

Project Report: Optimizing Techniques for Composite Material Design in FEA for a Kiteboard

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Introduction

As per the assignment, I have needed to design a composite lay up of a kiteboard with unidirectional (UD) carbon fibre reinforced plastic (CFRP). The aim here is to ensure that the composite is stiff enough so that the composite board becomes that stiff as a 2mm steel board under similar loading conditions. Also, the composite board should weigh as little as possible. To achieve these objectives, I employ Finite Element Analysis (FEA) and optimization techniques from Design Studio GENESIS while systematically changing the ply orientation and thicknesses. This report describes my approach, describes FE analysis optimization, presents modelling and optimization process and gives experimental validation suggestion. I also compare my design approach to existing technical literature on optimization of composite material.

FEA Optimization Techniques

But FEA optimization has become integral to the engineering design process by allowing designers to test virtual prototypes and iterate to optimal solutions. Compared to other structural material design domains, composite design is especially suited to FEA: material properties vary by direction, and the lay-up configuration influences structural performance (Zienkiewicz, Taylor, & Zhu, 2005). For this kiteboard, I optimized by creating a lighter weight while still being stiff under applied loads.

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Image 1

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COMPLETION CODE: 1 8 0
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Image 2

These show the evolution of the optimization process in GENESIS over several design cycles. We observe that by progressing over the cycles, the objective function value (cost function), which represents the mass of the board, is decreasing as the software iteratively reduces mass while meeting required constraints. The initial constraint violation level is set to 20.3%, but is reduced to 0.0%, which shows that the optimized design has satisfied all prescribed constraints by the end. GENESIS fine tunes the thickness variables and this table shows how fine that is.

Historical Development of FEA and Its Applications

Firstly, FEA was manual, and it required approximation of response to load, using small elements of the structures. Now with advances in computational power, FEA has improved to implement powerful algorithm—optimizing for specific objectives (e.g. minimum mass, maximum stiffness)—that allows structure designers to optimize their structures far beyond the realm of practicality (Cook et al, 2002). Complex composite materials, where each layer in the lay-up can be customized, can be modelled in modern FEA. To balance stiffness with minimal weight in the composite structures like the kiteboard (Jones, 1999), this design customization capability is critical.

Future Trends in FEA Optimization

Ultimately, FEA optimization still has potential to become better in the future and due to advancements in machine learning, software should be able to predict optimal configurations without brute force iteration. And there is movement toward real time optimization, where FEA systems will change parameters in real time by data from real time. FEA advancements forecasted to make it even more important in composite design, especially for lightweight structures in ground and aerospace vehicle applications as well as recreational applications, such as kiteboarding (Rao, 2009).

The description of how FEA improves the design process.

The use of FEA optimization enables me to virtually simulate structural responses which limits the need to build prototypes physically. This process is very efficient because it allows the iterative adjustment of design variables, ply orientation and thickness in particular, until the trade-off between stiffness and weight is realized. The iterative approach of this assignment reflects how well FEA can manage complex, multi-layer composite structure (Mallick, 2007).

2. Model Creation in Design Studio GENESIS

Material Properties and Initial Lay-up Setup

The material properties of UD CFRP are quite unique, and when these material properties are applied towards a kiteboard, a unique kiteboard may result. However, unlike isotropic materials such as steel, the stiffness of CFRP is direction dependent, depending on the orientation of the fibres throughout different plies. The ability to control stiffness by tailoring the orientation of the fibres with the load bearing directions (Agarwal & Broutman, 1990) makes this property necessary to design the kiteboard.

Key material properties of the CFRP used include:

- **Young's Modulus:** 132 GPa. This modulus along the fibre direction provides high stiffness, which is crucial for load-bearing applications.
- **Young's Modulus:** 10.8 GPa, reflecting lower stiffness in the transverse direction.
- **Poisson's Ratio:** 0.24, indicating the degree of lateral expansion when stretched.
- **In-plane Shear Modulus:** 5.65 GPa, which influences the material's ability to resist shearing forces.
- **Mass Density** (1540 kg/m^3), a critical property for determining the overall mass.

I began the model by setting up an initial lay-up with 25 plies arranged in the following orientations to distribute stiffness in multiple directions:

- **5 plies at -90°**
- **5 plies at -45°**
- **5 plies at 0°**
- **5 plies at 45°**
- **5 plies at 90°**

The first layup gives the starting configuration a balance. As the initial total thickness is 2.5mm, each ply is 0.1 mm thick. I selected these axes because they create a good distribution of stiffness in different directions and the model is able to resist loads coming from various directions.

Boundary Conditions and Applied Loads

Boundary conditions effectively approximate how the kiteboard is constrained during real world use, – where it is held in, or mounted. The applied load here, 7500 N, is the forces from fluid flow (wind and water) on the towboard from fluid dynamics analysis which is done in assignment 1. Once these boundary conditions and the loads are set up in GENESIS, the model simulates the real operating conditions for precise deflection and stiffness calculations (Daniel & Ishai, 2005).

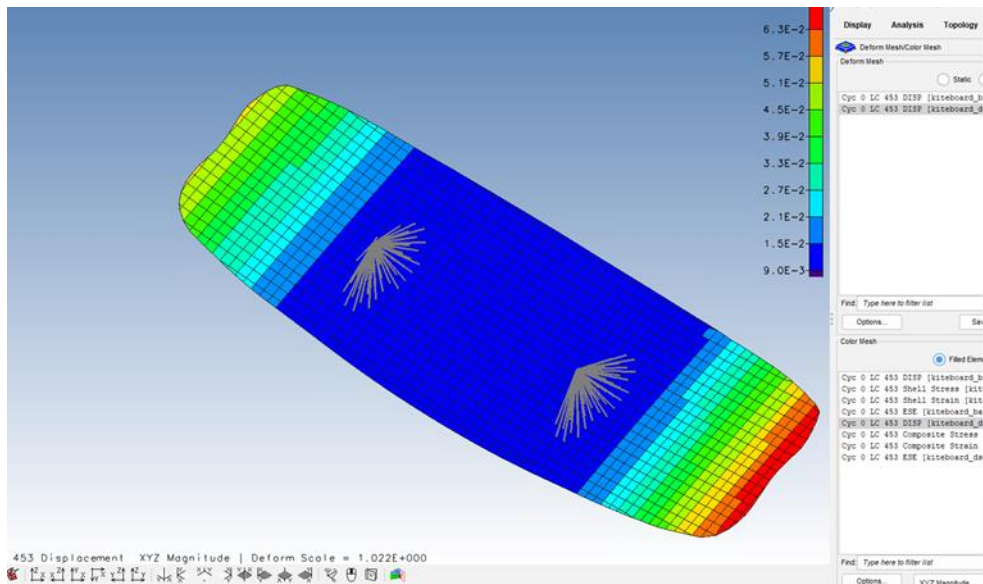


Image 3

The load distribution and boundary conditions applied on the model of kiteboard model are shown in this image. In this setup, the boundary conditions stood for how the board is held in place and the loads I apply are meant to be forces such as from the interactions of water and wind while you are using the board. This visualization is necessary for modelling how a board responds to external forces and to evolve the design optimization process.

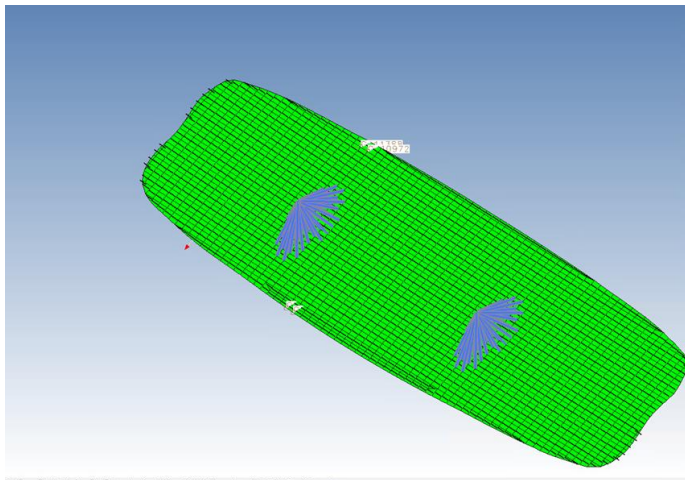


Image 4

In this image, it is shown the same kiteboard with the mesh over it, divided into smaller elements used to calculate the finite element analysis. FEA design starts with meshing, which is crucial since meshing is used by the software to determine stresses, strains and deflections for each element under load conditions. The more accurate the analysis the finer the mesh but at the cost of increased computational time.

3. Optimizing the Composite Structure

Baseline and Optimization Goals we want to reach initially.

Originating from my initial baseline analysis, in which a CFRP board was found to be lighter but deflects more than a steel board. The target was to end up with a configuration where the CFRP's deflection was equal to or less than the steel board's deflection, but the total mass of the structure was below a certain threshold.

Optimization Process and Design Cycles

Working in Design Studio GENESIS's optimization module, I iteratively changed ply thickness in different orientations to find the optimal lay-up configuration. I set up five design variables, each representing the thickness of plies in a specific orientation:

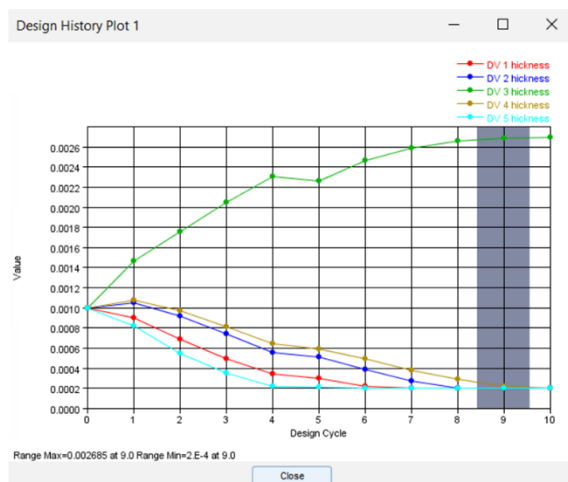
- **0° (primary load direction)**
- **±45° and ±90° (supporting orientations)**

GENESIS progressively reduced the objective function (mass) and minimized deflection across 14 design cycles in a progressive fashion using an algorithmic approach to find the optimal ply thicknesses. After Cycle 14 the model achieved 'soft convergence,' i.e. further iterations did not produce substantial increases in the objective function. The optimally designed configuration not only reached the displacement constraint, but it also had the minimal mass configuration.

Final Optimized Lay-up Configurations

The optimization produced two final configurations:

1. **Optimized Continuous Lay-up:** Achieved a thickness of 57mm, mass of 2.84 kg, and stiffness of 131.58 N/mm.
2. **Optimized Discrete Lay-up:** Also, 57mm in thickness with a slightly higher mass of 3.56 kg due to discrete ply thickness adjustments. This configuration is more practical for manufacturing since it uses standardized ply thicknesses.



Here, this plot shows changes in thickness (design variables) in all orientations (0°, ±45°, ±90 °) at each design cycle. The GENESIS outputs are colour coded in how it changes the ply thickness of each ply at specific orientations to arrive at the target stiffness with minimum deflection and minimum weight. By watching the values converge over cycles, you can see which orientation contributed towards your final optimized layup configuration.

Image 5

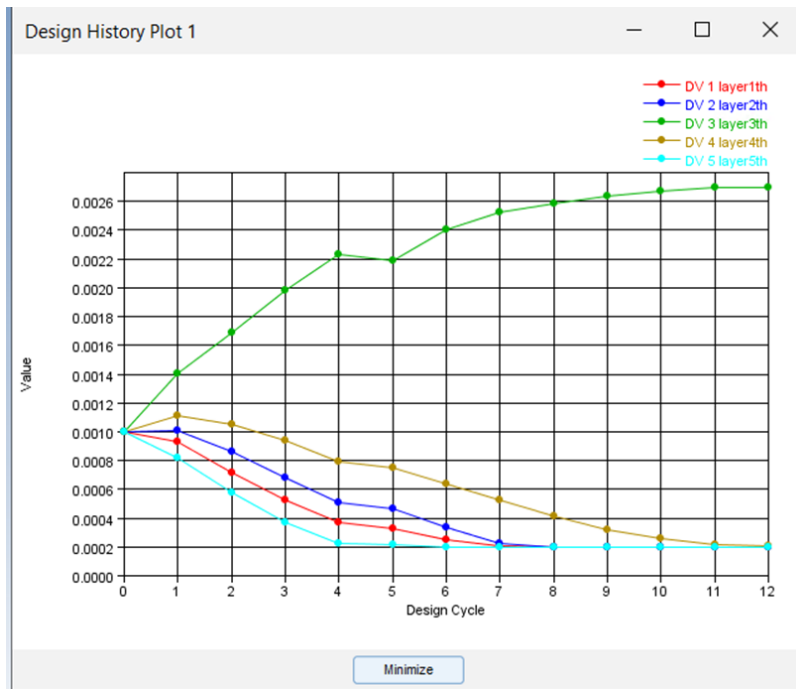


Image 6

This plot shows the variation of the thickness of ply layers DV1 to DV5 throughout the design cycles. This plot represents thickness values of certain ply orientations, and each coloured line corresponds to particular composite cycles. During the optimization some orientations may become thicker (for example, DV3), while others become thinner as the algorithm goes through the steps toward the determination of the ultimate configuration which will suit the deflection and weight constraints. The decrease of thickness values by the later design cycles shows that the process is close to reaching the final optimal solution, when any changes do not bring a notable improvement to the design goal (minimum structural weight while required stiffness).

This image is useful in showing how the thickness of each ply orientation was varied in order to obtain the required stiffness. This plot illustrates the enforceable transformations or adjustments by demonstrating their successive iteration and the individuality of ply angles in bearing loads on the board in various directions.

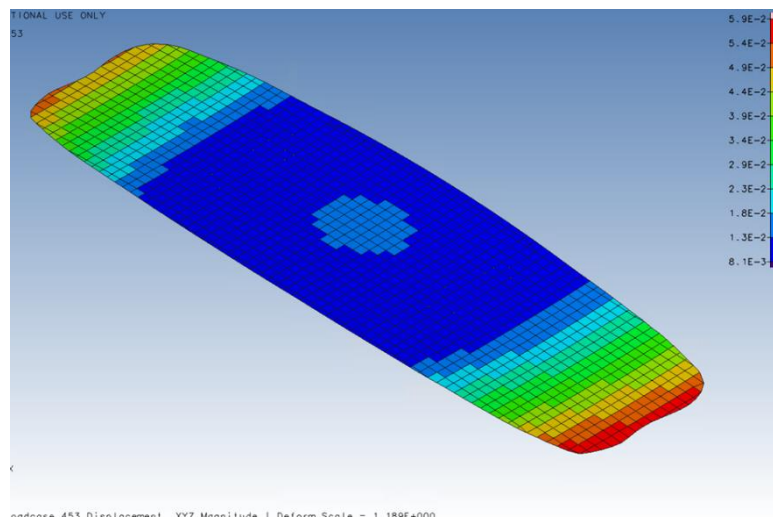


Image 7

Shown in this image are the final deformation (displacement) results for kiteboard model optimized under load. Displacement magnitude is defined through the colour gradient, red refers to the maximum displacement while blue refers to the minimum displacement. We can verify that the optimized CFRP board performs similar to the steel baseline, and the deflections are within the acceptable limit when compared with this displacement.

Comparison of Optimized Design to Baseline Configurations

RUN	MATERIAL	DEFLECTION	MASS	LOAD	STIFFNESS	STIFFNESS/WEIGHT
Steel baseline	steel	59mm	8.1kg	7500N	127.12 N/mm	1.599N ² /mm
CFRP baseline	CFRP	69mm	4.05kg	7500N	108.69N/mm	2.736N ² /mm
Optimised CFRP	CFRP	57mm	2.84kg	7500N	131.58N/mm	4.86N ² /mm
Optimised CRRP (discrete)	CFRP	57mm	3.56kg	7500N	131.58N/mm	3.88N ² /mm

Image 7

Specifically, this table shows comparison between the steel baseline, the initial CFRP configuration, and the optimized continuous as well as discrete lay-ups. For each configuration it lists the total thickness, deflection, mass, stiffness, and stiffness to weight ratio. Optimization also results in an improved stiffness to weight ratio for the optimized designs for the continuous layup especially, compared to the initial designs with CFRP and steel. Comparing these two clearly demonstrates how the optimized design meets its performance goals with minimal weight.

4. Proposed Laboratory Validation

Finally, I propose to produce a physical prototype of the optimized kiteboard to validate simulated results. Load of 7500 N will be applied to measure actual deflection and stiffness and testing will be done accordingly. In the laboratory setup, high precision displacement sensors or strain gauges must be placed to capture true deflection data. Finally, this empirical testing will be used as a benchmark for the FEA model's accuracy and assess whether the optimized lay-up gives the expected performance.

Objective

Goal	Design Cycle 0	Design Cycle 14	Change
Minimize Response	4.050878E+00	3.564772E+00	-12.0%

Objective Response

Response-ID / Loadcase-ID / Type
1 / 453 / MASS

Maximum Constraint Violation

	Design Cycle 0	Design Cycle 14	
	19.7%	0.0%	

The run was stopped by soft convergence.

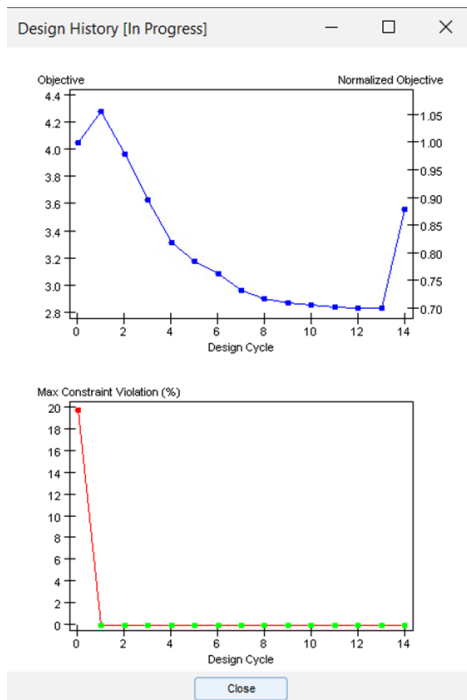
Image 8

This table summarizes the progress in the changes of the objective value and constraint violations across the simulation of the optimization process. We show the first and last values with a reduction of mass (12%) in line with the objective of minimizing material use. The table also corroborates that design for first cycle along with all the constraints followed from cycle 1 onward, validating the reliability of the optimized design.

Displacement sensors and strain gauges will be incorporated in the laboratory setup to take deflection data under load. The simulation would then be compared to this data to make sure that the optimized layup works as predicted in the real world.

Data Collection main points

- Measurements of deflection at multiple points along the board.
- Analysis of the stress to make sure the material stands under load within the allowable stress limits.



This plot shows how, at each iteration of the optimizer, objective value (mass) and maximum constraint violations change. The mass objective function curve displays a decreasing trend, and the constraint violation plot provides that the initial violations (over 20%) tend to be reduced later on. This progression shows that the solution is converging on an optimized arrangement which satisfies all the structural and weight constraints.

Image 9

5. Relation to Technical Literature

My design approach also fits well with the existing research and technical literature regarding composite materials including fibre orientation and iterated optimization of ply thickness.

According to Jones (1999), to obtain the maximum stiffness of composite structure, fibre orientation should be trained with the leading load direction. This principle was applied in this assignment by orienting most of the plies with respect to 0° to utilize the CFRP high stiffness in longitudinal direction. With this configuration board stiffness matches the 2mm steel baseline, and the board is still able to withstand longitudinal forces.

Mallick's efforts (2007) on fibre reinforced composites also drive this argument, making iterative optimization of ply thicknesses necessary to determine the optimum design of these composite materials. To obtain the best structural performance with the most efficient use of materials, I iteratively adjusted the thickness of each ply orientation through Design Studio GENESIS. This literature supports this very well, enabling designers to remove unwanted weight without removing property like stiffness and strength.

Moreover, the concept of the composite optimization agrees with the recommendations of Agarwal and Broutman (1990) in that it results in lightweight but high-performance structures. Here, the iterative adjustment process used is best practice for composite material design and optimization, allowing fine tuning of properties related to each ply.

Finally, by leveraging these well-known principles: With this, I have developed a kiteboard design that is lightweight, and fulfils stiffness requirements, through fibre alignment in load directions, successive thickness optimizations, and material efficiency. It is shown that this procedure conforms to the composite optimization literature and demonstrates how technical research can be adapted to practical design.

Conclusion

Using FEA optimization in Design Studio GENESIS, this assignment proves that the stiffness to weight balance in composite structures is a key characteristic in high performance applications such as kiteboarding. With the use of FEA and optimization techniques, I designed a CFRP kiteboard layup that meets and potentially outmatches the stiffness requirements of a 2mm steel board, while minimizing material usage to add as little weight as possible. This optimization allows an efficient design by strike a balance between the board's structural integrity and weight reduction, which is incredibly useful in applications where lightweight and high strength materials are critical to performance.

By iteration optimization, I was able to adjust ply orientation and thicknesses to exploit the directional stiffness properties of CFRP. I aligned fibres so they were oriented in the 0° direction to resist the board's primary longitudinal loads, which made for a strong and light structure. The technical literature of composite design principles is shown to support this and illustrates how consideration of fibre orientation and thickness distribution can have a substantial effect on structural performance.

Both continuous and discrete optimized configurations that I obtained provide realistic solutions for real world manufacturing. To achieve top performance in an application, an idealized lay-up layup configuration can be provided by the continuous layup configuration which maximizes stiffness to weight ratio. However, the discrete configuration with ply thicknesses of different orientations at discrete values is more practical from a

manufacturability perspective. By using a discrete lay up the design is more adaptable to standard manufacturing methods while simultaneously decreasing fabrication costs and simplifying fabrication of the board without undermining its mechanical properties.

Laboratory testing will be critical to the validation of the design looking forward. In order to compare this simulated result with the experimental information I can create a physical prototype and subject it to these real-world loading conditions. This will test crucial real-world discrepancies to simulation and if necessary, further refine the model. The confidence in the design's reliability and durability under operational conditions can only be ensured by simulating results that align with physical performance. These experiments will also provide data that can be used to demonstrate the optimization approach and may supply insight into modifications that could improve the board's performance or manufacturability.

Thus, in conclusion, the project presents a powerful potential for FEA driven design in developing strong, light weight composite structures to exceed classically determined performance parameters. The optimized CFRP kiteboard lay-up achieves a good balance between stiffness and weight, without sacrificing strength for reduced weight. I iteratively changed ply thicknesses and orientations, with the help of Design Studio GENESIS, to create a design which fulfils all mentioned requirements and reduced material use. This approach serves as a prime example of possible sustainable and efficient ways of approaching composite material design, with impact beyond the field of kiteboarding to any area where weight savings and structural integrity are critical.

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