



Joseph Nelhams

Application of Computer Aided Engineering Processes

School of Applied Computing
ACDB5007 Computer Aided Engineering

Academic Year: 2025 - 2026

Lecturer: Andrew Noble

May 2026

Table of Contents

List of Figures.....	iii
List of Tables.....	iv
List of Equations.....	v
Abstract.....	1
1 Introduction.....	2
1.1 Computer-Aided Engineering.....	2
1.2 Report Breakdown	2
1.3 Case Study Overview	2
2 Case Study.....	4
2.1 Case Study Description	4
2.1.1 Simplifications made for the model.....	5
2.2 Relevance to OME.....	6
3 Analytical Solution	8
3.1 Hugoniot Calculation.....	8
3.1.1 Particle Velocity.....	8
3.1.2 Material Properties of Copper	8
3.1.3 Calculating the shock velocity	8
3.1.4 Calculating the shock pressure	9
3.2 Calculating the duration of the experiment.....	9
3.3 Simplified plate model.....	10
3.4 Failure Assessment	11
4 CAE Model Setup.....	12
4.1 CAD Model	12
4.2 Dimensions and Materials.....	13
4.3 Setting up the simulation.....	14
4.3.1 Mesh	17
4.3.2 Boundary Condition and Load	19
5 Results	20
6 Conclusion.....	25
References.....	26
Appendices.....	27
Appendix A : Summary table of results from the analytical solution.....	27

List of Figures

Figure 1 - On the left is an image of a typical Particle Velocity gauge used at the Los Alamos National Laboratory, on the right is the gauge embedded within a target, this is the typical configuration we see from experiments using this diagnostic [3].	3
Figure 2 – CAD model for the test case created in Fusion.	5
Figure 3 - A 2D diagram of the Impactor	12
Figure 4 – A 2D diagram of the Target.	13
Figure 5 – The workflow used in ANSYS workbench	14
Figure 6 – The material properties for copper.	15
Figure 7 – The material properties for polycarbonate.	16
Figure 8 – A screenshot of the explicit dynamics solver as the simulation was being run, the centre of the viewport shows the start point of the simulation. The left side of the image shows the simulation outline, listing each step taken before the analysis is run.	17
Figure 9 – A screenshot of the assembly with a mesh applied. The sabot, at the top of the image, has tetrahedral elements, and the rest of the parts have hexahedral elements.	18
Figure 10 – A screenshot of the gauge mesh.	19
Figure 11 – A sequence of 6 screenshots showing the results of the simulation	20
Figure 12 – A sequence of 8 screenshots showing the deformation of the gauge throughout the duration of the simulation. The colour represents the von Mises stress in the part.	21
Figure 13 – An image showing the selected nodes used for collecting and plotting data on shear stress and particle velocity.	22
Figure 14 – A scatter plot showing the shear stress in the gauge.	23
Figure 15 - A scatter plot showing the particle velocity of nodes in the gauge.	23
Figure 16 - A scatter plot showing the max principal stress in the gauge.	24

List of Tables

Table 1 – The material properties of copper taken from the LASL Shock Hugoniot Data [5] 8

Table 2 – The linear hugoniot data for a PVDF gauge [6] 9

Table 3 – The gauge dimensions used for the analytical solution. 10

Table 4 – Dimensions and material selected for each part of the model assembly. 13

Table 5 – A list of all the parameters calculated in the analysis found in section 3. 27

List of Equations

$U_p = V_{impact}^2$ Equation 1	8
$U_s = 3940 + 1.489U_p$ Equation 2	8
$P = \rho_0 \times U_s \times U_p$ Equation 3	9
$U_{sPV\ Gauge} = C_0 + (s \times U_p)$ Equation 4	9
$\sigma_{max} = \beta \cdot q \cdot a^2 t^2$ Equation 5	10
$F_{Failure} = 3.59 \times 10^{13} \times 10^7 \approx 7.18 \times 10^5$ Equation 6	11

Abstract

This report looks to break down the importance of CAE in the OME industry through a case study. The case study focuses on the survivability of a particle velocity gauge; a diagnostic used in explosive gas-gun experiments. The results of the CAE simulation will be used alongside a mathematical analysis to understand the chances of the gauge surviving the duration of the experiment.

1 Introduction

1.1 Computer-Aided Engineering

Computer-aided engineering is a vital part of modern engineering design and testing. The tools that are used, such as ANSYS Workbench, a Finite Element Analysis tool, allow companies and engineers to simulate real-life problems at a fraction of the cost of conducting physical tests. This is of particular importance to defence and explosive industries, where tests are hazardous, expensive, and, in some instances, unjustifiable. For instance, countries are no longer able to conduct nuclear weapons testing due to the Comprehensive Nuclear-Test-Ban Treaty [1], which was adopted in 1996; however, with CAE, and more specifically FEA, these tests can now be performed in computer simulations instead. These tools help reduce the risk and the costs of developing OME.

1.2 Report Breakdown

This report explains some of the Computer-Aided Engineering tools which are used within the engineering industry, particularly applying to the explosives industry. These tools will be applied to a case study on the operation of particle velocity gauges. A simplified mathematical model will be derived from the fundamental physical principles [2], and then the problem will be solved through ANSYS Workbench. Solving the problem in these two ways will provide an effective validation for the computer model by directly comparing the results. This report will also break down the effects of boundary conditions and mesh sizes on the simulation outputs.

1.3 Case Study Overview

The case study chosen investigates the survivability of particle velocity gauges under test conditions. A particle velocity gauge (Figure 1) is a diagnostic used in gas-gun experiments involving explosive targets. The typical configuration has the gauge embedded at a 30° angle within the explosive; the target is placed within a magnetic field. This target will be impacted by a flyer which has a flat face. As the flyer imparts a shock into the target, the particle velocity gauge will

move with the shock wave through the magnetic field, generating a current in the elements in the gauge through Faraday's law of induction.

For this experiment to work, the gauge must survive the shock long enough to generate a current and transmit it to an oscilloscope. The case study investigates how long the gauge can survive during the experiment.

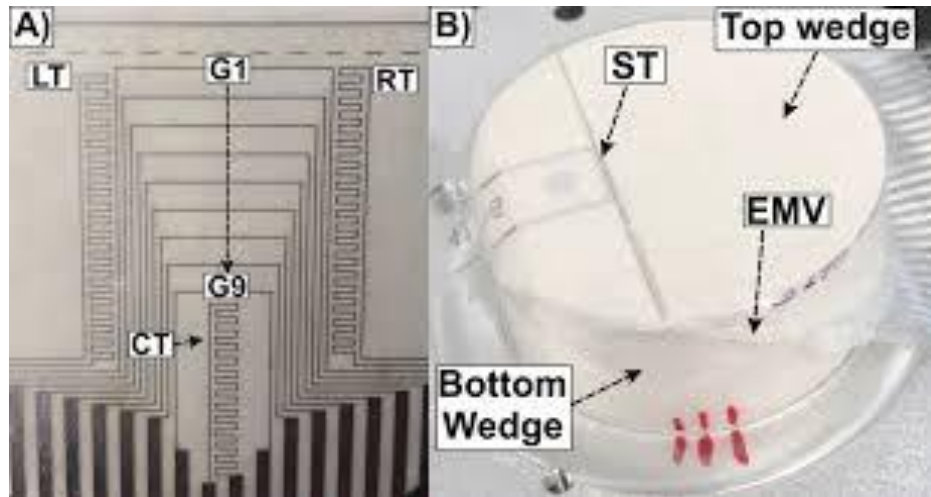


Figure 1 - On the left is an image of a typical Particle Velocity gauge used at the Los Alamos National Laboratory, on the right is the gauge embedded within a target, this is the typical configuration we see from experiments using this diagnostic [3].

2 Case Study

2.1 Case Study Description

The particle velocity gauge diagnostic has been used in shock initiation experiments since the early 1980s and was developed by Erickson et al at the Lawrence Livermore National Laboratory [4]. The gauge relies on Faraday's Law of induction to measure the particle velocity within an explosive as it is detonating. The results of these experiments can be used to derive pressure-velocity graphs, which are used to calculate the shock Hugoniot. This information contributes to the calculation of the equation of state properties of an explosive, which are used to create hydrodynamic models of explosive systems

Due to the nature of these experiments, the gauge can experience pressures up to and exceeding 40 GPa over a duration of less than 50 μ s. Under these pressures, the gauge is going to be obliterated throughout the duration of the experiment; the gauge does not need to survive the whole experiment, it only needs to survive long enough to send an electrical signal out of the target. The shock wave in the material will travel at the speed of sound of the material; for most secondary explosives, this sits between 5000m/s and 9000m/s. The speed at which an electrical signal propagates through a wire is a fraction of the speed of light (greater than 150,000,000m/s). Due to the comparative speed between these two forces and the orientation and placement of the gauge within the target, the likelihood is that the signal would travel out of the gauge way before the gauge starts to break down; however, several experiments have resulted in zero data collection due to the gauge dying too soon.

This case study looks into the theoretical likelihood that a gauge would fail during the course of the experiment, by solving the problem mathematically and through FEA, we will be able to learn the conditions required to kill the gauge, and compare that to typical pressures experienced throughout the course of the experiment to understand the chances of failure.

The setup of the model (Figure 2) involves a copper flyer attached to a polycarbonate sabot travelling at a velocity of 750m/s towards the target. The

target consists of two polycarbonate wedges mated together to form a cuboid. Embedded between these two wedges is a thin rectangular copper sheet, which represents the particle velocity gauge. The target is attached to a copper buffer plate to represent how it would typically be fielded in a gas gun trial.

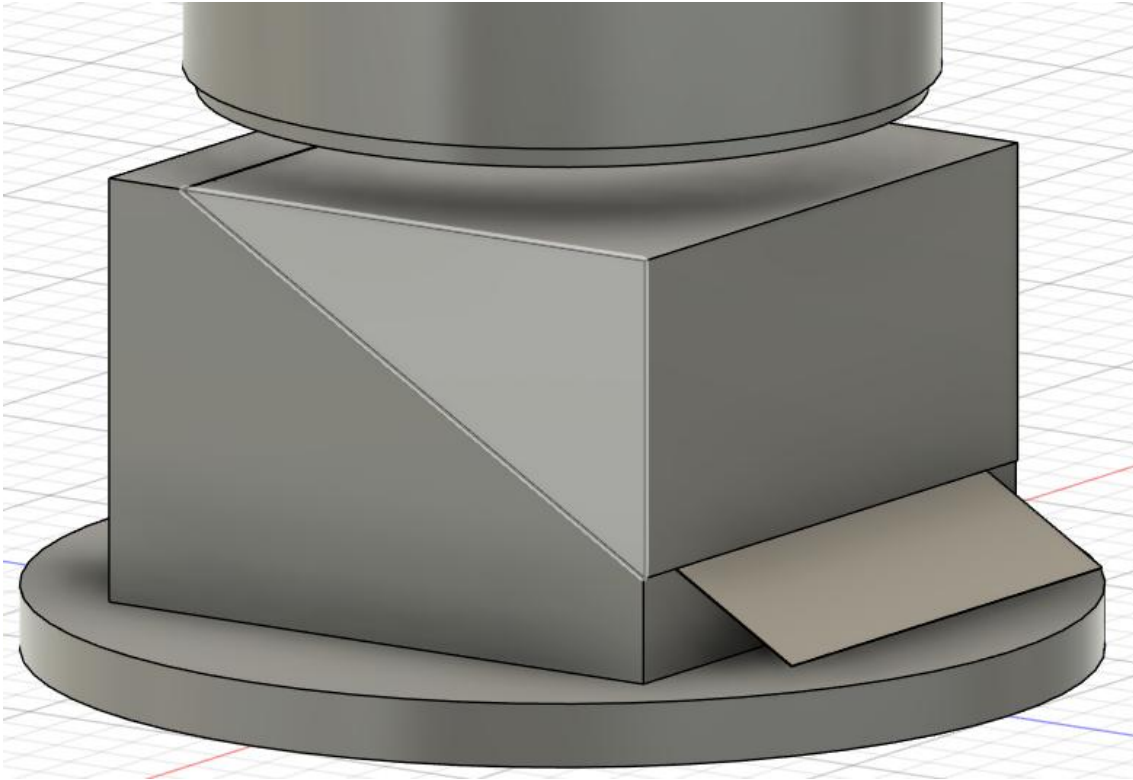


Figure 2 – CAD model for the test case created in Fusion.

2.1.1 Simplifications made for the model

The construction of a particle velocity gauge typically involves etching a conductive metal, usually aluminium or copper, into a substrate such as Kapton. The construction of gauges this way allows gauges to be between 50µm and 110µm; the thinner the gauge, the better, as a thicker gauge would disrupt the shock wave as it propagates through the target. Kapton is typically used as it has a good impedance match with HMX-based explosives. The design of these gauges is quite complex to fit the specific requirements of the trial; there is no need to simulate the gauge to this degree of complexity to successfully determine the survivability. The only part of the gauge that needs to be simulated is the conductive element that sits within the gauge. To further reduce the complexity

and aid with the meshing and processing times, the gauge was represented by a sheet of copper with a thickness of 50 μ m. This simplification also makes the problem easier to solve mathematically, as it reduces the need to perform calculations for a complex shape. The rest of the model has been kept close to the design of the original experiment.

2.2 Relevance to OME

In the field of OME and defence, billions of pounds are spent each year in the UK to produce, maintain and decommission weapons and ordnance. Given the level of investment in the sector, each product needs to be extensively tested before being put into service. Testing and evaluating diagnostics used in explosive trials is key to validating that the product behaves as expected.

One of the areas of research that underpins the functionality of OME is the field of Materials Physics, specifically DMR (Dynamic Material Response). DMR looks to research both explosive and non-explosive material under shock conditions. The gas gun, an expensive yet somewhat common piece of lab equipment, is used to impart shocks into materials in a controlled manner. The basic principle behind a single-stage gas gun is to fill gas cylinders with high-pressure light gas, such as helium. This light gas will be released into the barrel of the gun all at once, creating a pressure wave confined within the barrel. Sat within the barrel can be either a small projectile, such as a ball bearing, or, on guns with larger bores, a sabot with a flat cylindrical flyer glued to the front face. This projectile is pushed down the barrel by the gas at very high velocities; some gas guns can exceed 2 km/s. For the case study selected, the sabot with a flyer attached will have a planar impact with the target, achieving a shock front in the target up to and exceeding 40 GPa, depending on setup and testing conditions.

The particle velocity gauge is the primary diagnostic used in explosive experiments involving gas guns. The reasoning behind this is due to a couple of factors. Firstly, it is vital that the diagnostic can take measurements from within the material itself; secondly, the diagnostic should have little to no effect on the shock wave as it propagates through the material. Other diagnostics could, in principle, achieve this, such as a PDV probe or an array of ionisation probes, but

embedding them within an explosive target would be difficult. Additionally, embedding probes at different points within an explosive would change the shock front profile as it passes through the material, because the probes have entirely different material properties. The particle velocity gauge was designed to be as thin as possible, so that as the shock wave passed through the gauge, it minimised the effects the gauge would have on the shock wave. The material that the gauge package sits within is also selected to have a close impedance match with the target, again to further minimise the effects on the shock front. All of this culminates in a diagnostic that essentially allows a researcher to see what is happening inside an explosive material as it is being shocked, from the moment of the impact to the ramp-up to detonation of the explosive, at which point the gauge will die.

Over 40 years, the diagnostic has been collecting data on the performance and properties of explosives. It is a vital part of ensuring the explosive models are accurate, which in turn limits the number of full-scale tests that need to be performed on OME.

3 Analytical Solution

The analytical solution presents a simplified version of the case study to estimate the shock pressure at which the gauge is likely to fail and to compare it with the shock pressure achieved during the experiment.

3.1 Hugoniot Calculation

3.1.1 Particle Velocity

As the flyer and the gauge are the same material, then the impedance match means that the particle velocity is half the impact velocity.

$$U_p = \frac{V_{impact}}{2}$$

Equation 1

$$U_p = \frac{750m/s}{2}$$

$$U_p = 375 m/s$$

3.1.2 Material Properties of Copper

Table 1 – The material properties of copper taken from the LASL Shock Hugoniot Data [5]

Property	Symbol	Value
Density	ρ_0	8960 kg/m ³
Hugoniot Coefficients	U_s	3940 + 1.489 U_p (m/s)

3.1.3 Calculating the shock velocity

To calculate the shock velocity, we need to input the particle velocity calculated with equation 1 into the Hugoniot coefficient (U_s).

$$U_s = 3940 + 1.489U_p$$

Equation 2

$$U_s = 3940 + (1.489 \times 375)$$

$$U_s = 3940 + 558.4$$

$$U_s = 4498.4 \text{ m/s}$$

3.1.4 Calculating the shock pressure

Once the particle velocity and the shock velocity have been calculated, they can be multiplied by the density of copper to obtain the shock pressure.

$$P = \rho_0 \times U_s \times U_p$$

Equation 3

$$P = 8960 \times 4498.4 \times 375$$

$$P \approx 15.1 \text{ GPa}$$

3.2 Calculating the duration of the experiment

In this context, the duration of the experiment refers to the time it takes for the shockwave to travel through the gauge; this is called the shock transit time. This can be calculated using the linear Hugoniot data for a PV gauge, and multiplying this by the particle velocity calculated in equation 1. The entire gauge package, including the surrounding substrate that encapsulates the gauge elements, will be included in the calculation.

Table 2 – The linear hugoniot data for a PVDF gauge [6]

Parameter	Symbol	Value
<i>Bulk Sound Speed</i>	C_0	<i>2340 m/s</i>
<i>Hugoniot Slope</i>	s	<i>1.6</i>

$$U_s(PV \text{ Gauge}) = C_0 + (s \times U_p)$$

Equation 4

$$U_s(PV Gauge) = 2340 + (1.6 \times 375)$$

$$U_s(PV Gauge) = 2940 \text{ m/s}$$

By dividing the thickness of the gauge package (Table 3) by the particle velocity within the gauge, we can calculate the shock transit time.

$$t_{transit} = \frac{0.00011}{2940}$$

$$t_{transit} \approx 37 \text{ ns}$$

3.3 Simplified plate model

In this section, the maximum stress that the gauge could experience during the experiment will be calculated using Roark's formulas for stress and strain [7].

Table 3 – The gauge dimensions used for the analytical solution.

Parameter	Symbol	Size (m)
Length	a	0.01
Width	b	0.01
Thickness	t	0.00011

$$\sigma_{max} = \frac{\beta \cdot q \cdot a^2}{t^2}$$

Equation 5

$$\sigma_{max} = \frac{0.2874 \times (15.1 \times 10^9) \times 0.01^2}{0.00011^2}$$

$$\sigma_{max} \approx 3.59 \times 10^{13} \text{ Pa} = 35.9 \text{ TPa}$$

3.4 Failure Assessment

The gauge's failure rate can be calculated as a factor by dividing the maximum stress by its yield stress.

$$F_{Failure} = \frac{3.59 \times 10^{13}}{5 \times 10^7} \approx 7.18 \times 10^5$$

Equation 6

The failure rate shows that the gauge experiences pressure over 700,000 times greater than the yield stress of the gauge, the likely pressure at which the gauge would die. This is completely expected, as we know the gauge does not survive the experiment. The key factor to consider for the gauge survivability is the shock transit time, as we know the gauge can't survive the experiment, all we need to understand is whether the gauge can survive the 37ns window of time when the data is collected. The full table of results calculated from the analysis can be found in Appendix A. From this analysis, we can use CAE to optimise the design of the gauge to ensure that each element survives for 37ns from the time at which it receives the initial shock.

4 CAE Model Setup

4.1 CAD Model

The model was created in Fusion (Figure 2) and consists of an assembly of 6 individual parts. Those 6 parts combine to create the 2 pieces of the model, the impactor (Figure 3) and the target (Figure 4). The impactor consists of 2 parts: the sabot, a cylindrical shell with one end face. Attached to the end face is the flyer, which is in the shape of a disc, slightly smaller than the diameter of the cylinder.

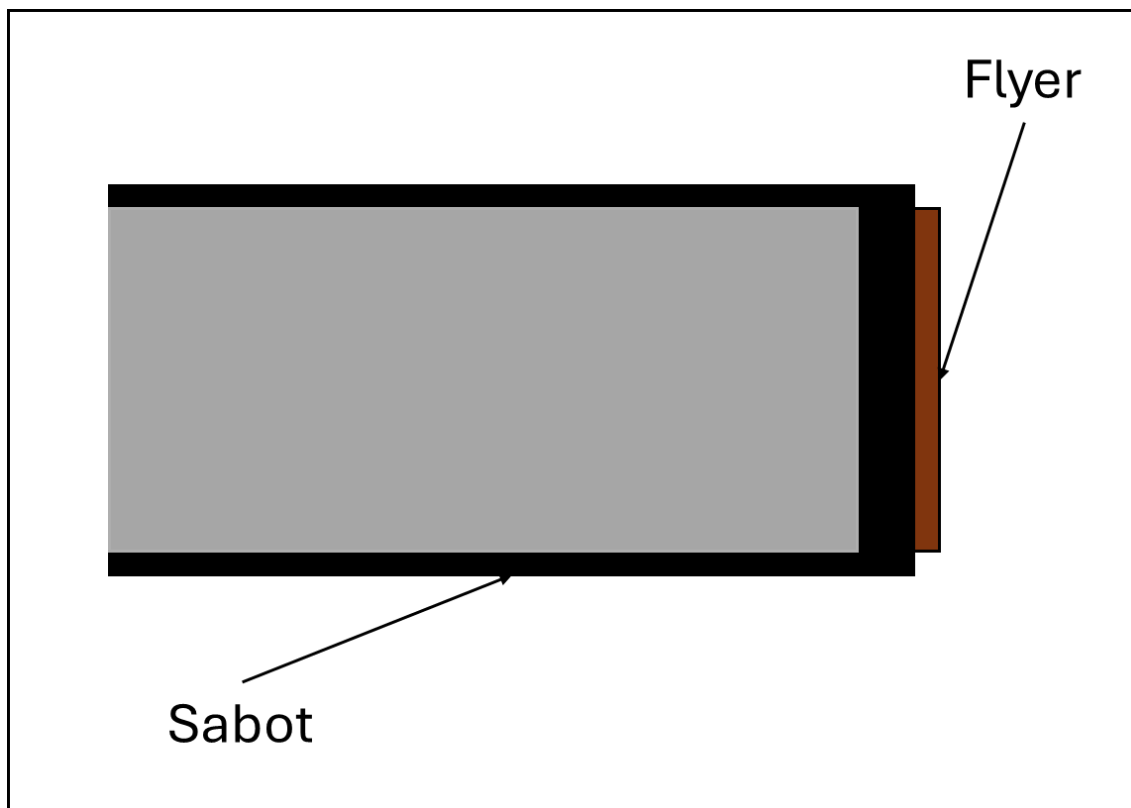


Figure 3 - A 2D diagram of the Impactor

The target comprises 4 parts. At the base is the buffer plate; the rest of the assembly is attached to it. Attached to the buffer plate is the bottom wedge; the gauge is attached to the angled face of the bottom wedge, and the top wedge is attached to the gauge and the bottom wedge to form a cuboid target.

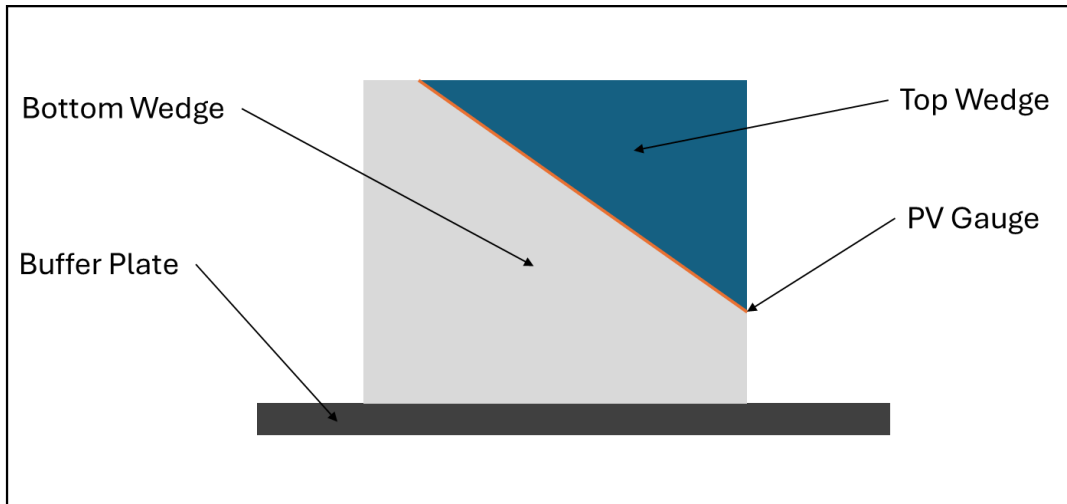


Figure 4 – A 2D diagram of the Target.

4.2 Dimensions and Materials

Table 4 – Dimensions and material selected for each part of the model assembly.

Part	Length (mm)	Width/Diameter (mm)	Height/Thickness (mm)	Material
<i>Sabot</i>	-	50	125	<i>Polycarbonate</i>
<i>Flyer</i>	-	48.5	5	<i>Copper</i>
<i>Buffer Plate</i>	-	65	10	<i>Copper</i>
<i>Bottom Wedge</i>	40	40	30	<i>Polycarbonate</i>
<i>Particle Velocity Gauge</i>	20	20	0.005	<i>Copper</i>
<i>Top Wedge</i>	30	40	25	<i>Polycarbonate</i>

4.3 Setting up the simulation

The simulation was performed in ANSYS Workbench using the Explicit Dynamics solver (Figure 5).

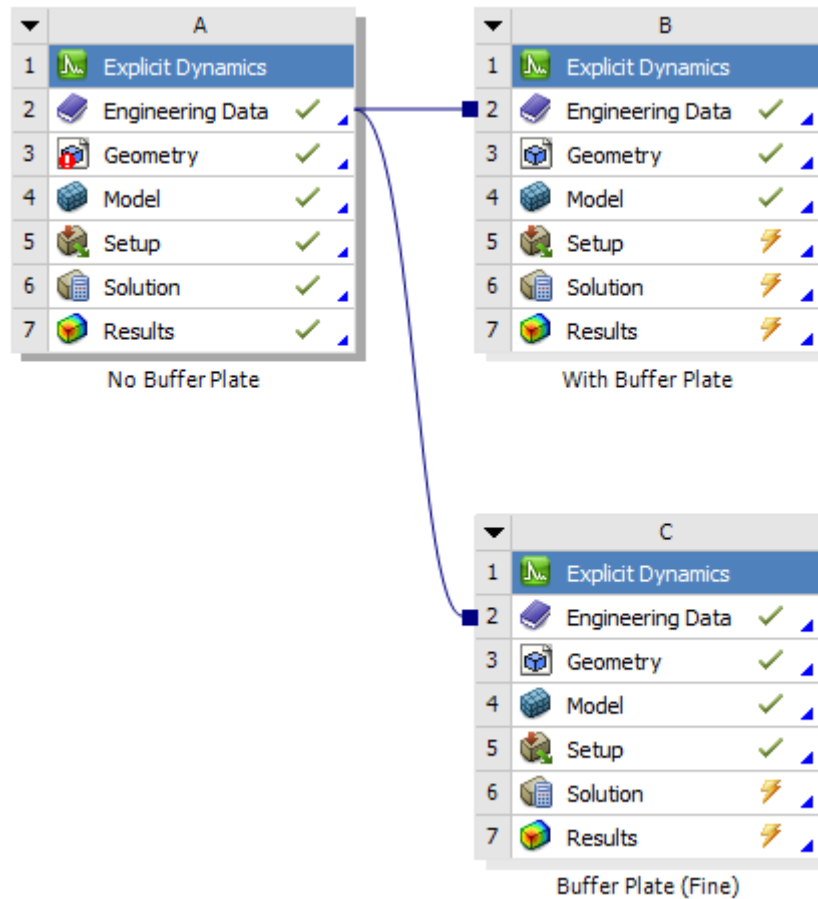


Figure 5 – The workflow used in ANSYS workbench

The initial step was to insert the material parameters to be applied to the parts within the model. The two materials selected were polycarbonate and copper; the corresponding parts are listed in Table 4. The properties of the materials (Figures

6 and 7) were selected from the engineering data workflow preloaded into ANSYS Workbench.

Properties of Outline Row 5: CU-OFHC					
	A	B	C	D	E
1	Property	Value	Unit		
2	Material Field Variables	Table			
3	Density	8930	kg m ⁻³		
4	Specific Heat Constant Pressure, C _p	383	J kg ⁻¹ ...		
5	Steinberg Guinan Strength				
6	Initial Yield Stress Y	1.2E+08	Pa		
7	Maximum Yield Stress Ymax	6.4E+08	Pa		
8	Hardening Constant B	36			
9	Hardening Exponent n	0.45			
10	Derivative dG/dP G'P	1.35			
11	Derivative dG/dT G'T	-1.798E+07	Pa C ⁻¹		
12	Derivative dY/dP Y'P	0.003396			
13	Melting Temperature Tmelt	1516.9	C		
14	Shear Modulus	4.77E+10	Pa		
15	Shock EOS Linear				
16	Gruneisen Coefficient	2.02			
17	Parameter C1	3940	m s ⁻¹		
18	Parameter S1	1.489			
19	Parameter Quadratic S2	0	s m ⁻¹		

Figure 6 – The material properties for copper.

Properties of Outline Row 6: POLYCARB					
	A	B	C	D	E
1	Property	Value	Unit		
2	 Material Field Variables	 Table			
3	 Density	1200	kg m ⁻³		
4	 Multilinear Isotropic Hardening	 Tabular			
5	Scale	1			
6	Offset	0	Pa		
7	 Shear Modulus	1E+09	Pa		
8	 Shock EOS Bilinear				
9	Gruneisen Coefficient	0.61			
10	Parameter C1	1933	m s ⁻¹		
11	Parameter S1	2.65			
12	Parameter C2	2350	m s ⁻¹		
13	Parameter S2	1.6			
14	Relative Volume VB/V0	0.742			
15	Relative Volume VE/V0	0.701			
16	 Plastic Strain Failure				
17	Maximum Equivalent Plastic Strain EPS	2			

Figure 7 – The material properties for polycarbonate.

After the material parameters were input into the workflow, the geometry was uploaded into the explicit dynamics solver. Within the solver, the load, boundary conditions, mesh and analysis settings can be set.

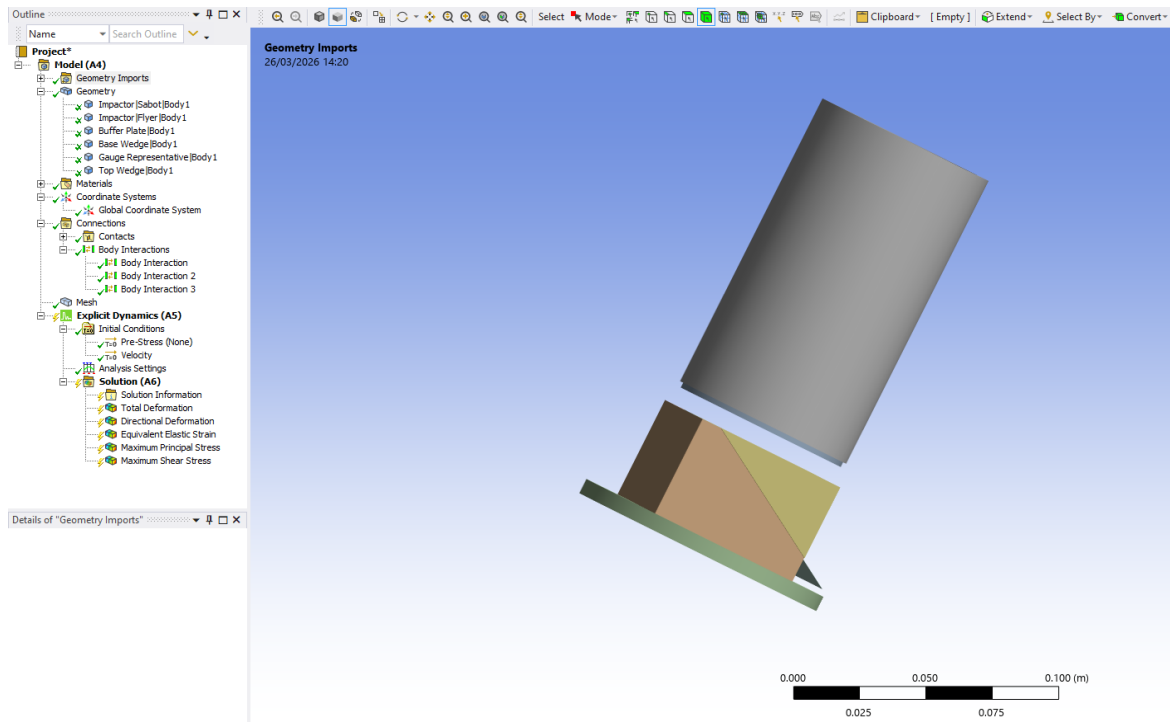


Figure 8 – A screenshot of the explicit dynamics solver as the simulation was being run, the centre of the viewport shows the start point of the simulation. The left side of the image shows the simulation outline, listing each step taken before the analysis is run.

3 body interactions were set for the simulation: the first allows all parts in the assembly to collide with one another; the second interaction models the bonding between the flyer and the sabot; and the third interaction models the bonding between the gauge and the two wedges.

4.3.1 Mesh

The next step of setup was to apply a mesh to the parts. In ANSYS Workbench, this is done automatically, with less control over mesh adaptation than in other FEA software, such as ABAQUS. The size of the elements could be changed, and spherical regions within the part could be selected to apply a denser mesh in the regions of interest. However, the shape of the elements in the mesh could not be controlled. The sabot was defined with a tetrahedral mesh, four-sided pyramidal shapes. All other parts had a hexahedral mesh; the meshed parts are shown in Figure 9.

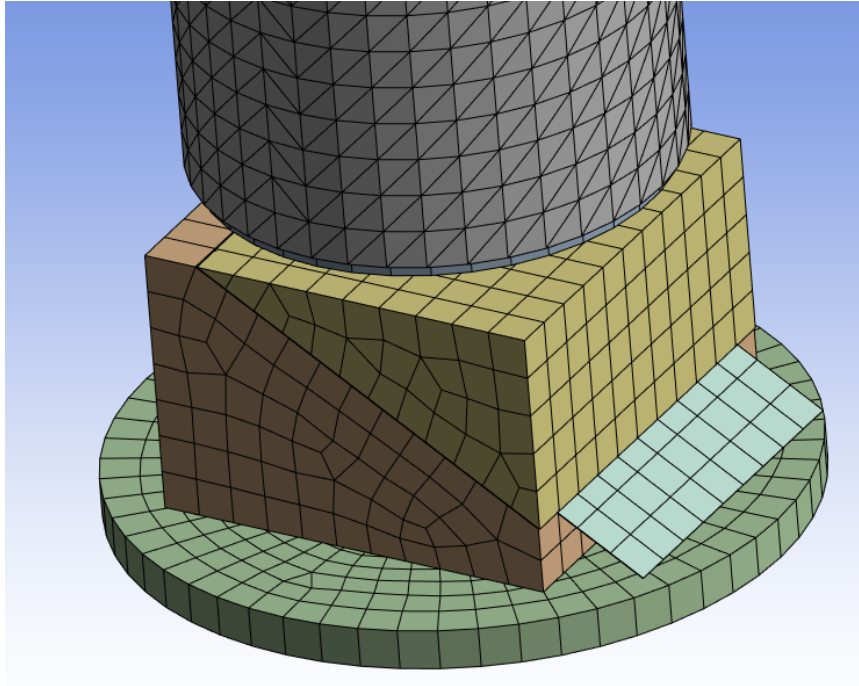


Figure 9 – A screenshot of the assembly with a mesh applied. The sabot, at the top of the image, has tetrahedral elements, and the rest of the parts have hexahedral elements.

The mathematical basis behind the two different element shapes differs and affects how the analysis interpolates the solution for each part.

For linear tetrahedral elements, the strain is constant throughout the entire element. This differs from hexahedral elements, where the strain can vary across an element. This can be quite problematic for analysis, running a tetrahedral mesh where a varying strain is present throughout the problem, which is quite common in stress-related test cases.

For this test case, the key part in the assembly is the gauge, which has a hexahedral mesh (Figure 10). This is better for this test case, as it will provide a more accurate answer. Additional benefits of this element shape include a lower element count across the part and less processing time.

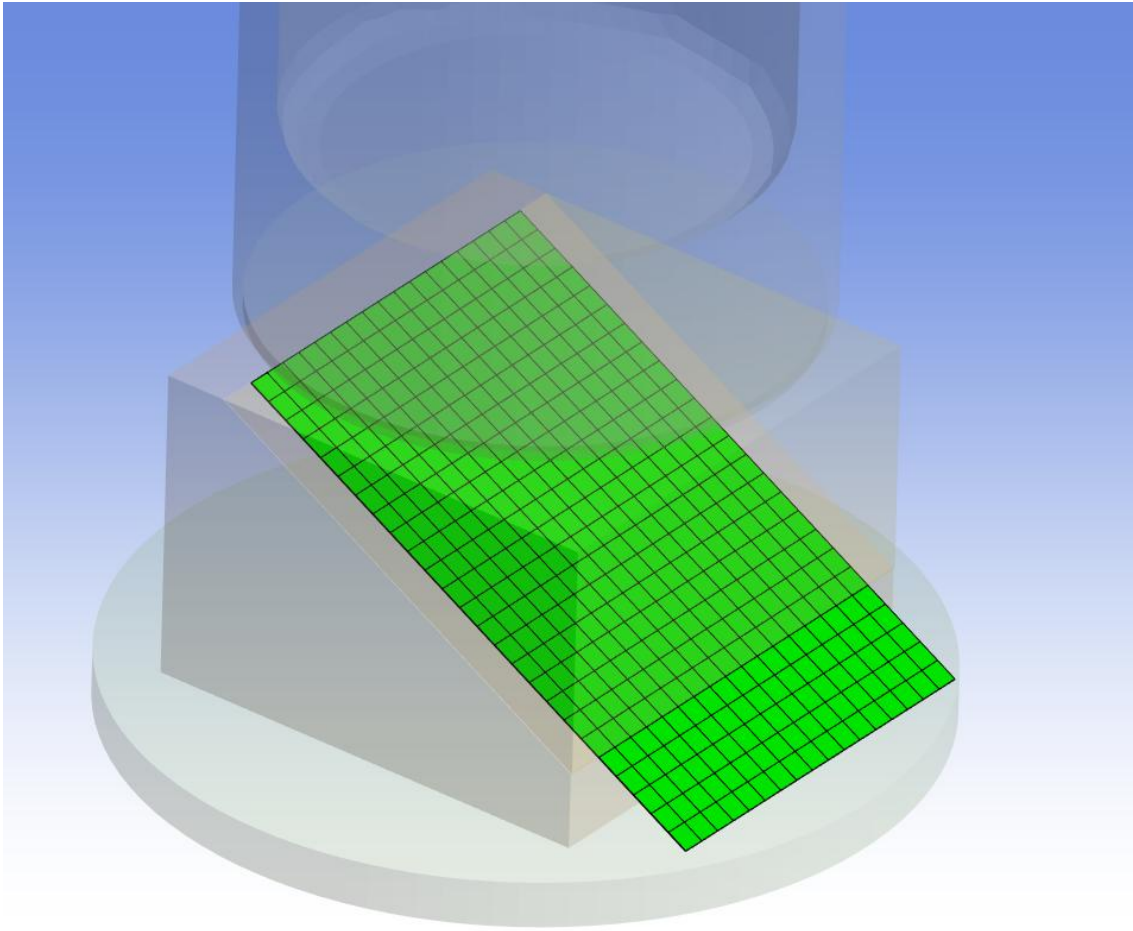


Figure 10 – A screenshot of the gauge mesh.

4.3.2 Boundary Condition and Load

A fixed boundary condition was applied to the buffer plate; further investigation showed it to be unnecessary, as by the time the shock reached the buffer plate, the gauge was destroyed.

The load applied to the sabot and flyer was 750 m/s toward the target's front face. The analysis was set to run up to the point at which the sabot began to deform on the surface of the buffer plate, which exceeds the gauge survival window.

5 Results

Figure 11 shows the sequence of the entire simulation. It shows the deformation of the sabot and the target over 60 μs .

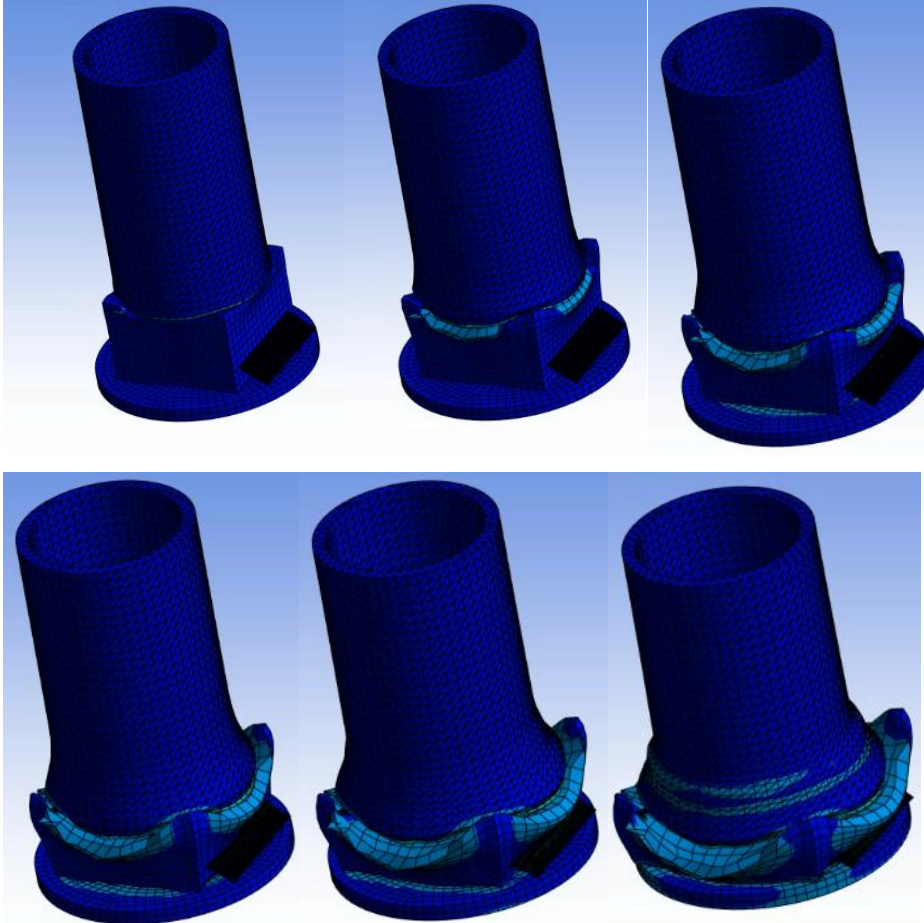


Figure 11 – A sequence of 6 screenshots showing the results of the simulation

Figure 12 shows the simulation results, with only the particle velocity gauge shown. The first 6 screenshots follow the same time frame as Figure 11, 10 μs increments ending at 56 μs . The last 2 screenshots show the gauge deformation at 76 μs and 96 μs , respectively. It is worth noting that this is the simulation time, not the experiment period, as the flyer had a standoff distance of 5mm from the target face.

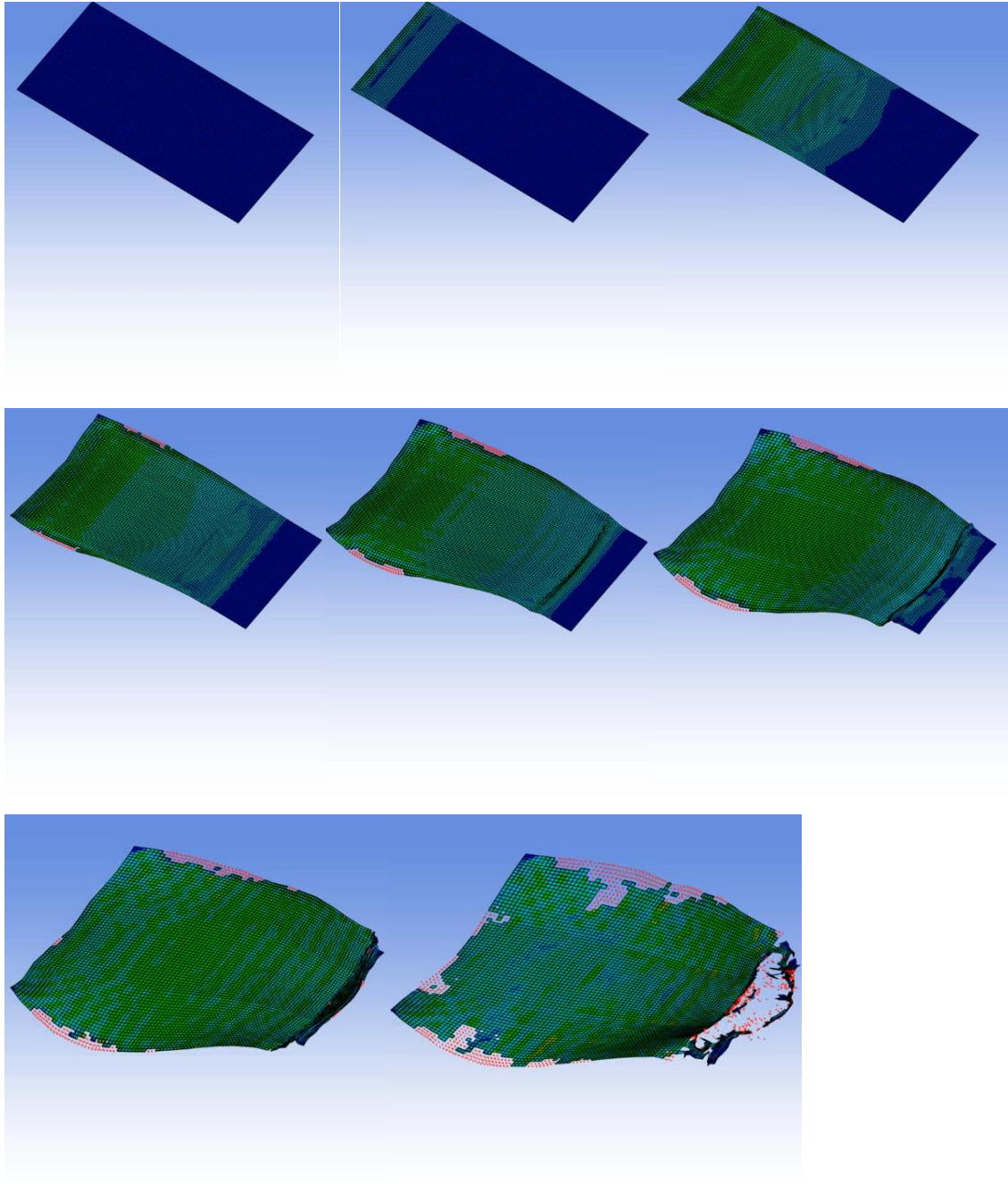


Figure 12 – A sequence of 8 screenshots showing the deformation of the gauge throughout the duration of the simulation. The colour represents the von Mises stress in the part.

Figures 11 and 12 show how the gauge deforms and breaks during the experiment, as expected. The edge of the gauge begins to break apart at 36 μs into the simulation. The target is impacted at approximately 6 μs into the simulation. According to the numerical calculation the gauge needs to survive 37

ns. This breakage happens well after this set window which leaves enough time for the oscilloscopes to receive data from the gauge.

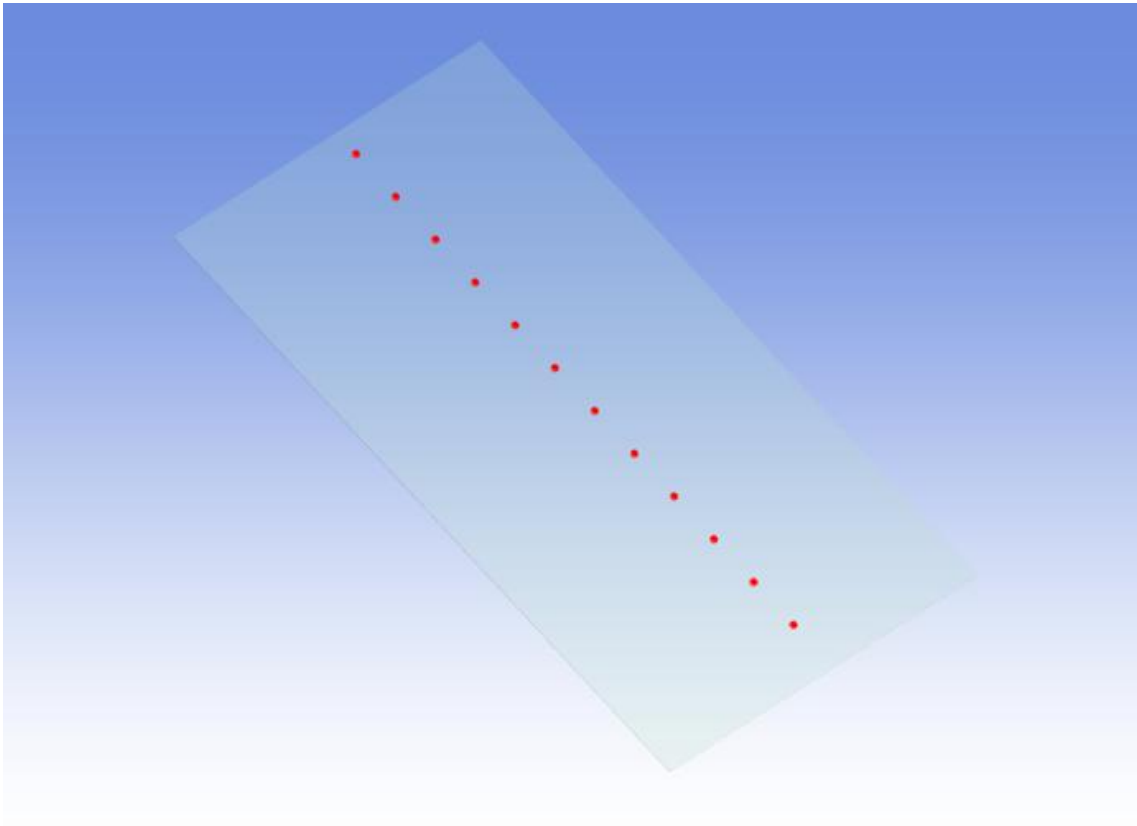


Figure 13 – An image showing the selected nodes used for collecting and plotting data on shear stress and particle velocity.

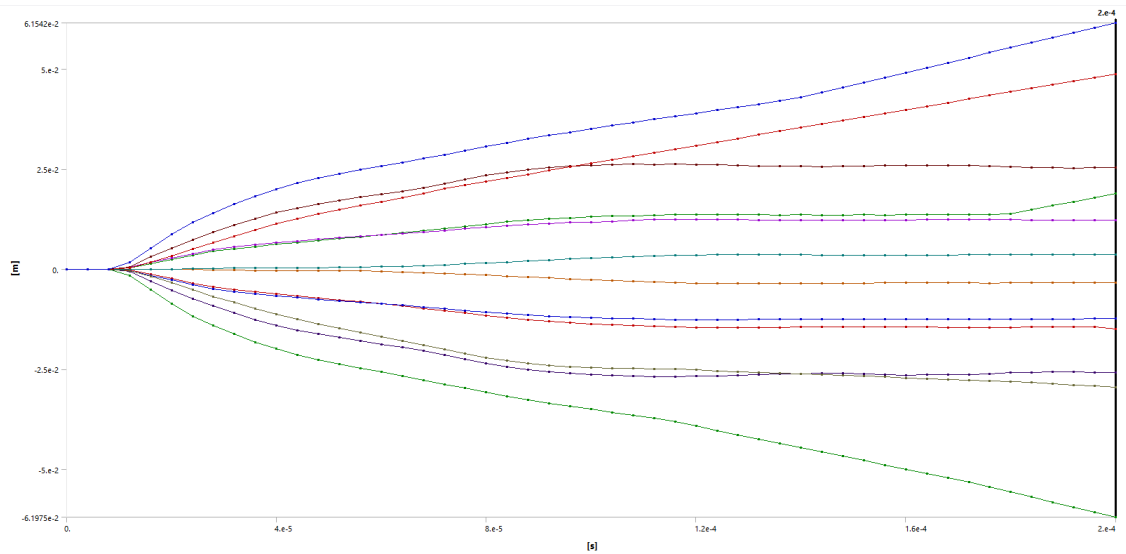


Figure 14 – A scatter plot showing the shear stress in the gauge.

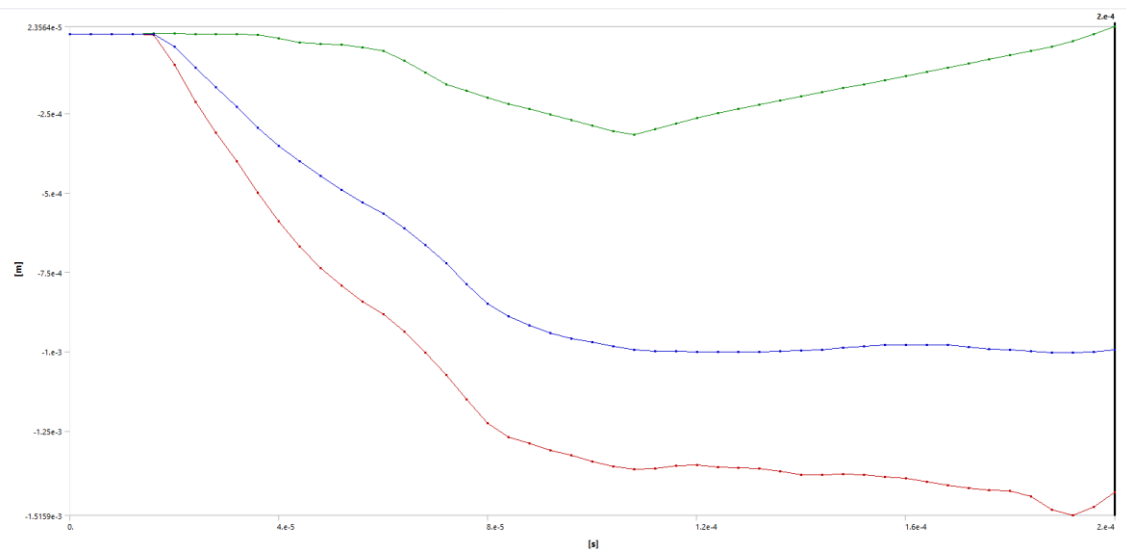


Figure 15 - A scatter plot showing the particle velocity of nodes in the gauge.

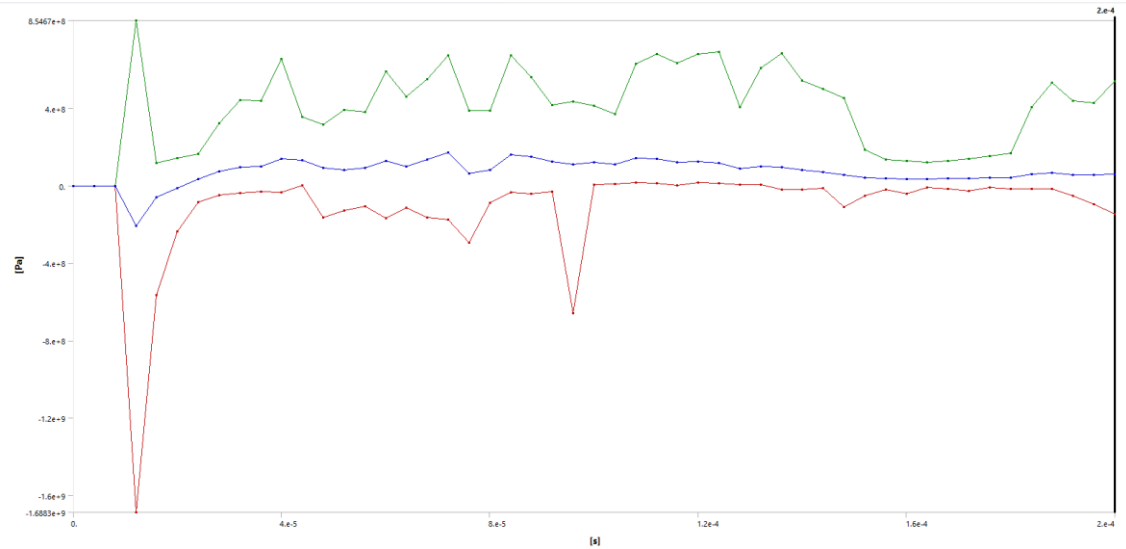


Figure 16 - A scatter plot showing the max principal stress in the gauge.

The scatter plot shows that the gauge receives an initial shock amounting to over 8×10^8 Pa, this is much higher than the yield stress of 5×10^7 Pa. Though it is hard to accurately determine the time it takes to ramp-up to this pressure, we can estimate that this ramp-up took at most $4 \mu\text{s}$. While this would indicate that the gauge would survive long enough to obtain data from the experiment, the analysis is inconclusive and would require further refinement to acquire a confident answer.

6 Conclusion

CAE is an effective tool to use for predicting the outcome of a result without the costs or dangers of performing the physical tests. CAE tools are best implemented alongside an in-depth numerical solution to help refine the model and save on setup and processing time.

An independent mesh study should also be performed to achieve a balance between processing time and analysis accuracy. In theory the denser a mesh the better the result at the cost of time. This is due to the compounding errors experienced when using coarser meshes, however, there is a sweet spot to be found for each analysis between accuracy and processing time which would depend on the importance of the analysis.

References

- I. "Test Ban Treaty (1963)," *National Archives*, Feb. 08, 2022.
<https://www.archives.gov/milestone-documents/test-ban-treaty>
- II. L. G. Hill, R. L. Gustavsen, R. R. Alcon, and S. A. Sheffield, "Shock Initiation of New and Aged PBX 9501 Measured with Embedded Electromagnetic Particle Velocity Gauges," Sep. 1999. doi: 10.2172/10722.
- III. M. J. Burns and C. Chiquete, "Shock initiation of the HMX-based explosive PBX 9012: Experiments, uncertainty analysis, and unreacted equation-of-state," *Journal of Applied Physics*, vol. 127, no. 21, Jun. 2020, doi: 10.1063/1.5144686.
- IV. L. M. Erickson, C. B. Johnson, N. L. Parker, H. C. Vantine, R. C. Weingart, and R. S. Lee, "Electromagnetic velocity gauge: use of multiple gauges, time response, and flow perturbations," Apr. 1981. [Online]. Available: <https://www.osti.gov/biblio/5549207>
- V. S. P. Marsh, *LASL shock Hugoniot data*. 1980. [Online]. Available: <http://ci.nii.ac.jp/ncid/BA23839570>
- VI. F. Bauer, "PVDF Gauge Piezoelectric Response under Two-Stage Light Gas Gun Impact Loading", *AIP Conference Proceedings*, 620(1), p. 1149.
- VII. R. G. Budynas and A. M. Sadegh, *Roark's formulas for stress and strain; seventh edition*. 1989. [Online]. Available: <https://reserves.ub.rwth-aachen.de/record/137578?ln=en>

Appendices

Appendix A : Summary table of results from the analytical solution

Table 5 – A list of all the parameters calculated in the analysis found in section 3.

Parameter	Value
<i>Impact Velocity</i>	<i>750 m/s</i>
<i>Particle Velocity</i>	<i>375 m/s</i>
<i>Shock Velocity in Cu</i>	<i>4498.4 m/s</i>
<i>Shock pressure</i>	<i>15.1 GPa</i>
<i>Shock Velocity in PV gauge</i>	<i>2940 m/s</i>
<i>Transit time through gauge</i>	<i>37 ns</i>
<i>Max bending stress</i>	<i>$3.59 \times 10^{13} \text{ Pa}$</i>
<i>PV gauge yield strength</i>	<i>50 MPa</i>
<i>Factor of overstress</i>	<i>718,000</i>