

ACMA6010 – Structural and Fluid Analysis – Designing a race car rear wing: Structural Design

Introduction

In this report I will discuss the Finite Element Analysis (FEA) modelling method, how it can be used to optimise components, and how this can be applied to realistic physical testing.

I will apply this to the design of a race car rear wing to optimise its weight for the required stiffness/deflection.

FEA Optimisation Techniques

Finite Element Analysis

Finite Element Analysis (FEA) is a mathematical method of modelling real world scenarios by dividing a 3D modelled component into a “mesh”. The mesh is made up of many vertices that can each be treated independently. Calculations are then done on each of the vertices of the mesh, which allows for a finite amount of calculation to be done making it possible to get a representation of physical effects of loads and boundary conditions on the model. Loads refers to forces applied to the model. Boundary conditions are how the part is held while the force is being applied.

The result from FEA is not a perfect representation of the physical phenomena as realistically forces are applied throughout the whole component and not just in the defined mesh. A real part also has geometric inaccuracies, defects, and material inconsistencies that will affect the result, which cannot be feasibly modelled due to their complexity and randomness. In order to get closer to a real scenario the mesh generated can be very detailed, referred to as a “fine” mesh. This means the vertices are very short, creating many more vertices across the part, giving more calculations and hence a more accurate model. However this comes at the cost; as more calculations are done this can take much longer to process, and may not even be possible without a more powerful computer to handle the processing.

Simulation Software

There are many different software packages available that use the FEA method to test a model. Some of these are built into CAD software, often referred to as add-ons, while others are dedicated packages. While the basic math behind each package is the same, the computational efficiency and the tools available in each package vary. For this reason the choice of package is largely preference based, but can also be driven by the requirement of the user.

Optimisation

As well as calculating the immediate effects of loads and boundary conditions, FEA software can also be used to optimise a model to achieve a desired output by altering other parameters of the part. For instance, FEA optimisation can be used to reduce the weight of a part by altering geometry while maintaining its strength, or it could be used to reduce deformation whilst maintaining weight. More complex applications of FEA optimisation can optimise whole part geometries based on internal stresses or other constraints.

Future Developments

FEA is used widely in design and engineering, and will continue this way for a long time as it's a fundamental tool for testing components without the need to fully manufacture or prototype them or do extensive manual calculations. However even with its current usage, FEA is constantly developing, and will continue to grow within future design and engineering applications.

Advances in Computational Power

FEA has developed massively over the years due to improvement in computational power. FEA models run a large number of calculations even on a simple component, and the number of calculations increases as the parts geometric complexity increases, as the mesh size decreases to make a more accurate model, or as a more complex optimisation is done. As such a powerful computer is needed to run more advanced models and optimisations.

As the processing power of computers has increased, as has the potential to run more complex simulations, which has allowed FEA to be used for a wider range of applications and in more industries reliably, rather than just for small scale research and development uses.

The applications for FEA will continue to increase as more powerful computers become common place in engineering and design companies, along with more software being developed for a wide range of uses.

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Supercomputers and Cloud Computing

In order to run large scale complex FEA studies, even powerful computers often aren't enough. For this reason supercomputers, a network of computers working together are used. This allows the simulation work to be broken down into chunks and shared between the various processors in order to dramatically reduce the time taken to run the simulation, and even then some simulations can take weeks to run.

Cloud computing is a new way to build supercomputers. A number of computers are linked across a network to run the simulation work. This allows a theoretically unlimited number of computers to be connected regardless of their location, and allows collaborative use of the supercomputer from any location. As data networks are getting more powerful and more reliable, this form of computing is beginning to become more widely used.

Machine Learning and Artificial Intelligence

Outside the normal use of FEA there are more complex technologies that are slowly being applied to FEA in research and development, including Machine Learning (ML) and Artificial Intelligence (AI). AI and ML can both be used to increase the accuracy and efficiency of FEA modelling. (Structural Numerical Research Centre, 2024)

One example of ML being used for FEA is Surrogate Modelling.

Surrogate Modelling

Surrogate Modelling is the process of training an ML system on an FEA model so it can predict the outcome using different constraints without the need to run a full FEA simulation. This can save a lot of time and resource as the prediction from the ML system does not require arduous calculations. This can be useful where a number of different scenarios must be tested, such as different loading conditions, or different allowable stresses in varying conditions.

It is possible to use AI to a similar effect, which may even allow for some standard systems to be predicted without the need to run FEA at all as long as enough prior data is available. AI systems are relatively new, so they are currently still in the domain of early development and experimental testing for the most part.

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Modelling

Using Genesis Design Studio, FEA modelling has been carried out on an imported Computer Aided Design (CAD) model of the race car rear wing. The steps taken to achieve this are shown below.

Material Properties

Carbon Fibre Reinforced Plastic (CFRP) has been chosen for its good strength to weight ratio and rigidity. The material properties of CFRP below are inputted into the program as shown (Figure 1).

Young's Modulus in the longitudinal direction (E ₁):	132 GPa
Young's Modulus in the lateral direction (E ₂):	10.8 GPa
Poissons Ratio (Nu ₁₂):	0.24
Inplane Shear Modulus (G ₁₂):	5.65 GPa
Transverse Shear Modulus (1-Z plane)(G _{1z}):	5.65 GPa
Transverse Shear Modulus (2-Z plane)(G _{2z}):	5.65 GPa
Mass Density (Rho):	1540 kg/m ³
Allowable longitudinal stress in tension (Xt):	1513 MPa
Allowable longitudinal stress in compression (Xc):	1000 MPa
Allowable transverse stress in tension (Yt):	43.4 MPa
Allowable transverse stress in compression (Yc):	43.4 MPa
Allowable inplane shear stress (S):	43.4 MPa

Once the material properties are known to the software, the lay-up of the material's ply's can be done. This is done by creating a material group and telling the software how each layer in the group is applied (Figure 2).

Edit a Material : 2-D Orthotropic Properties	
E ₁ :	1.32E+11
E ₂ :	1.08E+10
Nu ₁₂ :	0.24
G ₁₂ :	5.65E+9
G _{1z} :	5.65E+9
G _{2z} :	5.65E+9
Rho:	1540.0
A ₁ :	
A ₂ :	
Tref:	
GE:	
F12:	
☒ Stress Limits ☐ Strain Limits	
Xt:	1.513E+9
Xc:	1.E+9
Yt:	4.34E+7
Yc:	4.34E+7
S:	4.34E+7

Figure 1 – Material properties

Edit a Group : Choose Composite Property Values					
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					
	857142 Unidirectional ...	5.E-4	-90.0	Yes	+ -
Layer 2					
	857142 Unidirectional ...	5.E-4	-45.0	Yes	+ -
Layer 3					
	857142 Unidirectional ...	5.E-4	0.0	Yes	+ -
Layer 4					
	857142 Unidirectional ...	5.E-4	45.0	Yes	+ -
Layer 5					
	857142 Unidirectional ...	5.E-4	90.0	Yes	+ -

Figure 2 – Material lay-up

The number of ply's, and the material, thickness, and angle of the ply's are inputted. In this case, 5 ply's have been used, each with a thickness of 0.0005 m or 0.5mm, representing 5 of 0.1mm thickness ply's at each orientation. Each set of the 5 of 0.1mm thick ply's are laid up 45° from each other to increase the materials strength.

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Load Case

Once the material properties were set, the load case could be built. The full mesh of the rear wing model is shown below (Figure 3).

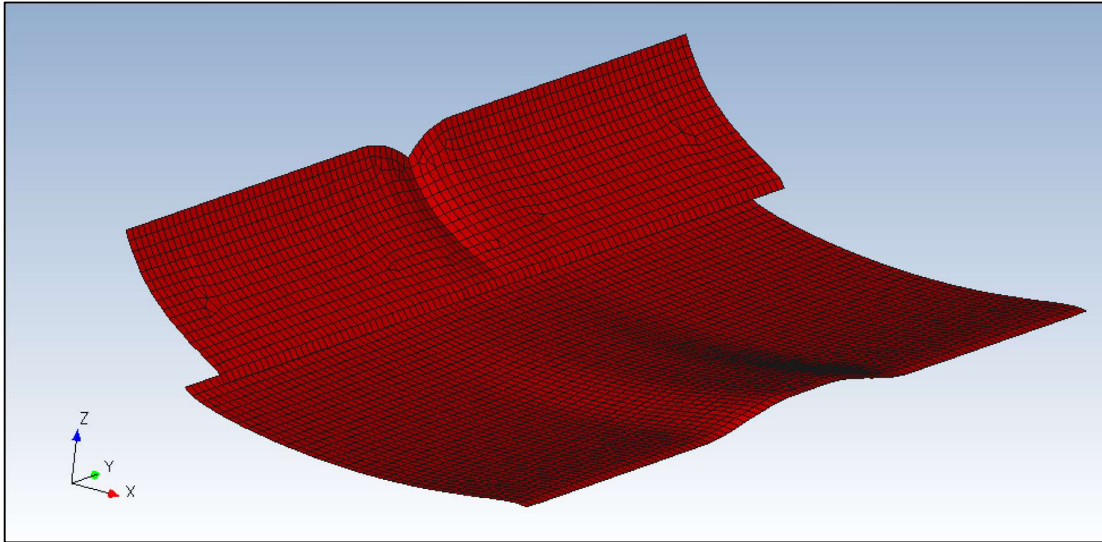


Figure 3 – Rear Wing Model

Firstly the sides of the mesh need to be treated as static, so the program is told they cannot move through a Load Case. A force is also added to the load case, applied towards the centre of the wing to replicate the standard F1 wing test method as follows (Figure 4):

“The skins of the rear wing elements may deflect no more than 2mm when a 60N force is applied to the skin normal to and away from the element. The force will be applied using a vacuum cup of 50mm diameter and the deflection will be measured at the outer diameter of the cup.” 2023 FORMULA 1 TECHNICAL REGULATIONS ISSUE 4, 07 DECEMBER 2022.

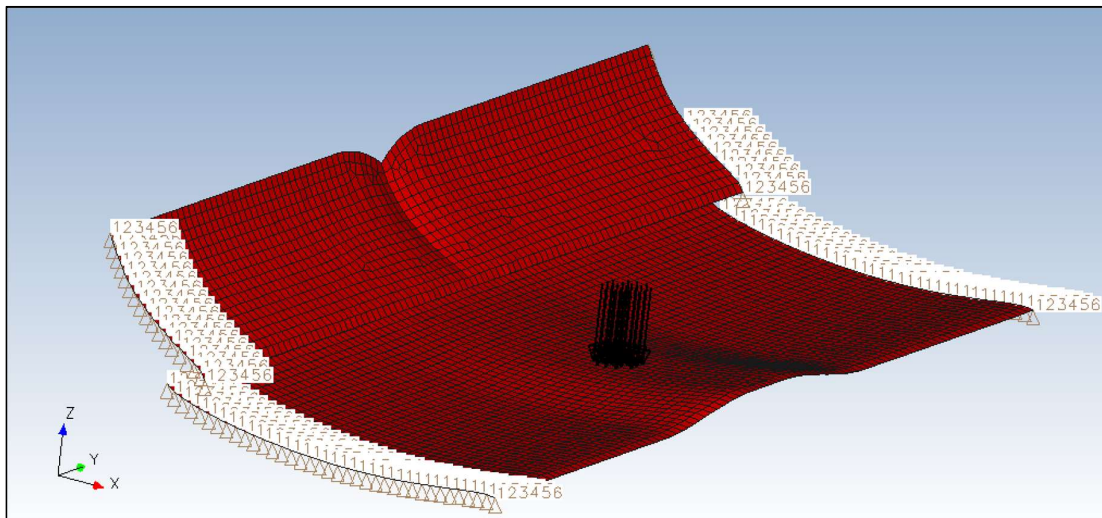


Figure 4 – Load case, static and vacuum cup.

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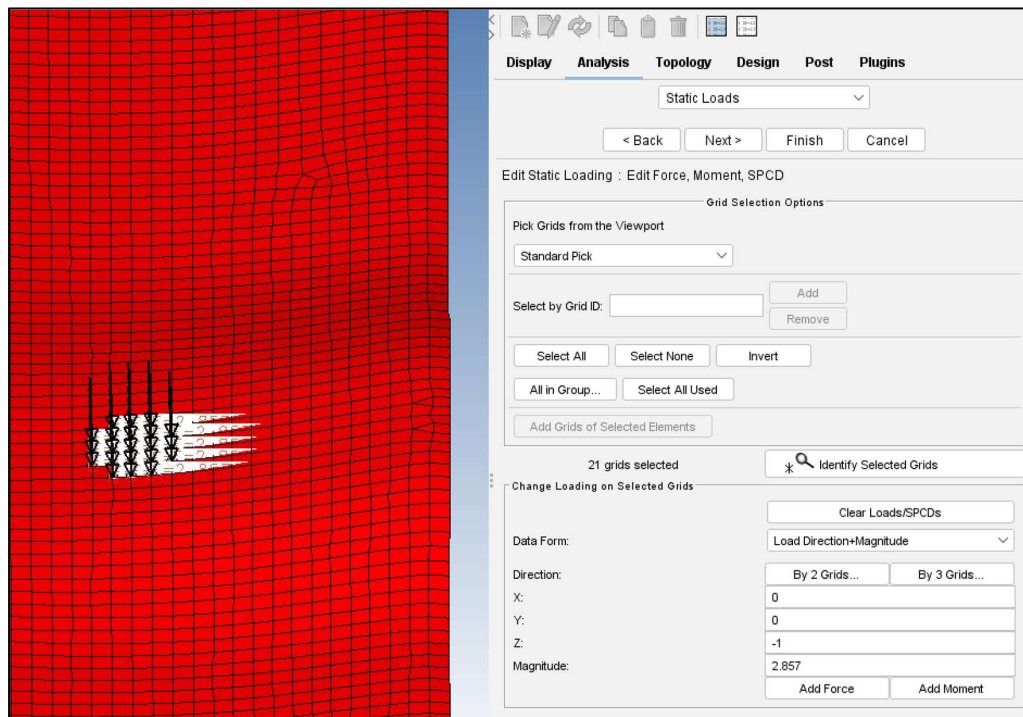


Figure 5 – Vacuum cup load.

The 60N force applied as per the F1 standard is divided by the number of nodes the force is applied to in the 50mm circle. With this mesh density, the number of nodes is 21, so the force is 2.857 per node as shown in Figure 5.

Once the load case is built, the mesh vectors are generated and set to align widthways along the component so all the calculations happen in the correct orientation (Figure 6).

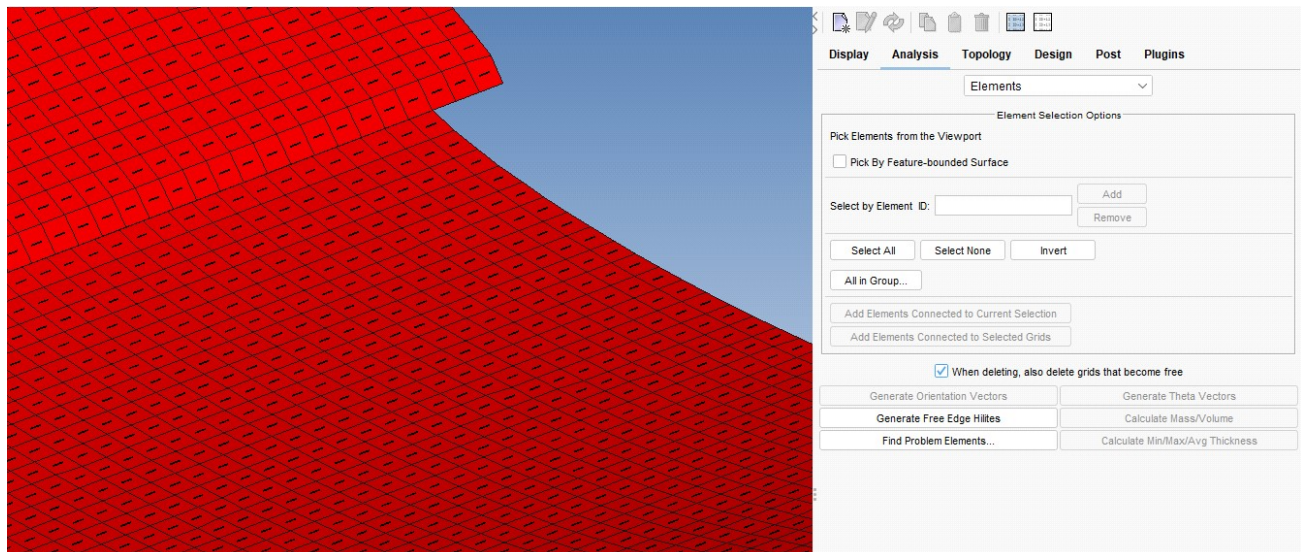


Figure 6 – Theta Vectors

The simulation of the force is now ready to run.

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Results

The results given from the simulation can be viewed as a colour map which exaggerates the deformation to clearly show where it is the worst. The maximum deflection shown below (Figure 7) is 0.000043m or 0.043mm. Given that the maximum allowable deflection is 2mm, this is well within tolerance. The mass of the wing as per the current design is 1.88kg.

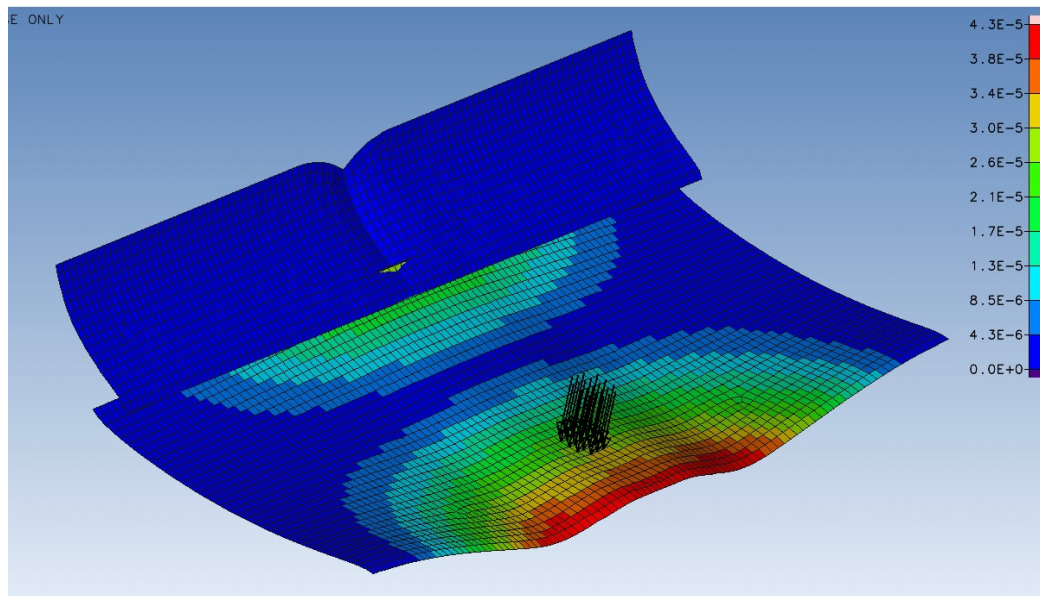


Figure 7 – Deflection from load.

Model Optimisation

FEA optimisation is a process of adapting the model to improve its desired characteristics through a series of iterative calculations that get progressively closer to a target outcome. It can be used to improve the model by first setting the following values:

- Objectives - targets that the model must achieve.
- Constraints, limits which it has to work within to achieve the objective.
- Variables, things it can change to achieve the objective.

These are set up in the design tab in Design Studio.

Objectives

The objective is the final target of the calculations. In this case, the program has been told to minimise the mass of the component (Figure 8).

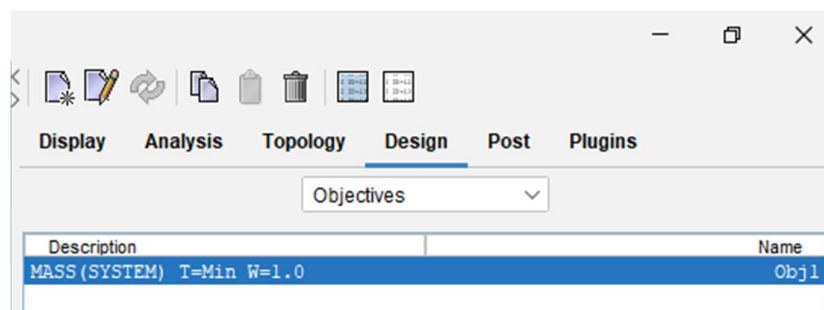


Figure 8 – Mass Objective

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Constraints

The constraints are what must be maintained whilst aiming for the objective. In this case, following the F1 standards mentioned earlier, the maximum displacement or deflection of the rear wing must not exceed 2mm, so a maximum displacement constraint of 2mm has been placed on the program (Figure 9).

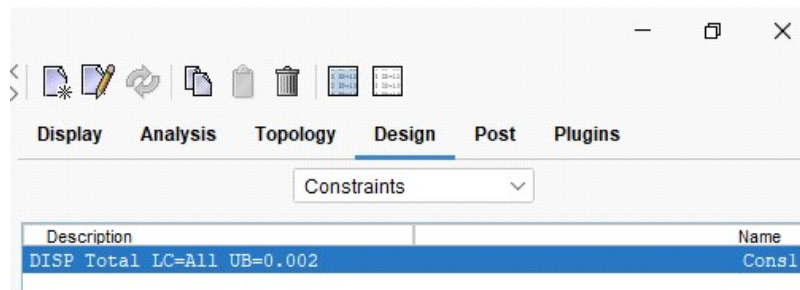


Figure 9 – Displacement Constraint

Variables

The variables are what must be changed to achieve the objective. In this case, the five variables are the layer thickness of each set of 5 ply's (Figure 10).

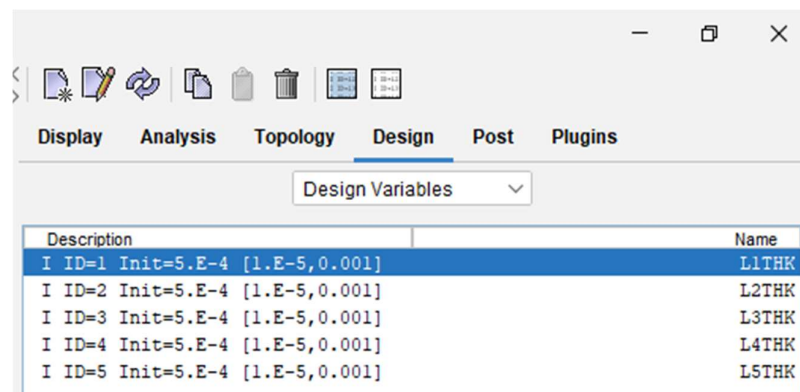


Figure 10 – Layer Thickness Variables

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Results

The optimisation ran 41 steps before achieving an outcome, however it achieved an ideal result with a maximum deflection of 2mm, and a mass of 0.05942kg or 59.42g (Figure 11). The data shows the iterations and how the Objective and Constraint Violation stabilise. The constraint violation is how far the current result is away from meeting the given constraint. The constraint here is the deflection of 2mm, so a constraint violation of 95% would be a deflection of 3.9.

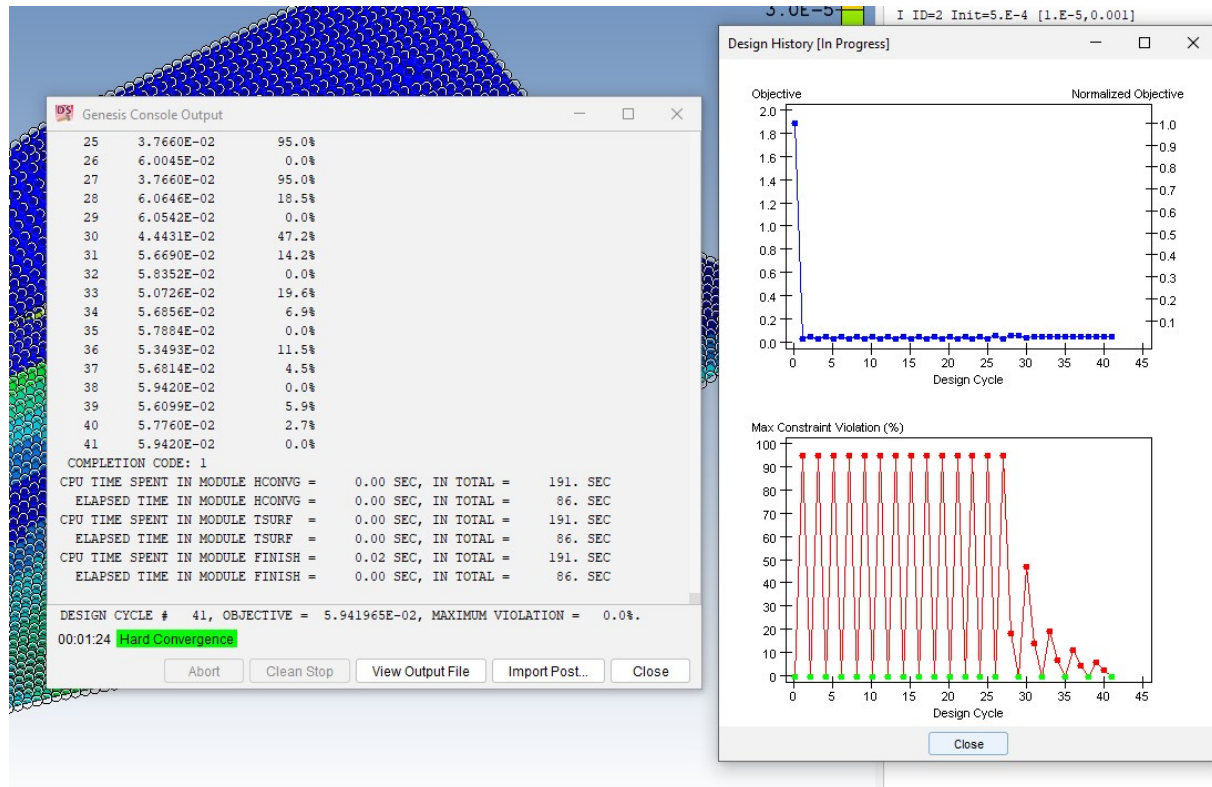


Figure 11 - Optimisation

The resulting layer thicknesses are as follows:

- Layer 1 – 1.14E-5 0.0000114m 0.0114mm
- Layer 2 – 1.7E-5 0.000017m 0.017mm
- Layer 3 – 2.18E-5 0.0000218m 0.0218mm
- Layer 4 – 1.73E-5 0.0000173m 0.0173mm
- Layer 5 – 1.14E-5 0.0000114m 0.0114mm

Summary of results:

	Initial	Final
Weight	1.88kg	59.42g
Total Thickness	2.5mm	0.0789mm
Maximum Deflection	0.043mm	2mm

Although the maximum deflection is 2mm, the F1 standard test actually records the deflection around the diameter of the vacuum cup. To determine this the colour map can be used to gauge the deflection range around that area.

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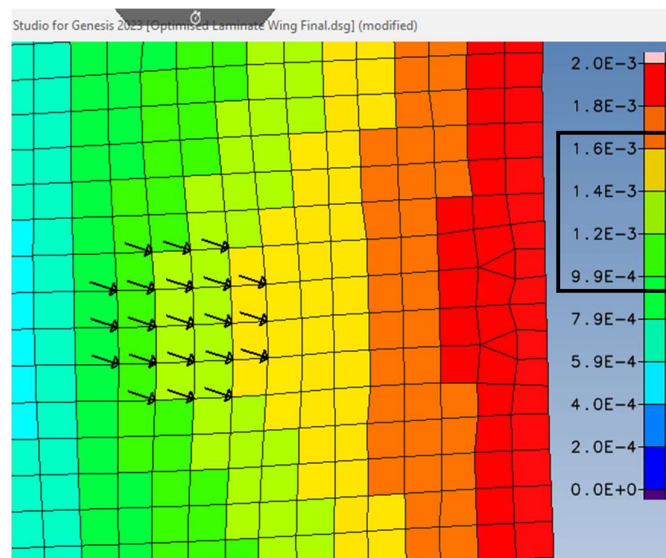


Figure 12 – Colour Map Showing Deflection Around the Vacuum Cup

From the colour map above (Figure 12), the deflection around the cup is actually 0.99mm - 1.6mm, showing that the wing is still within tolerance.

Result Realism

Although the results given are a theoretically perfect solution, the ply thicknesses provided are much less than a normal single ply, and are to a very high accuracy, however some CFRP materials can be much thinner, with thin CFRP being between 20-60 μ m (Joel Galos, 2020). The part would still not be realistic to manufacture, and a limit would need to be applied to the optimisation model to change the thickness in increments of 0.1mm for a standard single ply, or 0.02mm for thin ply's. This would mean the wing would inevitably be heavier.

Other design considerations would also be needed, such as what the realistic forces applied to the wing during a race would be, and how this would affect the part lay-up.

Laboratory Testing

FEA optimisation is often used as a baseline for physical modelling such as prototyping. The simulation results will never fully model the real world scenario, so the simulation results are not often used on their own. Physical testing is normally done to prove the simulation results, and often test other requirements of the component.

Prototype

Prototyping is the process of creating a one off part that is used for testing. Prototypes are often smaller than the final part as to reduce material and manufacturing costs, as well as to make testing easier, the results are then scaled up to suit the final part. Scaling errors can occur using small scale prototypes, so a full scale prototype or pre-production part is often made once the prototype is proven and tested.

In the case of the race car rear wing, it would normally be prototyped at full scale as the forces on the wing, and the rest of the car, during testing are complex and don't scale easily.

Testing and Correlation to Simulation

The primary form of testing done on the race car is wind tunnel testing. During this test the car is exposed to high velocity airflow and the deflection, downforce, and aerodynamics are monitored. A number of standard regulation tests are also done on the prototype such as the vacuum cut test for the rear wing deflection.

Data Acquisition

Load cells are used under the car to measure downforce while image analysis is done to measure deflection during testing. Any devices fitted to the car to measure deflection could alter the aerodynamics and hence impede the test, so they aren't used.

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Conclusion

The FEA optimisation used in the simulation was not realistic due to the thin layers it suggested, however it did show that a very lightweight component could be used and still conform to the regulation standards. Further simulation would be needed to suggest a realistic layer thickness, however using thin ply's, the result was not far off a realistic design.

Once a realistic simulation was done, prototyping of the rear wing could be done either with a small scale prototype or a full scale prototype.

References

2023 FORMULA 1 TECHNICAL REGULATIONS ISSUE 4. (07 DECEMBER 2022). 3.15.3 *Rear Wing Skins*.

Structural Numerical Research Centre. (2024). Future of Finite Element Analysis. Available at: <https://numericalarchive.com/2023/03/30/future-of-finite-element-analysis/>. Accessed 23/03/2024.

Joel Galos. (2020). *Thin-ply composite laminates: a review*.