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Designing a Kiteboard: Structural Design Assignment

STRUCTURAL & FLUID ANALYSIS (ACMA6010)

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1.0 Introduction

This report will explore optimisation techniques offered in Design Studio for the Genesis CAD package. A brief history of FEA optimisation will be followed by a detailed explanation of steps taken in Design Studio to optimise the given kiteboard design. The design is to be made from carbon fibre reinforced plastic (CFRP) and must perform at least as well as the same geometry made from steel.

Lastly, a prototype has been proposed to be manufactured and a relevant experiment to verify the results found in Design Studio; this report will discuss how to produce the prototype and run the experiment.

2.0 History and Future of FEA Optimisation

Finite Element Analysis (FEA) optimisation is a broad term describing a range of techniques engineers use to refine a design; these optimisations can reduce weight, increase strength, ensure safety factors are met, and modify a wide range of other design parameters. FEA studies will predict the behaviour of materials in certain situations; for example, an FEA study could predict the deflected shape of a steel beam when a known load is applied to it; taking this to another level, complex FEA studies could predict the deflection of a building will have when a certain speed wind is striking it.

In the 1950s and 60s, the first FEA programs emerged through work by mathematicians such as Richard Courant (Liu & Tadepalli, 2014, p 3-31). These early programmes allowed engineers to solve differential equations and predict material behaviour. The optimisation was largely manual but could be achieved by modifying the input parameters and recording the output results; engineers would change variables such as boundary conditions and material properties (Bendsoe and Kikuchi, 1988).

By the 1980s, mathematicians and software developers had figured out new techniques to optimise CAD designs; these included gradient-based optimisation. This method uses the vector of the partial derivatives of a function to find a minimum or maximum value; in turn, this allows the program to modify values to achieve an optimised design (Bendsoe and Kikuchi, 1988).

Through the decades, computing power increased, so the calculations that could run on these machines became more extensive and complex. This led to nonlinear analysis being targeted by mathematicians, during the 2000's engineers became able to have multi-objective simulations running, which allowed them to optimise models more efficiently and accurately, instead of running an optimisation for weight and another for strength and manually combining the results into a new CAD model the programs were able to combine the objectives and generate the new lightweight but still strong enough design for the engineers (Haftka and Gürdal, 1992).

More recent updates to FEA optimisation are coming from machine learning and Artificial Intelligence (AI). Machine learning allows computers to discover more efficient ways to solve equations, and AI is being investigated to help bridge gaps in our current equations and programs.

The future of FEA and optimisation will be embedded within more excellent machine learning arrays and AI; quantum computers will open a new gateway for these programming techniques due to the complexity and speed they are able to solve equations, they will also allow for multiple versions of the study to run at once, where traditional binary computers are great at solving calculations they are restricted by the CPU cores on how many calculations they can solve at one time. They are highly efficient at solving large and complex equations. Once Quantum computers become more readily available, it is predicted that FEA, Computational Fluid Dynamics (CFD) and other engineering problems will be much quicker and more accurate.

A vital parameter to consider in any FEA study is the size or amount of elements that are considered, in simple terms the model that the study is being carried on is split into minute facets, these elements join each other and cause intersection points, these points are where the displacement or other variable is measured, the more of these points there are in a model, the more accurate the output will be, but equally the more of these points there are, the more calculations the study will need to run to compute a final answer, this leads to the well known issue of mesh density vs time and output validity (Haftka and Gürdal, 1992) (Bendsoe and Kikuchi, 1988).

3.0 Kiteboard in Design Studio

A model of the kiteboard has been created within Design Studio; the model must have the correct material properties and represent the boundary conditions found in assignment 1 for this module.

Prior to this report SolidWorks 3D Computer Aided Design (CAD) model was created with the appropriate 3D geometry of the kiteboard. The first step was to import the .dat file outputted from SolidWorks into Design Studio. Figure 1 shows the file in Design Studio.

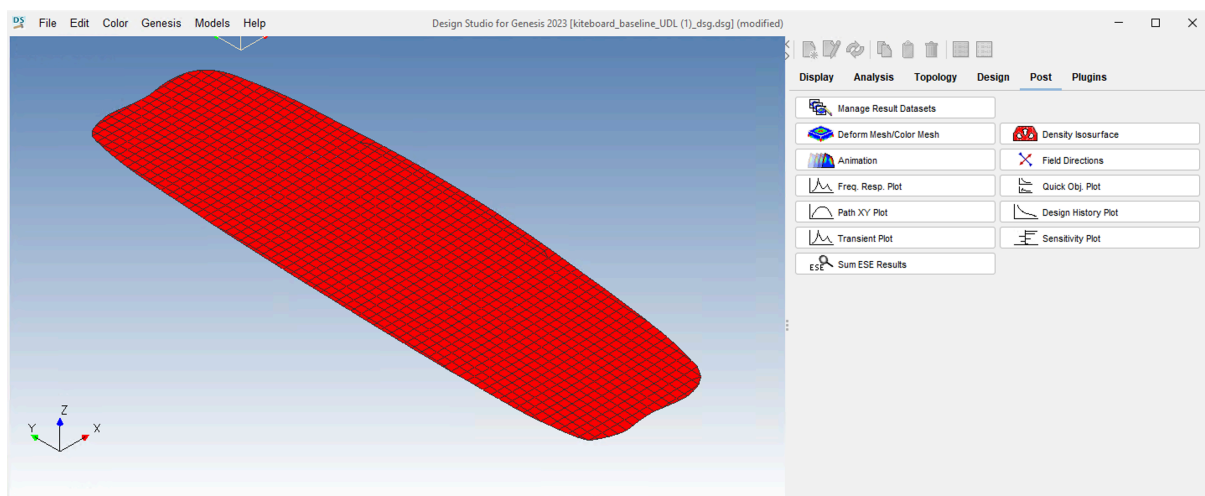


Figure 1 Kiteboard comparison file imported into Design Studio (U'Dell, 2024)

The workflow is to run through a Genesis optimisation simulation trying to achieve the same maximum displacement with layered unidirectional CFRP material compared to the maximum displacement using steel. The study will also attempt to create the best layering pattern, the number of layers in each direction to get the stiffest kiteboard.

3.1 Baseline Model

The first step is to create a baseline model using the steel material parameters. The imported .dat file brings through the steel material properties and the basic static load and constraints required to run a baseline study to compare the optimised model against.

The elements need to be aligned along the y-axis. To do this, the theta vectors are generated in Design Studio and aligned along the y-axis. Figure 2 shows the output for this action.

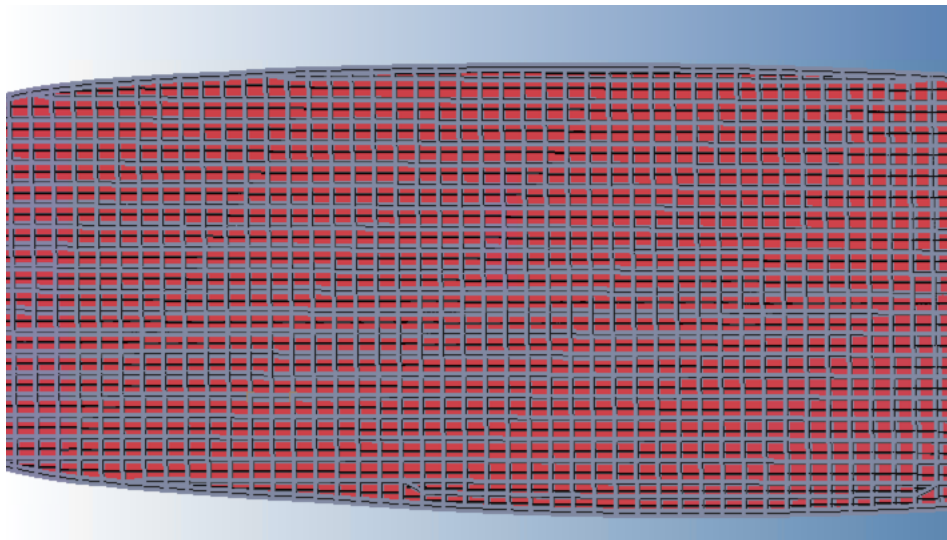


Figure 2 Kiteboard element direction (U'Dell, 2024)

The static load supplied in the model shows a 1-newton force in the z direction on every single element to simulate a user on the kiteboard; this has been modified to simulate an 80kg (max user weight discussed in assignment 1) rider by selecting the elements around the foot constraints and then dividing 785 newtons by the number of elements. Figure 3 shows this process.

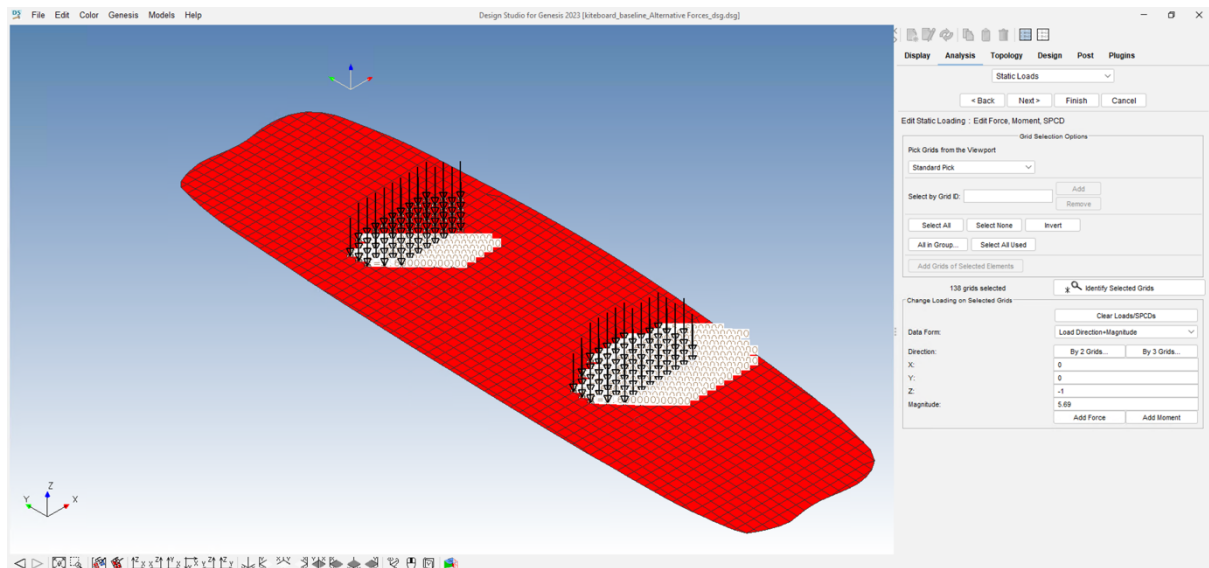


Figure 3 Static Load (U'Dell, 2024)

As shown in Figure 3, this leaves a 5.69 Newton force on 138 Grids around the area where the rider's feet would be.

Figure 4 shows the constraints (Grid-Component Sets) supplied in the .dat file for the simulation; the first allows movement in directions 2 and 4, and the second only in direction 4.

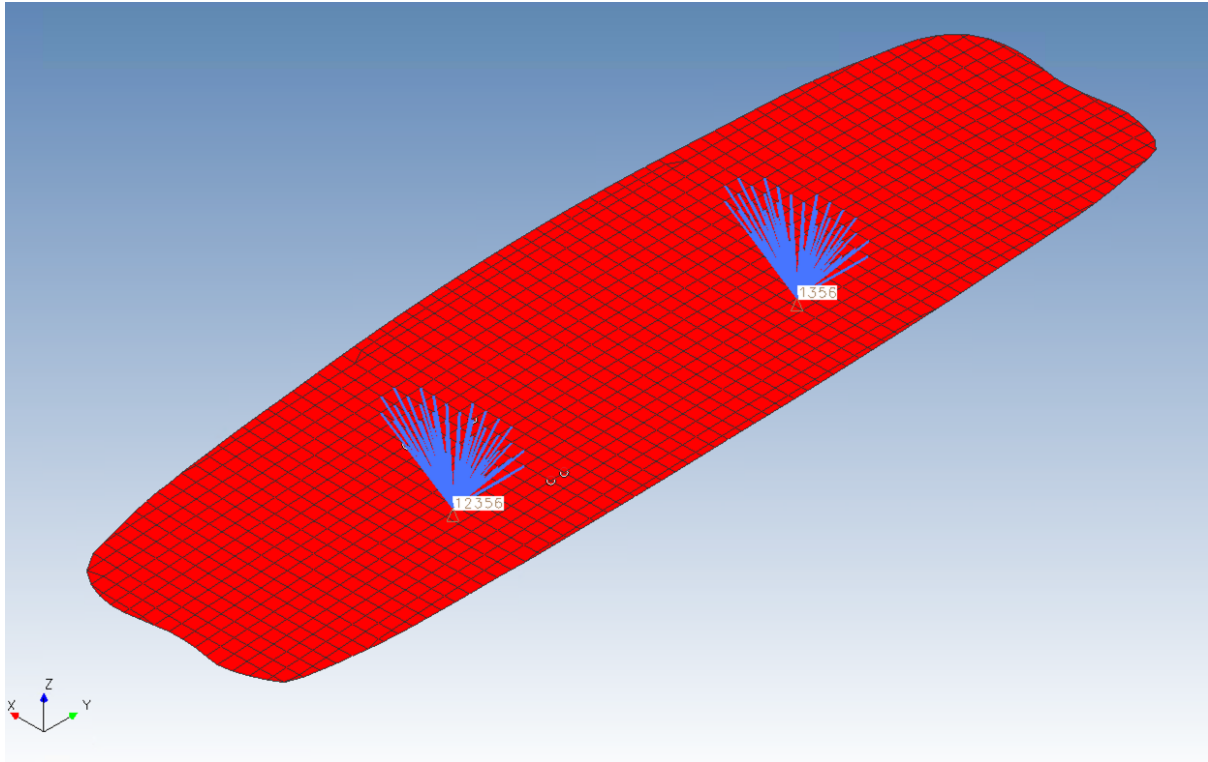


Figure 4 Baseline Constraints (U'Dell, 2024)

With these parameters, the baseline displacement can be simulated. Figure 5 shows the output; a maximum of $6.3\text{e-}4$ m of m has been recorded. Looking at the model statistics, it can be seen that the mass of the model is 8.1 kg.

3.2 Unidirectional CFRP Optimisation

A new material, CFRP, has been created within the Design Studio. The values used are shown in Figure 5. This material was added as the original steel material properties are not correct for the CFRP material, CFRP is a unidirectional material so it is important to input these values correctly and using the correct material type. Using the wrong material type or values would deem the study incorrect.

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
A_1:	
A_2:	
Tref:	
GE:	
F12:	
☒ Stress Limits ☐ Strain Limits	
Xt:	1.513e+9
Xc:	1e+9
Yt:	4.34e+7
Yc:	4.34e+7
S:	4.34e+7

Figure 5 CFRP Material Properties (U'Dell, 2024)

When optimising carbon fibre layered designs, the design's manufacturability needs to be considered; this is done by setting up design constraints and variables. Within Design Studio 5, individual layers have been created; each material layer is offset 45 degrees from the previous (-90, -45, 0, 45 and 90). This is typically how carbon fibre products are manufactured. Assuming the kiteboard is to be made using 0.2mm thick carbon fibre sheets, a further design constraint can be implemented into the model so that these five layers can only be created using a multiple of 0.2mm, 0.2mm – 3mm has been inputted.

Figures 6 – 9 show various objectives, design constraints and properties for the model.

Display Analysis Topology **Design** Post Plugins

Sizing

< Back Next > Finish Cancel

Edit a Group : Choose Composite Property Variables

Z0: Not Designed

Nonstructural Mass: Not Designed

GE: Not Designed

Layer 1

Material: 857143 CFRP

Thickness: 1 L1THK I=0.001

Angle: =-90.0 (Not Designed)

Layer 2

Material: 857143 CFRP

Thickness: 2 L2THK I=0.001

Angle: =-45.0 (Not Designed)

Layer 3

Material: 857143 CFRP

Thickness: 3 L3THK I=0.001

Angle: =0.0 (Not Designed)

Layer 4

Material: 857143 CFRP

Thickness: 4 L4THK I=0.001

Angle: =45.0 (Not Designed)

Layer 5

Material: 857143 CFRP

Thickness: 5 L5THK I=0.001

Angle: =90.0 (Not Designed)

Figure 6 CFRP Layer sizing (U'Dell, 2024)

Display Analysis Topology **Design** Post Plugins

Objectives

< Back Next > Finish Cancel

Edit Design Objective : Enter Name and Type

Name: Obj1

Response Type

☒ Mass Entire Model

☐ Volume Entire Model

☐ Strain Energy Entire Model

☐ Displacement

☐ Stress Selected Groups

☐ Grid Stress von Mises

☐ Failure Index Selected Groups

☐ Buckling Load Factor 1

☐ Frequency Mode Number 1

☐ Reaction Force (SPCF)

☐ Von Mises Index

☐ Synthetic Response

☐ More Response Types...

Objective Definition Switch

☐ Max

☒ Min 0.0

☐ Target

Weight 1.0

MinMax Param:

Figure 7 Minimum Mass Goal (U'Dell, 2024)

Display Analysis Topology Design Post Plugins		
Design Variables		
Description	Name	
D ID=1 Init=0.001 [2.E-4,0.003]	L1THK	
D ID=2 Init=0.001 [2.E-4,0.003]	L2THK	
D ID=3 Init=0.001 [2.E-4,0.003]	L3THK	
D ID=4 Init=0.001 [2.E-4,0.003]	L4THK	
D ID=5 Init=0.001 [2.E-4,0.003]	L5THK	

Figure 8 Design Variable - Layer thickness (U'Dell, 2024)

Constraints

< Back

Next >

Finish

Cancel

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

Allowed Fail Probability

6.4E-4

☒ Actual
☐ Scale of Initial

0.0

Figure 9 Constraint - Displacement (U'Dell, 2024)

3.3 Optimisation Results

Design Studio has generated an optimised layer configuration in 14 design cycles. This is done by changing the thickness of each layer, re-running the simulation, and optimising by changing another variable to see how this affects the maximum deflection.

Figure 10 shows the history of the design cycles with the cycle number along the x-axis and layer thickness on the y-axis. The optimisation program changes the thickness of the 5 layers and then simulates the load with the given restraints and will then modify the layer thickness as required to improve the displacement value gained from the simulation.

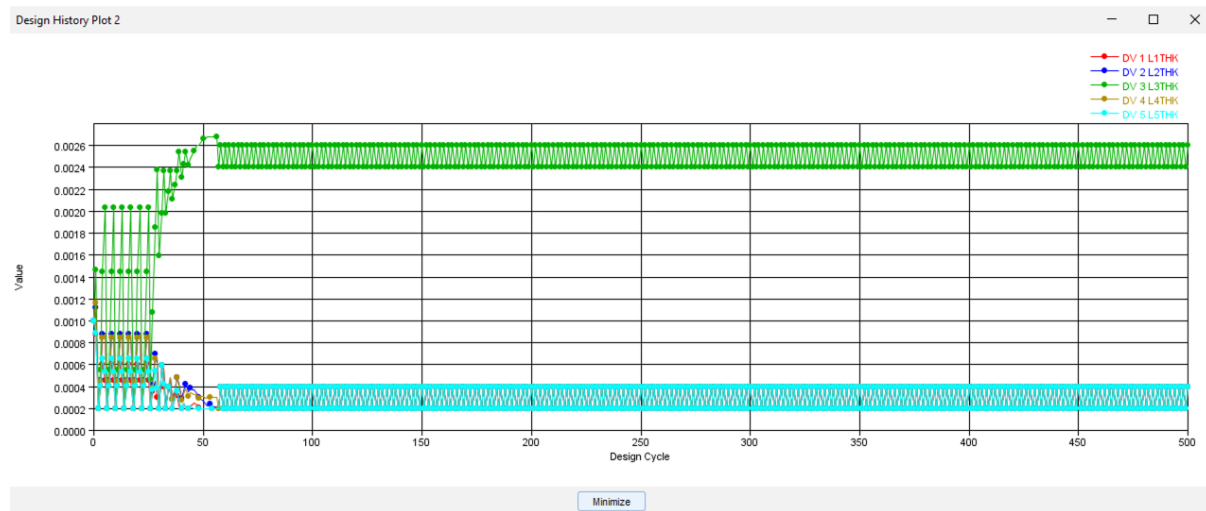


Figure 10 Design History Plot (U'Dell, 2024)

When reading the history file with a text reader, the optimisation resulted in layers 1, 2, 4, and 5 being 0.4mm (two layers) and the middle layer (layer 3) being 2.6mm (12 layers). Figure 11 shows the raw data. The data shows the thicknesses of the 5 layers. This study ran for 500 cycles. The history graph shown in Figure 10 suggests that the optimal layer configuration was found around cycle 70.

```
DESIGN CYCLE # 500, OBJECTIVE = 3.402737E+00, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE # 1 = 4.000000E-04 L1THK
DESIGN VARIABLE # 2 = 4.000000E-04 L2THK
DESIGN VARIABLE # 3 = 2.600000E-03 L3THK
DESIGN VARIABLE # 4 = 4.000000E-04 L4THK
DESIGN VARIABLE # 5 = 4.000000E-04 L5THK
```

Figure 11 Final Cycle Raw Data (U'Dell, 2024)

Lastly, the optimised design's mass is shown in the model summary; the model weighs 4.05kg, a 50% reduction from the steel version.

Looking at the maximum displacement of the optimised model (Figure 12), it can be seen that the maximum displacement is 5.6×10^{-4} or 0.56mm.

In conclusion, the optimised variant has half the mass of the steel variant and a maximum deflection of 0.56mm vs 0.64mm.

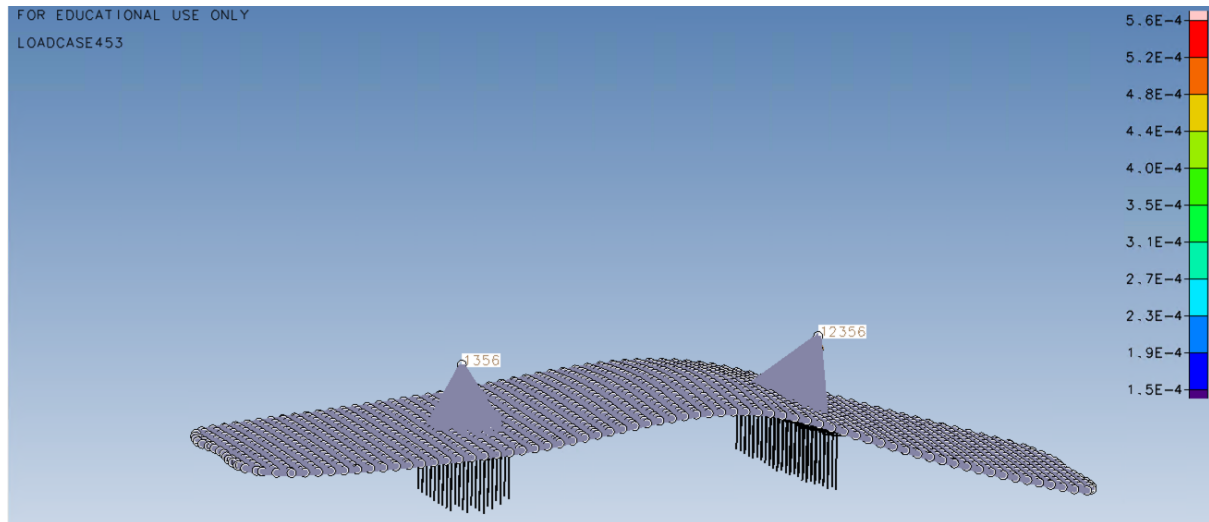


Figure 12 Optimised Displacement Visual (U'Dell, 2024)

4.0 Prototyping

Prototyping can be a great way to test a design's real-world characteristics and compare them to simulation-based results; this helps confirm simulation results for future comparison and allows for any natural-world phenomenon that can not be captured with the current state of simulation programs.

Historically, prototyping large designs such as this has been challenging. The only practical way to make a full-sized replica using traditional manufacturing techniques is to create a plywood mould and then lay the carbon fibre sheets onto it, following the layer thicknesses given by the model. For this type of design, a cheap option would be to create a plywood mould and then lay the carbon fibre sheets onto it.

Creating the plywood mould would require skilled craftsmanship; luckily, with today's technology, a large industrial CNC router could make the mould from some high-density foam in minutes.

A full-scale model would be required for fluid flow, as the effect does not simply scale like other mechanical characteristics.

One set-up for the required experiment would be to suspend the prototype in a water tank; the prototype would have displacement sensors scattered along the surface of the kiteboard. A pneumatic piston would apply the appropriate force onto the board in; this would simulate a human's feet by using custom-built adaptors to go on the end of the piston that replicate the feet of the rider.

A pump would be installed in the water tank, allowing the relevant water to flow against the board while the piston applied the user's force. The displacement sensors would accurately record the board's movement.

5.0 Summary

In summary, the optimisation carried out within this report uses industry-grade optimisation programming and has managed to quickly and efficiently produce a working instruction on how to layer the CFRP sheers to create the most potent version of the design; this is all with only modifying the thickness of each of the five layers.

To take this optimisation to the next level, the study could look at the angle of each layer instead of being stuck to the five positions locked in within the model; this would allow the design to adjust the individual layer angle to produce an even more robust design, the model could also have more authority over the number of layers. Currently, it is restricted to using only five layers, which is advantageous compared to using more. These suggestions would result in a more robust design, making manufacturing the kiteboard significantly more difficult due to complex angles and constantly changing angles in between layers.

The suggested experiment would be an accurate way to check that the FEA and suggested CFD studies are producing accurate outputs. It is a well-known golden practice procedure to perform a real-world test on any computer-simulated study to validate its output.

References

Bendsoe, M. P., & Kikuchi, N. (1988). Generating Optimal Topologies in Structural Design Using a Homogenization Method. *Computer Methods in Applied Mechanics and Engineering*, 71(2).

Haftka, R. T., & Gürdal, Z. (1992). Elements of Structural Optimization. *Kluwer Academic Publishers*.

Liu, W. K., & Tadeipalli, S. C. (2014). *History and Review of Finite Element Structural Optimisation*. *Archives of Computational Methods in Engineering*, 21st Ed.

U'Dell, J (2024) Design Studio graphics

(Bendsoe and Kikuchi, 1988)

(Haftka and Gürdal, 1992)