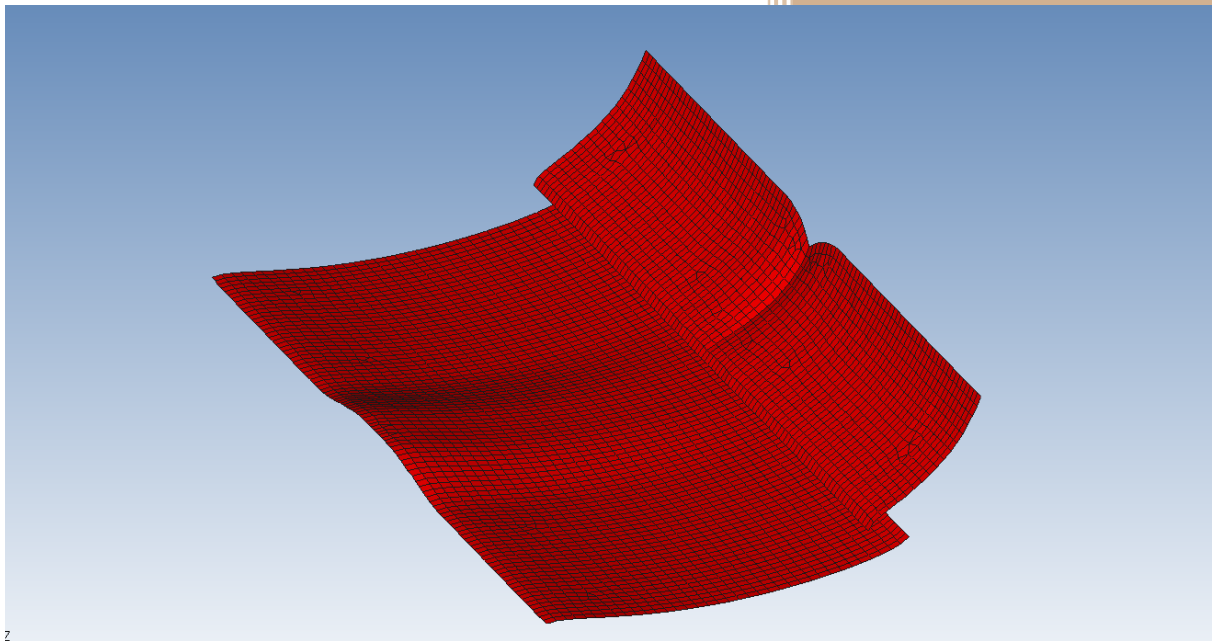


Structural and
Fluid Analysis

Designing a Race Car Rear Wing: Structural Design



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Structural and Fluid Analysis

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Introduction

This assignment is a follow up on the previous assignment (Knight, 2023) which looked at a rear wing for a motorsport vehicle and how fluid flow affects it. In this assignment I will be looking into FEA technology and seeing how it can be used to help optimise the shape and material of the rear wing. I will then be covering my experience of using design studio and reviewing the results from the analysis report. I will then touch on the legislation and industrial standards that can have an impact on the design of the rear wing.

Task 1: FEA Optimisation

What is FEA?

FEA stands for Finite Element Analysis. It is a computational technique used in engineering and physics to simulate the behaviour of complex structures and systems. FEA breaks down a system into smaller, finite elements and analyses how these elements interact with each other to predict how the entire system will behave under various conditions. It's widely used for tasks such as stress analysis, heat transfer, and fluid flow simulations to assess the performance and safety of designs in fields like mechanical, civil, and aerospace engineering. According to (NAFEMS, 2022), using FEA optimization during the design stage embraces the ideology of “right first time” using minimum design cycles.

History of FEA

The history of Finite Element Analysis (FEA) dates back to the mid-20th century:

1940s-1950s: The origins of FEA can be traced to researchers and engineers looking for ways to solve complex structural analysis problems. Notable contributors during this period include Richard Courant and Kurt O. Friedrichs, who developed numerical methods that laid the groundwork for FEA.

1960s: FEA gained momentum in the 1960s, particularly in the aerospace industry. According to (Cadferm.net,2023), Dr. Ray W. Clough is often credited with Coining the term Finite Element Analysis. Engineers and researchers started developing the mathematical and computational foundations for FEA.

1970s: In the 1970s, the development of commercial FEA software, like NASTRAN and ANSYS, marked a significant milestone. This made FEA more accessible to engineers and industries, leading to widespread adoption.

1980s: With the increasing computational power of computers, FEA simulations became more sophisticated and capable of modelling complex problems in various fields, including structural analysis, heat transfer, and fluid dynamics.

1990s-Present: FEA continued to expand its applications, extending beyond structural analysis to fields like electromagnetics, acoustics, and more. It has become an indispensable tool in industries ranging from automotive and civil engineering to medicine and material science.

Advancements in Parallel Computing and Solver Technology: In recent years, FEA has benefited from advances in parallel computing and solver technology, allowing for even more complex and real-time simulations.

Integration with CAD and CAE Tools: FEA software has become tightly integrated with computer-aided design (CAD) and computer-aided engineering (CAE) tools, streamlining the design and analysis process.

Today, FEA is an essential tool for engineers and scientists, enabling them to model and simulate a wide range of physical phenomena and assess the behaviour of complex systems before physical prototypes are built. Its history is marked by a continuous evolution in both theory and software, making it a cornerstone of modern engineering and design.

Future of FEA Optimisation

The future of Finite Element Analysis (FEA) can go through many different avenues and provide us for many potential benefits:

Advanced Simulation Capabilities: As FEA continues to evolve with more advanced capabilities, enabling simulations of greater complexity and more dynamic systems. This includes improved accuracy in modelling materials, nonlinear behaviour, and multi-physics simulations.

AI and Machine Learning: The use of artificial intelligence (AI) and machine learning will enhance FEA's predictive capabilities. AI can assist in automating the setup of simulations, optimizing designs, and improving the accuracy of results.

Sustainability and Optimization: FEA will be used to optimize designs for sustainability and energy efficiency, helping industries reduce their environmental impact.

Material Design and Discovery: FEA will contribute to the development of new materials by simulating their behaviour at the atomic and molecular levels, leading to innovations in materials science.

Human-Machine Interaction: FEA may become more accessible to non-experts through intuitive interfaces and augmented reality, allowing a broader range of professionals to utilize its capabilities.

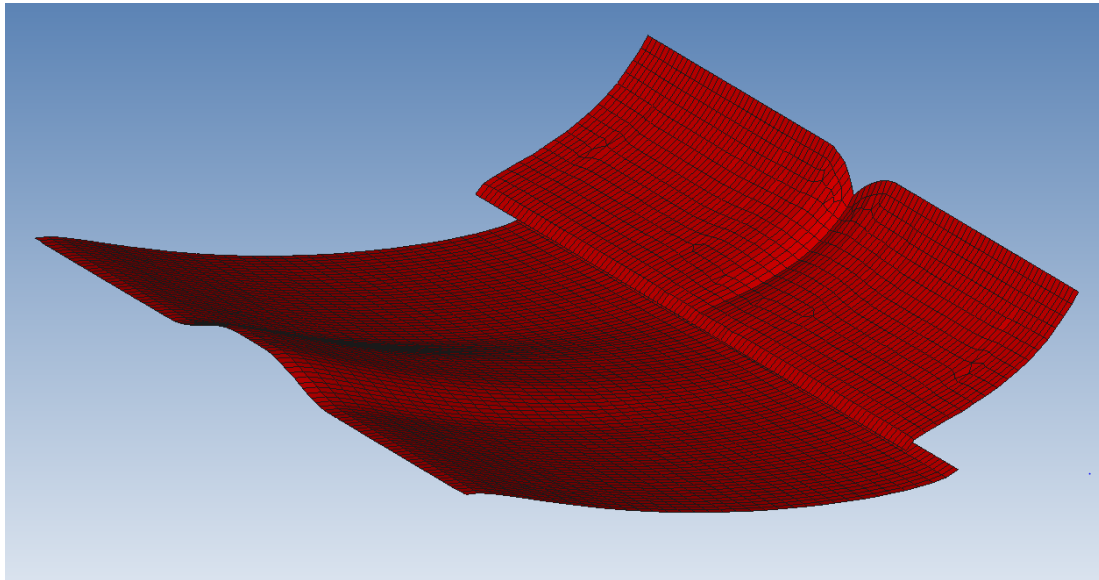
Industry-Specific Applications: FEA will continue to expand into new industries, such as healthcare and consumer products.

Overall, the future of FEA is characterized by increased accessibility, integration with emerging technologies, and a broader range of applications. It will play a crucial role in optimizing designs, improving product performance, and driving innovation across various sectors.

Task 2: Creating a CFRP Wing

Wing Model Base Line

To start the design development of the wing, I used an existing model of the wing, this was provided. The wing provided was made out of a steel material. The problem with this material is that it would be too heavy for its purpose and based off my previous assignment (Knight, 2023) I had determined that carbon fibre reinforced plastic would be the most optimal choice of material for its high strength to weight ratio and design flexibility.



Through the research completed in the previous assignment (Knight, 2023) it was discussed that the amount of force that would act upon the wing is not universally applied and will actually act upon different areas of the wing with varying levels. Due to this, a more realistic representation would need to be shown in the test.

Using the dynamic pressure calculator (Engineeringtoolbox.com, 2023) and the forces discussed in the previous assignment (Knight, 2023) I can work out the dynamic pressure applied to the wing.

Dynamic Pressure Calculator - SI Units

The default values below are for water with density of 1000 kg/m^3 .

ρ - density of fluid (kg/m^3)

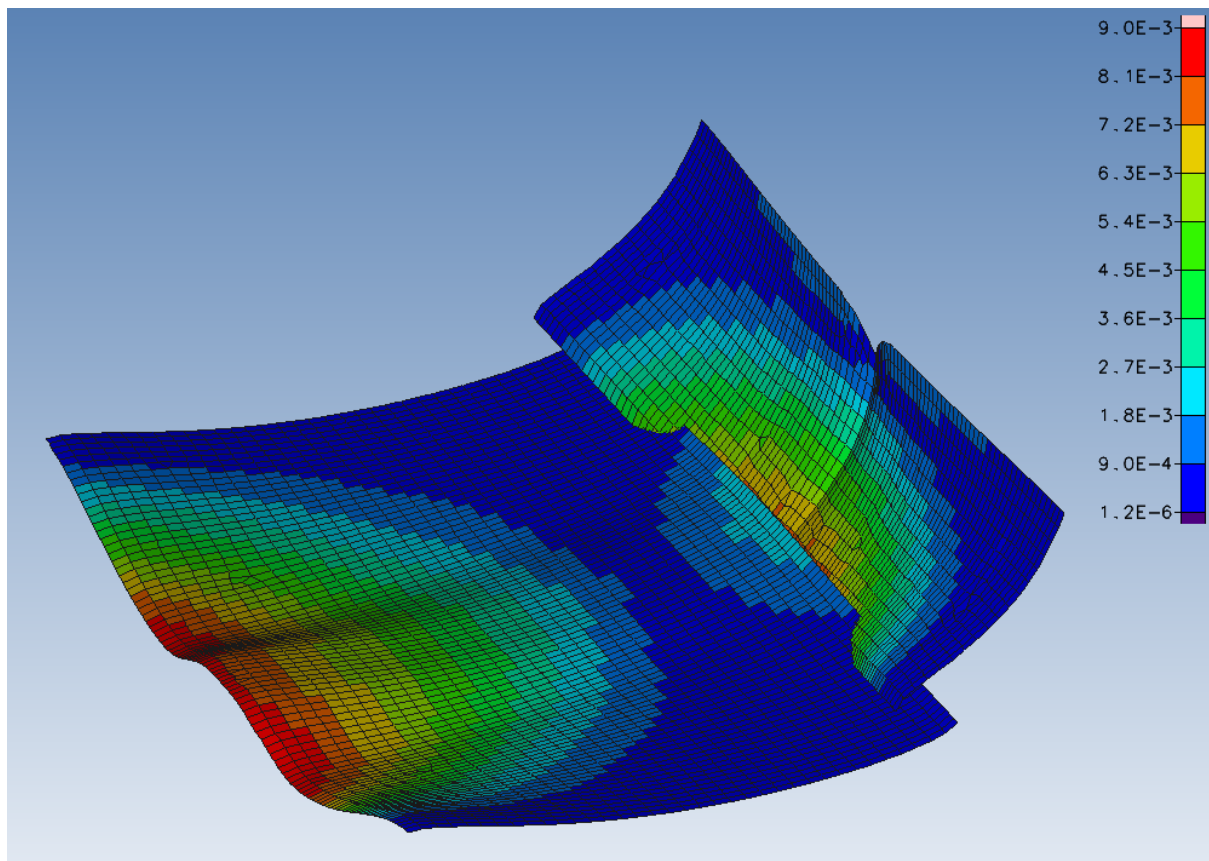
v - velocity (m/s)

- Dynamic pressure (N/m^2 , Pa): **23.5**
- Dynamic pressure (lb/ft^2 , psf): **0.491**
- Dynamic pressure (lb/in^2 , psi): **0.00341**

As this figure of 23.5 N/m^2 is an assumption it was rounded up to 25 N for simplicity.

Without knowing exactly how much force is being applied to each individual node on the wing, it is impossible to avoid having to make some assumptions. The optimisation can still be run by using the assumptions discussed in the previous assignment.

The steel wing's deflection under the forces applied was then simulated through single analysis. As shown in the image below, the deflection was coming up with a value of 9mm on certain areas of the wing, primarily on the leading edges of the wing. What the red sections highlight is that the wing would suffer the greatest deformities/damage of this magnitude. However, since the design studio uses a linear solution, it cannot determine when a part's elastic limit has been reached.



The material data collected from the single analysis shows the current mass of the wing is 7.53176kg.

For 5020 selected elements:

Volume Sum = 0.000978150, Min = 8.17250×10^{-8} , Max = 2.99597×10^{-7} , Avg = 1.94851×10^{-7}
Mass Sum = 7.53176, Min = 0.000629282, Max = 0.00230690, Avg = 0.00150035

CFRP Base Development

To create a blade from CFRP, the new material had to be created using the specification provided in the brief. Below show the properties of both the steel and CFRP materials.

Materials

< Back Next > Finish Cancel

Edit a Material : Isotropic Properties

E: 2.1E+11

G: 7.9E+10

Nu: 0.28

Rho: 7700.0

A: 130000.0

Tref: 298.0

GE:

ST: 7.2383E+8

SC:

SS:

Steel Properties

Edit a Material : 2-D Orthotropic Properties

E_1: 132e9

E_2: 10.8e9

Nu_12: 0.24

G_12: 5.65e6

G_13: 5.65e6

G_23: 5.65e6

Rho: 1540

A_1:

A_2:

Tref:

GE:

F12:

☒ Stress Limits

☐ Strain Limits

Xt: 1513

Xc: 1000

Yt: 43.4e6

Yc: 43.4e6

S: 43.4e6

CFRP (Carbon Fibre Reinforced Plastic) Properties

Setting up layers

As specified in the brief, the blade is to consist of 5 layers of ply's, with a ply thickness at 0.05mm, and the layers set at -90 degrees, -45 degrees, 0 degrees, 45 degrees and 90 degrees. The baseline was then set at 5 Ply per layer. The image below shoes these figures.

Edit a Group : Choose Composite Property Values

Name: UD

Z0:

Nonstructural Mass:

Tref:

GE:

Interlaminar Shear Limit:

Failure Theory: None

Laminate: All Plies

Type: Regular

Global Ply ID	Material	Thickness	Angle	Output
Layer 1				
857143 CFRP	5.E-4	-90.0	Yes	+ -
Layer 2				
857143 CFRP	5.E-4	-45.0	Yes	+ -
Layer 3				
857143 CFRP	5.E-4	0.0	Yes	+ -
Layer 4				
857143 CFRP	5.E-4	45.0	Yes	+ -
Layer 5				
857143 CFRP	5.E-4	90.0	Yes	+ -

The material data collected from the single analysis shows the new mass of the wing is now 1.88294kg.

For 5020 selected elements:

Volume Sum = 0.00122269, Min = 1.02156e-07, Max = 3.74497e-07, Avg = 2.43563e-07
Mass Sum = 1.88294, Min = 0.000157321, Max = 0.000576725, Avg = 0.000375087

Task 3: Optimisation of Wing

Objectives Variables and Constraints

The results from the single analysis of both materials can be summed up by saying that the design without optimisation is unsuitable for their intended use since they both sustained enough deformation/damage from the imposed forces. The structure required will need to be optimised in order for the CFRP to become viable. To begin the FEA optimisation process, I will need to outline three factors: Objectives, Variables and Constraints.

Objectives

My main goal for this design is to have the wing be as light as possible whilst maintaining its function to produce the drag force necessary for a sports car. The current weight of the wing is 1.88294kg as previously stated. However, the wing failed the analysis test at this weight, so it is anticipated that the weight value will likely increase in order to provide sufficient strength. I have given a minimum weight of the wing to be 1.5kg, as shown in the image below.

Edit Design Objective : Enter Name and Type

Name: Minimise Mass

Response Type

- ☒ Mass
- ☐ Volume
- ☐ Strain Energy
- ☐ Displacement
- ☐ Stress
- ☐ Grid Stress
- ☐ Failure Index
- ☐ Buckling Load Factor
- ☐ Frequency Mode Number
- ☐ Reaction Force (SPCF)
- ☐ Von Mises Index
- ☐ Synthetic Response
- ☐ More Response Types...

Objective Definition Switch

- ☐ Max
- ☒ Min
- ☐ Target

Weight: 1.5

MinMax Param:

Variables

For the variables, I have looked at the thicknesses of the layers of materials. The model was given 5 layers, each with 5 Plies at a thickness of 0.1mm resulting in a layer thickness of 0.5mm and a total thickness of 2.5mm. In order for design studio to simulate the most effective method to fill the layers, a minimum and maximum number of Plies were entered with a value of 0.3mm.

Design Variables	
Description	Name
I ID=1 Init=5.E-4 [3.E-4,0.003]	Layer 1 Thickness
I ID=2 Init=5.E-4 [3.E-4,0.003]	Layer 2 Thickness
I ID=3 Init=5.E-4 [3.E-4,0.003]	Layer 3 Thickness
I ID=4 Init=5.E-4 [3.E-4,0.003]	Layer 4 Thickness
I ID=5 Init=5.E-4 [3.E-4,0.003]	Layer 5 Thickness

Constraints

For the constraint, I gave a maximum displacement of 0.009mm.

Edit Design Constraint : Enter Name and Type

Name:

Response Type

☐ Mass

☐ Volume

☐ Strain Energy

☒ Displacement

☐ Stress

☐ Grid Stress

☐ Failure Index

☐ Buckling Load Factor

☐ Frequency Mode Number

☐ Reaction Force (SPCF)

☐ Von Mises Index

☐ Synthetic Response

☐ More Response Types...

Entire Model

Entire Model

Entire Model

Selected Groups

von Mises

Selected Groups

1

1

Constraint Bounds

Lower Bound

Upper Bound

Bound Type

☒ Actual

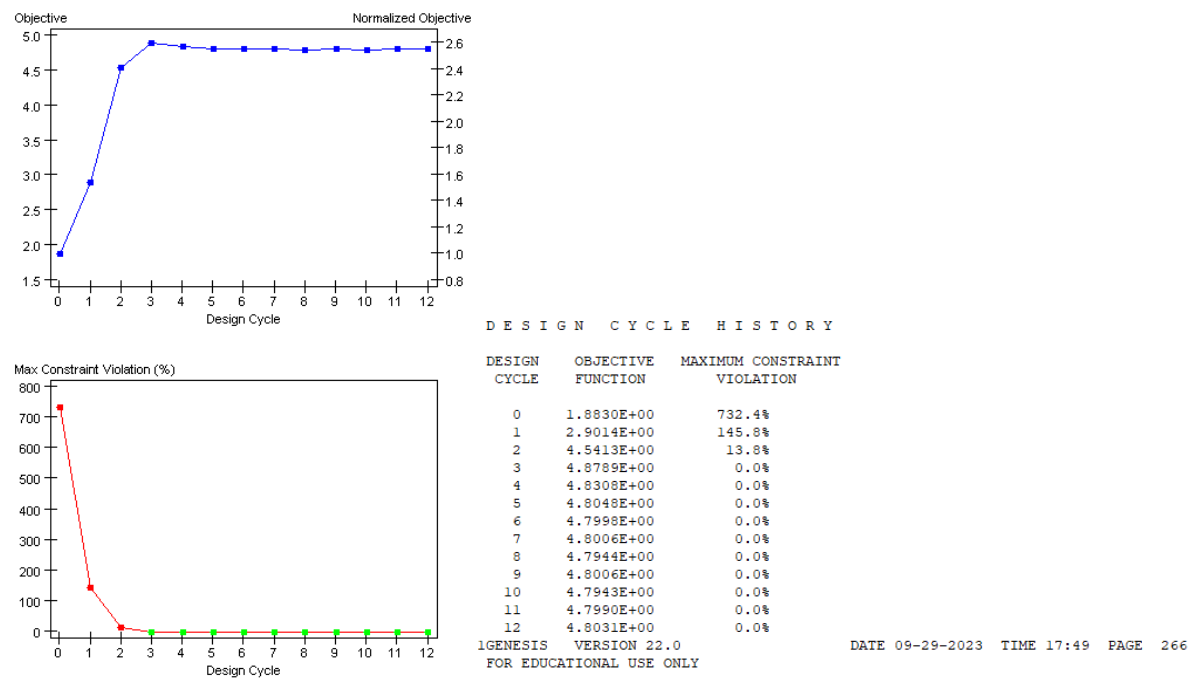
☐ Scale of Initial

Allowed Fail Probability

Optimisation Results

Now that the parameters have been inputted into design studio, the analysis process itself can begin.

The software ran the model through multiple cycles to get the model to meet the parameters set. I set a maximum limit of 15 cycles for the software to run, however, the software only ended up completing 12 cycles. By the time cycle 3 had occurred, the constraints had been met. The following cycles had the variables be regularly altered to try and minimise the weight of the design.



DESIGN VARIABLE HISTORY					
DESIGN CYCLE	DESIGN VARIABLE 1	DESIGN VARIABLE 2	DESIGN VARIABLE 3	DESIGN VARIABLE 4	DESIGN VARIABLE 5
	hickness	hickness	hickness	hickness	hickness
0	5.0000E-04	5.0000E-04	5.0000E-04	5.0000E-04	5.0000E-04
1	4.4600E-04	9.4966E-04	1.0950E-03	9.4725E-04	4.1426E-04
2	5.1180E-04	1.4581E-03	2.0839E-03	1.4990E-03	4.7664E-04
3	4.2011E-04	1.5417E-03	2.4644E-03	1.6286E-03	4.2269E-04
4	3.5828E-04	1.5002E-03	2.5843E-03	1.6153E-03	3.5566E-04
5	3.1632E-04	1.4590E-03	2.7084E-03	1.5878E-03	3.0769E-04
6	3.2025E-04	1.4529E-03	2.7036E-03	1.5819E-03	3.1395E-04
7	3.0000E-04*	1.4189E-03	2.8095E-03	1.5268E-03	3.1835E-04
8	3.0653E-04	1.4129E-03	2.8022E-03	1.5210E-03	3.2278E-04
9	3.1952E-04	1.4094E-03	2.7856E-03	1.5226E-03	3.3650E-04
10	3.0600E-04	1.3904E-03	2.8191E-03	1.5290E-03	3.2073E-04
11	3.1861E-04	1.3879E-03	2.8001E-03	1.5307E-03	3.3416E-04
12	3.2736E-04	1.3918E-03	2.7637E-03	1.5518E-03	3.4239E-04

* = DESIGN VARIABLE AT UPPER OR LOWER BOUND

The design variable history shown above shows the thicknesses of each of the layers during each cycle of the optimisation process. This shows the steps the design studio took in order to reduce the weight of the wing whilst also maintaining the desired maximum deflection.

The table shows that during start of the optimisation, all the layers were identical at 0.5mm thick. However, by the time cycle 12 is conducted, the layers by the end have all changed quite drastically with the following results:

Layer 1: 0.327mm Layer 2: 1.391mm Layer 3: 2.763mm Layer 4: 1.552mm
 Layer 5: 0.342mm

Giving a total thickness of 6.375mm, around 2.5x thicker than the original design. However, it is interesting that the design has made the outer layer thinner whilst finding that the inner layers needed to become thicker in order to provide the strength the wing requires.

Optimisation for Manufacturing Capabilities

Design studio has been able to give results that give to the nearest 0.0001mm, however, in reality this would be quite difficult to produce physically. For manufacturing, the wing would need dimensions that go to the nearest 0.1mm.

In reality, the layers would be made to the following thicknesses:

Layer 1: 0.3mm (3 Ply) Layer 2: 1.4mm (14 Ply) Layer 3: 2.8mm(28 Ply)
 Layer 4: 1.6mm (16 Ply) Layer 5: 0.3mm (3Ply)

Total thickness of 6.4mm

Task 4: Prototype Testing

When prototyping the rear wing, it can become expensive and time consuming to produce multiple versions of the wings and then test them. Thanks to the model that is used in the optimisation tests, it is possible to produce scaled versions of the design using a few methods.

The rear wing can be 3D printed to a smaller scale version. With this, the prototype can be tested in a lab rather than on a racecourse. As discussed in the previous assignment (Knight, 2023) the F1 teams use a 60% scale model of the vehicle and conduct tests in a wind tunnel (MercedesAMGF1, 2021). The scaled down model would then need to have the velocity of the force increased proportionally to the size reduction to the full-scale model. This type of testing relies on the rest of the vehicle also being manufactured for the test.

If only the wing needs to be tested, the prototype can be produced on its own and be tested in a smaller wind tunnel. This would still require a fan of some sort that can produce the air flow required to recreate the forces that would act upon the wing. If this air velocity is not achievable, a full-scale wing could be produced if the rest of the vehicle is not required for the test. The wing can be installed onto a stand and fixed in place for the duration of the test.

To measure the deflection of the wing, the use of laser-based measuring equipment can be used to get deflection figures of high accuracy. Scanning technology can also be used to develop a model of the wing. Comparisons of the 'before' model and the 'after' model can be made to see if any deformation/damage has occurred.

Strain gauges can be located on key locations of the wing, the digital values can be fed into software so that the results of the prototype and the FEA analysis can be compared. If the values are comparable, this would validate the software model as reliable. However, if the results are starkly different, this could be a result of a factor missed in the prototype testing or it may indicate that the inputs in the model may require revision.

Task 5: Industry Standards

Standards

The field of Finite Element Analysis (FEA) adheres to several industry standards and guidelines to ensure the accuracy, consistency, and reliability of simulations. Some key standards and organizations related to FEA include:

International Organization for Standardization (**ISO**):

ISO 13773: Provides guidelines for calculating aerodynamic performances of road vehicles, including parameters that rear wings may impact.

ISO 11555: These standards specify methods for measuring the aerodynamics of ground vehicles. They can be relevant for evaluating the aerodynamic performance of a rear wing on a vehicle.

The Federation Internationale de l'Automobile (**FIA**):

The FIA has standards that cover all aspects of vehicles used in motorsports. This would stand to reason that they will have regulations on the specifications of the rear wing of a vehicle. The FIA has standards that detail the allowable types of materials that can be used as well as dimensional parameters such as wing size and where the wing can be positioned on the vehicle.

Industry-Specific Standards:

Various industries, such as aerospace, automotive, and civil engineering, have their own specific standards and guidelines for FEA, often tailored to the unique challenges and requirements of those sectors.

It's important to note that the specific standards and codes used in FEA can vary depending on the industry, application, and location.

HSE Legislation

HSE (Health, Safety, and Environment) legislation and regulations play a critical role in ensuring the safe and responsible use of Finite Element Analysis (FEA) technology, especially in industries where safety is paramount. While specific HSE regulations can vary by country and region, there are some common principles and considerations:

- 1. Occupational Health and Safety:** Employers are often required to ensure the health and safety of their employees when using FEA software, which may involve ergonomic considerations, training, and providing necessary safety equipment.
- 2. Environmental Regulations:** Some FEA simulations involve the study of environmental impacts. In such cases, regulations related to environmental protection and impact assessments may apply.
- 3. Materials and Chemical Safety:** When FEA involves the analysis of materials or chemicals, compliance with regulations governing their safe handling and disposal is essential.

4. **Export Control Regulations:** For companies that develop or use FEA software with potential military or dual-use applications, export control regulations can apply.

5. **Quality Management Systems:** Many industries, such as aerospace and automotive, require compliance with quality management standards (e.g., ISO 9001) to ensure the reliability of FEA results.

6. **Industry-Specific Regulations:** Various industries, including nuclear, pharmaceutical, and aviation, have specific regulations and standards that must be adhered to when using FEA for design and analysis.

7. **Certification and Licensing:** In some cases, professionals who use FEA technology may need specific certifications or licenses to ensure their competence and compliance with industry standards.

8. **Product Liability and Safety Standards:** For industries producing physical products, adhering to product liability laws and safety standards is crucial. FEA helps in ensuring products meet safety requirements.

It's important for organizations and professionals using FEA technology to stay informed about the specific HSE regulations and standards that apply to their industry and region. Compliance with these regulations not only ensures safety but also helps in preventing legal and ethical issues related to FEA simulations. Consulting with legal and HSE experts is advisable for comprehensive compliance.

Conclusion

Thanks to the FEA software, I have been able to analyse the existing wing model and improve upon it through its design and material choices. The software is very effective in helping with the design stages of any project and I can see the benefit it can have on cost and time factors. The final design has come out much lighter but will still maintain the strength required to perform its function. The wing will also be easily manufactured using 3D printing technology, providing a more complex shape that would normally be difficult to produce whilst also creating less waste material.

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