

DESIGNING A KITEBOARD: STRUCTURAL DESIGN

STRUCTURAL & FLUID ANALYSIS (ACMA6010 - 2024)

Dylan Payne
Renishaw Quality Technician

Kelvin Lake
Lecturer

Word Count: 2993

Contents

1. Introduction	3
2. FEA Optimisation Techniques	4
2.1 FEA Historical Development & Optimisation	4
2.2 Current and Future Trends in FEA Optimisation	5
2.2.1 Topology Optimisation	5
2.2.2 Topometry Optimisation	5
2.2.3 Shape Optimisation	5
2.3 Advantages of Optimisation in the Design Process	6
3. Kiteboard Initial Composite Lay-Up & Modelling	7
3.1 Design Studios Model Setup	7
3.2 Material Properties	7
3.3 Initial Lay-Up Design	7
3.4 Initial Lay-Up Analysis	8
3.4.1 Results	8
4. Composite Lay-Up Optimising for Minimum Weight	8
4.1 Continuous Optimisation	9
4.2 Discrete Optimisation	10
4.3 Optimisation Analysis	11
4.3.1 Results	11
5. Experimental Prototype Testing	12
5.1 Experimental Setup Methods	12
5.1.1 Three-point Bending Test	12
5.1.2 Distributed Load Testing with Hydraulic Actuation	12
5.1.3 Strain Gauge Array	12
5.2 Data Acquisition Techniques	13
5.2.1 Laser Displacement Sensors	13
5.2.2 Load Cells	13
5.3 Experimental Data & Simulation Results Comparison	13

5.3.1 Deflection Analysis.....	13
5.3.2 Stress Distribution and Strain Analysis	13
5.3.3 Error and Discrepancy Analysis	13
6. Design Relation to Technical Literature	14
6.1 Stiffness-to-Weight Ratio Optimisation	14
6.2 Composite Material Optimisation	14
6.3 Validation Techniques.....	14
7. Conclusion	15
8. Bibliography	16
9. Appendices	18
10. Design Studio Data	18
10.1 Optimised Composite.....	18
10.2 Optimised Composite (Discrete)	19

1. Introduction

In engineering design, it is becoming more and more important to include optimisation techniques into Finite Element Analysis (FEA) in order to create structures that are not only effective and high-performing but also lightweight and reasonably priced. FEA is a numerical method for estimating approximate solutions to challenging mathematical problems involving differential equations. This technique was created to address challenging engineering issues, particularly those involving elliptic partial differential equations and complex geometries in the modelling of structural mechanics and elasticity (Baccouch, 2021).

The purpose of this project is to investigate and use these optimisation strategies in the kiteboard's composite design. The goal is to minimise weight while making sure the kiteboard, which is made of unidirectional carbon fibre reinforced plastic (CFRP), matches or exceeds the stiffness of a 2mm steel baseline.

To do this, the kiteboard lay-up will be modelled, examined, and optimised using Design Studio for Genesis 2022 software. The study will model and optimise the board's performance under fluid forces utilising important FEA techniques. It will concentrate on finding the best ply orientation to satisfy the stiffness requirement while using the least amount of material possible. The study will entail choosing the best ply arrangement to preserve stiffness and establishing boundary conditions based on forces found in an earlier fluid flow assessment.

2. FEA Optimisation Techniques

2.1 FEA Historical Development & Optimisation

FEA has seen substantial development since its introduction in the mid-20th century, where it was initially developed for aerospace applications to enhance structural performance while controlling weight limitations. Turner, M. J., Clough, R. W., Martin, H. C., and Topp, L. J. released the first publication on the Finite Element Method (FEM) in 1956, and later coined the term “finite elements” in an article in 1960. The first program to use FEM for structural analysis, NASTRAN, was commissioned by NASA in 1965 and subsequently made available for purchase as MSC/NASTRAN in 1969. The reliability of FEM was demonstrated during the 1970s by fundamental modelling techniques and mathematical demonstrations, and the p-version of FEM was introduced for more complex structural applications. While model hierarchies and commercial tools like StressCheck, which established standards for error management, were introduced in the 1990s, FEA software such as FIESTA and PROBE expanded FEM applications, such as aerospace, in the 1980s. StressCheck was in the forefront of compliance with the stringent verification standards that ASME and NASA had instituted by the 2000s. By 2012, standardised procedures and simulation governance were developed, establishing FEA's place in accurate and trustworthy engineering analysis (ESRD, 2024).

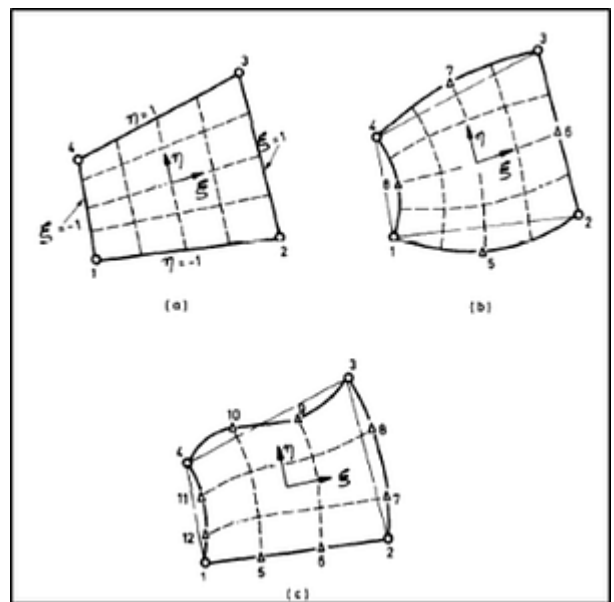


Figure 1 - Ergatoudis, I., Irons, B. M., and Zienkiewicz, O. C. (1968). Curved, isoperimetric, “quadrilateral” elements for finite element analysis. *International Journal of Solids and Structures*, 4(1), 31-42. (ESRD, 2024)

FEA optimisation methods, which started out as human modifications based on the expertise and intuition of the designer, have grown to become more automated with time. Time-consuming prototype processes were frequently the result of traditional approaches that used CAD models that were manually evaluated and changed. On the other hand, advancements in gradient-based techniques, evolutionary algorithms, and topological optimisation propelled the emergence of automated optimisation procedures in the latter half of the 20th century (ESRD, 2024). By using these techniques, alongside methods such as parametric, shape, sizing and material optimisation, engineers have been able to determine the best component configurations early in the design process, which has shortened the number of prototypes and sped up development cycles (Suchdeo, 2024).

2.2 Current and Future Trends in FEA Optimisation

Depending on the application, there are now a variety of FEA optimisation techniques available. The three main forms of optimisation commonly used are:

2.2.1 Topology Optimisation

By eliminating unnecessary material, this method finds the best load paths within a structure, producing lightweight designs. As additive manufacturing has advanced, this technique has gained popularity because it enables intricate geometries that were previously impossible to achieve with conventional methods (Leapaust, 2020).

2.2.2 Topometry Optimisation

This is especially helpful in casting and structural applications when uniform material thickness is not necessary because it concentrates on different thicknesses and material distribution within a predetermined shape (Leapaust, 2020).

2.2.3 Shape Optimisation

Here, the geometry itself is modified to achieve optimal performance under given constraints. By enhancing surface contours, shape optimisation helps to improve aerodynamics and load-bearing capacity (Leapaust, 2020).

Combining optimisation techniques with artificial intelligence (AI) and machine learning (ML) is one of the emerging topics in FEA. Pre-processing optimisation techniques including automatic meshing, boundary condition recognition, and material property predictions are few AI platforms that can be utilised to improve FEA. Predictive modelling and the possibility of evaluating a greater variety of design variants in real time are made possible by these techniques. In multi-objective optimisations, when objectives like minimising weight and maximising stiffness or durability are balanced, AI-enhanced optimisation also increases efficiency. Several limitations must be considered when using AI for material predictions and recommendations. First, since any errors or gaps in the data might affect the results, the quality and completeness of the database have a major role in how accurate these predictions are. Furthermore, the reasoning behind some recommendations may occasionally be muddled; this is known as the "black box" characteristic of AI, where the explanation behind ideas isn't always obvious. Sustainability is predicted to propel optimisation strategies in the future, promoting the creation of high-performance, lightweight materials that use less energy and produce less waste (Jinto, 2024).

2.3 Advantages of Optimisation in the Design Process

By automating modifications, cutting down on the time and expense of several prototypes, and enhancing first-iteration reliability, optimisation inside FEA simplifies the design process. Computer aided engineering designs forecast component performance ahead of physical prototypes in sectors like automotive and aerospace, facilitating sustainable design by reducing material consumption without compromising strength and accelerating feedback loops. FEA allows for customised designs that optimise strength-to-weight ratios and reduce material costs in applications involving composite materials. All things considered, FEA optimisation improves sustainability and efficiency, indicating further developments in high-performance design (Kelley, 2010).

3. Kiteboard Initial Composite Lay-Up & Modelling

3.1 Design Studios Model Setup

The supplied .dsg.dat file was used to load the kiteboard model into Design Studio for Genesis 2023. The model was examined to make sure the dimensions and geometry matched the requirements. Boundary conditions were used to mimic loading circumstances and limits seen in the actual world (Figure 2 as reference):

- To provide realistic displacement behaviour under loading, the board's nose was disregarded when loading, as shown in Figure 3.
- A uniformly distributed load of 735.75N was applied across the surface, simulating the downwards forces the board would experience in actual use.



Figure 2 - Kiteboarding (Turespana, 2021)

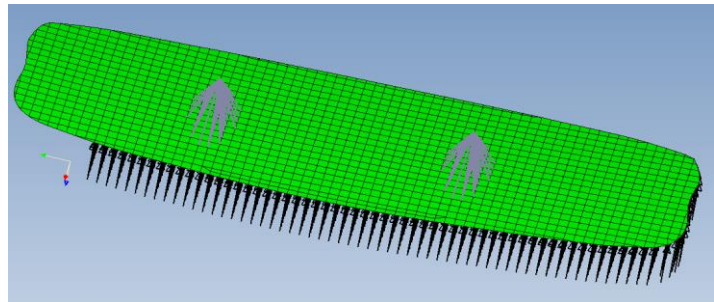


Figure 3 - Kiteboard Loads

3.2 Material Properties

The material used for the kiteboard was defined as unidirectional (UD) carbon fiber reinforced plastic (CFRP) with orthotropic properties, as shown in Figure 3.

The fibre orientation was changed to align the longitudinal (0°) direction with the board's length, and each ply thickness was set at 0.1 mm.

3.3 Initial Lay-Up Design

An initial composite lay-up was defined to ensure the kiteboard could achieve the necessary stiffness. The kiteboard consists of 25 plies, arranged in five 0.5mm thick layers of unidirectional CFRP with orientations at 0° , $\pm 45^\circ$, and $\pm 90^\circ$, resulting in a 2.5mm thick unidirectional CFRP board.

3.4 Initial Lay-Up Analysis

The performance of the initial composite lay-up was assessed through a single analysis in Design Studio.

3.4.1 Results

Material	Thickness (mm)	Deflection (mm)	Mass (Kg)	Load (N)	Stiffness (N/mm)	Stiffness/Weight Ratio
Steel	2	28	8.1	735.75	26.28	33.07
Unidirectional CFRP	2.5	110	2.03	735.75	6.69	33.59

Table 1 - Initial Lay-Up Results

As can be seen in the results, the deflection of the CFRP board is significantly higher than that of the target steel board, suggesting that the original CFRP lay-up failed to meet the stiffness objective. However, because the CFRP has a lower mass (2.03 kg compared to 8.1 kg for steel), its stiffness-to-weight ratio is equivalent to that of the steel's, even with the higher deflection. These findings show that in order to increase stiffness and attain the required deflection without appreciably increasing mass, the ply thickness and orientation must be further optimised.

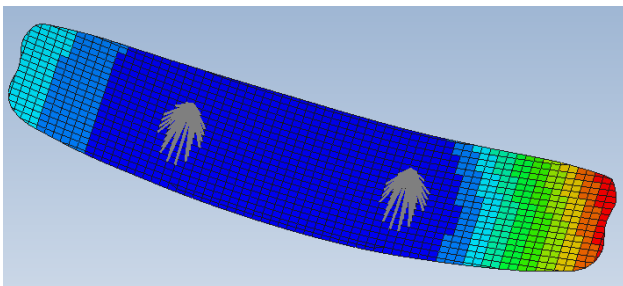


Figure 4 - Steel Baseline

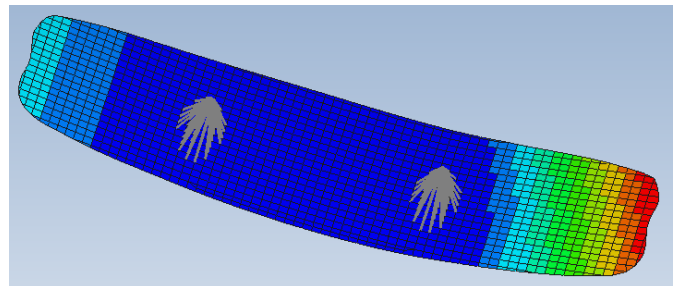


Figure 5 - Composite Baseline

4. Composite Lay-Up Optimising for Minimum Weight

The purpose of this task is to minimise the weight of the kiteboard by using composite lay-up while satisfying the deflection constraint. The performance of the board under 735.75N load are reviewed and compared to that of the steel baseline. The optimisation was conducted in two stages: a continuous optimisation followed by a discrete optimisation to ensure manufacturability.

4.1 Continuous Optimisation

The initial optimisation aimed to increase the stiffness/weight ratio of the composite kiteboard while keeping the mass to a minimum. To achieve this, a minimum mass objective was set in Design Studio, as well as setting a 28mm upper bound design constraint on the displacement to match that of the steel baseline.

Next, design variables were set up to allow the thickness of each orientation can range between 0.1mm and 2mm. Across all 5 layers, the initial value was set to 0.5mm, the lower bound set to 0.1mm and the upper bound set to 2mm. This process of defining variables for each ply layer allowed the thicknesses to vary within the specified bounds to achieve optimal stiffness with minimum mass.

Genesis OPTIMISE was then used with a max cycle count of 30 to ensure design studio converged on a solution, which it did after 6 cycles which can be shown in the graphs in Figure 6.

Initially at cycle 0 the constraints were being violated by 313.7%. But, from cycle 2 to cycle 6 the board was optimised to a 0% violation on the constraints.

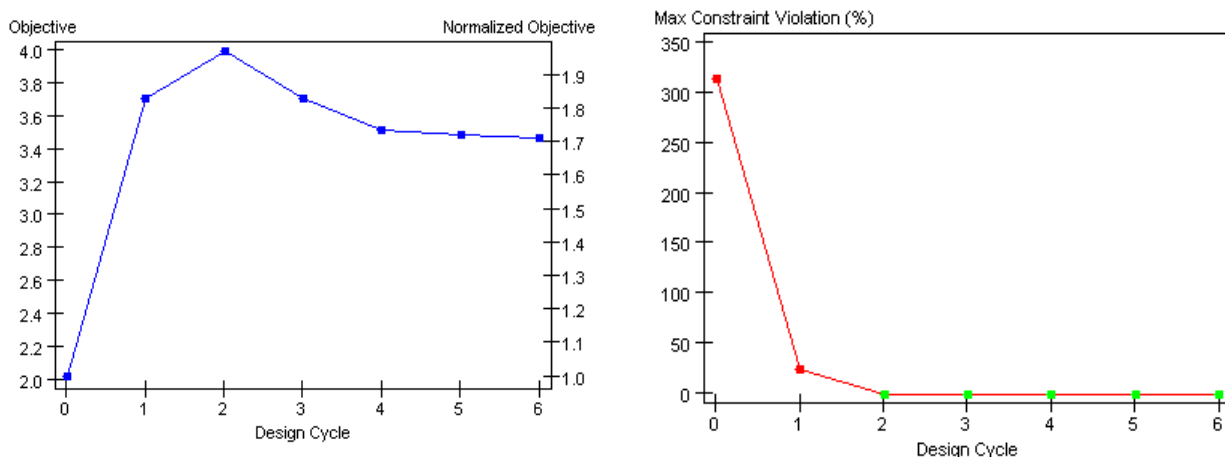


Figure 6 - Optimised Graphs

4.2 Discrete Optimisation

To ensure manufacturability, the continuous optimised ply thickness values were converted into discrete values that aligned with standard ply thickness increments. This process adjusted the optimised lay-up into a configuration suitable for production without compromising performance.

From the continuous optimisation we obtained the following lay-up:

```

DESIGN CYCLE #      6, OBJECTIVE = 3.471639E+00, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE #      1 = 4.264030E-04      L1THK
DESIGN VARIABLE #      2 = 8.415365E-04      L2THK
DESIGN VARIABLE #      3 = 1.998202E-03      L3THK
DESIGN VARIABLE #      4 = 7.933875E-04      L4THK
DESIGN VARIABLE #      5 = 2.255159E-04      L5THK

```

The variables required to become discrete values as it is not possible to manufacture ply's of these values. For this, each design variable was modified to now have the following discrete design variables. The initial value and the increments were set to 0.1mm, and the number of additional values was set to 19, meaning that we would get 0.1mm increments from 0.1mm to 2mm. Once again, Genesis OPTIMISE was used to generate a solution, which it did, this time after 10 cycles, as show in Figure 7.

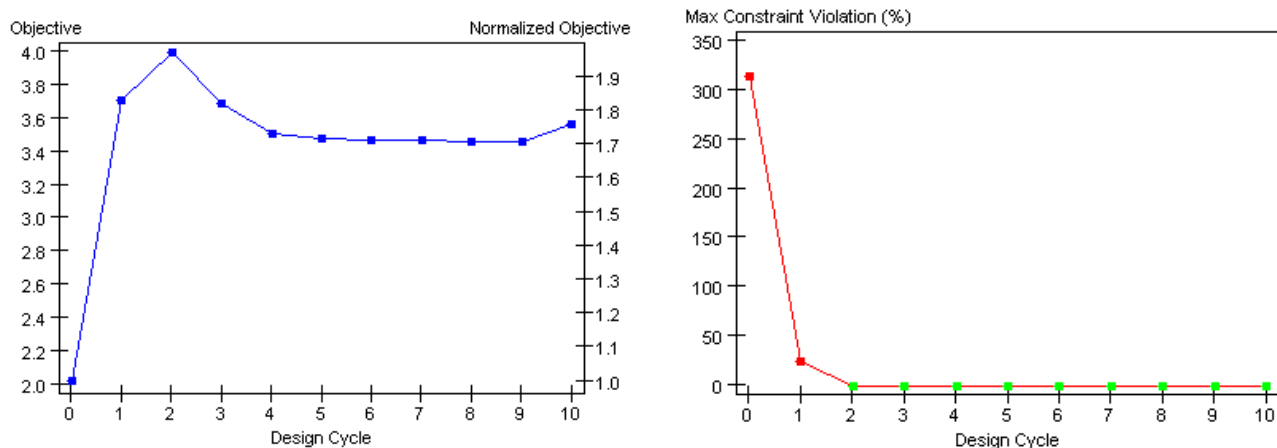


Figure 7 - Optimised (Discrete) Graph

From the discrete optimisation we obtained the following lay-up:

```

DESIGN CYCLE #      10, OBJECTIVE = 3.564772E+00, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE #      1 = 4.000000E-04      L1THK
DESIGN VARIABLE #      2 = 9.000000E-04      L2THK
DESIGN VARIABLE #      3 = 2.000000E-03      L3THK
DESIGN VARIABLE #      4 = 9.000000E-04      L4THK
DESIGN VARIABLE #      5 = 2.000000E-04      L5THK

```

4.3 Optimisation Analysis

4.3.1 Results

Material	Thickness (mm)	Deflection (mm)	Mass (Kg)	Load (N)	Stiffness (N/mm)	Stiffness/Weight Ratio
Steel	2	28	8.1	735.75	26.28	33.07
Unidirectional CFRP	2.5	110	2.03	735.75	6.69	33.59
Optimised Composite	4.29	27	3.47	735.75	27.25	80.05
Optimised Composite (Discrete)	4.4	26	3.56	735.75	28.3	81.03

Table 2 - Optimisation Results

The continuous optimisation produced a configuration that achieved the necessary stiffness while significantly reducing the weight compared to the steel baseline. This optimisation demonstrated high material efficiency through an improved stiffness-to-weight ratio, achieved by adjusting ply thicknesses precisely. However, the continuously optimised ply thickness values, while effective for weight reduction, presented impracticalities for real-world manufacturing, as they would require non-standard thicknesses that may be impossible to manufacture.

The discrete optimisation provided a manufacturable configuration that retained the high stiffness-to-weight ratio established by the continuous optimisation. With a total mass of 3.56 kg and slightly enhanced stiffness, the discrete lay-up not only met performance requirements but also offered a practical solution suitable for production. Because it satisfies both structural and manufacturing requirements, this final discrete solution is the recommended option for the kiteboard application.

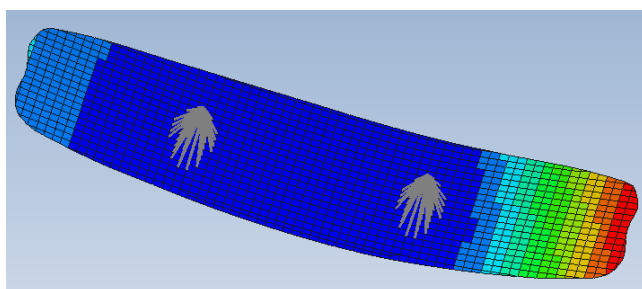


Figure 9 - Optimised

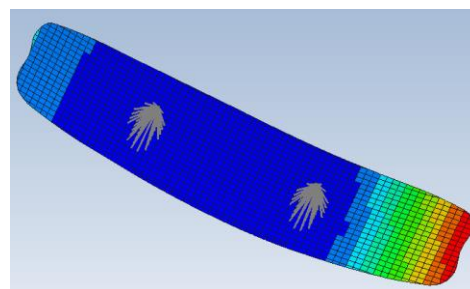


Figure 8 - Optimised (Discrete)

5. Experimental Prototype Testing

By testing the kiteboard's deflection under a controlled load comparable to the previously stated simulated conditions, it will be possible to verify that the optimised composite lay-up satisfies the necessary stiffness constraints.

The prototype kiteboard will be built utilising the discrete optimised lay-up configuration, with a mass of 3.56Kg and a total thickness of 4.4mm, in order to precisely collect the necessary data. In order to ensure consistent comparison, this setup is the same as the simulation model used in the FEA optimisation.

5.1 Experimental Setup Methods

5.1.1 Three-point Bending Test

The kiteboard would be supported at both ends (where required to replicate real-world conditions) in a three-point bending test arrangement, and a central load of 735.75N would be applied to cause deflection. This method allows for exact control of loading locations while simulating a simplified version of the dispersed load (University of Cambridge, n.d.). This technique is frequently used to assess the stiffness and bending properties of composite structures and allows for the simple measurement of deflection at the centre of the board (Sun, et al., 2021).

5.1.2 Distributed Load Testing with Hydraulic Actuation

A hydraulic actuator would be used to apply a load that is evenly distributed across the kiteboard surface, more closely replicating the load conditions in the simulation. With the help of a pressure bladder system or a group of actuators, this method evenly distributes force, allowing for a precise assessment of the board's response to actual loading circumstances along its whole length (H, 2018) (HBM, 2021).

5.1.3 Strain Gauge Array

In order to record strain responses under load, strain gauges can be positioned strategically on the board at key points (the centre, edges, and along ply orientations). Instead of just measuring deflection, this method provides a more thorough understanding of the interior stress distribution. By concentrating on strain, this approach offers a thorough comparison with the ply-specific stress responses anticipated by FEA, revealing how the composite lay-up manages localised stress (Castro, et al., 2020).

5.2 Data Acquisition Techniques

5.2.1 Laser Displacement Sensors

Laser Displacement Sensors can be positioned at the centre of the board and at additional points, to measure deflection precisely as the load increases. High-frequency sampling ensures accurate data, especially for the three-point bending and distributed load tests (Keyence, 2024).

5.2.2 Load Cells

In order to guarantee compliance with simulation loading conditions, load cells can be incorporated into the loading equipment. Load cells are used to track applied forces and provide real-time feedback by converting a physical force into a measurable electrical voltage. This guarantees that during analysis, any departure from the expected load is taken into consideration (ZwickRoell, 2024).

5.3 Experimental Data & Simulation Results Comparison

5.3.1 Deflection Analysis

A direct comparison can be made possible through the use of a load vs deflection graph created from both the simulation and experimental data. The simulation's projected deflection of 26mm can be compared with the measured deflection at the board's centre. Variances can be further calculated to determine the accuracy of the FEA model in predicting real-world deflection.

5.3.2 Stress Distribution and Strain Analysis

For every ply orientation, strain predictions from the simulation can be plotted against experimental strain data. Variations in the distribution of strain point to possible places where the simulation can overestimate or underestimate stiffness, which serves as a foundation for model improvement (Castro, et al., 2020).

5.3.3 Error and Discrepancy Analysis

Using variables such as material inconsistencies or deviations from the boundary conditions, a thorough error analysis can be utilised to find differences between the simulated and experimental data. These results are used to suggest model modifications that could improve the accuracy of future FEA simulations in simulating real-world performance (Awork, 2024).

6. Design Relation to Technical Literature

The optimised kiteboard design, utilising unidirectional Carbon Fiber Reinforced Plastic (CFRP) and a custom ply orientation, aligns closely with current technical literature on composite material optimisation. Established research, including stiffness-to-weight optimisation, composite lay-up procedures, and experimental validation techniques, supports the design decisions made in this project.

6.1 Stiffness-to-Weight Ratio Optimisation

According to studies on load-specific material combinations, achieving a high stiffness-to-weight ratio is essential to composite design. Findings from 'Effect of Fiber Orientation on Nonlinear Behaviour of CFRP Composites' demonstrates that CFRP lay-ups with mixed orientations maximise material efficiency under bending loads, which we can directly compare to the optimised kiteboard stiffness-to-weight ratio calculated. Additionally, this method reduces material waste, promoting sustainable design objectives. The design adheres to best practices in material efficiency and weight reduction as emphasised in current composite research by choosing a CFRP configuration that suits the kiteboard's directional strength requirements (Sadeghian, et al., 2008).

6.2 Composite Material Optimisation

Applications such as sporting equipment, automotive, and aerospace that require high stiffness-to-weight ratios frequently use composite materials, especially CFRP. According to studies, CFRP provides better performance through directional strength, which enables designers to modify layer thicknesses and ply orientations to customise stiffness along particular load courses. The effectiveness of ply-angle optimisation, as used in this kiteboard design, is highlighted by (Raja, et al., 2019), who claim that with proper ply orientation in composite lay-ups, stiffness improvements can be achieved without the addition of more material.

6.3 Validation Techniques

Research indicates that experimental validation of FEA models is essential in composite design, especially when performance under load must be precise. Experimental techniques such as distributed load testing and three-point bending tests have been well-documented in the literature as efficient ways to verify simulated deflection and stiffness in composite lay-ups (Sun, et al., 2021) (H, 2018).

7. Conclusion

This report demonstrates how to build a lightweight, robust composite kiteboard using Finite Element Analysis (FEA) and optimisation techniques. In comparison to a steel baseline, an effective composite lay-up was developed by preliminary modelling and ongoing optimisation, resulting in a high stiffness-to-weight ratio and a lower mass design. The design was further improved by discrete optimisation, guaranteeing manufacturability without sacrificing performance. In line with well-established technical literature in composite engineering, the suggested experimental approaches offer a framework for design validation. This project highlights the benefits of combining advanced simulation tools and optimisation techniques to develop sustainable, high-performance materials for real-world applications.

8. Bibliography

Awork, 2024. *Error Analysis*. [Online]

Available at: <https://www.awork.com/glossary/error-analysis>

[Accessed 29 October 2024].

Baccouch, M., 2021. *Finite Element Methods and Their Applications*. ISBN 978-1-83962-356-1 ed. London: IntechOpen.

Castro, F. G. et al., 2020. μ -Si strain gauge array on flexible substrate for dynamic pressure measurement. *Sensors and Actuators A: Physical*, Volume 315, p. 112274.

ESRD, 2024. *A Brief History of FEA*. [Online]

Available at: [https://www.esrd.com/simulation-technology/brief-history-of-](https://www.esrd.com/simulation-technology/brief-history-of-fea/#:~:text=The%20first%20paper%20on%20the%20finite%20element%20method%20(FEM)%20was,in%20an%20article%20in%201960.)

[fea/#:~:text=The%20first%20paper%20on%20the%20finite%20element%20method%20\(FEM\)%20was,in%20an%20article%20in%201960.](https://www.esrd.com/simulation-technology/brief-history-of-fea/#:~:text=The%20first%20paper%20on%20the%20finite%20element%20method%20(FEM)%20was,in%20an%20article%20in%201960.)

[Accessed 06 October 2024].

HBM, 2021. *Precise Load and Force Measurement in Smart Actuators*. [Online]

Available at: <https://www.hbm.com/fr/8939/precise-load-and-force-measurement-in-smart-electric-and-hydraulic-actuators/>

[Accessed 27 October 2024].

H, R., 2018. *HYDRAULIC TEST ACTUATOR*, s.l.: MOOG Inc..

Jinto, A. J., 2024. *AI FEA is Revolutionizing Engineering Analysis - Now!*. [Online]

Available at: <https://www.linkedin.com/pulse/ai-fea-revolutionizing-engineering-analysis-now-jinto-a-j-3algc/>

[Accessed 07 October 2024].

Kelley, T. R., 2010. *Optimization, an Important Stage of Engineering Design*, Utah: Purdue University.

Keyence, 2024. *Laser Displacement Sensors*. [Online]

Available at: [https://www.keyence.co.uk/products/measure/laser-](https://www.keyence.co.uk/products/measure/laser-1d/#:~:text=KEYENCE's%20laser%20displacement%20sensors%20enable,categories%3A%20confocal%20and%20laser%20triangulation.)

[1d/#:~:text=KEYENCE's%20laser%20displacement%20sensors%20enable,categories%3A%20confocal%20and%20laser%20triangulation.](https://www.keyence.co.uk/products/measure/laser-1d/#:~:text=KEYENCE's%20laser%20displacement%20sensors%20enable,categories%3A%20confocal%20and%20laser%20triangulation.)

[Accessed 27 October 2024].

Leapaust, 2020. *Topological Optimisation with FEA*. [Online]

Available at: [https://www.leapaust.com.au/blog/fea/topological-optimisation-with-](https://www.leapaust.com.au/blog/fea/topological-optimisation-with-fea/#:~:text=With%20topology%20optimisation%2C%20an%20optimal,sizing%20dimensions%20over%20the%20structure.)

[fea/#:~:text=With%20topology%20optimisation%2C%20an%20optimal,sizing%20dimensions%20over%20the%20structure.](https://www.leapaust.com.au/blog/fea/topological-optimisation-with-fea/#:~:text=With%20topology%20optimisation%2C%20an%20optimal,sizing%20dimensions%20over%20the%20structure.)

[Accessed 07 October 2024].

Raja, V. et al., 2019. Optimization Of Orientation Of Carbon Fiber Reinforced Polymer Based On Structural Analysis. *INTERNATIONAL JOURNAL OF SCIENTIFIC & TECHNOLOGY RESEARCH* , 8(11), pp. 3020-3029.

Sadeghian, P., Rahai, A. R. & Ehsani, M. R., 2008. Effect of Fiber Orientation on Nonlinear Behavior of CFRP Composites. *Journal of Reinforced Plastics and Composites*, 28(18), pp. 2261-2272.

Suchdeo, A., 2024. *Essentials Of Finite Element Analysis (FEA) For Design Optimization*. [Online] Available at: [https://www.rishabheng.com/blog/design-optimization-with-fea/#:~:text=Finite%20element%20optimization%20can%20be,material%20properties%20\(material%20optimization\).](https://www.rishabheng.com/blog/design-optimization-with-fea/#:~:text=Finite%20element%20optimization%20can%20be,material%20properties%20(material%20optimization).)

[Accessed 06 October 2024].

Sun, Z. et al., 2021. Three-point bending properties of carbon fiber/honeycomb sandwich panels with short-fiber tissue and carbon-fiber belt interfacial toughening at different loading rate.

Composites Part A: Applied Science and Manufacturing, Volume 143, p. 106289.

Turespana, 2021. *Flying over the Balearic Islands: the best kitesurfing spots*. [Online]

Available at: <https://www.spain.info/en/discover-spain/flying-over-balearic-islands-best-kitesurfing-spots/>

[Accessed 11 October 2024].

University of Cambridge, n.d. *The Three Point Bend Test*, England: Academic department in Cambridge.

ZwickRoell, 2024. *Load Cells*. [Online]

Available at: <https://www.zwickroell.com/accessories/load-cells/#:~:text=In%20the%20field%20of%20materials,which%20can%20then%20be%20measured.>

[Accessed 28 October 2024].

9. Appendices

Figure 1 - Ergatoudis, I., Irons, B. M., and Zienkiewicz, O. C. (1968). Curved, isoperimetric, “quadrilateral” elements for finite element analysis. International Journal of Solids and Structures, 4(1), 31-42. (ESRD, 2024)	4
Figure 2 - Kiteboarding (Turespana, 2021)	7
Figure 3 - Kiteboard Loads	7
Figure 4 - Steel Baseline	8
Figure 5 - Composite Baseline	8
Figure 6 - Optimised Graphs	9
Figure 7 - Optimised (Discrete) Graph	10
Figure 9 - Optimised (Discrete)	11
Figure 8 - Optimised.....	11
Table 1 - Initial Lay-Up Results	8
Table 2 - Optimisation Results	11

10. Design Studio Data

10.1 Optimised Composite

```

DESIGN CYCLE #      0, OBJECTIVE = 2.025439E+00, MAXIMUM VIOLATION = 313.7%.
DESIGN VARIABLE #      1 = 5.000000E-04      L1THK
DESIGN VARIABLE #      2 = 5.000000E-04      L2THK
DESIGN VARIABLE #      3 = 5.000000E-04      L3THK
DESIGN VARIABLE #      4 = 5.000000E-04      L4THK
DESIGN VARIABLE #      5 = 5.000000E-04      L5THK
DESIGN CYCLE #      1, OBJECTIVE = 3.703079E+00, MAXIMUM VIOLATION = 25.3%.
DESIGN VARIABLE #      1 = 7.890475E-04      L1THK
DESIGN VARIABLE #      2 = 9.186180E-04      L2THK
DESIGN VARIABLE #      3 = 1.254216E-03      L3THK
DESIGN VARIABLE #      4 = 8.704824E-04      L4THK
DESIGN VARIABLE #      5 = 7.383479E-04      L5THK
DESIGN CYCLE #      2, OBJECTIVE = 3.992496E+00, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE #      1 = 7.204166E-04      L1THK
DESIGN VARIABLE #      2 = 9.559393E-04      L2THK
DESIGN VARIABLE #      3 = 1.744955E-03      L3THK
DESIGN VARIABLE #      4 = 9.028524E-04      L4THK
DESIGN VARIABLE #      5 = 6.037766E-04      L5THK
DESIGN CYCLE #      3, OBJECTIVE = 3.704397E+00, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE #      1 = 5.366450E-04      L1THK
DESIGN VARIABLE #      2 = 8.316451E-04      L2THK
DESIGN VARIABLE #      3 = 1.999889E-03      L3THK
DESIGN VARIABLE #      4 = 7.792867E-04      L4THK
DESIGN VARIABLE #      5 = 4.248735E-04      L5THK
DESIGN CYCLE #      4, OBJECTIVE = 3.515985E+00, MAXIMUM VIOLATION = 0.0%.

```

```

DESIGN VARIABLE #      1 = 4.647368E-04    L1THK
DESIGN VARIABLE #      2 = 8.135163E-04    L2THK
DESIGN VARIABLE #      3 = 1.996121E-03    L3THK
DESIGN VARIABLE #      4 = 7.626537E-04    L4THK
DESIGN VARIABLE #      5 = 3.027537E-04    L5THK
DESIGN CYCLE #    5, OBJECTIVE = 3.488858E+00, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE #      1 = 4.337108E-04    L1THK
DESIGN VARIABLE #      2 = 8.306195E-04    L2THK
DESIGN VARIABLE #      3 = 1.999390E-03    L3THK
DESIGN VARIABLE #      4 = 7.808336E-04    L4THK
DESIGN VARIABLE #      5 = 2.617455E-04    L5THK
DESIGN CYCLE #    6, OBJECTIVE = 3.471639E+00, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE #      1 = 4.264030E-04    L1THK
DESIGN VARIABLE #      2 = 8.415365E-04    L2THK
DESIGN VARIABLE #      3 = 1.998202E-03    L3THK
DESIGN VARIABLE #      4 = 7.933875E-04    L4THK
DESIGN VARIABLE #      5 = 2.255159E-04    L5THK
COMPLETION CODE: 1      7      0

```

10.2 Optimised Composite (Discrete)

```

DESIGN CYCLE #    0, OBJECTIVE = 2.025439E+00, MAXIMUM VIOLATION = 313.7%.
DESIGN VARIABLE #      1 = 5.000000E-04    L1THK
DESIGN VARIABLE #      2 = 5.000000E-04    L2THK
DESIGN VARIABLE #      3 = 5.000000E-04    L3THK
DESIGN VARIABLE #      4 = 5.000000E-04    L4THK
DESIGN VARIABLE #      5 = 5.000000E-04    L5THK
DESIGN CYCLE #    1, OBJECTIVE = 3.703079E+00, MAXIMUM VIOLATION = 25.3%.
DESIGN VARIABLE #      1 = 7.890475E-04    L1THK
DESIGN VARIABLE #      2 = 9.186180E-04    L2THK
DESIGN VARIABLE #      3 = 1.254216E-03    L3THK
DESIGN VARIABLE #      4 = 8.704824E-04    L4THK
DESIGN VARIABLE #      5 = 7.383479E-04    L5THK
DESIGN CYCLE #    2, OBJECTIVE = 3.992287E+00, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE #      1 = 7.008420E-04    L1THK
DESIGN VARIABLE #      2 = 9.770109E-04    L2THK
DESIGN VARIABLE #      3 = 1.757859E-03    L3THK
DESIGN VARIABLE #      4 = 9.156608E-04    L4THK
DESIGN VARIABLE #      5 = 5.763089E-04    L5THK
DESIGN CYCLE #    3, OBJECTIVE = 3.688219E+00, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE #      1 = 5.163343E-04    L1THK
DESIGN VARIABLE #      2 = 8.495372E-04    L2THK
DESIGN VARIABLE #      3 = 1.997066E-03    L3THK
DESIGN VARIABLE #      4 = 7.874213E-04    L4THK
DESIGN VARIABLE #      5 = 4.020114E-04    L5THK
DESIGN CYCLE #    4, OBJECTIVE = 3.508056E+00, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE #      1 = 4.494034E-04    L1THK
DESIGN VARIABLE #      2 = 8.282361E-04    L2THK
DESIGN VARIABLE #      3 = 1.997176E-03    L3THK
DESIGN VARIABLE #      4 = 7.680779E-04    L4THK
DESIGN VARIABLE #      5 = 2.871020E-04    L5THK
DESIGN CYCLE #    5, OBJECTIVE = 3.476903E+00, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE #      1 = 4.172487E-04    L1THK
DESIGN VARIABLE #      2 = 8.389539E-04    L2THK
DESIGN VARIABLE #      3 = 1.999783E-03    L3THK
DESIGN VARIABLE #      4 = 7.797203E-04    L4THK
DESIGN VARIABLE #      5 = 2.558367E-04    L5THK
DESIGN CYCLE #    6, OBJECTIVE = 3.469388E+00, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE #      1 = 4.117437E-04    L1THK

```

```

DESIGN VARIABLE #          2 = 8.566470E-04    L2THK
DESIGN VARIABLE #          3 = 1.998086E-03    L3THK
DESIGN VARIABLE #          4 = 7.995603E-04    L4THK
DESIGN VARIABLE #          5 = 2.162298E-04    L5THK
DESIGN CYCLE #    7, OBJECTIVE = 3.469165E+00, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE #          1 = 4.049095E-04    L1THK
DESIGN VARIABLE #          2 = 8.633712E-04    L2THK
DESIGN VARIABLE #          3 = 1.997588E-03    L3THK
DESIGN VARIABLE #          4 = 8.050148E-04    L4THK
DESIGN VARIABLE #          5 = 2.111081E-04    L5THK
DESIGN CYCLE #    8, OBJECTIVE = 3.459928E+00, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE #          1 = 3.840313E-04    L1THK
DESIGN VARIABLE #          2 = 8.702315E-04    L2THK
DESIGN VARIABLE #          3 = 2.000000E-03    L3THK
DESIGN VARIABLE #          4 = 8.122289E-04    L4THK
DESIGN VARIABLE #          5 = 2.040984E-04    L5THK
DESIGN CYCLE #    9, OBJECTIVE = 3.459928E+00, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE #          1 = 3.840313E-04    L1THK
DESIGN VARIABLE #          2 = 8.702315E-04    L2THK
DESIGN VARIABLE #          3 = 2.000000E-03    L3THK
DESIGN VARIABLE #          4 = 8.122289E-04    L4THK
DESIGN VARIABLE #          5 = 2.040984E-04    L5THK
DESIGN CYCLE #   10, OBJECTIVE = 3.564772E+00, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE #          1 = 4.000000E-04    L1THK
DESIGN VARIABLE #          2 = 9.000000E-04    L2THK
DESIGN VARIABLE #          3 = 2.000000E-03    L3THK
DESIGN VARIABLE #          4 = 9.000000E-04    L4THK
DESIGN VARIABLE #          5 = 2.000000E-04    L5THK
COMPLETION CODE: 1      10      0

```