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Academic integrity declaration

I declare that:

- the thesis submitted has been written by me alone.
- the thesis submitted has not been previously submitted to this university or any other.
- that all content, including primary and/or secondary data, is true to the best of my knowledge.
- that all quotations and references have been duly acknowledged according to the requirements of academic research.

I understand that to knowingly submit work in violation of the above statement will be considered by examiners as academic misconduct.

Abstract

This assignment will critically assess and discuss Computer Aided Engineering (CAE) processes as a tool to be used in engineering design processes. This assessment will cover the credibility of CAE as an Engineering tool, analysing the strength, weaknesses and limitations that are associated with the use of CAE. It shall involve a simulation which is modelled based of an existing CAE published paper. This shall be used to validate the results of the simulation, to prove that it works. Furthermore, it will be used to compare the differences within CAE software packages, before being analysed against expected real world results.

‘CAE or Computer-Aided Engineering is a term used to describe the procedure of the entire product engineering process, from design and virtual testing with sophisticated analytical algorithms to the planning of manufacturing.’ [1] It is used worldwide to speed up the engineering development process, from the creation of Engineering design as CAD drawings standardised i.a.w. BS8888 faster, with easily rectified mistakes compared to traditional hands on drawing, whilst removing the requirement for interpreting handwriting before the testing and creation process, CAE which allows for these designs to be tested via repeatable 3D simulations before getting sending them for large scale production, so you have an accurate idea on whether the part/ component is suitable for the job at hand and will function as intended.

CAE is used within all areas of engineering, from motorsport, mechanical, civil, electronic to the area of which it is being used within this report; WOME engineering, particularly the explicit dynamic solver within ANSYS.

Table of Contents

Academic integrity declaration.....	i
Abstract	ii
List of Figures.....	iv
List of Equations.....	v
List of Abbreviations	vi
1 Case Study.....	7
1.1 Background.....	7
1.2 Method.....	8
1.2.1 Design	8
1.2.2 Set Up	12
1.2.3 Results	13
2 Discussion	22
2.1 Case Study	22
2.1.1 Simulation 1 - Low Quality Mesh – 10mm	23
2.1.2 Simulation 2 – Default Quality Mesh – 1.935mm	23
2.1.3 Simulation 3 – High Quality Mesh – 0.5mm	24
2.2 CAE vs Real World Trials	25
3 Validation.....	28
3.1 Case Study vs Published Report	28
3.1.1 Literature Review	32
3.2 Calculations	34
3.3 Conclusion	37
References	38

List of Figures

Figure 1 - Armour Plate Drawing	9
Figure 2 - Projectile Drawing	10
Figure 3 - Complete CAD Solution	11
Figure 4 - Simulation 1 - Set up.....	13
Figure 5 - Simulation 1 - End Result.....	14
Figure 6 - Simulation 1 - Total Velocity Graph.....	15
Figure 7 - Simulation 2 - Setup.....	16
Figure 8 - Simulation 2 - End Result.....	17
Figure 9 - Simulation 2 - Total Velocity Graph.....	18
Figure 10 - Simulation 3 - Set Up	19
Figure 11 - Simulation 3 - End Result.....	20
Figure 12 - Simulation 3 - Total Velocity Graph.....	21
Figure 13 - Published Journal Simulation Result.....	29
Figure 14 - Published Journal CAE Set Up	31
Figure 15 - Example 1 - 7.62mm Round	32
Figure 16 - Example 2 - 7.62mm Round	32

List of Equations

Equation 1 - Steel Thickness to Prevent Projectile Perforation	34
Equation 2 - Residual Velocity from Steel Plate Target.....	35

List of Abbreviations

CAD	Computer Aided Design
CAE	Computer Aided Engineering
IAW	In Accordance With
WOME	Weapons Ordnance Munitions Explosives
FEA	Finite Element Analysis

1 Case Study

1.1 Background

This purpose of this case study is to review CAE software and their feasibility to be used as an accurate engineering tool by identifying the strengths, weaknesses and reliability associated with the process.

For this case study the Explicit Dynamics Solver within the Ansys CAE software package was used. According to Ansys, 'Explicit dynamics is a time integration method used to perform dynamic simulations when speed is important. Explicit dynamics account for quickly changing conditions or discontinuous events, such as free falls, high-speed impacts, and applied loads. Because these "nonlinear dynamics" are integrated into the simulation, explicit dynamics is the preferred choice for simulating highly transient physical phenomena.' [2]

The idea was to model and simulate a ballistic impact based on a public paper to analyse the deformation and effects when repeating the simulation to judge the reliability and suitability CAE. To conduct this trial, the following tasks were completed:

- Background Research
 - Size of Projectile / Armour Plate.
 - Material Specifications.
 - Simulation Values:
 - Projectile Velocity
- CAD Model
 - Projectile & Armour Plate.
- CAE Simulation
 - Boundary Conditions
 - Mesh Analysis

1.2 Method

1.2.1 Design

The Design was made within the SolidWorks CAD package and consisted of a Steel Armour Plate and a Steel Projectile. The simulation was modelled from an online published academic journal [3], the drawings and assembly can be seen in the figures that follow. The purpose of this was to model a previously tested design, so that the results from this test could be compared to this published paper to test the reliability and accuracy of CAE software by being able to replicate the original results before identifying any issues or flaws with the CAE process.

To enable a realistic validation review of the simulation, the measurements used to design both parts of the CAD models, were the exact same as those used within the referenced journal [3]. The reason this was a requirement is to ensure that any inaccuracies or similarities within the final simulation can be attributed to the use of CAE software or material data, removing an additional source of error to aid the core purpose of this report; being to review the accuracy of CAE software rather than a comparison of ballistics.

Following the creation of the CAD assembly, an ANSYS Workbench was set up, using the Explicit Dynamic Solver to which the assembly was imported into, before both the projectile and the armour plate were assigned a material, and relevant boundary conditions, e.g. distance from target, projectile velocity, direction of travel, fixed support etc. After this, 3 simulations were run, each inhibiting a different 'mesh' to identify the effect of meshing on the solutions, displaying a visual model of what happened.

1.2.1.1 Armour Plate

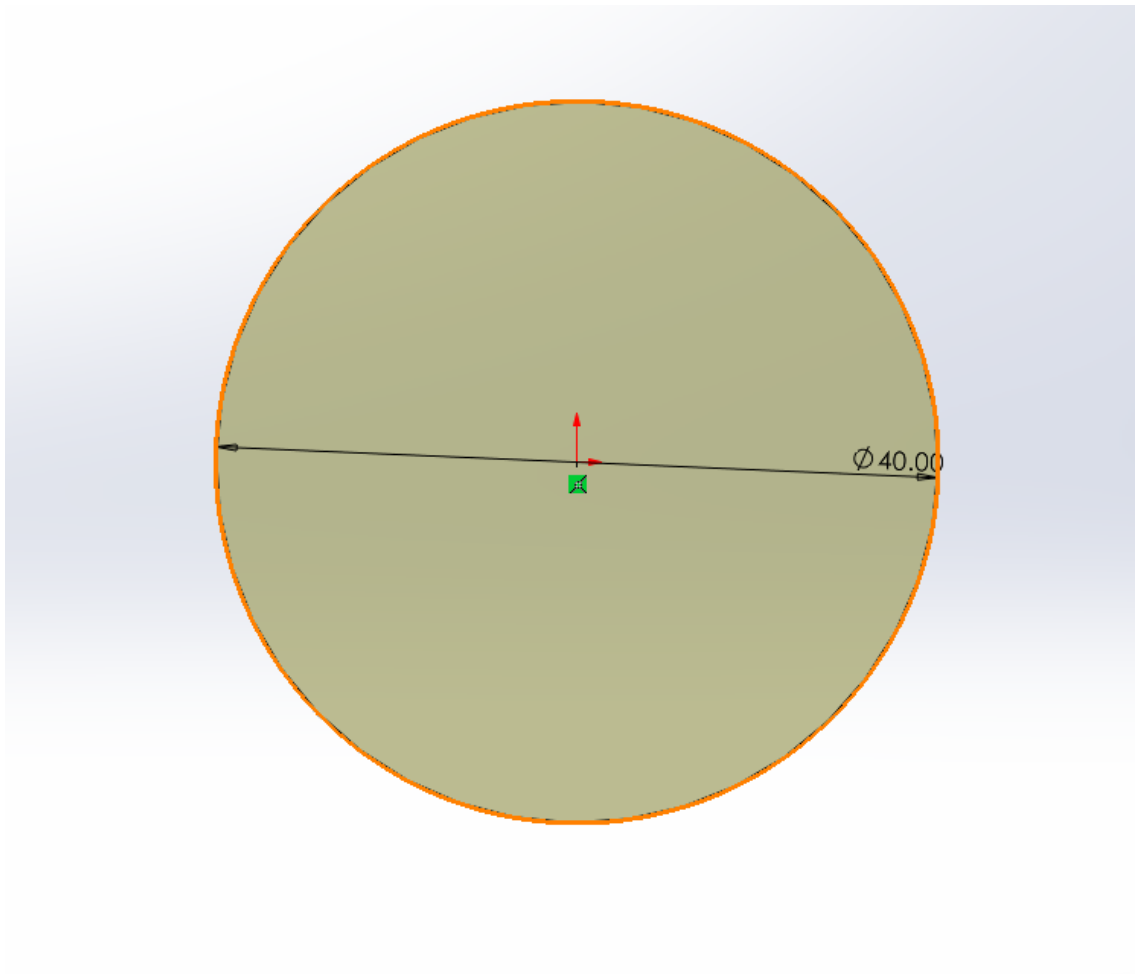


Figure 1 - Armour Plate Drawing

The Armour Plate is a 40mm Diameter circle which was been extruded by 4mm.

1.2.1.2 Projectile

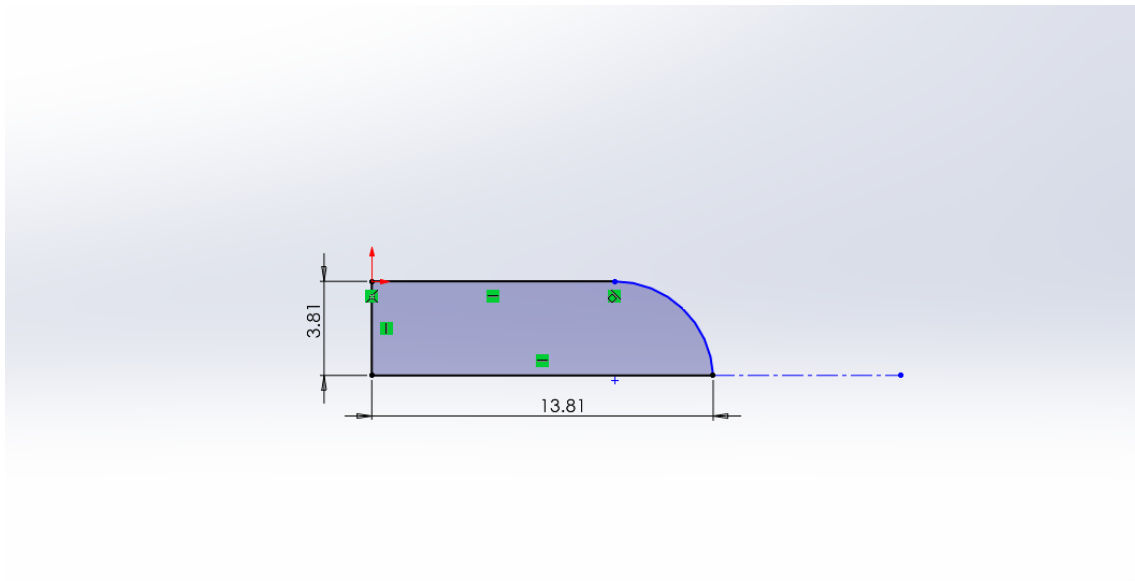


Figure 2 - Projectile Drawing

The Projectile is a 7.62mm x 13.81mm steel round. This involved creating an initial drawing, seen above, before using the 'revolve boss/bass' around the blue sketch centreline.

1.2.1.3 Assembly

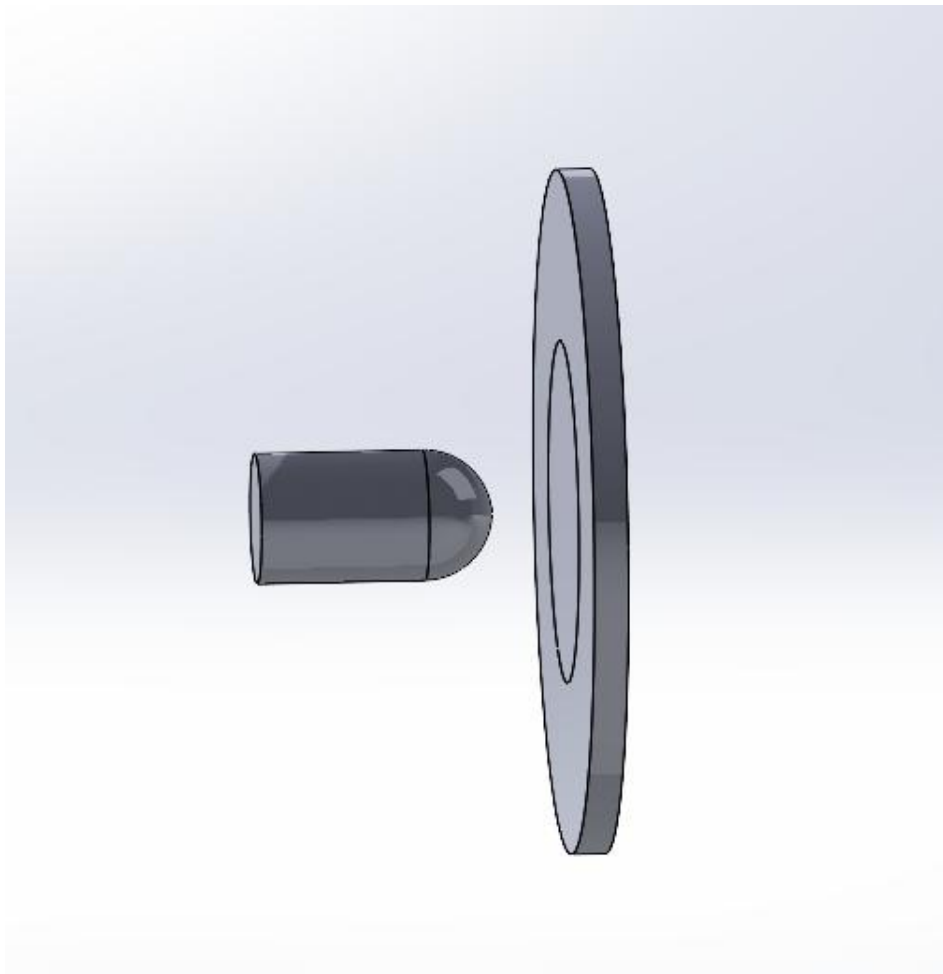


Figure 3 - Complete CAD Solution

Figure 3 shows final assembly which involved mating the projectile and the plate to ensure centre contact and adequate distance for the simulation.

1.2.2 Set Up

The parameters used for the simulation included:

- Material – Steel 4340. This was selected i.a.w. the completed study [3] to keep the simulation as accurate as possible. However, the Steel 4340 material values that was used was taken from the explicit material resource section within Ansys due to lack of exact online data. However, when comparing the Ansys material to the limited material data provided by the report, they were extremely similar. As you would expect for the same grade of steel.
- Velocity – 1000m/s. This was extracted from the online report.
- Fixed Support. To ensure the stability of the target plate, the outside side was used as a fixed support. This would of course lead to slight differences if replicated within a real-life setting.
- End Time - 0.00005s.
- Mesh – This was changed 3 times, from a low quality to a high-quality mesh to analyse the impact of meshing on CAE accuracy.

1.2.3 Results

1.2.3.1 Low Quality Mesh – 10mm – Simulation 1

Pre Simulation

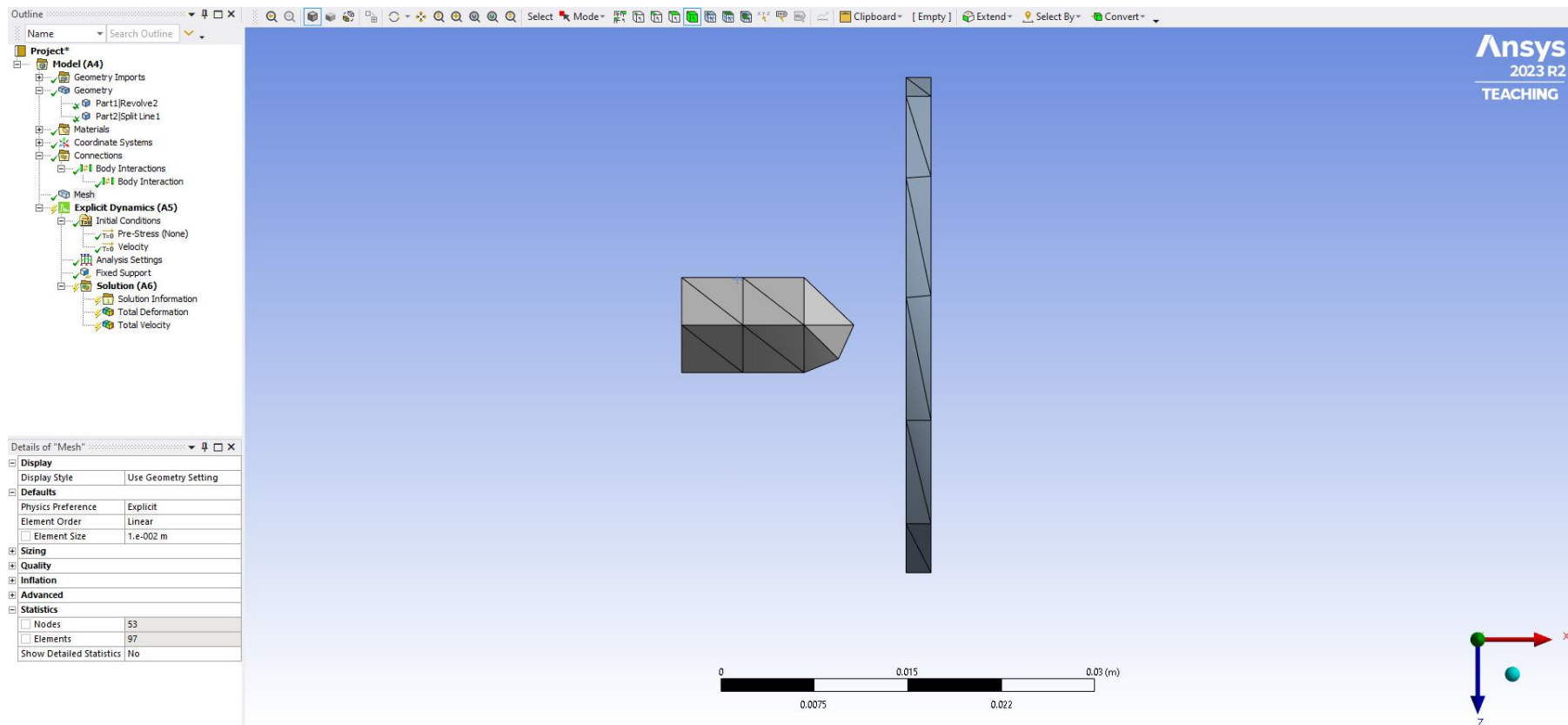


Figure 4 - Simulation 1 - Set up

Post Simulation

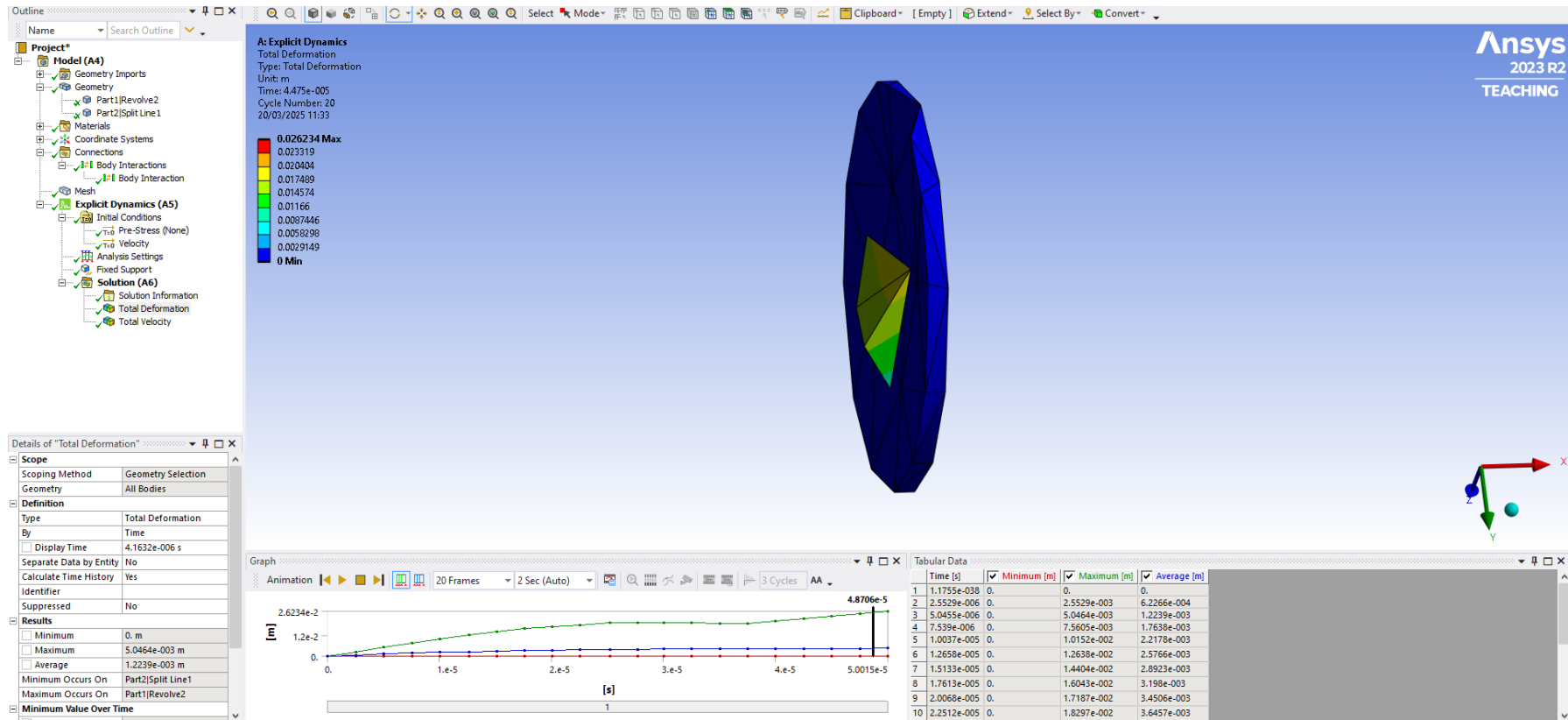


Figure 5 - Simulation 1 - End Result

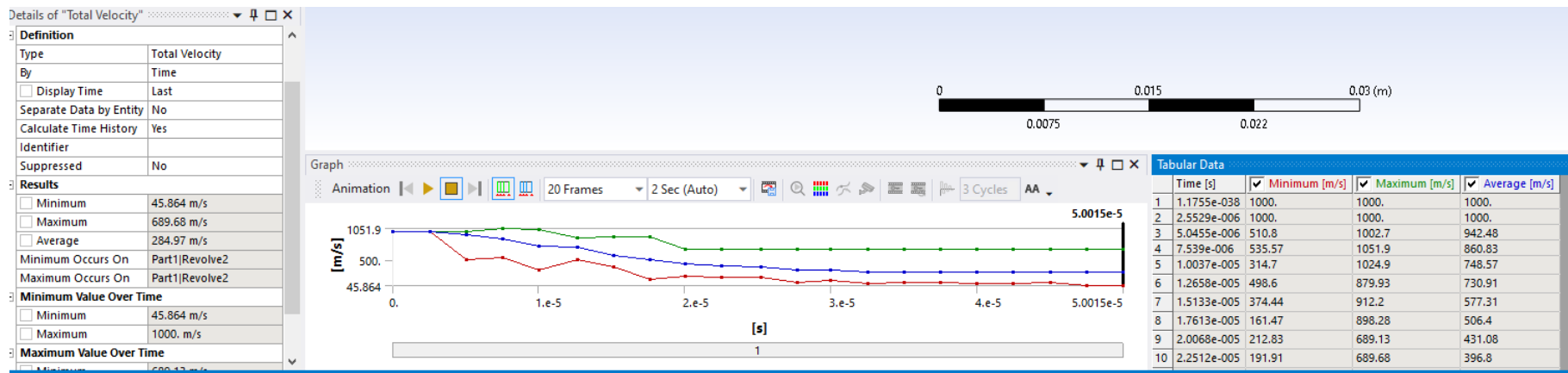


Figure 6 - Simulation 1 - Total Velocity Graph

1.2.3.2 Default Mesh – 1.935mm – Simulation 2

Pre Simulation

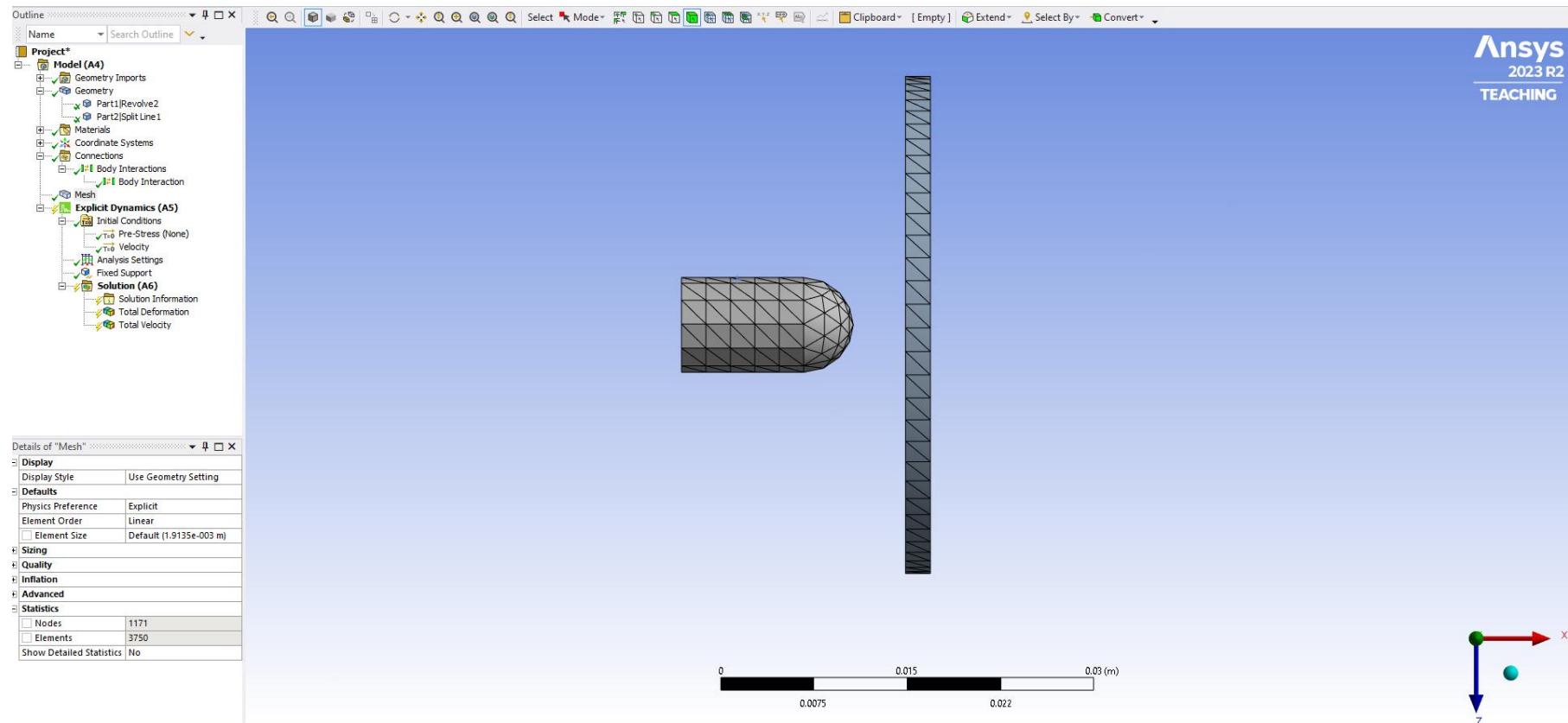


Figure 7 - Simulation 2 - Setup

Post Simulation

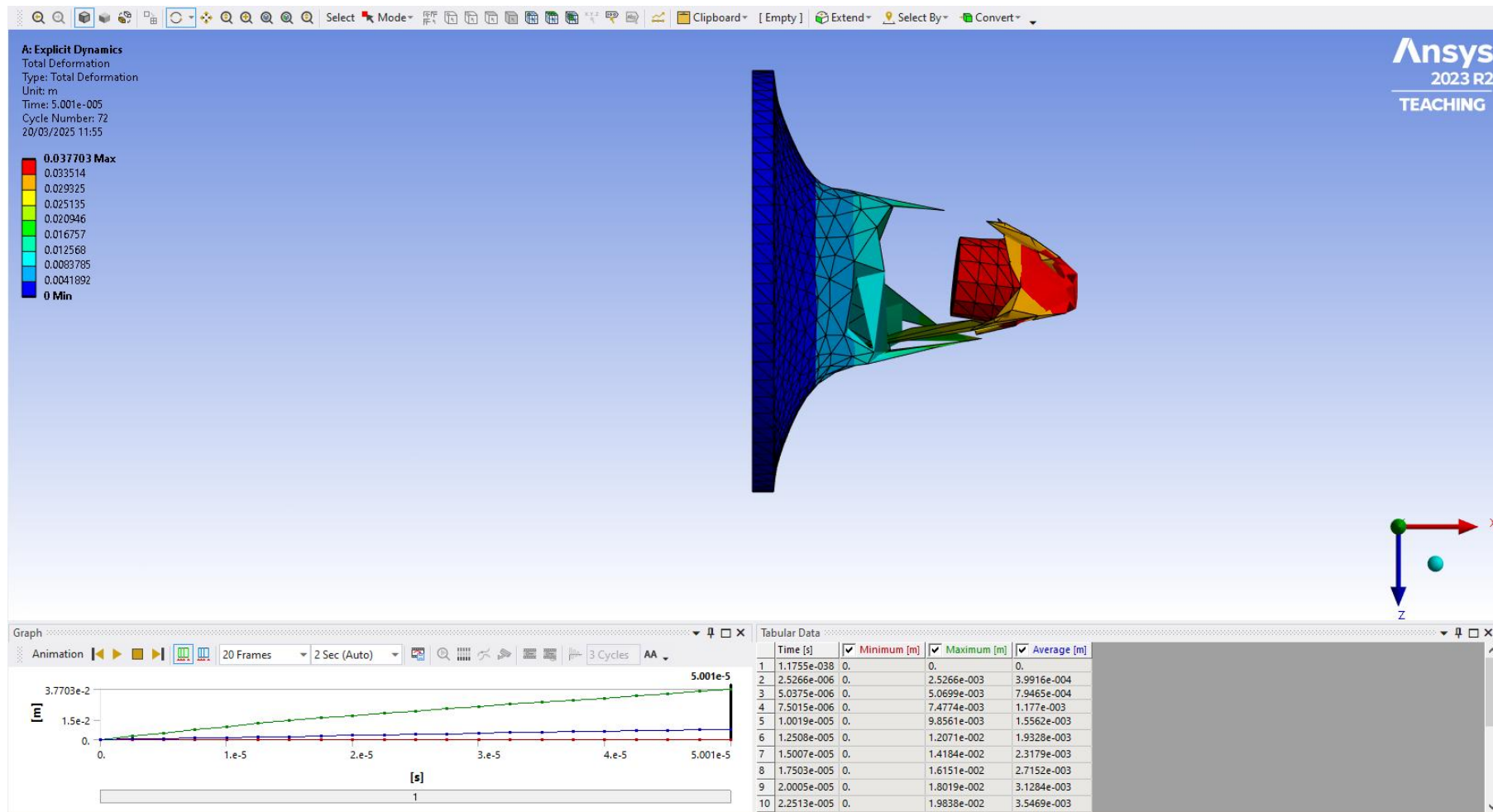
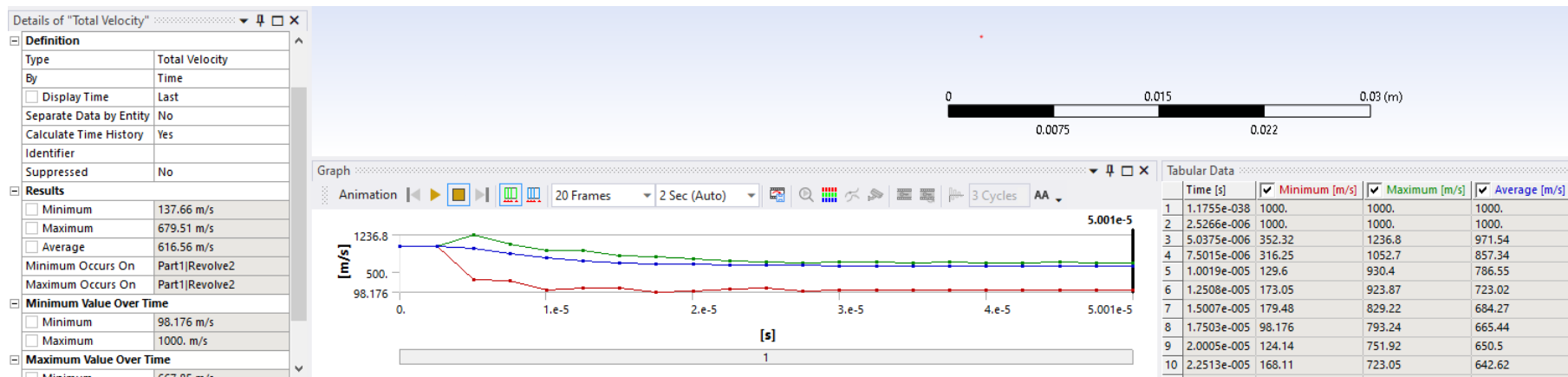


Figure 8 - Simulation 2 - End Result



1.2.3.3 High Quality Mesh – 0.5mm – Simulation 3

Pre Simulation

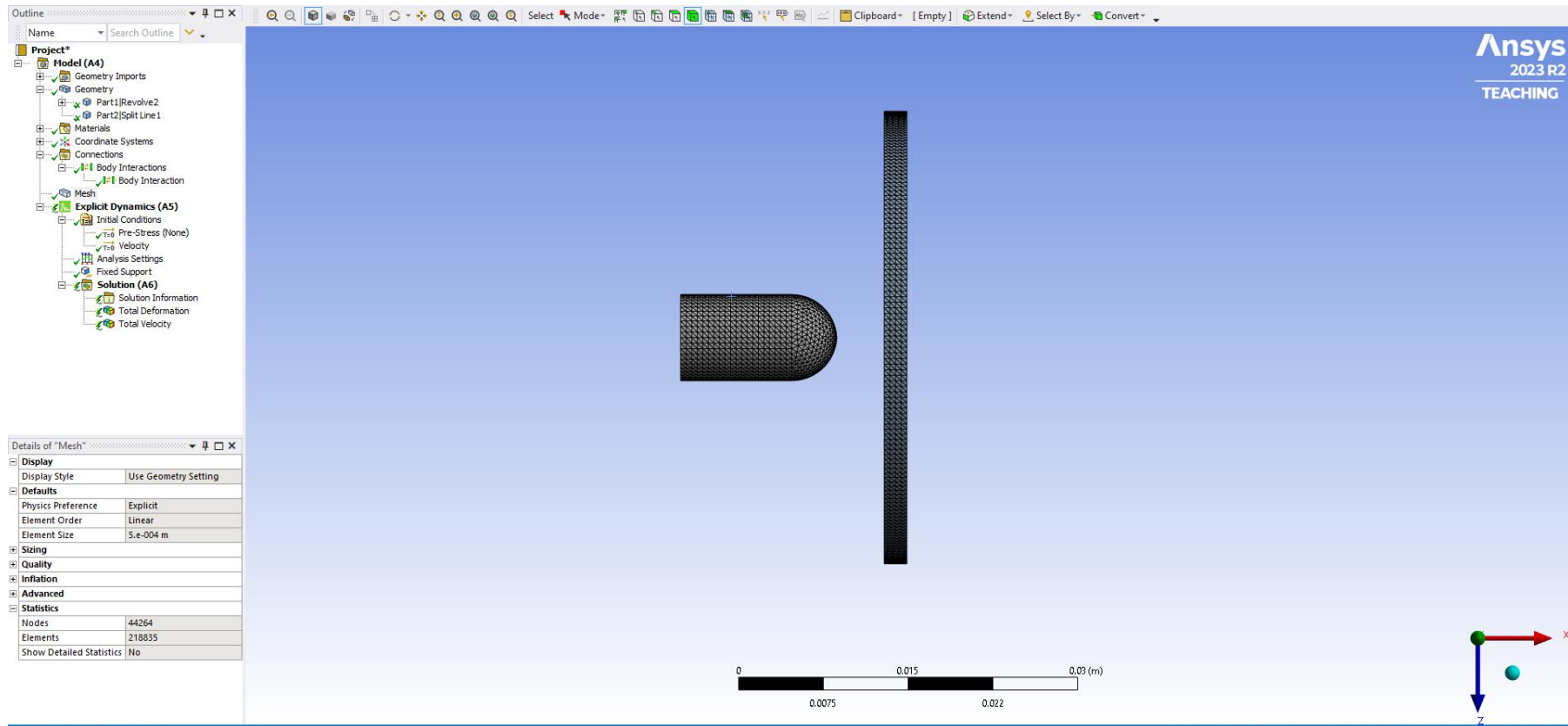


Figure 10 - Simulation 3 - Set Up

Post Simulation

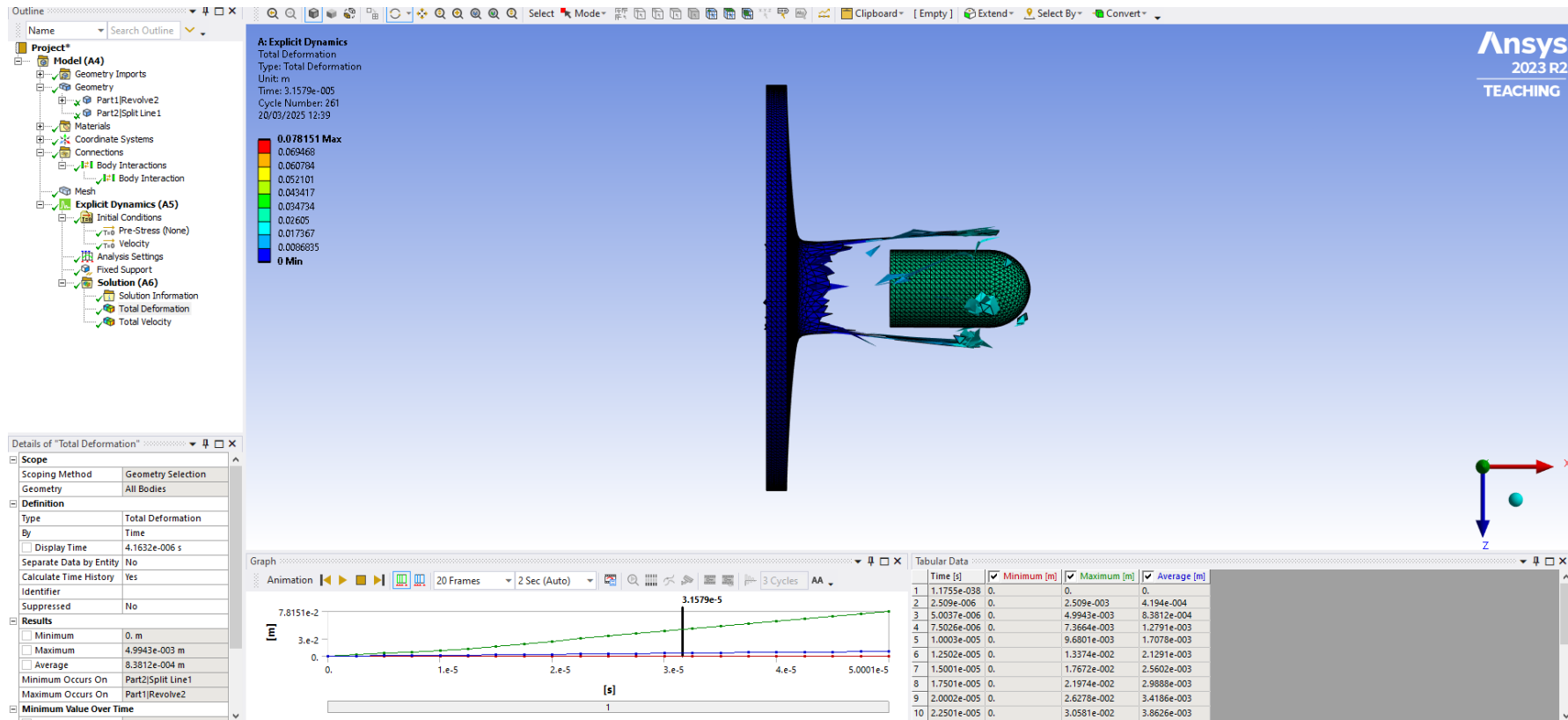


Figure 11 - Simulation 3 - End Result

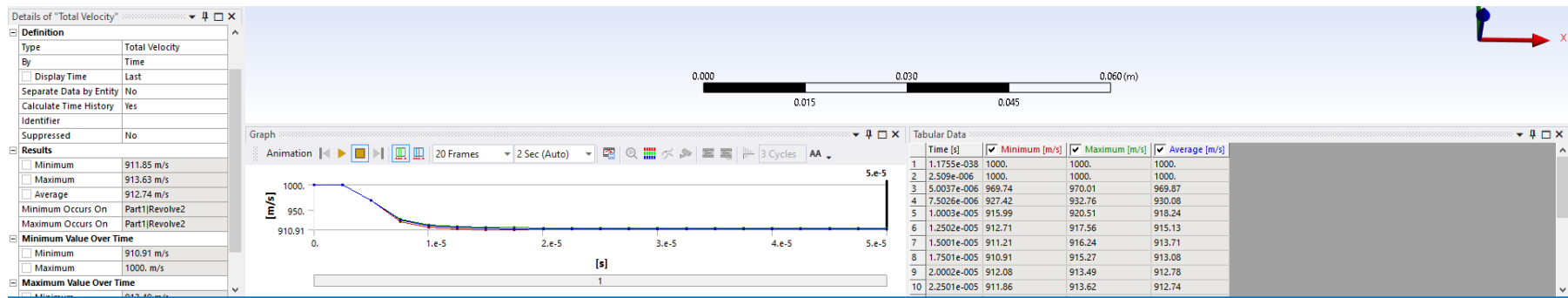


Figure 12 - Simulation 3 - Total Velocity Graph

2 Discussion

2.1 Case Study

This case study involved 3 different simulations; within each simulation, the constraints and properties are all the same except for mesh size. The purpose of this was to analyse the effect different 'quality' mesh's had on the results of the simulation.

'A mesh is made up of elements which contain nodes (coordinate locations in space that can vary by element type) that represent the shape of the geometry. An FEA solver cannot easily work with irregular shapes, but it is much happier with common shapes like cubes. Meshing is the process of turning irregular shapes into more recognizable volumes called "elements."' [4]

This is a requirement due to CAE programme having to mathematically calculate the forces and pressures on each object, so meshing allows the formation of the designed shape using tens, up to hundreds of thousands of smaller shapes such as triangles, in which the mathematical modelling software can perform large scale individual calculations leading to a higher level of accuracy.

Each simulation involved the same projectile, travelling and impacting an armour plate. To allow for this, ANSYS uses Finite Element Analysis (FEA) where the stresses and strains are calculated on individual nodes (size dependant on the mesh) which are used to define the selected geometries to provide accurate deformation and displacements at set time steps within the simulation.

2.1.1 Simulation 1 - Low Quality Mesh – 10mm

Within this simulation, a low-quality mesh was used where it contained 53 nodes and 97 elements, as can be seen, this led to the projectile not retaining its designed shape, and as a result it did not penetrate and squashed into a flat object on impact. This is due to the projectile transferring all of its kinetic energy into the plate, due to the high stresses and strain it was put under, with an inaccurate mesh leading to minimal constant stress strain calculations being completed by the FEA solver, and the ones that were completed were representing a large area of the projectile as if they were the same exact part. For example, the circular point at the front of the projectile will experience a much different stress strain load compared to the rear face.

2.1.2 Simulation 2 – Default Quality Mesh – 1.935mm

Within this simulation, the default mesh was used. This is the mesh that ABAQUS automatically assigns on detection of the objects, to attempt to strike a balance between shape structure and simulation speed. When reviewing this simulation, it is obvious that the shape of the projectile is fairly accurate, however, the curved face at the front, from the side view shown in figure 7 it still looks fairly course and not a smooth rounded face.

This simulation achieved penetration of the armour plate, as expected. However, it changes direction slightly, and the deformation of the armour plate is not as expected, with more plasticity, shown by the bending of material. As well as the elements being enlarged and some losing definition. This shows that the mesh should be refined to a higher quality using more nodes and elements at a smaller size.

Within this simulation you can see the high levels of stress and strain that is placed onto both the projectile and armour plate, with the dark blue representing minimal and red representing maximum deformation. It shows a lot of bulging within the plate compared to simulation 1 and 3, this is due to the plate absorbing a lot of the kinetic energy the projectile has, showing that although the projectile managed to fully penetrate the plate, it experienced a lot more resistance than

simulation 3, which is reinforced from the slight deformation and bend the projectile experienced shown within figure 8 alongside the reduced velocity post impact, showing that a lot of this energy was transferred into the armour plate.

2.1.3 Simulation 3 – High Quality Mesh – 0.5mm

Within this simulation a higher quality mesh was selected with an element size of 0.5mm, shown on the left-hand side of figure 10. This showed a vast improvement in the shape of the modelled projectile, from where the increased number of elements has allowed the software to create a much more realistic curved surface.

The post simulation shows the projectile easily penetrating through the armour plate with no obvious damage and a decreased speed from 1000m/s to 912m/s, showing that the round had penetrated the plate with ease. This is reinforced by the fact you can see minimal stresses and strain outside the impact central zone, with no bulging showing less energy transfer from the projectile to the plate. Although the plate shows a much more accurate flaking/ deformation, it still shows some elements that had increased size and stretched significantly, showing that the mesh can still be improved as these elements should be separated and spread out further.

2.2 CAE vs Real World Trials

When comparing the use of CAE to real world trials, there are a vast number of simplifications, limitations and assumptions that are made, regardless of how the simulation, such as:

- Geometry: Within CAE, the geometry is subjected to a mesh, which will always be an approximation, due to being created using a vast number of smaller shapes. This leads to complex structures such as round edges or chamfers to become inaccurate or assumed to have flat surfaces. Furthermore, in real life, the geometry will be made within a certain tolerance or have a surface finish which cannot be completely replicated within software-based solutions.
- Material Parameters: These are always an assumption due to metal alloys almost never being the exact same, unless you analyse the material you are modelling precisely prior to the CAE simulation. For example, Steel 4340 can have between 95.195% - 96.33% [5] which will affect its material properties. Furthermore, all factories will have variation within the production process, whether that be in the quenching or tempering processes. This can be seen in the fact the material data for Steel 4340 that overlap between the online journal and the ANSYS material data directory are both slightly different.
- Damage Models: Models such as Johnson cook damage parameters, are taken as an approximation. The same value is used throughout the models within CAE, whereas in real life, the damage will vary throughout the material rather than be one exact equation. Furthermore, unless this value is obtained yourself, there is no guarantee it will be an exact match to the material you are choosing to simulate.
- Perfect Conditions: Within this aspect of CAE, things such as contacts/ mates are made from an assumption. Where you set an exact impact zone for the projectile, alongside a set distance and velocity. This can be theoretically correct; however, the gun system is unlikely to be pointing in the exact height and distance set, with a tolerance variation in relation to the velocities for every bullet shot. This is combined with the changes of

propellant and cartridge case down to human tolerances, all of which will impact the direction and speed of travel.

- Boundary / Environmental Conditions: Within this CAE simulation, it assumes no inaccuracies when firing, e.g. discounting human factors, recoil, machined tolerances etc, which would cause variation in the location of impact. Furthermore, the simulation was running with a uniform fixed hold, meaning that each side of the armour plate was completely secure with no effect on the firing. Replicating this in a real-world scenario would be extremely difficult and not likely and would lead to different results. Environment conditions such as wind strength, direction, humidity, which would all have a bearing on the accuracy, speed and result of the trial, with wind resistance reducing the speed of the projectile, generating additional heat and causing it to move.

All the above are small inaccuracies, limitations and assumptions that are applicable when conducting a CAE case study, which when they combine, can influence solution accuracy when comparing a simulated trial and a real-life trial (in this case a ballistic trial), and will lead to discrepancies between the results. However, these discrepancies are frequently accepted due to the drastically reduced cost of conducting a CAE trial, compared with a real-life firing trial. Cost of software and employee wages, compared with the cost of hiring a range, conducting health and safety mitigations, material costs, employees' wages alongside liability insurance. The cost of real-life firing trials starts in the region of tens of thousands and can go up to millions, depending on what, where and when and how much is being tested. The use of CAE allows realistic simulation tests for a fraction of the cost, whilst allowing you to make mistakes, e.g. material selection/ sizing and adjust the CAD until you find a solution that meets your requirements which can then be subjected to a real-life firing trial if required.

A major limitation to CAE is computational processing power. When conducting complex simulations, such as the ones referred to within this report, the amount of processing power required can reach extreme highs. Within each simulation (1,2 and 3) as the complexity of the simulation increased due to increased meshing,

they took longer to run. For example, simulation 1 was completed within seconds, whereas simulation 3 took longer than an hour to run. If this simulation was completed again with an even finer mesh size, on the machine used this could take over 24 hours for a small explicit simulation. If you were looking to increase the size of the armour plate, round and add in multiple materials, this would require a high level of processing power, which for individuals would be extremely challenging to achieve, and for businesses would raise the cost burden significantly.

3 Validation

3.1 Case Study vs Published Report

To validate this simulation, every aspect of CAE used has been analysed against the source material. Starting with the CAD designs, which can be easily validated against the report by using the same measurements for both the size and shape of the projectile & armour plate.

To ensure that the results from the simulation could be used and compared to the results in the source journal, the simulation set up had to be validated. This was done by ensuring the set up was as accurate as possible, using all the information available within the report such as:

- Bullet Velocity – This was set as 1000m/s, i.a.w. the published journal. On review, this speed seems fairly high for the for a 7.62mm round, especially with an abnormal shape. With typical values of around 800m/s [6] seen in live firing trials, with an impact velocity of 775m/s showing that the projectile slows down whilst in flight.
- Fixed Hold – This ensured that the armour plate would remain secured within a fixed position, rather than be scattered on impact.
- Mesh – The effect of meshing on the results of the simulation was analysed within this report using 3 different mesh's.
- Correct mating – Ensured that the projectile and armour plate were correctly mated so that impact would hit the plate at the middle.
- Run time – This was set i.a.w. the published journal to ensure that the simulation would have enough time to complete.

Following the validation of the setup and designs, the results could be validated. With the published journal showing the following results:

- Bullet Velocity decrease from 1000m/s to 830/ms
- Armour Plate structural damage. Due to not having the source CAE simulation file a mathematical analysis could not be achieved. However, a review of the post simulation images from both can be reviewed for

similarity. For this, simulation 3 was reviewed against the source simulation – see below.

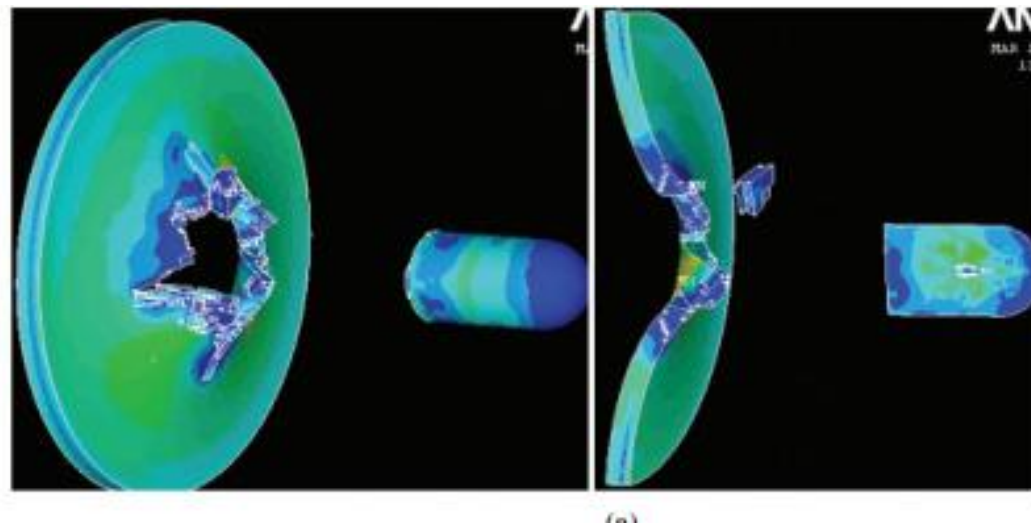
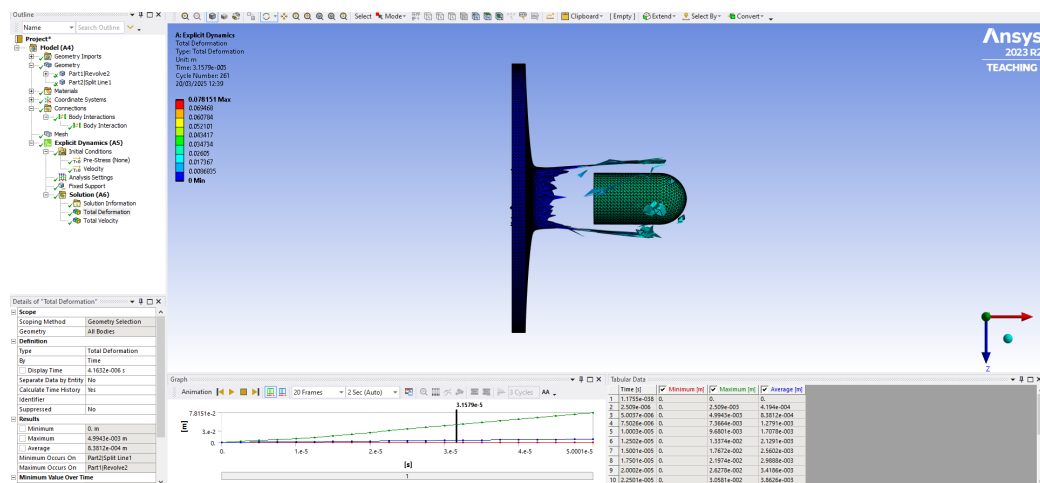


Figure 13 - Published Journal Simulation Result



Using the two images above, the following similarities and differences can be identified:

Similarities:

- Lack of Projectile Deformation.
- Clear Projectile Penetration.
- Armour Plate petal flaking outwards.

Differences:

- Post Penetration Bending of Armour plate.

On review of these simulations, clear similarities can be identified. Aligning with the coloured 'total deformation' representation, both simulations led to a full penetration of the material, with petalling occurring to the armour plate. Where it differs slightly is the exact deformation to the armour plate that occurs. The key difference is the reduced amount of overall bending of the armour plate within simulation 3, where it seems to cause less damage to the whole plate. This is also consistent with the change in velocities, where the projectile within the published paper suffered a decrease in velocity of 170m/s compared to simulation 3, which suffered a decrease in velocity of 88m/s. This shows that the published simulation's projectile was affected more by impact with the plate, leading to slow to its velocity decreasing much more, and causing the plate to bend out further compared to simulation 3, being impacted by the plate a lot less and subsequently damaging the plate outside of the impact site less.

This difference in results could be attributed to the following two things:

- Mesh.
- Material data.

The mesh in the published paper, seen below, appears much finer at the centre of the plate, in comparison to the uniform mesh within simulation 3, which means the impact zone and its surrounding areas could produce a more reliable results, whilst reducing the overall processing power needed to run the simulation. To achieve a more accurate result, this mesh could be replicated – potentially even finer to try and replicate a real-world result as accurately as possible.

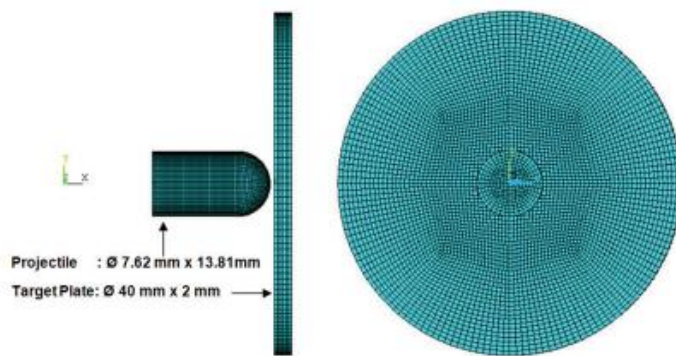


Figure 1. FE model of the bullet and target door plate for Case-1 analysis.

Figure 14 - Published Journal CAE Set Up [3]

The material data provided within the published paper wasn't adequate for use within this version of ANSYS, so the same type of material, available for use via ANSYS material directory was used. Although this was the same type of steel, it would still have some slight difference which could also contribute to the slight difference in material deformation.

3.1.1 Literature Review

The published simulation adequately modelled a projectile penetrating through a circular armour plate. However, it most likely wouldn't be a suitable paper to use when reviewing the suitability of a 7.62mm bullet due to the design and function of the intended round. The 7.62mm round is a very common round adopted by lots of countries worldwide, however, the design of this round looks a lot different to the projectile used within this simulation. Two examples of the projectile component of a standard 7.62mm round can be seen below (with the cartridge case not being shown due to the CAE software assigning the projectile a speed without the requirement of propellant).

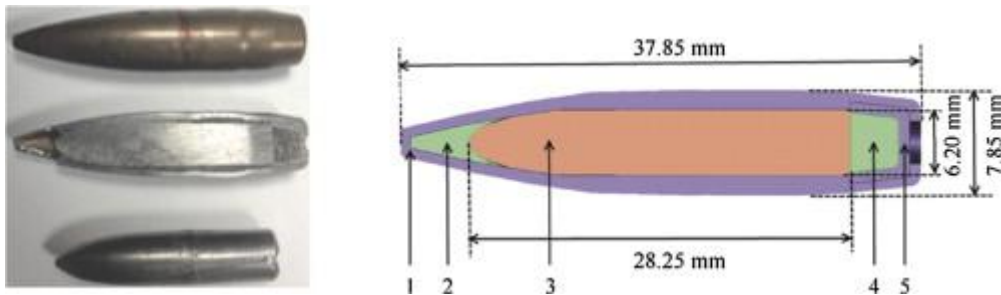


Figure 15 - Example 1 - 7.62mm Round [7]

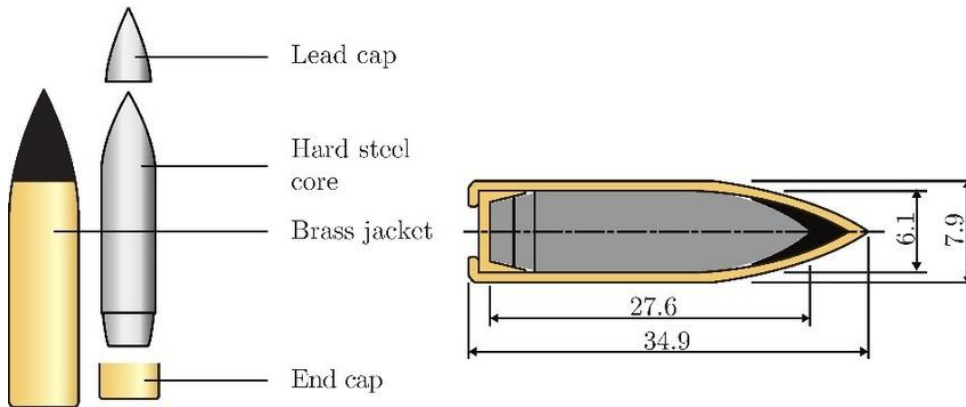


Figure 16 - Example 2 - 7.62mm Round [8]

As you can see, both examples are surrounded with a brass jacket, and have a lead cap as well as a hard steel core. The use of a brass jacket within CAE is not required, as this is a soft metal with the primary objective to protect the barrel from wear. However, the lead cap is quite important as it is a hard material which is used to hit the target first, to assist the projectile with penetration. Furthermore,

the shape of the steel core within these standard rounds are much different to the shape of the simulated rounds. This shape is more aerodynamic and has a reduced curved prior to the curve, leading to improved penetration performance. Although the simulated round still penetrated the armour plate with ease, the effects minor effects of the brass jacket, lead cap as well as the different design would all cause slightly different damage results to the armour plate, leading to the simulation being less accurate than you would want. Should you model a standard 7.62mm round instead of the shape used, you would expect a penetration with a more concentrated penetration zone, with even less losses to projectile velocity.

3.2 Calculations

Seen below are two equations, equation 1 being 'Steel Thickness to Prevent Projectile Perforation' and equation 2 being 'Residual Velocity from Steel Plate Target' both of which have come from the following US Department of Defence publicly released study of ballistic resistance.

$$T_s = D \left(\frac{vm^{0.5} \cos^{0.8} \theta}{1.125 D^{1.5} \log_{10} BHN} \right)^{1.25}$$

Where:

v = impact velocity (m/s) (initially use maximum muzzle velocity from Appendix C.)

D = projectile diameter (mm) (see Appendix C)

T_s = thickness of steel plate to prevent perforation (mm)

θ = angle of obliquity (degrees)(see glossary)

m = mass of projectile (kg) (see Appendix C)

BHN = Brinnell Hardness Number (see Table 5-3)

Equation 1 - Steel Thickness to Prevent Projectile Perforation [9]

$$V = 1000\text{m/s}$$

$$D = 7.62\text{mm}$$

$$\theta = 0 \text{ degrees (Direct hit)}$$

$M = 9.53\text{g}$ (0.00953kg) – Due to the projectile/ material used being completely simulated, this value has been selected i.a.w. BS 5051 standard 7.62mm ammunition, seen within Annex C of Reference [9].

$$BHN = 217 [5]$$

$$T_s = D \left(\frac{vm^{0.5} \cos^{0.8} \theta}{1.125 D^{1.5} \log_{10} BHN} \right)^{1.25}$$

$$T_s = 7.62 \left(\frac{((1000 \times 0.00953)^{0.5} \cos^{0.8} 0)}{(1.125 \times 7.62)^{1.5} \log_{10} 217} \right)^{1.25}$$

$$T_s = 14.4\text{mm}$$

$$v_r = \left\{ v^2 - \left[\frac{1.1275 \left(\frac{t}{D} \right)^{0.8} D^{1.5} \log_{10} BHN}{m^{0.5} \cos^{0.8} \theta} \right]^2 \right\}^{0.5}$$

Where:

t = thickness of steel plate (mm)

v_r = residual velocity (m/s)

v = impact velocity (m/s)

Equation 2 - Residual Velocity from Steel Plate Target [9]

$$V_r = \left\{ V^2 - \left[\frac{1.1275 \left(\frac{4}{7.62} \right)^{0.8} 7.62^{1.5} \log_{10} 217}{0.00953^{0.5} (\cos^{0.8} \times 0)} \right]^2 \right\}$$

$$V_r = 940 \text{ m/s}$$

Using these equations, the simulation can be validated by proving that the projectile should be able to penetrate the steel plate and at what velocity it should be travelling at following this penetration. The first equation gave a result of 14.11mm, meaning that the projectile should be able to penetrate upto 14mm of steel. This validates the simulation as it provides further evidence to suggest that that the projectile performed as expected within the simulation.

The second equation provides the calculated speed of 940m/s post penetration. This is compared to the speed of around 920m/s post penetration within the third simulation. Considering the lack of defined values (multiple values being used from various sources) this is a fairly accurate result, with the differences potentially being resolved with a finer mesh, sole source material values and an expectation that simulated values will always contain some discrepancies.

However, these results haven't been obtained with exact values, for example:

- BHN – This hasn't been taken from the exact material used (instead it has been taken from an online Steel 4340 material sheet [5]), due to ANSYS material database not providing this.

- Weight of Projectile – Due to this projectile being made in CAD, the weight is not able to be found, with material differences, this value could be higher or lower than the one used.
- Further inaccuracies – Within CAE due to the use of perfect Johnson cook parameters, assumed material perfections, ideal point of impact and lack of external factors, it is likely that the CAE simulation would achieve different results.

3.3 Conclusion

This report concludes that CAE is an effective tool to use as a time and cost-efficient design improvement methodology, which can be used to analysis and validate ideas to an extent, before conducting real world analyse to minimise the number of unsuccessful trials. The case study conducted shows that simulations and studies can be repeated with a level of high level of accuracy, dependant on the accuracy of the information used. It proved that with even with highly complex, explicit dynamics simulations, they can be ran successfully with an output result like what you would expect in a real-life scenario.

However, for areas where high levels of safety and efficiency are required, CAE shouldn't be used as the sole evidence prior to use/ production. Rather it should be used as an effective aid to help the individual(s) refine an existing product or idea to test it prior to conducting real life tests. For instance, integrating the use of CAE within the design process of an engineering firm, to avoid wasted, costly production of useless components and to optimise effective design improvement strategies.

Further improvements that would improve the Case Study would involve the testing and analysis of the chosen materials (for both the projectile and the armour plate) to have a single source of values, so that the weight, damage parameters and material values would be as accurate as possible and would lead to improved realism within the CAE software with the use of an extremely fine mesh to improve the calculated results. Furthermore, completion of a live firing trial to validate these results and to identify the margin of error, as well as improved values for impact velocity etc.

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