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Module: Structural & Fluid
Analysis

Module Code: ACMA6010

Assignment Title: Designing a
race car rear wing: Structural
Design

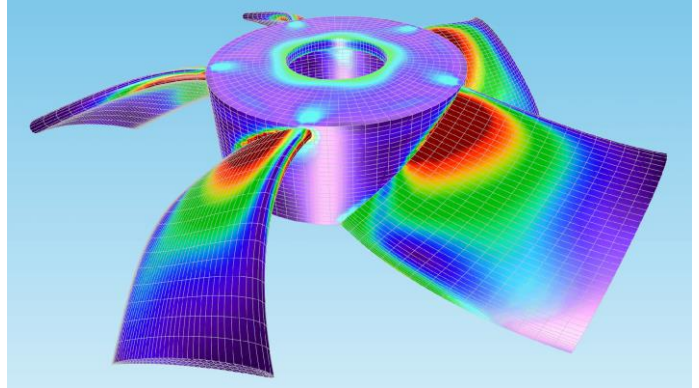
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Introduction

Finite Element Analysis (FEA) is a numerical simulation technique used to analyse the behaviour of structures and systems by dividing them into smaller, finite-sized elements. Throughout this assignment we will take an in depth approach to analysing different types of FEA techniques; how the technique has developed and will continue to develop in the future; the benefits of utilising this technique through different types of software; and fully explain of this technique can be utilised in real world conditions by laying-up composite material (Carbon Fibre Reinforced Plastic) on a formula 1 cars rear wing and optimising the design utilising FEA to meet real world constraints.

When the practical assessment is completed, we will further discuss how this proposed prototype could be manufactured and testing in order to compare/validate the FEA technique to real world conditions/FIA scrutineering.



(N/A, 2017)

Throughout the report, all testing and data used through testing will be taken from reputable sources of as close to real world conditions as possible to make the testing as accurate and realistic as can be.

FEA Optimisation Techniques

There are many different ways in which Finite Element analysis is used in the optimisation process of a particular design, prior to any prototypes being manufactured. These FEA methods are used to improve on the design of a structure or system based on the simulation results. By utilising optimisation techniques, the designers aim is to establish the best configuration, dimensions or material properties to achieve their specified performance objectives, whilst simultaneously reducing weight cost and any other established constraints. Some of these optimisation techniques are as follows:

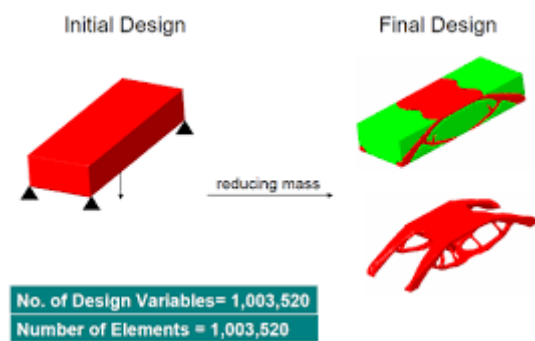
Size Optimisation

This technique involves the optimisation of the dimensions of a structure/component in order to meet established performance criteria. In many cases, this would mean changing the thickness or cross-sectional area of the of the elements in the FEA model. The main reason why this method would be used to is minimise the amount of material used, whilst maintaining performance design requirements, which would in-turn save costs and improve efficiencies.

Shape Optimisation

This technique is commonly used on parts like airfoils or structural components with complex shapes and focuses on changing the geometric shape of the component whilst keeping its dimensions constant.

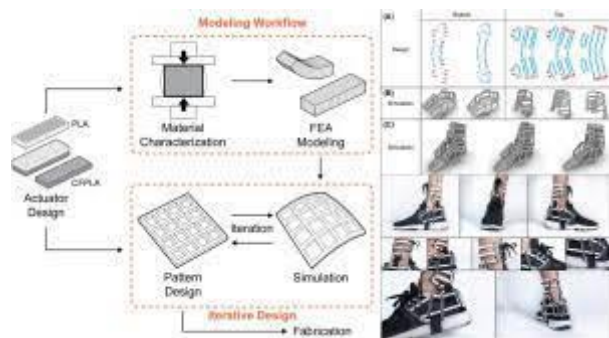
The aim of this is to increase the components performance characteristics, reduce stress concentrations and minimise the weight.



(Leap, 2023)

Material Optimisation

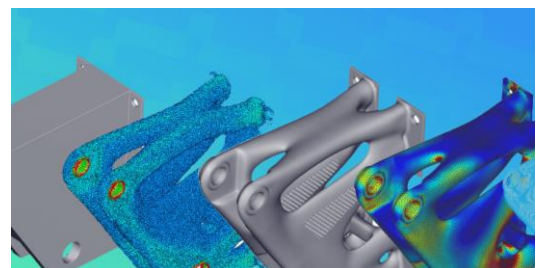
This technique involves constructing a specific model and applying the constraints required. When doing this, the material used for the construction of the component can be easily changed through the software. This can then utilise FEA to determine the best material for the application before having to create prototypes. This often involves choosing materials with different mechanical properties such stiffness or strength to meet design requirements, whilst minimising critical factors such as cost and component weight.



(Yu, 2020)

Topology Optimisation

This technique is most commonly used to determine the most efficient material distribution within a components design in order to achieve the best stiffness-to-weight ratio. This in volves removing unnecessary materials from low stress points within the component and redistributing them into areas of high stress, which is easily established during the FEA testing process. Specific algorithms can be utilised within design programs to aid topology exercises.



(Hin, 2023)

Sensitivity Analysis

This technique helps identify the most critical design variables that will effect the performance of the define structure. This will help guide the designer during the optimisation process by highlighting specific parameters that require adjustment in order to achieve the specified design goals.

Design Of Experiments (DOE)

DOE is a systematic approach to determine how certain variations in the defined design parameters affect the output or parameters. This technique helps to define the design space and understand the model in order to optimise it correctly through different simulation tests.



(Altair, 2023)

Multi-Objective Optimisation

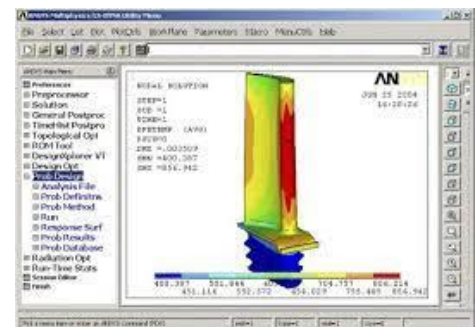
In many cases, there are conflicts in the design optimisation requirements. An example of this would be if you were to create a design and specify that the stiffness must be maximised, whilst minimising the weight. By utilising this technique, it allows the optimisation process to trade-off the conflicting objectives and create a trade off between the two in order to achieve the best out of the circumstance whilst not compromising on either.

Modal Optimisation

This technique aims to tune into natural frequencies that certain components may be exposed to during service to avoid resonance or even meet vibration requirements. An example of this could be in Aerospace where vibrations need to be kept to a minimum to increase component lifecycles and avoid fatigue.

Probabilistic Optimisation

This technique incorporates certain levels of variability within the optimisation process. This is especially useful when FEA is being undertaken on a component where the input parameters or loading conditions aren't fully understood or cannot be established.



(Reh, 2006)

FEA Historical Development

Finite Element Analysis techniques have significantly evolved, developed and improved over the years. These improvements have been driven by advancements in computing power, software capabilities/availability and an improved understanding of numerical methods. The following section of the report will delve deeper into the advancements over the years.

Initial Development (1950 – 1980)

FEA was initially used at the start of the 1950s where engineers started using numerical methods for structural analysis. During these times software was limited and the focus was primarily on linear statistical analysis, which was used for Civil and Mechanical engineering applications.

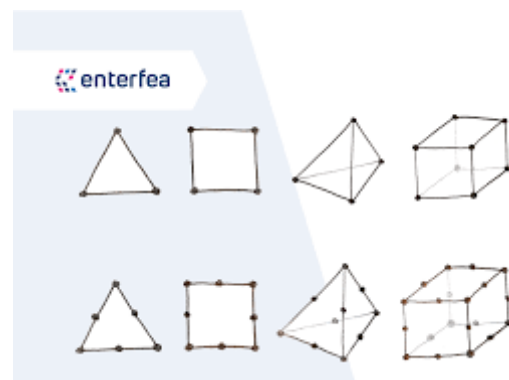
Expansion Of Element Types (1980 – 2000)

Throughout this time period, FEA began to incorporate a wider range of element types, in order to handle various types of problems, which include:

- Truss Elements
- Beam elements
- Shell elements
- Solid elements

It was also the time where dynamic analysis capabilities for modal, harmonic and transient analysis was established. There was also a continued improvement in pre-processing and

post-processing tools for mesh generation and result visualisation.



(Odonell, 2022)

The 1990s also saw a significant advancement on non-linear analysis capabilities, which allowed engineers to address problems that specifically involved non-linearity within the component behaviour, geometric non-linearity and contact. These techniques became increasingly popular for simulating complex behaviours, such as; Plastic Deformation; Large Deflections and Buckling.

Multiphysics Simulations (2000 – 2019)

FEA expanded to include multiphysics capabilities, which enabled the simulations to be combined with phenomena such as fluid structure integration (FSI), thermal stress coupling and electromagnetic structural coupling.

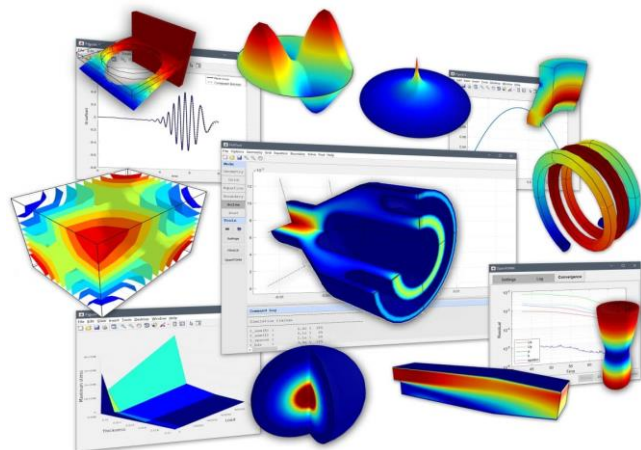
Throughout this time period simulations of diverse fields such as:

- Heat transfer
- Acoustic
- Electromagnetic

Were all integrated into FEA software and techniques.

High Performance Computing (2010 - Today)

As can be seen throughout all engineering applications, today's high performance computing abilities have opened up a new



(N/A, 2022)

world. Some of the ways in which advancements have been made in the last decade are as follows:

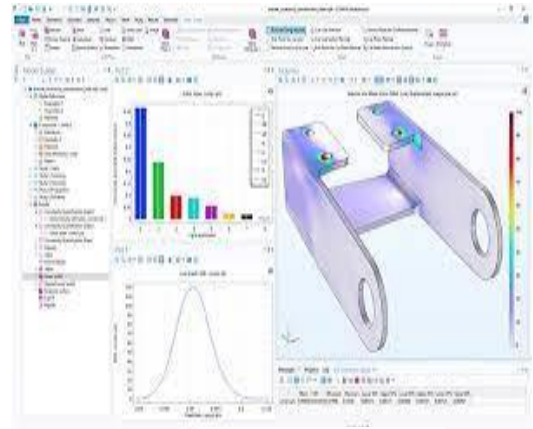
- Advancements in computing power and parallel processing has now enabled the analysis of larger and more complex models with relative ease.
- Optimisation techniques such as Topology have increased in popularity in order to specifically reduce component weights and design efficiencies.
- Cloud based FEA tools have become more easily accessible which offers these types of resources to a wider ranger of people.
- Huge improvements in material modelling capabilities have meant further advancements into modelling which has meant analysis of composite materials is much easier and improved the understanding of how real-world materials behave under different circumstances.
- Expansions of how uncertainty can be addressed through probabilistic analysis and stochastic modelling, which are now critical in the Aerospace industry, where the safety and reliability of the component is extremely important.
- Improved integration of FEA with product lifecycle management (PLM) systems and simulation data management tools for the management and sharing of simulation data. This has significantly improved the collaboration and traceability throughout all stages of product development.
- The most recent advancement within the field is the integration of FEA with machine learning and artificial intelligence, which has shown of simulations can be automated from optimisation to result analysis. These advancements in technology can now be utilised for predictive modelling and improving the efficiency of the overall simulation process.

FEA Developments for the future

As can be seen throughout the historical developments of FEA, the future is very bright for this analysis technique during component design. Similarly to a lot of other computational methods, automation and integration to emerging technologies will become the norm.

Some of the believed future advancements in FEA are as follows:

- Increased automation and AI integration, utilising machine learning which will significantly advance mesh generation, model setup and post-processing, the utilisation of AI algorithms may aid in the future by suggesting design changes during the optimisation of a component based on what has been witnessed during the simulation.
- Further advancements in the ability to multi-scale model components, allowing analysis of structures and materials at different scales which would be significant for material sciences and nanotechnology.
- The use of improved material modelling using composites will become more popular and FEA will be further relied upon to improve on these manufacturing methods by aiding the development of more accurate and comprehensive material models.
- With the world being driven to become greener, FEA will be further utilised to understand product lifecycles and their impact and optimise these designs. Further aiding manufacturers to adhere to environmental regulations.
- Virtual reality is thought to be used to interact with FEA models, further providing an immersive and detailed way of understanding and manipulating simulations, it is thought that this will significantly improve on design review processes and allow for decisions to be made faster with an improved understanding of the components.
- The exciting developments in the field of quantum computing will mean that extremely complex FEA simulations will be accelerated and much more efficient by the computer ability to handle and process much more data within a much shorter time frame than what we currently see.



(Wong, 2022)

As can be seen above, the future for FEA is very bright by the technology advancements currently being seen and what is planned for the future.

How can FEA improve the overall design process

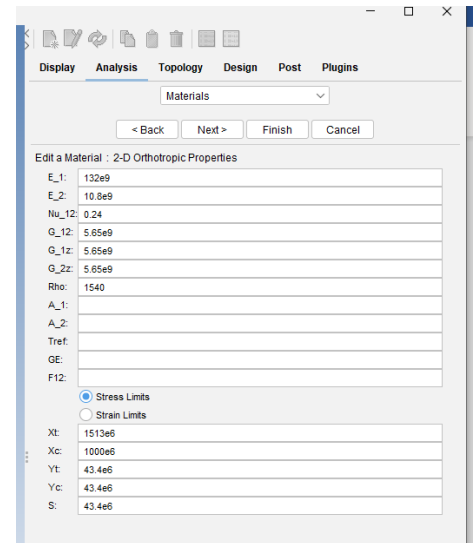
Finite Element Analysis has proven to be a huge advancement and aid in the overall design process and product development as a whole. These benefits include:

- It allows for design engineers to test and validate initial design ideas in the very early stages of product development, which significantly reduces testing costs and the need for design changes later on in the process.
- As mentioned above, this heavily reduces the needs of prototype testing which saves massive amounts of time.
- Increases the safety and confidence levels in the designs from the very early stages.
- Component manufacturability is taken into consideration from the very start of the design process to ensure there are no stumbling blocks at the latter stages.
- It aids in the materials selection process by utilising performance predictions.
- Designs can be easily changed and retested quickly and efficiently.
- Many programs generate test reports automatically which can be shared to wider teams with ease, which aids in the knowledge sharing of the product.
- It can aid the designers in understanding the environmental impact of the component and allows them to make more environmentally conscious decisions.

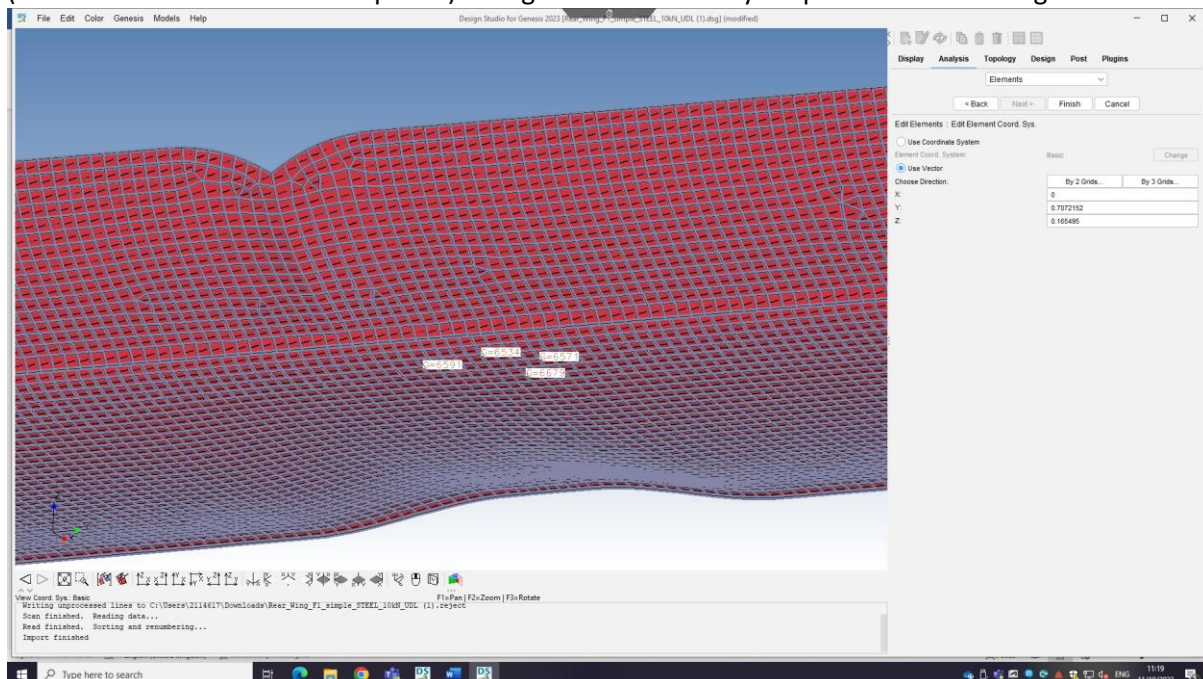
Laying Up F1 Racing Car Rear Wing

After the model is imported into the FEA software, the initial step of the lay-up process is to define the unidirectional material properties for the Carbon Fibre Reinforced Plastic, as per the design specification:

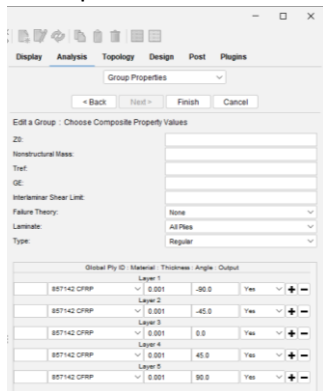
It is essential to define these properties accurately before any FEA is undertaken to maintain a high level of accuracy and repeatability from the overall testing.



Due to the fact that the force was a uniformly distributed load and the wing is fixed at both end, the Vectors were aligned to run in the global y direction to correspond with 0 degrees. This is done to primarily correct any vectors running in the default x axis and to standardise material properties (due to the fact that it is a composite) and give a more reliably output from FEA testing.



Once all vectors were aligned, the lay-up process was undertaken to create the 5 layers of 25 Plys of a composite Carbon Fibre Reinforced Plastic at the desired thickness of 0.1mm.

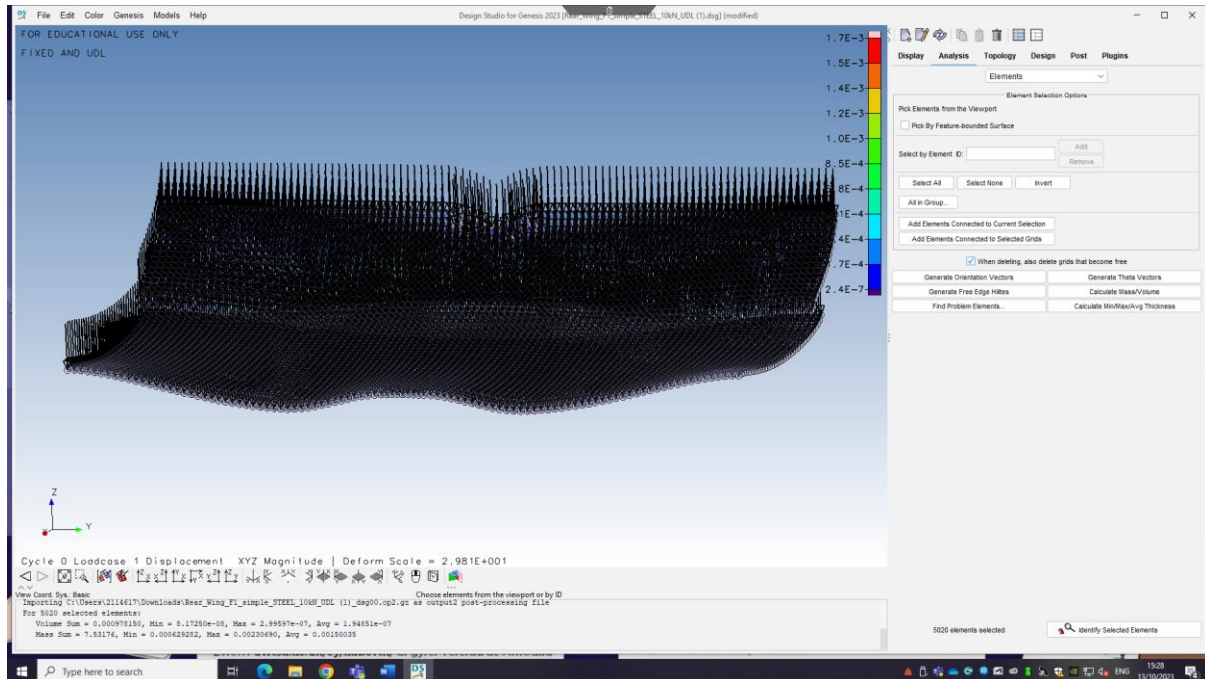


As can be seen in the image, each layer was layed unidirectionally starting at -90 degree, all the way around to +90 degrees, this is to give the component rigidity in all axis and improves on the stiffness to weight ratio. This is achieved by meshing layers ensuring no weak spots are created by fibres running in all directions which are help together by strong composites.

At this stage of the FEA process, the component (Rear Wing) has undergone a large amount of changes from a standardised steel model to a unidirectionally layed up Carbon Fibre Reinforced Plastic. Whereby, the layers have been strategically positioned in order to achieve what is believed to be the optimum structural properties. The component was now ready to undergo the Optimisation process.

Component Optimisation In Order To Minimise Mass

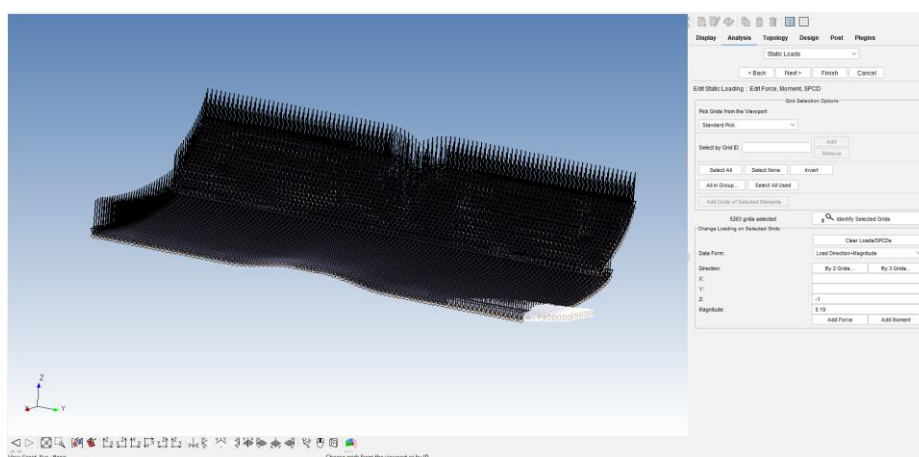
Prior to any optimisation or definition of control parameters, the initial deflection of the Steel Component was 1.7mm.



Defining Critical Parameters and Controls Prior to Optimisation

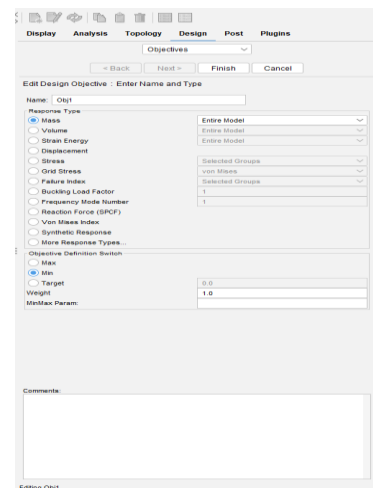
Before starting the Optimisation process, it was critical to define the direction in which the force is acting upon to wing to be able to apply the correct static load. This was initially done by conducting Single Analysis on CFRP component to understand the deflection.

By conducting the single analysis, it showed us how the load was acting on the component. By doing this, we were able to set the static loads Magnitude to 1000 Newtons acting downwards in the Z Direction, uniformly distributed across all segments of the shape by dividing up the force evenly over all surface area shown from the Single Analysis. This is believed to be the most accurate representation of Formula 1s Governing Body, the FIA, scrutineering process to give the upmost confidence that the wing will comply to all regulations, and allow its use in the professional testing Circuit (N/A, 2021).



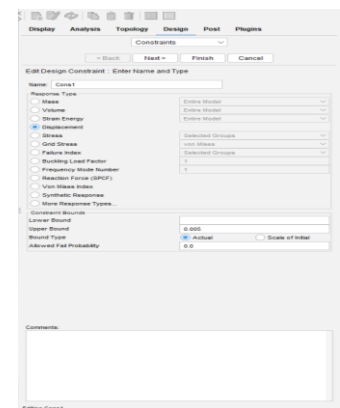
Once the Load conditions and behaviour was defined, the Optimisation process was able to be undertaken.

Before test runs were undertaken and the FEA program was utilised to optimise the component manufacturing design, it was essential that the desired design constraints were put in place in order to achieve the desired results from the Optimisation process. As can be seen, the main objective of this optimisation process was to minimise the overall Mass of the component. The overall mass of a racing car is extremely important and it is critical that its kept to an absolute minimum to give the racing team the best possible chance of winning races.

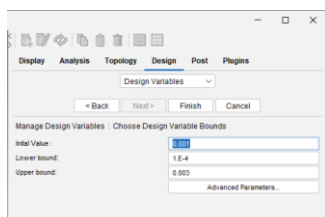


If the only consideration that needed to be taking into account was the mass of the component, the optimisation process would make the plys/layers as thin as possible to reduce material used. However, this is not the only consideration.

There are many detailed constraints applied to designs, to ensure that adhere to strict rules and regulations. The main constraint that must be accounted for during this optimisation process would be to ensure that the wing does not deflect any more than 5mm in either direction, to comply with the new 2023 FIA scrutineering criteria (Vilesetti, 2022).

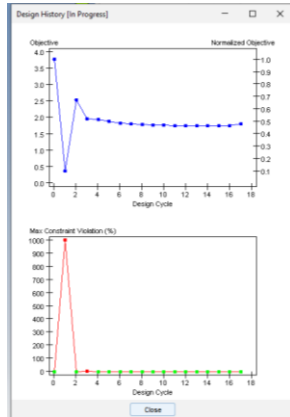


Along with the constraints and objectives, design variables must be added to ensure that the overall ply thickness did not exceed 0.1 mm.

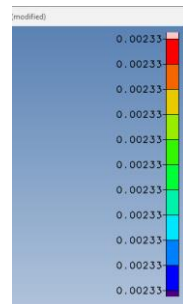


Optimising The Component

Through the chosen FEA system, the component underwent the Optimisation process, whereby, the system will run many cycles constantly analysing the critical outputs and comparing them to the objectives and constraints. It took 17 cycles of optimisation before the component was optimised by the program, and the results of the optimisation steps can be found below:



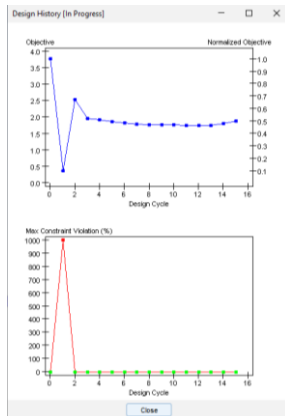
Although the component was now fully optimised and met all predefined parameters/conditions, it is extremely important that the manufacturability of the design is taken as a priority. When looking at the overall thickness of the CFRP layers, it was realised that the level of accuracy would not be achievable in real world conditions.



With the layer thickness' being unachievable, it was critical that a discrete design variable of a lower and upper bound of thickness was applied to each layer.



The component was then re-optimised and very little difference was observed apart from a minor increase in deflection, but still within the specifications requirements.



Results Comparison & Analysis After Optimisation

As with all rear wings, one of the main factors that must be taken into consideration with material and design selection processes, is the stiffness to weight ratio, throughout each steps of the design process, these were calculated and are as follows:

$$Stiffness = K = \frac{F}{x}$$

$$F = 1000 \text{ Newtons}$$

$$Deflection (x) = ?$$

$$Stiffness \text{ to Weight ratio} = \frac{Stiffness}{Mass \times Gravity}$$

Simple Steel Structure:

$$Mass = 7531.75 \text{ grams}$$

$$K = \frac{1000}{1.7}$$

$$K = \frac{588.24N}{mm}$$

$$Stiffness \text{ To Weight Ratio} = \frac{588.24}{7531.75 \times 9.81}$$

$$Stiffness \text{ To Weight Ratio} = 0.0796N^2 / mm$$

CFRP Before Optimisation:

$$Mass = 3765.9 \text{ grams}$$

$$K = \frac{1000}{1.7}$$

$$K = \frac{588.24N}{mm}$$

$$\text{Stiffness To Weight Ratio} = \frac{588.24}{3765.9 \times 9.81}$$

$$\text{Stiffness To Weight Ratio} = 0.0159N^2/mm$$

CFRP After Optimisation:

$$\text{Mass} = 1752.63 \text{ grams}$$

$$K = \frac{1000}{4.8}$$

$$K = \frac{208.3N}{mm}$$

$$\text{Stiffness To Weight Ratio} = \frac{208.3}{1752.63 \times 9.81}$$

$$\text{Stiffness To Weight Ratio} = 0.0121N^2/mm$$

Manufacturable CFRP After Optimisation:

$$\text{Mass} = 3765.88 \text{ grams}$$

$$K = \frac{1000}{4.5}$$

$$K = \frac{222.2N}{mm}$$

$$\text{Stiffness To Weight Ratio} = \frac{222.2}{3765.88 \times 9.81}$$

$$\text{Stiffness To Weight Ratio} = 0.0601N^2/mm$$

Before Optimisation:

DESIGN CYCLE #	0,	OBJECTIVE =	3.765982E+00,	MAXIMUM VIOLATION =	0.0%.
DESIGN VARIABLE #	1 =	1.000000E-03	L1THK		
DESIGN VARIABLE #	2 =	1.000000E-03	L1THK2		
DESIGN VARIABLE #	3 =	1.000000E-03	L1THK3		
DESIGN VARIABLE #	4 =	1.000000E-03	L1THK4		
DESIGN VARIABLE #	5 =	1.000000E-03	L1THK5		

After Optimisation:

DESIGN CYCLE #	15,	OBJECTIVE =	1.882991E+00,	MAXIMUM VIOLATION =	0.0%.
DESIGN VARIABLE #	1 =	2.000000E-04	L1THK		
DESIGN VARIABLE #	2 =	4.000000E-04	L1THK2		
DESIGN VARIABLE #	3 =	1.300000E-03	L1THK3		
DESIGN VARIABLE #	4 =	4.000000E-04	L1THK4		
DESIGN VARIABLE #	5 =	2.000000E-04	L1THK5		

Although the stiffness to weight ratio is extremely important, the software was set up in order to prioritise design pre-requisites, which were:

1. The component must be optimised in order to minimise mass.
2. Must be layed up using 5 layers of 25 plys, which must be 0.1mm thick.

3. The deflection of the component must not exceed 5mm in either direction when loaded with 1000 Newtons.
4. Layer Thicknesses must be achievable in the manufacturing of the wing.
5. The plys must be placed at the specified orientation.

As can be seen throughout each optimisation step, the mass decreases after every optimisation but the deflection does increase only to within the specified constraint. This shows how the FEA software pushes the material to its specified limits to achieved the best results.

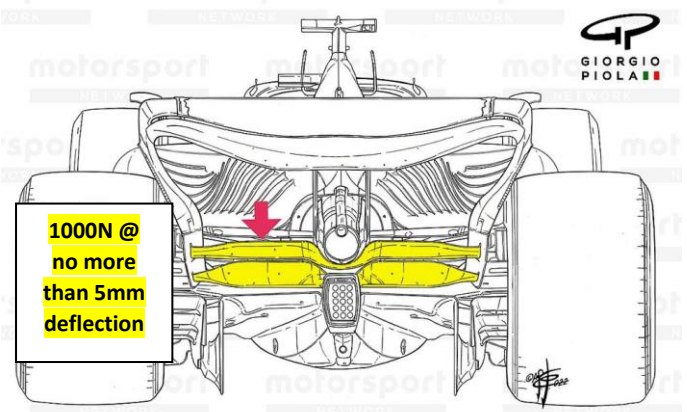
Prototype testing

Due to the fact that all constraints and regulations that we have worked to have been taken directly from the Fédération Internationale de l'Automobile (FIA) most recent guidelines for Formula 1s rear wing of their professional racing cars. A laboratory test would be set up to replicate testing during vehicle scrutineering as closely and accurately as possible. The FIA regularly conducts load testing on F1 cars rear wings, to ensure that all teams comply with the sport technical regulations (which have been specified and tested in the FEA model). These tests are extremely important in the verification of rear wings abilities to withstand forces that they would regularly be subjected to during high-speed races without excessively deforming or failure.

Before completing any tests an accurate wing must be constructed to the exact ply specifications, lay-up and material grades to ensure complete repeatability and accuracy.

Although load testing procedures and equipment are ever evolving, the testing that would be undertaken on this rear wing would be as follows:

1. Before any load testing is conducted, the wing must undergo a thorough inspection and ensure that the manufacturing process and specification has been adhered to. All critical dimensions of the shape are accurate and comply with technical regulations.
2. Setting up the testing facility in a repeatable area which has temperature and humidity control to ensure that material properties are not effected by ambient conditions.
3. When conditions are stable and the wing has been thoroughly inspected, it must be securely mounted/fixed at either end to ensure six degrees of freedom, as per the specification. This fixture will ensure that the wing is in the correct position during testing.
4. As per the FEA testing, a load of 1000 Newtons will be applied in the minus Z direction (as per FIA testing), a



(Summerfield, 2022)

calibrated mechanical testing system, such as a hydraulic ram with a plate made to suit the wing design and ensure even pressure distribution would be used to apply the load to the.

5. The duration of the 1000 Newtons would comply with FIA standards and the levels of deflection and deformation would be taken.
6. The deflection and deformation of the wing would be monitored and plotted throughout the test by utilising (Summerfield, 2022) various sensors and strain gauges strategically placed around the wing to measure the deformation and stress.
7. After testing the wing would be meticulously examined for any signs of damage or deformation, along with structural failures. Often times, this initial inspection after testing will show early signs of non-compliance.
8. Once the test is performed the data must be analysed to compare the real world testing results to the FEA. Deflection measurements will be compared along with the stiffness to weight ratios to ensure they are identical. If there are any discrepancies, the test must then be repeated once the inaccuracies have been established.
9. If the data shows that the wing is deemed safe, the FIA would then allow the team to use it during the racing circuit, but if failure occurs, teams will often face large penalties, this shows how imperative FEA accuracy and manufacturing methods are to the overall process.



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