

Designing a race car rear wing: Structural Design

Structural and Fluid Analysis Assignment 2

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FEA optimisation techniques

Background history:

Finite Element Analysis was first developed around 1950s, it was initially utilized within the Aerospace then the Automotive industries. M.J Turner, H.C Martin, L.J Top and R.W Clough were the first to publish papers on its methodology and use, and it was used by many universities during its early years. (Tipton, 2017). Its means was for finding approximate solutions to boundary value problems for PDE's. Its infancy and development can be traced back to 1941 via the works of A.Hrennikoff and R.Courant (Crahmaliuc, 2023). Hrennikoff was a structural Engineers at the University of British Columbia. He published a paper on membrane and plate modelled lattice framework, and it was this work that was believed to be the birth of FEM (Wing Kam Liu, 2022). Hrennikoff's lattice structure of the solution domain is noted as the earliest fabrication of Mesh structure which will be covered later in this assignment. Courant thought the systematic use of Rayleigh – Ritz method had solved a second order PDE on a cylinder under Torsion. In this process Courant used triangular sub domains (Wing Kam Liu, 2022). Prior to the creation of FEA and other methods, engineers relied on actual physical experimentation to conclude if designs could survive service along with where it was likely to fail. In the time from 1960's-70s NASA applied FEA to use in Non-linear problematic scenarios through the uses of software technology (Davila, 2023).

Finite Element Analysis is a process that consists of using mathematic calculations and models (PDEs, variational method etc) to study and examine behaviours of an object or an individual part when exposed to physical conditions (Kanade, 2022) (Noraphaiphapaksa, 2023). Such physical systems can vary from deformation of solid structures under loads and forces, heat conduction, thermodynamic and fluid study (Giraldo, 2023). Within construction FEA enables Engineers to generate simulations of supporting structures and produce stiffness and strength visualisations whilst reducing weight, vary the materials (Kiritsis, 2009). From this we understand Engineers use FEA to assess elements of concern within the design of product and gather information to optimize it. This helps in the

streamlining of the design of the product and make any necessary changes within the model prior to construction or physical prototyping. This assignment is focused on the FEA analysis of a race car rear wing, when realising the importance of a car's rear wing as Engineers we can often overlook its importance. For instance, the need for maximum grip ensures that the driver can achieve the maximum speeds and the cars' ability to manoeuvre (Engineer, 2021). The tyres do provide the driving force, braking force, and steering force through friction with contact to the ground. These tangential forces can be exceeded and when this happens the vehicle will no longer grip the track and have difficulty in maintaining control. The rear wing provides a staggering 80% of the cars grip, whilst the weight of the car around 20% of the grip (Zhou Tao, 2017) Without an effective rear wing in terms of Aerodynamic efficiency, one that which does not move, is rigid with minimal deflection and light enough to not add unnecessary weight can therefore allow the tyres to provide the maximum forces required to perform. The rear wing design is the best option for maximizing grip on the track, maximizing downforce with additional goal of reducing drag. These are immensely important in Aerodynamic concerns, nevertheless for the purpose of this assignment minimal deflectional and minimal weight are of importance and what the focus will be on in the simulation.

General Process flow of FEA

FEA begins by breakdown down larger structures into smaller Triangle or cubes as this helps to better define the model parameters (Kanade, 2022). In gaining an understanding as to how smaller elements work, we will have a clearer comprehension of how the overall object will behave. How accurate the FEA simulation will be is associated with how small the "elements" are made, the finer the mesh the closer the end solution result is likely to be (Comsol, 2017). This allows for stabilisation of performance and provides good approximations of results from model simulations.

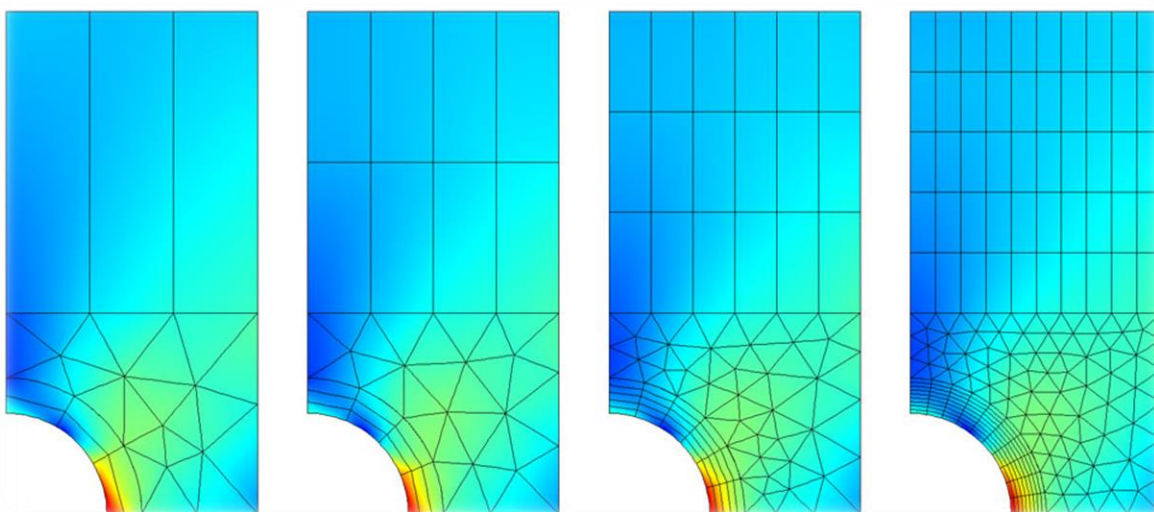


Fig 1: Image demonstrating Finite Element Mesh refinement (Comsol, 2017)

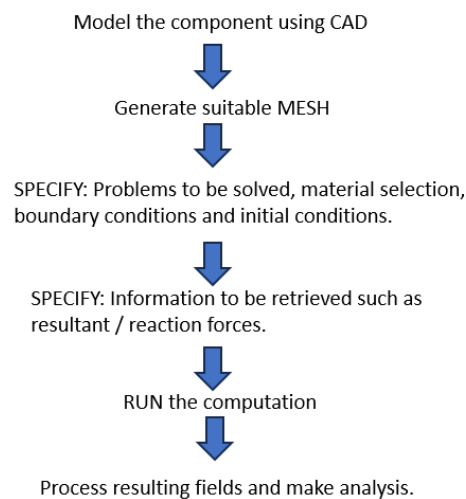


Fig 2: Image displaying process Flow of FEA (Giraldo, 2023).

Uses withing Formula 1

Formula 1 relies heavily on the uses of FEA and other simulation and modelling in analysing the effectiveness of a components in design. For example, in the study of aerodynamics, the effective design of the structure and panelling of a car body can increase speed of a F1 car by several horsepower, simply by using air flow efficiently. This ties in with the previous assignment, where simulations are carried out in wind tunnels allowing for physical measurement of wind deflections. However, when using FEA methods in the study of aerodynamics accurate discretization and turbulent

modelling will govern the precision and predictions of a simulation (Harish, 2023). The study of air flow via FEA must be compared with actual physical studies to determine the success of design in conjunction with simulation analysis. Nevertheless, in studying acting stresses of a component such as a Chassis of a F1 car, FEA can provide accurate results and provide numerical information for optimization prior to prototyping. Chassis are considered the backbone of a vehicle to which important components such as the transmission, axles suspension and steering are connected. For that reason, structural stiffness and strength analysis is critical and of high importance to provide strength and integrity for all connecting parts. The compromise between size, complexity of shape and weight can all be studied computationally (Rajkumar ., 2022)

Future development

FEA has progressed and evolved immensely since the days of its first inception and has reformed the design process of structures and mechanisms. As discussed previously, with the improvement in technology FEA accuracy and precision develops besides it. High performance computer systems allow for quick running of simulations and do so in with greater efficiency. These HPC due to their capabilities allow much more complex problems and simulations in a much quicker time, even advanced simulation techniques and with uses of optimization.

The use of Artificial Intelligence is predicted to transform FEA and provide much quicker due to the AI's Algorithms learning from previous simulation data gathered and harvested (archive, 2023). This capacity to do so will greatly reduce financial expenditure and run times of simulations. Within AI there is a process called "Surrogate Modelling" that is being used. This relies on machines learning algorithms that predict behaviours without requirement of FEA simulations. For example, these surrogate machines can learn information gathered from data collected from previous varied conditions (forces, materials etc). These algorithms can understand relationships between parameters inputted and output responses such as Stresses and any deformation (archive, 2023). With this information retained, engineers and users can input various design parameters ant once and the algorithm can forecast behaviours reducing the need for the engineer to run individual simulations for each parameter. The sharing ability of FEA will also have a notable impact on its succession and development in the future. Cloud Computing uses Cloud based software to allow Engineers anywhere in the world to access real time live simulations. NIST states:

"Cloud Computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources ... that can be rapidly provisioned and released with minimal management effort." (Ari, 2012)

Notably the large-scale computing resources can allow for enormous amount of computing resources to be accessed which in return allows for speedier solving of complex simulations. Many issues that arise within engineering communities are the IT limitations such as skills, tuning and updating and

even the maintenance of such systems. The Cloud service consequently provide cost saving in any additional training of staff, along with providing incredible sharing ability and opportunities within Engineering (Ari, 2012). Cloud technology allows more users to access high performance computing, however Xiaoyong states one of the limitations is that of the virtualisation paradigm, used within Cloud computing will decrease the running efficiency of the Physics machine (Xiaoyong, 2011) highlighting the limitation in the user's software. Despite that, the use of remote computing resources such as servers can be easily and readily accessed over the internet, allowing engineers to use Computing clusters. Therefore, any limitations in hardware and or software capabilities will not limit the extent to which simulation Engineers can run FEA simulations (archive, 2023). Many companies allow Engineers to upload their CAD designs and set up simulations and view the studies through an internet browser.

Virtual reality technology is now allowing Engineers to visualize simulations in a much more interactive and immersive way, by allowing them to be present with the current model. This provides a clearer understanding of how models respond to given conditions and may provide Engineers with solutions or information not recognized by viewing simulation results. The interactive aspect of VR will help users of less expertise and experience gain a better understanding of simulation results and encourages investigation (El-Tawil, 2016) Visualisation technology Augmented Reality (AR) have been developed for use on mobile phones. There is often a difficulty when using FEA simulations in being able to apply the results to the physical components, when they currently exist. Android package kits (APK) are easily installed onto mobile phones or various handheld devices. When the camera on the device is used and captures the real-life component, the software recognizes it and fits the 3D analysis onto the live component (Horan, 2021)

Android package kit recognizes the real solid model (Figure 8). The analysis result has been visualized on the real impeller part.

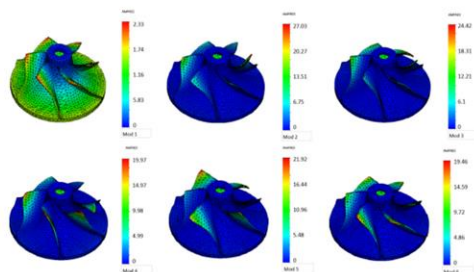


Figure 6. Amplitude values representation for modes 1 to 6.



Figure 7. An AR Android package kit camera view.

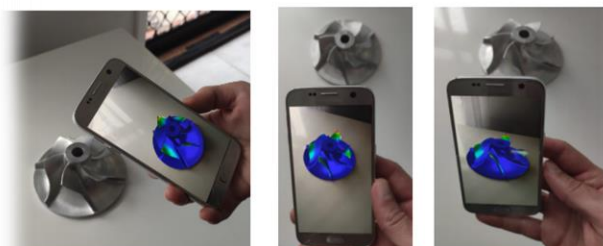


Figure 8. Modal analysis simulation results on the mobile AR visualization.

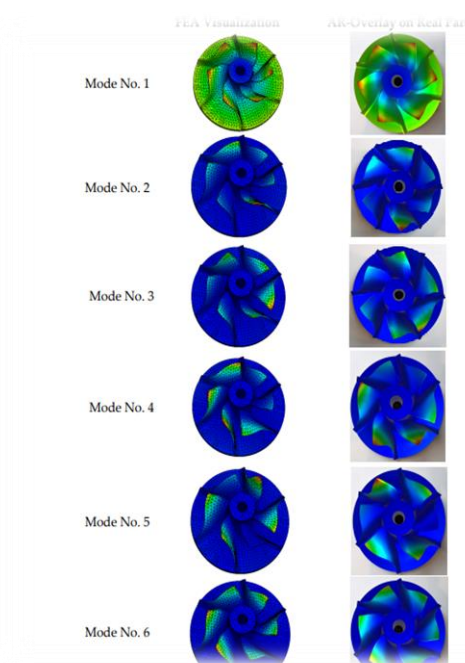


Fig 3: Modal analysis using Mobile phone AR visualization, and example of Android package (Horan, 2021).

Results from these advances

SPEED AND ACCURACY

These advances allow for quicker solving of results simply by processing various parameters and properties, the engineer may no longer need to run many individual simulations for each parameter change. This will free up time and reduce the cost of running many simulations and for the occupied time of the engineers. The accuracy of each simulation is greatly improved, due to the capability and processing power but also from the AI's ability to retain data from previous simulations.

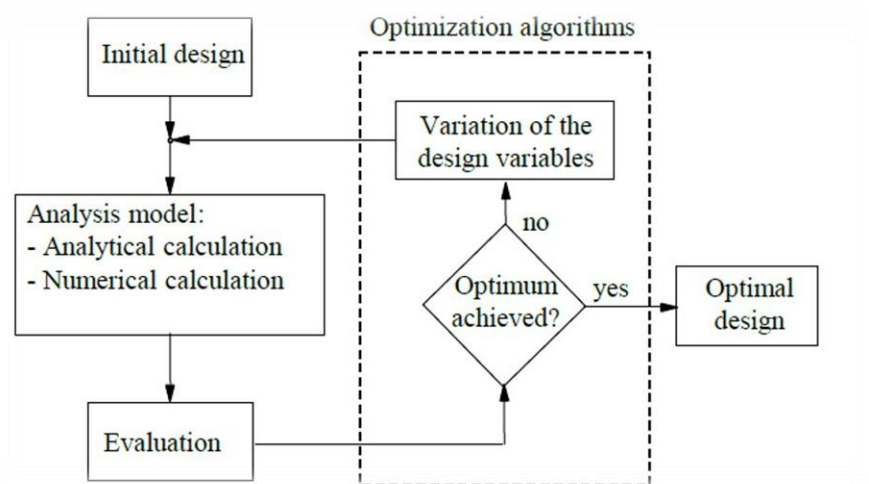
Use of advanced software and processors

With Cloud infrastructure, designers can upload their models through online networks and run simulations on HPCC's, allowing for the solving of extremely complex conditions. Fluid and thermodynamic studies are difficult to set up due to their requirement for accurate set up of boundary conditions. This also allows those of less experience to run their simulations and not hinder the study due to their lack of experience. The cost of such advanced software would also restrict those who cannot afford it or have access to such advancements, this sharing capability allows for a greater exposure within engineering.

VR and AR offer a completely unique learning and development experience in simulation studies, they allow us to view responses close to what would be experienced in real time. They allow us to interact with study and see the results differently, it allows for our curiosity to help look further into the scenario and find concepts that computational results may not highlight. Mobile AR apps can allow for quick analysis of results by superimposing FEA results onto real life parts. This aids engineers in visualization and understanding of responses and provide engineers with a quick response of critical areas.

How they improve the design process

Developing a product from a completely new or improving on a current model can prove to be a costly process, in time invested and financially. Often when design a product from new it will have many pre requirements from the customer or from the project, on occasions many variables may yet to have been tested. New materials and their properties may never have been utilised; geometries may be improved on but done so with some uncertainty. The use of FEA can allow engineers to design 3D models and set constraints and run simulations and gather results in a relatively short time depending on its complexity. They can complete this cycle, upgrading and optimizing the design until they have achieved their targeted parameters. This does not run into prototyping, which is a costly process, that ideal should require minimal design alterations.



Wing design an optimization.

The understanding of optimization

The process of developing the best design for purpose is called optimization, for example developing the developing the most lightweight and strong bike frame as far as the most efficient turbine blade. Naturally engineers and designers optimize automatically by judgement, gathered experiences and opinions. (Alan R. Parkinson, 2013). But it is now where computer technologies play a critical role within design optimization, it is used to search for the best designs, and we can establish optimisation parameters and constraints according to the design criteria using sophisticated and complex algorithms. This does require an understanding of the programmes in conjunction with theoretical information on the mechanics and physics of the subject. To optimize a product, we must first have a quantitatively developed model that will allow the computation of desired interests. It is common for up to 90% of optimization to be carried out validating models and running numerous simulations. Then once the near fully established model has been developed through the streamlining process our points of interest can be identified quickly (Alan R. Parkinson, 2013). Mapping is a term used in specifying the optimization problem, for example where the user selects the design variables (height/size/diameter) that occurs between the analysis space and design space, which can be displayed further in figure 5. We can see that the analysis space consists of many parameters and product properties, Engineers select the design variable that will be most compliant with our system. Analysis functions state attributes that we wish to revise for a particular outcome that can improve the design and evaluate areas we may be concerned about (such as aerodynamic forms, deflection of panelling). Within Formula 1 weight is a common characteristic that must be reduced as much as physically possible in terms of performance goals, however with the reduction in weight the part must still provide desirable properties such as strength, durability, and fatigue endurance.

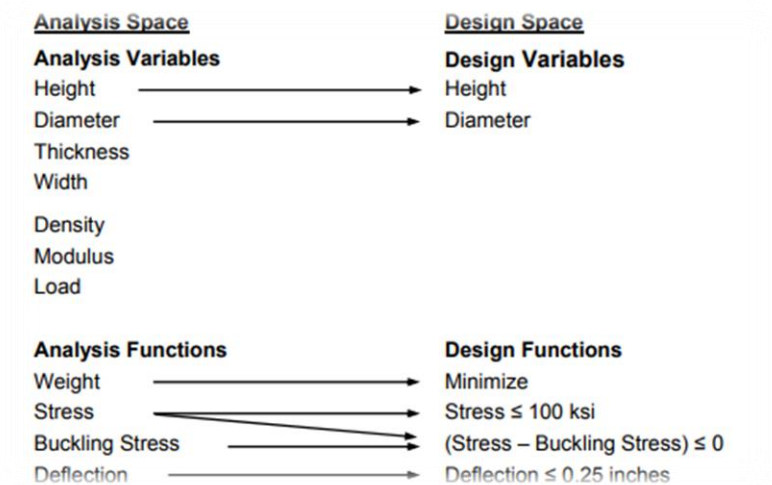


Fig 5: Demonstrating the process of mapping during optimization, where the above example was used for truss analysis (Alan R. Parkinson, 2013).

Simulation via Design studio and results comparisons

Initially the results were carried out using the standard wing design with 10kn load and the material was changed to CFRP. As see in figure below the wing has a UDL load as depicted by the arrows.

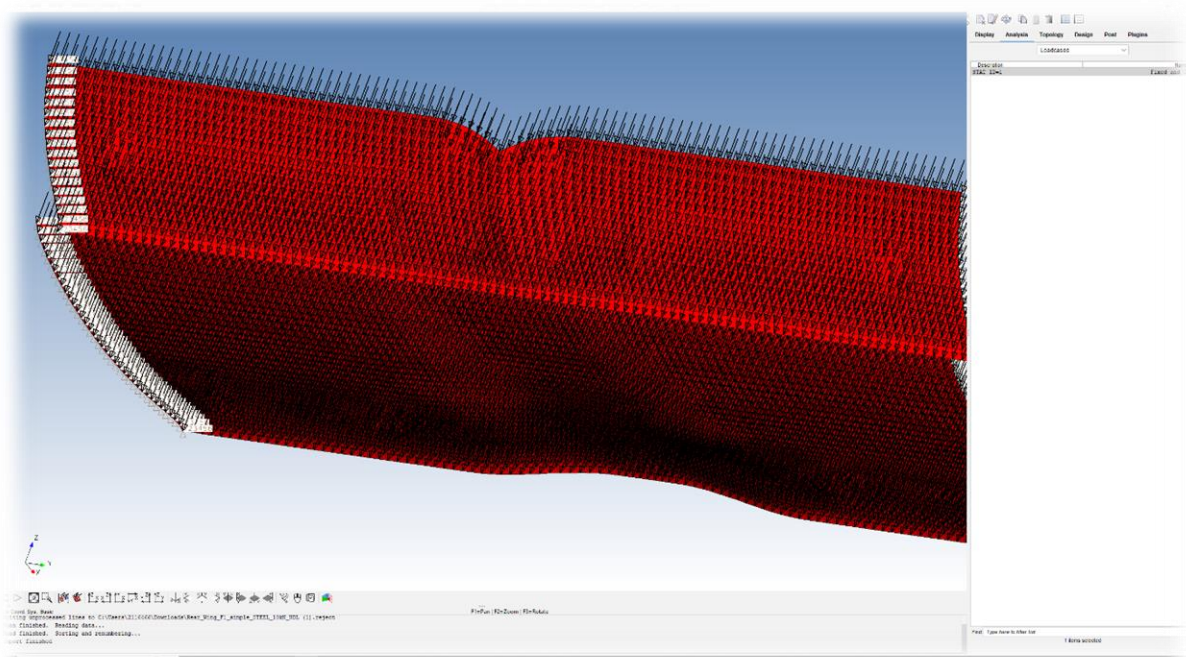


Fig 6: Displaying UDL direction on Rear wing for first initial trial.

The initial single analysis run as seen in figure below, after assigning the relative ply thicknesses of 0.1mm and at five ply's per layer which equates to 0. 5mm.The direction of each layer was entering as

-90°, -45°, 0°, 45° and 90°. In the first trial the maximum deflection result came in as 3.78×10^{-2} which converts to approximately 0.0378m of deflection highlighted red on the wing.

$$F = \frac{K}{X} = \quad K = \frac{F}{X} = \quad K = \frac{10000}{3.78} = 2645 \text{ N/mm}$$

Mass of wing = 18.8kg

$$\frac{\text{Stiffness}}{\text{Weight}} = 2645 / (18.8 * 9.81) = 14.34 \text{ N}^2/\text{mm}$$

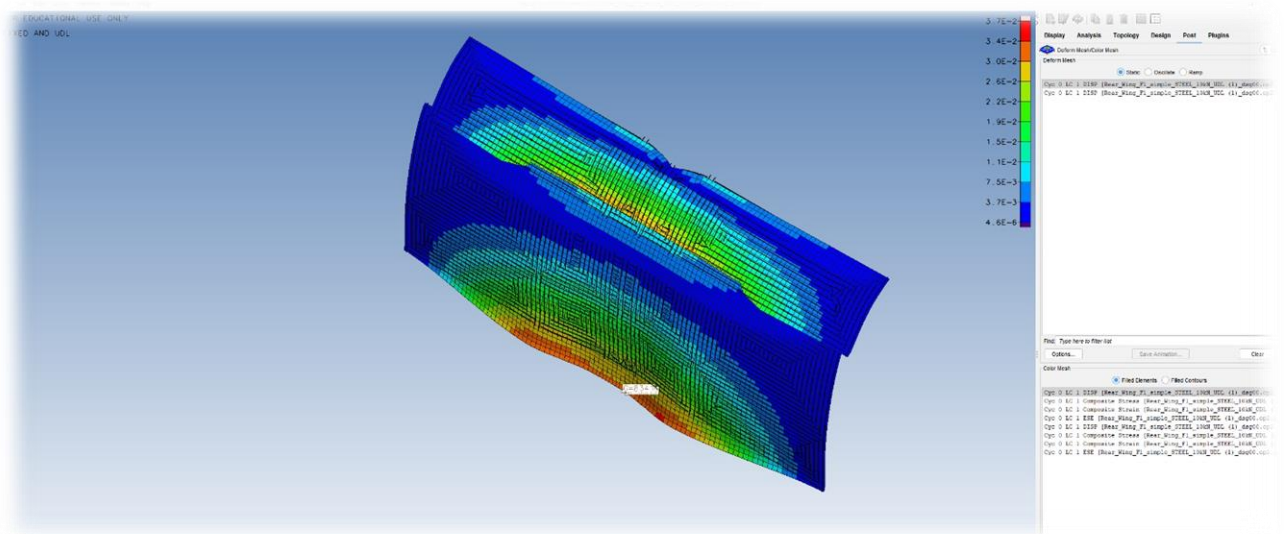


Fig 6.1: Demonstrating deflection contrast of rear wing.

To optimize the wing, we must firstly define the variables, objectives and constraints and using the existing CFRP material properties provided. The objective of the project is to 'minimize' the mass of the wing which will aid in performance and the efficiency of the vehicle, in doing so we must not exceed our set of constraints with regards to deflection. The maximum allowed deflection is based upon the previous acquired amount on initial trial, including the overall thickness which must also not be exceeded more than 2.5mm which is made up of 25 ply's at 0.1mm thick. In running optimization, it is important to increase the number of iterations to allow for full convergence. Providing all information is correct and accurate, there is no violations present. The results from the optimization trial provided the following information.

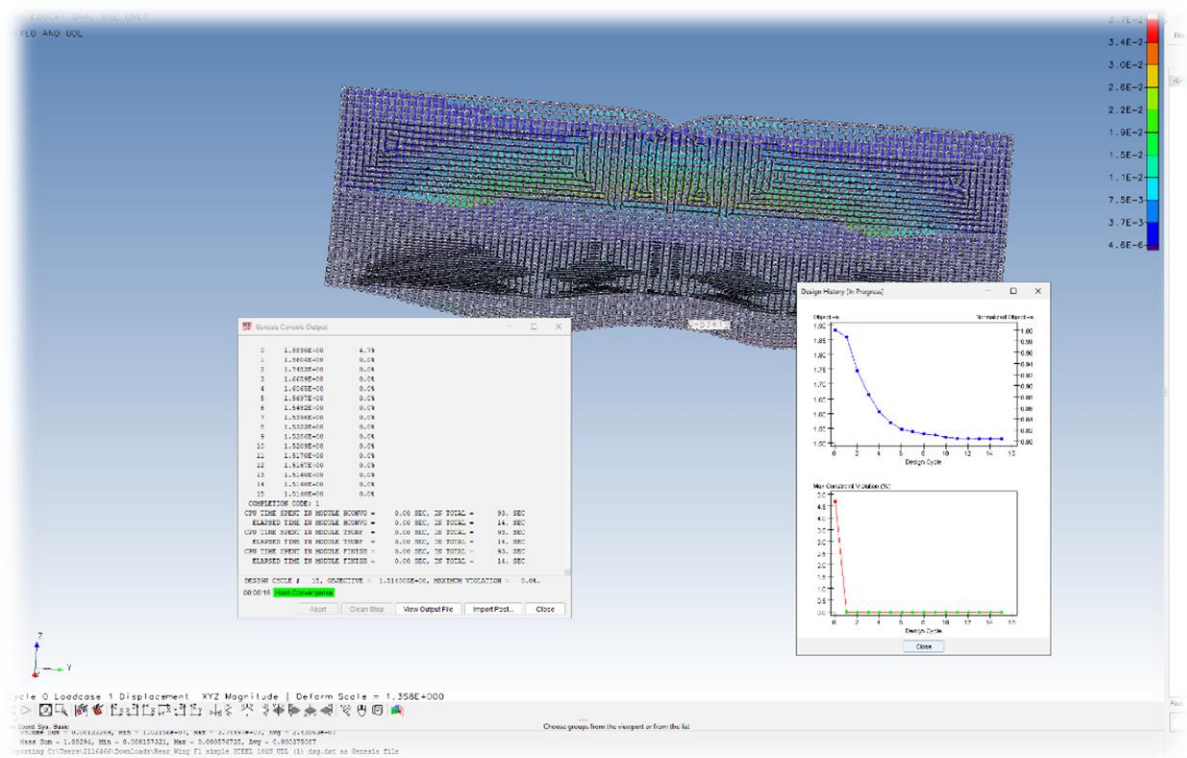


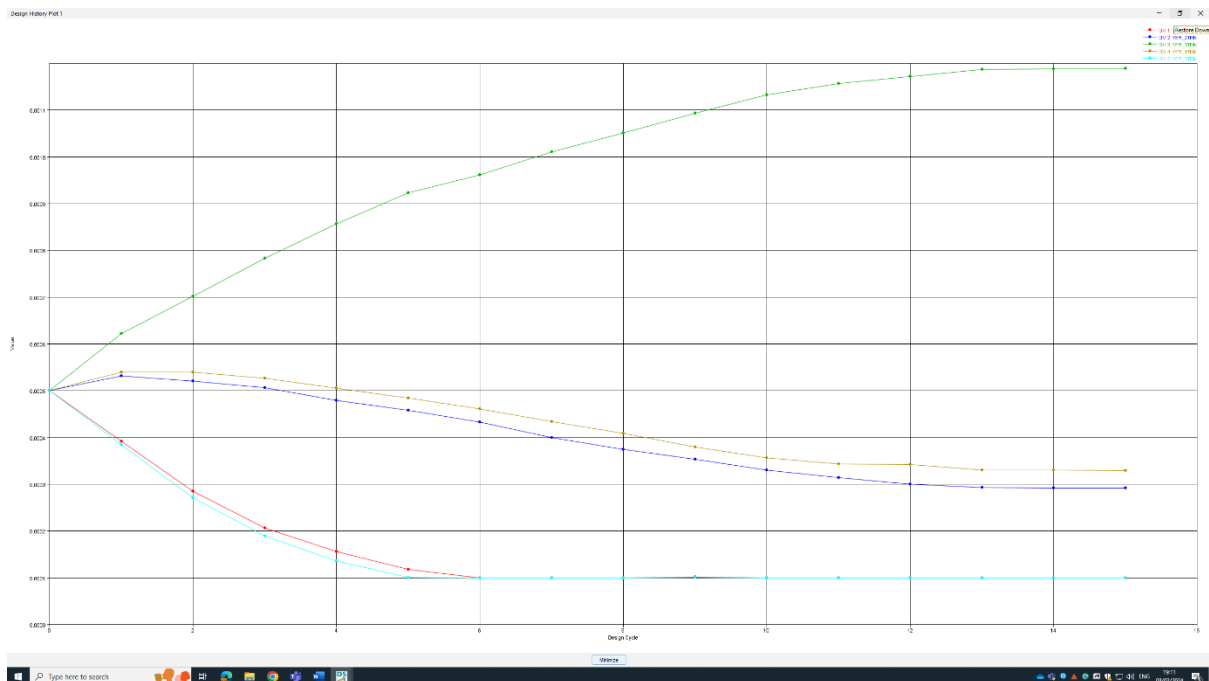
Fig 6.2: Ima on previous page including results and analysis from finished 15 Optimized design cycles.

The images depicted in fig 6.2 show how initially the system responds by increasing the mass drastically, and therefore in violation of our constraints. But the system does indeed regulate itself before finally achieving the optimized state.

DESIGN CYCLE # 15, OBJECTIVE = 1.514005E+00, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE #	1 = 1.000000E-04	YER_1THK
DESIGN VARIABLE #	2 = 2.917173E-04	YER_2THK
DESIGN VARIABLE #	3 = 1.189245E-03	YER_3THK
DESIGN VARIABLE #	4 = 3.291444E-04	YER_4THK
DESIGN VARIABLE #	5 = 1.000000E-04	YER_5THK

Fig 6.3: Text box showing the deviation of thicknesses of each layer ranging from -90° to +90°. As can be seen design variable three has the greatest thickness and this is due to the maximum deflection experienced during the simulation. This is where most of the work and stress is concentrated therefore the system applied the thickest layer to achieve the results pre-determined.



In calculating the stiffness to weight ratio from the optimised model we have:

$$F = \frac{K}{X} = \quad K = \frac{F}{X} = \quad K = \frac{10000}{3.6} = 2777 \text{ N/mm}$$

Mass of wing = 15.51kg

$$\frac{\text{Stiffness}}{\text{Weight}} = 2777 / (15.51 * 9.81) = 18.25 \text{ N}^2/\text{mm}$$

As noticed above the stiffness to weight ratio has increased therefore the layers of ply's have been constructed effectively in which with reduced mass of the wing to 15.51kg increase stiffness performance suited for high down forces and drag forces that come into play at various speeds.

```
SWActivateRequest_9020005362842051ZB zip.txt Rear_

File Edit View

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DESIGN VARIABLE # 3 = 6.223897E-04 YER_3THK
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Prototype and simulation process.

In conducting research and from gaining experience in the manufacturing environment it would prove invaluable to simulate and optimize the design prior to any prototyping. To emphasize this, an example in the Automotive industry physical prototypes can cost in the region of \$250,000 - \$1,000,000 dollars per vehicle, along with numerous prototypes for each build (up towards 50-70) within the development plan (Writers, 2023). For newer starting companies, even companies that are organizationally smaller these kinds of investments can prove costly and reduce the ability to remain competitive within industry. The ability to discover technicality issues early within a project can reduce the time scale of development and major physical tests are dependent on working prototypes (Writers, 2023). In competition to simulation analysis, prototyping depending on methods used can aid in discovering initial design flaws, provide direction on manufacturing and machining methods. For example modelling a scaled down vehicle out of modelling clay and testing aerodynamic forces can be done on a minimal budget. Prototyping carries from sketching generic ideas allowing understanding of intended design. As mentioned above creating appearance models, that replicate the sketch forms and features however can't function mechanically. An additional heavily used method within 'rapid prototyping' is via use of three-dimensional printing machines (Mata, 2021) All optimized data would be collected, and any necessary calculations carried out, the optimized number of ply's and thickness and mass would be inputted to the prototype. However additional work would need to be carried out when considering the manufacturing processes, as it is simply not possible to manufacture odd sizes ply thicknesses. To calculate the number of layers, the thickness would need to be divided by 0.1mm to provide us with the number of layers.

A whole scale vehicle model does not need to be manufactured, testing the deflection of the wings can be simulated close enough although not completely accurate by using methods such as maximum deflection test jigs. Where a wing set up is conducted and a bladder is used through inflation along with DTI clocks to measure and capture the deflection of the wing. The image depicts a knock up to resemble a plane wing, although it would be possible to replicate similar model builds for a rear race car wing. These methods can be used after Optimisation software has produced outcomes, and to validify these results somewhat for understanding before potentially producing a full prototype.



Fig 7.0: Highlighting basic carbon fibre deflection test, of air plane wing to scale (Aero, 2021)

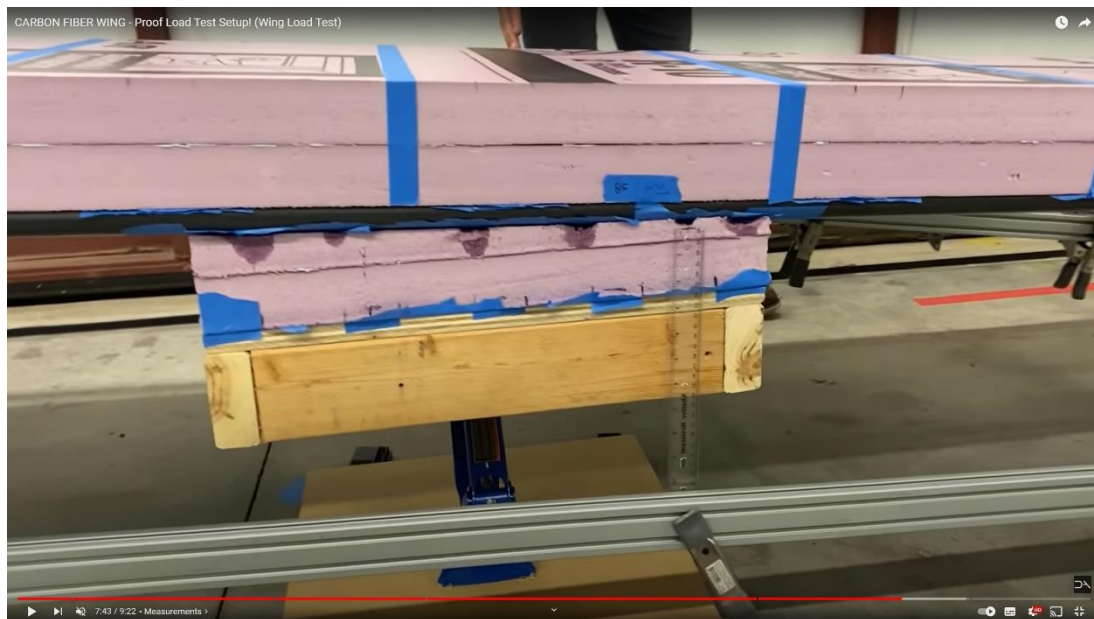


Fig 7.1: Simple method for measuring deflection of wing, although using DTI clocks would prove more accurate to within thous (Aero, 2021).

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