



Prifysgol Cymru
Y Drindod Dewi Sant
University of Wales
Trinity Saint David

Designing a Kiteboard: Structural Design
Structural & Fluid Analysis (ACMA6010)
Part 2

Scott Roberts

Student No: 1451418

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1 Introduction

Finite Element Analysis (FEA) optimisation is critical aspect of engineering design which combines numerical simulation with optimisation techniques to enhance structural performance, reduce weight and improve overall efficiency (Seshu, 2004). This report builds upon the previously submitted report, Design a Kiteboard: Fluid Flow Assessment, Structural & Fluid Analysis (Roberts, 2024). The initial report provided an overview of the fundamental engineering principles relevant to kiteboard design, including structural consideration and fluid dynamic.

This report is intended to document the optimisation of a kiteboard utilising composite material, ensuring that it does not flex beyond the deflection observed in a 2mm steel equivalent. The material selected for the optimisation is carbon fibre reinforced plastic (CFRP). This report uses computational simulations to analyse the structural response depending on different ply orientation to determine the optimal lay up configuration.

This report also explores the historical developments in FEA optimisation techniques, assess the feasibility of a prototype validation experiment and how this should performed.

1.1 Aims & Objectives

1.1.1 Aim

The aim of this report is to apply FEA optimisation techniques to design a lightweight and structurally efficient kiteboard by optimising the layup configuration of CFRP. This will be performed while ensuring that its deflection does not exceed that of a 2mm steel equivalent.

1.1.2 Objectives

The aim will be achieved by achieving the following objectives:

- 1) Discuss FEA optimisation techniques, exploring how they have developed historically and how they may develop in the future.
- 2) Develop and assess an initial model of the board, implementing material properties, applying forces and evaluating deflections.
- 3) Optimise the composite structure, minimising the mass by adjusting ply orientation while maintaining the structural integrity.
- 4) Discuss experimental validation of a prototype, how this would be performed and data obtained to compare to simulation results.

2 Finite Element Analysis and Optimisation

2.1 Background to Finite Element Analysis

Finite Element Analysis (FEA) optimisation techniques have undergone significant advancements, evolving from manual calculations to sophisticated computational methods. These developments have been driven by increasing computational power and the refinement of numerical techniques (Ramamurty, 2013). FEA emerged as a crucial tool for solving complex engineering problems that are challenging or impossible to address analytically. The process involves the discretising a structure into smaller finite elements, assigning material properties, defining boundary conditions and incorporating environmental factors to simulate real world performance. Figure 1 provides an overview of the FEA workflow, illustrating the systematic approach used to model and optimise structural performance.

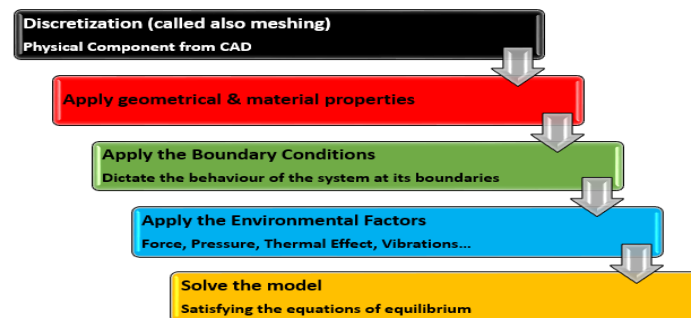


Figure 1: Summarised steps involved in performing FEA (FEA Academy, 2025).

FEA provides a means to evaluate stress, deformation and other critical structural parameters. This provides an insight into a structure's performance under various loading condition allowing for an optimal design to be selected.

2.2 Historical Development of FEA Optimisation

FEA optimisation in engineering predates the use of modern computational methods, with early structural optimisations relying on manual calculations and analytical techniques. Before the rise of digital computing, engineers used simplified mathematical models to refine structural design. One of the earliest approaches to discretisation was introduced in the 1940s by A.Hrrenikoff, who developed a lattice framework model to approximate membrane and plate behaviour publishing his findings in the ASME Journal of Applied Mechanics (Liu, et al., 2022).

The concept of FEA based optimisation gained momentum in the 1960s to 1970s, driven by the need for more efficient structural designs. Early optimisation focussed on shape and size optimisation, improving structural performance while minimising material use (Schmit, 1960).

These early optimisation techniques adopted using FEA began the integration of mathematical programming techniques with the use of digital computation.

In the 1980s, topology optimisation emerged as a major advancement in structural design. This was as a result of the development of the homogenisation method by Martin Bendsoe and Nobu Kikuchi, the method is a mathematical approach used in topology optimisation to determine optimal material distribution in a design (Bendsoe & Kikuchi, 1988). Their work has formed the foundation for modern topology optimisation techniques.

As computational power has continued to grow, FEA optimisation has become increasingly sophisticated, enabling more efficient integration of advanced design techniques. The development of specialised FEA software has further streamlined the optimisation process, providing engineers with intuitive tools to refine and enhance structural designs with greater accuracy and efficiency.

2.3 Future Development of FEA Optimisation

The future of FEA optimisation is predicted to be shaped by advances in artificial intelligence (AI), further improvements in computational power, quantum computing and further advances in simulations (Banga, 2021). The future developments will likely lead to the development of deep learning models and reinforced learning, which will improve efficiency by enabling the reduction of computational cost. Quantum computing could also improve structural optimisation by enabling the solving of complex multi-variable problem faster than traditional methods. Additionally, advancing real-time optimisation where real time sensor data can update FEA models to adapt designs (Glaessgen & Stargel, 2012).

2.4 Design Process Improvements using FEA

FEA optimisation has become an essential tool for engineers and designers across various industries, providing numerous benefits that enhance the design process. According to a blog published by Rishabh Engineering (Rishabh Engineering , 2025), the following are key factors that highlight the benefits of FEA optimisation:

- Material Selection and Optimisation.
- Risk Mitigation.
- Comprehensive Analysis.

2.4.1 Cost Efficiency. Material Selection and Optimisation

FEA can aid correct material selection and optimisation enabling engineers to simulate performance of various materials under different conditions. The use of topology optimisation, allows engineers to distribute materials efficiently within a design to reduce

weight without compromising strength or durability (Bendsoe & Sigmund, 2003). This is of particular value in industries such as aerospace, where material efficiency leads to significant performance improvements and cost savings.

2.4.2 Risk Mitigation

FEA plays a critical role in risk mitigation allowing engineers to predict and solve potential failure points in the design before the creation of physical prototypes. By being able to simulate how the design reacts under different conditions then FEA can identify potential weak spots, reducing the risk of costly or dangerous incidents (Gibson, et al., 2014). The use of FEA can help to simulate extreme conditions, such as high pressures or impact scenarios which can prevent catastrophic failures. FEA optimisation can also assist in optimising designs for durability and long term performance where potentially repeated stress could be a factor (Reddy, 2006).

2.4.3 Comprehensive Analysis

FEA allows for comprehensive analysis by simulating a design's performance across a range of different parameters such as mechanical, fluid, thermal behaviours all in a single integrated model (Zienkiewicz & Taylor, 2005). This comprehensive approach enables the optimisation of complex systems considering all interacting factors.

2.4.4 Cost Efficiency

FEA offers a cost efficient way to design and optimise by enabling virtual testing, which reduces the need for physical prototypes and extensive testing. It allows engineers to predict performance and design flaws early in the process, which saves both time and money. FEA optimisation can also reduce the number of prototypes required hence also reducing material usage (Svanberg, 2007). This is an important benefit especially in industries where high quality materials are expensive such as in aerospace and automotive industries.

3 Baseline Board Analysis

3.1 Steel Baseline Simulation

The purpose of the baseline kiteboard analysis is to evaluate the performance of the provided kiteboard design, as shown in Figure 2. This initial simulation will assume the board is constructed from 2mm steel with typical material properties as seen in Table 1. The results from this baseline simulation will serve as a reference point for subsequent FEA optimisation.

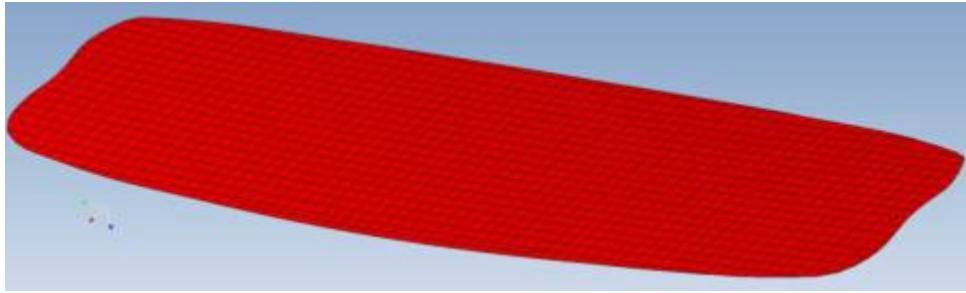


Figure 2: Geometry of the Kiteboard Design.

3.2 Application of the Uniformly Distributed Load (UDL)

A uniformly distributed load (UDL) was applied to the model to simulate forces acting on the board. This UDL would remain a constant when performing FEA optimisation. The UDL was selected based off previous research performed during assignment 1, within this assignment it was concluded that a total compressive force of 1464 N could be foreseeable on the kiteboard. This UDL was applied to the underside of the kiteboard, as shown in Figure 3.

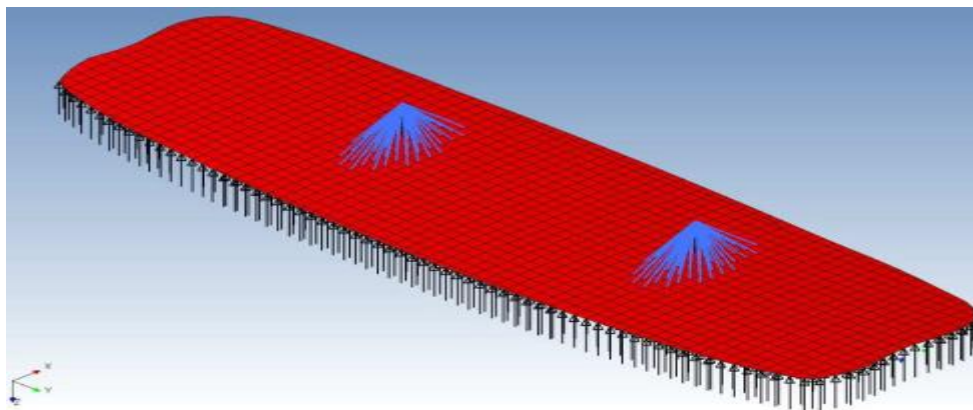


Figure 3: Application of a 1464 N UDL.

The baseline simulation was performed using the single analysis function, resulting in a maximum deflection of 59 mm as shown in Figure 4.

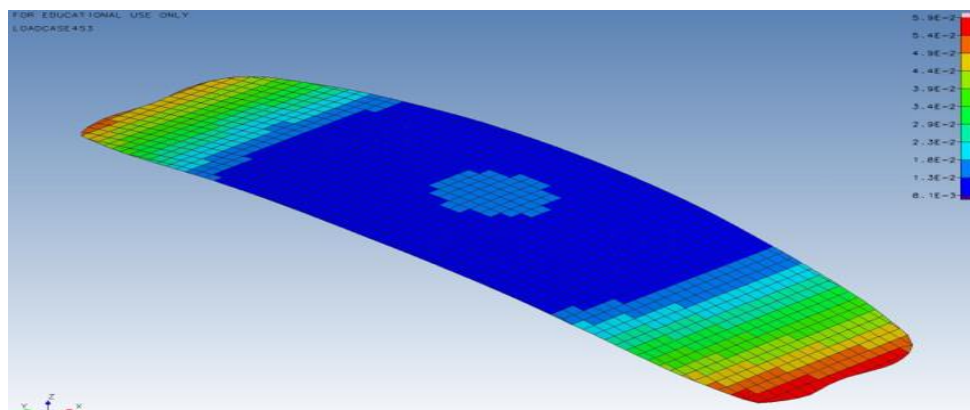


Figure 4: Baseline Kiteboard (2mm Steel) Simulation Result.

The baseline kiteboard, constructed from 2mm thick steel had a total weight of 8108.79 grams. The stiffness of the kiteboard was determined using Equation 1 (Hibbeler, 2017). The results from the simulation of the steel baseline kiteboard are summarised in Table 1.

$$k = \frac{F}{\delta} \quad (Eq. 1)$$

Where:

k = Stiffness

F = Applied Force

δ = Deflection

Simulation	Material	Thickness (mm)	Deflection (mm)	Mass (g)	Load (N)	Stiffness (N/mm)	Stiffness/Weight Ratio (N ² /mm)
Steel Baseline	Steel	2	59	8108.79	1462	24.78	0.0003117

Table 1: 2mm Steel Kiteboard Baseline Simulation Results.

3.3 CFRP Baseline Simulation

Prior to performing FEA optimisation of the kiteboard design, a baseline CFRP simulation was necessary to compare its performance against the initial 2mm steel construction. The material properties were adjusted to represent CFRP, with typical material properties seen in Table 2.

Young's Modulus in the longitudinal direction	132 GPa
Young's Modulus in the lateral direction	10.8 GPa
Poissons Ratio	0.24
Inplane Shear Modulus	5.65 GPa
Transverse Shear Modulus	5.65 GPa
Transverse Shear Modulus	5.65 GPa
Mass Density	1540 kg/m ³
Allowable longitudinal stress in tension	1513 MPa
Allowable longitudinal stress in compression	1000 MPa
Allowable transverse stress in tension	43.4 MPa
Allowable transverse stress in compression	43.4 MPa
Allowable inplane shear stress	43.4 MPa

Table 2: Summary of Material Properties used for the Unidirectional CFRP.

The unidirectional CFRP material was arranged in the layup sequence shown in Table 3, with each layer assumed to be 0.1 mm thick. This resulted in a total of 25 layers, giving the structure an overall thickness of 2.5 mm.

Fibres oriented at -90 degrees	5 Layers
Fibres orientated at -45 degrees	5 Layers
Fibres orientated at 0 degrees	5 Layers
Fibres orientated at 45 degrees	5 Layers
Fibres orientated at 90 degrees	5 Layers

Table 3: Lay-up Sequence of CFRP Baseline Simulation.

The baseline CFRP kiteboard, constructed from 2.5 mm CFRP had a total weight of 2025.44 grams. The simulation concluded a deflection of 230 mm as shown in Figure 5. The results from the simulation of the CFRP baseline are summarised in Table 4.

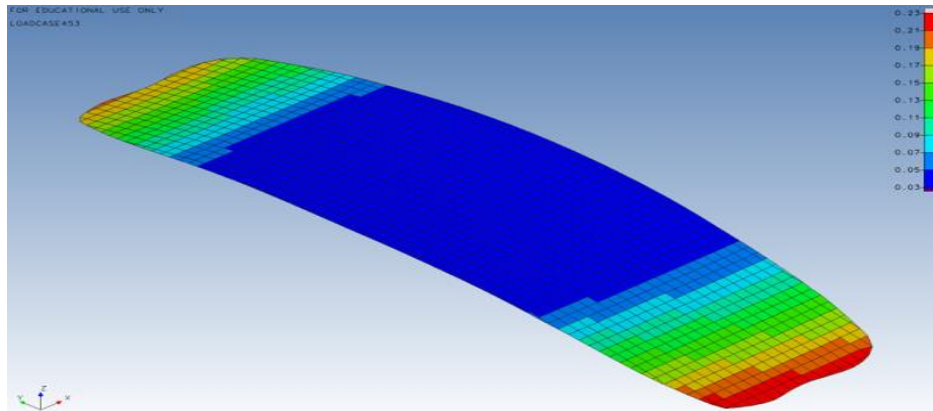


Figure 5: Baseline CFRP Kiteboard Simulation Result.

Simulation	Material	Thickness (mm)	Deflection (mm)	Mass (g)	Load (N)	Stiffness (N/mm)	Stiffness/Weight Ratio (N ² /mm)
CFRP Baseline	CFRP	2.5	230	2025.44	1462	6.36	0.0003199

Table 4: CFRP Kiteboard Baseline Simulation Results.

3.4 Steel vs CFRP Baseline Comparison

The CFRP baseline simulation demonstrates a significant mass reduction, achieving a 75% decrease compared to the 2mm steel baseline. However, this comes at the cost of increase deflection, with the CFRP baseline design exhibiting a 290% higher deflection that the steel baseline. As a result, the stiffness to weight ratio does not show a clear advantage.

The key optimisation focus is to minimise deflection, ensuring that the CFRP constructed kiteboard does not exceed the deflections observed in the 2mm steel baseline simulation of 59 mm. Additionally, the optimisation process will aim to reduce material usage to further decrease weight while maintaining the structural integrity and performance.

4 FEA Optimisation of CFRP Kiteboard

4.1 Optimisation 1

FEA optimisation of the CFRP kiteboard was focussed on the reduction of the deflection. Therefore, further simulations were setup with a constraint to limit deflection to 59 mm equalling the deflection achieved by the 2 mm steel baseline design. The simulation was performed on the CFRP kiteboard design, using the same material properties as the CFRP baseline simulation. The results from the first CFRP optimisation run are summarised in Table 5.

Simulation	Material	Thickness (mm)	Deflection (mm)	Mass (g)	Load (N)	Stiffness (N/mm)	Stiffness/Weight Ratio (N ² /mm)
CFRP Optimised	CFRP	4.02	58	3254.38	1462	25.21	0.0007895

Table 5: CFRP Kiteboard Optimisation 1 Simulation Results.

The simulation returned a deflection of 58 mm as shown in Figure 6, as a result increasing the stiffness to weight ratio.

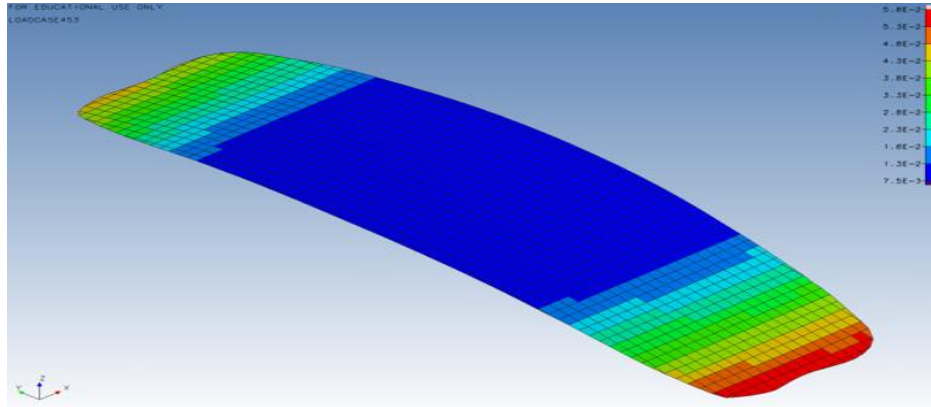


Figure 6: CFRP Kiteboard Optimisation 1 Simulation Result.

The simulation optimised the CFRP design to achieve the required deflection by increasing the thickness of the CFRP, which consequently led to a higher mass compared to the initial CFRP baseline. The optimisation process determined an ideal unidirectional CFRP layup sequence, as shown in Table 6 with each layer assumed to be 0.1 mm thick.

Fibres orientated at -90 degrees	2.04 Layers
Fibres orientated at -45 degrees	2.97 Layers
Fibres orientated at 0 degrees	20 Layers
Fibres orientated at 45 degrees	14 Layers
Fibres orientated at 90 degrees	1 Layers

Table 6: Lay-up Sequence of CFRP Optimisation 1 Simulation.

However, the optimisation process selected an impractical layup sequence, with both -90 degrees and -45 degrees layers not being able to be manufactured using 0.1 mm ply's. As a result of this a further FEA optimisation was performed using discrete values for the layer thicknesses to ensure manufacturability.

4.2 Optimisation 2

Discrete design variable settings were applied to restrict the layer thicknesses to increments of 0.1 mm. The results from the second CFRP optimisation run are summarised in Table 7.

Simulation	Material	Thickness (mm)	Deflection (mm)	Mass (g)	Load (N)	Stiffness (N/mm)	Stiffness/Weight Ratio (N ² /mm)
CFRP Discrete	CFRP	4.2	55	3402.74	1462	26.58	0.0007963

Table 7: CFRP Kiteboard Optimisation 2 Simulation Results.

The simulation returned a deflected of 55 mm as shown in Figure 7, again resulting in an increase in the stiffness to weight ratio.

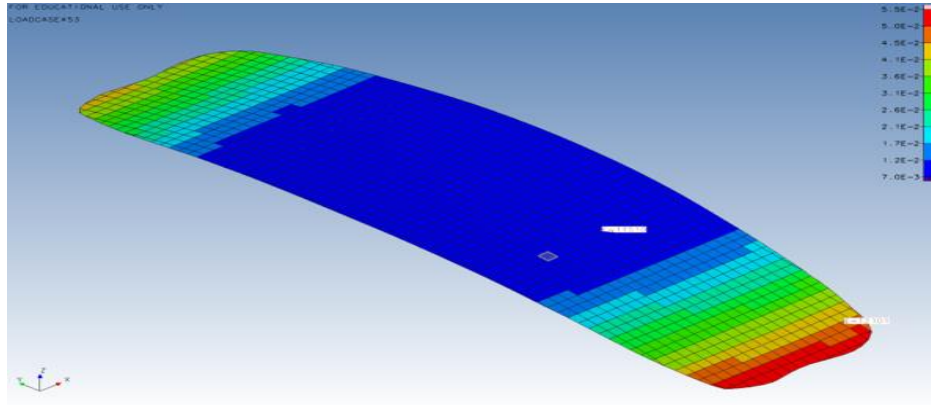


Figure 7: CFRP Kiteboard Optimisation 1 Simulation Result.

The optimisation successfully provided a practical layup sequence as shown in Table 8 while achieving a reduced deflection result.

Fibres oriented at -90 degrees	3 Layers
Fibres orientated at -45 degrees	4 Layers
Fibres orientated at 0 degrees	20 Layers
Fibres orientated at 45 degrees	14 Layers
Fibres orientated at 90 degrees	1 Layers

Table 8: Lay-up Sequence of CFRP Optimisation 2 Simulation.

4.3 FEA Optimisation Analysis

To achieve the same deflection as the 2 mm steel baseline, the CFRP baseline design required an increase in both thickness and mass. The thickness was increased from 2.5 mm to 4.2 mm, resulting in a 68% mass increase compared to the second CFRP optimisation with applied discrete variable.

However, despite this increase the optimised CFRP design achieves a 58% mass reduction when compared to the initial 2 mm steel baselined, which established the deflection benchmark of 59 mm. Additionally, the optimised CFRP design demonstrates a 155% improvement in the strength to weight ratio over the steel baseline, highlighting significantly more efficient design in terms of both weight reduction and structural performance.

5 FEA Simulation Validation Testing

To validate the FEA simulation model, an experimental setup could be designed and analysed to compare real world deflection with the simulated results. The primary objective of the simulation model was to predict deflection across various kiteboard designs. The experimental validation will ensure the accuracy and reliability of the simulation by confirming that it accurately represents real world behaviour, increasing confidence in the simulation model's predictive capabilities.

5.1 Test Method

The experimental validation must be designed to enable the controlled application of load, allowing for accurate measurement of a prototype board's deflection. The FEA simulation model applied a UDL of 1464 N across the kiteboard. Therefore, the chosen test method must closely replicate these loading conditions to ensure a valid comparison between the experimental and the simulation model. The following testing specifications would be required:

- **Kiteboard Specification:** Kiteboard prototype would be produced using the correct dimensions and material CFRP properties with the correct lay-up.
- **Load Application:** A UDL of 1464 N must be applied across the kiteboard.
- **Deflection Measurement:** High precision instruments will be used to measure displacement.
- **Data:** Captured via a measurement system collecting deflection data, process and analysed against FEA simulation results.

To effectively apply a UDL across the kiteboard, a stable and reliable test environment is required. A steel support structure is the most suitable choice, as it provides the necessary rigidity to prevent unwanted deformation, which would otherwise introduce errors into the results. A simplified representation of the proposed support structure is shown in Figure 8.

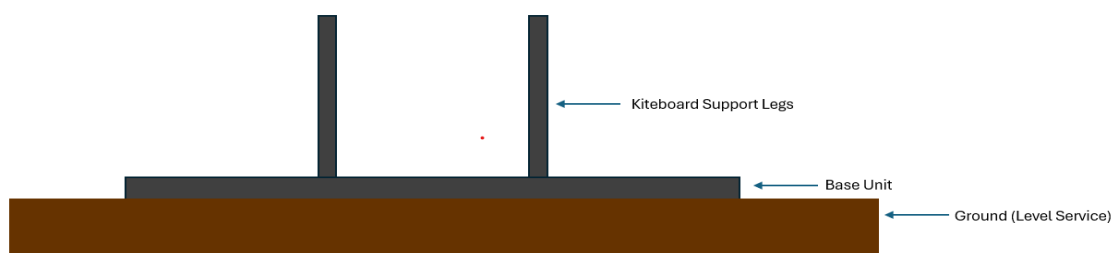


Figure 8: Illustration of Steel Support Structure.

To measure the deflection it is proposed to use dial test indicator (DTI) gauges. The board will be positioned on the support structure, placed on the support legs as shown in Figure 9.

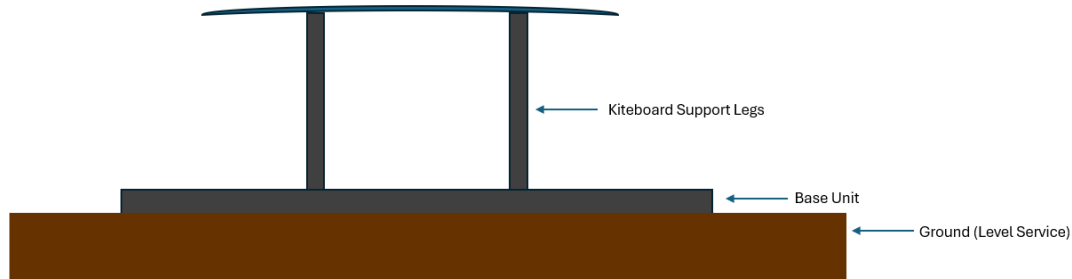


Figure 9: Illustration of the proposed placement of Kiteboard.

DTI gauges will be strategically placed across the kiteboard to monitor deflection. A UDL of 1464 will be applied evenly across the kiteboard's surface. As the load is introduced, the DTI gauges will record deflections at the designated measurement points. To apply the UDL, it is proposed to use sandbags as a cost effective method of distributing the force across the board. Assuming the use of a 10 kg sandbag, the number of sandbags required can be determined by first calculating the weight of a single sandbag using Equation 2. This equation calculates the weight in Newtons based on the sandbag's mass.

$$w = m * g \quad (Eq. 2)$$

Where:

w = Weight of a single sandbag in N

m = Mass of Sandbag (Kg)

g = Gravity (m/s^2)

The weight of a 10 kg sandbag is calculated to be 98.1 N, meaning that approximately 14.9 sandbags are needed to apply a total force of 1464N. However, to ensure the load is uniformly distributed and accurately reflects the simulations the sandbags must be placed in a way that maintains even distribution. It is proposed that the sandbags be grouped into clusters at different sections of the board and secured to achieve uniformity. While it would be ideal to place the sandbags at 0.1 meter intervals assuming a 1.5 m length kiteboard, the practical consideration such as the size of the sandbags would mean there would be overlapping of sandbags and spacing would be difficult to implement. Therefore, a more realistic approach would involve adjusting the spacing between clusters to accommodate the bag size and then monitor the distribution.

Data will be collected using DTI gauges, providing an accurate and cost effective method for measuring deflection. This gauges will be positioned across the kiteboard to capture real life deflection data. The record measurements with then be analyse and compared against the FEA simulation results, ensuring validity and accuracy of the computational model.

6 Conclusion

In conclusion, this assignment successfully applied FEA optimisation techniques to design a structurally efficient and lightweight CFRP kiteboard. This design ensure that the deflection remained within the limits of the 2mm steel structure equivalent. The baseline analysis revealed a significant weight reduction of 75% when using CFRP rather than steel at the cost of increased deflection. Through the use of FEA optimisation, the CFRP layup was configured to achieve both the required structural stiffness and to minimise material usage. The final optimised designed not only met the deflection constraint but also demonstrated a 58% mass reduction compared to the steel baseline. Additional achieving a 155% improvement on the stiffness to weight ratio.

This conclusion highlights the effectiveness FEA optimisation in enhancing both performance and material efficiency. A structured experimental validation methodology was proposed to ensure real-world testing aligns with simulation predictions. This approach reinforces the reliability of the FEA model and establishes a foundation for future refinements. By achieving its objectives, this study underscores the critical role of FEA in engineering design, offering a systematic approach to optimising composite materials for strength, weight efficiency, and manufacturability.

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