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Designing a Kiteboard: Structural Design Assessment

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Abstract

This report presents the results of a structural optimisation project. The project's goal was to minimise weight while ensuring that a carbon fibre-reinforced plastic kiteboard matches the displacement of a 2mm steel counterpart. This was done under simulated wave forces determined in a previous fluid flow analysis. The optimal design resulted in a board thickness of 3.7 mm, with a stiffness-to-weight ratio of 2.7 times greater than steel's. It was decided that weighted bags would be used for prototype testing to apply the load and measure the displacement with dial test indicators. This structural analysis demonstrated that carbon fibre-reinforced plastic would outperform steel as a kiteboard material when the ideal lay-up configuration is used.

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1. Introduction

1.1. Summary of the Fluid Flow Assessment

Before this report, a fluid flow analysis was performed to investigate the fluid dynamics of kiteboarding and understand the forces acting on the board (Evans, 2024). The report found that the main forces acting on the board are drag and lift due to its interaction with the water. In determining flow characteristics, the Reynolds number and boundary layer are considered. Further investigation indicates that the flow begins as laminar at the leading edge due to a low local Reynolds number. However, as it flows beneath the board and over the length, it transitions to a turbulent flow as it detaches from the surface.

1.2. Purpose of the Report

This report focuses on optimising an existing kiteboard by designing the lay-up of a unidirectional (UD) carbon fibre-reinforced plastic (CFRP) material. The goal is to ensure the kiteboard does not flex more than a board made from 2mm thick steel. The final design must be strong enough to withstand the force identified in the fluid flow assessment and be lightweight. Minimising weight is a crucial benefit of using composite materials in sporting goods (Crameri, Stojcevski, and Usma-Mansfield, 2023). Otherwise, there is little to no competitive advantage to changing the material, as it will cost more than steel (Öchsner and Altenbach, 2020; Gratwick, 2023). This report will use finite element analysis (FEA) optimisation techniques to determine the best lay-up to achieve the desired properties.

1.3. Assumptions and Consequences

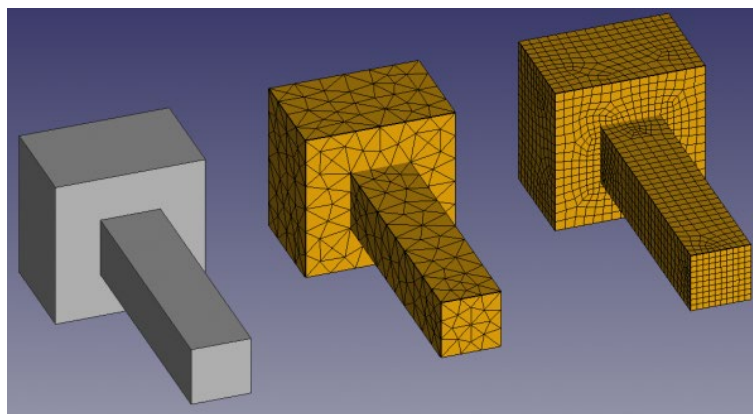
The kiteboard model provided for this assessment looks like a twin-tip kiteboard with a three-stage rocker (Laurinaityte, 2023), like the one in the fluid flow analysis. With accompanying consequences, the following assumptions and decisions are made to simplify the optimisation process and reduce the required computational power: Twin-tip boards usually have four fins, which are absent in the model. The fins likely offer structural support as they run along the length of the board, but without them, the board may be more flexible. The force is applied from below in one direction, simplifying the simulation but failing to consider the loads from dynamic movements such as turning, jumping, rolling, and other advanced manoeuvres (Prokite Alby Rondina, 2020; Gratwick, 2023).

2. FEA Optimisation Techniques (Task 1)

2.1. Introduction to Finite Element Analysis

Finite element analysis is a computational technique which utilises the finite element method (FEM) to predict how a mechanical structure will respond to different environmental factors, such as force and temperature (Madier, 2020). This method can simulate complex geometries by dividing them into smaller finite element segments. Figure 1 illustrates various levels of mesh density with differences in element shapes. The middle example features triangles, while the right uses quadrilaterals. When applying the governing partial differential equations, these elements are more manageable and accurate for calculating properties like displacement (The Efficient Engineer, 2021; Ansys, 2024). This makes FEA especially useful for optimising sporting goods like kiteboards. It approximates localised stress and strain on the boards, minimising prototyping costs and lengthy reworks.

Figure 1 Examples of Element Shapes



(Source: FreeCAD, 2024)

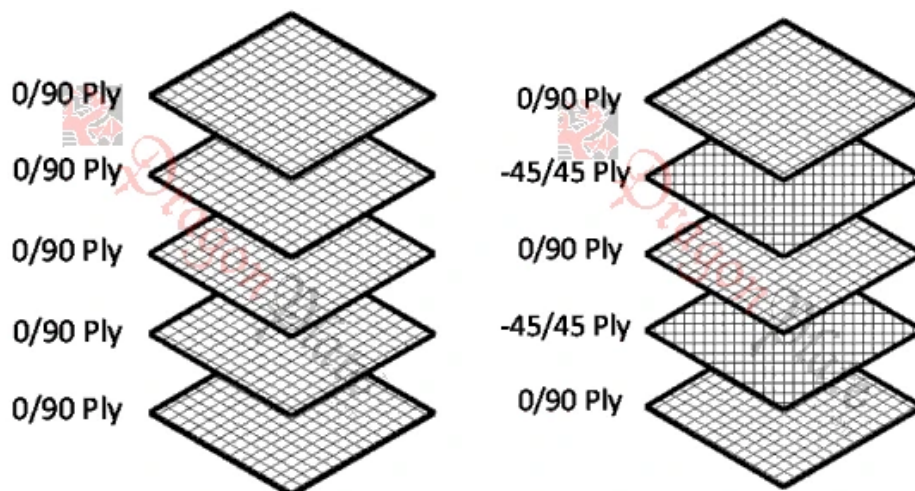
The history of FEA dates to the early 1940s. During this time, Hrennikof modelled the bending of plates using a lattice structure, which is like how modern FEM uses finite elements (Liu, Li, and Park, 2022). However, this method experienced significant limitations due to a lack of computational power at the time. One of the earliest instances of using computers to solve these problems used an IBM 701 digital computer at UC Berkley in the late 1950s, but it was limited to coarse meshes (FEA Academy, 2024). As technology improved, it became a popular design tool in industries like automotive and aerospace. Software like Ansys and Genisis have made the technology even more accessible.

2.2. Optimisation Techniques for Composites

Manufacturers often choose CFRP for kiteboard construction because it has a high-strength-to-weight ratio, low thermal expansion, and high fatigue strength (Öchsner and Altenbach, 2020; Wiedemann, 2023). As discussed in the fluid flow analysis, these properties help the board maintain dimensional stability during repeated impacts from landings, tricks, and general abuse from travelling and storage (Evans, 2024).

Figure 2 shows two different types of CFRP lay-ups. On the left is a 0/90 lay-up, while on the right is a -45/45 quasi-isotropic lay-up. The latter option is the most common because it offers a more balanced response in all in-plane directions, although it can be more expensive to produce (DragonPlate, 2019; The Efficient Engineer, 2023). This makes it more appropriate for dynamic sporting applications like kiteboarding, where the board will encounter forces from multiple directions while riding the waves.

Figure 2 Lay-up Comparison: 0/90 and -45/45



(Source: DragonPlate, 2019)

This optimisation effort aims to reduce the number of CFRP plies to decrease the mass while ensuring it does not flex more than its 2mm steel counterpart. The layers are arranged at angles of 0° , $\pm 45^\circ$, and 90° to approximate a quasi-isotropic lay-up and to observe its behaviour. The board thickness will be the variable. Design Studio for Genesis will seek to adjust the thickness until it achieves the optimal balance between weight and stiffness.

2.3. Future of FEA Optimisation

The future of FEA will likely include artificial intelligence (AI) and a significant increase in element counts. As computational power improves, this will lead to more accurate simulations in real time. This evolution would be reminiscent of how FEM was initially dismissed as a reasonable design tool but became more accessible with the rise of computers and FEA software. Ansys (2022; 2024), a developer of FEA software, supports these ideas. They state that high-performance computers (HPC) and cloud computing will help engineers solve the ever-increasing complex challenges in energy production, automation, and deep space travel more efficiently than ever.

Autodesk (2024) has already developed a cloud-based generative design solution. Although the tools are not technically FEA, they use a similar iterative process to Design Studio but by using AI (Formlabs, 2024). They adjust variables based on loading conditions to determine the best solution. While this example is unsuitable for this project, it improves the design process for 3D-printed components, enabling the production of highly lightweight, organic structures. As companies continue integrating AI into their workflows, FEA could improve through better structure response models, greater design accuracy, and faster setup times.

3. Initial Model in Design Studio (Task 2)

3.1. Material Properties and Orientation

Because of its superior properties, the kiteboard will use a unidirectional CFRP. It will be arranged in a quasi-isotropic lay-up to ensure directional stiffness. Table 1 lists the material properties input into Design Studio Genesis to simulate how it will behave. The Young's Modulus represents the stiffness of a material. In this instance, the material is much stiffer in the longitudinal direction than in the lateral. Since the material's stiffness varies with direction, the orthotropic material is assigned in the FEA setup (Solidworks, 2024).

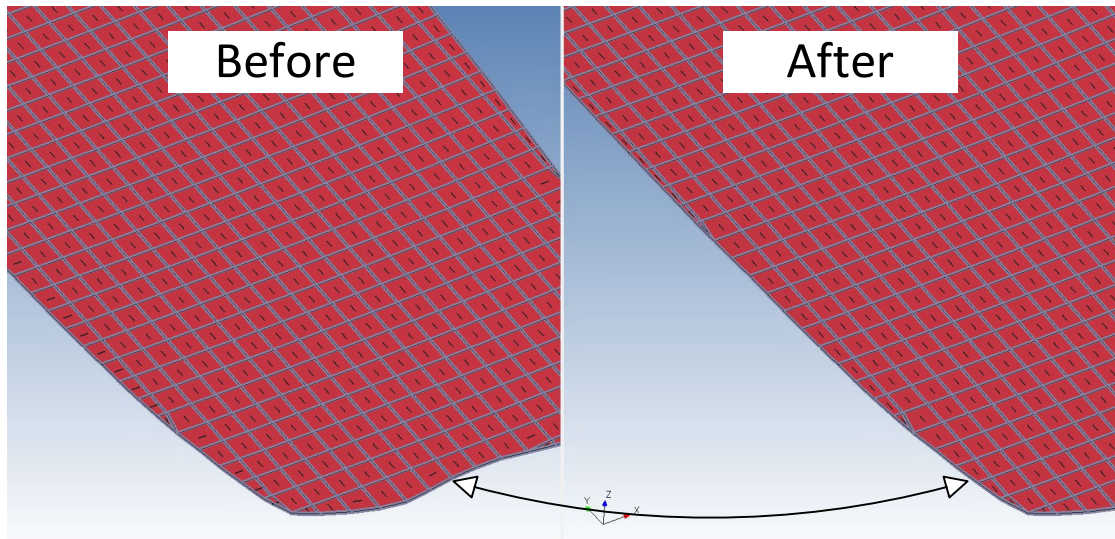
Table 1 Material Properties for CFRP

Material Properties	CFRP Values	Design Studio Input
Young's Modulus (Longitudinal)	132 GPa	132e9
Young's Modulus (Lateral)	10.8 GPa	10.8e9
Poisson's Ratio	0.24	0.24
In-plane Shear Modulus	5.65 GPa	5.65e9
Transverse Shear Modulus (1-Z plane)	5.65 GPa	5.65e9
Transverse Shear Modulus (2-Z plane)	5.65 GPa	5.65e9
Mass Density	1540 kg/m ³	1540
Allowable Longitudinal Stress in Tension	1513 MPa	1513e6
Allowable Longitudinal Stress in Compression	1000 MPa	1000e6
Allowable Transverse Stress in Tension	43.4 MPa	43.4e6
Allowable Transverse Stress in Compression	43.4 MPa	43.4e6
Allowable In-plane Shear Stress	43.4 MPa	43.4e6

(Source: Lake, 2024)

The next step was to address the orientation of the material. To maximise the advantages of the longitudinal Young's Modulus, the elements must align with the direction where the board experiences the most bending and flex, specifically along its length. This will help to minimise bending caused by the rider's weight, as their feet are placed along the length of the board and from any water impacting underneath. The elements of the initial model primarily ran longitudinally, except for this in the outer layer, which was disorganised. While the difference is subtle, it is illustrated in Figure 3.

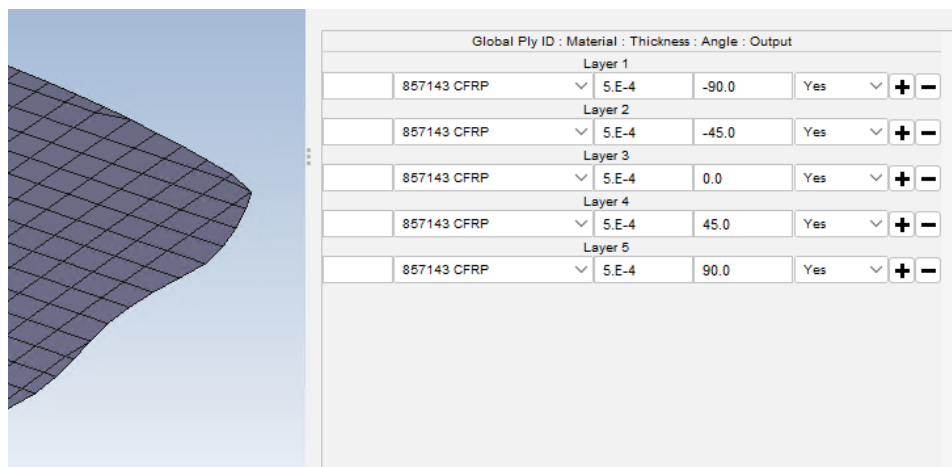
Figure 3 Before and After Element Corrections



(Source: Author's Figure)

The initial lay-up consists of 25 plies, each measuring 0.1mm thick. As per the project requirements (Lake, 2024), this results in a total board thickness of 2.5mm. Five plies are initially placed at an angle of -90° , and then the layers are rotated in increments of 45° until they reach an angle of 90° to create the quasi-isotropic lay-up. Figure 4 shows a screenshot of the lay-up. Please note that the total thickness measured is 0.025, as the software uses the International System of Units (SI).

Figure 4 Initial CFRP Lay-up in Design Studio

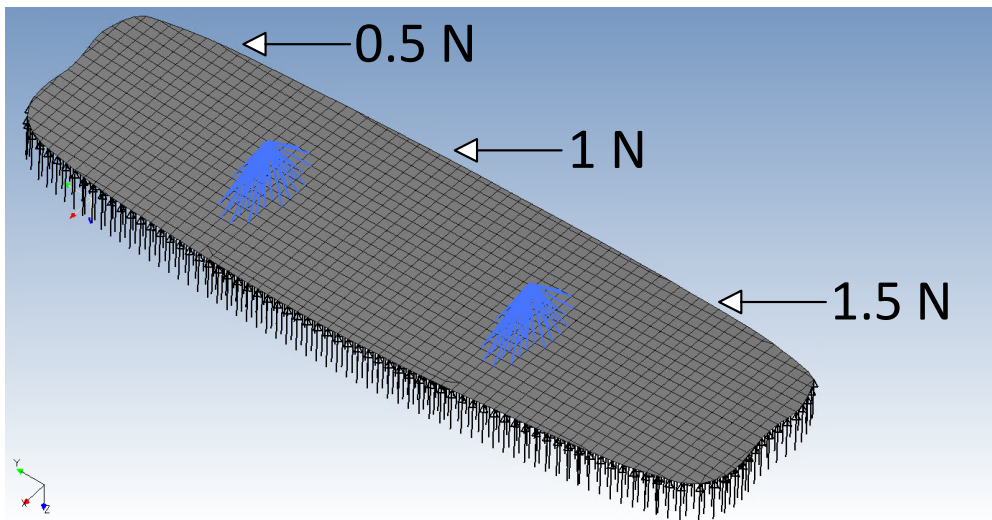


(Source: Author's Figure)

3.2. Boundary Conditions and Load-cases

The original file includes a uniformly distributed load (UDL) of one Newton applied to the bottom of the board. Since this application aims to determine the ideal number of plies needed to match the deflection of a 2mm steel board under the same conditions, this would likely be suitable. However, based on previous studies, there is an opportunity to refine this to more accurately represent how water interacts with the board in real life. For instance, the fluid flow analysis shows pressure changes across the kiteboard during operation (Evans, 2024). The leading edge will face the most pressure, which reduces towards the rear as the flow becomes turbulent. The board in Figure 5 is divided into three sections to create a more realistic simulation. The front experiences a force of 1.5 N, the middle section has a force of 1 N, and the rear section is 0.5 N. The board comprises 1464 grids, divided into three sections of approximately 488 each.

Figure 5 Static Load-case Distribution

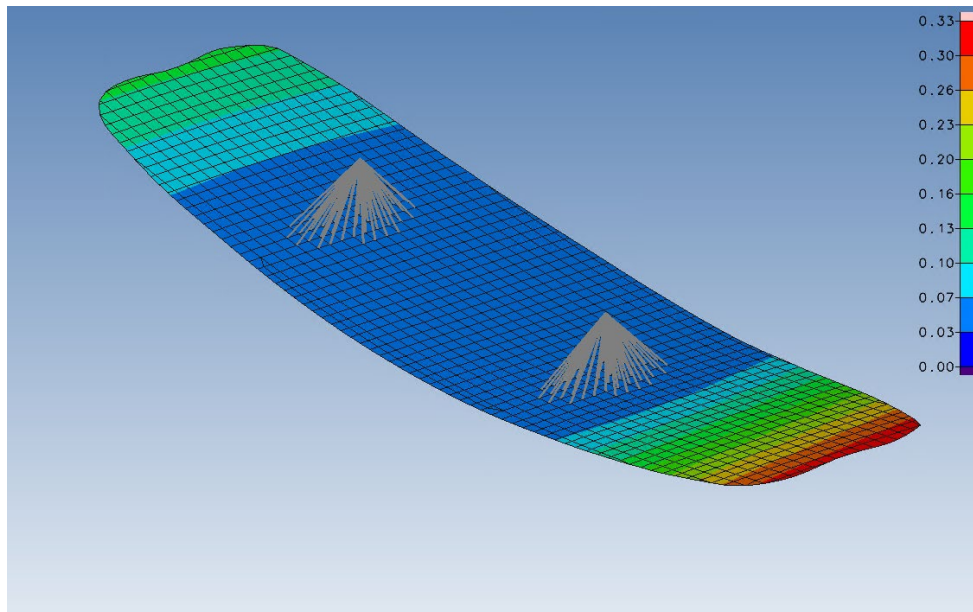


(Source: Author's Figure)

3.3. Initial Model Assessment

This analysis assesses how well the initial CFRP lay-up resists flexing and whether it matches or exceeds the displacement performance of a 2mm steel kiteboard under the same environmental conditions. Figure 6 shows the displacement contours of the CFRP, highlighting a maximum displacement of 0.33mm at the leading edge. In contrast, the steel board achieved a maximum displacement of 0.083mm (or $8.3\text{E-}2$).

Figure 6 Initial Model's Displacement Contours



(Source: Author's Figure)

In conclusion, the initial model did not attain a maximum displacement less than the target value of 0.083 of the steel board. This indicates that the current ply count or lay-up requires further refinement. The next step uses Design Studio Genesis to conduct the iterative calculations to optimise the CFRP board's performance. The initial model has served as a good starting point, with a displacement similar to the target properties.

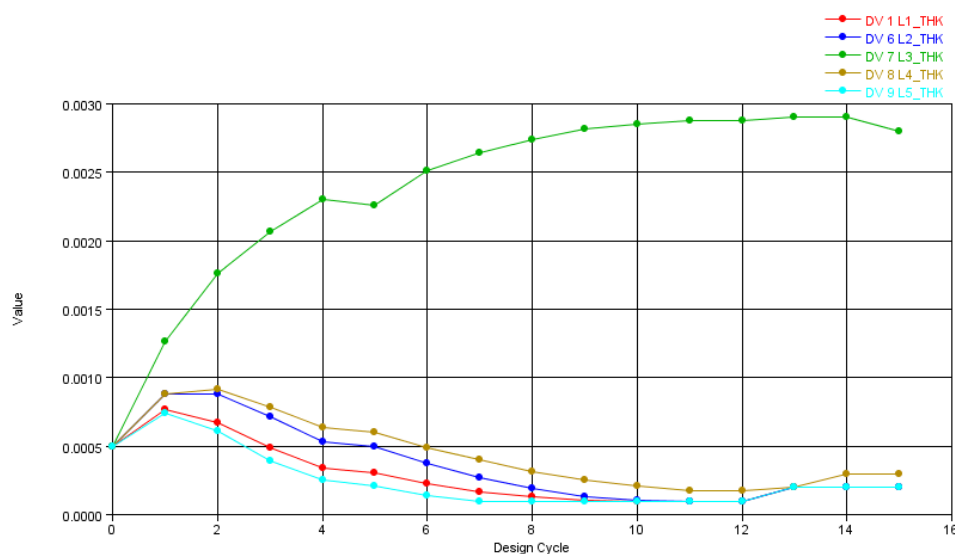
4. Structural Optimisation (Task 3)

4.1. Optimisation of Ply Thickness

Before optimising, three elements must be definable: the objective, the constraint, and the variables (Antoniadis, 2024). The design objective is clear: minimise the mass of the CFRP kiteboard while ensuring that its displacement is the same or less than the steel variant. This also introduces the design constraint: the maximum allowable displacement is 0.083mm, the steel board's limit. Additionally, the design variables focus on the layer thicknesses rather than the angles. The lowest bound for these thicknesses and the increments of their values are set to one ply. By limiting the thickness increments to 0.1mm, Design Studio Genesis will create components with thickness variations suitable for manufacturing.

Appendix A details how Design Studio Genesis completed 15 optimisation cycles before finalising the configuration. The final design features 31 plies and a total thickness of 3.7mm. It meets the displacement requirements while keeping the mass to a minimum. Figure 7 displays a graph that shows the design history. The horizontal axis represents the design cycle or iteration, while the vertical axis represents the layer thickness value. Interestingly, the layer that needed to be the thickest was L3_THK. It runs lengthwise down the board at an angle of 0° and is six times thicker than the other layers.

Figure 7 Design Cycle Iterations for Layer Thickness



(Source: Author's Figure)

Table 2 contains the lay-up configuration as determined by the optimiser. As previously noted, L3_THK (0°) is the thickest, measuring 2.8mm, equivalent to 28 plies of CFRP. The next is L4_THK (45°) at 0.3mm or three plies. The remaining layers are 0.2mm or two plies each. These results support prior assumptions. This is why the elements were repositioned to ensure that 0° runs lengthwise down the board in task 2. The total weight of the kiteboard is 2.99 kilograms, with a total thickness of 3.7mm.

Table 2 Optimised Lay-up Configuration

Layer Name	Layer Thickness (mm)	Ply Count	Angle (°)
L1_THK	0.2	2	-90.0
L2_THK	0.2	2	-45.0
L3_THK	2.8	28	0.0
L4_THK	0.3	3	45.0
L5_THK	0.2	2	90.0

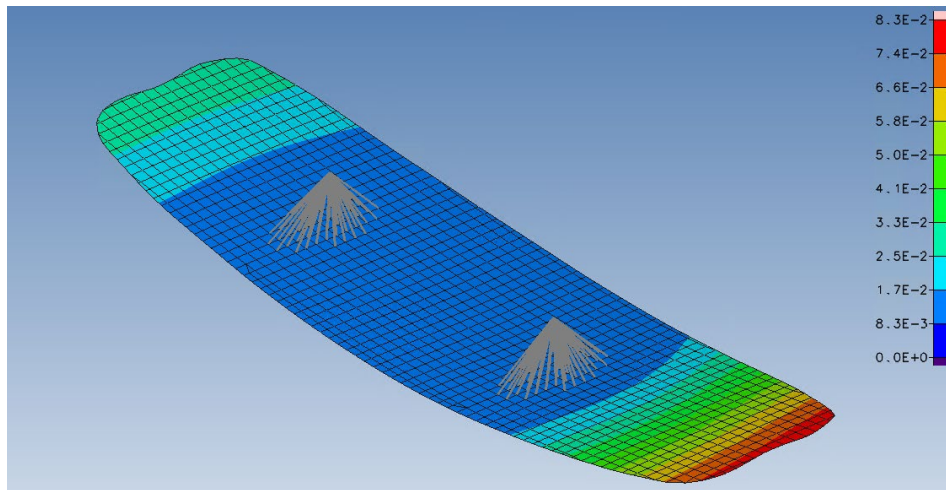
(Source: Author's Table)

4.2. Analysis of the Simulation Results

The final optimised lay-up successfully achieved the design objective of minimising weight while satisfying the displacement constraint of 0.083mm. In the optimisation setup, the maximum design cycles were set to an arbitrary 30 and the maximum thickness to 3 millimetres. Since neither limit was reached, the iterations proceeded as intended, and the optimisation was completed. Each design cycle adjusted the layer thickness by the intended increments, as shown in the design history in Appendix A. This continued until the displacement did not exceed the set constraint. As a result, the CFRP board successfully matched the stiffness of the steel while using minimal material.

Figure 8 shows the displacement contours from Design Studio Genesis, illustrating how the optimised kiteboard responded to the load case. As expected, the maximum displacement occurs at the leading edge, while the region below the rider's feet or bindings displaced the least. These were designated as rigid bodies in the simulation. The displacement distribution reflects the modified load case, which aimed to simulate the water pressures.

Figure 8 Optimised Model's Displacement Contours



(Source: Author's Figure)

4.3. Calculating Stiffness-to-Weight Ratio

The optimised CFRP component weighs 2.99 kilograms, significantly lighter than the 8.1-kilogram steel board. To further emphasise this achievement, the following calculations produce the stiffness-to-weight ratios of both materials. According to the Engineers Toolbox (2008), stiffness (k) is defined as force divided by mass. Since the baseline steel and optimised CFRP boards experience the same loading conditions and demonstrate the same amount of deflection, they have the same stiffness value.

$$k = \frac{1464}{0.083} = 17638.55 \text{ N/mm}$$

Next, the ratios are calculated. As the name implies, the ratio is determined by dividing the stiffness by weight (W). Weight is calculated by multiplying mass and gravity (BBC, 2024). The CFRP board achieved a stiffness ratio of 601.34, while the steel board had a ratio of 221.98. This means the optimised board is 2.71 times stiffer per unit weight than the steel.

$$\frac{k}{W_{Steel}} = \frac{17638.55}{8.1 * 9.81} = 221.98 \text{ N}^2/\text{mm}$$

$$\frac{k}{W_{CFRP}} = \frac{17638.55}{2.99 * 9.81} = 601.34 \text{ N}^2/\text{mm}$$

5. Prototype Testing and Validation (Task 4)

5.1. CFRP Kiteboard Construction

Prototype testing aims to create physical models based on the simulated designs to test them in real-world conditions. This ensures that the displacement, stiffness, and mass are consistent with the simulation data. Therefore, it is essential to construct the kiteboard prototype using the same method as the optimised CFRP board. This means using 0.1mm thick plies and arranging the layers in a -45/45 lay-up. Deviating from these properties will compromise the results as the physical foundation will differ from the digital version. The initial prototype should be cost-effective, built with minimal equipment, and represent the digital model. The proposed manufacturing method is a simple hand lay-up technique.

An operator applies resin to a pre-made mould and layers the carbon fibre cloth according to the optimal lay-up configuration (Easy Composites, 2024a). The mould will be machined from a high-temperature epoxy tooling board with a sealed surface, making it suitable for use as a mould (Easy Composites, 2017; Easy Composites, 2024b). The material is quite expensive, costing approximately £500 for a 1500 x 500 cm sheet that is 50mm thick. This size is necessary to fit a kiteboard's large dimensions and achieve the deep curvature required for the kiteboard's rocker (Liweuwe, 2024). Alternatively, the lay-up can be done separately on a glass plane and then shaped using a wooden rocker table for a lower cost (Fibreglass Supply, 2021), as shown in Figure 9.

Figure 9 DIY Kiteboard Rocker Table



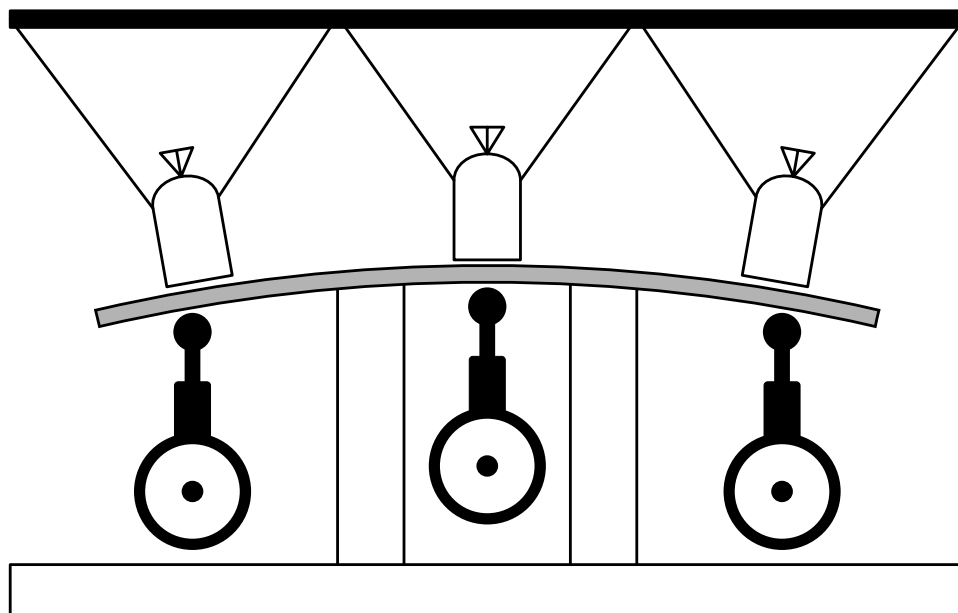
(Source: Fibreglass Supply, 2021)

5.2. Testing and Validation Methods

After finishing the initial CFRP kiteboard prototype, it will undergo testing to ensure it meets the required specifications and that the current simulation provides accurate displacement results. The testing method must simulate the forces the board experiences in Design Studio Genesis. This involves a gradual load case that starts at 1.5 newtons at the leading edge, decreases to 1 newton in the middle, and drops to 0.5 newtons at the end.

The proposed testing system will be set up as follows: The board will be mounted upside down on two columns where the rider's feet would usually be fixed. This configuration aligns with the rigid bodies used in the simulations, ensuring the results remain accurate. Several dial test indicators will be placed underneath the board, facing up, to measure the displacement as the load is applied. By increasing the number of indicators, measuring any twist in the board is also possible. Figure 10 illustrates the prototype testing setup, utilising weighted bags to replicate wave forces. This approach is inspired by water weights, sometimes employed in industry for testing cranes and bridges (Unique Group, 2020; Scaffold Type, 2024).

Figure 10 Prototype Displacement Testing Setup



(Source: Author's Figure)

One concern about applying the weight is how to attach it safely without affecting the board's construction. For instance, it is preferable to avoid placing the bags directly on the board, clamping them, or tying them down. Instead, the bags will be suspended from above and lowered onto the board. This method will prevent the bags from falling off and causing harm while minimising external factors that could affect the results. The weight of the bags will vary based on the specified force and location: 1.5 N at the front, 1.9 N in the middle, and 0.5 N at the rear. Using Newton's second law of motion, the following calculations produce the mass needed to apply the desired forces.

$$F = ma \therefore m = \frac{F}{a}$$

$$m_{front} = \frac{1.5}{9.81} = 0.153kg$$

$$m_{middle} = \frac{1.9}{9.81} = 0.194kg$$

$$m_{rear} = \frac{0.5}{9.81} = 0.051kg$$

After collecting the data, the results must be reviewed and compared with the simulation. If there are any significant discrepancies, the entire design will need to be reworked, and the prototype and testing phases will need to be repeated.

6. Conclusion

This FEA optimisation project successfully met the displacement goals outlined in the assessment specification. The final thickness measured 3.7mm and had a mass of 2.99 kilograms, resulting in a stiffness-to-weight ratio 2.71 times greater than that of the steel board. The prototype testing method applied the specified loads and measured the resulting displacement to validate the simulation results. The project demonstrated the potential of CFRP as a material for kiteboards. However, there is room for improvement as the current design differs from the fluid flow analysis and industry standards, which typically use sandwich structures to minimise weight (Evans, 2024; Appletree Surfboards, 2024). Future work should revisit these designs, incorporate fins into the simulation model, and reassess the optimisation potential with them.

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8. Appendices

8.1. Appendix A

DESIGN CYCLE # 0, OBJECTIVE = 2.025439E+00, MAXIMUM VIOLATION = 296.4%.

DESIGN VARIABLE # 1 = 5.000000E-04 L1_THK

DESIGN VARIABLE # 6 = 5.000000E-04 L2_THK

DESIGN VARIABLE # 7 = 5.000000E-04 L3_THK

DESIGN VARIABLE # 8 = 5.000000E-04 L4_THK

DESIGN VARIABLE # 9 = 5.000000E-04 L5_THK

DESIGN CYCLE # 1, OBJECTIVE = 3.682552E+00, MAXIMUM VIOLATION = 22.4%.

DESIGN VARIABLE # 1 = 7.706220E-04 L1_THK

DESIGN VARIABLE # 6 = 8.846847E-04 L2_THK

DESIGN VARIABLE # 7 = 1.266405E-03 L3_THK

DESIGN VARIABLE # 8 = 8.808730E-04 L4_THK

DESIGN VARIABLE # 9 = 7.427903E-04 L5_THK

DESIGN CYCLE # 2, OBJECTIVE = 3.920526E+00, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE # 1 = 6.723787E-04 L1_THK

DESIGN VARIABLE # 6 = 8.801575E-04 L2_THK

DESIGN VARIABLE # 7 = 1.757813E-03 L3_THK

DESIGN VARIABLE # 8 = 9.184337E-04 L4_THK

DESIGN VARIABLE # 9 = 6.103246E-04 L5_THK

DESIGN CYCLE # 3, OBJECTIVE = 3.606241E+00, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE # 1 = 4.861653E-04 L1_THK

DESIGN VARIABLE # 6 = 7.146512E-04 L2_THK

DESIGN VARIABLE # 7 = 2.064532E-03 L3_THK

DESIGN VARIABLE # 8 = 7.891018E-04 L4_THK

DESIGN VARIABLE # 9 = 3.967347E-04 L5_THK

DESIGN CYCLE # 4, OBJECTIVE = 3.292903E+00, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE # 1 = 3.411856E-04 L1_THK

DESIGN VARIABLE # 6 = 5.346900E-04 L2_THK

DESIGN VARIABLE # 7 = 2.299355E-03 L3_THK

DESIGN VARIABLE # 8 = 6.396095E-04 L4_THK

DESIGN VARIABLE # 9 = 2.495916E-04 L5_THK

DESIGN CYCLE # 5, OBJECTIVE = 3.144811E+00, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE # 1 = 3.046276E-04 L1_THK

DESIGN VARIABLE # 6 = 4.981319E-04 L2_THK

DESIGN VARIABLE # 7 = 2.262797E-03 L3_THK

DESIGN VARIABLE # 8 = 6.030515E-04 L4_THK

DESIGN VARIABLE # 9 = 2.130336E-04 L5_THK

DESIGN CYCLE # 6, OBJECTIVE = 3.039717E+00, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE # 1 = 2.286456E-04 L1_THK

DESIGN VARIABLE # 6 = 3.781585E-04 L2_THK

DESIGN VARIABLE # 7 = 2.512429E-03 L3_THK

DESIGN VARIABLE # 8 = 4.924209E-04 L4_THK

DESIGN VARIABLE # 9 = 1.402699E-04 L5_THK

DESIGN CYCLE # 7, OBJECTIVE = 2.896756E+00, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE # 1 = 1.678337E-04 L1_THK

DESIGN VARIABLE # 6 = 2.669610E-04 L2_THK

DESIGN VARIABLE # 7 = 2.643678E-03 L3_THK

DESIGN VARIABLE # 8 = 3.969940E-04 L4_THK

DESIGN VARIABLE # 9 = 1.000000E-04 L5_THK

DESIGN CYCLE # 8, OBJECTIVE = 2.812315E+00, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE # 1 = 1.309471E-04 L1_THK

DESIGN VARIABLE # 6 = 1.903984E-04 L2_THK

DESIGN VARIABLE # 7 = 2.736951E-03 L3_THK

DESIGN VARIABLE # 8 = 3.128795E-04 L4_THK

DESIGN VARIABLE # 9 = 1.000654E-04 L5_THK

DESIGN CYCLE # 9, OBJECTIVE = 2.759512E+00, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE # 1 = 1.063746E-04 L1_THK

DESIGN VARIABLE # 6 = 1.341342E-04 L2_THK

DESIGN VARIABLE # 7 = 2.814570E-03 L3_THK

DESIGN VARIABLE # 8 = 2.509885E-04 L4_THK

DESIGN VARIABLE # 9 = 1.000000E-04 L5_THK

DESIGN CYCLE # 10, OBJECTIVE = 2.728255E+00, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE # 1 = 1.000000E-04 L1_THK

DESIGN VARIABLE # 6 = 1.022266E-04 L2_THK

DESIGN VARIABLE # 7 = 2.853055E-03 L3_THK

DESIGN VARIABLE # 8 = 2.122038E-04 L4_THK

DESIGN VARIABLE # 9 = 1.000000E-04 L5_THK

DESIGN CYCLE # 11, OBJECTIVE = 2.714662E+00, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE # 1 = 1.000000E-04 L1_THK

DESIGN VARIABLE # 6 = 1.000000E-04 L2_THK

DESIGN VARIABLE # 7 = 2.877265E-03 L3_THK

DESIGN VARIABLE # 8 = 1.734428E-04 L4_THK

DESIGN VARIABLE # 9 = 1.000000E-04 L5_THK

DESIGN CYCLE # 12, OBJECTIVE = 2.714662E+00, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE # 1 = 1.000000E-04 L1_THK

DESIGN VARIABLE # 6 = 1.000000E-04 L2_THK

DESIGN VARIABLE # 7 = 2.877265E-03 L3_THK

DESIGN VARIABLE # 8 = 1.734428E-04 L4_THK

DESIGN VARIABLE # 9 = 1.000000E-04 L5_THK

DESIGN CYCLE # 13, OBJECTIVE = 2.997649E+00, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE # 1 = 2.000000E-04 L1_THK

DESIGN VARIABLE # 6 = 2.000000E-04 L2_THK

DESIGN VARIABLE # 7 = 2.900000E-03 L3_THK

DESIGN VARIABLE # 8 = 2.000000E-04 L4_THK

DESIGN VARIABLE # 9 = 2.000000E-04 L5_THK

DESIGN CYCLE # 14, OBJECTIVE = 3.078667E+00, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE # 1 = 2.000000E-04 L1_THK

DESIGN VARIABLE # 6 = 2.000000E-04 L2_THK

DESIGN VARIABLE # 7 = 2.900000E-03 L3_THK

DESIGN VARIABLE # 8 = 3.000000E-04 L4_THK

DESIGN VARIABLE # 9 = 2.000000E-04 L5_THK

DESIGN CYCLE # 15, OBJECTIVE = 2.997649E+00, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE # 1 = 2.000000E-04 L1_THK

DESIGN VARIABLE # 6 = 2.000000E-04 L2_THK

DESIGN VARIABLE # 7 = 2.800000E-03 L3_THK

DESIGN VARIABLE # 8 = 3.000000E-04 L4_THK

DESIGN VARIABLE # 9 = 2.000000E-04 L5_THK

COMPLETION CODE: 1 13 0