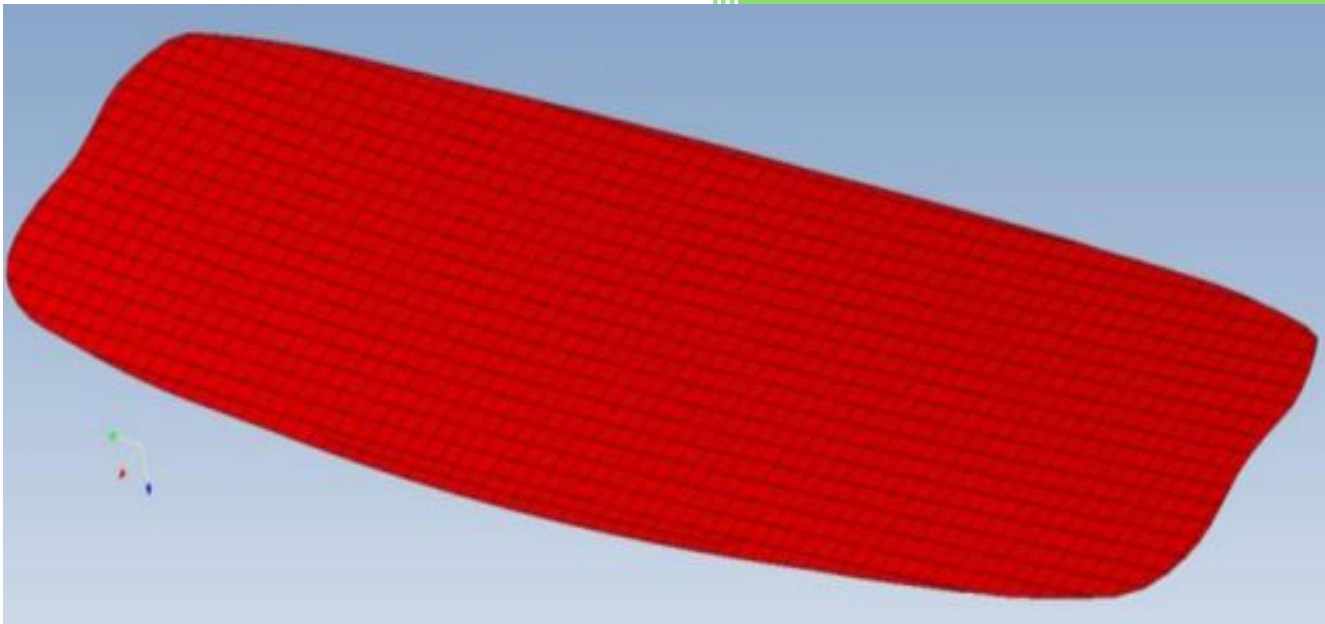


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Designing a Kiteboard: Structural Design



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UWTSD: Structural and Fluid Design

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1.Introduction

This report focuses on the optimisation techniques that can be used with finite element analysis (FEA). In assignment one the relationship between fluid flow and mechanical performance in kiteboards was explored and how material selection influences the performance of the board. Carbon fibre reinforced plastic (CFRP) is thought to be an excellent material for kiteboards, Ensinger (2024) discusses due to its high modulus of elasticity the material is ideal for application in which rigidity is the predominant requirement. The aim of this report was to design the lay-up of the carbon fibre reinforced plastic so that when the force, discussed in assignment one, is applied the board does not exceed the deflection seen by a 2mm steel kiteboard. Weight reduction is a vital consideration for this design, this needed to be completed using as little material as possible. This was done by exploring FEA optimisation techniques, including their historical development, future trends and impact on the design process. A model of the kiteboard with the appropriate material properties was created in Design Studio. GRM (2024) states Design Studio is a pre- and post-processor for structural analysis and optimisation. The optimisation technique is executed to minimise the mass while meeting the displacement constraints. In addition to this, a prototype is proposed for testing to validate the results found in the optimisation software.

2. Finite element analysis (FEA)

In assignment one it was discussed that FEA is a simulation technique that models physical phenomena using a numerical method known as the finite element method. While many physical properties can be analysed through differential equations, FEA becomes essential in complex scenarios where multiple variables and equations are involved, making it the preferred method for performing intricate analysis.

2.1 Historical development of FEA

Mueller (2020) states finite element analysis originated in the mid-1950s to solve complex engineering problems using numerical methods. It was initially limited by the computational power of the time but would later evolve with advancements in optimisation techniques such as pareto optimisation, dynamic sensitivity analysis and topology optimisation, Liu & Li (2022). Recently FEA has integrated the use of artificial intelligence to improve the design process through processes such as machine learning, as depicted in a news article by the Institution of Mechanical Engineering (2022).

2.1.1 1956-1969: Introduction of FEA

In 1956 the earliest form of the finite element method was published by M.J Turner, R.W Clough, H.C Martin and L.J Topp in the Journal of Aeronautical science. They published the first 2-D – FEM for an arrowed aircraft wing and developed a mathematical model to calculate the strength and stiffness for steel and aluminium. After this article the direct stiffness method was the primary approach to FEA, Dr. J. Dean (2024), tells that this method allowed for engineers to create matrices that captured the stiffness of individual elements to solve structural problems and is considered a fundamental of FEA. In the late 1960s NASA developed Nastran, the first FEA computerised software, built for the aerospace industry, it provided engineers with a comprehensive simulation solution for insight into structural behaviour, NASA (2024). Although computational power was still limited it allowed for linear elastic problems to be solved.

2.1.2 1970-1989: Advancements in Computational Power

Liu & Li (2022) state at the start of the 70s there was an advancement in non-linear FEA when database technology was introduced to software's. MacDonald (2020) discusses in their textbook '*Practical stress analysis with finite elements*' non-linear FEA is applied when the idea of linearity is not valid, meaning forces and displacements are no longer propositional or reversible. It is possible of modelling complex behaviours such as large deformations, buckling and dynamic loads in a wide range of advanced engineering problems. After this saw the introduction of early topology optimisation, Altair, (2020) explains the idea of employing computing power to speed up the development of structures that

are adjusted for features such as mass and stiffness was introduced in academia. Following this Novedge (2024) explains commercialised FEA software packages such as Nastran, Ansys and Abaqus offered built in optimisation techniques directly alongside FEA environments.

2.1.3 1990-2024: Topology integration and introduction of Artificial Intelligence

FEA optimisation techniques have evolved significantly over the past three decades, addressing various challenges and improving efficiency in design. In the 1990s significant advancement were made in FEA technology with the progression of computational power. Halpern (1998) wrote that model preparation time was significantly reduced due to the introduction of pre-processing technology, FEA models were able to be created and updated directly from CAD models, further streamlining the preparation process. Further advancements were made in dynamic simulation technology, FEA solutions (2024) explain how this involves optimising structures for time-dependent forces ensuring it can perform as intended under cyclic loads and vibrations. In the last decade FEA has seen the integration of artificial intelligence (AI) and machine learning. Andrade-Campos & Gasper (2019) discussed to simulate material behaviour and increase the precision of constitutive models, researchers have explored the use of machine learning models, such as artificial neural networks. They go on to state that the models are trained using virtual materials and are integrated into FEA codes to evaluate their performance in complex strain. Another FEA advancement in recent years is cloud-based solutions, Grigoras (2022) conveys that engineers frequently have FEA problems that demand substantial computational resources to accurately analyse mechanical component behaviour, cloud-based solutions provide an alternative by utilising remote computer power for faster, highly accurate, complex solutions.

2.2 The Future of FEA

Finite element analysis is expected to continue evolving in the future and significantly impact industries to improve efficiency and enhance product performance. A capability being explored is real-time simulation testing, Matellio (2024) explains development of real-time simulation capabilities will enable engineers to see the effects of modifications instantly, significantly accelerating the design and testing stages. This feature would be highly beneficial in dynamic environments with fast changing conditions. Tavares (2024) writes about the potential of digital twins, which are virtual replicas of physical systems, playing a significant role in enhancing the reliability of numerical modelling tools for aircraft structural design. By combining sensor data, operational inputs and historical records, digital twins would offer a solution to accurately predict structural behaviour and performance throughout an aircraft's life cycle. With the addition of machine learning, continuously

feeding the system with new updated information could improve the accuracy in predicting structural behaviour.

3. FEA Results

The aim of the FEA was to design the lay-up of unidirectional carbon fibre reinforced plastic such that when the force seen on the board from the fluid flow discussed in assignment one was applied, the board does not exceed the deflection seen by a 2mm thickness steel board.

Reconsiderations have been made for the estimated force on the kiteboard made in assignment one due to the board now having a known area. It is assumed that the kiteboard is flat against the water and the drag force is the primary force acting on the bottom of the board.

Drag force

$$\text{Drag force} = \frac{1}{2} \rho A C_D V^2$$

Where;

ρ = Density of seawater, assuming that the surface temperature of the seawater is 20 ° C density is 1025 kg/m³, Engineering toolbox (2024).

V = Velocity, 8.9 m/s is the average speed of a kiteboard from kitesurf (2024).

C_D = Drag coefficient, from the shape of the model it can be assumed that the kiteboard has a drag coefficient of 0.2, Surfhydronamics (2023).

A= The area can be calculated by knowing the volume and thickness of the kiteboard.

$$\text{Volume} = 0.00105218 \text{ m}^3$$

$$\text{Thickness} = 0.002 \text{ m}$$

$$\text{Area} = \frac{\text{Volume}}{\text{Thickness}} = \frac{0.00105218}{0.002} = 0.52609 \text{ m}^2$$

The drag force can be calculated as;

$$\text{Drag Force} = \frac{1}{2} \times 1025 \times 0.52609 \times 0.2 \times 8.9^2 = 4271.34 \text{ N}$$

There are 1462 nodes on the kiteboard model, UOC (2024) describes that a node is a point in space, defined by its coordinates at which degrees of freedom are defined. The force is acting on the whole of the board with 2.92 Newtons on each node.

3.1 Displacement of Steel board (2mm thickness)

From the force of 4271.34 Newtons a displacement of 170mm was observed, this can be seen in *figure 1*, The board has been fixed at two centre points to imitate a rider.

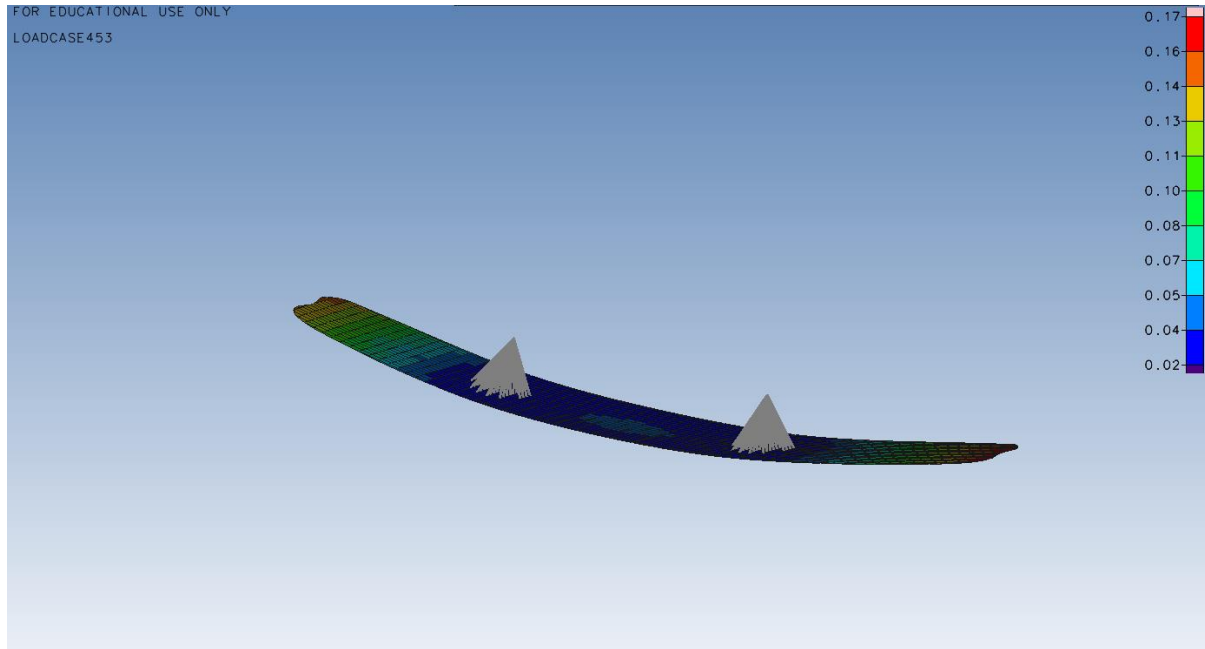


Figure 1

From this the stiffness to weight can be calculated;

$$Force = \frac{stiffness}{displacement}$$

$$f = kx$$

$$k = \frac{f}{x}$$

$$k = \frac{4271.34}{0.170} = 25.126 \frac{N}{mm}$$

Mass = 8.1 kg

$$\frac{Stiffness}{Weight} = \frac{25.126}{8.1 \times 9.81} = 0.31 \frac{N^2}{mm}$$

3.2 Displacement of Unidirectional CFRP (2.5mm thickness)

EasyComposites (2022) describes that unidirectional carbon fibre reinforced plastic is a type of composite reinforcement with all the carbon fibres aligned in the same direction, this type of reinforcement makes it possible to create strong, lightweight components by precisely orientating the carbon fibres to provide maximum strength in the direction its needed most. The composite was compiled as:

Layer	Plys	Thickness (mm)	Orientation
One	5	0.5	-90°
Two	5	0.5	-45°
Three	5	0.5	0°
Four	5	0.5	45°
Five	5	0.5	90°

Figure 2

The board was thus made up of 25 plys with a total thickness of 2.5mm.

Figure 3 shows the material properties of the carbon fibre reinforced plastic. The stiffness of E1 is higher as it is driven by the stiffness of the carbon fibres, whereas the stiffness of the E2 direction is significantly less as this is the stiffness of the epoxy. The model was orientated so E1 is running along the length of the kiteboard.

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:	43.3e6
S:	43.3e6

Figure 3

With those material properties, boundary conditions and the same forces acting on the board as the steel board, the CFRP kiteboard model had a displacement of 660mm, this is represented in *figure 4*.

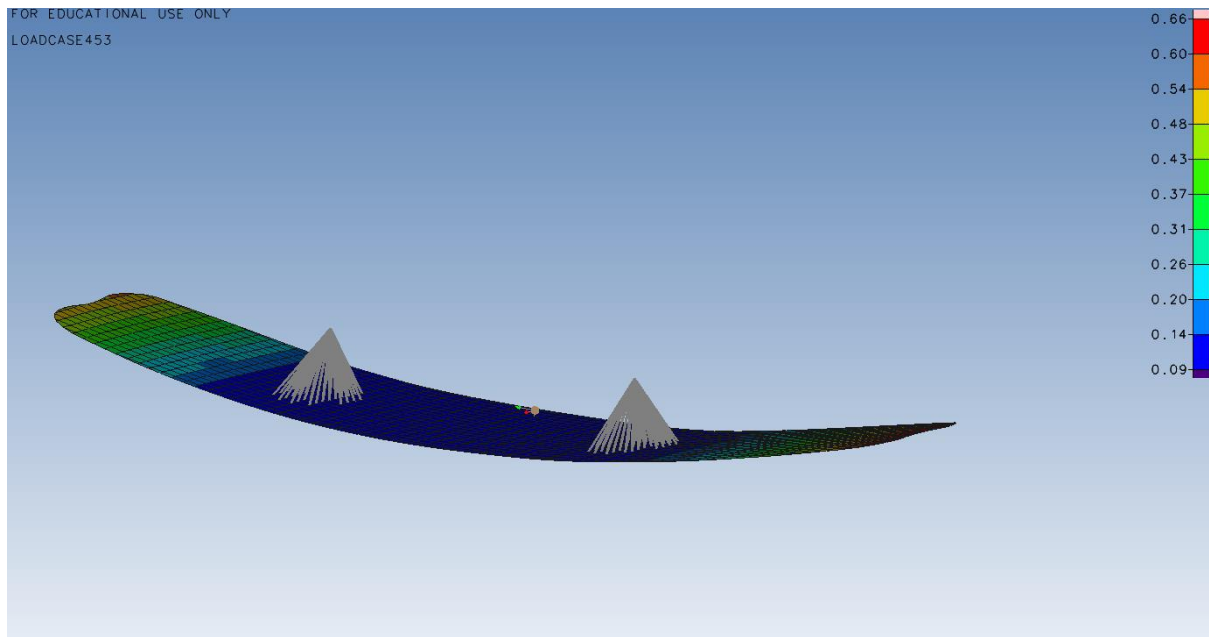


Figure 4

From this the stiffness to weight ratio can be calculated;

$$k = \frac{f}{x}$$

$$k = \frac{4271.34}{660} = 6.47 \frac{N}{mm}$$

Mass = 2.02 kg

$$\frac{Stiffness}{Weight} = \frac{6.47}{2.02 \times 9.81} = 0.32 \frac{N^2}{mm}$$

3.2.1 Comparison of Steel and CFRP model

	Material	Thickness (mm)	Deflection (mm)	Mass (kg)	Load (N)	Stiffness (N/mm)	Stiffness/weight (N ² /mm)
Steel Baseline	Steel	2	170	8.1	4271.34	25.126	0.31
Composite Baseline	CFRP	2.5	660	2.02	4271.34	6.47	0.32

Figure 5

Reviewing the data, in terms of stiffness to weight ratio having an arbitrary laid up composite structure offers little to no benefit compared to steel in this scenario. The stiffness to weight is similar for each material and the additional cost of manufacturing a CFRP kiteboard would not be beneficial.

3.3 Optimisation of CFRP Kiteboard

Instead of arbitrarily laying up the structure with 25 plies at -90 to 90 degrees the structure was optimised in Design Studio to minimise the mass whilst not exceeding the deflection observed by the 2mm steel board, this was done by setting objectives, constraints and design variables.

- Objective – minimise mass.
- Constraint – Displacement constraint of 170 mm across all the 1462 grids in the model, ensuring none of them constrain by this fatigue.
- Design variable – The design variable was set up as seen in *figure 6*.

Variable Name	Initial Value (mm)	Lower Bound (mm)	Upper Bound (mm)
Layer 1 Thickness	0.5	0.1	2.0
Layer 2 Thickness	0.5	0.1	2.0
Layer 3 Thickness	0.5	0.1	2.0
Layer 4 Thickness	0.5	0.1	2.0
Layer 5 Thickness	0.5	0.1	2.0

Figure 6

The optimised structure had a displacement of 170mm with a mass of 3.44 kg. The stiffness to weight can be calculated as;

$$k = \frac{f}{x}$$

$$k = \frac{4271.34}{170} = 25.126 \frac{N}{mm}$$

$$\frac{stiffness}{weight} = \frac{25.126}{3.44} = 0.74 \frac{N^2}{mm}$$

3.3.1 Design History of optimisation

The graphs in *figure 7* show the design history of the optimisation stage. The top graph focuses on the objective, which was to minimise mass, the y-axis is the objective which is mass (kg) and the x-axis shows the design cycle. In design cycle zero the mass is that of the unoptimised structure, 2.02kg, it then goes up to 3.95kg in design cycle two but starts to decline in further cycles as Design Studio orientates the plies to minimise the mass. The bottom graph shows how the optimisation was violating the constraint. Initially it was violating the constraint and displacing by more than 170 mm, it then started to add mass to the structure to lower the violation of the constraint. By design cycle 2 there was 0% violation and mass starts to be reduced by orientating the plies.

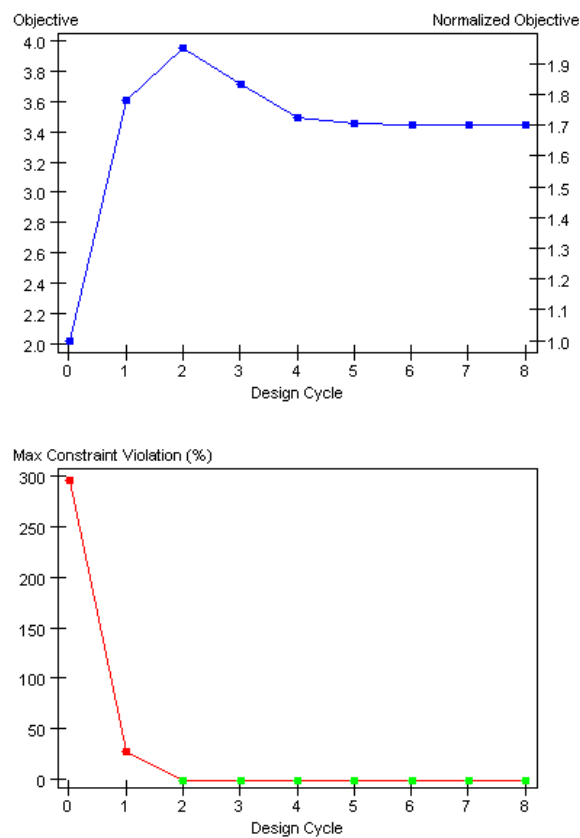


Figure 7

3.3.2 Thickness of each layer

Figure 8 is a graph showing how the thickness of each layer changed through the design cycle. In design cycle zero all the variables started at 0.5 mm which is 5 plys in each layer. The plys at layer 3 increased to the upper bound which was 2 mm, this was expected as those are the elements with the orientation of the fibres at zero degrees, this will contribute most to the stiffness of the board.

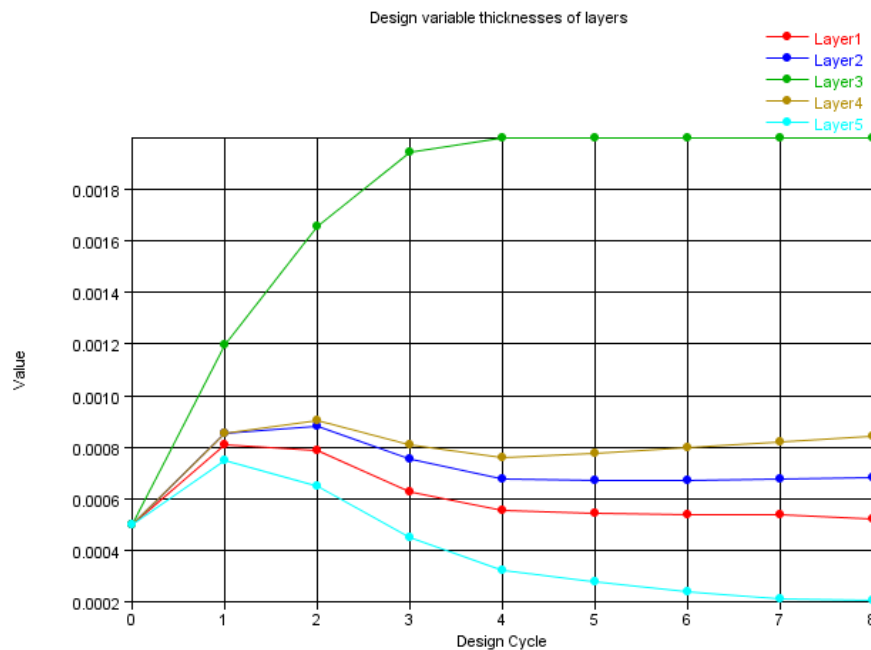


Figure 8

From this the thickness of the optimised structure can be calculated;

Layer	Orientation	Plys	Thickness (mm)
One	-90°	5.22	0.522
Two	-45°	6.84	0.684
Three	0°	19.98	1.998
Four	45°	8.41	0.841
Five	90°	2.49	0.249
Total thickness = 4.294 mm			

Figure 9

The optimisation met all the criteria that was put in place for the study, a displacement of 170mm with a mass of 3.34 kg leading to a thickness of 4.29 mm. Theoretically this is correct, but it is not possible to have the plys achieved in the study in this position for manufacturing. The plys need to be considered as discrete variable increasing in 0.1 mm increments. It is possible that this can add mass to the structure, but it ensures the model is manufacturable.

3.4 Optimisation of CFRP Kiteboard for manufacturing

For this stage of the study the objective and constraint stayed the same, but the design variable changed from an independent design variable to a discrete design variable. The initial value, lower bound and upper bound remained the same but discrete values were added in 0.1 mm increments to 2 mm to ensure the plys were of a manufacturable thickness, seen in *figure 10*.

Manage Design Variables : Choose Discrete Variable Bounds

Initial Value : 5.E-4

Lower bound: 1.E-4

Upper bound: 0.002

Advanced Parameters...

Generate Discrete Values :

First Discrete Value :

Increment:

Num. of additional values:

Generate & Add Values

Discrete value: 1.E-4

Discrete value: 2.E-4

Discrete value: 3.E-4

Discrete value: 4.E-4

Discrete value: 5.E-4

Discrete value: 6.E-4

Discrete value: 7.E-4

Discrete value: 8.E-4

Discrete value: 9.E-4

Discrete value: 0.001

Discrete value: 0.0011

Discrete value: 0.0012

Discrete value: 0.0013

Discrete value: 0.0014

Discrete value: 0.0015

Number of Discrete Values : 20

Editing ID=6 Layer 1 I=5.E-4

Figure 10: Discrete variable bounds – Source, Rhys Brannan (2024).

The use of discrete variables showed a displacement of 160mm, this still met the constraint of a maximum of 170 mm but the kiteboard became slightly stiffer as discrete plys were used. Also, the mass increased by 40 grams to 3.48 kg. The stiffness to weigh can be calculated as;

$$k = \frac{f}{x}$$

$$k = \frac{4271.34}{160} = 26.7 \frac{N}{mm}$$

$$\frac{Stiffness}{Weight} = \frac{26.7}{3.48 \times 9.81} = 0.78 \frac{N^2}{mm}$$

3.4.1 Thickness of each layer for manufacturing

It took eight design cycles for Design Studio to reach an optimised manufacturable lay up of plys in each layer for the model. The graph in *figure 11* is comparable to *figure 8* but there are now discrete values and whole plys in each layer.

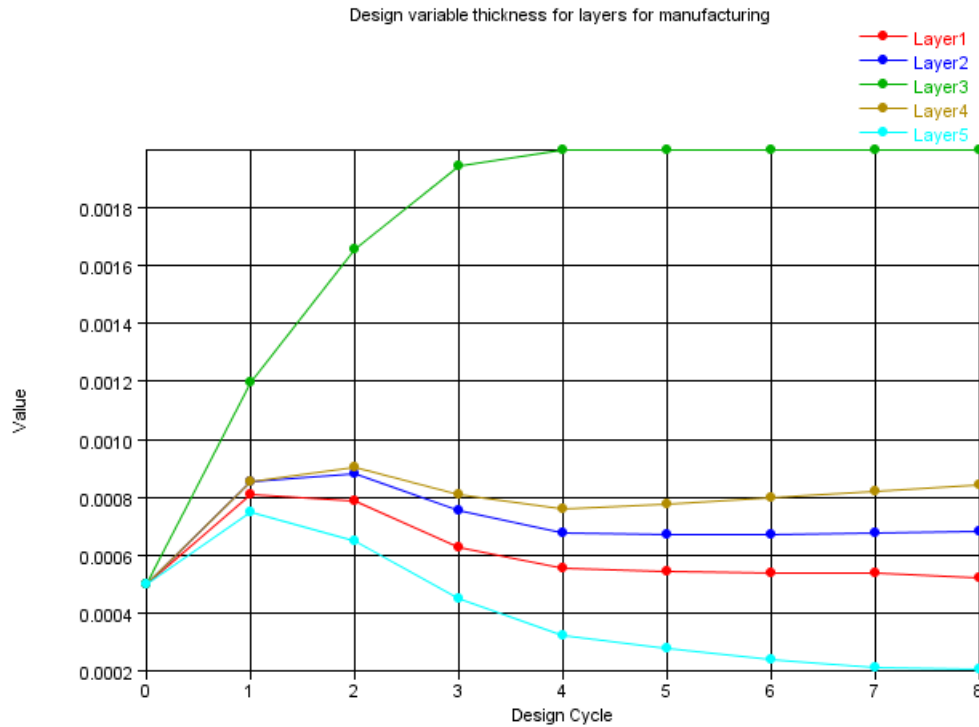


Figure 11

From this the thickness of the optimised structure can be calculated;

Layer	Orientation	Plys	Thickness (mm)
One	-90°	5	0.5
Two	-45°	7	0.7
Three	0°	20	2
Four	45°	9	0.9
Five	90°	2	0.2
Total Thickness = 4.3 mm			

Figure 12: Thickness of optimised structure for manufacturing

3.5 Comparison of results

Figure 13 shows a summary of the results obtained from the Design Studio study.

	Material	Thickness (mm)	Deflection (mm)	Mass (kg)	Load (N)	Stiffness (N/mm)	Stiffness/Weight (N ² /mm)
Steel baseline	Steel	2	170	8.1	4271.34	25.126	0.31
Composite baseline	CFRP	2.5	660	2.02	4271.34	6.47	0.32
Optimised baseline	CFRP	4.294	170	3.44	4271.34	25.126	0.74
Optimised baseline (discrete values)	CFRP	4.3	160	3.48	4271.34	26.7	0.78

Figure 13: Results obtained in design studio.

The optimised structure had a much higher stiffness to weight in comparison to the steel baseline and composite baseline, with the addition of mass to the structure it ensured the model would not deflect more than 170 mm. But this theoretical design layup of plys was not manufacturable. The optimised baseline with discrete values is in fact more efficient with a higher stiffness/weight which outweighs the addition of 40 grams to ensure the design is manufacturable.

4. Prototype Testing

For the validation of the FE simulation a full-scale experiment can be conducted. A prototype of the kiteboard would need to be produced with the layup seen in *figure 12*, it is proposed that the board is manufactured via wet lay-up. Penta (2024) states this is a simple way of manufacturing carbon-fibre products in which the material is cut to the correct dimension before being laid into a mould, the resin is then applied and left to cure, this is repeated until the required thickness is attained.

To correlate with FEA simulation the force needs to act on the whole area of the board with two central fixed points to replicate how a rider would be positioned in actual conditions. This could be done using two clamps or bolted fixtures that match the spacing of a riders feet position. To apply the force to the entire boards surface it is proposed a load frame can be used, this load frame would need to be able to provide a force of 4271.34 Newtons. The shape of the board would also need to be manufactured, this could be done via waterjet cutting of sheet steel to apply the force evenly across the board.

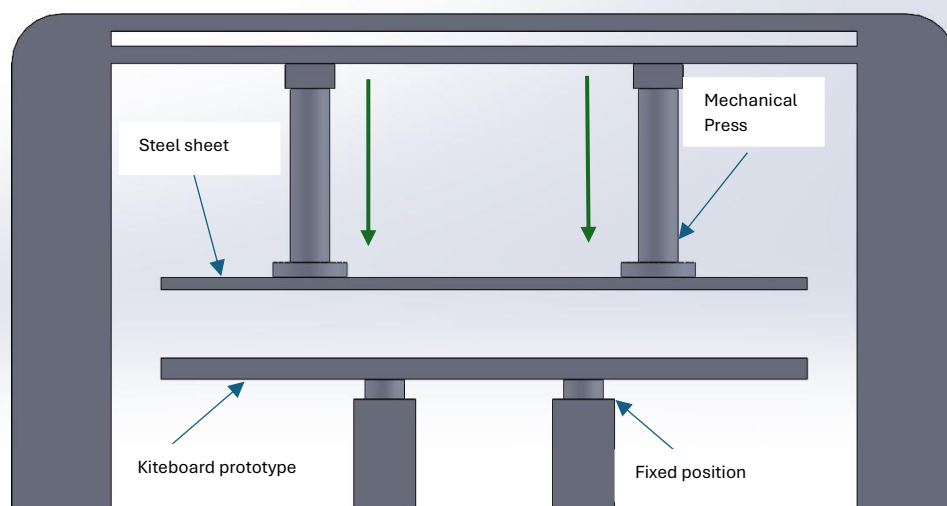


Figure 14: Illustration of prototype testing set-up – Source, Rhys Brannan (2024).

Data can be acquired from this testing method via a 3D digital image correlation system. Dantec (2024) states this is full field image analysis method, based on grey value digital images that can determine the contour and displacement of an object under load. This is a non-contact method so requires no mechanical connection to the test object surface meaning there are no mechanical limitations or constraints.

After testing, using the 3D image correlation system the experimental data can be analysed to find the maximum displacement. The results then need to be compared with the observations from the FEA

model, this includes the overall shape and deflection patterns of the board. From the results adjustments can be made to the FEA model as there is now physical data which will help refine the design and FEA model for future optimisation.

5. Related Technical literature

Jyothi (2024) discusses in their journal the orientation of fibres plays a crucial role in determining the mechanical behaviour of CFRP composite products. They go to state that unidirectional fibre orientation at zero degrees results in high tensile and flexural strength due to the fibre alignment running along the loading direction. This correlates with the final optimised design where zero degrees had the most amount of plies to ensure minimum deflection of the board.

In addition to this Sulaiman (2021) completed a study on composite optimisation of automotive carbon fibre strut bar using FEA optimisation. It included developing a lightweight CFRP design to replace steel bars whilst maintaining stiffness and minimising the weight, similar techniques were used seen in this report. Increasing the number of plies in different orientations maintained the stiffness/weight of the steel strut bars and saw a weight reduction of 40%, the optimised kiteboard design for manufacturing had a mass reduction of 67%.

6. Conclusion

Following on from assignment one the design, analysis, optimisation and prototype testing of a composite CFRP kiteboard has been presented. By using FEA techniques, the deflection of a steel 2mm thickness board was found to be 170 mm. The input of carbon fibre reinforced plastic material properties and ply orientations was then integrated to simulate the model's deflection under the same applied force as the steel board.

The kiteboard model was arbitrarily layered with a unidirectional CFRP configuration of 25 plies at orientation from -90 to 90 degrees. This showed a larger deflection of 660 mm but due to the material properties the mass was reduced by 85%. In terms of stiffness to weight ratio having an arbitrary laid up composite structure offered little to no benefit compared to steel in this scenario. The stiffness to weight is similar for each material and the additional cost of manufacturing a CFRP kiteboard would not be beneficial.

Instead of arbitrarily laying up the structure it was optimised in Design Studio to minimise the mass whilst not exceeding the deflection observed by the 2mm steel board, this was done by setting objectives, constraints and design variables. The ply orientation was refined to maintain the structural integrity of the steel board whilst keeping mass at a minimum. This resulted in a stiffness/weight of $0.74 \text{ N}^2 / \text{mm}$, more than double of the previous models analysed. But the layup of plies was purely theoretical and was unable to be manufactured. The design layup was changed from an independent design variable to a discrete design variable, discrete values were added in 0.1 mm increments to 2 mm to ensure the plies were of a manufacturable thickness. The results showed that the stiffness/weight of the board increased from 0.32 to $0.78 \text{ N}^2 / \text{mm}$, whilst having a mass of 3.48kg.

A laboratory experiment to validate the FEA results was outlined. By applying similar loading conditions using a load frame and a 3D image correlation system to measure the displacement a detailed deformation map could be obtained to compare with the data found in the FEA. This testing would provide real-world insight into the mechanical performance of the CFRP.

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