

Structural & Fluid Analysis
Designing a race car rear wing: Structural Design

Coursework 2 of 2

Resit



Academic Coursework submitted in partial fulfilment of the requirement of

University of Wales Trinity Saint David for the award of the

BACHELOR OF ENGINEERING

in

MECHANICAL & MANUFACTURING ENGINEERING

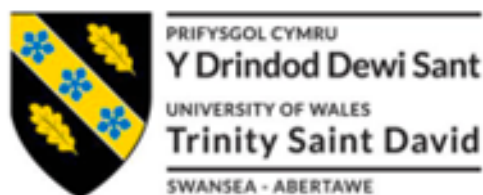
Submitted by

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Task Description – Coursework Brief

In class we have been discussing optimisation techniques that can be used within FEA. This assignment consolidates and builds upon this. Figure 1 shows the rear wing used in assignment 1. In this exercise you will optimise the composite construction of the wing to ensure that it does not flex excessively so that it is not considered to be a moveable structure. You must reference any sources you use, including AI (eg. ChatGPT).

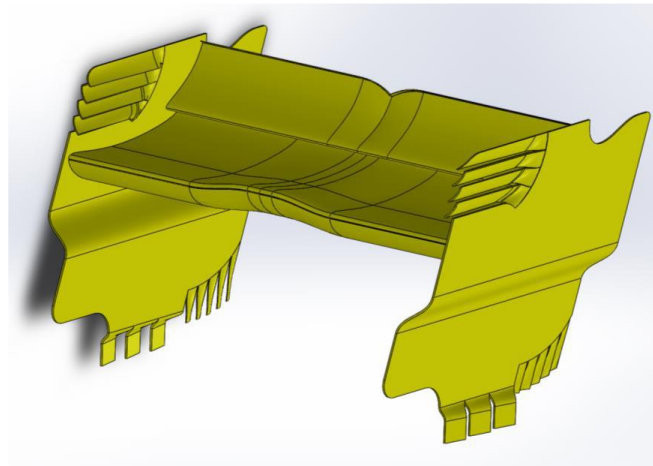


Figure 1: The rear wing

Figure 2 shows an FE model of the simplification of the wing. It is proposed that the wing is to be made from a unidirectional (UD) carbon fibre reinforced plastic (CFRP). The ends of the wing connect to the side supports such that these can be assumed to be fixed in 6 degrees of freedom.

Your task is to design the lay-up of the composite material such that when the forces seen on the wing as considered in assignment 1 are applied, the wing is still considered to be 'fixed' (i.e. the deformation is not large enough so that the wing is a movable structure). This wing needs use as little material as possible to reduce the weight of the wing.

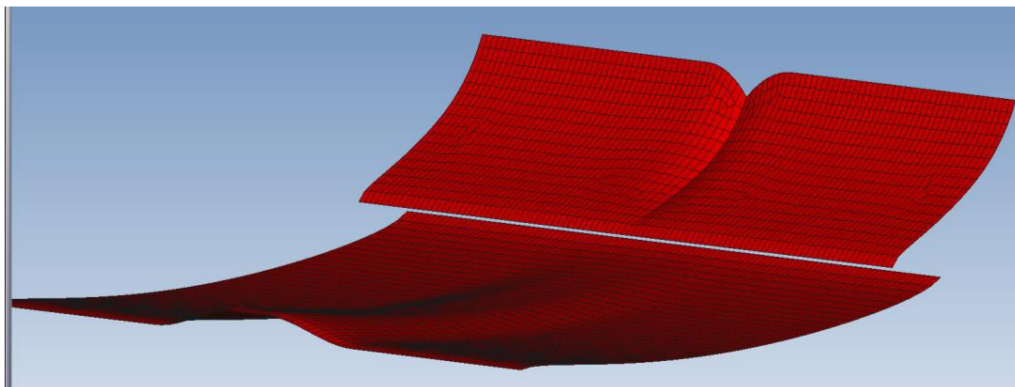


Figure 2: An FE model of the simplification of wing.

The unidirectional CFRP has the following material properties, and each ply is 0.1mm thick. Assume that zero degrees runs 'fore to aft' along the length of the vehicle.

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 (ν_{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 (ρ):	1540 kg/m ³
Allowable longitudinal stress in tension (X_t):	1513 MPa
Allowable longitudinal stress in compression (X_c):	1000 MPa
Allowable transverse stress in tension (Y_t):	43.4 MPa
Allowable transverse stress in compression (Y_c):	43.4 MPa
Allowable inplane shear stress (S):	43.4 MPa

Given the geometry of the assembly, and a NASTRAN deck of the simplified wing (with steel material properties) generated in Solidworks, you are required to carry out the following tasks;

1. Discuss FEA optimisation techniques and by referencing appropriate sources, show how they have developed historically and discuss how you think they may develop in the future. Discuss how they improve the design process.
2. Create a model of the wing with the correct material properties in Design Studio. Lay this up with 25 plies of the UD. 5 at -90 degrees, 5 plies at -45 degrees, 5 plies at 0 degrees, 5 plies at 45 degrees and 5 plies at 90 degrees.
3. Optimise the structure to minimise the mass of the wing whilst meeting the displacement constraint. Your variables are the number of plies at each orientation. These plies can be placed at -90 degrees, -45 degrees, zero degrees, 45 degrees and 90 degrees.
4. During the development of this component, it is proposed that a prototype is produced and tested in a laboratory to understand the deformation of the wing when subjected to the forces seen and to correlate it to the simulation carried out in task 3. Discuss how you think this experiment should be carried out and how the acquisition of data should be obtained and compared to the simulation.
5. Relate your design to any technical literature and standards that cover this component.

You are required submit a report equivalent to 3000 words which discusses the above tasks.

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Section 1

Discuss FEA optimisation techniques and by referencing appropriate sources, show how they have developed historically and discuss how you think they may develop in the future. Discuss how they improve the design process.

What is FEA optimisation:

The Finite Element Analysis (FEA) is the simulation of any given physical phenomenon using the numerical technique called the Finite Element Method (FEM). Engineers use FEA software to reduce the number of physical prototypes and experiments and optimize components in their design phase to develop better products faster while saving on expenses. (simscale, 2024)



Figure 3 – shows an FEA software ANSYS (ANSYSimg, 2024)

FEA optimisation techniques:

Finite element optimization can be classified into methods based on optimizing grid locations (shape optimization), geometric properties (sizing optimization), or material properties (material optimization). Below they are discussed:

Topology Optimization:

In the realm of material optimization, topology optimization is a specialized method dealing with element material fractions between 0 and 1. Applied at the conceptual level of design development, it aims to distribute material more effectively across a model, minimizing strain energy. This mathematical approach considers designer-set boundaries, applied loads, and space limitations to craft a design. The results obtained are often fine-tuned for manufacturability, prioritizing efficiency over aesthetics in material distribution. The primary advantage lies in its capability to reduce unnecessary weight, translating into substantial cost savings in competitive markets.



Figure 4 - shows a motorbike that as been topology optimised to have as little material as needed. (motorbikeIMG, 2024)

Shape Optimization:

Shape optimization focuses on selecting optimal structural geometry to enhance desired mechanical behaviour while respecting specific constraints. Automated design optimization tools aid engineers in exploring creative solutions, especially in problems involving potentially hundreds of design variables. These tools estimate the effects of modifying numerous design parameters, encompassing not only straightforward dimensional changes but also general alterations in shape. Shape optimization involves both linear and nonlinear finite element analysis, offering versatile solutions for intricate design challenges.

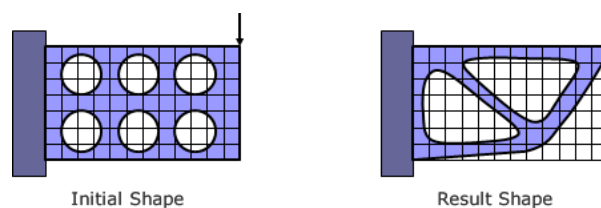


Figure 5 – above image shows shape optimisation. (quint, 2024)

Sizing Optimization:

Throughout the design phases, panels, beams, and joints can undergo sizing optimization, addressing cross-sections and thickness properties of finite elements. This optimization method effectively reduces the weight of various materials and panel concepts, yielding consistent and manufacturable designs. The ease of calculating sensitivities for sizing optimization purposes makes it applicable even in handling the most complex problems. This approach ensures efficient use of materials and resources, contributing to cost-effective and high-performance outcomes in diverse engineering scenarios. (rishabheng, 2024)

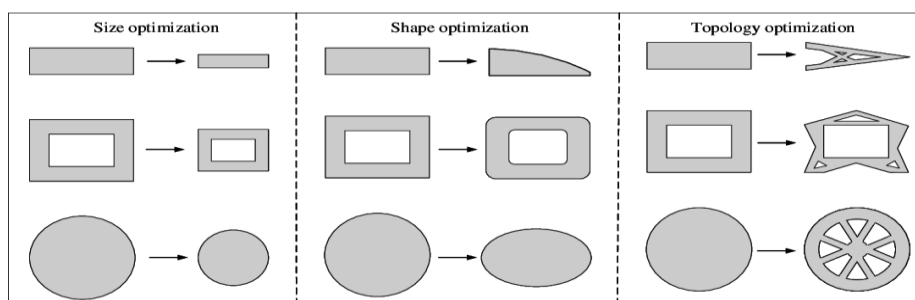


Figure 6 – shows the difference between the 3 optimisations. (Yingjun Wang, 2018)

How have FEA optimisation techniques developed historically:

FEA was developed in the 1950 in the Aerospace Industry by Boeing and Bell Aerospace in the US and Rolls Royce in the UK. One of the first papers to lay out the method was published by M.J. Turner, R.W. Clough, H.C. Martin and L.J. Top in 1956. One of the authors of this first paper was Ray Clough who was a Professor at Berkeley. He was working at Boeing as a summer job, and he wrote a second paper that first used the term “finite elements”. Berkeley quickly became a centre of FEA research and a lot of the early development in FEA took place at Berkeley.

A professor at Berkeley, E. Wilson, developed one of the first FEA programs and it became very popular in the 1960's since it was a freeware program. This software was used by numerous universities and continued to be developed for several years.

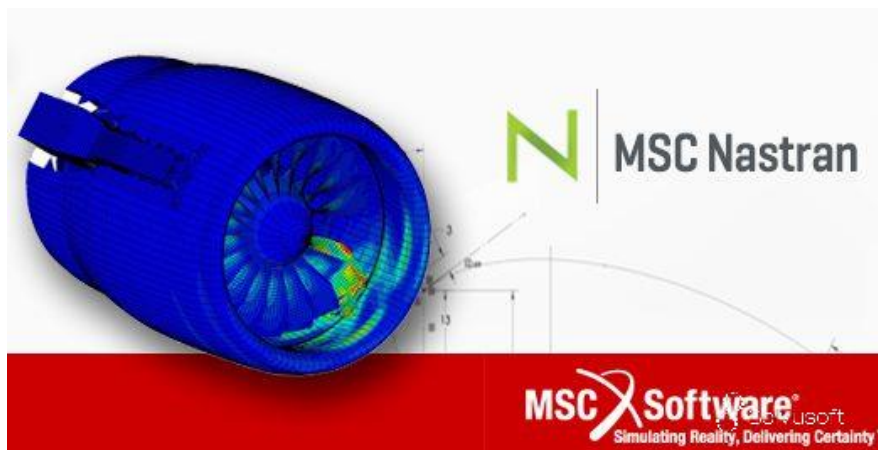


Figure 7 – above image shows NASTRAN (solvusoft, 2024)

In 1965, NASA funded a project lead by Dick MacNeal to develop a more capable FEA software program and this became the program NASTRAN. This program cost \$3,000,000 to develop which is close to \$30,000,000 in today's dollars. This program initially launched as freeware but was soon commercialized and released as a for profit company, MacNeal-Schwendler.

Also, in the 1960's, Westinghouse Electric Corp engineer John Swanson was developing another FEA software for nuclear reactor analysis that became known as ANSYS. In 1969, Swanson left Westinghouse and founded a commercial ANSYS company. (nlsde, 2024)

How may FEA optimisation techniques develop in the future:

Artificial Intelligence (AI) and Machine Learning (ML) have already transformed several industries, and engineering is no exception. In FEA, AI and ML can help improve the accuracy and efficiency of simulations. For instance, AI algorithms can learn from previous simulation data and predict the behaviour of a structure or mechanical system under different conditions. This can significantly reduce the time and cost required for simulations. Furthermore, AI and ML can help optimize the design of products by identifying the best design parameters for a given set of constraints.

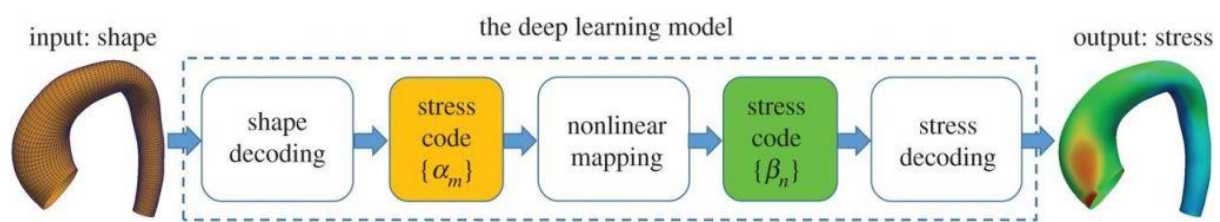


Figure 8 – the above image shows the deep learning model of ai in FEA. (aiFEAimg, 2024)

One specific area of AI and ML that is already being applied to FEA is called surrogate modelling. Surrogate models are machine learning algorithms that can accurately predict the behaviour of a structure or mechanical system without requiring a full FEA simulation. These models can be trained on a dataset of previous simulations to make predictions quickly and efficiently. Surrogate models are particularly useful for optimization problems, where the goal is to find the best design parameters for a given set of constraints. (numericalarchive, 2024)

Section 2

Create a model of the wing with the correct material properties in Design Studio. Lay this up with 25 plies of the UD. 5 at -90 degrees, 5 plies at -45 degrees, 5 plies at 0 degrees, 5 plies at 45 degrees and 5 plies at 90 degrees.

A model of a rear wing has been created and then imported into Design Studio Genesis software.

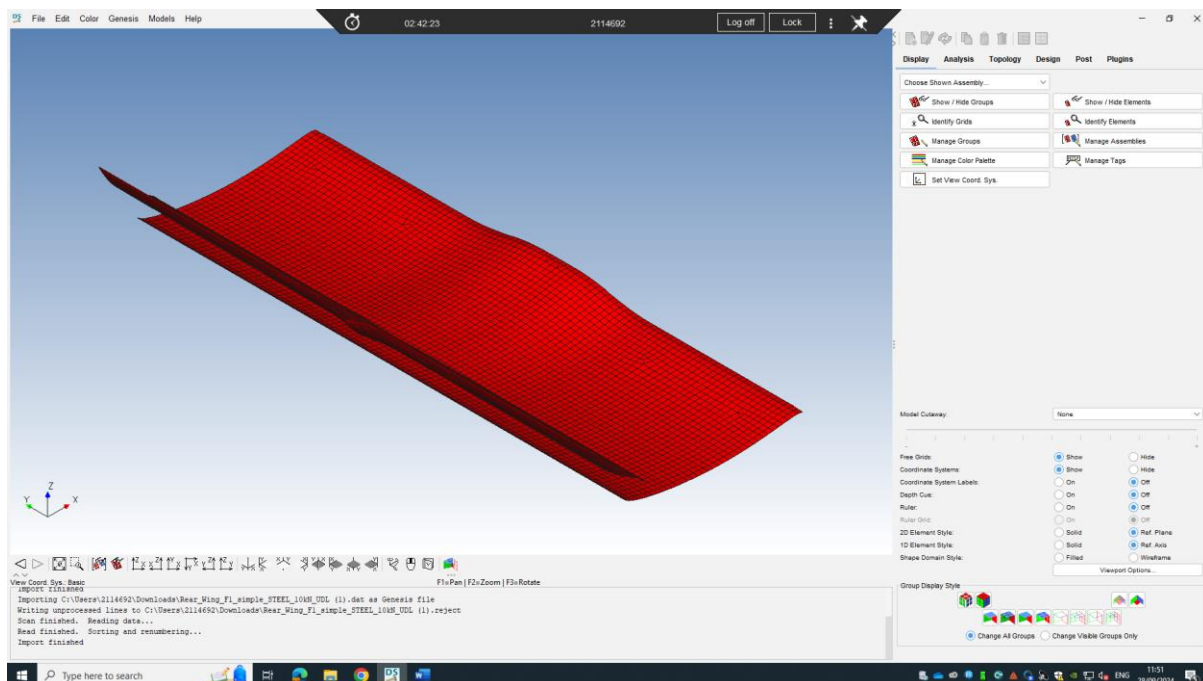


Figure 9 – shows rear wing as it is initially imported.

The model of the rear wing is initially setup as an isotropic steel material, but it is desired to be a much lighter orthotropic material of carbon fibre reinforced plastic (CFRP) as this is what modern race cars use. Isotropic materials are those that exhibit the same mechanical properties in all directions. Orthotropic materials, on the other hand, exhibit different mechanical properties in three mutually perpendicular directions. (thisvsthat, 2024)

For the initial material we can see its mass by an analysis.

Volume Sum = 0.000978150, Min = 8.17250e-08, Max = 2.99597e-07, Avg = 1.94851e-07

Mass Sum = 7.53176, Min = 0.000629282, Max = 0.00230690, Avg = 0.00150035

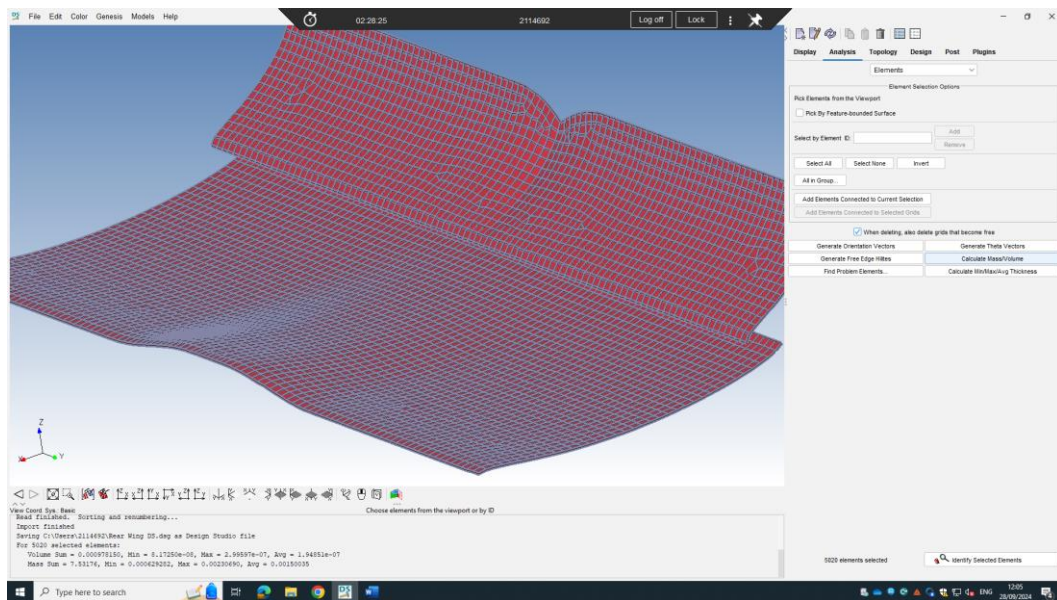


Figure 10

Then we must make a new material that is orthotropic and name it CFRP. Insert the material properties as shown below.

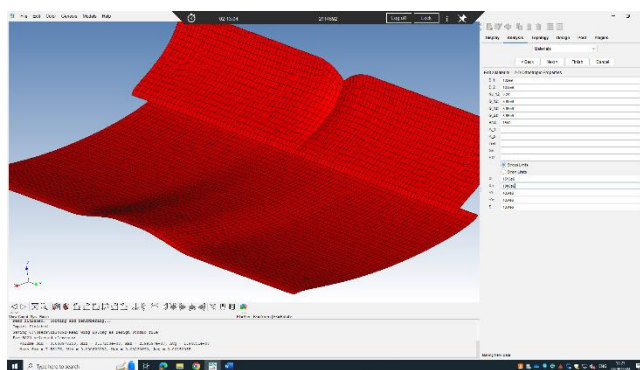


Figure 12

Materials

< Back Next > Finish Cancel

Edit a Material : 2-D Orthotropic Properties

E_1:	132e9
E_2:	10.8e9
Nu_12:	0.24
G_12:	5.65e9
G_1z:	5.65e9
G_2z:	5.65e9
Rho:	1540
A_1:	
A_2:	
Tref:	
GE:	
F12:	

☒ Stress Limits ☐ Strain Limits

Xt:	1513e6
Xc:	1000e6
Yt:	43.4e6
Yc:	43.4e6
S:	43.4e6

Figure 11

Then we want to ensure that the fibres are unilateral. So, we change the theta vector.

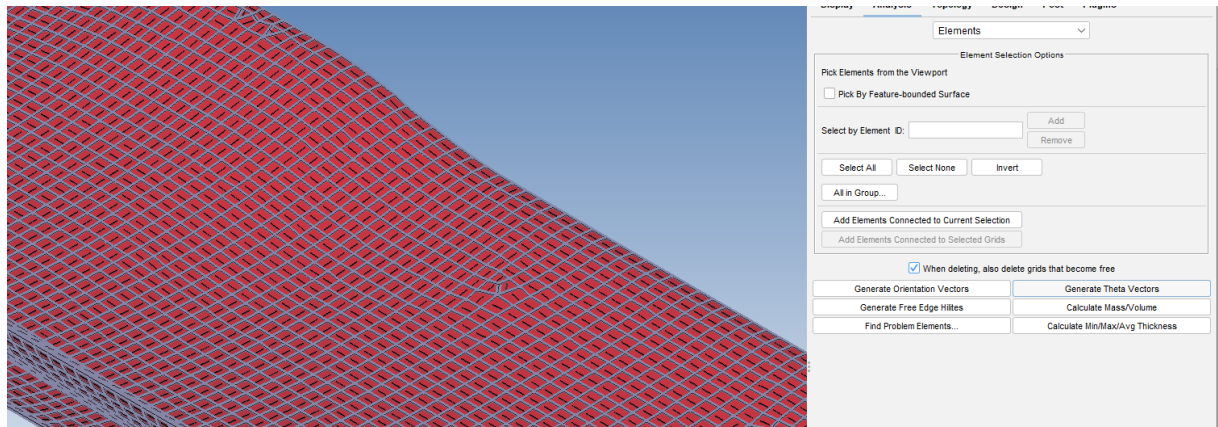


Figure 13 – Can see that fibres do not all run in the same direction.

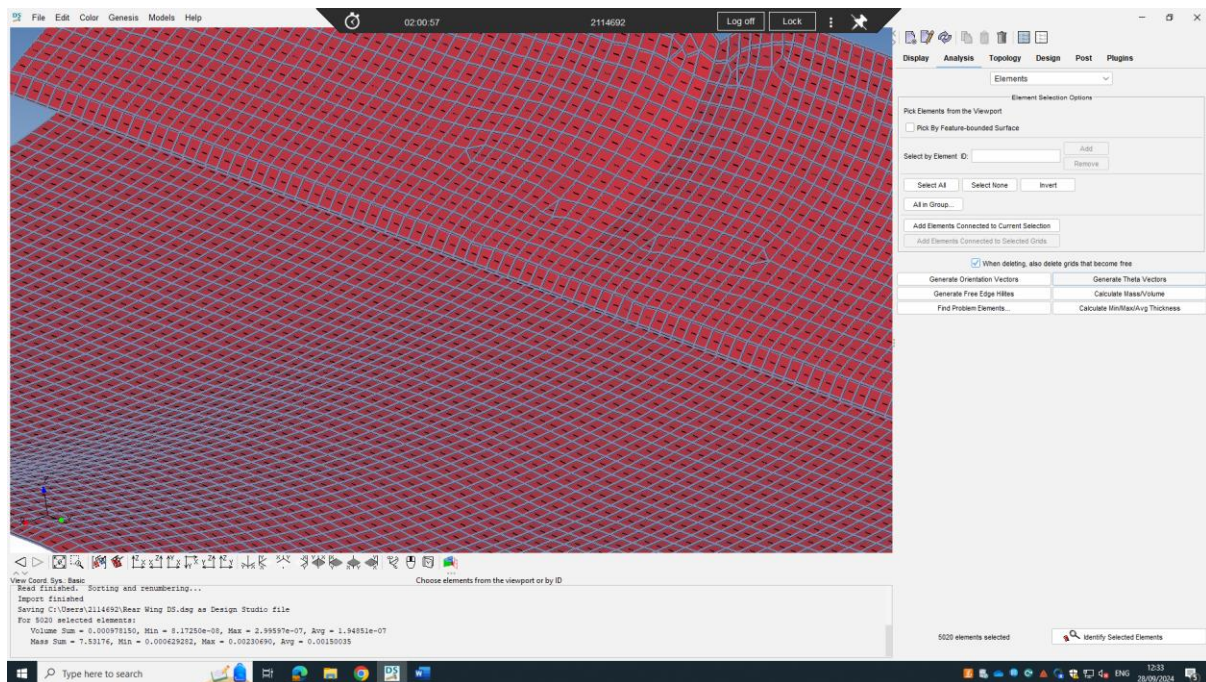


Figure 14 – can see that the fibres are all the same direction.

Having the fibres run in all the same direction means that E1 has a higher stiffness, and E2 has a lower stiffness as it is now mainly driven by the epoxy in the structure rather than the fibrous material.

As carbon fibre is a fibrous material that is made up of many plies that make many layers we must input this within group properties. We must insert the number of layers and each layer thickness. We have been told that there are 5 layers. Due to each layer having 5 plies at 0.1mm thick, each layer is 0.5mm thick. Thus, the total thickness is 2.5mm.

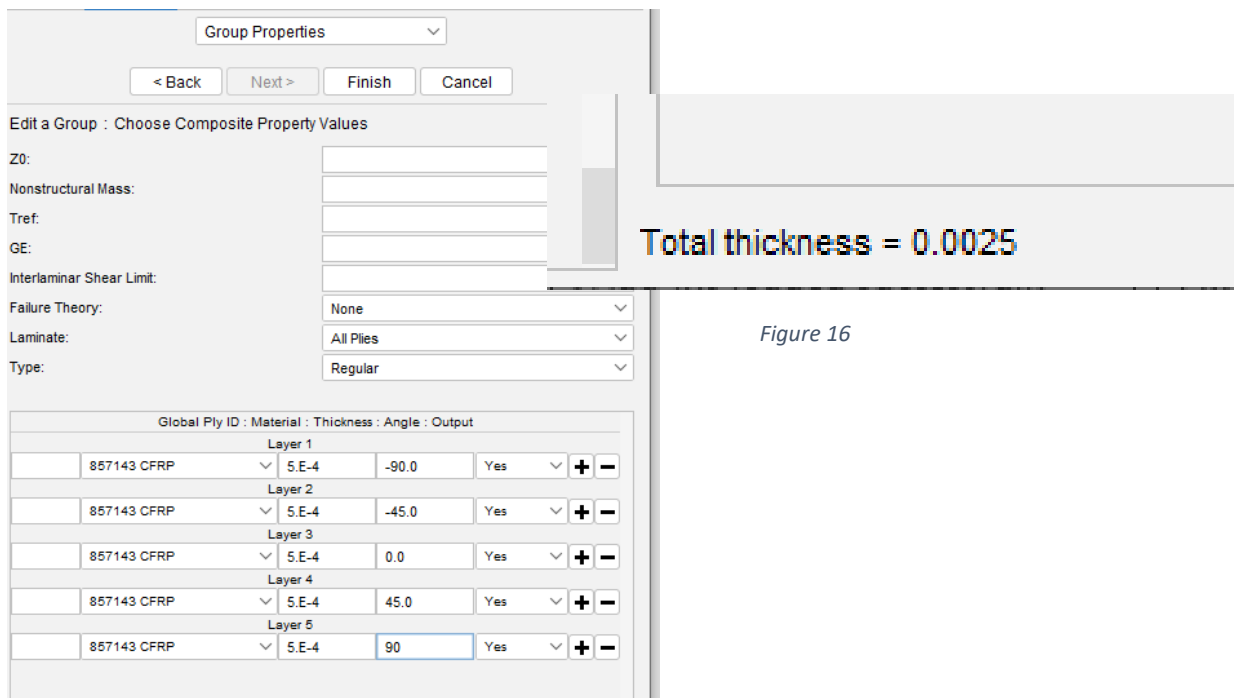


Figure 16

Figure 15

Final step is to change the element group to the PCOMP material in every cell.

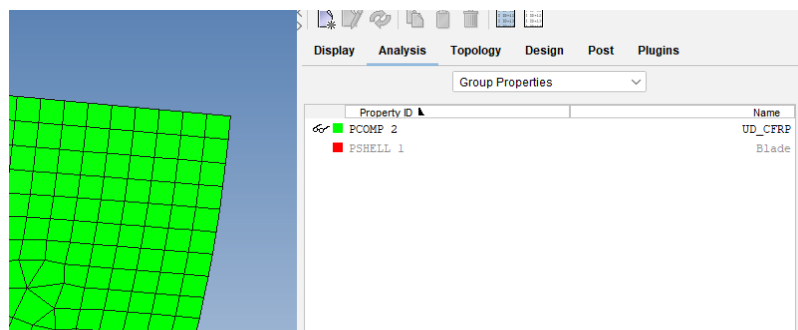


Figure 17

Section 3

Optimise the structure to minimise the mass of the wing whilst meeting the displacement constraint. Your variables are the number of plies at each orientation. These plies can be placed at -90 degrees, -45 degrees, zero degrees, 45 degrees and 90 degrees.

Research into load and deflection constraint

The regulatory test figures for a rear wing are to load the wing with a 200N force and inspect that the wing does not deflect more than 2mm.

'The second test demands that the rear wing can deflect no more than 2mm vertically when a 200N load is applied vertically.' - (Noble, 2020)

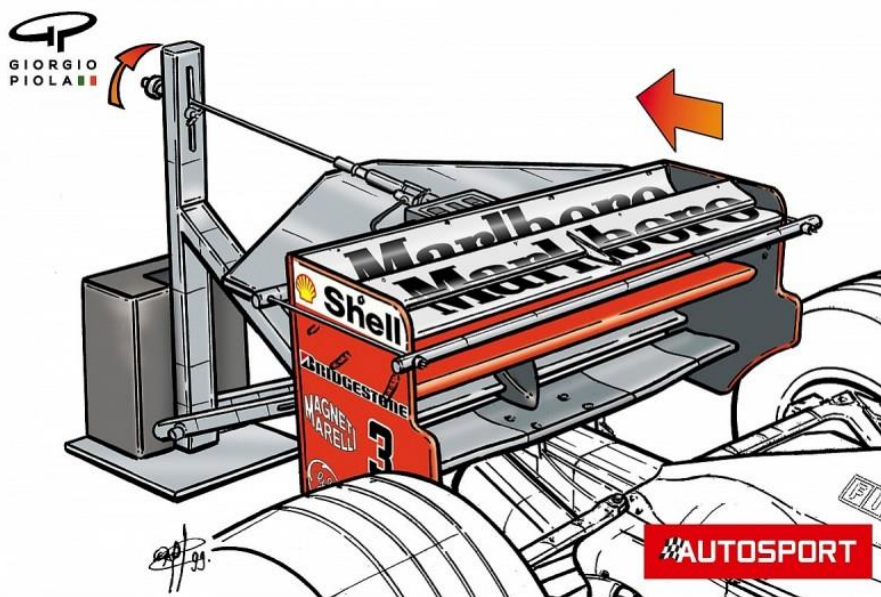


Figure 18 – shows how the wing may tested in a horizontal position as well as vertical.

Design Control Variable - Adding Force for testing

Magnitude

The user must convert the UDL force required into a magnitude for each grid present in the structure.

The magnitude of force refers to the quantitative measure of the strength or intensity of a force acting on an object. It specifically indicates the amount of push or pull exerted and is represented by a numerical value. The unit of measurement for force is the Newton (N), and the magnitude of force is crucial in understanding the impact and influence a force has on the motion or equilibrium of an object. (PHYSICSCALC, 2024)

$$\text{Magnitude} = \text{force (N)} / \text{No. of Grids} = 200 / 5263 = 0.03800114$$

The below figure shows the user inputting the magnitude at a Z-1 direction so that the 200N of force is equally pressing down on the entire structure.

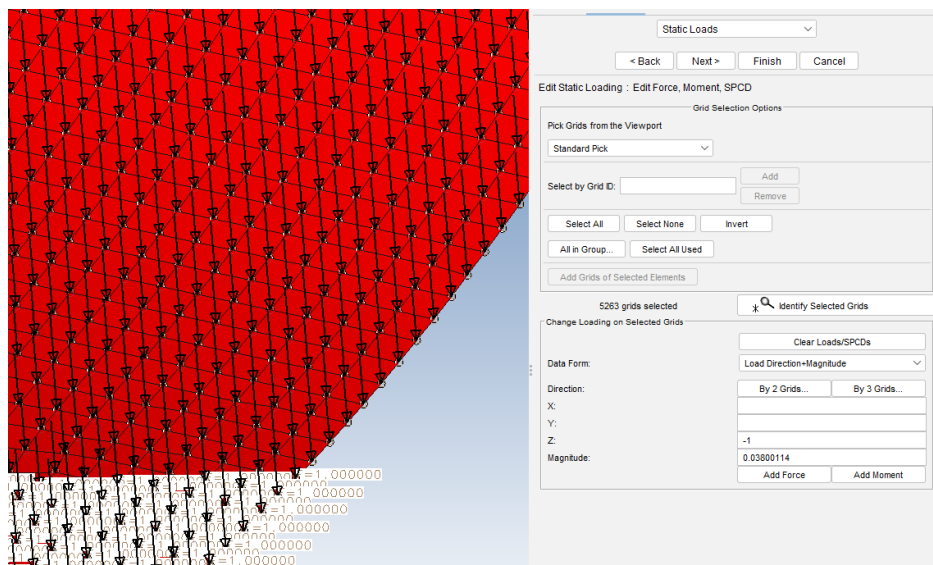


Figure 19

The user can also see that there is only a single loadcase acting vertically. This verifies the static load has been set correctly..

Design constraint – Displacement

Inputting constraint

Here a design constraint has been inputted for a maximum (upper bound) displacement of 1.9mm. From research, the regulations will allow 2mm of deflection. So it makes sense to set the limit on the safe side of the regulation, as real world material properties may not be as accurate as the computer generated ones on GENESIS.

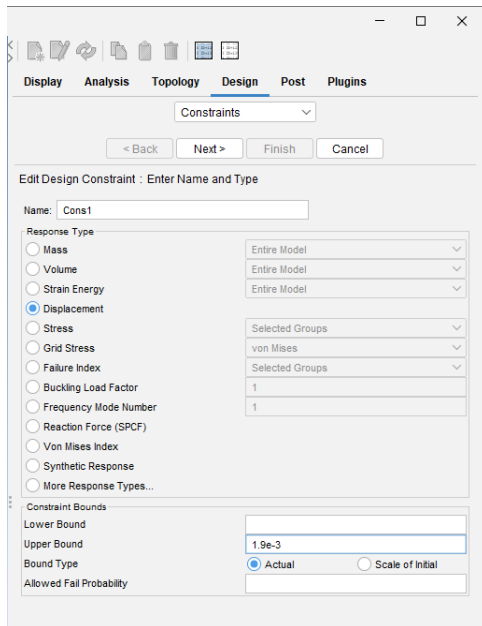


Figure 21

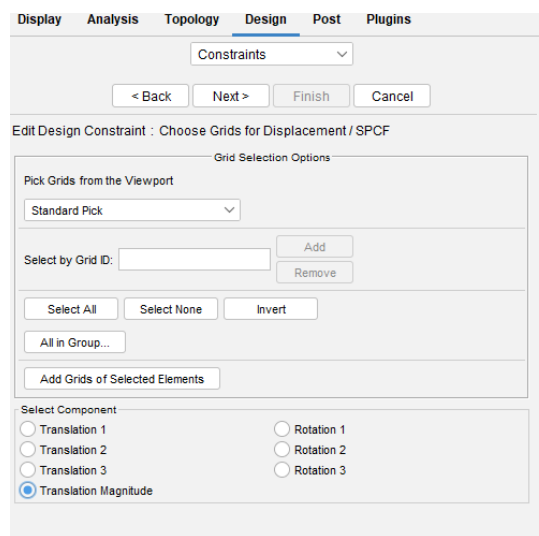


Figure 20

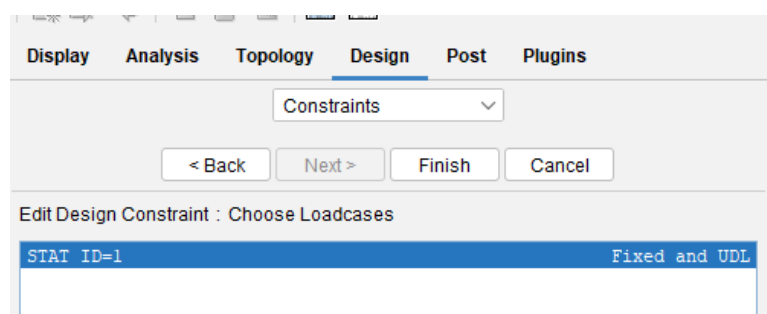


Figure 22

Description	Name
DISP Total LC=All UB=0.0019	Cons1

Figure 23

Design Objective – Minimising the mass

One of the biggest factors in automotive design is mass, and the desire to reduce the weight the total structure has. Thus, increasing its power to weight ratio, making the vehicle faster. So now the user has ensured the rear wing passes regulatory testing of load displacement, the user can optimise the design to pass but with as little wasted mass as possible.

The screenshot shows the 'Edit Design Objective' dialog box with the following settings:

- Tab: Design
- Objectives: Objectives
- Name: Obj1
- Response Type: Mass (selected)
- Objective Definition Switch: Min (selected)
- Weight: 1.0
- MinMax Param: (empty)

Figure 24 – shows the user setting the software to look for the minimum mass possible.

Baseline Materials

As seen in Appendix.1, the model has been stimulated for a baseline of steel, and an initial CFRP before any constraints were set. Below you can see the outcome of such stimulations.

Run	Material	type	Ply	Layers	Thickness (mm)	Deflection (mm)	Mass (g)	Mass (kg)	Load (N)	Stiffness (N/mm)	Stiffness/Weight (N ² /mm)	
Steel Baseline	Steel	isotropic			2	9	7532	7.53	200	22.22222222	0.297823318	Very similar results
Composite Baseline	CFRP	Orthotropic	0.001 x 5 = 0.005	5	2.5	37	1883	1.88	200	5.405405405	0.293339406	

Figure 25

From the above table we can see that the two materials have very similar stiffness to weight ratios despite differences thickness, deflection, and mass. From initially looking at the table we can see that there is a significant deflection of 37mm when subject to 200N UDL, at 2.5mm thickness. This tells us that for the wing deflection to come down the thickness and mass are likely to increase.

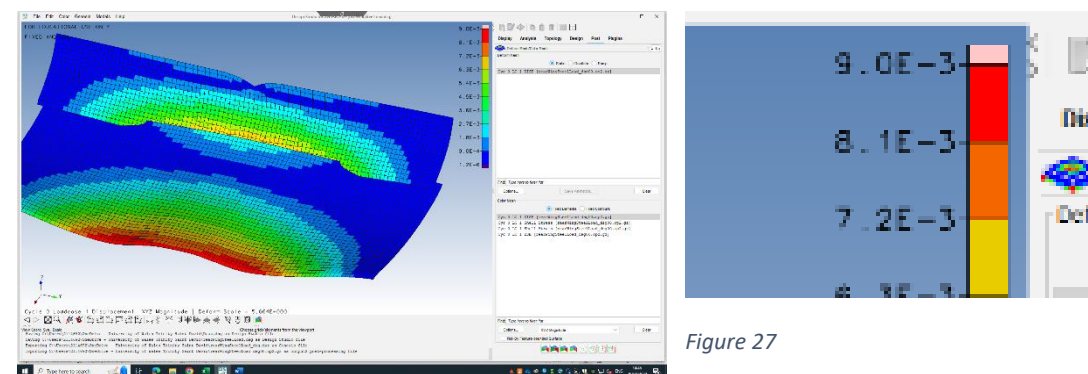


Figure 26

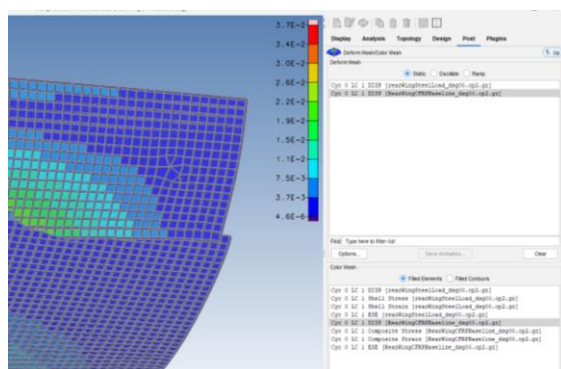


Figure 28

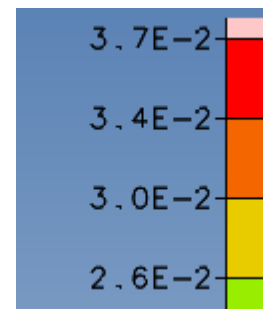


Figure 29

The above figures show deform mesh/colourmesh analysis on each material with a 200N UDL load.

Optimisation

Once the variable has been set up the user runs Genesis optimisation. Here the programme changes the mass/thickness of the structure each cycle to find 0.0% violation with the rules set up and at a minimum mass.

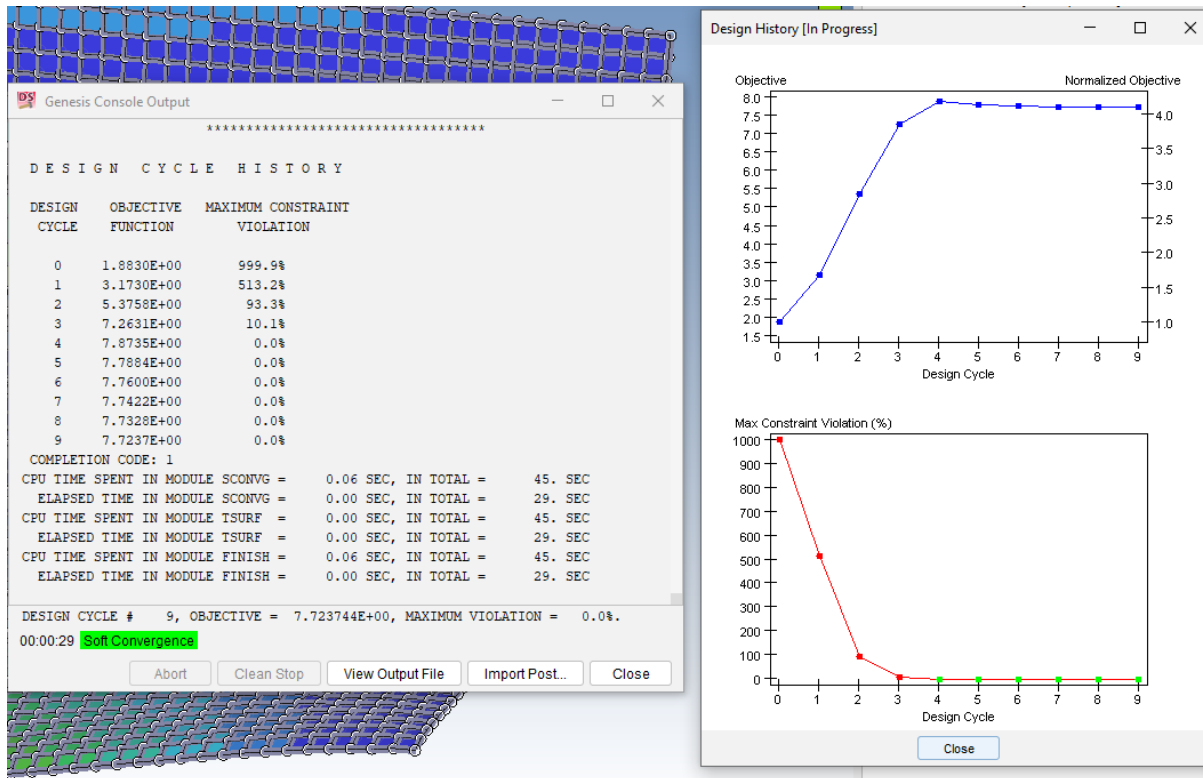


Figure 30

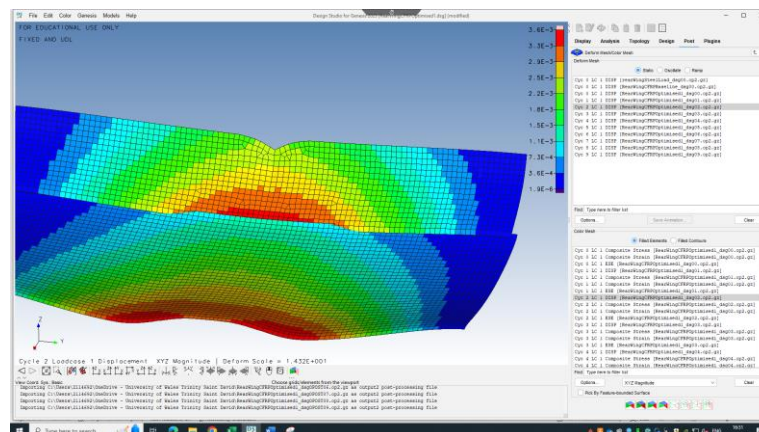


Figure 31

Can see that when the programme through mass at the structure the displacement grew. The software then minimised the mass and displacement in later cycles.

The user can see that the max displacement is now 1.9mm as set just below the 2mm target.

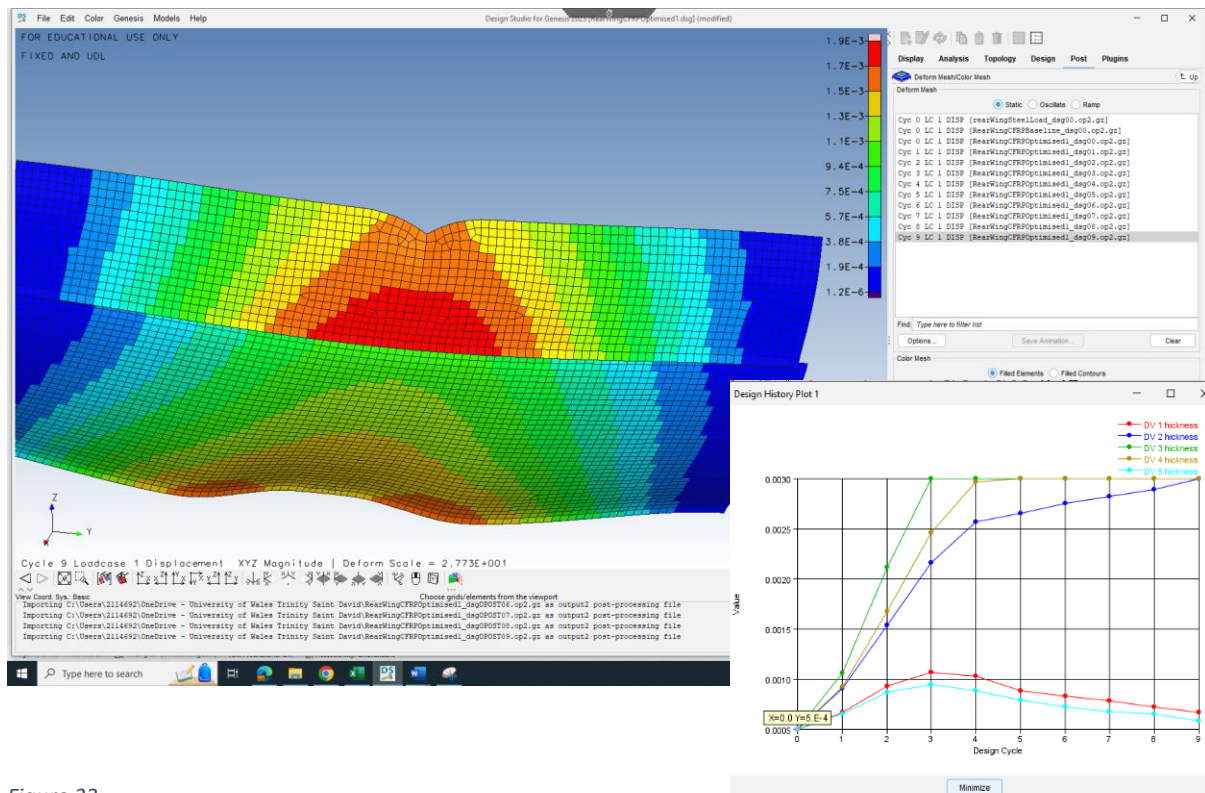


Figure 31

Figure 32

The above data shows the final design cycle from the HIS report ran to optimise the wing. The wing deflects 1.9mm, so it is within tolerance, but the mass has increased to 7.72kg.

Run	Material	type	Ply	Layers	Thickness (mm)	Deflection (mm)	Mass (g)	Mass (kg)	Load (N)	Stiffness (N/mm)	Stiffness/Weight (N ² /mm)	
Steel Baseline	Steel	isotropic			2	9	7532	7.53	200	22.22222222	0.297823318	Very similar
Composite Baseline	CFRP	Orthotropic	0.001 x 5 = 0.005	5	2.5	37	1883	1.88	200	5.405405405	0.293339406	results
Optimised composite	CFRP	Orthotropic			10.3	1.9	7724	7.72	200	105.2631579	1.390407377	Improved

Figure 34

Stiffness (N/mm)	Stiffness/Weight (N ² /mm)	
22.22222222	0.297823318	Very similar
5.405405405	0.293339406	results
105.2631579	1.390407377	Improved

When inputting the data into a table as shown in the above figure. The user can see that the mass of the optimised CFRP is like that of the Steel Baseline. However, the strength to weight ratio of the optimised CFRP is significantly greater now.

Design for Manufacturing Issues

The data below shows the number of plies within each of the 5 layers in the structure generated.

Table 1

Optimised Composite final Design Cycle

DESIGN CYCLE # 9, OBJECTIVE = 7.723744E+00, MAXIMUM VIOLATION = 0.0%.

Layers	(m)	(mm)	No.Plys	DfM?
1 = 6.692279E-04	0.00067	0.67	6.7	not manufacturable
2 = 3.000000E-03	0.003	3	30	Manufacturable
3 = 3.000000E-03	0.003	3	30	Manufacturable
4 = 3.000000E-03	0.003	3	30	Manufacturable
5 = 5.853923E-04	0.00059	0.59	5.9	not manufacturable

102.6

As shown in Table 1, the structure has been optimised for weight reduction but without any input on manufacturing needs. The thickness of ply is 0.1mm so to have an awkward thickness of 0.67mm means that it is not possible to currently manufacture. This means the user must go back the software and add further limits on the optimised outcome.

DfM Optimisation – Discrete Variables

The user changes the design variables to discrete variable bounds. Starting with 0.2mm thickness, going up in 0.2mm increments. This means that the final design will have manufacturable layer thicknesses, as a single ply is 0.1mm thick. The user had gone up in 0.2mm increments for further ease of manufacturability, as 0.1mm increments may be too difficult and costly to produce.

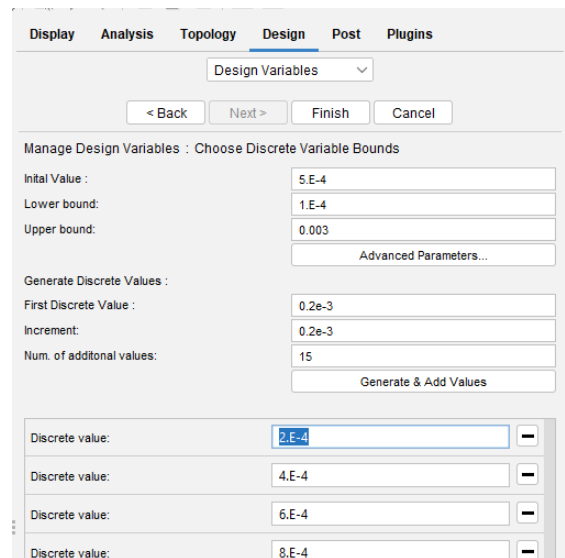


Figure 35

The optimisation process was run with a further 11 cycles. The mass of the structure has lightly increased at the price for ease of manufacturing.

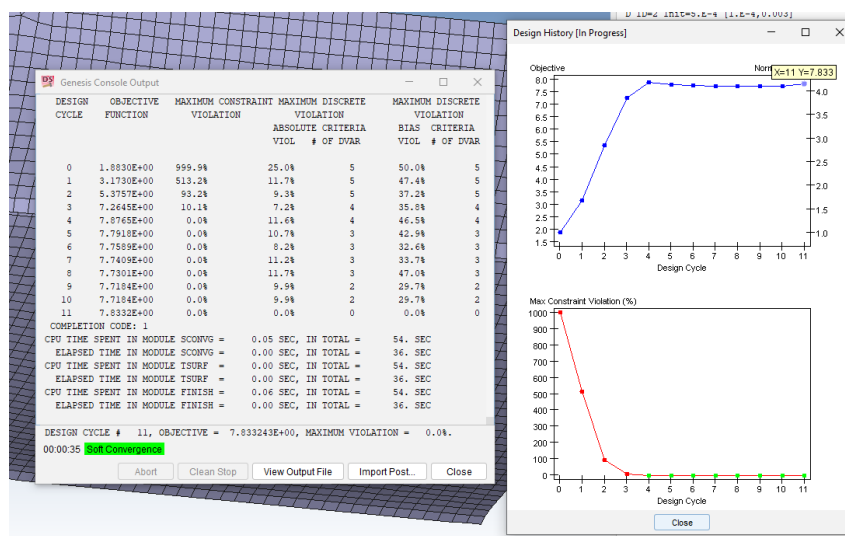


Figure 36

Optimised Manufacturable Layers

The below table shows each layer now with thickness suitable to that of 0.1mm thick plys.

The data shows that the majority of the plys run at -45/0/45 degrees due to the longitudinal strength required in the flexing. The total number of plys is 104, making the structure 10.4mm thick, and a mass of 7.83kg.

Table 2

Discrete Optimised Final design Cycle

DESIGN CYCLE # 11, OBJECTIVE = 7.833243E+00, MAXIMUM VIOLATION = 0.0%.

Layers	(m)	(mm)	No.Plys	DfM?
1 = 8.000000E-04	0.0008	0.8	8	Manufacturable
2 = 3.000000E-03	0.003	3	30	Manufacturable
3 = 3.000000E-03	0.003	3	30	Manufacturable
4 = 3.000000E-03	0.003	3	30	Manufacturable
5 = 6.000000E-04	0.0006	0.6	6	Manufacturable

104

Comparison

The below table shows the total data from each investigation. The user can see that strength to weight ratio has ever so slightly dropped between the final two structures. But the final one is actually manufacturable.

Run	Material	type	Ply	Layers	Thickness (mm)	Deflection (mm)	Mass (g)	Mass (kg)	Load (N)	Stiffness (N/mm)	Stiffness/Weight (N ² /mm)	
Steel Baseline	Steel	isotropic	0.001 x 5 = 0.005	2	9	7532	7.53	200	22.22222222	0.297823318	Very similar results	
Composite Baseline	CFRP	Orthotropic		2.5	37	1883	1.88	200	5.405405405	0.293339406		
Optimised composite	CFRP	Orthotropic		10.3	1.9	7724	7.72	200	105.2631579	1.390407377	Improved	
Optimised Composite (discrete)	CFRP	Orthotropic		10.4	1.9	7833	7.83	200	105.2631579	1.370874196	Manufacturable	

Figure 37

Section 4

During the development of this component, it is proposed that a prototype is produced and tested in a laboratory to understand the deformation of the wing when subjected to the forces seen and to correlate it to the simulation carried out in task 3. Discuss how you think this experiment should be carried out and how the acquisition of data should be obtained and compared to the simulation.

Formula 1 teams often produce prototypes to further test any component on their vehicles because no matter how accurate, how expensive, and how detailed your virtual computer aided software is, it will never be as good as the real thing.

A prototype is an early sample, model or release of a product created to test a concept or process. Typically, a prototype is used to evaluate a new design to improve the accuracy of analysts and system users. It is the step between the formalization and the evaluation of an idea. Prototypes are a crucial part of the design process, and a practice used in all design disciplines. From architects, engineers, industrial designers and even service designers, they make their prototypes to test their designs before investing in their mass production. (medium, 2024)

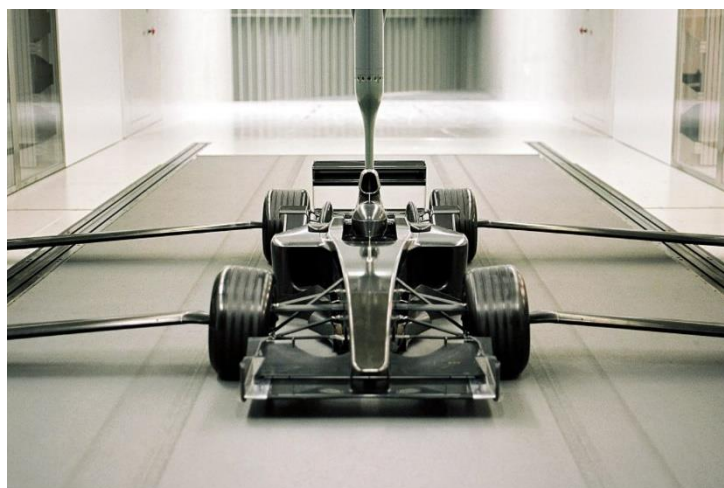


Figure 38 - (gpfans, 2024)

Down Scale

In the real-life prototype, the user should downscale the design by 50%. The goal of the model shop is to create a 50% scale model of the car that is fit for use in the wind tunnel. Hundreds of parts, designed by the aerodynamic team, will be manufactured at the factory for the model only, all using a variety of different processes.

When operating at 50% scale, you can also make new parts faster and cheaper for testing, than with a full-size car; indeed, all teams operate at either 50% or the maximum permitted by the FIA, 60% scale. (auto123, 2024)

Data acquisition

The data acquisition can be carried out many ways such as by a visual inspection. This does not just mean by eye. As the user can use high tech camera/visual systems on section. During wind tunnel tests a visible smoke can be pumped into the air flow, combined with slow motion cameras, the engineer team can review air flow around the rear wing when under different loads.

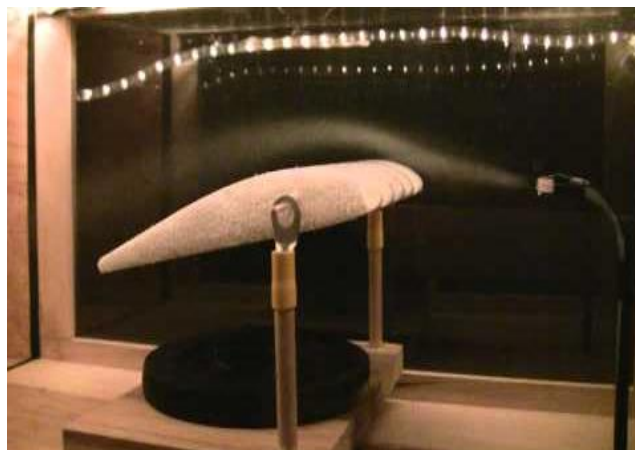


Figure 39 - (smokeimg, 2024)

Other methods for obtaining quantitative data is by using laser level sensors. The engineering team could load the rear wing and accurately measure the displacement using laser light at different points on the beam.

Another sensor that could be used is a force sensor. If the top side of the wing is attached to a pull-meter, then when the wing is under load and deflects downwards. A numerical figure can be seen on the sensor.

The great thing about gaining this data is that the parts are nearly double as quick to re-manufacture due to scaled down process.

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