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Dynamic Stress – Strain Investigation.

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Executive Summary:

An investigation was made into the elements of stress and strain relative to a 'normal' impact of an undefined projectile into a ductile aluminium plate. This was undertaken to demonstrate an understanding of basic mechanical and structural attributes of physics and engineering science. A computational simulation was undertaken through ABAQUS and endorsed through complimentary theoretical exploration. Analysis of this data was exercised and concluded that the defining parameters entered into the software are based on approximation and so is limited in its execution. Tensile stress is the dominant force exuded within this simulation and; that with an increase in initial velocity there is a successive increase in retention of magnitude to fabricate the residual velocity of a projectile.

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1 INTRODUCTION

1.1 Objective

The objective of this report was to demonstrate understanding of basic mechanical and structural attributes of physics and engineering science. An investigation was made into the elements of stress and strain relative to a 'normal' impact of an undefined projectile into a ductile aluminium plate with a range of velocities.

1.2 Standard Theory

There is importance to understand underlying and subordinate theoretical concepts to fully embrace the content of this report.

1.2.1 Loading

Loading is a key consideration when assessing any physical problem as direction and type of force is equally as important as its magnitude. Different types of force will yield different

experimental results if exerted on the same material model and are always subject to a datum or point of reference. There are five underlying types of force described below and demonstrated graphically in **FIGURE 1 - Types of Loading [1]**:

Tension is essentially application of force to pull the material apart and stretch it.

Compression is the inverse of tensile loading in that it is constriction of a material.

Shear could be termed as an offset compression; in that a force would be applied above a reference point in one direction and that an opposing force would be applied just below the reference point. An application of shear loading would be scissors.

Bending happens when a curve appears in a material meaning that a compression is formed on the inner part of the curve and tension on the opposed.

Torsion is the product of rotational forces acting upon a material.

In addition to the types of loading when reference of force over a period of time is required; consideration should be made to the application of force in that whether it remains constant (referred to as static loading) or whether it is subject to cyclic loading. An example of cyclic loading could be a road bridge; having vehicles applying load for time periods before relieving at the end of the traverse. [1, 2.]

1.2.2 Stress (σ)

Stress in a mechanical sense can be defined as force applied over an area and is generally termed as the force that will deform a body. In reality material property will play heavily in the distribution of stress through it. For instance, if abnormalities are present within a material such as a casting it will drastically alter what happens when stress is applied. For the purpose of this assignment assumptions are made that there is no material abnormality. Stress is measured in Pascal's (Pa) or Newtons per square metre (Nm^2).

$$\sigma = \frac{Force}{Area} = Pa = Nm^2$$

Consideration should be made to the axiom that the areas that can be interpreted are infinite and often are assumed to be an average stress in three axes. Much like loading stresses are with respect to a reference point and the three aforementioned planes running in the direction of x, y, and z wherein x and y are 'normal' to each other but parallel to the plane of interest and z set normal to the plane. A fully theoretical approach to stress at a given point can be defined by a 'stress tensor' holding nine stress components as shown in **FIGURE 2**. [1, 3.]

1.2.3 Strain (ϵ)

Strain is essentially the deformation of a material subjected to stress, it would be fair to say that strain is one of the products of stress. Strain is defined as change in length of the material divisible by the original length; this means no units are attached to the achieved result.

$$Strain (\epsilon) = \frac{Elongation}{original\ length} = \frac{\Delta l}{l_o}$$

Primarily, strain defines a materials ability to retain its material properties and dimensions post stress event; if deformation occurs but the material remains unchanged it is termed as elastic deformation as the point of yield has not been passed on the stress strain curve. If the yield properties are surpassed from the application of stress, then the material will not return to its original point and will become work or strain hardened and from the yield point

through the ultimate tensile strength (UTS) point to failure is referred to as plastic deformation. [1, 3.]

1.2.4 Stress strain curve

The purpose of plotting a stress strain curve is to enable the user to interrogate the material model; Young's modulus (E), point of yield and UTS are all identifiable on this type of graph. In addition, from the origin of the curve until the yield point denotes the Elastic period and post yield point the plastic respectively. It should be stated that a stress strain curve is intended to give a guideline to the materials reaction as it is not a dynamic assessment and refers only to the original dimension of the material being assessed. **FIGURE 3** is an explanation of how to interpret a stress strain curve and **FIGURE 4** is a plot for the chosen material Aluminium 6201 with various treatments; the material to consider is Aluminium 6201 T6. [1, 3.]

1.2.5 Young's modulus (E)

Young's modulus is often referred to as the stiffness of a material; it is denoted on a stress strain graph as the initial incline leading to the proportional limit point. Hooke's law states that stress is proportional to strain and the equation for Young's modulus is a demonstration of this law. [1]

$$\text{Youngs modulus} = \frac{\text{stress}}{\text{strain}} = \frac{\sigma}{\epsilon}$$

1.2.6 Direct vs shear stress

Direct stress can be defined as a load applied perpendicular to the plane of interest, referring to **1.2.1**, it can be deemed that tensile and compressive force loading relative to the point of reference supply a product of direct stress.

Shear stress is the product of applying a loading in shear as defined in **1.2.1**. [1]

1.2.7 Newton's second law

Newton's second law states that force corresponds to mass magnified by the area to which it's applied. [1]

$$F = ma$$

But using the equations of motion

$$a = V - \frac{U}{t}$$

Therefore

$$F = m \left(\frac{V - U}{t} \right)$$

1.2.8 Elastic and Inelastic collisions

A 'perfect' elastic collision is one in which all of the kinetic energy is transferred, and an Inelastic collision is one in which the energy is not fully transferred and losses are observed. [1]

1.2.9 Coefficient of restitution (e)

This coefficient is defined as the ratio between the velocity post impact divisible by the initial velocity. [1]

$$e = \frac{V_2}{V_1}$$

1.2.10 Poisson's ratio (ν)

Poisson's ratio is a way to define the 'necking' effect of a material when exposed to strain across more than one direction and can be defined as: [1]

$$\nu = \frac{\text{lateral } \epsilon}{\text{longitudinal } \epsilon}$$

1.2.11 Density (ρ)

Density is a measure of mass per unit volume and standard SI units are in Kg/m^3 . Density can be acquired by way of: [1].

$$\rho = \frac{\text{mass}}{\text{volume}}$$

1.2.12 Conservation of momentum

Conservation of momentum works on the assumption that if no external factors are present the energy in equates to the energy out and so: [1]

$$\text{Momentum before impact} = \text{momentum post impact}$$

$$m_1U_1 + m_2U_2 = m_1V_1 + m_2V_2$$

1.2.13 Conservation of Kinetic Energy (KE)

The conservation of kinetic energy is the mathematical depiction of an elastic collision and assumes no losses meaning the energy in equates to the energy out therefore: [1]

$$KE \text{ before impact} = KE \text{ post impact}$$

$$KE = \frac{1}{2}mV^2 = \text{joules}$$

1.3 Ballistic impact theory

Ballistic impact theory is often termed as terminal ballistics and the key focus of such studies are based primarily on the relationship between the target and projectile in context of penetration and projectile velocity. [6, 7]

1.3.1 Note on projectile

For this report the projectile in question will not distort and retain its geometric shape, mass and generic integrity. This is for simplicity and to focus on the plate's reaction to the impact. [1, 6.]

1.3.2 Descriptors of impact types

- Ricochet - indentation of plate, projectile effectively bounces off.
- Penetration – projectile enters the plate perforating the initial surface only.
- Embedment – projectile is lodged into the plate.
- Perforation – projectile passes through the entirety of the plate.
- Ballistic limit – the lowest velocity at which a perforation will occur. [7]

1.3.3 Considerations for impact scenario

For this report there are no external forces acting on the dynamic simulation and so, the key components that affect the result are

Plate thickness:

As the target plate becomes thicker stress wave reflection becomes more prominent in its effect to the dynamic event (initial penetration).

Shape of the projectile

Flat ended projectiles on penetration will likely cause a plug to be punched out of the plate material whereas ogival or pointed projectiles will often cause the other types of effects detailed in **FIGURE 5**. [6, 7]

1.3.4 Ballistic velocity impact

Ballistic velocity (though varied) can generally be deemed to be under 1000ms^{-1} , this type of impact can be defined by its material property; principally stress. If a projectile impacts a plate within the materials elastic limit it will likely ricochet, and only localised plastic deformation will occur however, above the yield strength there will be permanent plastic deformation, work hardening then post UTS, strain softening before failure. A common interest of ballistic velocity impacts is, the depth the projectile penetrates the plate this can be defined by: [6, 7.]

$$X_p = \frac{mV^2}{A2Y_c}$$

Where X_p is the distance of penetration, m is mass, A is area, V is velocity and Y_c is cavity strength (approx. 3 times the yield strength) [6, 7.]

1.3.5 Hydrodynamic velocity impact

Hydrodynamics is the study of material under extreme conditions that make them behave like a fluid; an example of this would be an impact of over 1000ms^{-1} . Essentially hydrodynamic impact is when the forces exerted by the projectile far exceed the targets material strength and the material takes on fluid like behaviour. Hydrodynamic often is relative to Bernoulli's principle wherein velocity is inversely proportional to pressure. [6, 7.]

1.3.6 Intermediate velocity impacts

These impact types are where initial impacts are within the hydrodynamic regime and through perforation attain ballistic type properties. This equates to a 'threshold' type impact between two states wherein initially the material undertakes fluid like behaviour then material strength is re-instated as velocity and inertia reduce. [6, 7.]

1.3.7 Target consideration

The results of each experiment will differ dependant not only on the material model as in its material properties but also; its geometric parameters play a tremendous part in the rate and type of deformation and/or failure. The use of a ductile material will likely suffer more deformation prior to failure unlike a ceramic material which has little deformation before catastrophic failure. [6, 7.]

1.3.8 Failure types

FIGURE 5 expresses some generic types of target failure found when impacted by a projectile at a given speed. In reality a projectile is subject to infinite axes of freedom whilst in free air and so it is often the case results of a test will comprise of a series of the failure types annotated. Failure types are subject to defining parameters that include projectile velocity and impact trajectory, material model, temperature et al. It would be fair to state that the geometric parameters for instance; target thickness will also play a substantial part in the failure type achieved. It is often assumed that a projectile will compress material in its path to make room for the projectile to pass. However, in a thinner plate the material has little to combat the inertia of the projectile and so dependent on the material model a petalling effect can be seen. Petalling is where at comparatively low pressures to that of a thicker plate; a rupture occurs similar to seen in a radial fracture, yet stress is still focussed upon the cracks which cause a shearing or tearing type motion resulting in the plate retaining 'triangular petals' post impact having allowed the traverse of the projectile. [1, 6, 7.]

1.3.9 Hertzian theory

This theory is a substantial measure of contact mechanics theory relative to stress. Hertz's theory works on the principal of a potential function of a layer with distributed density with an infinitely flattened ellipsoid with uniform mass distribution between two bodies under compression; commonly termed as theory of the triaxial ellipsoid. As is evident this conceptually is hard to grasp and was simplified by Constantin Weber in 1948 as a sectional area of an arbitrary stress distribution over the surface of the half space inside a stress ellipse comparing the loaded elliptical face with a circle. The Hertzian cone depicts the stress

wave propagation through the material when impacted by a sphere or more specifically the tip of an ogival projectile and is shown in **FIGURE 6**. Hertzian theory contextually makes the assumptions; of isotropic homogeneous material models, contact area is wholly smooth, contacting surfaces retain a linearly elastic relationship and the contact area remains small. [1, 8, 10.]

2 EXPERIMENT DESCRIPTION

2.1 Description of the computational simulation

A simulation of a ballistic impact was created; the projectile was a non-deforming mass of 30g retaining an ogival shape Ø9.8mm x 9.95mm in length with a $104^{\circ}_{Approx.}$ conical point. Its axis of travel was perpendicular (normal) to the largest face of the plate, it had a small stand-off and was impacted into the plate at 4 exponential increments initiating at 100 ms^{-1} to 800 ms^{-1} assessment was focussed upon the velocity of the projectile and the shear and tensile forces acting upon the plate. Given the trajectory of the projectile it is estimated that direct stress is the main component affecting the plate.

2.2 Material selection

There was a necessity to decide on a grade of aluminium to place in the simulation, the rationale behind the decision was to avoid a common type of aluminium with the appropriate material properties available the decision was arbitrarily made to continue with Aluminium 6201 – T6.

2.2.1 Material model

The chemical composition of Aluminium 6201 alloy is 98.5% Al (aluminium), 0.8% Mg (Magnesium) & 0.7% Si (Silicon)

This simulation only had a requirement to add a limited amount of material properties these are detailed in **TABLE 1 - Material model data [12]**. In addition, the sound speed is required in order to pose theoretical calculation; for the purpose of these calculations a generic sound speed of Aluminium is used at a value of 5100Vms^{-1} . [11, 12, 13.]

2.2.2 Applications

Common applications of Aluminium 6210- T6 are as follows but not limited to: high strength wire rod, piping/tubing, conductive bars and plate's et al. [5, 11.]

2.2.3 Material Assumptions

For the purpose of this assignment there is an assumption that the target plate retains Isotropic and homogeneous properties and no account has been made for any abnormalities within the plate.

2.3 Computational experimental layout

2.3.1 Software

The simulation software used was Dassault Systemes SIMULIA Abaqus CAE 2018.

2.3.2 Material properties

Material properties were altered from the predefined model assembly to match that of the material model referenced in **2.2.1. (TABLE 1)** as shown in **FIGURE 7 - Material editFIGURE 7**.

2.3.3 Dynamic Properties

The predefined model supplied was edited; an exponential range of velocities was input to the software as shown in **FIGURE 8** these were arbitrarily defined as:

- 100ms^{-1} or 100mps
- 200ms^{-1} or 200mps
- 400ms^{-1} or 400mps
- 800ms^{-1} or 800mps

- 2.3.4 Tensile force
The max principal stress was assessed this is relative to the vertical component of stress specifically the tensile forces.
- 2.3.5 Shear force
The shear stress was evaluated in the S23 (Y/Z) plane.
- 2.3.6 Velocity
Initial and residual velocity of the projectile was assessed by selecting a node at the tip of the ogival projectile and plotting its magnitude against time.
- 2.3.7 **Note:**
The mesh to particle transfer point referred to as smooth particle hydrodynamic (SPH) was set at 150×10^6 (150 MPa) due to program constraints.

3 EXPERIMENTAL DATA

3.1 Theoretical estimation

Calculations made in theory to attain an initial contact stress which can be used AD-HOC as an upper limit to which FEA analysis should not be greater than. This estimate is defined by the equation;

$$\sigma = \rho c V$$

Where ρ is the material density of the value 2690 kg/m^3 ,

c is sound speed denoted as 5100 Vms^{-1} and,

V is velocity is the variable accounted for below. the resultant will be defined in Pascals (Pa)

- 3.1.1 100 ms^{-1}
 $\sigma = (2690)(5100)(100) = 1.3719 \text{ GPa}$
- 3.1.2 200 ms^{-1}
 $\sigma = (2690)(5100)(200) = 2.7438 \text{ GPa}$
- 3.1.3 400 ms^{-1}
 $\sigma = (2690)(5100)(400) = 5.4876 \text{ GPa}$
- 3.1.4 800 ms^{-1}
 $\sigma = (2690)(5100)(800) = 10.9752 \text{ GPa}$

3.2 Computational imagery

- 3.2.1 100 ms^{-1}
Two figures demonstrate the plate impact at $7.0034 \times 10^{-5} \text{ seconds}$ with a velocity of 100 ms^{-1} for reference contour limits were set at $\pm 6 \times 10^7$. In terms of ballistic description, the cycle involves radial fracture and embedment; there is a visible flexure of the plate when the projectile velocity reduces to zero and the kinetic force is transferred into elastic stress within the plate. The cycle has maximum tensile stresses of +351MPa and -969MPa.

FIGURE 9 denotes the max principal stress formation at the given time; there is an obvious Hertzian cone outlined by the yellow band expanding on **1.3.9**. the Hertzian cone is an indefinite 100° cone set 130° from the trajectory axis of the projectile and is often the cause of spalling type failure shown in **FIGURE 5**. **FIGURE 9** is showing a tensile wave emanating from the shaft section of the projectile potentially from hoop stresses coming to meet the reflection from the initial impact wave causing compression highlighted by the blue positioned either side of the crack. The black lines symbolise zonal stress areas and can be

likened to a shock wave travelling through the material and are in process of returning to the impact area to interfere with the propagation of stress, though this; like the hoop stress has not been endorsed. At any point where there is an indication of over $\pm 195\text{MPa}$ of stress then plastic deformation will occur and although not constrained it should only happen within the grey areas. Any other stresses should be elastic; maximum tensile stresses shown within **FIGURE 9** are $+1.7\text{GPa} - 3.28\text{GPa}$.

FIGURE 10 is a demonstration of Shear stress components; it can be seen immediately that areas of shear stress are most prominent around the impact point where tensile stress is of a lower magnitude. Shear stress can also be seen around failure points and cracking suggesting the cracking is a product of shear stress in the cycle the maximum shear stress is $+122\text{MPa} - 118\text{MPa}$.

In this simulation it can be deemed that tensile stresses are dominant in terms of magnitude.

3.2.2 200 ms^{-1}

As in **3.2.1**, two figures demonstrate the plate impact at $3.0007 \times 10^{-5}\text{seconds}$ with a velocity of 200ms^{-1} for reference contour limits were set at $\pm 5 \times 10^7$. In terms of ballistic description, the cycle again involves radial fracture and embedment; there is a visible flexure of the plate when the projectile velocity reduces to zero and the kinetic force is transferred into elastic stress within the plate. The cycle has maximum tensile stresses of $+3.269\text{GPa}$ and -3.31GPa and so SPH particles are formed.

FIGURE 11 denotes the max principal stress formation at the given time, it can be seen that a Hertzian cone has formed, contacted the opposing free face of the material and rebounded back into the main impact zone.

FIGURE 12 is a demonstration of Shear stress components; it can be seen immediately that areas of shear stress are most prominent around the impact point where tensile stress is of a lower magnitude. The maximum shear stress is $+115.3\text{MPa} - 114.5\text{MPa}$. It is evident that when shear stress has propagated to the opposing free surface then stress emanates around cracking in the mid-section of the plane

Again, in this simulation it can be deemed that tensile stresses are dominant in terms of magnitude

3.2.3 400 ms^{-1}

The duet of figures for the plate impact at $1.0073 \times 10^{-5}\text{seconds}$ with a velocity of 400ms^{-1} retained contour limits set at $\pm 5 \times 10^7$. In terms of ballistic description, the cycle involves brittle fracture due to work hardening of the material i.e. plastic deformation between yield and UTS causes the material to become hardened and therefore brittle; the cycle has maximum tensile stresses of $+1.724\text{GPa}$ and -3.305GPa and results in the projectile perforating the plate. In spite of the perforation the stress waves still follow suit to the two previous speeds but at a much faster rate and the rebounding tensile wave then has a noticeable contribution to the plastic deformation and generation of SPH particles.

FIGURE 13 denotes the max principal stress formation at the given time which is close to the point of impact. Although expected compression is not evident due to being on a tensile setting it is apparent that, with the increase in speed there is still the start of a Hertzian cone but there is also an obvious lateral tensile force that elicits immediate failure and SPH generation potentially again caused by hoop stress. There is also a clear reflection of the shock wave defined by the contour line at the opposing side of the plate.

FIGURE 14 is a demonstration of Shear stress components; it can be seen immediately that areas of shear stress are most prominent around the impact point where tensile stress is of a lower magnitude. If an arbitrary line of best fit is taken through the areas of higher stress it is a clear demonstration of the Hertzian cone. The maximum shear stress is $+124.6\text{MPa} - 124.1\text{MPa}$.

In this simulation it can be deemed that tensile stresses are dominant in terms of magnitude

3.2.4 800 ms⁻¹

The pair of figures for the plate impact at 1.0005×10^{-5} seconds with a velocity of 800ms⁻¹ retained contour limits set at $\pm 5 \times 10^7$. In terms of ballistic description, the cycle again involves perforation and brittle fracture due to work hardening of the material i.e. plastic deformation between yield and UTS the cycle has maximum tensile stresses of +8.582GPa and -14.02GPa. This cycle is in close proximity to the hydrodynamic regime discussed in **1.3.5**, and so failure is more prominent at an earlier time as the material property limitations are exceeded on impact implying a more fluid like behaviour. When the projectile has fully penetrated the plate there is catastrophic plastic failure and the area surrounding the projectile is almost entirely converted to SPH particles. As the tip of the projectile comes parallel with the original opposing free face of the target the majority of the opposing face within the projectile has ruptured.

FIGURE 15 denotes the max principal stress formation at the given time the tensile wave has contacted and returned from the opposing face and only the tip of the Hertzian cone remains as the rest has been obscured by radial hoop stress and reverberated interference stress. The contour lines demonstrate an almost steady state lateral sound stress wave propagating to the edge of the plate.

FIGURE 16 is a demonstration of Shear stress components; it can be seen immediately that areas of shear stress are most prominent around the impact point where tensile stress is of a lower magnitude and failure is almost immediate; the maximum shear stress is +114.8MPa -114.8MPa signifying a balanced distribution of shear stress.

In this simulation it can be deemed that tensile stresses are dominant in terms of magnitude

3.2.5 Contour lines

Contour lines shown in Figures referenced within **Section 3** equate to zonal stress waves highlighting the stress wave which could be interrogated to attain an accurate representation of the material sound speed

3.2.6 Boundary Failure

Failure shown at the edge of the image is due to magnitude doubling at the boundary

3.2.7 **Note**

Work hardening in front of projectile and compression not shown in the software in max principal and S23 interrogation

3.3 Projectile velocity

3.3.1 100mps

As per 2.3.6 projectile velocities were attained and detailed in **TABLE 2** plotted in **FIGURE 17**

3.3.2 200mps

As per 2.3.6 projectile velocities were attained and detailed in **TABLE 3** plotted in **FIGURE 18**

3.3.3 400mps

As per 2.3.6 projectile velocities were attained and detailed in **TABLE 4** plotted in **FIGURE 19**

3.3.4 800mps

As per 2.3.6 projectile velocities were attained and detailed in **TABLE 5** plotted in **FIGURE 20**

3.3.5 Percentile interpretation

Using a conglomeration of data in **TABLE 2 – 5** divisible by each section's initial projectile velocity detailed in

will provide velocity data in ratio aspect and so comparable to one another. A graphical representation of this is found in **FIGURE 21** and is an alternate way to interpret the coefficient of restitution

3.3.6 Coefficient of restitution

100mps

$$e = \frac{V_2}{V_1} = \frac{0}{100} = 0$$

200mps

$$e = \frac{V_2}{V_1} = \frac{0}{200} = 0$$

400mps

$$e = \frac{V_2}{V_1} = \frac{242.6075}{400} = 0.6065$$

800mps

$$e = \frac{V_2}{V_1} = \frac{660.9299}{800} = 0.8262$$

4 ANALYSIS

4.1 Comparison

4.1.1 Theoretical exercise

Comparison of theoretical estimation in **Section 3.1.** and interpretation of computational Imagery in **Section 3.2.** endorses the majority of the results attained in that the calculated estimation for initial contact stress is not exceeded through the simulation. The only outlier being the negative tensile forces for 800ms⁻¹ which is reaching the threshold for a hydrodynamic velocity impact

4.1.2 Dominant forces

As evaluated in **Section 3.2.** computational imagery it can be deemed that tensile or maximum principal stresses are dominant in terms of magnitude, these forces seem to cause the majority of the plastic deformation of the target plate. However, it can be seen through the same evaluation that the higher levels of shear are evident in close proximity to cracks and fractures in the material. Uncertainty remains for the cause of this and would require further research to understand and quantify.

4.1.3 Velocity of the projectile

As detailed in **3.3.5.** it can be shown that as velocity increases closer to a hydrodynamic state; the initial velocity of the projectile compared to its residual velocity attains a closer relationship. in that it can be observed that an increase in initial velocity means retention of a greater percentage of that input velocity as its residual. This is graphically represented in **FIGURE 21.**

4.1.4 Ballistic limit

Although it cannot be quantifiably stated with real accuracy this report has defined the ballistic limit; the point at which perforation occurs within the range of 200ms⁻¹ and 400ms⁻¹

4.2 Error

During experimental activity there is error that needs to be accounted for stated. **Section 4.2** is potential error sources that have not been fully addressed through the report and perhaps could affect data stated and evaluated throughout this report.

- 4.2.1 Mesh
Coarse mesh leads to inaccuracy in the data.
- 4.2.2 Expectations
Expected compression in front of bullet not apparent within computational imagery.
- 4.2.3 Accountancy
Radial hoop stress not accounted for.
- 4.2.4 Material model
The material model for this exercise is inadequate and undefined for FEA analysis.
- 4.2.5 Planning
Graphical outputs regarding energy were omitted due to content requirement far exceeding given word count.

4.3 Review and learning initiative

To assess this report and all its subordinate activity it is required to make recommendations based on the delivery of what can be altered to potentially produce a better experiment.

- 4.3.1 Finite approach
An axis symmetric view to give more detail in a single plane.
- 4.3.2 Mesh
Mesh could be made finer around the projectile impact area in order to gain a more finite representation of the data.
- 4.3.3 Modelling
Model ¼ of the projectile and plate due to symmetry of the experiment means 1000 node limitation of the 'student' software will allow for more information by a factor of 4.
- 4.3.4 Material model
Further detail is required in the material model to include damage modelling et al.
- 4.3.5 Geometric approach
Expand the surface area of the plate in order to negate reflected stress waves interference with the point of interest at the impact point.
- 4.3.6 Boundary
Ensure the outer perimeter of the plate is radial to ensure even reflection of stress waves.
- 4.3.7 Assignment requirement
Hone content requirement for assignment to remove ambiguity and partial delivery of information. Et al.

5 CONCLUSION

To conclude this report, the simulation executed is an approximation based on the information entered into the software. In order to attain greater accuracy an in-depth material model should be entered to attain a greater level of realism. The simulation has highlighted that tensile stress is the overriding resolution of force in terms of magnitude and that with an increase in initial velocity there is a successive increase in retention to amount to; residual velocity of a projectile. Finally the simulation highlighted a range that contains the ballistic limit of this simulation of between 200-400ms⁻¹

6 FIGURES AND TABLES

6.1 Figures

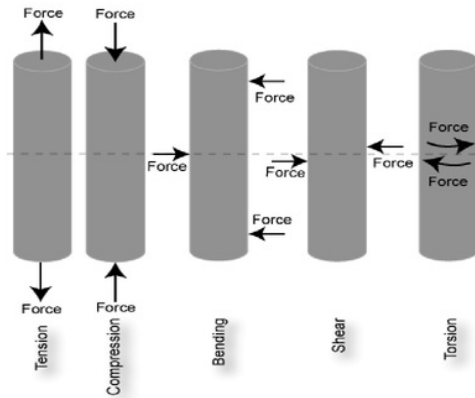


FIGURE 1 - Types of Loading [1]

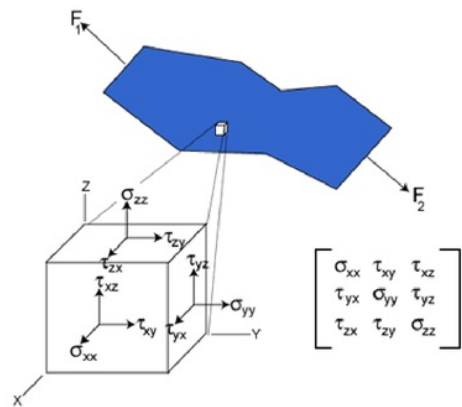


FIGURE 2 - Stress Tensor [3]

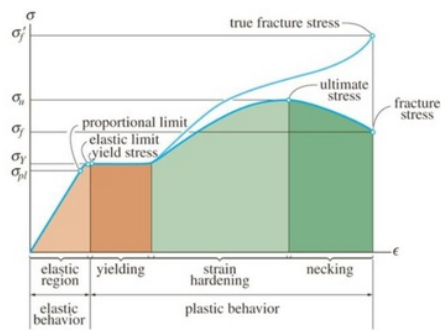


FIGURE 3 - Stress strain explanation [4]

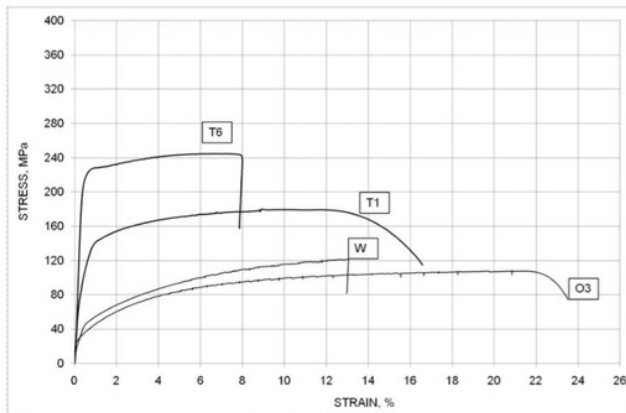
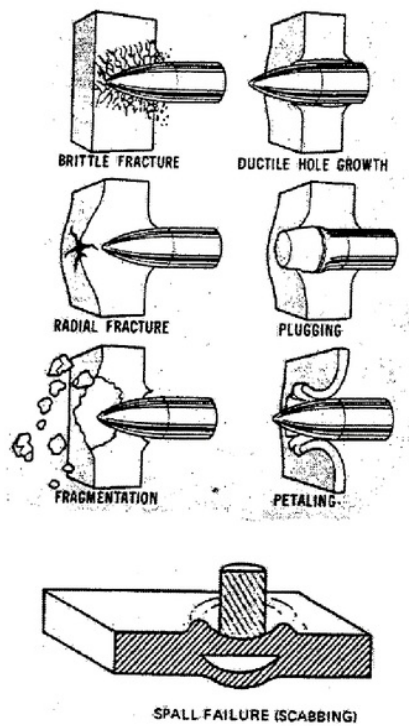


FIGURE 4 - Chosen material stress strain curve [5]



Typical penetration modes (from Army Research Laboratory report ARL-TR-1741, John F. Chinella, Brian Pothier, Martin G. H. Wells, "Processing, Mechanical Properties, and Ballistic Impact Effects of Austempered Ductile Iron," (1998))

FIGURE 5 - Types of projectile penetration [9]

Hertzian cone crack

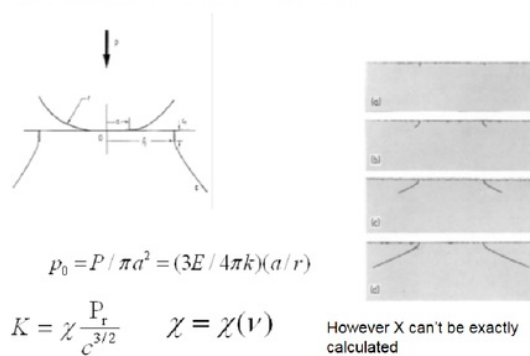


FIGURE 6 - Hertzian cone crack demonstration [10]

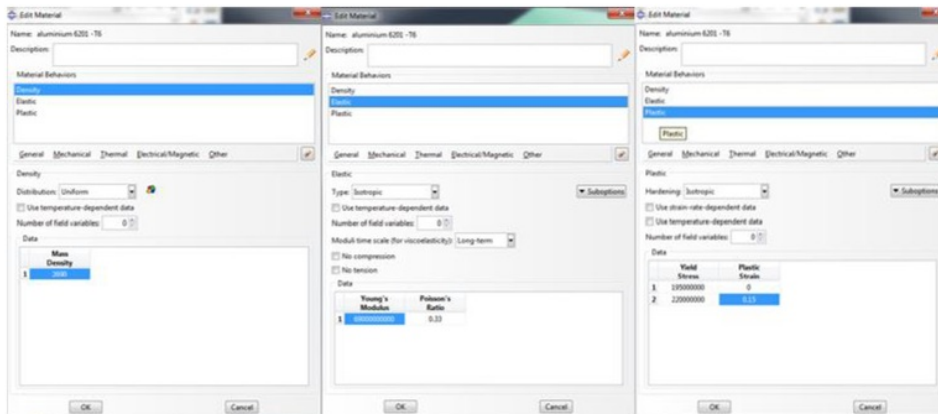


FIGURE 7 - Material edit



FIGURE 8 - Velocity edit

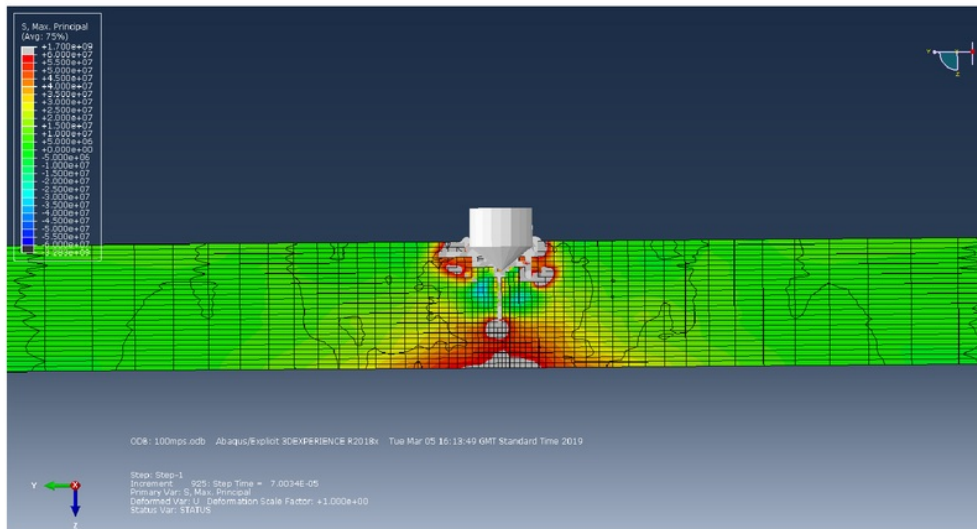


FIGURE 9 - Max principal 100mps 7.0034e-5

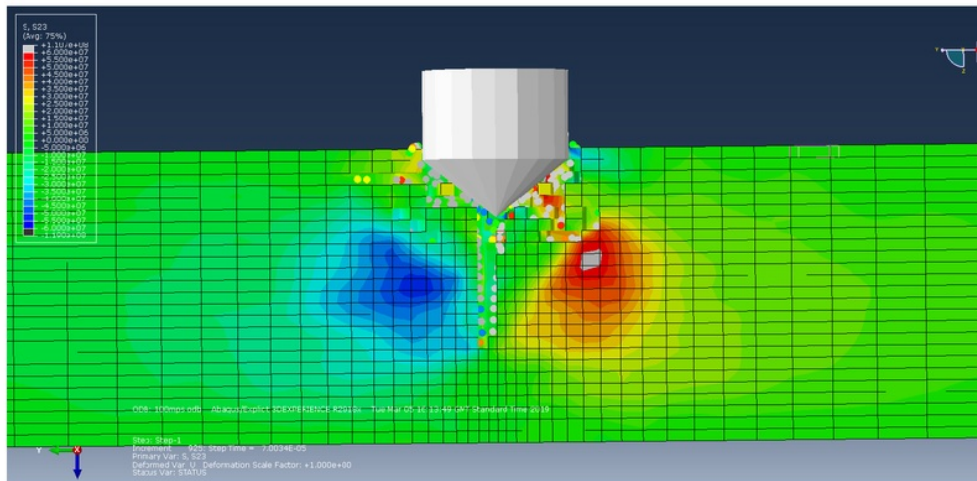


FIGURE 10 - S23 100mps 7.0034e-5

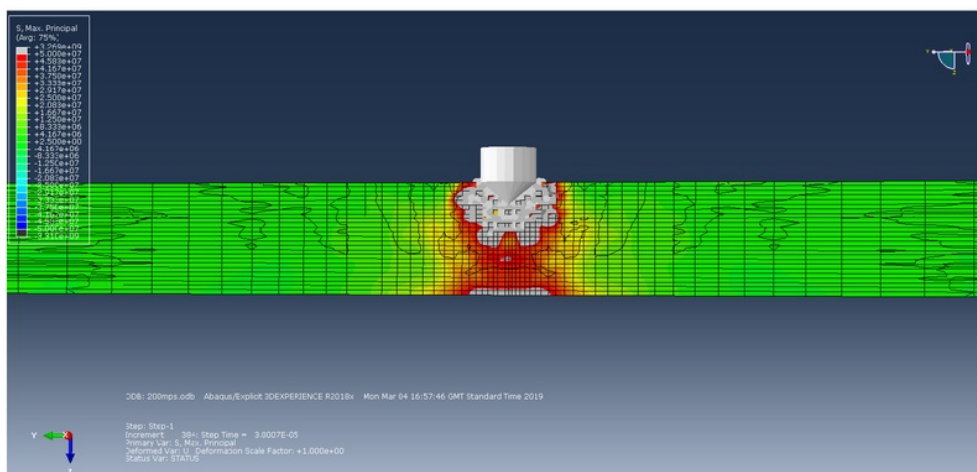
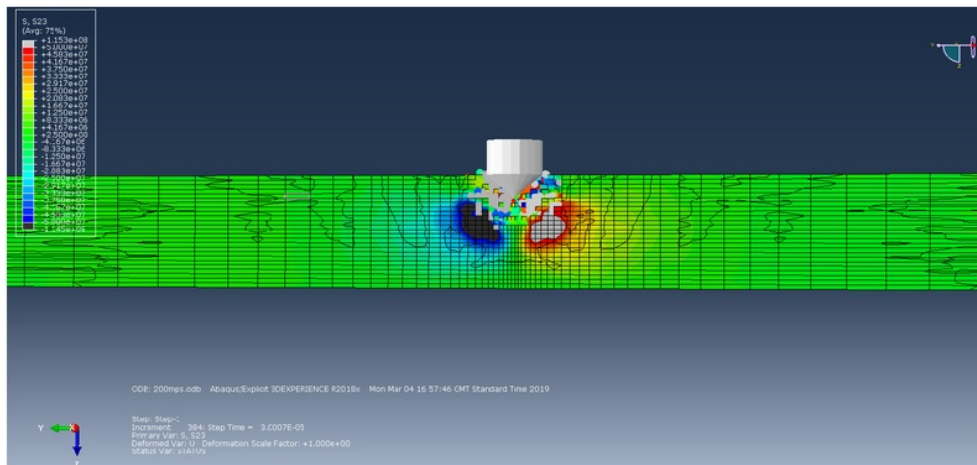


FIGURE 11- Max principal 200mps 3.0007e-5





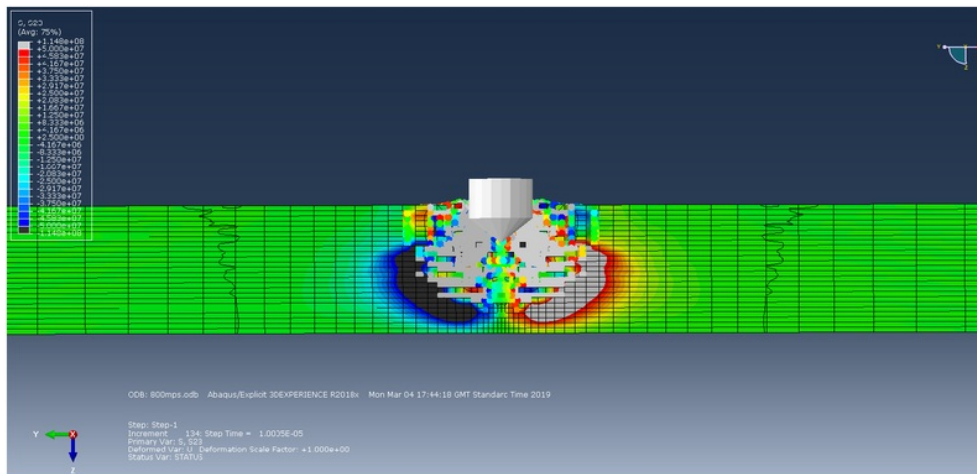


FIGURE 16 - S23 800mps 1.0005e-5

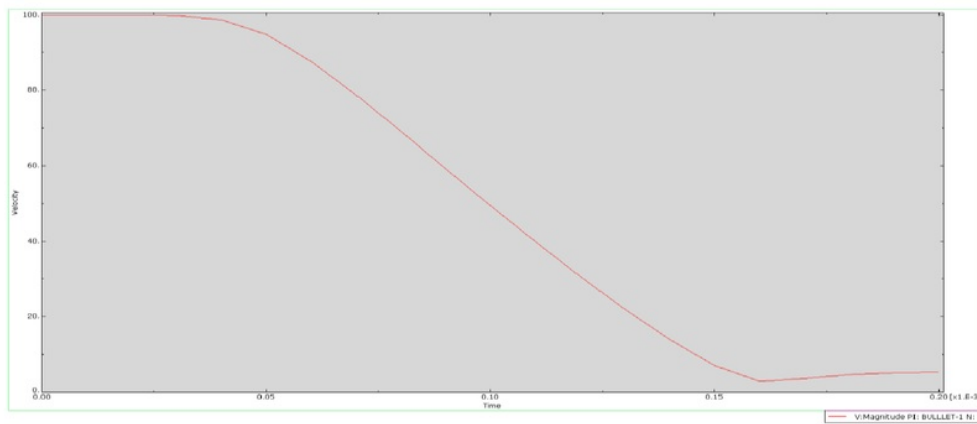


FIGURE 17- Bullet velocity 100mps

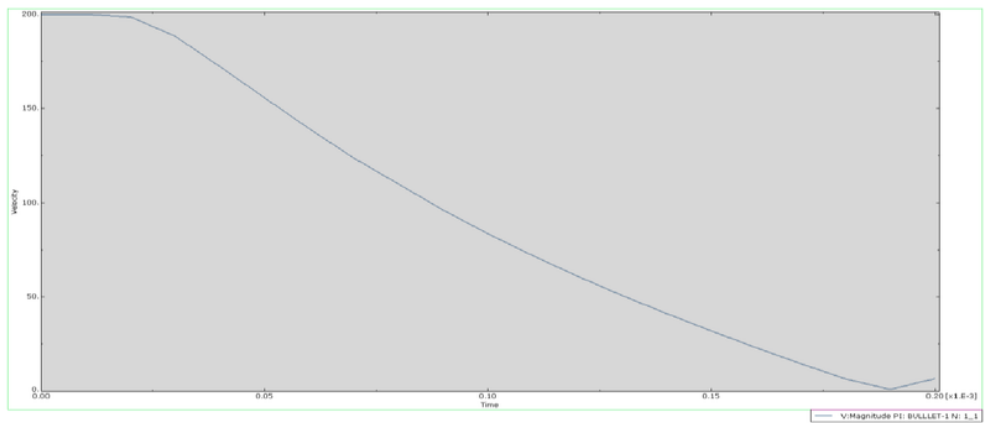


FIGURE 18 - Bullet velocity 200mps

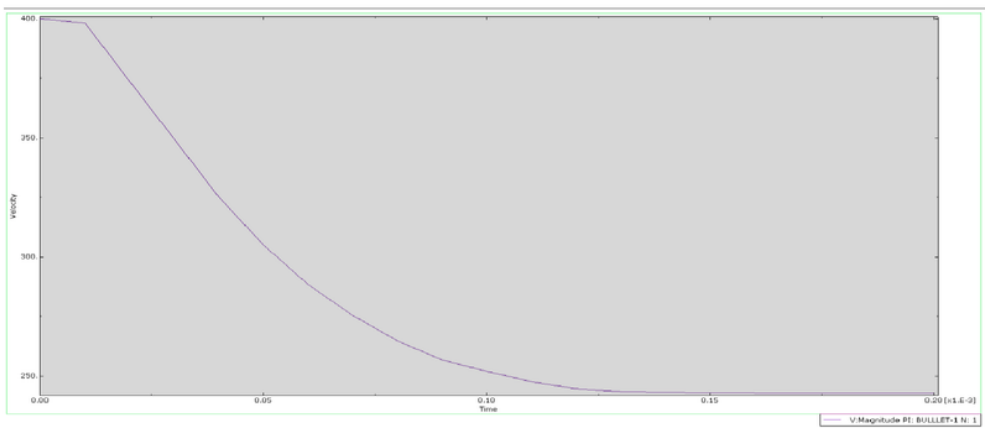


FIGURE 19 - Bullet velocity 400mps

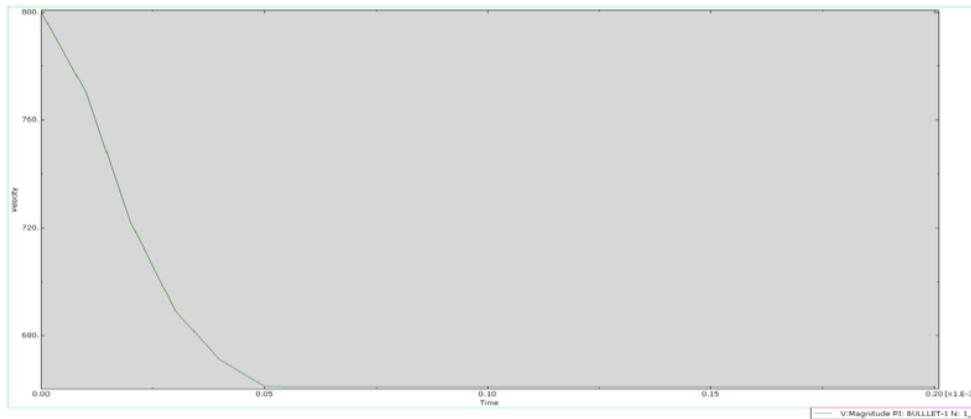


FIGURE 20 - Bullet velocity 800mps

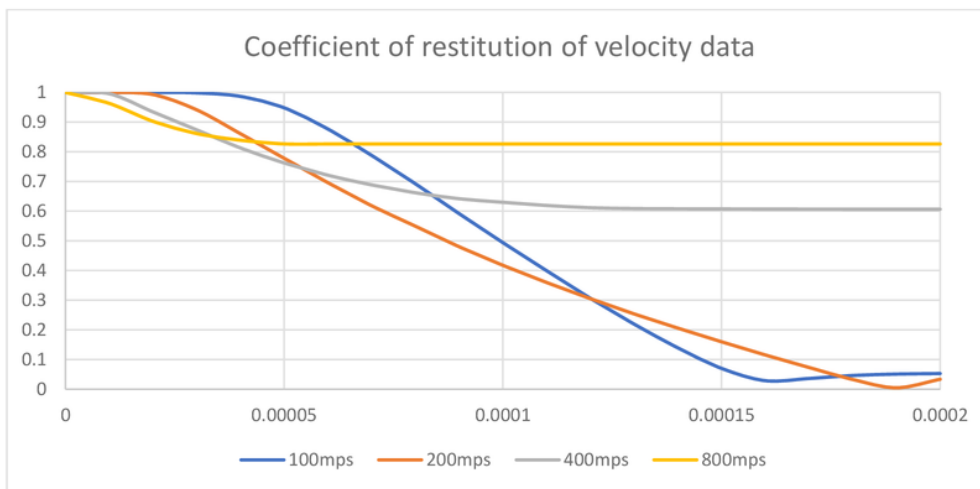


FIGURE 21- Graphical comparison of *coefficient of restitution of velocity data*

6.2 Tables

TABLE 1 - Material model data [12]

Property	
Mass density	2690 Kg/M ³
Young's modulus	69 GPa (69x10e9)
Poisons ratio	0.33
Yield stress	195MPa (195x10e6)
Ultimate tensile strength	@15% 220MPa (220x10e6)

TABLE 2 - 100mps projectile velocity data

time	velocity
0	100
1E-05	100
2E-05	100
3.01E-05	99.8344
4E-05	98.63958
5E-05	94.804
6E-05	87.64215
7E-05	78.76777
8E-05	69.1892
9E-05	59.16824
0.0001	49.39867
0.00011	39.90054
0.00012	30.65058
0.00013	21.92183
0.00014	13.92218
0.00015	7.008769
0.00016	2.870586
0.00017	3.614016
0.00018	4.619712
0.00019	5.093903
0.0002	5.285215

TABLE 3 - 200mps projectile velocity data

time	velocity
0	200
1E-05	200
2E-05	198.5439
3E-05	188.2525
4.01E-05	172.0847
5E-05	155.6001
6E-05	139.1591
7E-05	123.6301
8E-05	109.8081
9E-05	96.03062
0.0001	83.50214
0.00011	71.8886
0.00012	61.06475
0.00013	50.72207
0.00014	41.16183
0.00015	31.93804
0.00016	23.05282

0.00017	14.61243
0.00018	6.544524
0.00019	0.97607
0.0002	6.690214

TABLE 4 - 400mps projectile velocity data

time	velocity
0	400
1.01E-05	398.17
2E-05	373.7515
3E-05	349.5024
4E-05	325.0673
5E-05	304.9618
6E-05	288.3764
7E-05	275.3924
8E-05	264.7233
9E-05	256.7274
0.0001	251.9008
0.00011	247.6141
0.00012	244.6042
0.00013	243.4288
0.00014	243.0755
0.00015	242.9221
0.00016	242.789
0.00017	242.6711
0.00018	242.6096
0.00019	242.6075
0.0002	242.6073

TABLE 5 - 800mps projectile velocity data

time	velocity
0	800
1E-05	770.3203
2E-05	722.1639
3E-05	689.1415
4E-05	671.05
5E-05	661.1856
6E-05	660.9283
7E-05	660.9286
8E-05	660.9287
9E-05	660.9285
0.0001	660.9286

0.00011	660.9279
0.00012	660.9291
0.00013	660.9295
0.00014	660.9298
0.00015	660.9293
0.00016	660.9301
0.00017	660.9299
0.00018	660.9304
0.00019	660.9308
0.0002	660.9308

TABLE 6 - Fully comparative projectile velocity data

Raw data					percentile table				
time	100mps	200mps	400mps	800mps	time	100mps	200mps	400mps	800mps
0	100	200	400	800	0	1	1	1	1
1E-05	100	200	398.17	770.3203	1E-05	1	1	0.995425	0.9629
2E-05	100	198.5439	373.7515	722.1639	2E-05	1	0.992719	0.934379	0.902705
3E-05	99.8344	188.2525	349.5024	689.1415	3E-05	0.998344	0.941263	0.873756	0.861427
4.01E-05	98.63958	172.0847	325.0673	671.05	4.01E-05	0.986396	0.860423	0.812668	0.838813
5E-05	94.804	155.6001	304.9618	661.1856	5E-05	0.94804	0.778	0.762404	0.826482
6E-05	87.64215	139.1591	288.3764	660.9283	6E-05	0.876422	0.695795	0.720941	0.82616
7E-05	78.76777	123.6301	275.3924	660.9286	7E-05	0.787678	0.618151	0.688481	0.826161
8E-05	69.1892	109.8081	264.7233	660.9287	8E-05	0.691892	0.549041	0.661808	0.826161
9E-05	59.16824	96.03062	256.7274	660.9285	9E-05	0.591682	0.480153	0.641819	0.826161
0.0001	49.39867	83.50214	251.9008	660.9286	0.0001	0.493987	0.417511	0.629752	0.826161
0.00011	39.90054	71.8886	247.6141	660.9279	0.00011	0.399005	0.359443	0.619035	0.82616
0.00012	30.65058	61.06475	244.6042	660.9291	0.00012	0.306506	0.305324	0.61151	0.826161
0.00013	21.92183	50.72207	243.4288	660.9295	0.00013	0.219218	0.25361	0.608572	0.826162
0.00014	13.92218	41.16183	243.0755	660.9298	0.00014	0.139222	0.205809	0.607689	0.826162
0.00015	7.008769	31.93804	242.9221	660.9293	0.00015	0.070088	0.15969	0.607305	0.826162
0.00016	2.870586	23.05282	242.789	660.9301	0.00016	0.028706	0.115264	0.606973	0.826163
0.00017	3.614016	14.61243	242.6711	660.9299	0.00017	0.03614	0.073062	0.606678	0.826162
0.00018	4.619712	6.544524	242.6096	660.9304	0.00018	0.046197	0.032723	0.606524	0.826163
0.00019	5.093903	0.97607	242.6075	660.9308	0.00019	0.050939	0.00488	0.606519	0.826164
0.0002	5.285215	6.690214	242.6073	660.9308	0.0002	0.052852	0.033451	0.606518	0.826163

7 REFERENCES

- [1] K. Donne Ordnance Munitions & Explosives Degree programme year 1 Physics of OME module course delivery, handouts and 'Moodle' links 2018/2019
- [2] NDT resource (1996) Materials and processes- loading [Online] Available:
<https://www.nde-ed.org/EducationResources/CommunityCollege/Materials/Mechanical/Loading.htm>
- [3] NDT resource (2001) Materials and processes- stress and strain [Online] Available:
<https://www.nde-ed.org/EducationResources/CommunityCollege/Materials/Mechanical/StressStrain.htm>
- [4] Pearson Prentice Hall Inc. (2005) materials in mechanical design slide 5 [Online] Available:
<https://slideplayer.com/slide/4817531/>
- [5] Metal (2011) Influence Of Temperature And Time Of Ageing On 6201 Grade Almgisi Wire And Rod [Online] Available:
<http://konference.tanger.cz/data/metal2011/sbornik/lists/papers/1048.pdf>
- [6] panoptesv.com (2018) under the hood [Online] Available:
http://panoptesv.com/RPGs/Equipment/Weapons/Projectile_physics.php
- [7] Dr.G. Kalsi Ordnance Munitions & Explosives Degree Subject Matter Expert support: FEA/Physics presentations
- [8] Schmelz F., Seher-Thoss C.HC., Aucktor E. (1992) Hertzian Theory and the Limits of Its Application. In: Universal Joints and Driveshafts. Springer, Berlin, Heidelberg [Online] Available:
https://link.springer.com/chapter/10.1007/978-3-662-02746-2_3
- [9] John F. Chinella et al. (1998) Processing, Mechanical Properties, and Ballistic Impact Effects of Austempered Ductile Iron [Online] Available:
http://panoptesv.com/RPGs/Equipment/Weapons/Projectile_physics.php
- [10] Huai Huang (2016) Indentation Fracture and How to Apply to Thin Films [Online] Available:
<https://slideplayer.com/slide/9840994/>
- [11] Indiamart (1996-2019) product detail [Online] Available:

<https://www.indiamart.com/proddetail/aluminium-alloys-6201-64401-pipe-tube-14137460255.html>

- [12] MATWEB (2001) material properties for aluminium 6101-t6 [Online] Available:
<http://www.matweb.com/search/DataSheet.aspx?MatGUID=21a761c947e24155b7e95baf05d7743e&ckck=1>
- [13] Hyper Physics (2016) Sound velocities [Online] Available:
<http://hyperphysics.phy-astr.gsu.edu/hbase/Tables/Soundv.html>