

Luke Malcolm 2030773 - Applications of CAE

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Application of Computer-Aided Engineering

L5 COMPUTER-AIDED ENGINEERING (ACDB5007)

LUKE MALCOLM (2030773)

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Abstract

This paper will assess the general application of Computer-Aided Engineering (CAE) and discuss the associated merits, problems and limitations that its use poses.

A case study will be used, focusing on a gun barrel being unevenly heated (for example, wind or rain cooling one surface of a hot barrel), and the resulting effect on the point of impact (POI) at distance.

Case Study – Background

General

Heating is known to have a significant effect on the accuracy and consistency of both small arms and medium/large calibre fire. It is difficult to model completely for reasons which will be discussed later (especially on more complex self-loading weapons). According to the author's own observation, two identical high-quality precision rifles can exhibit completely different characteristics as they warm up.

Usually, the effect of heating is seen in two ways. The first is the "cold bore effect" – where the first shot of a day is taken, or when the bore has had time to fully cool, often the first shot will fall away from the rest of the group if firing continues. This effect is usually consistent to a specific gun – i.e. "one minute of angle up and half a minute to the left".

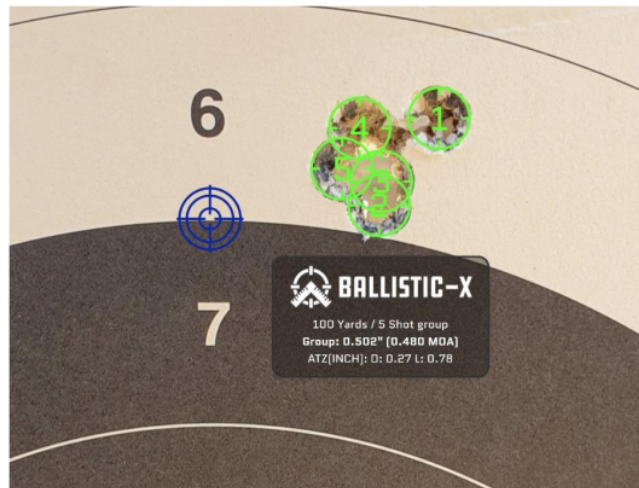


Figure 1 - 5-shot group at 100 yards with relatively minor "cold bore" effect seen on shot 1. Credit - author

The second widely observed effect is the "stringing" of shots. This is when shots begin to progress further and further away from the central group, usually in a linear fashion. Stringing is common in barrels of a light profile (comparatively thin) and in self-loading weapons which have gas blocks, and suchlike attached to their barrel, when sustained fire is maintained or the weapon is not allowed to cool between shots.

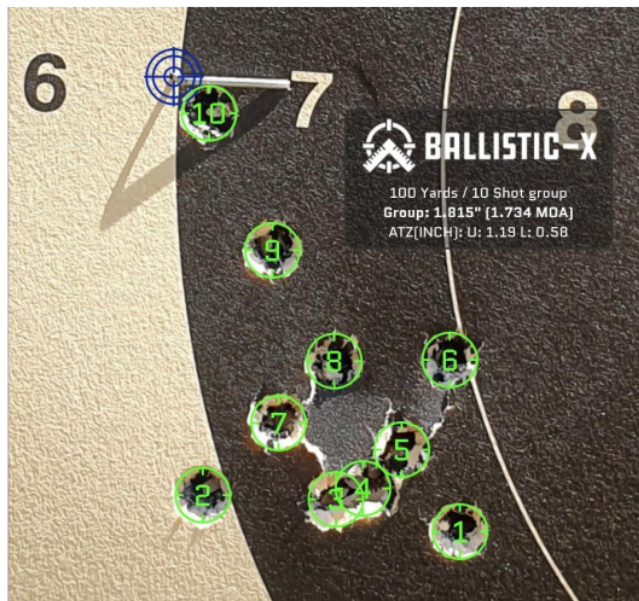


Figure 2 - Vertical stringing at 100 yards in a rapid-fire 10-shot group. Credit - author

This report will focus on the small arms due to it being the author's area of professional expertise, but some examples and lessons will be taken from the "big gun" world as the concepts are much the same.

Factors affecting accuracy

The mechanical accuracy of a gun system throughout a string of fire is mainly dependent on barrel heating (more variable) and barrel harmonics (more fixed, ammunition dependent).

While this paper will focus on the heating, for completeness and for discussion in the limitations & future work section, harmonics will be described briefly.

When a rifle is fired, a pressure of circa. 445 MPa (in the example case of 5.56 ammunition) [1] is produced in the chamber. This violent "wave" of pressure travels up the barrel with the bullet. The barrel is only fixed at the breech end of the firearm and is mostly free to reverberate (the only constraints are gas blocks/tubes etc). The barrel will reverberate as a shot is fired – the bullet is accelerated into a rapid spin (reaction torque on the barrel), the internal pressure wave builds and exits, and the stock and action move rapidly as the muzzle climbs following a shot. This can be imagined as the end of a barrel tracing out a "sine wave" form in all axes. The barrel should ideally be as free to reverberate as possible, that way it will return to the same point each time, and each shot will leave the barrel at roughly the same point in the cycle.

Thicker barrels containing more material will reverberate (or "whip") less than an identically chambered thin barrel. This is why entirely free-floated (not contacting any part of the system, other than where it threads into the receiver) free-floated heavy-profile barrels are used on precision bolt-action rifles.

There are numerous schools of thought followed when it comes to negating the effects of barrel heating. Typically, these fall into two camps – one “make it as slow to heat up as possible” (heavy barrel profile, lots of material), and two “make it cool down quickly” (flutes). There are more tradeoffs to consider – namely, physical burden for the operator (flutes and light barrel contours will reduce weight), and the actual likelihood of needing to maintain accurate sustained fire.

As a point of interest, there is a small amount of anecdotal evidence that barrel flutes are detrimental to accuracy - it purportedly causes the barrel to heat and cool at different rates along its surface, aside from imparting additional machining stresses – a test was purportedly carried out by Accuracy International in Portsmouth some years ago. Three lasers (barrel, receiver, scope) were fitted to two otherwise identical rifles, one with a fluted barrel and one without. The lasers were all collimated at 100 yards and firing commenced. The lasers diverged sooner on the fluted barrel example [2]. Unfortunately, no actual data from this test is available online.

Thermal sleeves are a common sight on many medium and large caliber guns – this aims to ensure the uniform heating and cooling of the barrel, and therefore a consistent fall of shot on target. Some units (for example, the 120mm main gun of the Challenger 2 tank) are also fitted with “muzzle reference systems” to compensate for barrel bend. This consists of a laser and receiver towards the breech end, and a reflector just above the muzzle. The receiver feeds a signal proportional to the measured barrel deflection into the electronic fire control system, allowing an instant compensation to be applied.

Neither of the two above systems are generally fitted to small arms for reasons of weight, practicality, and mechanical accuracy.

CAD/CAE Background

Computer-Aided Design (CAD) and Computer Aided Engineering (CAE) is a concept with far-reaching applications, allowing designs for parts to be created, evaluated, and redesigned without the complexities of having to produce them or put them into play in an expensive real-world scenario. [3] It is the cost saving and the ability to tweak designs quickly which is of particular value to the engineer.

Further to the above, the ability to complete entire assemblies in CAD ensures that simple things don’t get missed in respect to system interaction especially if multiple departments who don’t always communicate as well as they should are involved in the design of an all-up system.

Despite the above, CAE is not a panacea for design, engineering or testing. The detailed dependencies of CAE will be discussed in detail later in the report; however, the key dependencies are listed below:

- CAD MODEL – the model of the part(s) must be accurate
- MATERIALS – properties must be correct, and correctly assigned
- MESH – must be fine enough to ensure good results, but coarse enough for computational constraints to be met. The point of “mesh independence” should be found.
- CAE MODEL – must be correctly set up, constraints and boundary conditions applied, etc.

CAE Process

The CAE process is loosely described in short below. While it will be discussed later, it is important to ensure all steps are correctly followed as errors can be carried forward and significantly affect the result.

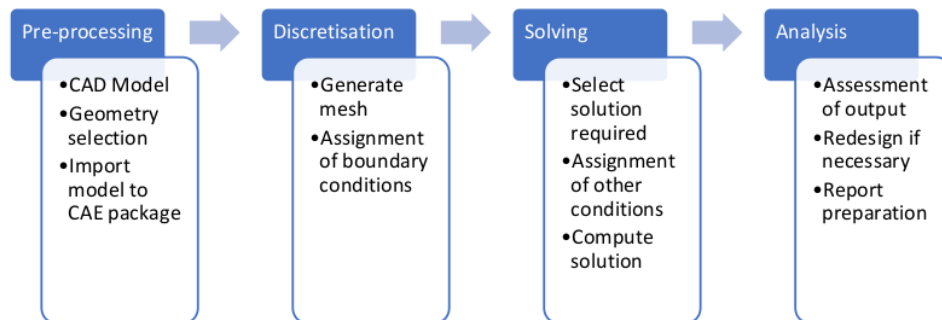


Figure 3 – The CAE process

Value of CAE to Defence

R&D in defence is particularly expensive – trials frequently cost hundreds of thousands of pounds, and mistakes and holdups can bring a program to its knees financially. Test & Evaluation is also tied to a range slot, availability of SEQP personnel, serviceable equipment, etc etc. CAE can be used to undertake a large variety of activities which could traditionally only be performed on a range, often at great cost.

CAE has many different definitions, though at its core, it can be taken to mean the use of technology, particularly within computers and software, to resolve engineering problems – as such, it should also be considered outside of the traditionally thought of FEA or “3D model-based” systems. A variety of wide-reaching examples are given below:

- Small arms load development, internal ballistics and propellant burn rate modelling programs – QuickLOAD
- Large scale blast trials against structures - ConWep
- Penetration and armour - ABAQUS and other FEA packages
- External ballistics and projectile flight - Applied Ballistics
- Probability of lethal injury from bullet – Timberwolf
- Rocket motor design – Burnsim
- Circuit design and simulation - Proteus

The opportunities are virtually limitless once you have found the right computer-aided tool for the job - finite element analysis is but one tool among many.

The ability to perform a “trial at your desk” at a fraction of the time and cost cannot be overlooked.

FEA Basic Principles

FEA breaks the wider problem down into a finite number of smaller elements – this is otherwise known as the process of meshing (or “discretization”). The relevant calculations are performed for each individual element, with the result of the element before feeding into the variables for the one after. Elements are assumed to be connected to each other, but only at the points called “nodes” – this is where the force is calculated.

Constraints governing how the model interacts with the environment must be set – these are known as “boundary conditions”. These can be fixed constraints, temperature, flows, pressures, forces, etc etc – they effectively set out the conditions within which the problem must be solved [4].

Methodology

This study discussed in this paper was performed across SolidWorks and Ansys. Both are in common use throughout industry. Material properties for the AISI 4140 steel were taken from the Granta EduPack database. Validation studies were performed covering both thermal and structural models.

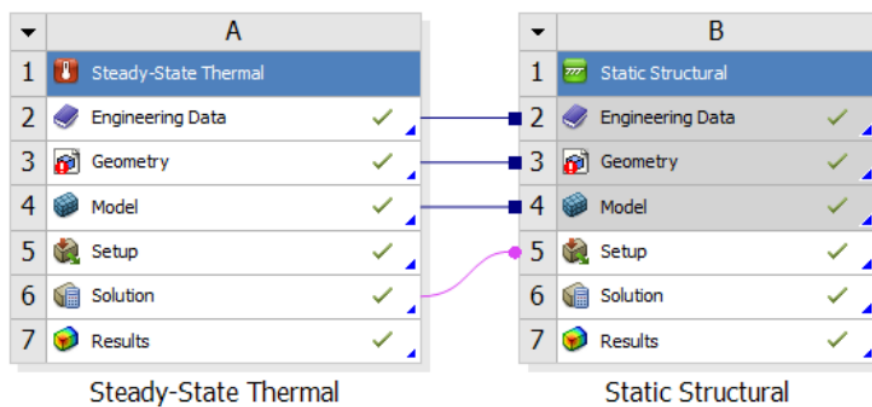


Figure 4 - ANSYS project schematic

CAD Model

A model of a 20-inch government-profile M16A1 barrel was taken from the open-source “GrabCAD” library. [5]. SolidWorks was used to manipulate the model and split it into two planes, allowing a temperature to be applied to one side but not the other. The barrel extension, barrel nut, flash hider, and crush washer were removed for simplicity. AISI 4140 steel, a common barrel material, was assigned to the model.

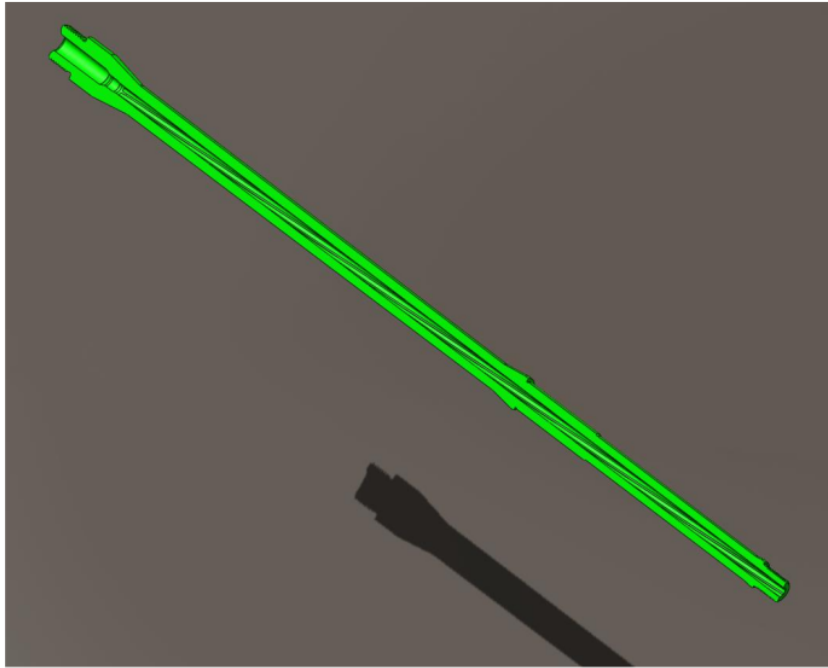


Figure 5 - Section view of barrel model

Meshing

A mesh size of $1\text{e-}03$ meters was found to have an acceptable processing time, while being accurate enough for an initial assessment of the model. The program was permitted to define an appropriate mesh shape, which resulted in tetrahedral mesh. A relatively fine mesh was used throughout as the processing time was considered reasonable – a graduated mesh was not required.

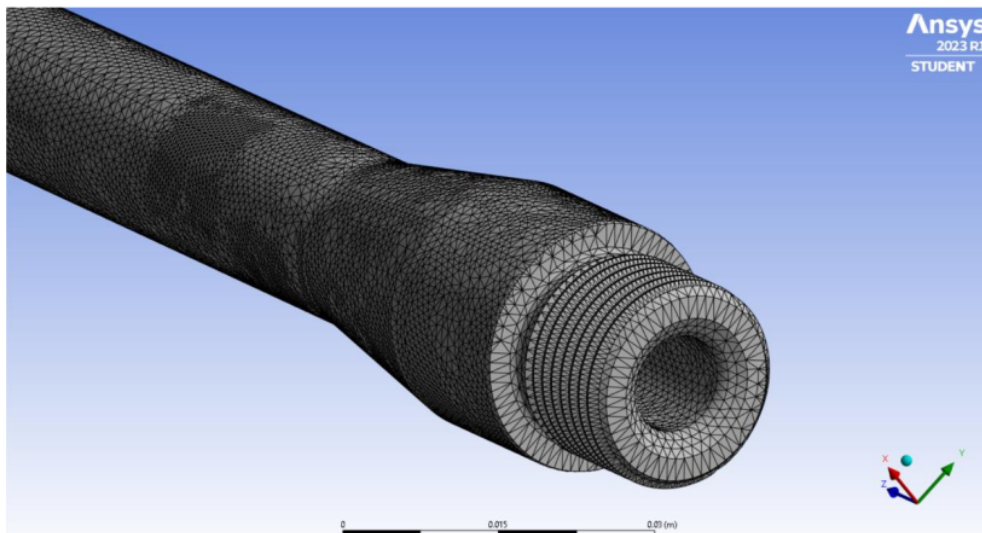


Figure 6 - closeup of mesh on the breech face and threads

Results

The barrel was constrained using the fixed support function on the face highlighted below in figure 5. This is where the “barrel extension” would usually mate against, which in turn slots into the upper receiver.

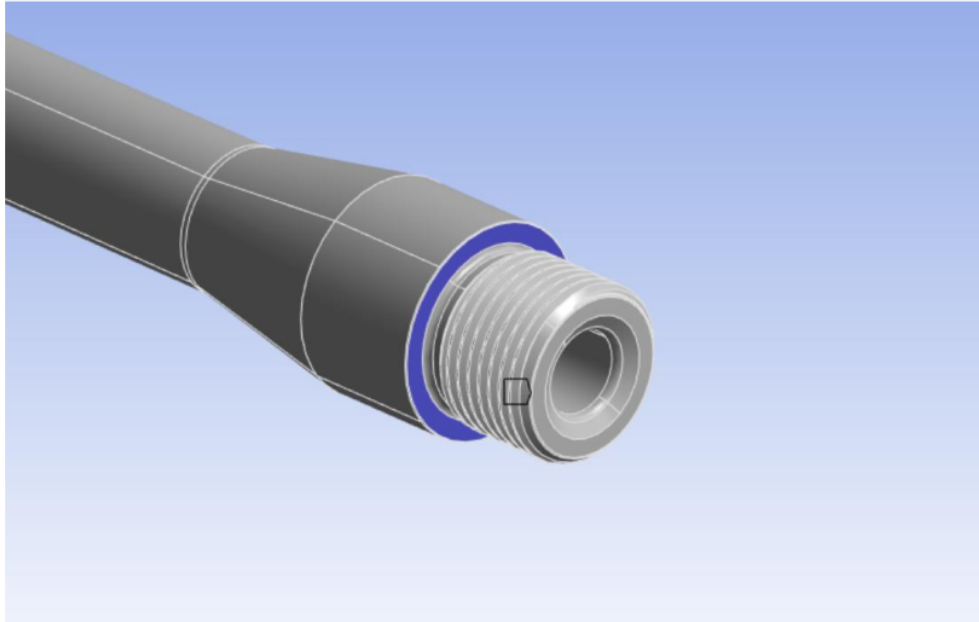


Figure 7 - fixed support location

Using the convection tool within the steady-state thermal section, the barrel was “heated”. This was then fed into a static structural study. An ambient temperature of 25C was applied to one side, and a ramped temperature of 25C to 35C. A result of maximum deformation over time was taken.

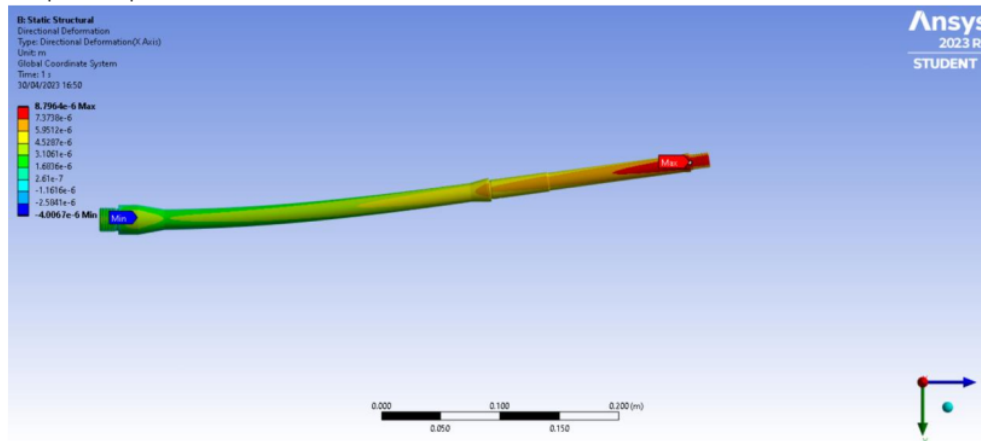


Figure 8 – a greatly exaggerated deflection result

The end of the barrel deflected approximately 8.7964×10^{-6} mm (0.0000087964 mm). This is frankly unrealistic, and results in a POI difference in fall of shot of circa 17 mm if traced out to 1000 m using basic trig. There is little further discussion to be had, the model requires extensive refinement.

"If you are going to be wrong, be wrong as simply and cheaply as possible!" [6]

Validation

Purpose

Validation is the process of assigning a quantifiable value to the accuracy of a computational simulation in comparison to the result of an identical real-world scenario [7] – this helps prove the methodology of the simulation in question, therefore increasing confidence in the experiment result. In effect, it proves the software and the basic math behind the simulation can be trusted.

A variety of software OEMs publish validation studies which compare a program output to the result gained from a traditional "handwritten" analytical formula.

Two validation studies are used in this report – as the study has both structural and thermal elements, one study should be undertaken for each. The examples in question are a simple cantilever beam [8] and a bimetallic strip [9].

Cantilever

An identical beam was drawn in SolidWorks and imported into the Ansys Workbench software. Material properties were assigned, and pressure of 2750 Pa was applied to the top face of the model. A total deformation result of 165 mm was output by the software. This contrasts to a 157.143 mm result as derived from the "hard copy" analytical solution. This is a delta of circa. 4.89%. For the purposes of this study, it is an acceptable deviation from the analytical result [10].

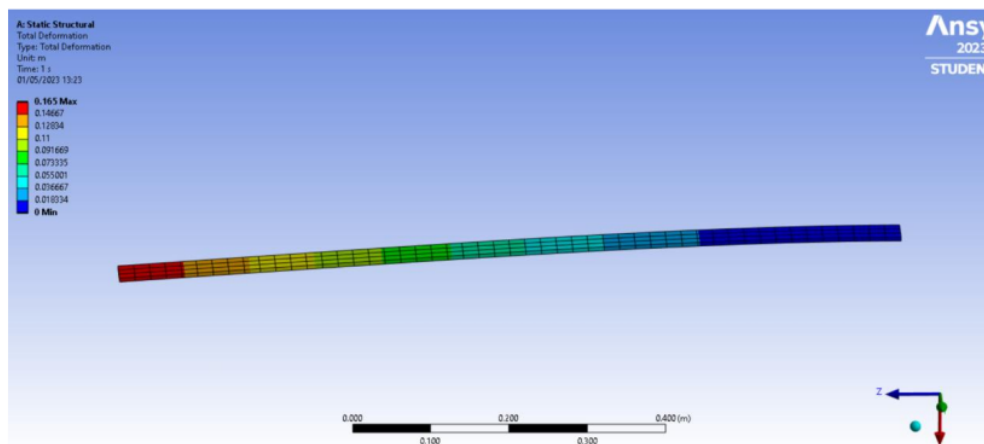


Figure 9 – Cantilever beam validation model

Bimetallic Strip

A thermal validation study was also carried out, assessing the deformation of a bimetallic strip due to an applied temperature. This was successful, and the delta between the analytical calculation and the FEA simulation was 1.01% - this gives high confidence in the thermal model used by ANSYS.

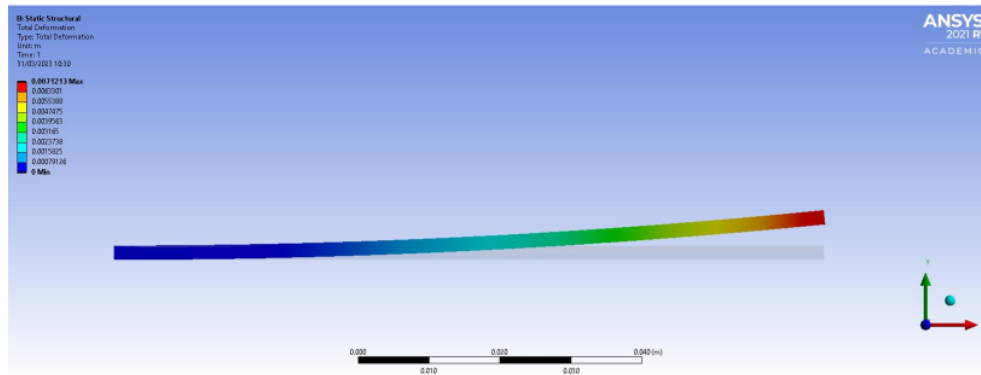


Figure 10 - Bimetallic strip validation model

The somewhat unrealistic result given by the barrel model combined with the reasonably good result from the validation models points to some severe inadequacies in the barrel model, which require investigation and correction.

Limitations

Dependencies

The CAD/CAE toolset is undeniably complex – a competent operator is critical to a good model and therefore good results. The operator must have a good understanding of a variety of different concepts outside of the obvious CAD/CAE software itself – materials properties, thermodynamics, fluid flow, stress & strain, to name but a few – this is a skillset which takes years to master!

Errors can easily be “carried down the chain” if they go unnoticed, particularly early in the process – check every single step. A full suite of material data is often not available, especially in the case of exotic materials.

Computational resourcing is also a key consideration of the CAE process – the meshing and solving of a model is a computationally intensive task, which can take a significant amount of time to complete even if the unit the task is being performed on is adequately equipped to do so - this adds a second consideration to the entire process, the engineer must now consider what is an acceptable mesh size for accuracy (and how far it is from the point of “mesh independence”, if known) and what is an acceptable time for the entire simulation to take.

Mesh independence is defined the point at which the solution is independent of the underlying mesh [11]. Assessing the point of mesh independence is an important part of any FEA/CFD assessment to allow the optimization of “time versus effort” – there is no point making a mesh much finer and therefore computationally intensive if a coarser mesh provides a virtually identical solution. A mesh independence study was not undertaken in the case presented in this paper due to time and computational/license constraints.

One point of note not described by the models presented in this report is the existence of “graduated mesh”. This allows the model to use a fine mesh in the area of most importance (e.g. around an impact location), and a coarser easier-to-compute mesh in less important areas like the edge of the plate being hit.

In addition to the computational limits, many software packages put a hard limit on the number of elements available in certain versions of their program – for example, with an element size of 1mm, this results in a little over 330,000 elements present in the model described in this paper. The student version of Ansys is limited to 1000 elements.

Assumptions

The software package assumes otherwise perfect conditions which can very seldom be replicated in the real world. Materials are assumed to be perfect representations of their ideal spec sheets. Coatings are assumed to be of uniform width/depth. Tolerance and runouts are perfect. Constraints are assumed to be fixed and completely immovable. This is seldom the case in real life, and this must be considered when assessing the output of the CAE model.

Furthermore, in the case of the convection heating applied to this model, in a real gun system, the chamber and throat are the warmest parts, the muzzle is coolest as the combustion gases have had some time to cool from their peak temperature (and the pressure has reduced) by the time the muzzle is reached.

The author recommends that in the case of trials which would require very little cost and effort to undertake (such as this one), the trial is conducted physically rather than computer simulations prioritised. While it may not provide an entirely complete assessment without expensive equipment and considerable effort, even a small physical study using a few thermocouples would provide valuable model-specific validation data. Some thermocouples and an hour of range time is relatively inexpensive!

“Finite element computer programs have become common tools in the hands of design engineers. Unfortunately, many engineers who lack the proper training or understanding of the underlying concepts have been using these tools. Given the opportunity, FEA will confess to anything” [12]

Future work

Doing some real-world testing to understand the implications of barrel heating could be carried out relatively simply. A simple proposed experimental setup would be the use of thermocouples placed along the length of a barrel, firing through an Automatic Shot Position Indication (ASPI) unit. In addition to building up a more realistic barrel temperature gradient to be applied to the initial model (a potential failure of the current model is the “block application” of a temperature on one side versus the other), it would also allow the effect of barrel heating to be loosely determined – this could then be used as validation data for a proposed model.

- A study should also be undertaken to allow the understanding of the harmonic factors at play before feeding the results into the thermal model
- The point of mesh independence should be sought
- The drawing board should be re-visited, a new model should be created

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FINAL GRADE

54/100

GENERAL COMMENTS

Instructor

There are some good citations used in places in the report, that have been used appropriately to support the relevant areas of discussion. There was scope to incorporate more literature use in the work, perhaps finding results from other similar published studies to compare to. Some higher quality academic references could have been found, but generally a reasonable use of referencing to inform the work conducted.

There is some good contextual knowledge demonstrated, it is clear that you have a good level of knowledge on the subject area and have discussed some of the expected outcomes with supporting evidence which was good. It is a shame that you did not more directly refer back to these areas more when looking at the results that you obtained from the study you conducted.

You gave some reasonable discussion about the CAE process as a whole, but could have gone into more detail on some of the key areas that influence the outcome of solutions. Considering the importance of discretisation through meshing it would have been logical to have conducted some further investigations into these areas to determine what sort of impact they can have on the results. The validation studies would have been a very quick and easy area to have done this through. Mesh independence and mesh element type influence could have been studied. Similar with boundary condition application, these are key areas were only briefly discussed in the report. Given that your results did not come out in the range you expected, it would have been good to have had some data to show where the errors may be coming from. You did discuss them towards the end of the report, but these could have been more targeted and specific to the results you obtained.

Normally, you would validate the software prior to commencing the main studies.

The subject of the main study you conducted is perfectly fine and relevant to your industrial experience, however it would have been good to have had some more iterations and attempts at resolving the issues from what is a relatively simple to run case. Given that you note the deflection amount is not correct and that more extensive refinement of the model is needed, there was not any evidence of this being done which was a shame. Ideally, you would have looked further into the accuracy of your boundary conditions, the representation and influence of the mesh on the model etc. You identified the error, but did not chase it to find out where it came from or what may resolve it. You do offer some reasonable areas of discussion about some of the possible influences toward the end of the report, but it would have been nice to have seen further investigations conducted to try and support these statements.

The report formatting was lacking in things like section heading numbers, new major sections should start on fresh pages, abstract should come before the contents page and be a complete overview of what was set out to investigate, what was done and what the key findings were, yours read as an introduction. Otherwise, the document conveyed the information well enough.

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