

ACDB5007 – Computer Aided Engineering

Application of Computer Aided Engineering Processes

Using a combination of CAD and FEA software to model the impact of a 120mm HESH shell on structural strength concrete, and analysing the accuracy and limitations of the chosen software.

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Abstract

This report aims to look at the strengths and drawbacks of using computer aided engineering (CAE) tools within the defence domain. In order to do this, a structural analysis impact case was devised involving a large calibre high explosive squash head (HESH) shell against a structural grade concrete target using ANSYS' finite element analysis (FEA) software, comparing the results with known analytical and in-use data from years of in-service use and other tests and experiments performed on the 120mm projectile in the physical domain.

The simulation entailed a realistic reproduction of a 120mm HESH in-service military munition using a well-known CAD package, using known and publicly available geometric data. Information such as the round's known muzzle velocity, range, and drag coefficient, were used to calculate an accurate velocity of impact against the target, and then an FEA software simulation was run demonstrating the impact. The results gathered showed a decent degree of accuracy, although the level of penetration of the round in to the target structure itself exceeded what would be expected during this impact.

Reasons for this could include, but are not limited to, the way in which the structure's material properties are classified, such as knowing exactly what sort of concrete is being

attacked, or the fact that the munition in this report has the capacity to attack and defeat armoured steel, which is stronger than concrete. If the round impacts upon concrete at its maximum impact velocity, penetration is possible or even inevitable. As a result, making sure the initial parameters are correct is key.

There were also issues balancing the time constraints of the report and the limitations of user knowledge and ability with ensuring accurate results. Mesh refinements within the system would certainly have contributed to a better set of results, but to do the required work to achieve these results would require simulations that would take hours to compute and complete. There is no reason, however, why this would not be feasible in a professional setting, and so there is still scope to say that FEA software, despite the issues encountered in this report, provides a good long-term alternative to putting on expensive firing trials within the defence and aerospace domain, and this will only improve as the software packages also improve.

Another issue specific to this report that had an impact on results, but does not necessarily compromise the software itself, is the restriction to publicly available information relating to the in-service munition. It is almost certain that other, restricted, information, if it had been used in the design of the scenario, would have refined results further.

Introduction

The prevalence of computer aided engineering solutions to solving complex engineering problems has increased over recent years, not only as a solution to rising costs of manufacturing and prototyping, but also due to the computer's ability to solve highly complex mathematical scenarios in a much shorter time than traditional methods. The defence industry is not different, and carrying out physical trials can be an incredibly expensive and time consuming process, when it could be theoretically possible to accurately design components for trials using design software such as SolidWorks, and then model most conventional trial scenarios using existing FEA software. In defence and aerospace, there is a requirement for trials to be completed at speed to meet rapidly-changing customer demands. FEA software has seen increased use in a range of applications across the industry, as referenced in [1], from engineering solutions relating to vehicle survivability to live firing trials.

Computer Aided Engineering is the umbrella term given to the stage of the computational process between initial design and final manufacture of a product [2]. It allows for the performing of rigorous testing and analysis on computer designed prototypes across a variety of engineering domains, from fluid dynamics to thermal state analysis. By testing components, systems and assemblies for their reliability, the number of physical

prototypes required for testing is reduced, as is the time taken for a product to make the market [2].

In the case of this report, finite element analysis (FEA) is the method of choice to be deployed to solve the case study. This process uses the finite element method (FEM) of breaking down an entire system into a number of smaller parts, in the case of Ansys, a discrete mesh, on which individual calculations can be carried out over a period of time to develop results. The user has control over how they want the mesh to look and function to best balance the need for accuracy with time-efficiency. The number of elements in a mesh can have a significant impact on the accuracy and reliability of results, and so how the user programs their simulation to work is a key decision in the process.

Firing and impact trials within the defence industry take time and cost money. Customers demand new technologies faster and for better value all the time. In the engineering process, it is always desirable to catch any errors or flaws as early on in the process as possible to save time and money. The earlier a problem is found, the easier it is to go back and rectify. Not having to prototype physical test assets saves time and resources, and with the improvement in FEA systems and their models, customers can be more sure of the accuracy of the obtained results.

However, nothing can be perfect. FEA software, particularly in trials such as the one modelled in this report, where there is a tremendous change in strain rates and stresses applied over a short period of time, will have its pitfalls. In the real environment, it will be easier to see the impact of the trial, and how it is affected by real-world events that only a trial in a physically simulated combat zone. The use of finite elements also adds in scope for discrepancy, on the basis that a real world scenario would not have a target made up of thousands of small discrete chunks, instead it would be one single continuous structure. The density, and intricacy, of the mesh used, will have an impact in this regard, but a more intricate mesh will lead to a more time-consuming and expensive simulation.

It is why there is often a benefit to using a validation case, programming a simple model into the system with known theoretical results, and comparing the two, to make sure that the software is at least producing accurate results where those results can be well studied. It would lead to a natural assumption that there is a good degree of accuracy in the main case study.

Case Study

Main Case - Impact of 120mm HESH shell on structural grade concrete

Background

As explained in [3] and [4], the L31A7 120mm is a large calibre high-explosive round, commonly fired from Britain's Challenger 2 battle tank [5]. It is a high-explosive squash head (HESH) round, and consists of a thin steel outer shell. The majority of the inside of the shell is filled with a high explosive composition, and the nose of the shell is filled with a non-explosive material, similar to coal-tar.

Figure 1 pictures the shape of the projectile.



Figure 1: Image of a 120mm HESH L37A1 projectile from [3].

It is primarily an anti-structural or anti-tank round. On impact with a structure, the projectile squashes up in to a disc, or pat, on the surface, to maximise the surface area. Once the base fuze, which is fitted with a very short delay to allow the explosive and tar disc to form fully, it detonates, which causes large amounts of spalling on the inner face of the structure or tank, significantly weakening it and causing damage to the inside.

Figure 2 details the inside of the projectile.

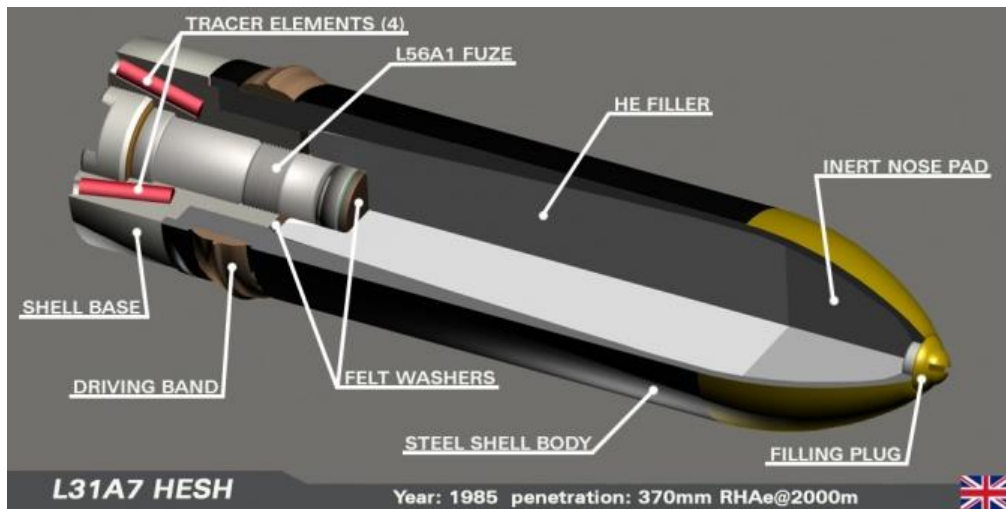


Figure 2: Detailed diagram of a L31A7 HESH round from [4].

A key thing to note about the L31A7 120mm HESH round is that it is not an armour penetrator. It is not designed for, and should not be capable of, penetrating armour. It is key that any impact with a structure does not weaken it to the extent that the round goes straight through, or the desired terminal effect will not be achieved.

Validation Conditions

In many CAE scenarios, even those within the defence industry such as vehicle survivability, where forces, durations of forces and strains are well-known, well-established and can be predicted with relatively simple mathematical methods, in simulations involving high speed, high stress ballistic impacts taking place over an extremely short period of time of just a few milliseconds or less, as would be expected in, known validation cases can be, and are, far more difficult to come across, particularly in a domain where technical restrictions and classifications govern much of what can be released. In these types of simulations, instead of running validations for which a basic theoretical number is known, validation instead is typically carried out by looking at existing experimental data, or in the case of a munition such as this, which has been in service with the British military since the 1940's, known trends, expectations and results from its use in real combat zones.

Many thousands of L31 120mm HESH projectiles have seen use over the years, and so there is little doubt as to what would be expected to occur if the FEA software was producing valid results.

In an experiment with results that would align with real-world use of these rounds, an observer would expect:

- The projectile to impact upon the target and begin to squash, with the front end opening out in to an adhesive disc and the explosive composition opening out and

sticking to it. This would be shown with large scale deformation visible in the results.

- Little to no penetration of the structure itself, as the round is not armour piercing and too much penetration would limit the effectiveness of the munition.
- Limited but possibly visible deformation of the inside face, with a clear indication of which area of the inside face is likely to produce the destructive spalling.
- A total impact time of around 1.5ms from a starting distance of 30mm from the target.

The videos in [6] and [7] show the impact that would be expected, and figures 3 and 4 are taken from those videos as a visual representation of the impact that would be expected to occur.

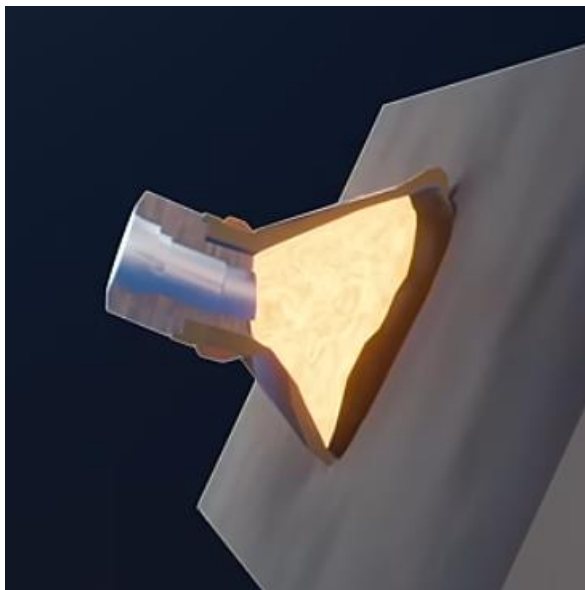


Figure 3: HESH round compressed against target, as shown in [6]



Figure 4: HESH round compressed against target, as shown in [7]

Parameters & Setups

The purpose of this report was to set up an impact simulation between a L31A7 HESH round and two different structural targets, one made of structural grade concrete, and one made of armoured steel.

Before any further work could be done within the simulation software, the geometry needed to be created using a CAD package. In this case, SolidWorks was used.

For the first step, the external shell geometry was created as a single part, ensuring to follow the available geometric information for the 120mm projectile to achieve the best possible results. This was left as a single complete part, as it will consist of only a single material when the time for material assignment comes in the FEA software. Figure 5 shows what this completed design looks like.



Figure 5: SolidWorks design of the external casing for the 120mm projectile for use in the simulation.

Next, the internal fillings, as shown in Figure 6, were created as separate parts and assembled together, the reason for creating them separately being that they would need to be assigned as two different materials when uploaded into the FEA software later, and so the software would need to be able to distinguish them as two separate parts. Once assembled, and mated to ensure they cannot come apart, the internal filling was then assembled in to the external shell, ensuring no gaps or voids between the outer edge of the filling and the internal walls of the shell existed. This would be likely to cause fatal error in the software when running the simulation if there were gaps in the structure.



Figure 6: SolidWorks design of the internal filling of the 120mm projectile for use in the simulation.

Finally, the concrete plate, a simple design with simple geometry, and with a realistic thickness based on structural concrete used in [8], was created, and the whole scenario assembled together, as in Figure 7. The circle shape sketched on to the face of the concrete plate was a 'split sketch', which enables the ability to refine this area of the mesh when it comes to meshing the model in Ansys prior to carrying out the simulation. This is a helpful tool because it allows refinement only of the area of the mesh where there is the most need to high accuracy data, in this case the area of the plate expected to take the direct impact from the shell.

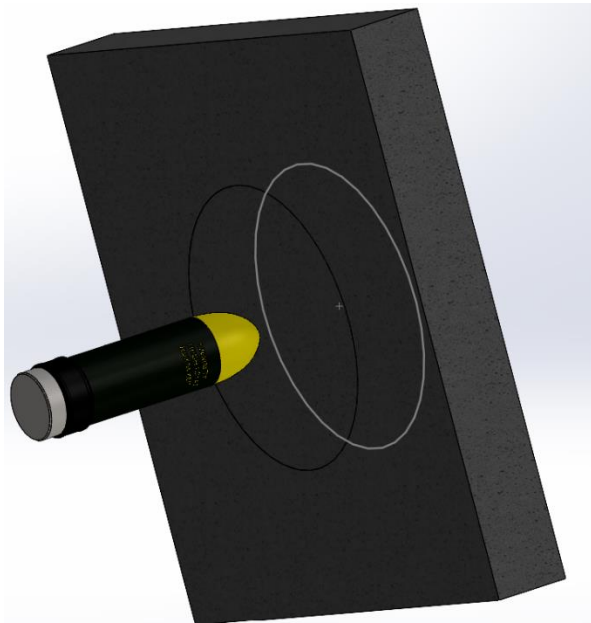


Figure 7: Full SolidWorks design of the modelled scenario including impact plate.

To maintain the best accuracy possible, known information about the 120mm projectile was used to calculate a realistic impact velocity with the plate, to make sure the correct initial forces were being applied in Ansys, and the time the projectile should take to flatten against the surface, to know how long the simulation should be set-up to last.

The velocity was calculated using understanding of Newtonian mechanics and drag forces, to give an impact velocity of 417ms^{-1} , with a full set of calculations, raw data and assumptions made available in the appendix of this report.

Once in to the Ansys software, with a new Explicit Dynamics project loaded, further customisations were made to refine the simulation.

The Ansys software has a highly customisable materials database, both containing a large list of materials and material properties but also allowing the ability to add additional property information where needed.

For this scenario, the following materials were taken from the database, all with their basic mechanical properties already in the system.

- Steel – *for the projectile's outer shell and the second target.*
- Concrete – *for the first target.*
- Comp-B – *for the projectile's high explosive fill.*
- Coal-Tar – *for the projectile's inert nose-cone fill.*

Each material was physically assigned to each part of the geometry, to make each part take on the properties associated with them.

Owing to the fact that the scenario being modelled is one of extraordinary high non-linear strain with huge forces at play over an extremely small time period, there was a need to add additional mechanical information.

The Johnson-Cook material model, developed in 1980, describes the behaviour of materials under high-strain rates, based on existing experimental data. It is commonly used when modelling ballistic impact as it can model the intense and dynamic forces that take place during these scenarios [9].

For all the materials in the list above, the Johnson-Cook damage parameters were found in order to improve accuracy of the simulation, which can be found in Table 1.

Values	Sym.	STEEL ¹	CONC ²	COMP B ³	C-TAR ⁴
Static yield strength (MPa)	A	350	140	0.42	10
Strain hardening coefficient (MPa)	B	275	500	237	100
Strain hardening exponent	n	0.36	0.61	0.498	0.75
Strain rate coefficient	C	0.022	0.007	1.767	0.005
Thermal softening exponent	m	1	1.03	0.73	1.2
Melting temperature (K)	T _m	1811	1600	353	1200K
Specific Heat Capacity	J/kg/K	452	879	1500	1380

Table 1: Table listing the used Johnson-Cook damage and plasticity values for steel, concrete, Comp-B and coal-tar.

In this instance, because the projectile was designed in a way that it consists of three separate parts, the parts had to be set up within the software in a way that they were placed in solid contact with each other and could not come apart from each other in simulation.

Meshing the object required the need for a balance between accuracy and time taken to run the simulation. In professional environments where more time and resources would be afforded to a trial, it would be easier to have perfectly refined and customised meshes to obtain the best results.

¹ Johnson-Cook values for steel taken from existing data in the Ansys materials database

² Johnson-Cook values for concrete taken from [11], [10], [8]

³ Johnson-Cook values for Comp-B taken from [12]

⁴ Johnson-Cook values for Coal-Tar taken from [13]

In this instance, a 1mm mesh was applied across the design, with the exception of the area marked within the circular outline in Figure 5 on the concrete plate, which was reduced to a 0.5mm mesh, as this would be an area of high impact and incredibly high strain rates. Having too large a mesh in the impact area could cause changes in calculations so extreme between two individual time steps, that the program crashes.

The simulation was then set up for a time of 0.002s based on the time taken for the projectile to fully impact the plate as calculated in Appendix B (0.00153s), to allow the impact to fully play out.

Finally, an initial force was applied to the whole projectile of 417ms^{-1} , the velocity calculated in Appendix A as the velocity of the HESH round immediately before impact.

At this stage, the simulation was finally ready to run.

Results

Figure 8 shows a key mapping the level of deformation, in metres, of the structure during impact.

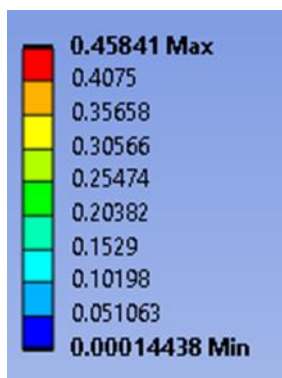


Figure 8: Key showing deformation levels (in metres) of the structure during impact

Figures 9 and 10 detail the front face of the impact between the projectile and the target plate at two different stages, with figure 9 occurring around the half-way point, and figure 10 being taken from a late-stage during the impact.

It can be seen in figure 9 that the projectile penetrated quite deeply in to the surface of the target plate, with the levels of deformation on the projectile of between 5 and 45cm, increasing from the nose to the rear end of the round. The back half of the round at the mid-stage is undergoing a high strain and experiencing large deformation as it begins to squash up, whilst it can be seen that the front half of the round has opened up in to a disc, or pat, on the surface of the target.

Later on, as shown by figure 10, the distinctive disc shape of the squashed up HESH projectile is clearly visible. The very rear end of the round is still going through its squash phase and it is at about this point (1.4ms) in to the impact, that the rear fuze on the round would be expected to arm, and ultimately detonate the explosive disc. There has been

further penetration in figure 10 compared to figure 9, but this has slowed, so complete penetration of the target has been avoided.

Deformation levels across the impact zone have remained consistent across the two figures, such that where deformation is highest, the level of deformation is around 45cm.

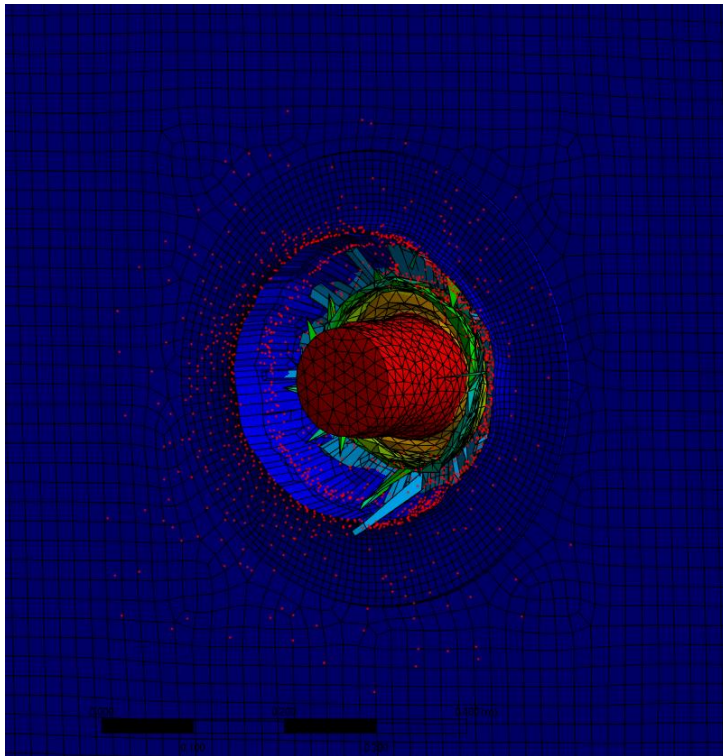


Figure 9: A mid-impact screengrab during the impact of the 120mm HESH projectile and the target plate.

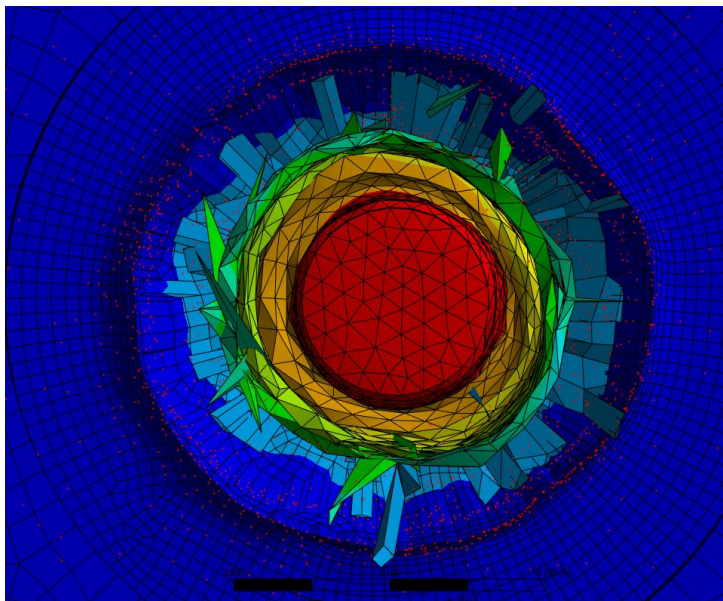


Figure 10: A close-up, late impact screengrab towards the end of the impact between the 120mm HESH projectile and target plate.

Figure 11 shows a late stage back-side view of the concrete target plate, showing the deformation of the plate as the front end has been impacted by the HESH projectile.

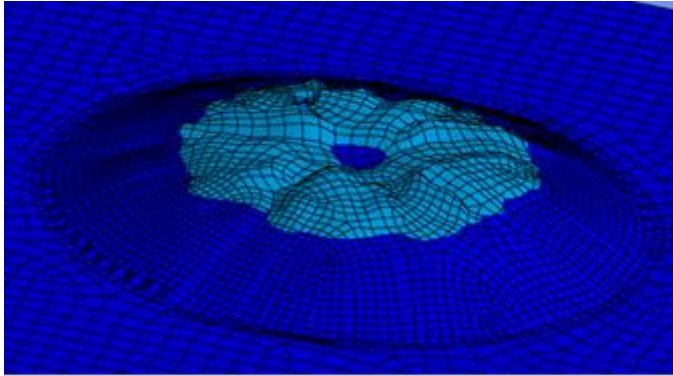


Figure 11: Deformation of the concrete back fact at 1.4ms in to the 1.5ms impact.

It shows that a visible deformation has been noted on the inside surface of the target. Deformation is not large, limited to 10-15cm in the middle area with the lighter blue colouring, and to within 5cm in the visibly deformed central area with darker colouring.

At the point of detonation, which has not been modelled in this report, but could be, the structure has been significantly weakened at the impact point to generate a large spalling on the inside of the structure, perhaps even blowing a hole straight through the impact area due to the scale of penetration of the projectile in to the outer face of the target.

Despite running several simulations of this scenario with a number of meshes, it was never possible to actually complete a full run of this model. Around the 1.4ms stage of the 1.5ms impact, the simulation encountered a critical error due to large scale deformation of the mesh and closed down. The mesh used for this run-through was found to be the best at sustaining the model for as long as possible, whilst balancing time constraints. A more crude mesh simply brought the program to an end much quicker, as the computer could not handle the large scale changes in loading on such a crude mesh, and a more refined mesh, which would allow for a smoother set of strain-rate changes, was too time-consuming, taking anywhere up to an estimate 10 hours or more to complete in full. After several attempts at tweaks, the mesh explained in the set-up phase was deemed to produce the most complete set of workable results in a realistic time-frame.

Discussion & Analysis

In general, there was a marry between the expectation gained from years of in-service use and live firing trials, visually shown in figures 3 and 4, and the observations seen in figures 9, 10 and 11.

The 120mm HESH projectile did not penetrate through the concrete target in the way that it would be expected for a armour piercing round to do, which aligns with expectations.

On impact, the round began to deform wildly, up to 45cm from its original position, as it flattened out in to a disc, or pat, on the target. This again is in-line with what would be expected during this type of impact. The concrete back-face weakens significantly as a result of this impact, and figure 9 shows a clear area of deformation of the inner face of the target structure caused by being impacted upon. Once the round detonates, there is no doubt that this area of the structure would be separated from the target plate at high speed and create spall which is designed to damage the structure, and any equipment inside. This is once again a match with the design specification of the round itself.

However, the significant difference between the expectation and the results produced in this simulation relates to the scale of target penetration achieved by the round before it completely squashes. It would not be expected to see a round of this sort impact on a structural grade target and have it go so far in to the target. The scale of the penetration is such that, when detonation occurs, the structure would not generate spall in the typical sense of the word but instead a hole would be blown wide open on the target, which would limit the effect of the projectile and any debris generated from the explosion.

There are a number of plausible reasons for why this would be the case, relating both to the FEA software itself and to the parameters applied to the system by the user.

In terms of the Ansys software, the mesh, and how the geometry is put together, plays a key role in the results. The way in which the scenario was constructed meant that, although the projectile was mated together as a single item, it was still, in reality, a collection of different interfaces interacting with each other. This means that significant stresses would have occurred at contact zones between the parts that would differ from the reality, which has the potential to alter results.

It is possible that a better refined mesh could also have led to more expected results with regards to penetration but, as discussed, the mesh refinement that was selected was a conscious decision made to achieve the best results possible without needing 10+ hours to complete a single run-through. This could be easily fixed in a professional trial environment with more time and resources, but for the purpose of this report, could have, and likely did, play a key role in the differences in results.

Concrete comes in many forms. There are many papers and material databases that reference concrete, and each has a slightly different set of damage parameters. Given this, there is a possibility that the values used for the Johnson-Cook evolution of concrete did not match the specific numbers used for high-grade structural strength concrete used in buildings. If the numbers were too low, then it stands to reason that an accurately designed munition would simply penetrate the structure without strong resistance.

The projectile itself, an L31 120mm large calibre HESH projectile, is an in-service munition strong enough to generate spall even when used against enemy battle-tanks. Typically, these would be made of armoured steel, and so the L31 needs to have the

ability to generate spall against armoured steel. Given that fact, and the fact that armoured steel is stronger than structural grade concrete, it may well be expected that against concrete, if the round were fired with the same amount of propelling charge as if it were fired against steel, there would be a degree of penetration against the structure. Based on that, it may have been that the assumptions and values used to calculate the impact velocity were actually the values that would be used to defeat steel, in which case the level of penetration is perfectly explainable.

The final caveat to the results, a hurdle that would not exist in the environment in which these models would be run for real, is the fact that the model of the projectile created for the simulation was based only off of information available in the public domain. The reality is that there would be extra things required to be added or tweaked to the design, with the addition of the restricted technical information relating to the round. It is entirely likely that this extra technical information could, or would, impact the results in some way.

Conclusions

In conclusion, there is unquestionable evidence that, in the right environment, FEA software provides a long-term solution to the challenges of holding expensive and time-consuming live trials of defence assets.

There are obvious technical caveats that limited this investigation, particularly surrounding time constraints and the reliance on public source information, but these are hurdles which would not exist in the environment that these models would be used in, where accuracy would be favoured above all else, and 10 hours, if needed, to complete a simulation, is still significantly less time than the weeks needed to plan, schedule and perform a live firing trial.

The results produced by the software, despite these limitations for the report, still aligned in many cases with known and expected results, with caveats, showing that FEA software has the ability to accurately re-create high-speed impacts where there are huge energy transfers taking place in a fraction of a second. This offers a cost, time and safety-effective alternative to firing trials, although the limitations encountered in this investigation should not be simply ignored.

They show that the software is only as good as its user, and as the data given to it to work with. If the damage evolution values for concrete were, as suspected, slightly downgraded from where they should have been, the results will be different from the expectation, and from when used in a live environment. If the meshing, or the initial parameters, were different from one simulation to the next, the results would once again come out differently.

Iteration is the key to success and, although it was not possible in this investigation to carry out a long list of iterations to fine-tune the model, with the time and money saved by using this software instead of performing live exercises in a professional environment, iteration is entirely possible. Working to find the most suitable meshing and base parameters for the software is the best way to ensure that the results being produced are correct.

This investigation was not perfect and still produced a set of results healthy enough to conclude that CAE software, from the initial product design all the way through to immersing it in a digital test and evaluation environment, as it continues to grow in prevalence and improve, does have a clear place in the defence and aerospace industry as a means of alternative to expensive and time-consuming live firing exercises. However, there will never be a better, or more accurate way, of seeing how a munition will work in a combat environment than actually firing one.

Despite the validity of FEA software in future testing and evaluation methods, how the industry navigates that trade-off remains to be seen.

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Appendices

Appendix A: Calculations of 120mm projectile impact velocity

Known Quantities	Value ⁵
Shell diameter	0.12m
Density of air	1.225kg/m ³
Coefficient of drag for 120mm projectile	0.2
Mass of projectile	13kg
Muzzle velocity	670m/s
Projectile range	3000m

Drag force acting on a body:

$$F_d = \frac{1}{2} \rho v^2 C_d A$$

Cross-sectional area of the shell: =

$$A = \pi r^2 = \pi (0.06)^2 = 0.0113 \text{ m}^2$$

Finding the initial drag force acting on the shell:

$$F_d = \frac{1}{2} (1.225)(670)^2 (0.2)(0.0113) = 597 \text{ N, or } -597 \text{ N}$$

as the force is acting **against** the motion of the object.

Assuming **constant deceleration** to give a realistic, but simplified impact velocity, Newton's second Law of Motion says that

$$F = ma$$

and so therefore

$$a = \frac{F}{m}$$

Deceleration of the shell due to drag:

$$a = -\frac{597}{13} = -45.92 \text{ ms}^{-2}$$

Final velocity is calculated using the SUVAT equation

$$v^2 = u^2 + 2as$$

- Initial velocity, u: 670m/s
- Acceleration due to drag, a: -45.92m/s²
- Displacement, s: 3000m

$$v = \sqrt{u^2 + 2as} = \sqrt{670^2 + (2 \times -45.92 \times 3000)} = 417 \text{ ms}^{-1}$$

⁵ Values relating to the capabilities of the 120mm projectile are taken from [5].

Appendix B: Calculation of time taken for projectile to fully impact the target.

- Distance between tip of shell nose and front of wall = 30mm
- Concrete thickness = 137mm
- Length of shell = 470mm
- Distance from back of shell to back of concrete = 637mm

Time taken at 417m/s for back of shell to pass through concrete:

$$t = \frac{d}{v} = \frac{637 \times 10^{-3}}{417} = \frac{0.637}{417} = 0.00153s$$