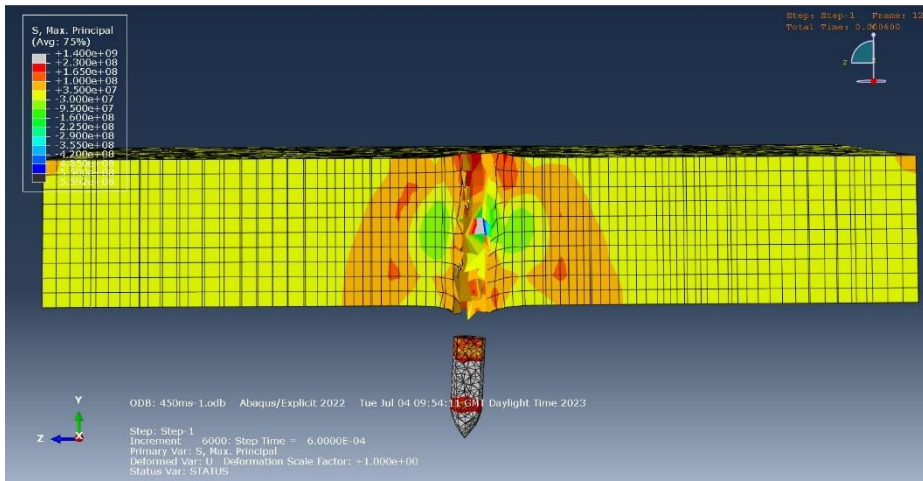
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SMAX





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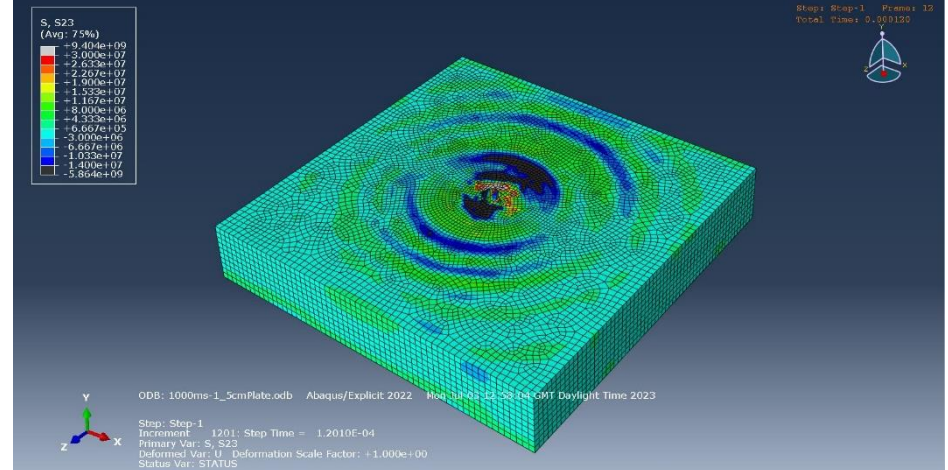
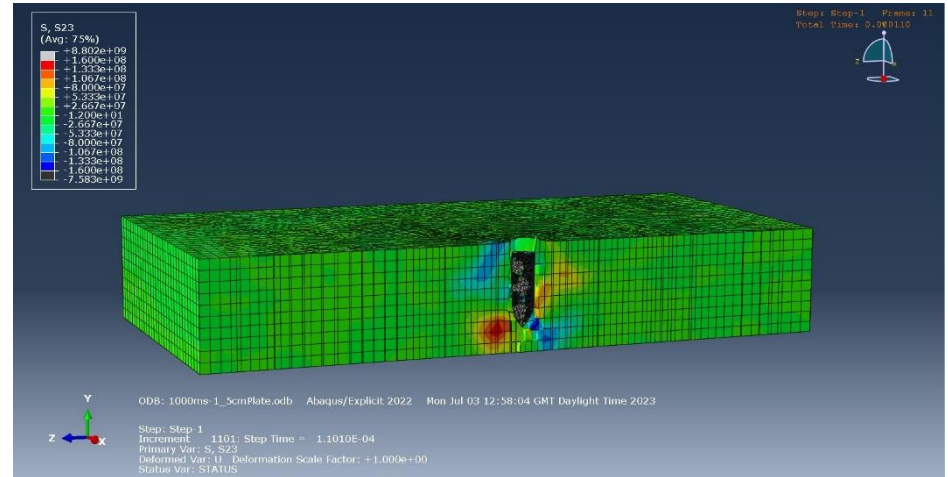
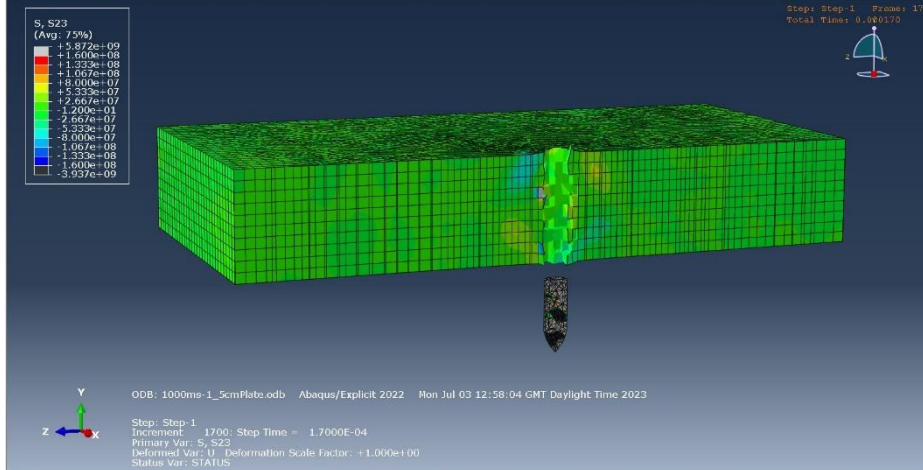
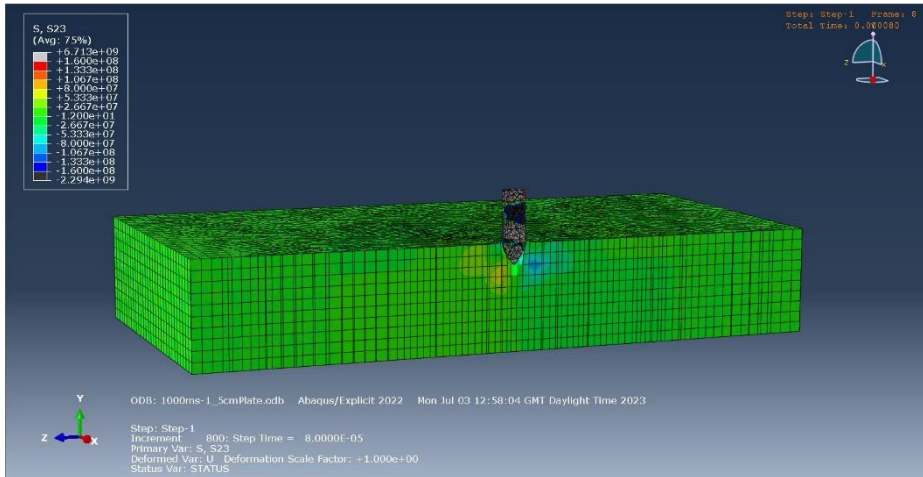
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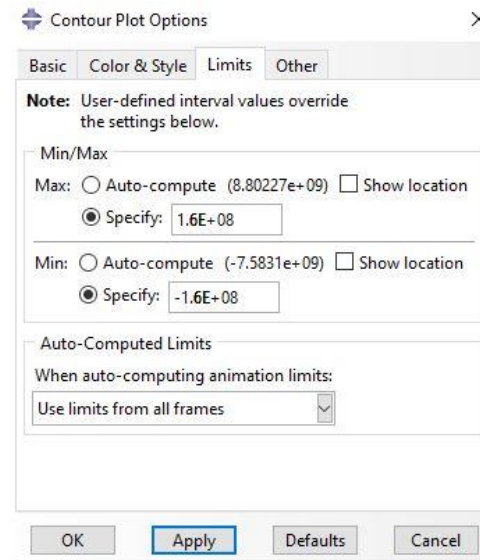
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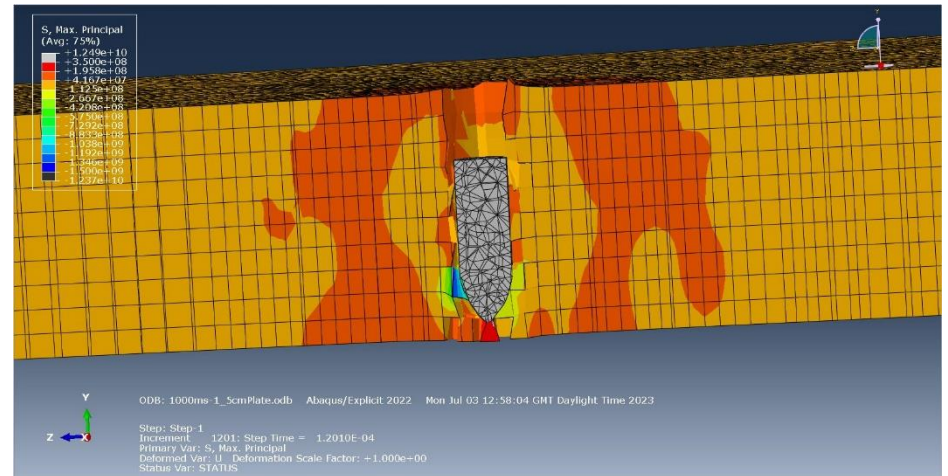
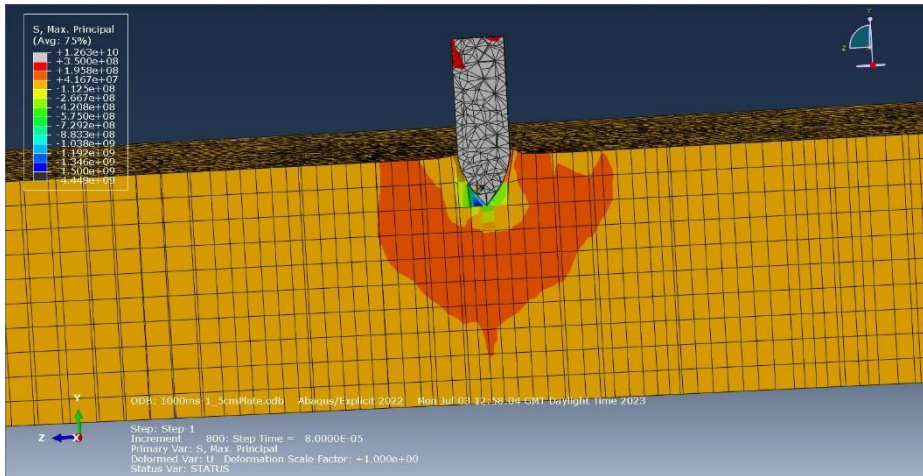
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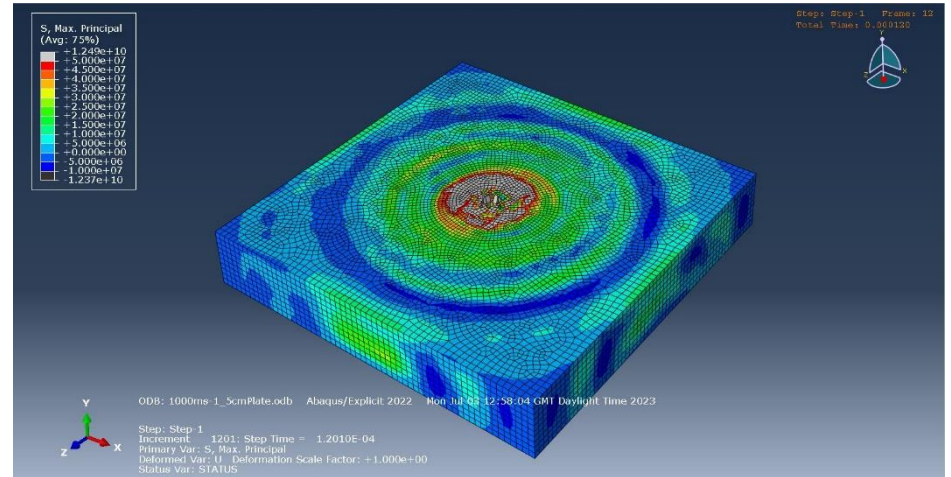
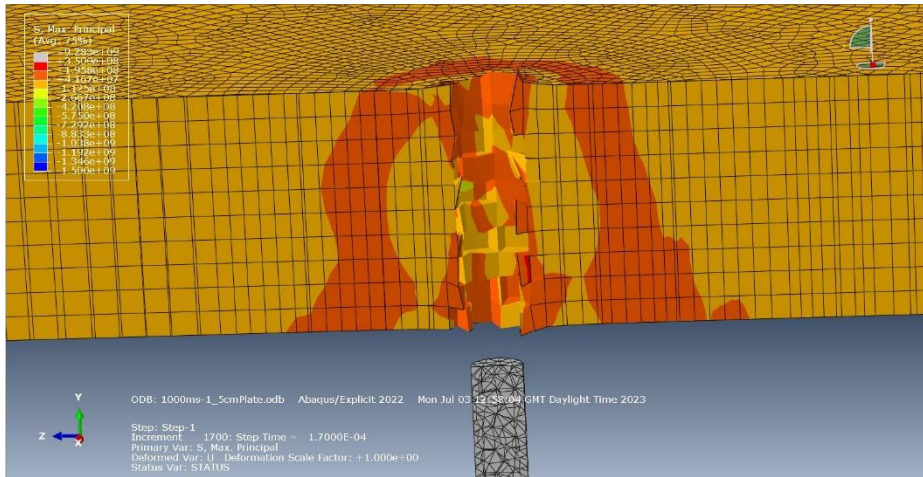
1000MS⁻¹





SMAx





Contour Plot Options

Basic Color & Style Limits Other

Note: User-defined interval values override the settings below.

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Auto-Computed Limits

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OK Apply Defaults Cancel

APPENDIX B – MATLAB PLOTTING SCRIPT

```
CLC
clear all

data1 = readmatrix('343ms-1_V2.txt');

X1 = data1(:,1);
Y1 = abs(data1(:,2));

plot(X1,Y1,"Marker","+","Color","b")

hold on

data2 = readmatrix('450ms-1_V2.txt');

X2 = data2(:,1);
Y2 = abs(data2(:,2));

plot(X2,Y2,"Marker","o","Color","g")
hold on

%%

data3 = readmatrix('1000ms-1_V2.txt');

X30 = data3(:,1);
X3 = X30;

i=1;
while i<=length(X30)
    X3(i) = (X30(i))*X2(length(X2))/(X30(length(X30)));
    i=i+1;
end
Y3 = abs(data3(:,2));

plot(X3,Y3,"Marker","*","Color","r")

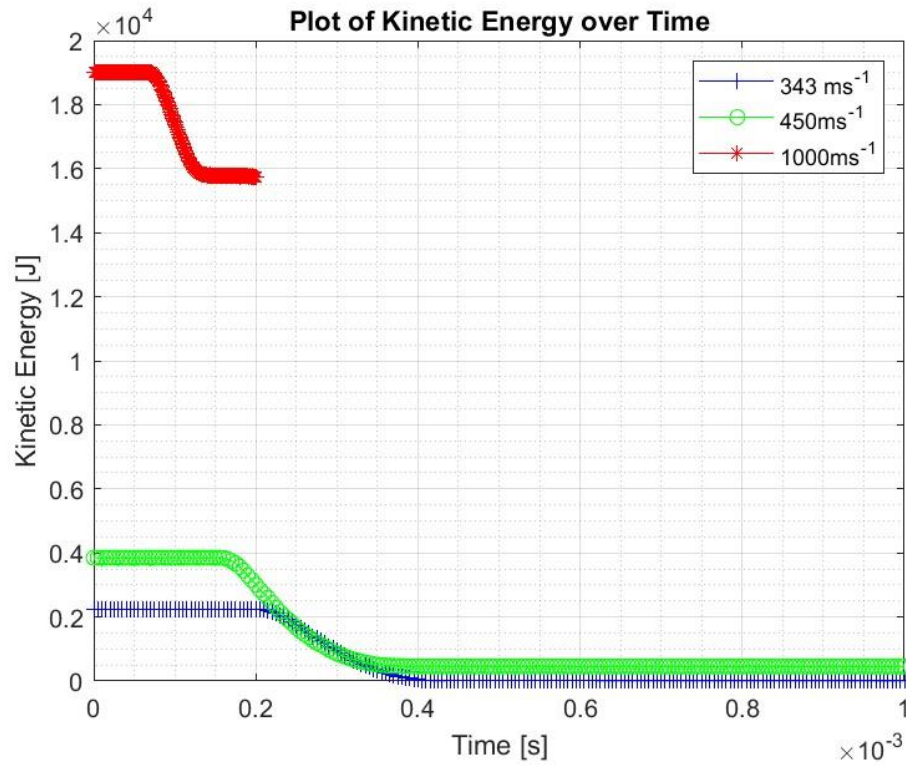
title('Plot of Projectile Velocity over Time')
xlabel('Time [s]')
ylabel('Velocity [ms-1]')
legend('343 ms-1','450ms-1','1000ms-1')
grid on
grid minor

hold off

%%
```

APPENDIX C – UNSCALED PLOTS

UNSCALED KINETIC ENERGY PLOT



UNSCALED VELOCITY PLOT

