

University of Wales Trinity Saint David

Designing a kiteboard: Structural Design

Lewys Jack Thorne

Student number: 2214464

BACHELOR OF ENGINEERING IN MECHANICAL AND MANUFACTURING
ENGINEERING

03/11/2024

Structural and Fluid Analysis: ACMA6010

Word Count: 3143



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

Contents

1. Introduction	4
2. Finite Element Analysis (FEA)	5
Historical development of FEA	5
FEA Optimisation Techniques	5
Shape Optimisation	5
Topology optimisation	5
Size optimisation	6
How FEA techniques improve the design process	6
Future developments to FEA	6
3. Design Studio and FEA	7
Steel Board	7
Composite Board	10
4. Optimised Composite	12
Discrete Composite	14
Results	15
5. Prototype Experiment Testing	16
Experiment Setup	16
Instruments and Methods for Measurement	16
Gathering Data and Analysis	16
Evaluation and Findings	16
6. Technical Literature	17
7. Conclusion	18
8. References	19

Table of Figures

Figure 1 - Topology Optimisation (Velling, 2020).....	6
Figure 2 - Example of Kitesurfing (Bequir, 2022)	7
Figure 3 - Steel Kiteboard with static load	8
Figure 4 - Steel Kiteboard with static load comparable to real world conditions	8
Figure 5 - FEA of Steel Kiteboard	9
Figure 6 - Material thickness and plys	10
Figure 7 - FEA of Composite board	11
Figure 8 - Design Variable Thicknesses	12
Figure 9 - Optimisation results	12
Figure 10 - Design history plot	13
Figure 11 – Thicknesses at each angle	13
Figure 12 - Design variables with discrete values	14
Figure 13 - Discrete thicknesses.....	14

1. Introduction

This project used Finite Element Analysis (FEA) to optimise the structural integrity of a composite kiteboard, resulting in a lightweight yet durable design that was compared to a 2mm steel benchmark. FEA techniques were utilised to analyse material performance under specific physical conditions, which guided design decisions without the need for actual prototypes. The study looked at the history and current applications of FEA, such as topology, shape, and size optimisation, which allowed engineers to fine-tune composite structures by altering ply orientations and thickness. Carbon fibre reinforced plastic (CFRP), a popular material for high-performance sports equipment, was chosen for its excellent strength-to-weight ratio and versatility. Experimental testing was recommended to validate FEA results, with deflection, strain, and stress measurements to ensure that the composite board satisfied the stiffness and performance requirements. This method was consistent with technological improvements and engineering standards, with the goal of producing a kiteboard that was both lightweight and durable.

2. Finite Element Analysis (FEA)

Finite element analysis (FEA) forecasts how objects will behave under specified physical conditions, whether dynamic or static, allowing designers to anticipate probable behaviour and inform design decisions (Brush, 2019). Engineers employ FEA software to eliminate the requirement for physical prototypes, resulting in better finished products at a lower cost (SimScale, 2018).

Historical development of FEA

(Prem Kythe and Wei, 2011, p.2) explain that Raw W. Clough was the first person to use the term finite element method in 1960. Clough created a matrix algebra tool that enabled pupils to solve finite element problems while learning programming (Madier, n.d.). Around this time, FEA was purely a numerical approach to solving complicated structural issues, primarily in mechanical and aerospace engineering.

As FEA developed, the applications were primarily linear static analysis programs. These methods allowed engineers to comprehend the behaviour of simple structures under continuous loads. Calculating stresses, displacements, and strains was the aim of this foundational phase, which was not yet optimised for material or shape (Madier, n.d.)

More sophisticated optimisation methods, such as shape and size optimisation, became possible by the 1970s and 1980s as computing power increased, enabling more intricate models and finer mesh resolutions. The development of topology optimisation in the 1990s revolutionised design procedures in the automotive and aerospace sectors by enabling engineers to eliminate unnecessary material while preserving strength (Liu, Li and Park, 2022).

FEA Optimisation Techniques

Shape Optimisation

Shape optimisation is the process of changing the exterior form of a structure in order to maximise efficiency within certain limits. It frequently removes surplus material from non-critical locations (sdcadmin, 2022). According to Suchdeo (2024), the technique focusses on determining the best geometry to improve mechanical performance. The F1 car chassis is a common example of this, as it saves weight while maintaining the rigidity and strength required to sustain extreme stresses during races.

Topology optimisation

Topology optimisation advances on the shape optimisation as it further develops the product by redistributing materials in a specific area of the product to achieve the best possible balance between strength, stiffness and weight (Abbey, 2018). Velling (2020) further explains that topology optimisation uses a 3D model which displaces or removes material in order to make the overall design more efficient. An example of topology optimisation is illustrated below in figure 1.

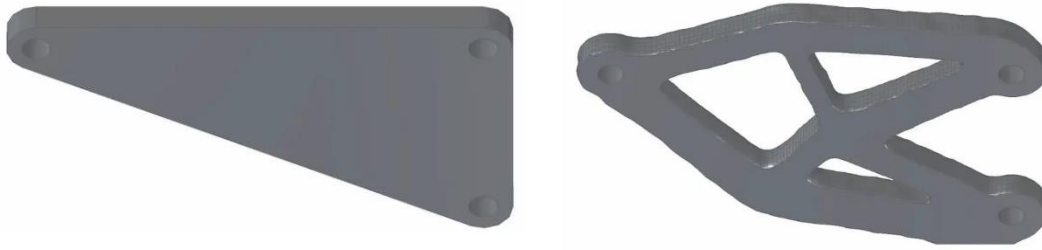


Figure 1 - Topology Optimisation (Velling, 2020)

Figure 1 depicts the outcomes of a topological optimisation, which demonstrates significant material removal. The product's holes remain in the identical locations both before and after, ensuring that it continues to perform as intended. The reduction of surplus material greatly reduces the product's total weight.

Size optimisation

Size optimisation is the process of modifying component dimensions, such as cross-sectional area or thickness, to minimise weight and material costs while meeting performance and safety standards. Engineers specify variables like flange width or wall thickness, which FEA algorithms iteratively modify to satisfy displacement and stress limitations (sdcadmin, 2022).

How FEA techniques improve the design process

Topology and size optimisation are FEA approaches that assist engineers in developing cost-effective, durable, and lightweight solutions without sacrificing safety. Designers can reduce production costs and environmental effect by optimising shape and topology (GMT Rubber, 2022). Brush (2019) observes that FEA optimisation simulates real-world performance, speeding up development and eliminating the requirement for physical prototypes. Furthermore, FEA enables exact adjustments that improve performance and reliability, which are critical in aircraft and automotive engineering (Team, 2023).

Future developments to FEA

Machine learning and artificial intelligence (AI) advancements have the potential to revolutionise FEA optimisation. AI and ML algorithms process massive datasets quickly, allowing for speedier design identification and real-time optimisation. Previously, FEA used labour-intensive calculations that limited complexity. AI improves accuracy and efficiency by automating operations such as mesh production, saving time and minimising errors. This enables engineers to quickly test multiple design variations, encouraging creativity. As AI develops, its integration with FEA is predicted to change engineering and open up new possibilities (Melissa, 2023).

3. Design Studio and FEA

The objective was to match the performance of a 2mm steel board while optimising the structure of the composite kiteboard for the least amount of weight. Both boards were subjected to Finite Element Analysis (FEA) with predetermined boundary and loading conditions. To fulfil the deflection constraints of the steel board and achieve the best possible mix of strength, stiffness, and weight, the carbon fibre reinforced plastic (CFRP) composite model needed precise ply orientation adjustments (-90° , -45° , 0° , 45° , and 90°).

Steel Board

Research into how Kitesurfing is performed was the first task as it was important to note that not all of the kiteboard would be subjected to the forces acting on it. Figure 2 below shows a typical kitesurfer.



Figure 2 - Example of Kitesurfing (Bequir, 2022)

A section of the kiteboard is above the water's surface in the image above, showing how water affects the underside of the board. This image was used as a guide for the model in design studio as it will give a better representation of real-world conditions.

Figure 3 shows the kiteboard (with the static load applied to it) when imported into design studio.

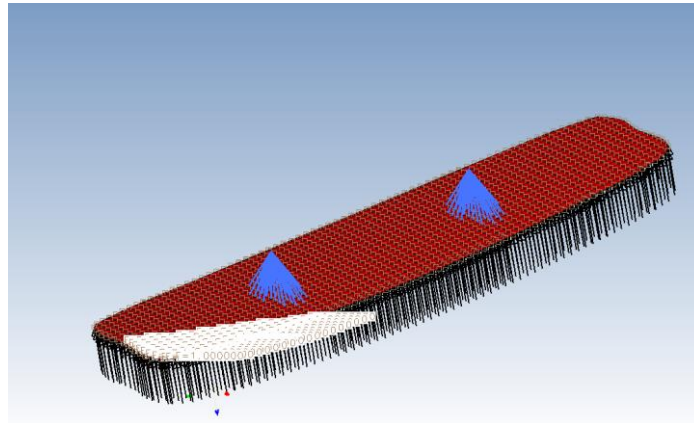


Figure 3 - Steel Kiteboard with static load

The image above illustrates a typical kiteboard design. There are two cone shaped forces applied to the top of the kiteboard which represent where the kitesurfer would stand. The black arrows on the bottom of the board represent the forces applying upwards to the underneath of the board. Each arrow or node has a force applied to it; in this instance the force is 1N.

As stated in Figure 2, the underbelly of the kiteboard is not completely in the water. This meant that the above kiteboard design needed adjusting.

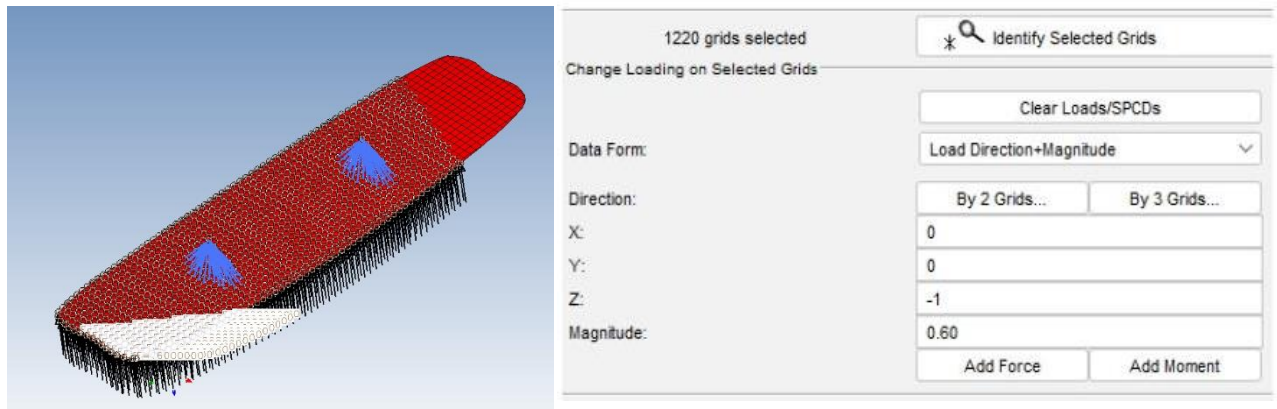


Figure 4 - Steel Kiteboard with static load comparable to real world conditions

A polygon region was used to select the area in which the underside of the board would be subjected to forces made by the water. The “Z” direction was made -1 which meant that the forces would be applied upwards against the board, representing the water.

The magnitude was calculated after some research. The average mass of a kitesurfer is 75kg (Kitemare.com, 2024). This multiplied by gravity (9.81m/s) gives the result of 735.75N of force acting downwards on the board. In order for the board to stay afloat the forces acting upwards should equal the down force. Figure 4 shows there are 1220 grids or nodes, meaning that each node has 0.60N of force acting upwards on the board.

$$\text{Each node} = \frac{735.75}{1220} = 0.60\text{N}$$

A single analysis was run on this steel board to calculate the displacement in metres. The results are shown below.

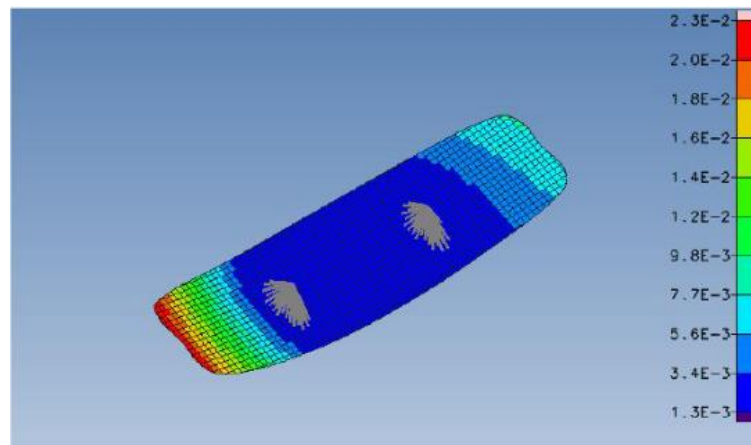


Figure 5 - FEA of Steel Kiteboard

The results show a FEA of the kiteboard. The displacement distribution across the board's surface is shown by the colour gradient, where red denotes locations with greater displacement and blue areas with less displacement. The red zones at the outer borders indicate that these areas undergo the most deflection under the imposed force. The maximum displacement value shown at the tip of the board is reading 2.3×10^{-2} metres or 23mm.

The weight of the board was also calculated using the “elements” tab in the Design studio software which returned a value of 8.10176Kg.

With these values, the stiffness and stiffness/weight ratio could be calculated:

$$\text{Stiffness (k)} = \text{Load (f)} / \text{Deflection (x)}$$

$$\text{Stiffness} = \frac{f}{x}$$

$$\text{Stiffness} = \frac{735.75}{23}$$

$$\text{Stiffness} = 31.98 \text{ N/mm}$$

$$\text{Stiffness/weight} = \frac{31.98}{9.81 \times 8.10}$$

$$\text{Stiffness/weight} = 0.40 \text{ N}^2/\text{mm}$$

Table 1 - Steel Calculations

Material	Thickness (mm)	Deflection (mm)	Mass (Kg)	Load (N)	Stiffness (N/mm)	Stiffness/Weight (N ² /mm)
Steel	2	23	8.10	735.75	31.98	0.40

This outcome served as a starting point for the composite board, which needed to be tuned to match the stiffness and performance of the steel board by minimising weight and achieving similar or lower deflection values.

Composite Board

For the composite board, the same nodes were applied to the underside of the board as the steel in Figure 4. Each node also had the same magnitude of 0.6N added to it to allow for a fair comparison when the FEA was run.

There were some slight changes to the composite board compared to the steel board. These were:

- Material properties
- Number of Plys

The material properties were supplied in the assignment brief and these were inputted into the “materials” tab on Design Studio.

The number of plys and their directions were inputted into the “group properties” tab on Design Studio, as seen in the picture below.

Global Ply ID : Material : Thickness : Angle : Output						
Layer 1						
	857143 Unidirectional	5.E-4	-90.0	Yes		+ -
Layer 2						
	857143 Unidirectional	5.E-4	-45.0	Yes		+ -
Layer 3						
	857143 Unidirectional	5.E-4	0.0	Yes		+ -
Layer 4						
	857143 Unidirectional	5.E-4	45.0	Yes		+ -
Layer 5						
	857143 Unidirectional	5.E-4	90.0	Yes		+ -

Figure 6 - Material thickness and plys

Figure 6 shows that there are a total of 5 layers, each with a thickness of 0.5mm. This is because the brief stated that there are 25 plys, all with a thickness of 0.1mm. So, 5 plys per layer at 0.1mm per ply gives a total thickness of the board of 0.25mm.

Once this was all complete, the FEA could now be run for the composite board. The results are seen below in Figure 7.

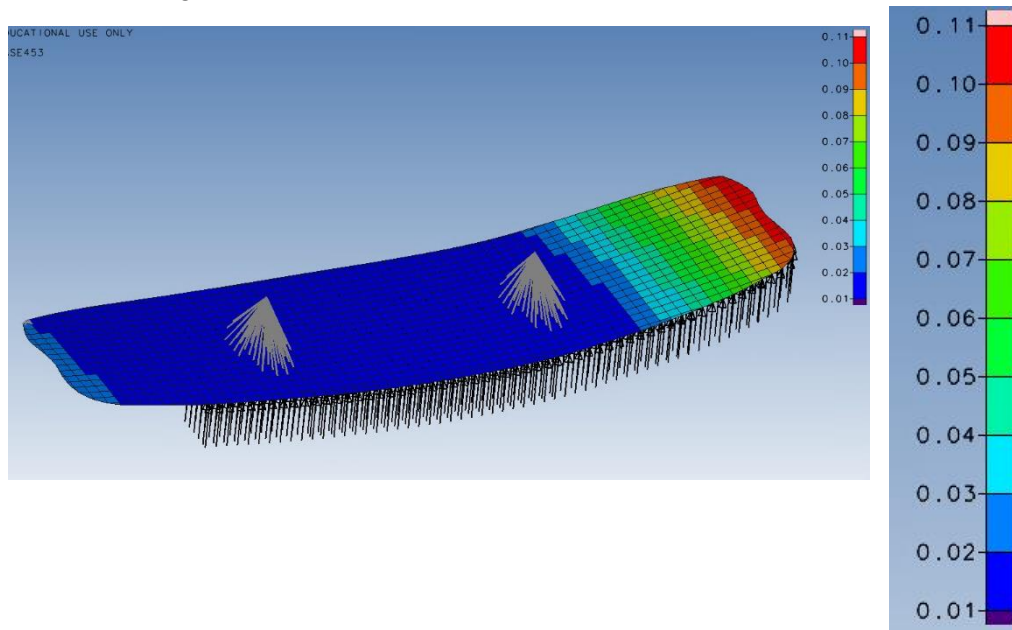


Figure 7 - FEA of Composite board

The largest deflection, as indicated by the deflection scale on the right in meters, is located close to the board's tail end and is roughly 0.11 meters (110 mm). The fact that this deflection is notably larger than that of the steel board indicates that the first composite layup did not yet reach the required stiffness.

Similar to the steel board, the mass of the composite board was calculated and a result of 2.02544Kg.

Using the same equations from earlier for stiffness and stiffness/weight, the results for the composite board are seen in the table below.

Table 2 - Steel and Composite Results

Material	Thickness (mm)	Deflection (mm)	Mass (Kg)	Load (N)	Stiffness (N/mm)	Stiffness/Weight (N ² /mm)
Steel	2	23	8.10	735.75	31.98	0.40
Composite	2.5	110	2.03	735.75	6.69	0.34

The table above shows that the composite material is a lot lighter than the steel which is beneficial for applications which are weight sensitive. The steel is a lot stiffer than the composite which makes it more deformation-resistant. The steel also has a higher stiffness/weight ratio indicating that steel has a higher rigidity per unit weight. Overall, the composite kiteboard's only advantage over the steel board is the mass, apart from this, the steel board is a much better product.

4. Optimised Composite

The composite kiteboard was optimised so that the orientation of the layers and their thicknesses were able to achieve the deflection that was seen on the steel kiteboard.

The upper bound constraint was set to 0.023m or 23mm which was the maximum deflection seen on the FEA of the steel board.

The design variables were then set, giving the thicknesses of each layer an upper and lower value.

ID=1 Init=0.001 [1.E-4,0.002]	L1THK
ID=2 Init=0.001 [1.E-4,0.002]	L1THK2
ID=3 Init=0.001 [1.E-4,0.002]	L1THK3
ID=4 Init=0.001 [1.E-4,0.002]	L1THK4
ID=5 Init=0.001 [1.E-4,0.002]	L1THK5

Figure 8 - Design Variable Thicknesses

Figure 8 shows that the lower limit was set to 1.E-4 (0.1mm) and the upper limit was set to 0.002m (2mm).

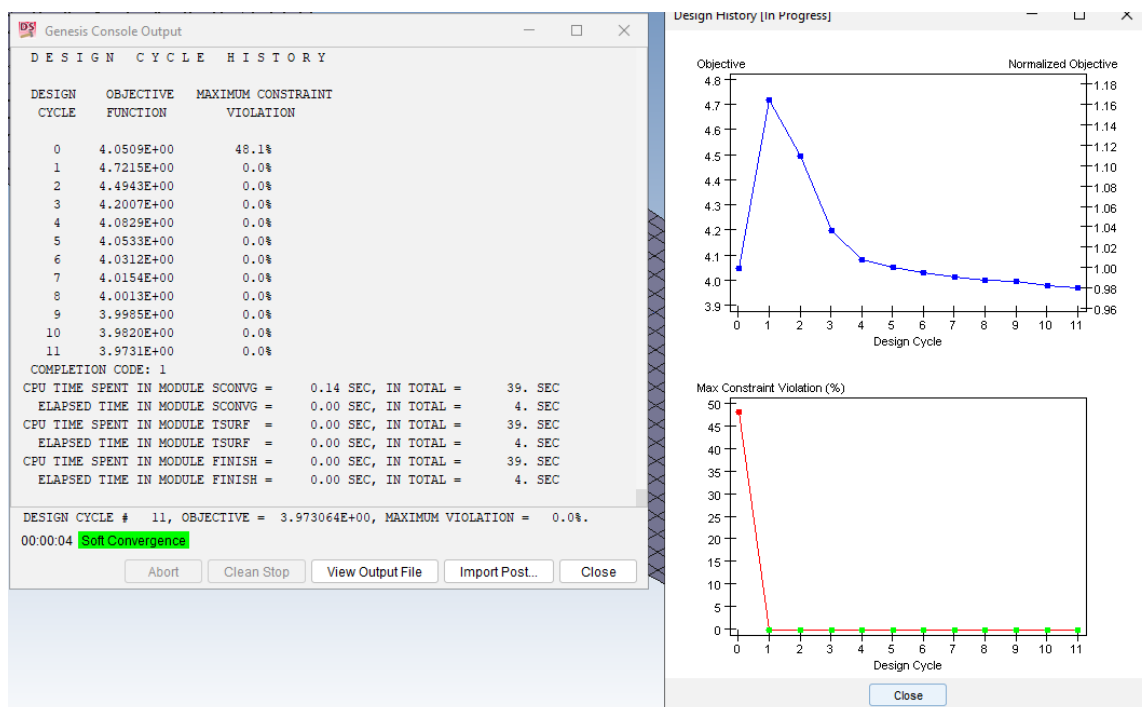


Figure 9 - Optimisation results

Once the design variables and constraints were set, the optimisation could begin. Below is an output of the results. The results show that at design cycle zero, which is the baseline, the mass of the board is 4.05kg and it is violating the constraint at 48.1%. By design cycle 11 the constraint is 0 and the displacement of 23mm has been met. The image also shows that the mass of the board has decreased slightly, starting at 4.05kg at design cycle 0 and finishing with 3.97kg at design cycle 11.

Figure 10 below shows the design history plot for the thicknesses of the plies.

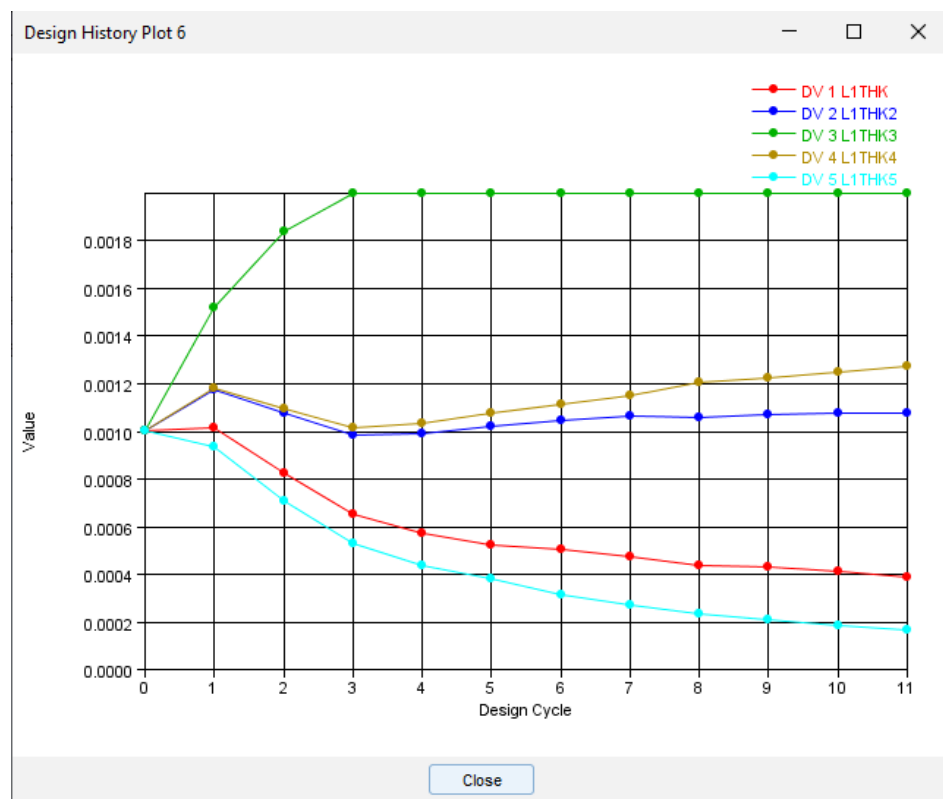


Figure 10 - Design history plot

The graph shows that all variables started at 1mm. Only one of the design variables maxed out at the top limit of 2mm which are the plies at 0 degrees. The plies at -45 and 45 degrees stayed around the 1mm (5 plies) mark until reaching design cycle 11. Finally, the design variables at -90 and +90 dropped down to around 0.2/0.4mm by design cycle 11.

The results below show the thicknesses of each layer.

```

DESIGN CYCLE #    11, OBJECTIVE =  3.973064E+00, MAXIMUM VIOLATION =   0.0%.
DESIGN VARIABLE #      1 =  3.877603E-04    L1THK
DESIGN VARIABLE #      2 =  1.076704E-03    L1THK2
DESIGN VARIABLE #      3 =  2.000000E-03    L1THK3
DESIGN VARIABLE #      4 =  1.271939E-03    L1THK4
DESIGN VARIABLE #      5 =  1.675509E-04    L1THK5
COMPLETION CODE: 1      11      0
  
```

Figure 11 – Thicknesses at each angle

The total thickness is: 4.9mm (0.388+1.08+2+1.27+0.168).

Discrete Composite

Finally, to get a more accurate result for ply thickness, the design variables were changed to discrete values. Once changed, the optimisation was generated again and the below is generated:

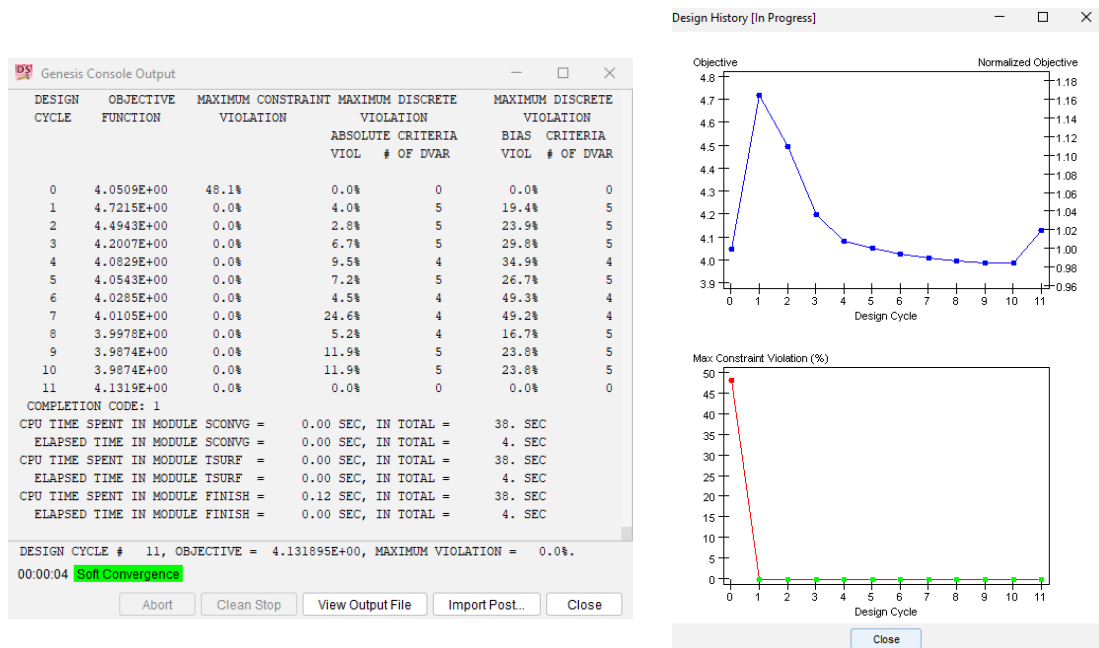


Figure 12 - Design variables with discrete values

The displacement was now 22mm. By design cycle 11 the mass of the board was now 4.13Kg which was slightly heavier than the non-discrete optimised composite.

The design history file also shows that at design cycle 11 the thicknesses at each degree are now discrete values.

DESIGN VARIABLE HISTORY					
DESIGN CYCLE	DESIGN VARIABLE 1	DESIGN VARIABLE 2	DESIGN VARIABLE 3	DESIGN VARIABLE 4	DESIGN VARIABLE 5
	L1THK	L1THK2	L1THK3	L1THK4	L1THK5
0	1.0000E-03	1.0000E-03	1.0000E-03	1.0000E-03	1.0000E-03
1	1.0141E-03	1.1757E-03	1.5194E-03	1.1822E-03	9.3635E-04
2	8.2209E-04	1.0761E-03	1.8424E-03	1.0968E-03	7.0995E-04
3	6.5316E-04	9.8450E-04	1.9999E-03	1.0175E-03	5.2980E-04
4	5.7515E-04	9.9154E-04	2.0000E-03*	1.0349E-03	4.3797E-04
5	5.2669E-04	1.0247E-03	1.9990E-03	1.0827E-03	3.7103E-04
6	5.0385E-04	1.0507E-03	2.0000E-03*	1.1161E-03	3.0175E-04
7	4.8875E-04	1.0687E-03	2.0000E-03*	1.1435E-03	2.4915E-04
8	4.7391E-04	1.0883E-03	2.0000E-03	1.1665E-03	2.0573E-04
9	4.4752E-04	1.1023E-03	1.9995E-03	1.1863E-03	1.8588E-04
10	4.4752E-04	1.1023E-03	1.9995E-03	1.1863E-03	1.8588E-04
11	5.0000E-04	1.2000E-03	2.0000E-03*	1.2000E-03	2.0000E-04

Figure 13 - Discrete thicknesses

Results

Table 3 - Final results of all kiteboards

Material	Thickness (mm)	Deflection (mm)	Mass (Kg)	Load (N)	Stiffness (N/mm)	Stiffness/Weight (N ² /mm)
Steel	2	23	8.1	735.75	31.98	0.40
Composite	2.5	110	2.03	735.75	6.69	0.34
Optimised Composite	4.9	23	3.97	735.75	31.98	0.82
Discrete Composite	5.1	22	4.13	735.75	31.98	0.79

The results show that the discrete composite part is around double the stiffness/weight than that of the steel part, with only half the mass. The discrete composite is more than double the width of the steel board, so if it essential that the board is as thin as possible then the steel board is beneficial, however for all other aspects the discrete composite board is favorable.

5. Prototype Experiment Testing

The experimental test aims to validate the FEA results by measuring the physical deformation of the composite kiteboard under controlled loads. This test assesses whether the composite board's performance is consistent with FEA projections and meets the performance standards established by the 2mm steel benchmark.

Experiment Setup

The kiteboard would be put on a test rig that accurately duplicates the FEA model's boundary conditions and load distribution. To replicate fluid flow loading, a force of 735.75 N would be applied equally across the board. The board's edges would be fixed to fit the FEA restrictions, ensuring that the deflection and stress patterns closely match the simulation (Poodts, Riccardo Panciroli and Giangiacomo Minak, 2013).

Instruments and Methods for Measurement

Accurate measurement instruments are necessary to capture the board's response. Strain gauges would be put at crucial spots to measure the strain distribution. It is important that the laboratory in which the testing takes place has followed industry standards such as ISO/IEC 17025:2017 which is the internationally recognised standard for testing and calibration laboratories. It ensures the quality and dependability of the testing and calibration outcomes (ISO, 2017). Digital image correlation (DIC) should also be used. This technique examines how a material sample changes under stress using optical data collected by one or more cameras (Digital Image Correlation, 2021). DIC generates a full-field displacement map, which is particularly useful for comparing to the FEA results.

Gathering Data and Analysis

The load would be applied slowly, with measurements taken at each stage to detect any progressive deformation or nonlinearity in response. The data collecting process would concentrate on deflection, strain, and overall structural integrity under load. The data points acquired during testing would be compared to the maximum deflection limit determined by the steel board's FEA simulation. Any variation from the expected findings would be documented and analysed for potential material or modelling changes.

Evaluation and Findings

The results of the physical test would be compared to the FEA predictions to ensure model accuracy. If the composite board exhibits excessive bending or stress over permitted limits, changes to ply orientation or ply count may be required. Re-testing may be necessary to ensure that the amended board satisfies both performance and weight targets.

6. Technical Literature

The kiteboard used in this study was carbon fibre reinforced plastic (CFRP) which is widely used throughout sporting industries such as kiteboarding and windsurfing (Jones, 2024). The reason CFRP is used is due to its high tensile strength (up to 2,500 MPa) and low density (1.6 g/cm³), allowing for lightweight yet sturdy structures (Ru-Min Wang, 2016, pp.7–8). Rana and Shiv Brat Singh (2016, pp.1–18) further explain that carbon fibres give very directional qualities that are very different from metals. They can be engineered to reduce mass in ways that metals cannot. As these are intentionally composited materials, the qualities and performance can be adjusted to the application by modifying the strength, length, directionality, and number of reinforcing fibres, as well as the polymer matrix. This is highly beneficial for applications such as the kiteboard which requires a high strength to weight ratio.

Ply orientation was a large part of this experiment in finding the optimum strength to weight ratio. Memarzadeh (et al., 2024) explains that the ply angle and fibre orientation are two fundamental parameters which play an important influence in defining the performance of composite plates, the research paper continues by explaining that the tensile strength of the composite plates varied according to the lay-up orientation angle. The study revealed the greatest tensile strength in specimens with a specified orientation angle lay-up, showing the considerable importance of ply orientation on this mechanical property.

According to Eckrich (et al., 2022), FEA-based optimisation approaches have shown promise in developing lightweight composite structures, notably in aerospace and automotive applications where material efficiency is crucial. FEA simulations assist in identifying appropriate ply layups that balance stiffness and strength, which is critical for applications such as kiteboards, where weight reduction improves performance without sacrificing structural integrity.

The design strategy used in this kiteboard project adheres to industry best practices, including CFRP, strategically organised ply orientations, and FEA optimisation. Each option is supported by research, demonstrating that this methodology is consistent with both engineering principles and the requirements of high-performance applications.

7. Conclusion

In conclusion, this study successfully demonstrated the use of Finite Element Analysis (FEA) to optimise the structural integrity of a composite kiteboard. By comparing the CFRP kiteboard's performance against a 2mm steel standard, the study revealed considerable advances in lightweight design without sacrificing durability. The study successfully used FEA techniques, such as topology, shape, and size optimisation, to fine-tune material properties and ply orientations, resulting in a kiteboard that satisfied performance standards. Experimental validation was recommended to check that the physical board met FEA predictions, with a focus on deflection and strain measurements. Finally, the project emphasised the importance of incorporating FEA into engineering design, supporting new and efficient solutions for high-performance sports equipment. The findings emphasised the significance of continual development in material optimisation and design approaches for future athletic applications.

8. References

- Abbey, T. (2018). *Topology Optimization (Part 1) - FETraining Resource Site* -. [online] FETraining Resource Site. Available at: <https://fettraining.net/topology-optimization-part-1/> [Accessed 29 Oct. 2024].
- Bequir, S. (2022). *Kitesurfing training: some tips*. [online] Water Sports Mallorca. Available at: <https://www.watersportsmallorca.com/blog/kitesurfing-training-some-tips/> [Accessed 2 Nov. 2024].
- Brush, K. (2019). *Finite Element Analysis (FEA)*. [online] SearchSoftwareQuality. Available at: <https://www.techtarget.com/searchsoftwarequality/definition/finite-element-analysis-FEA> [Accessed 28 Oct. 2024].
- Digital Image Correlation. (2021). *How Effective is 2D DIC in Materials Testing?* [online] Available at: <https://www.zwickroell.com/news-events/news/how-effective-is-2d-dic-in-materials-testing/> [Accessed 3 Nov. 2024].
- Eckrich, M., May, D., Arrabiyeh, P.A. and Dlugaj, A.M. (2022). Structural topology optimization and path planning for composites manufactured by fiber placement technologies. *Composite Structures*, 289, pp.115488–115488. doi:<https://doi.org/10.1016/j.compstruct.2022.115488>.
- GMT Rubber. (2022). *The Advantages of Finite Element Analysis*. [online] Available at: <https://www.gmtrubber.com/finite-element-analysis/> [Accessed 31 Oct. 2024].
- ISO (2017). *ISO/IEC 17025:2017*. [online] ISO. Available at: <https://www.iso.org/standard/66912.html> [Accessed 3 Nov. 2024].
- Jones, O. (2024). *Water Sports and Activities*. Megan Publishing Services.
- Kitemare.com. (2024). *Trainer Kite for Big Guys*. [online] Available at: <https://www.kitemare.com/trainer-kite-for-a-big-guy/> [Accessed 2 Nov. 2024].
- Liu, W.K., Li, S. and Park, H.S. (2022). Eighty Years of the Finite Element Method: Birth, Evolution, and Future. *Archives of Computational Methods in Engineering*, 29(6), pp.4431–4453. doi:<https://doi.org/10.1007/s11831-022-09740-9>.
- Madier, D. (n.d.). *History of Finite Element Method*. [online] FEA Academy. Available at: <https://www.fea-academy.com/index.php/component/content/article/27-blog/fea-generalities/73-fem-history?Itemid=101> [Accessed 28 Oct. 2024].
- melissa (2023). *Finite Element Analysis (FEA) and Artificial Intelligence (AI) | Trevilla Engineering*. [online] Trevilla Engineering and Design. Available at: <https://trevillaengineering.com.au/finite-element-analysis-and-artificial-intelligence/> [Accessed 31 Oct. 2024].
- Memarzadeh, A., Onyibo, E.C., Asmael, M. and Safaei, B. (2024). Dynamic Effect of Ply Angle and Fiber Orientation on Composite Plates. *Spectrum of Mechanical Engineering and Operational Research*, [online] 1(1), pp.90–110. doi:<https://doi.org/10.31181/smeor11202410>.
- Poodts, E., Riccardo Panciroli and Giangiacomo Minak (2013). Design rules for composite sandwich wakeboards. *Composites Part B: Engineering*, 44(1), pp.628–638. doi:<https://doi.org/10.1016/j.compositesb.2012.02.014>.

Prem Kythe and Wei, D. (2011). *An Introduction to Linear and Nonlinear Finite Element Analysis*. Springer Science & Business Media, p.2.

Rana, R. and Shiv Brat Singh (2016). *Automotive Steels*. Woodhead Publishing, pp.1–18.

Ru-Min Wang (2016). *Polymer Matrix Composites And Technology*. Woodhead Publishing, pp.7–8.

sdcaadmin (2022a). *Why do you need to optimize your FEA model?* [online] SDC Verifier. Available at: <https://sdcverifier.com/articles/why-do-you-need-to-optimize-your-fea-model/> [Accessed 28 Oct. 2024].

sdcaadmin (2022b). *Why do you need to optimize your FEA model?* [online] SDC Verifier. Available at: <https://sdcverifier.com/articles/why-do-you-need-to-optimize-your-fea-model/> [Accessed 30 Oct. 2024].

SimScale (2018). *What is FEA | Finite Element Analysis? - SimScale*. [online] SimScale. Available at: <https://www.simscale.com/docs/simwiki/fea-finite-element-analysis/what-is-fea-finite-element-analysis/> [Accessed 28 Oct. 2024].

suchdeo, alkesh (2024). *FEA Optimization: Need, Techniques, Steps and Use Cases*. [online] Rishabh Engineering Services - Quality Engineering Solutions. Available at: <https://www.rishabheng.com/blog/design-optimization-with-fea/> [Accessed 28 Oct. 2024].

Team, midasBridge (2023). *7 Reasons why learning a Finite Element Analysis software is important for a modern day engineer?* [online] Motivewith.com. Available at: <https://www.motivewith.com/en/insights/finite-element-analysis-benefits> [Accessed 31 Oct. 2024].

Velling, A. (2020). *Topology Optimisation | Benefits & Disadvantages | Software*. [online] Fractory. Available at: <https://fractory.com/topology-optimisation/> [Accessed 29 Oct. 2024].