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Structural and Fluid Analysis

Designing a Kiteboard: Structural Design

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1. Introduction

1.1 Background

Kiteboard design requires a balance between performance, durability, and weight. To achieve this, engineers rely on computational techniques like Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD). FEA helps predict the structural behaviour of the board under various load conditions, while CFD simulates the fluid flow around the board, optimising its hydrodynamic performance.

This report explores the use of FEA in kiteboard design, examining how these methods have evolved to improve the design process. It also covers the creation of a structural model, application of boundary conditions and forces, and optimisation for weight reduction while maintaining structural integrity.

1.2 Objectives

This report aims to:

- Discuss FEA optimisation techniques, their historical development, and potential future trends, while exploring how they improve the design process.
- Create a model of a kiteboard in Design Studio with correct material properties, boundary conditions, and fluid forces, and assess the structural response of a layup using 25 plies with different orientations.
- Optimise the kiteboard structure by minimising its mass while ensuring that it meets the necessary displacement constraints, using ply orientation as a variable.
- Propose an experimental approach to testing the prototype in a laboratory setting, detailing how to compare the data collected with the results from FEA simulations.
- Relate the design process to relevant technical literature to contextualise the innovations made in kiteboard engineering.

2. Historical Development and Future Trends in FEA Optimisation

[Task 1]

2.1 The Evolution of Finite Element Analysis (FEA)

Since the turn of the century, when finite element analysis (FEA) was first developed, considerable progress has been made in the field. FEA was first created to analyse complicated structural issues in mechanical and aerospace engineering. It was especially useful for assessing stresses and strains in important components. Because of the low computer capacity available in the early applications, solving structural equations required the use of reduced models and simple techniques. Despite these limitations, FEA proved invaluable for providing insights into stress distributions in complex geometries, a task that was previously unattainable with traditional analytical methods (*Erdemir et al., 2012*).

The evolution of FEA has been marked by several key milestones. The 1960s and 1970s saw the development of FEA software packages such as NASTRAN and ANSYS, which made FEA more accessible to engineers (*Plevris & Tsiatas, 2018*). These software tools incorporated advances in numerical methods, including matrix formulations and direct stiffness methods, enabling the analysis of more detailed and accurate models. The introduction of these tools significantly broadened the scope of FEA applications beyond aerospace to include civil and structural engineering, where it is now used to calculate displacements, stresses, and dynamic behaviours of structures (*Plevris & Markeset, 2018*).

In the 1990s, the growth of computational power allowed for the creation of high-fidelity models with finer mesh resolutions, which greatly increased the accuracy of simulations. This period also saw the integration of nonlinear materials, large deformation analysis, and dynamic simulations, further expanding the scope of FEA to address more complex engineering problems. The ability to simulate real-world conditions and predict structural responses has made FEA an essential tool in various fields. (*Erdemir et al., 2012*).

2.2 Current Optimisation Techniques in FEA

The current focus of Finite Element Analysis (FEA) optimisation approaches is on increasing the effectiveness and efficiency of simulations, especially when handling complicated geometries, materials, and loading conditions. These methods aim to save costs, time needed computing, and material consumption while enhancing design performance. Topology optimisation is a popular technique in which the applied loads and boundary conditions are used to optimise the material distribution within a design space. This process typically results in lightweight, highly-strength constructions by assisting in the identification of the most effective material layout for a particular design (*Song et al., 2019*). Another method is shape optimisation, which involves changing a structure's geometry to maximise performance in ways like reducing stress concentrations or enhancing aerodynamics. We will be looking at these methods when trying to optimise our kiteboard as seen in [Figure 1](#).

With parametric optimisation, it is possible to modify parameters like as material qualities, ply orientation, or thickness to satisfy performance requirements. To investigate several design configurations and identify the best one, it is frequently used in conjunction with response surface methodology (RSM) and design of experiments (DOE). Multi-disciplinary optimisation (MDO) is another recent development that combines Finite Element Analysis (FEA) with other analysis methods, such as Computational Fluid Dynamics (CFD), to optimise a design simultaneously in many domains, such as structural integrity and fluid performance. (*Song et al., 2019*).

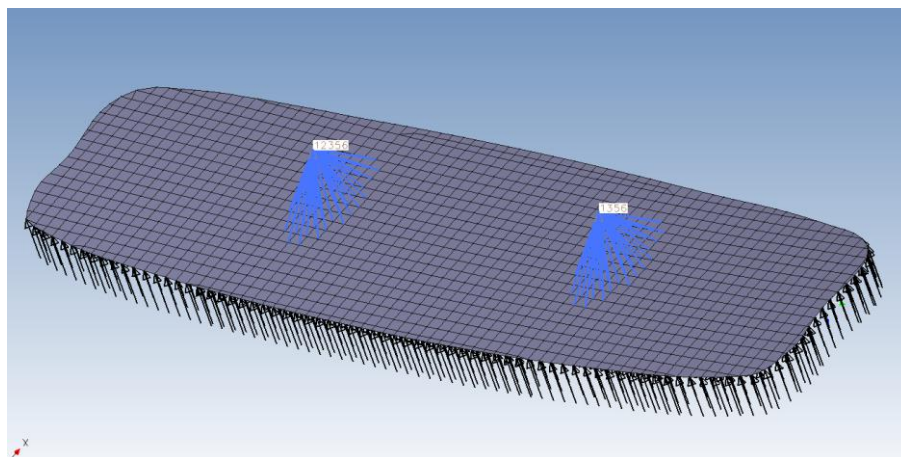


Figure 1.

2.3 Future Directions in FEA Optimisation

The future of FEA optimisation is poised to see significant advancements, driven by the integration of cutting-edge technologies such as artificial intelligence (AI), machine learning (ML), and cloud computing.

- **AI and Machine Learning:** One of the most anticipated advancements in FEA optimisation is the incorporation of AI and ML. These technologies can be used to automate the optimisation process by learning from previous simulations and predicting optimal design configurations. AI-driven optimisation can quickly identify patterns in the data, enabling faster convergence to optimal solutions with fewer simulations. (*Sonmezer, H. B., Muhtaroglu, N., Ari, İ., & Gokcin, D, 2021*). Malefice: machine learning assistance for ongoing computational engineering performance enhancement. Computation & Concurrency: This would drastically cut down on the time and computational resources needed for conventional trial-and-error methods. (*Sonmezer, H. B., Muhtaroglu, N., Ari, İ., & Gokcin, D, 2021*)
- **Cloud-Based and High-Performance Computing:** The growth of cloud-based FEA platforms is another trend for FEA optimisation in the future. Distributed processing, made possible by cloud computing, enables the division of intricate simulations over several servers, greatly accelerating calculation times. This technology is also more accessible to smaller businesses who lack the capacity for high-performance computer systems because it can run large-scale FEA models remotely.
- **Real-Time and Adaptive Optimisation:** Real-time and adaptive optimisation, in which the simulation adapts dynamically to changing conditions, are anticipated to be included in future FEA systems. Real-time optimisation, for instance, may make it possible to simulate in-service performance in sectors like aerospace and automotive (as shown in [figure 2.](#)), where the design adjusts based on real operating data. This would make it possible for engineers to continuously improve designs throughout their lives in addition to optimising them during the development stage.

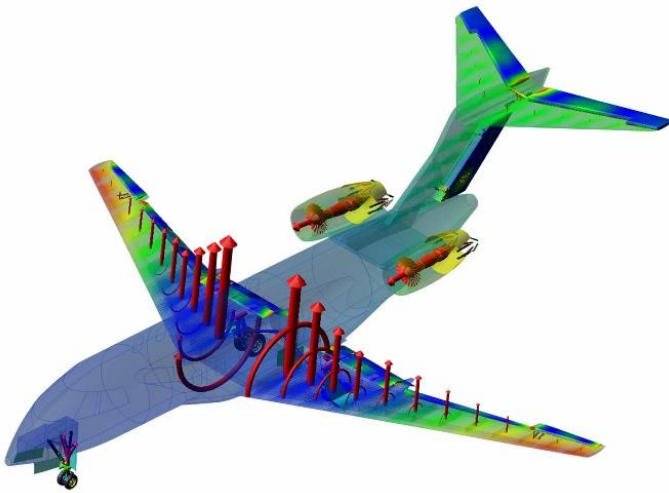


Figure 2.

A great example of the aerospace sector using FEA is on 'Enteknogrator's website. It shows the current power of FEA and CFD on a mega scale, such as on a aeroplane.

A much worth look going through this website to learn more about FEA and CFD on a big scale.

2.4 How FEA Enhances the Design Process

Finite Element Analysis (FEA) plays a crucial role in modern engineering design processes by allowing designers to simulate, test, and refine structures in a virtual environment prior to physical prototyping. This capability is particularly beneficial in applications such as kiteboard design, where factors like strength, flexibility, and weight distribution are critical. FEA enables rapid identification and assessment of stresses, strains, and deformations in materials and structures, which is essential for optimising performance under various loading conditions. For instance, Singhal highlights that FEA is instrumental in predicting how materials behave under different forces, thus facilitating the design of structures that can withstand specific operational stresses (*Singhal, 2023*). This predictive capability allows designers to optimise kiteboards for durability and performance while minimising weight, as they can simulate different scenarios, such as fluid pressures from water flow, across various ply orientations and thicknesses (*Singhal, 2023*).

Moreover, FEA supports the application of innovative materials and configurations tailored to specific load-bearing requirements. In the context of kiteboard design, varying ply orientations and thicknesses based on FEA insights ensures that the board meets performance demands without unnecessary reinforcement in areas that do not require it. This targeted optimisation not only leads to a lighter and more responsive product but also reduces material waste and manufacturing costs, aligning with sustainable design goals. The ability of FEA to accommodate complex design changes swiftly further enhances its value, allowing engineers to adjust

designs based on real-world data and evolving performance targets. As noted by Plevris and Markeset, the integration of FEA in design processes has become essential for developing high-performance structures, as it allows for the exploration of various design iterations without the need for extensive physical testing (*Plevris & Markeset, 2018*).

3. Model Creation in Design Studio: Material Properties and Boundary Conditions [Task 2]

3.1 Analysis of the Model in Design Studio

- Material Properties Used:

The unidirectional CFRP has the following material properties and each ply is 0.1mm thick. Assume that zero degrees runs longitudinally along the board.

Young's Modulus in the longitudinal direction (E ₁):	132 GPa
Young's Modulus in the lateral direction (E ₂):	10.8 GPa
Poissons Ratio (Nu ₁₂):	0.24
Inplane Shear Modulus (G ₁₂):	5.65 GPa
Transverse Shear Modulus (1-Z plane)(G _{1z}):	5.65 GPa
Transverse Shear Modulus (2-Z plane)(G _{2z}):	5.65 GPa
Mass Density (Rho):	1540 kg/m ³
Allowable longitudinal stress in tension (X _t):	1513 MPa
Allowable longitudinal stress in compression (X _c):	1000 MPa
Allowable transverse stress in tension (Y _t):	43.4 MPa
Allowable transverse stress in compression (Y _c):	43.4 MPa
Allowable inplane shear stress (S):	43.4 MPa

- Boundary Conditions and Forces Representation: The model in Design Studio replicates boundary conditions that replicate stresses found in the real world. These forces are applied where the board meets water, namely at the leading edges and surfaces under high dynamic loads, in accordance with the fluid flow considerations that I took from assignment 1.
- Assessment of the Model: The application of these circumstances and a first analysis show that a balanced ply orientation (e.g., 45° or 90° orientations for torsional strength and 0° fibres for longitudinal stiffness) aids in stabilising the board under multidirectional loads. This configuration reduces the chance of structural failure at high stress locations while enabling regulated flex in the board, which is crucial for performance. The consistent 0.5 mm thickness per ply, however, might add extra mass. This model lays the groundwork for a

more lightweight design in later stages by offering a strong basis for weight reduction optimisation without sacrificing mechanical integrity.

4. Optimising the Kiteboard Structure: Reducing Mass While Maintaining Performance [Task 3]

4.1 Analysis and Results

Before Optimisation of Kiteboard – 25 Plys

Orientation	Size of	Plys
-90	0.5mm	5
-45	0.5mm	5
0	0.5mm	5
45	0.5mm	5
90	0.5mm	5

Table 1.

After Optimisation of Kiteboard – 22 Plys

Orientation	Size of	Plys
-90	0.2mm	2
-45	0.2mm	2
0	1.4mm	14
45	0.2mm	2
90	0.2mm	2

Table 2.

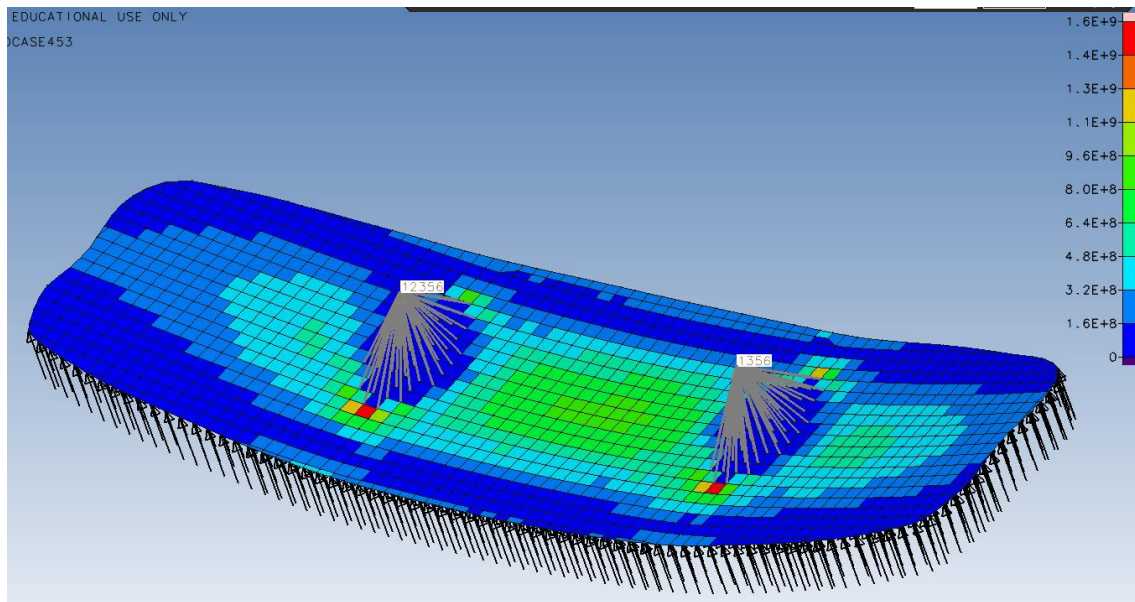


Figure 3.

The kiteboard's Finite Element Analysis (FEA) results show a considerable improvement in post-optimisation structural optimisation and material efficiency. The kiteboard was initially planned with five plies at 0.5 mm thickness for each angle (-90, -45, 0, 45, and 90 degrees) with a consistent ply thickness and distribution throughout all fibre orientations. Following optimisation, the ply thicknesses were carefully changed, strengthening the kiteboard in its main load-bearing direction by increasing the number of plies aligned at 0 degrees to 14 with a thicker layer of 1.4 mm. For the other orientations (-90, -45, 45, and 90 degrees), the number of plies and thickness were decreased to two plies each at a thickness of 0.2 mm.

Since most of the material is concentrated along the most important axis for bending force resistance, this optimised arrangement reduces the kiteboard's weight without sacrificing its structural integrity. This optimisation demonstrates how FEA can identify the precise requirements for material distribution, guaranteeing strength and flexibility where required and minimising unnecessary weight elsewhere.

Performance can be improved by focussing on ply orientations, which will increase the kiteboard's ability to endure fluid and structural forces.

5.4 Estimation of Forces Exerted on the Kiteboard

5.4.1 Drag and Lift Forces

Drag Force

$$F_D = \frac{1}{2} \times \rho \times (V)^2 \times C_D \times A$$

$$F_D = \frac{1}{2} \times 1025 \times (10)^2 \times 0.12 \times 1.6$$

$$L = 9,840 \text{ N}$$

Lift Force

$$F_L = \frac{1}{2} \times \rho \times (V)^2 \times C_L \times A$$

$$F_L = \frac{1}{2} \times 1025 \times (10)^2 \times 0.8 \times 1.6$$

$$F_L = 65,600 \text{ N}$$

Example Values, Based on a
1.6m x 1.0m x 0.3m
Kiteboard.

F_D = Drag Force
 F_L = Lift Force
 C_D = Drag Coefficient: **0.12**
 C_L = Lift Coefficient: **0.8**
 P_{ATM} = Atmospheric Pressure = **101325**
 ρ = Density: **1025kg/m³**
 V = Velocity: **10m/s**
 V_1 = V Pressure Side: **7m/s**
 A = Area: **1.6m²**

We can gain a better understanding of how drag and lift forces affect the kiteboard's design parameters, especially about material selection and structural optimisation, by using the drag and lift force estimations we made in Assignment 1. The previously determined drag and lift forces, for instance, reveal how the kiteboard needs to be strengthened in specific places to withstand fluid flow pressures without sacrificing weight or flexibility. According to calculations, choosing CFRP as the main material results in a notable weight reduction of roughly 75–80% when compared to an equivalent steel product. Performance is directly improved by this lighter weight since it lowers resistance and facilitates control in a variety of water conditions. Additionally, the forces estimated in Assignment 1 help determine the optimal ply orientation and thickness for stability, as evident in the post-optimisation ply configuration. This configuration ensures structural integrity under drag and lift forces while minimising material use and weight. Below is some estimates from Steel, to CFRP, and the weight savings that is made from this change.

Estimated Rider Weight – 70kg. (In relation to board size)

Steel Estimated Weight: 7kg.

CFRP Estimated Weight: 4kg. // **75% weight saving from Steel Kiteboard.**

Figures estimated from Online Research.

5. Prototype Testing: Correlating Laboratory Data with Simulation

[Task 4]

5.1 Proposed Experimental Setup for Prototype Testing

In this testing setup, a controlled laboratory environment with adjustable force parameters is essential for accurately assessing the performance of the kiteboard prototype. The initial step involves:

Prototype Construction and Instrumentation: where the optimised Finite Element Analysis (FEA) model is used to determine the precise ply thicknesses and orientations used in the construction of the kiteboard prototype. To guarantee that the mechanical qualities are equivalent, it is essential to use the same materials. To record deformation data under applied forces, strain gauges should be positioned strategically along key board parts, such as the edge and central regions. As a standard procedure in experimental mechanics to guarantee precise data gathering, load cells can be used at contact locations to evaluate force impact and distribution throughout the structure.

Simulated Fluid Forces: where the board can be tested in a water tank with variable flow rates or subjected to a hydrodynamic testing setup. Below in **figure 4**, you will see how this could possibly be set up. This approach allows for control over fluid forces at different attack angles and speeds, closely mirroring the boundary conditions set in the FEA. Adjustments in force application are necessary to replicate various environmental pressures, as well as angular and linear forces, accurately (*Sun et al., 2010*).

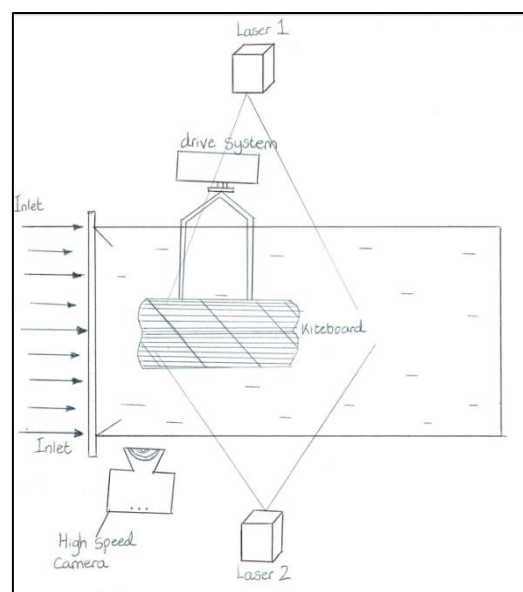


Figure 4. Hydrodynamic Testing Set-Up. *drawn*

Deformation and Displacement Measurements: high-resolution cameras and laser-based displacement sensors should be utilised to monitor the board's deformation patterns under applied loads. The measurements of displacement and strain from the lab tests can then be compared against the FEA predictions to validate the accuracy of the model. This validation process is critical, as discrepancies between laboratory and simulation results can reveal areas for refinement in simulation parameters or material specifications. The integration of experimental data with FEA predictions enhances the reliability of the design process and informs necessary adjustments to the model.

Data Acquisition and Analysis: the collected data from strain gauges, load cells, and displacement sensors can be analysed to quantify the board's resilience and flexibility under stress. The experimental results should be evaluated for correlation with the FEA model outputs. High consistency in data would confirm model accuracy, while discrepancies may suggest adjustments in ply orientation or thickness are necessary. This iterative process of validation and refinement is essential in engineering design, particularly in applications where performance and safety are paramount (*Trivedi, 2014*).

5.2 Comparing Experimental Results with FEA Simulations

The displayed structural integrity, load responses, and displacement patterns of the kiteboard model will be validated by comparing the experimental data with the optimised FEA simulations. To balance weight reduction with mechanical stability, the FEA findings show an optimised layup with a 1.4mm ply at 0° and lower ply thicknesses at other orientations (-90°, -45°, 45°, 90°). The displacement predictions from the simulation will be compared with strain data and deformation under applied forces during testing. The FEA model's accuracy will be confirmed by key indications including peak strain values and deformation sites.

Any disparities will draw attention to regions where the FEA might require improvement or modifications to the material parameters, boundary conditions, or ply orientation. The board's structural robustness under actual conditions can be better understood thanks to this comparison, which helps with further design revisions that aim to improve performance while still fulfilling safety and durability requirements.

6. Connecting Kiteboard Design with Technical Literature [Task 5]

6.1 Review of Composite Materials in Sports Equipment

Composite materials have significantly impacted the design of sports equipment, particularly in high-performance contexts like kiteboarding, where a balance between durability and lightness is critical. Materials such as carbon fiber and fiberglass enable the creation of boards that are both strong and lightweight, optimising performance by enhancing flexibility, stiffness, and control. The use of carbon fiber reinforced epoxy composites has been recognised for its significant characteristics, which play an essential role in various fields, including sports (*Xu et al., 2021*). In kiteboard design, layers of unidirectional (UD) plies are arranged at various orientations (0° , 45° , and 90°), allowing designers to fine-tune the board's properties to better handle dynamic forces and environmental challenges.

These composites also excel in absorbing impact, making them ideal for sports where equipment faces continuous stress. By adjusting the layering patterns and fiber orientation, designers can customise aspects such as torsional flexibility and rigidity, ensuring the board maintains its integrity and performance across varied conditions. The ability of composite materials to enhance energy absorption and delamination under impact is crucial for improving protective performance in sports applications. The result is a more responsive and resilient board that enhances safety, agility, and longevity, all of which are essential for an optimal kiteboarding experience (*Su, 2014*).

Furthermore, the integration of advanced materials such as thermoplastic elastomers and nanocomposites has been shown to improve the performance, adaptability, durability, and portability of sports equipment. The continuous evolution of composite materials in sports equipment design not only promotes better athletic performance but also contributes to the sustainability of sporting goods through the use of environmentally friendly materials. (*Subic et al., 2010*)

6.2 Hybrid CFD-FEA Models for Enhanced Performance

Hybrid models that combine Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) offer advanced insights into the performance of kiteboards

by allowing designers to simulate both fluid flow interactions and structural responses in a single integrated framework. The hybridisation of CFD and FEA provides a more complete understanding of the aerodynamic and hydrodynamic forces acting on the board during operation. This integrated approach gives a clearer view of how the board will deform, flex, and handle under realistic conditions, ultimately contributing to a more optimised, high-performance design (*Xu et al., 2021*).

This hybrid technique enables engineers to optimise the balance between strength, flexibility, and weight in kiteboard design by fine-tuning variables like ply thickness and orientation. Designers can decrease the requirement for several physical prototypes while increasing safety and durability by mimicking real-world conditions, such as fluid pressure and structural stresses. Improving the performance of composite materials used in sports equipment requires the capacity to precisely describe the interactions between fluid dynamics and structural mechanics. Manufacturers will find it easier to improve the board's performance and robustness in demanding conditions as hybrid modelling develops further as CFD-FEA approaches become more computationally efficient.

The integration of advanced modelling techniques not only streamlines the design process but also facilitates the exploration of innovative materials and configurations that can further improve the performance characteristics of kiteboards (*Subic et al., 2010*). This pattern is part of a larger trend in sports engineering that uses computational techniques to maximise material use and improve the general performance of sporting goods. As the industry develops, the ongoing creation of hybrid models will be crucial in determining how high-performance sports equipment is shaped going forward and guaranteeing that players have access to gear that can withstand the demanding requirements of their activity.

7. Conclusion: The Role of FEA and CFD in Kiteboard Design Optimisation

The integration of Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) plays a pivotal role in optimising kiteboard design, addressing both structural integrity and performance under various fluid flow conditions. In Assignment 1, we examined how CFD simulates the fluid dynamics around the board, helping predict performance under different angles and speeds. FEA, on the other hand, allows precise assessment of stresses and deformations within the kiteboard materials, enabling engineers to optimise the board's ply composition to meet strength requirements while minimising weight.

By combining these methods, designers gain a comprehensive understanding of both external forces and internal responses. This hybrid approach supports iterative design improvements and reduces the need for extensive prototyping by accurately forecasting real-world performance. As technology advances, the CFD-FEA synergy promises even greater efficiency and precision in kiteboard development, setting a foundation for creating lighter, more durable, and higher-performing boards tailored to the demands of kite surfing.

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Image

Figure 1. Image by Author. Kiteboard on DesignStudio 2013. Taken 25/10/24.

Figure 2. Enteknorate (Accessed 2024). <https://enteknorate.com/fea-cfd-aerospace-defence/>

Figure 3. Image by Author. Kiteboard on DesignStudio 2013. Taken 28/10/24.

Figure 4. Image by Author. Kiteboard in Hydrodynamic Testing Set-Up.