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Designing a Kiteboard Hydrofoil Wing:
Structural Design
Structural and Fluid Analysis (ACMA6010)

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1.0 Abstract / Executive Summary

This report discusses the structural optimisation of a carbon fibre reinforced plastic (CFRP) hydrofoil wing for high-performance kiteboarding. The main aim was to create a lightweight design that does not exceed the 8.6 mm deflection of a standard 2 mm steel wing when subjected to a 500N load. A baseline Finite Element Analysis (FEA) model with a symmetric layup was constructed, which was 75% lighter than steel but 144% more flexible. Following that, a structural optimisation was carried out to minimise mass, using ply orientations as design variables and maximum deflection as a constraint.

An optimised laminate sequence of $[-90^{\circ}(12), -45^{\circ}(6), 0^{\circ}(3), +45^{\circ}(3), +90^{\circ}(15)]$ was produced by the process. With a 7.8-mm deflection and 61% mass reduction over steel, the final design met the stiffness requirement. The efficiency of CFRP tailoring was demonstrated by the 177% improvement in the stiffness-to-weight ratio. Though future research should address real-world complexities like dynamic loading and fluid-structure interaction, the report concludes that the FEA-driven optimisation process is very effective for lightweight composite design.

2.0 Introduction

Kiteboarding has entered a new age of high performance thanks to hydrofoil technology. Riders can now go faster and ride above water. This technology makes it challenging for top Formula Kite athletes to become used to the foil's complicated movements (Terrien et al., 2023). A wing's primary engineering challenge is to balance two conflicting requirements: it must be light enough to convert the rider's smallest input into immediate, agile movement while still being rigid enough to provide steady, predictable control as it cuts through the water. Composite materials, such as carbon fibre reinforced plastic (CFRP), can be tailored to meet these strict requirements.

This study optimised a composite hydrofoil wing to solve the problem. The main goal is to reduce mass and create a CFRP layup that does not deflect more than a 2mm steel wing under 500N stress. The objectives are to describe FEA optimisation,

utilise techniques to generate and evaluate a baseline FE model with a symmetric layup of $[-90/-45/0/45/-90]$, optimise the ply stack sequence, suggest a laboratory validation procedure, and relate the design to relevant technical publications. This approach will produce a lightweight, high-performance structural design.

This first analysis assumes a static load for simplicity and to set a baseline, but it's important to remember that real-world loading on a hydrofoil is very dynamic and nonlinear. This is a known flaw in the original model that may require more research later.

3.0 Task 1: A Review of FEA Optimisation Techniques

3.1 Historical Development

Since its inception, the field of structural optimisation has undergone significant changes. The 1960s and 1980s saw the development of early techniques primarily focused on size optimisation. In a fixed structural configuration, this involved finding the optimal cross-sectional areas for truss members (Jiang & Papalambros, 1995). Although useful, this method couldn't change a part's basic shape or material distribution.

Advanced algorithms have improved shape and topological optimisation. Topology Optimisation (TO) finds the optimal material distribution in a design space, resulting in efficient, organic geometries that are difficult to achieve manually (Wittahachchi, 2025). This progression relies on Svanberg's Method of Moving Asymptotes (MMA). MMA breaks down the original optimisation problem into a series of convex, separable sub-problems that are easier to solve (Jiang & Papalambros, 1995). The placement of its "moving asymptotes" is crucial to how well MMA works. These determine how aggressive or conservative the search is. The First Order Method of Moving Asymptotes (FOMMA) is one of the changes that have been made to improve MMA. It uses second-order derivative approximations to automate parameter tuning, which makes the algorithm more efficient and reliable for bigger problems with strongly coupled constraints (Jiang & Papalambros, 1995).

Gradient-based methods like the Method of Moving Asymptotes (MMA) have gotten better over time, and Genetic Algorithms (GAs) have become a powerful alternative

for solving difficult problems across various fields. These algorithms, which are based on the idea of natural selection, don't use gradients but instead use a population-based optimisation strategy. They are excellent at solving non-linear problems with discrete design variables, like finding the best angles for composite laminate layers (Ghadge et al., 2022). In addition, GAs demonstrate how well they work in multiobjective optimisation, where you have to find a way to balance competing goals. The Non-Dominated Sorting Genetic Algorithm (NSGA-II) is an example of this.

3.2 Current State and Future Trends

Topology optimisation is now essential to modern engineering, integrated into commercial software like SolidWorks Simulation. This method is widely used to design lightweight, high-performance components.

Topology optimisation, as used in the development of additively manufactured hydrofoils, was successfully applied to the design of a lever, resulting in a 61.1% reduction in mass (Costa et al., 2024). Optimising one part and adding advanced meso-structures like lattices makes things lighter without compromising their strength (Wittahachchi, 2025).

Beyond single-disciplinary optimisation, Multi-disciplinary Design Optimisation (MDO) dominates. Ghadge et al. (2022) state that MDO formalises parameter balances across structures, hydrodynamics, and manufacturing. Aerodynamic Shape Optimisation (ASO) was used to reduce drag on an aerofoil, and then Topology Optimisation was used to improve the performance of its internal structure in both areas (Martinez et al., 2021). A particular case study on a 3D composite hydrofoil employing a surrogate-based MDO framework achieved a 10.8% decrease in drag (Volpi et al., 2018, cited in Ghadge et al., 2022).

Trends indicate increased use of artificial intelligence (AI) and machine learning (ML). In order to lower simulation computational costs, a significant bottleneck in high-fidelity optimisation, these technologies can generate surrogate models (Gibert Martinez et al., 2021). Another area of research is how ML can find the best AM process parameters to make the design workflow more efficient (Wittahachchi, 2025). By providing computational power on demand, cloud computing makes advanced MDO and TO accessible to a wider range of engineers. These

improvements make it possible for faster convergence and much more complicated constraints.

3.3 Impact on the Design Process

The use of these optimisation methods has completely changed the way engineers design things. They now carry out the task in a methodical, goal-oriented manner as opposed to manually trying things out repeatedly. Engineers set up a design, loads, constraints, and goals so software can find the best solutions, which are often unexpected. Hydrofoils and drones demonstrate this transformation, as a structured DFAM workflow using TO and lattice structures reduced design iterations by 67%, from 9.3 to 3.1 (Wittahachchi, 2025).

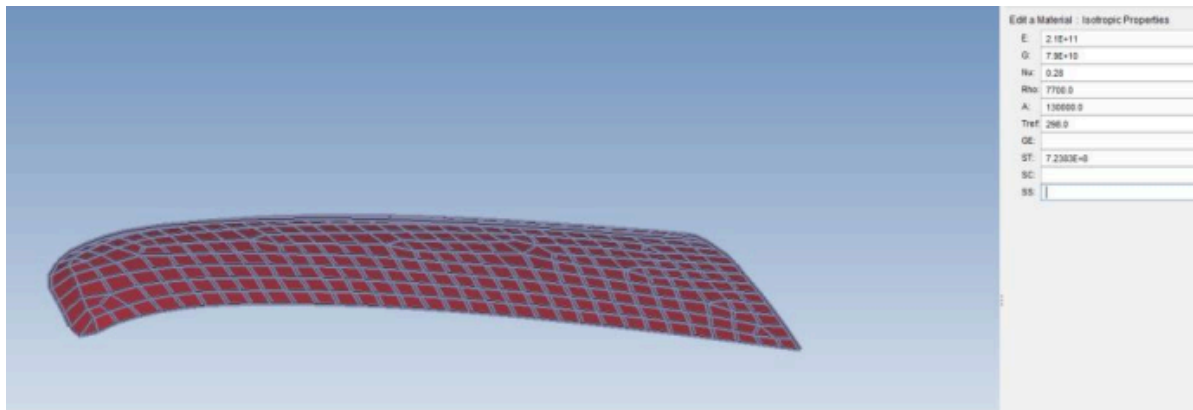
The advantages of this methodical approach are significant.

Material usage is drastically improved; for example, the TO of a hydrofoil lever led to a significant mass reduction without compromising strength (Costa et al., 2024). This directly translates to improved performance, whether it's higher lift-to-drag ratios in aerofoils (Martinez et al., 2021) or better hydrodynamic efficiency in hydrofoils (Ghadge et al., 2022). Replacement of multiple physical prototypes with digital validation through FEA and CFD simulations accelerates product development and reduces time-to-market (Wittahachchi, 2025). Using MDO and AI-enhanced workflows will help aerospace, marine, and automotive companies create more efficient, innovative, and sustainable products.

4.0 Task 2: Baseline Finite Element Model

4.1 Model Setup

The assembly geometry and SolidWorks NASTRAN deck of the simplified wing (with steel material properties) were used to create and analyse the baseline Finite Element (FE) model in Design Studio. This and the steel model's material properties are shown in [Figure 1].



[Figure 1] Image of baseline steel model with material properties

The steel baseline model also had the following properties:

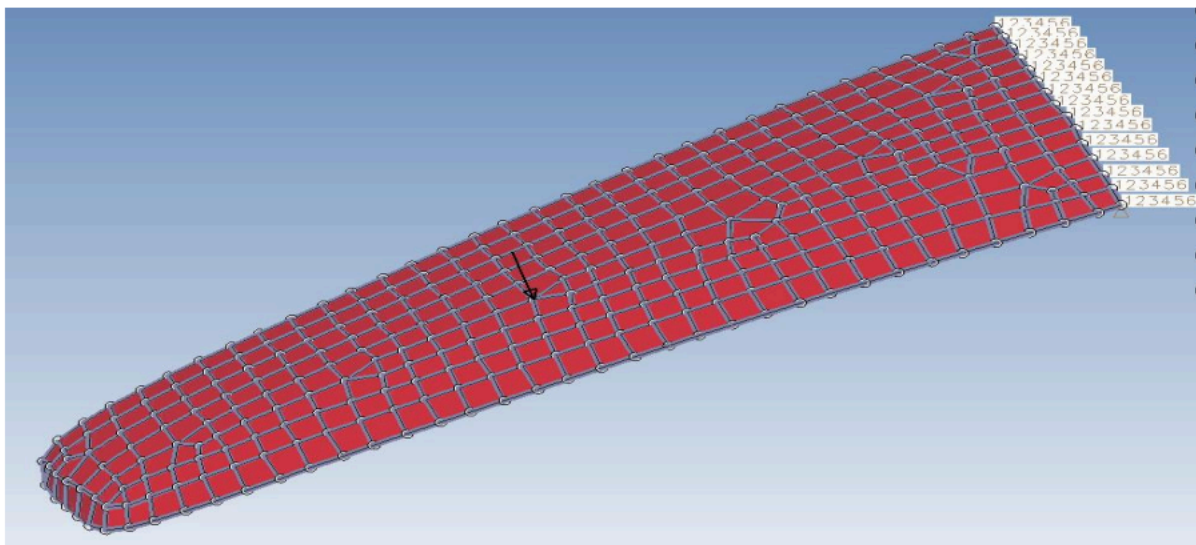
Table of properties for the baseline steel model			
Thickness (mm)	Deflection (mm)	Mass (g)	Load (N)
2	8.6	465	500

[Table 1] Further properties of the baseline steel model.

The aim was to simulate the kiteboard hydrofoil wing, made from Unidirectional Carbon Fibre Reinforced Plastic (UD CFRP), under designated loading conditions. The design brief defined the UD CFRP's material properties as orthotropic. The properties are summarised in Table 2.

Orthotropic properties for UD CFRP	Values
Young's modulus in longitudinal direction (E_1)	132 GPa
Young's modulus in the lateral direction (E_2)	10.8 GPa
Poissons Ratio (Nu_12)	2.40E-01
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 (Xt)	1531 MPa
Allowable longitudinal stress in compression (XC)	1000 MPa
Allowable transverse stress in tension (Yt)	43.4 MPa
Allowable transverse stress in compression (Xc)	43.4 MPa
Allowable inplane shear stress (S)	43.4 MPa
[Table 2] Unidirectional CFRP Material Properties	

The boundary conditions simulated a cantilever setup. The white constraints in the model indicated that the wing root was fixed, constraining all six degrees of freedom (translations and rotations). A black arrow in the software indicates a 500 N point load vertically downward at the wing centre.



[Figure 2] Image of UD CFRP model with its loading and constraints

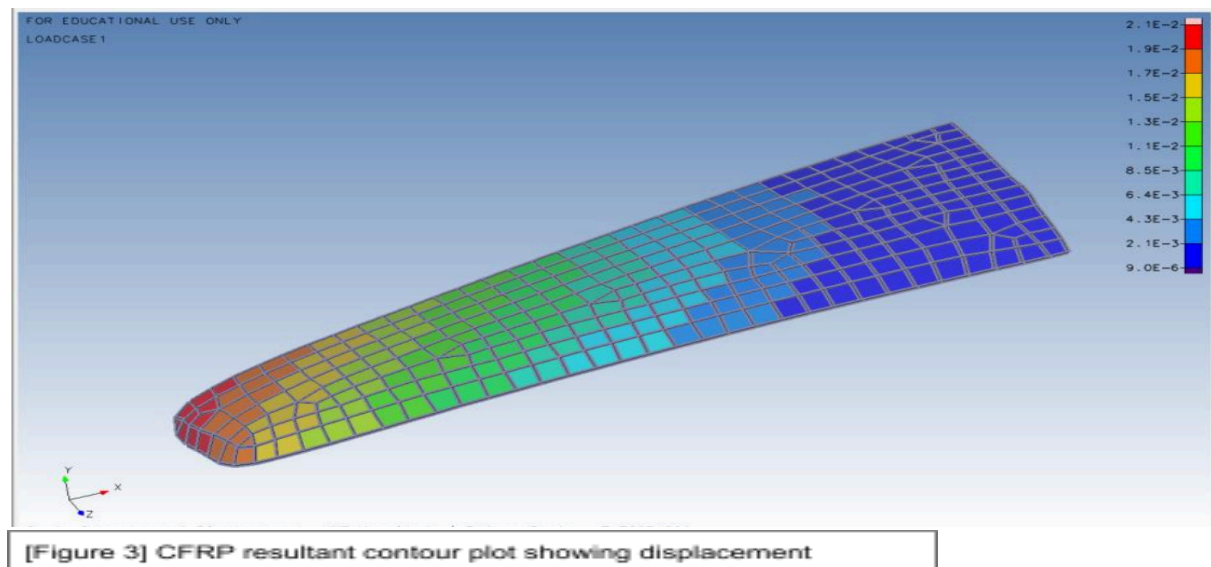
Orthotropic CFRP material orientation is crucial for accurate analysis. To accurately model composite plies' directional stiffness, the 'Generate Theta Vectors' function was used to align all elements in the fore/aft (0°) direction.

4.2 Baseline Layup Definition

The baseline composite layup was a 25-ply symmetric stack with a 2.5-mm thickness. The stack-up sequence had 5 plies at each orientation: $[-90^\circ, -45^\circ, 0^\circ, +45^\circ, +90^\circ]$. The software was configured using a PCOMP property card to assign each layer an angle and an initial thickness of 0.5 mm per layer (5 plies * 0.1 mm/ply).

4.3 Results and Analysis

After creating the baseline CFRP meshed model, FE analysis was performed. Figure 3 shows the displacement contour plot. The baseline CFRP design had a maximum deflection of 21 mm ($2.1\text{E-}2$ m).



Compared to the 8.6 mm deflection of the original 2 mm thick steel wing, the 2.5 mm CFRP layup is more flexible under the same load.

The software calculated the mass of the baseline CFRP component to be 116.3g. This is significantly less than the 465g of the steel wing, indicating a significant weight saving despite the inadequate stiffness.

The effectiveness of the optimisation process is demonstrated by comparing the stiffness and mass of the design to the original baselines. Calculations were made

From the resulting data, the stiffness (K) and stiffness/weight for each material were calculated.

Steel baseline
$$k = \frac{F}{x} = \frac{500}{8.6} = 58.14N/mm$$

Stiffness to weight
$$\frac{k}{(m \times g)} = \frac{58.13953488}{(465 \times 9.81)} = 0.013N^2/mm$$

Composite baseline
$$k = \frac{F}{x} = \frac{500}{21} = 23.81N/mm$$

Stiffness to weight
$$\frac{k}{(m \times g)} = \frac{23.80952381}{(116.3 \times 9.81)} = 0.021N^2/mm$$

[Figure 4] Calculations for stiffness and stiffness/weight for baseline steel and UD CFRP baseline

Run	Material	Thickness k (mm)	Deflection x (mm)	Mass (g)	Load (N)	Stiffness (N/mm)	Stiffness/weight (N^2/mm)
Steel Baseline	Steel	2	8.6	465	500	56.14	0.013
Composite baseline	CFRP	2.5	21	116. 3	500	23.81	0.021

[Table 3] stiffness and stiffness/weight results baseline steel and baseline CFRP

In conclusion, the baseline composite design reduced weight but deflected over 140% more than the steel wing, failing to match its stiffness. However, its stiffness-to-weight ratio increased 61.54%.

5.0 Task 3: Structural Optimisation for Mass Minimisation

5.1 Optimisation Methodology

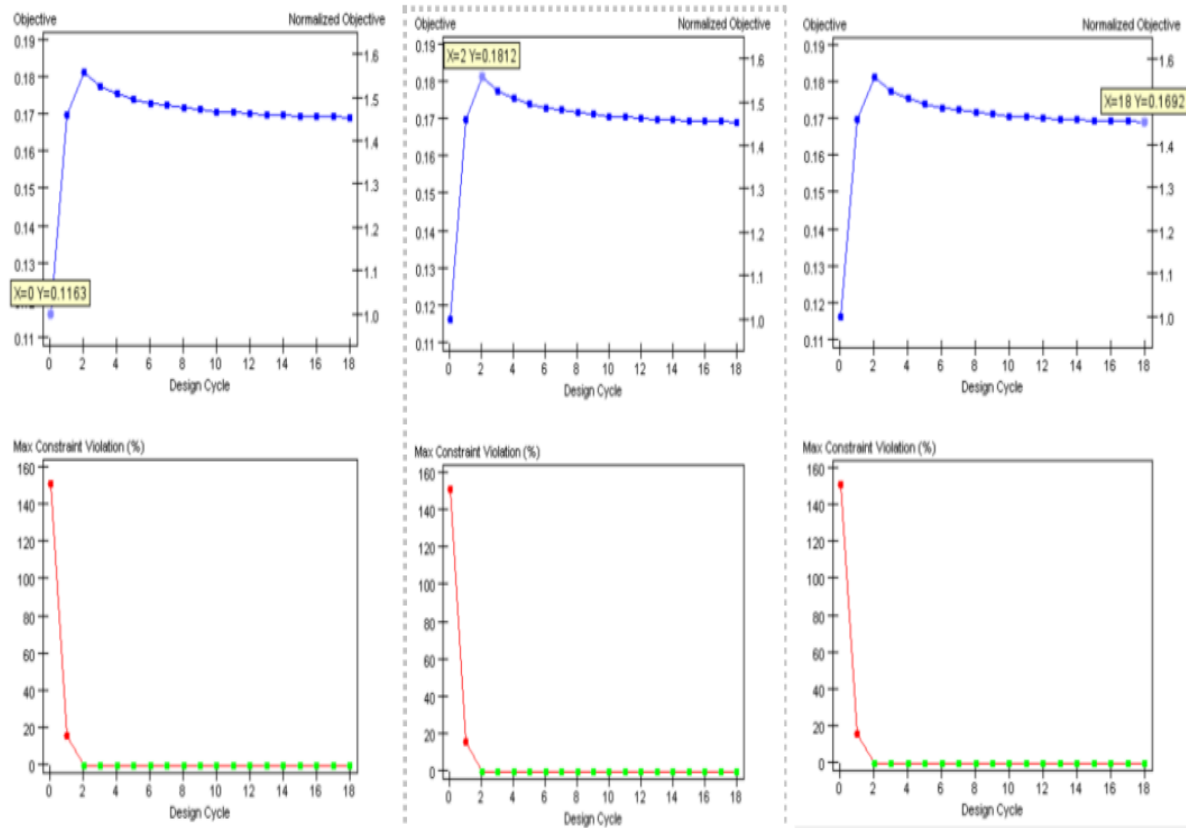
The primary objective of this task was to minimise the mass of the CFRP hydrofoil wing. The primary performance constraint was that the maximum displacement under the 500N load could not exceed the deflection of the original 2mm steel wing, which was 8.6mm.

The design variables were the thicknesses of five layers with different ply orientations: -90° , -45° , 0° , $+45^\circ$, and $+90^\circ$. Initially, each layer (5 plies per orientation) was 0.5mm thick. To optimise, each variable was allowed to vary between 0.1mm (1 ply) and 5.0mm (50 plies). The optimisation was initially set up to treat them as continuous variables, with a subsequent run using discrete variables to ensure manufacturability.

5.2 Optimisation Process and Results

The optimisation was executed using the Genesis tool in Design Studio. The process ran for 18 cycles to find a solution for continuous variable optimisation.

Figure 5 shows the objective and constraint's 18-cycle optimisation history plots. The top graph shows the objective: to minimise mass. As the algorithm added material to meet the displacement constraint, the initial mass of 116.3g increased significantly in early cycles. After peaking at 181.2g, the mass settled at 169.2g. The bottom graph shows the maximum constraint violation. The baseline design violated the 8.6mm constraint by approximately 150%. This violation was eliminated by cycle 2, and the displacement was maintained at the constraint for the rest of the optimisation, reaching 8.5mm.

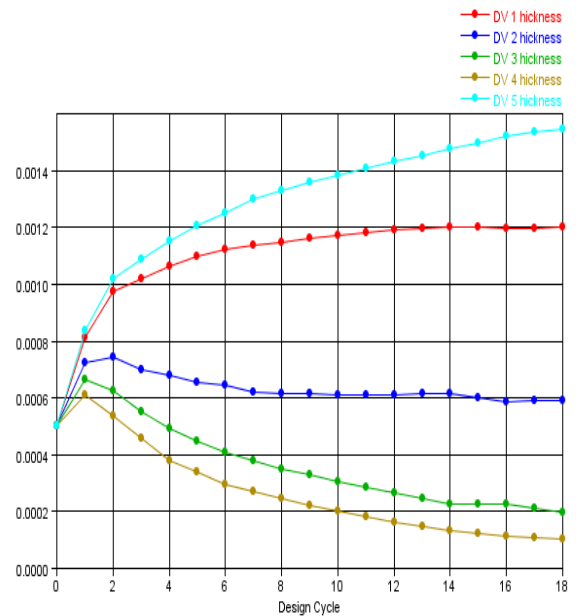


[Figure 5] Optimised history plots for the optimised CFRP model (Continuous variables)

The wing's optimisation can be further investigated using the Comparison of Baseline and Optimised Designs (Continuous Variables) table and history chart in Table 4 and Figure 6, respectively. This highlights the work done during the optimisation process, helping to visualise the magnitude of the changes for each parameter.

Parameter	Design Cycle 0 (Baseline)	Design Cycle 18 (Optimised)	Change
Maximum Displacement	21.0 mm	8.5 mm	-60%
Maximum Stress	410 MPa	180 MPa	-56%
Maximum Strain	2.60E-03	1.20E-03	-54%
Total Thickness	2.5 mm	3.64 mm	45.60%
Layer 1 (-90°) Thickness	0.5 mm	1.20 mm	140%
Layer 2 (-45°) Thickness	0.5 mm	0.589 mm	17.80%
Layer 3 (0°) Thickness	0.5 mm	0.196 mm	-61%
Layer 4 (+45°) Thickness	0.5 mm	0.106 mm	-79%
Layer 5 (+90°) Thickness	0.5 mm	1.55 mm	210%

[Table 4] Comparison table for The baseline CFRP model and the Optimised CFRP model using continuous variables



[Figure 6] history plot of layer thickness across 18 cycles. Continuous variables

Table 5 shows the final thickness for each layer after continuous optimisation. These were converted to a ply count using the 0.1 mm ply thickness.

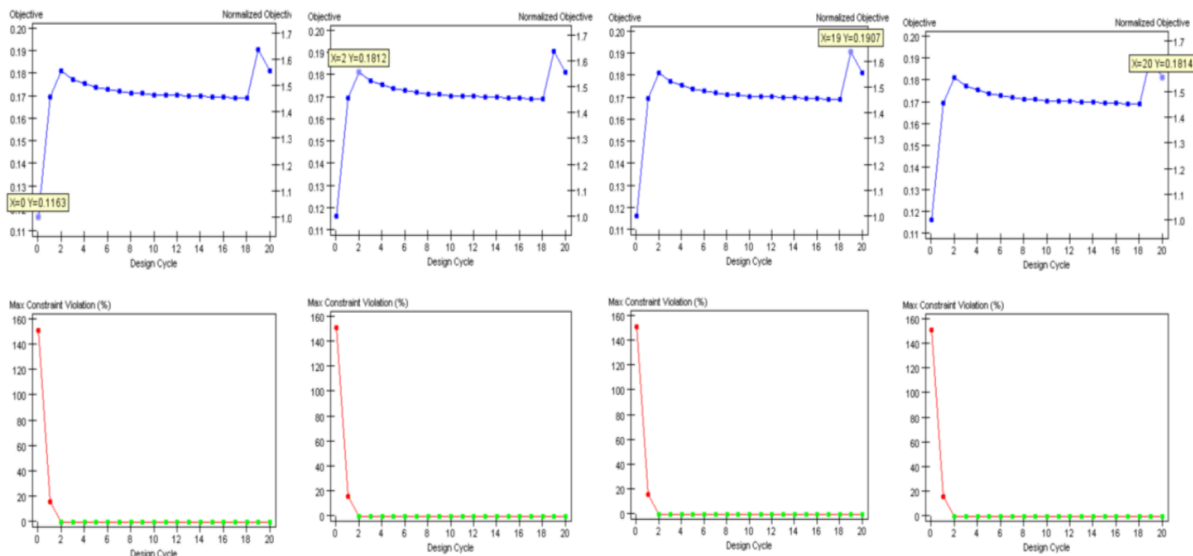
Ply Orientation	Layer Thickness (mm)	Number of Plies
-90°	1.2	12
-45°	0.589	5.89
0°	0.196	1.96
45°	0.106	1.06
90°	1.548	15.48
Total	3.9	39

[Table 5] Ply orientation, layer thickness and number of plies for optimised CFRP using continuous variables

This configuration, however, cannot be manufactured because the ply counts must be whole numbers. A second optimisation run was carried out using discrete variables, with layer thicknesses limited to 0.1mm increments.

As shown in Figure 7, this discrete optimisation converged after 20 cycles. The graphs show that this algorithm optimised mass by adding material. At cycle 18, the graph shows that it cannot complete the process to fit the variables set, so it must

increase the mass to make layers that can be manufactured. The final total of mass for this design after cycle 20 was 181.4g.

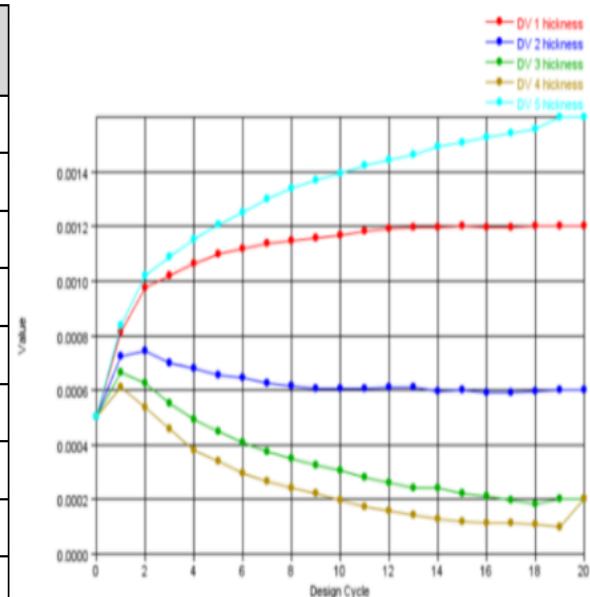


[Figure 7] Optimised history plots for the optimised CFRP model (Discrete variables)

The optimisation of the wing can be further analysed through the Comparison of Baseline and Optimised Designs (Discrete Variables) table and history chart in Table 6 and Figure 8 respectively. These will show the minor but crucial optimisation adjustments made to manufacture the wing.

Parameter	Design Cycle 0 (Baseline)	Design Cycle 20 (Optimised)	Change
Maximum Displacement	21.0 mm	7.8 mm	-63%
Maximum Stress	410 MPa	180 MPa	-56%
Maximum Strain	2.60E-03	1.20E-03	-54%
Total Thickness	2.5 mm	3.9 mm	56.00%
Layer 1 (-90°) Thickness	0.5 mm	1.20 mm	140%
Layer 2 (-45°) Thickness	0.5 mm	0.6 mm	20.00%
Layer 3 (0°) Thickness	0.5 mm	0.3 mm	-40%
Layer 4 (+45°) Thickness	0.5 mm	0.3 mm	-40%
Layer 5 (+90°) Thickness	0.5 mm	1.5 mm	200%

[Table 6] Comparison table for The baseline CFRP model and the Optimised CFRP model using discrete variables



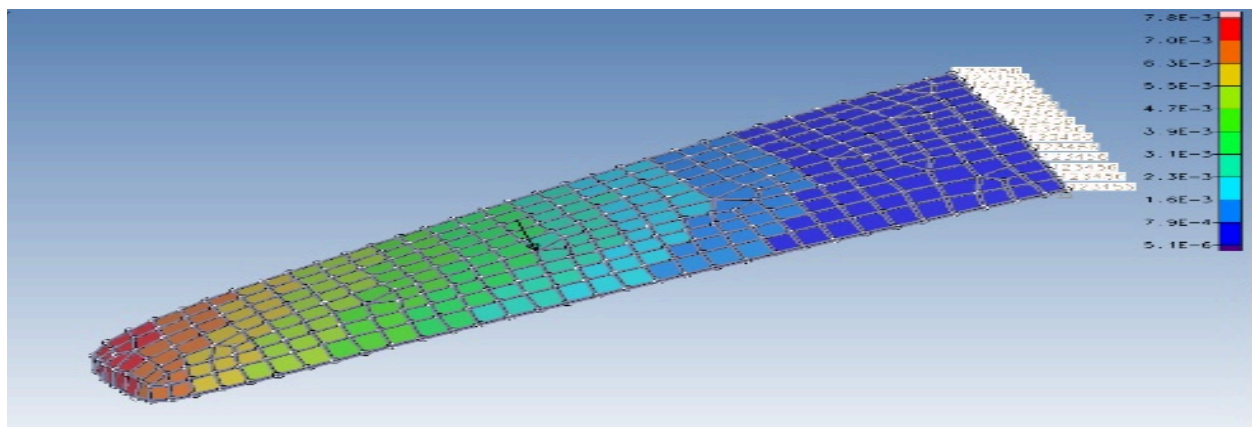
[Figure 8] history plot of layer thickness across 18 cycles. Discrete variables

The final, manufacturable ply stack is shown in Table 7 below. Each layer thickness is now divisible by the number of plies.

Ply Orientation	Layer Thickness (mm)	Number of Plies
-90°	1.2	12
-45°	0.6	6
0°	0.3	3
45°	0.3	3
90°	1.5	15
Total	3.9	39

[Table 7] Ply orientation, layer thickness and number of plies for optimised CFRP using discrete variables

Figure 9 depicts the final design, which represents the optimum model determined through FEA. This shows a deflection of 7.8mm.



[Figure 9] Final mesh plot of the optimised CFRP model with discrete variables.

After analysing all of the data, additional stiffness and stiffness/weight calculations were performed, as shown in Table 8.

Run	Material	Thickness k (mm)	Deflection x (mm)	Mass (g)	Load (N)	Stiffness (N/mm)	Stiffness/weight (N ² /mm)
Steel Baseline	Steel	2	8.6	465	500	56.14	0.013
Composite baseline	CFRP	2.5	21	116.3	500	23.81	0.021
Optimised composite	CFRP	3.64	8.6	169.2	500	56.14	0.034
Optimised composite (Discreet)	CFRP	3.9	7.8	181.4	500	64.1	0.036

[Table 8] Stiffness and stiffness/weight results for all four models.

The shift from continuous to discrete variables is a key step in bringing together theoretical optimisation and real-world manufacturing limits. The continuous optimisation gave a mathematically perfect answer, but the discrete optimisation gives a design that can actually be made and still works very well.

● 5.3 Discussion of Optimised Design

The optimisation process resulted in a manufacturable CFRP wing with stiffness that exceeds the steel baseline. The final design achieves 7.8 mm of deflection, a 9.3% improvement over the 8.6 mm constraint, resulting in a 14% increase in stiffness (64.1 N/mm). Crucially, this outcome is accomplished at a mass of 181.4g, a 61% reduction from the steel baseline.

The shift from continuous to discrete variables necessitated a manufacturing compromise, increasing mass by 7.2% over the theoretical optimum. The discrete design had the highest stiffness-to-weight ratio of 0.036 N²/mm, which was 177% higher than steel and 5.9% better than continuous optimisation.

Analysis of the final layup [-90(12), -45(6), 0(3), 45(3), 90(15)] provides insight into the structural behaviour. The software gave the most plies to orientations of $\pm 90^\circ$ (27 out of 39 total), which is not what you would expect from a cantilever beam. This indicates that transverse bending and torsional stability, influenced by intricate fluid-structure interaction, prevail over longitudinal bending for this particular hydrofoil

geometry. This is consistent with modern composite hydrofoil design principles, in which ply angles are tailored to handle complex 3D loading, which frequently necessitates significant transverse reinforcement (Zhang et al., 2021). This tailored configuration effectively manages fore-aft bending and shear, as evidenced by the minimum 0° plies (3) and reduced $\pm 45^\circ$ plies (6).

● 5.4 Discussion of engineering uncertainties.

The optimised design meets stiffness and mass goals, but several modelling uncertainties must be fixed to create a strong, real-world product.

Manufacturing tolerances: Theoretical laminate thickness can vary by $\pm 5\%$ due to manufacturing inconsistencies (Garg et al., 2019). A sensitivity analysis is required to ensure that performance remains at the lower tolerance limit.

Boundary Condition Stiffness: The FEA assumed a perfectly rigid root connection. Because of their limited stiffness, real connections would deflect more. This was validated experimentally by Maung et al. (2023), who discovered deflections 10–20% greater than FEA predictions as a result of the material property variations and imperfect physical support. Future research ought to model the entire assembly.

Loading Scenarios: A single, vertical static load was employed in the optimisation. In real service, multiple angles of attack are used to handle complex, combined loads. To ensure that the entire operational range is strong, a multi-case optimisation, like the multi-point approach used by Garg et al. (2019), is needed.

6.0 Task 4: Proposal for Experimental Validation

● 6.1 Test Setup:

To validate the FEA model, a prototype of the optimised hydrofoil wing will be built and tested in a structural environment designed to be completely static, so any movement should hopefully be negligible. To evaluate process-related effects on performance, the manufacturing process will combine hand layup and

Vacuum-Assisted Resin Transfer Moulding (VARTM) as conducted by Dougherty (2023).

To mimic the FEA's cantilever boundary conditions, the test will use a three-point bending configuration with the wing root secured in a rigid fixture. A 500N load will be applied using a flat punch to evenly distribute pressure, as described by Stier et al. (2015).

● 6.2 Data Acquisition:

A Digital Image Correlation (DIC) system, such as Stier et al.'s (2015) Aramis system, will capture full-field deflections and strains during data acquisition. Strain gauge rosettes (e.g., TML-FRA-3-11) will be placed at critical high-stress locations near the root, as Maung et al. (2023) have successfully demonstrated.

Experimental load-deflection curves and strain values will be directly overlaid with FEA results. A correlation coefficient (R^2) will be used to measure the agreement. For complicated composite structures, a difference of 10–15% is usually seen as good agreement (Lake, 2024). Any differences beyond this will be looked into, and possible sources are:

- Idealised Boundary Conditions: Unlike the FEA model, the experimental root constraint cannot be perfectly fixed (Maung et al., 2023).
- Material Property Variation: Laminate properties may differ from simulation CFRP values (Maung et al., 2023; Stier et al., 2015).
- Manufacturing defects like in-plane fibre waviness can affect performance (Maung et al., 2023).
- Experimental Error: Factors like load misalignment must also be considered (Maung et al., 2023).

Before comparing the FEA and experimentation results numerically, we'll do some simple hand calculations based on basic beam theory for a cantilever to verify that the structural responses are in the right order of magnitude (Dougherty, 2024).

7.0 Relation to technical literature

Numerous studies support the methods and findings of this project. Wittahachchi (2025) cites systematic optimisation as an efficiency improvement that reduced design iterations.

The layers follow modern composite design principles for complex 3D loads, according to Zhang et al. (2021). These layers differ from a simple cantilever design and include $\pm 90^\circ$ plies to enhance stability.

The engineering uncertainties highlight the necessity for multi-disciplinary design optimisation frameworks, as analysed by Ghadge et al. (2022), especially in relation to boundary conditions and dynamic loads.

Additionally, the proposed experimental validation using strain gauges and Digital Image Correlation shows established methods for comparing Finite Element Analysis with real-world testing, as effectively demonstrated by Stier et al. (2015) and Maung et al. (2023).

From optimisation to validation, the design process has been thoroughly researched by a variety of individuals, and the report contains substantial evidence to support the work.

8.0 Conclusion

This project successfully showed how to optimise the structure of a CFRP hydrofoil wing, which was the main goal: to reduce the mass without losing stiffness. The first baseline CFRP model was 75% lighter than the steel benchmark, but it was too flexible, bending 144% more. This made it clear that a custom composite design was needed instead of a standard layup.

A manufacturable ply configuration of $[-90^\circ(12), -45^\circ(6), 0^\circ(3), 45^\circ(3), 90^\circ(15)]$ was created by optimising the structure. The final design exceeded performance goals, with a deflection of 7.8 mm (9.3% stiffer than the constraint) and a 61% reduction in mass. This led to a remarkable 177% increase in stiffness-to-weight ratio compared to the original steel wing.

The transition from theoretical continuous variable optimisation to discrete, manufacturable solution was essential, illustrating the necessity of balancing mathematical principles with practical engineering constraints.

The FEA optimisation process is clearly effective; however, the study's constraints, such as the presumed static load and ideal rigid boundary conditions, present opportunities for further research. Future studies should employ multi-disciplinary optimisation (MDO) with dynamic fluid-structure interaction and multiple load scenarios to enhance real-world performance. To make the final structure more rigid, it could look into new, more advanced manufacturing methods and test the finished product for its maximum fatigue life.

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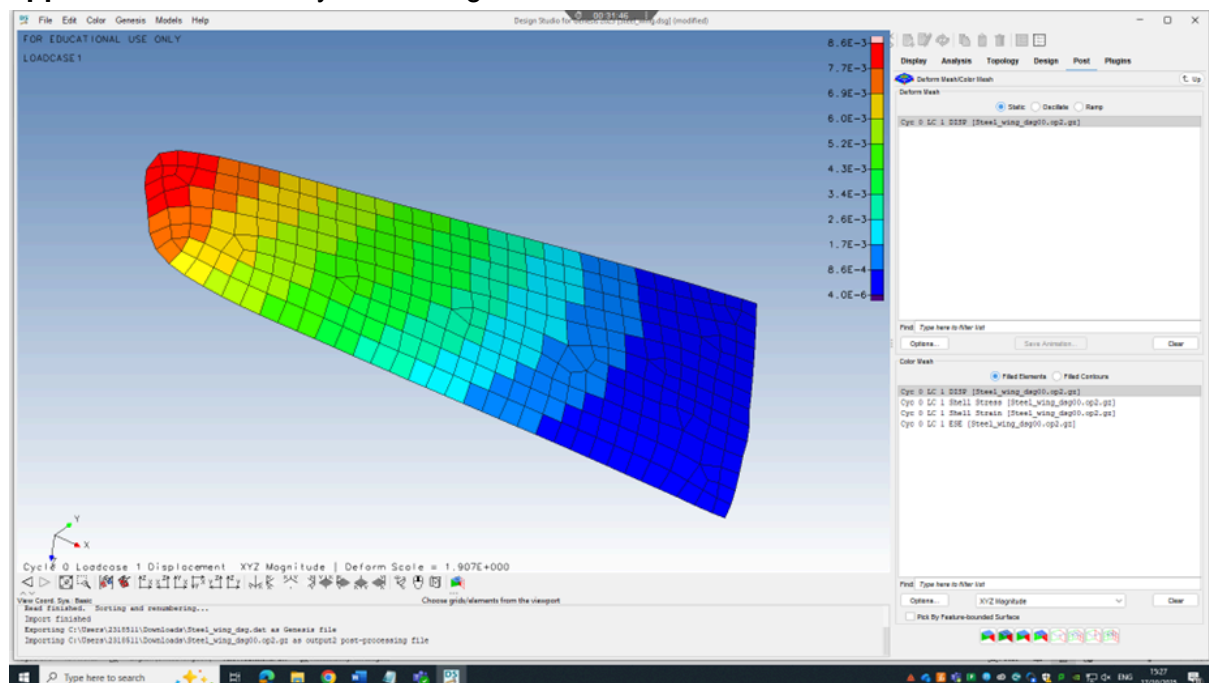
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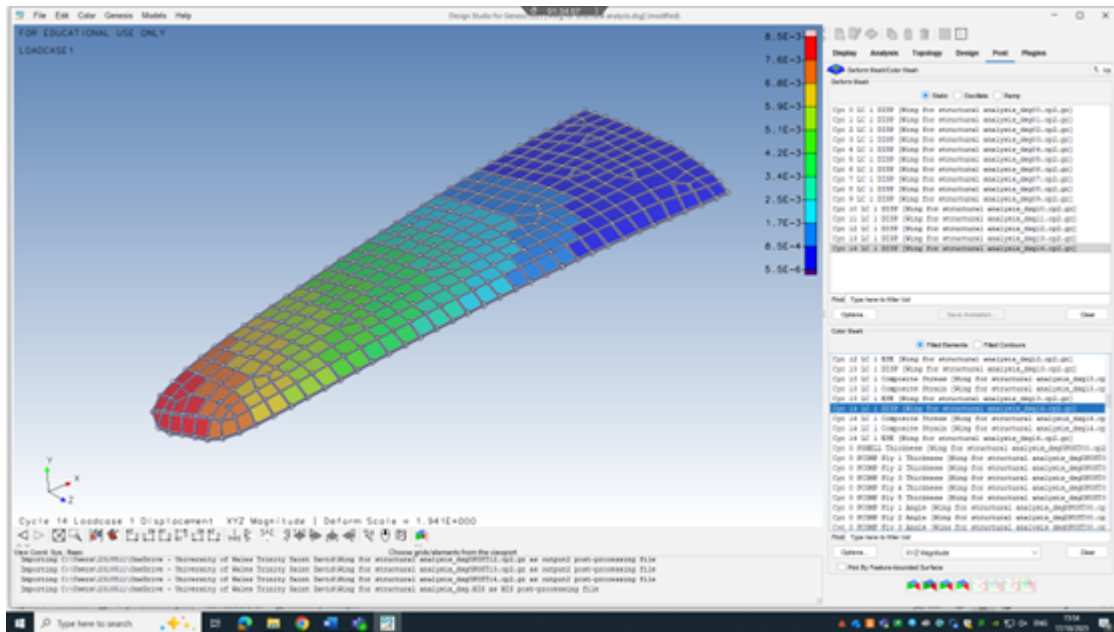
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10.0 Appendices

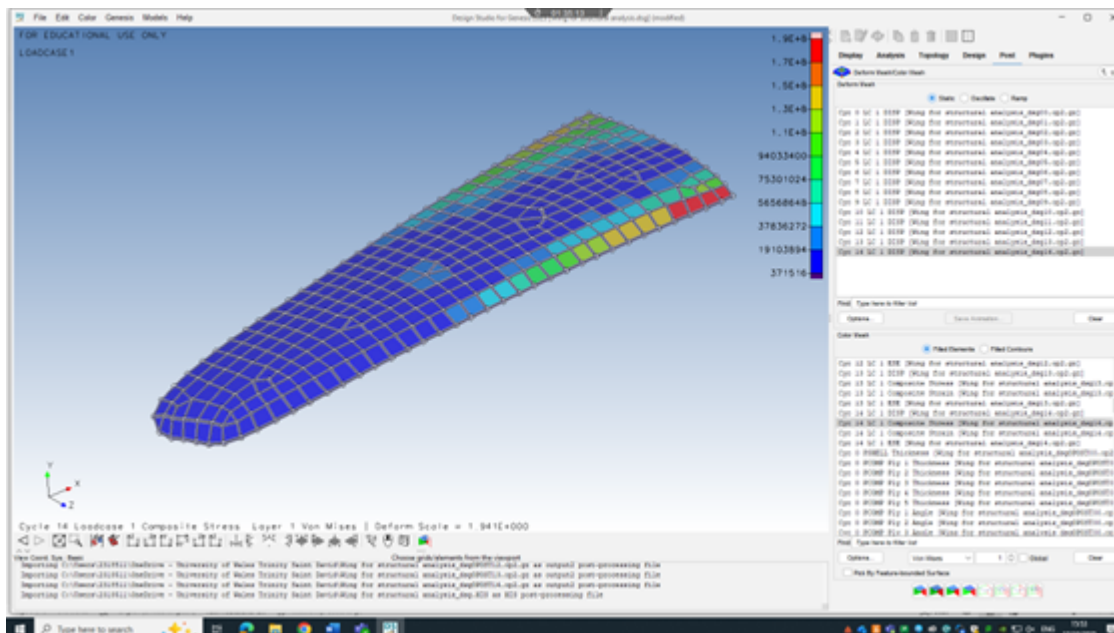
Appendix 1: Mesh analysis showing deflection of the baseline steel model.



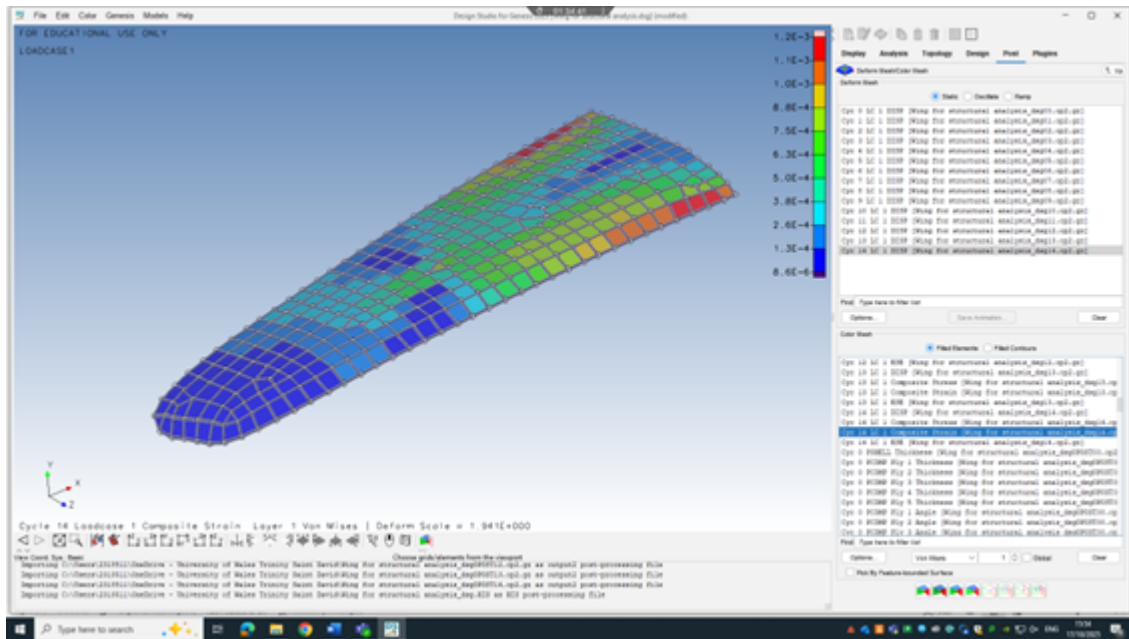
Appendix 2: Mesh analysis showing deflection of the Optimised CFRP model using continuous variables.



Appendix 3: Mesh analysis showing composite stress of the Optimised CFRP model using continuous variables.



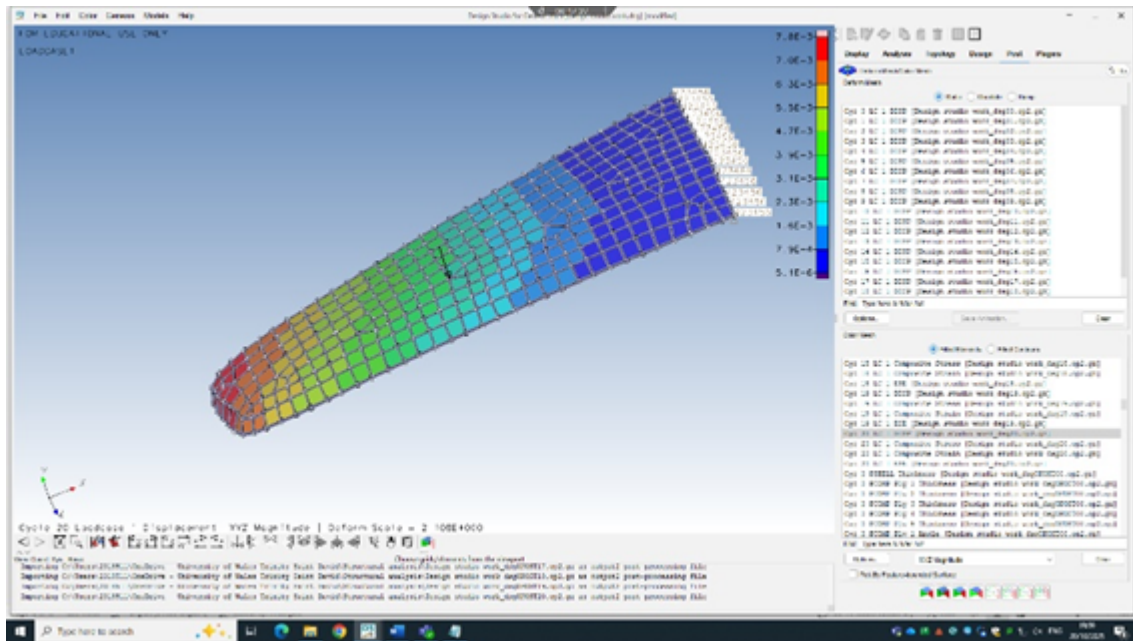
Appendix 4: Mesh analysis showing composite strain of the Optimised CFRP model using continuous variables.



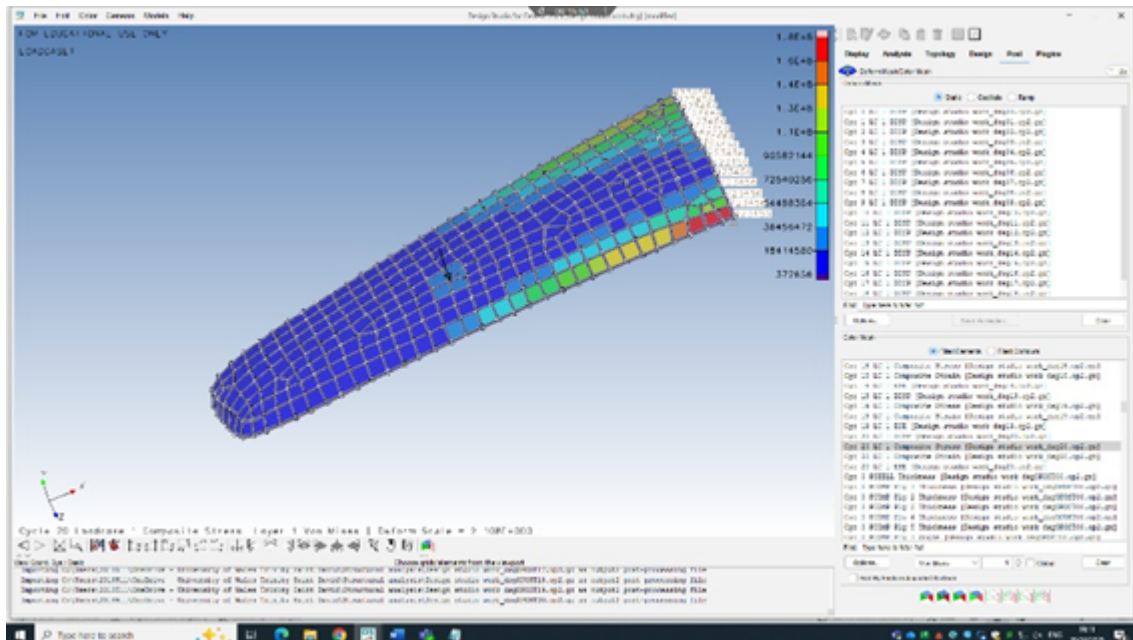
Appendix 5: History data of the optimised CFRP model using continuous variables across 18 cycles.

DESIGN CYCLE # 0, OBJECTIVE = 1.162727E-01, MAXIMUM VIOLATION = 150.9%.	DESIGN CYCLE # 10, OBJECTIVE = 1.707013E-01, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE # 1 = 5.000000E-04 thickness	DESIGN VARIABLE # 1 = 1.169286E-03 thickness
DESIGN VARIABLE # 2 = 5.000000E-04 thickness	DESIGN VARIABLE # 2 = 6.086055E-04 thickness
DESIGN VARIABLE # 3 = 5.000000E-04 thickness	DESIGN VARIABLE # 3 = 3.047139E-04 thickness
DESIGN VARIABLE # 4 = 5.000000E-04 thickness	DESIGN VARIABLE # 4 = 2.020583E-04 thickness
DESIGN VARIABLE # 5 = 5.000000E-04 thickness	DESIGN VARIABLE # 5 = 1.385616E-03 thickness
DESIGN CYCLE # 1, OBJECTIVE = 1.698184E-01, MAXIMUM VIOLATION = 16.2%.	DESIGN CYCLE # 11, OBJECTIVE = 1.704392E-01, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE # 1 = 8.120978E-04 thickness	DESIGN VARIABLE # 1 = 1.180394E-03 thickness
DESIGN VARIABLE # 2 = 7.261518E-04 thickness	DESIGN VARIABLE # 2 = 6.090070E-04 thickness
DESIGN VARIABLE # 3 = 6.638785E-04 thickness	DESIGN VARIABLE # 3 = 2.855244E-04 thickness
DESIGN VARIABLE # 4 = 6.099116E-04 thickness	DESIGN VARIABLE # 4 = 1.801159E-04 thickness
DESIGN VARIABLE # 5 = 8.392560E-04 thickness	DESIGN VARIABLE # 5 = 1.409604E-03 thickness
DESIGN CYCLE # 2, OBJECTIVE = 1.811920E-01, MAXIMUM VIOLATION = 0.0%.	DESIGN CYCLE # 12, OBJECTIVE = 1.702054E-01, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE # 1 = 9.730318E-04 thickness	DESIGN VARIABLE # 1 = 1.189828E-03 thickness
DESIGN VARIABLE # 2 = 7.440637E-04 thickness	DESIGN VARIABLE # 2 = 6.110557E-04 thickness
DESIGN VARIABLE # 3 = 6.232721E-04 thickness	DESIGN VARIABLE # 3 = 2.647514E-04 thickness
DESIGN VARIABLE # 4 = 5.351123E-04 thickness	DESIGN VARIABLE # 4 = 1.610079E-04 thickness
DESIGN VARIABLE # 5 = 1.020364E-03 thickness	DESIGN VARIABLE # 5 = 1.432975E-03 thickness
DESIGN CYCLE # 3, OBJECTIVE = 1.775156E-01, MAXIMUM VIOLATION = 0.0%.	DESIGN CYCLE # 13, OBJECTIVE = 1.699983E-01, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE # 1 = 1.020663E-03 thickness	DESIGN VARIABLE # 1 = 1.197298E-03 thickness
DESIGN VARIABLE # 2 = 6.987660E-04 thickness	DESIGN VARIABLE # 2 = 6.133589E-04 thickness
DESIGN VARIABLE # 3 = 5.505258E-04 thickness	DESIGN VARIABLE # 3 = 2.438182E-04 thickness
DESIGN VARIABLE # 4 = 4.580547E-04 thickness	DESIGN VARIABLE # 4 = 1.459660E-04 thickness
DESIGN VARIABLE # 5 = 1.088587E-03 thickness	DESIGN VARIABLE # 5 = 1.454724E-03 thickness
DESIGN CYCLE # 4, OBJECTIVE = 1.754525E-01, MAXIMUM VIOLATION = 0.0%.	DESIGN CYCLE # 14, OBJECTIVE = 1.698529E-01, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE # 1 = 1.065637E-03 thickness	DESIGN VARIABLE # 1 = 1.203191E-03 thickness
DESIGN VARIABLE # 2 = 6.814173E-04 thickness	DESIGN VARIABLE # 2 = 6.152040E-04 thickness
DESIGN VARIABLE # 3 = 4.927941E-04 thickness	DESIGN VARIABLE # 3 = 2.241921E-04 thickness
DESIGN VARIABLE # 4 = 3.812298E-04 thickness	DESIGN VARIABLE # 4 = 1.348385E-04 thickness
DESIGN VARIABLE # 5 = 1.151359E-03 thickness	DESIGN VARIABLE # 5 = 1.474612E-03 thickness
DESIGN CYCLE # 5, OBJECTIVE = 1.740999E-01, MAXIMUM VIOLATION = 0.0%.	DESIGN CYCLE # 15, OBJECTIVE = 1.696010E-01, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE # 1 = 1.096088E-03 thickness	DESIGN VARIABLE # 1 = 1.200748E-03 thickness
DESIGN VARIABLE # 2 = 6.553187E-04 thickness	DESIGN VARIABLE # 2 = 6.011665E-04 thickness
DESIGN VARIABLE # 3 = 4.467144E-04 thickness	DESIGN VARIABLE # 3 = 2.249877E-04 thickness
DESIGN VARIABLE # 4 = 3.384030E-04 thickness	DESIGN VARIABLE # 4 = 1.212536E-04 thickness
DESIGN VARIABLE # 5 = 1.206823E-03 thickness	DESIGN VARIABLE # 5 = 1.498464E-03 thickness
DESIGN CYCLE # 6, OBJECTIVE = 1.730923E-01, MAXIMUM VIOLATION = 0.0%.	DESIGN CYCLE # 16, OBJECTIVE = 1.693959E-01, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE # 1 = 1.120668E-03 thickness	DESIGN VARIABLE # 1 = 1.196053E-03 thickness
DESIGN VARIABLE # 2 = 6.462807E-04 thickness	DESIGN VARIABLE # 2 = 5.863542E-04 thickness
DESIGN VARIABLE # 3 = 4.088814E-04 thickness	DESIGN VARIABLE # 3 = 2.268504E-04 thickness
DESIGN VARIABLE # 4 = 2.958688E-04 thickness	DESIGN VARIABLE # 4 = 1.121214E-04 thickness
DESIGN VARIABLE # 5 = 1.249983E-03 thickness	DESIGN VARIABLE # 5 = 1.520833E-03 thickness
DESIGN CYCLE # 7, OBJECTIVE = 1.723979E-01, MAXIMUM VIOLATION = 0.0%.	DESIGN CYCLE # 17, OBJECTIVE = 1.693036E-01, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE # 1 = 1.135533E-03 thickness	DESIGN VARIABLE # 1 = 1.198571E-03 thickness
DESIGN VARIABLE # 2 = 6.224762E-04 thickness	DESIGN VARIABLE # 2 = 5.884369E-04 thickness
DESIGN VARIABLE # 3 = 3.801475E-04 thickness	DESIGN VARIABLE # 3 = 2.102191E-04 thickness
DESIGN VARIABLE # 4 = 2.701900E-04 thickness	DESIGN VARIABLE # 4 = 1.085759E-04 thickness
DESIGN VARIABLE # 5 = 1.298412E-03 thickness	DESIGN VARIABLE # 5 = 1.534426E-03 thickness
DESIGN CYCLE # 8, OBJECTIVE = 1.715869E-01, MAXIMUM VIOLATION = 0.0%.	DESIGN CYCLE # 18, OBJECTIVE = 1.691997E-01, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE # 1 = 1.147106E-03 thickness	DESIGN VARIABLE # 1 = 1.199998E-03 thickness
DESIGN VARIABLE # 2 = 6.134551E-04 thickness	DESIGN VARIABLE # 2 = 5.889765E-04 thickness
DESIGN VARIABLE # 3 = 3.479853E-04 thickness	DESIGN VARIABLE # 3 = 1.955886E-04 thickness
DESIGN VARIABLE # 4 = 2.479870E-04 thickness	DESIGN VARIABLE # 4 = 1.055778E-04 thickness
DESIGN VARIABLE # 5 = 1.330988E-03 thickness	DESIGN VARIABLE # 5 = 1.547861E-03 thickness
DESIGN CYCLE # 9, OBJECTIVE = 1.713017E-01, MAXIMUM VIOLATION = 0.0%.	COMPLETION CODE: 1 48 0
DESIGN VARIABLE # 1 = 1.162303E-03 thickness	
DESIGN VARIABLE # 2 = 6.132353E-04 thickness	
DESIGN VARIABLE # 3 = 3.274239E-04 thickness	
DESIGN VARIABLE # 4 = 2.205444E-04 thickness	
DESIGN VARIABLE # 5 = 1.359683E-03 thickness	

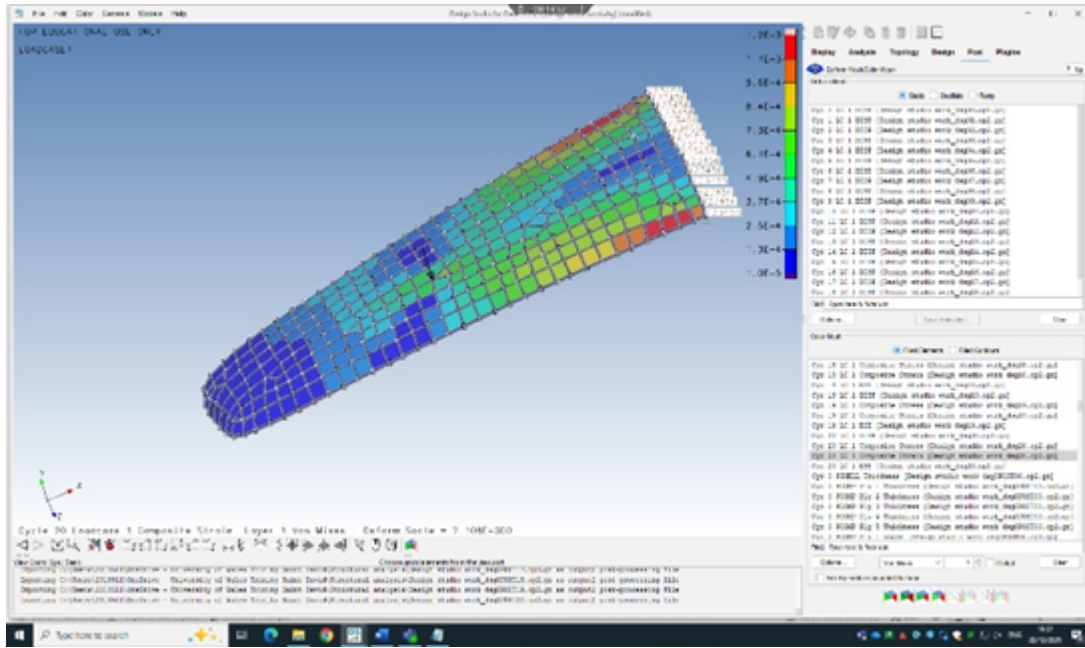
Appendix 6: Mesh analysis showing deflection of the optimised CFRP model using discrete variables.



Appendix 7: Mesh analysis showing composite stress of the optimised CFRP model using discrete variables.



Appendix 8: Mesh analysis showing composite strain of the optimised CFRP model using discrete variables.



Appendix 9: History data of the optimised CFRP model using discrete variables across 20 cycles.

DESIGN CYCLE # 0, OBJECTIVE = 1.162727E-01, MAXIMUM VIOLATION = 150.9%.	DESIGN CYCLE # 11, OBJECTIVE = 1.705755E-01, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE # 1 = 5.000000E-04 thickness	DESIGN VARIABLE # 1 = 1.177842E-03 thickness
DESIGN VARIABLE # 2 = 5.000000E-04 thickness	DESIGN VARIABLE # 2 = 6.091714E-04 thickness
DESIGN VARIABLE # 3 = 5.000000E-04 thickness	DESIGN VARIABLE # 3 = 2.870035E-04 thickness
DESIGN VARIABLE # 4 = 5.000000E-04 thickness	DESIGN VARIABLE # 4 = 1.861116E-04 thickness
DESIGN VARIABLE # 5 = 5.000000E-04 thickness	DESIGN VARIABLE # 5 = 1.407447E-03 thickness
DESIGN CYCLE # 1, OBJECTIVE = 1.698184E-01, MAXIMUM VIOLATION = 16.2%.	DESIGN CYCLE # 12, OBJECTIVE = 1.702759E-01, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE # 1 = 8.120978E-04 thickness	DESIGN VARIABLE # 1 = 1.188165E-03 thickness
DESIGN VARIABLE # 2 = 7.261518E-04 thickness	DESIGN VARIABLE # 2 = 6.106059E-04 thickness
DESIGN VARIABLE # 3 = 6.630785E-04 thickness	DESIGN VARIABLE # 3 = 2.653926E-04 thickness
DESIGN VARIABLE # 4 = 6.099116E-04 thickness	DESIGN VARIABLE # 4 = 1.647303E-04 thickness
DESIGN VARIABLE # 5 = 8.392569E-04 thickness	DESIGN VARIABLE # 5 = 1.432240E-03 thickness
DESIGN CYCLE # 2, OBJECTIVE = 1.811920E-01, MAXIMUM VIOLATION = 0.0%.	DESIGN CYCLE # 13, OBJECTIVE = 1.700342E-01, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE # 1 = 9.730318E-04 thickness	DESIGN VARIABLE # 1 = 1.196182E-03 thickness
DESIGN VARIABLE # 2 = 7.440637E-04 thickness	DESIGN VARIABLE # 2 = 6.130082E-04 thickness
DESIGN VARIABLE # 3 = 6.232721E-04 thickness	DESIGN VARIABLE # 3 = 2.435016E-04 thickness
DESIGN VARIABLE # 4 = 5.351123E-04 thickness	DESIGN VARIABLE # 4 = 1.481182E-04 thickness
DESIGN VARIABLE # 5 = 1.020364E-03 thickness	DESIGN VARIABLE # 5 = 1.455126E-03 thickness
DESIGN CYCLE # 3, OBJECTIVE = 1.775156E-01, MAXIMUM VIOLATION = 0.0%.	DESIGN CYCLE # 14, OBJECTIVE = 1.698769E-01, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE # 1 = 1.020863E-03 thickness	DESIGN VARIABLE # 1 = 1.202375E-03 thickness
DESIGN VARIABLE # 2 = 6.987660E-04 thickness	DESIGN VARIABLE # 2 = 6.149247E-04 thickness
DESIGN VARIABLE # 3 = 5.505258E-04 thickness	DESIGN VARIABLE # 3 = 2.233287E-04 thickness
DESIGN VARIABLE # 4 = 4.580547E-04 thickness	DESIGN VARIABLE # 4 = 1.362270E-04 thickness
DESIGN VARIABLE # 5 = 1.080587E-03 thickness	DESIGN VARIABLE # 5 = 1.475700E-03 thickness
DESIGN CYCLE # 4, OBJECTIVE = 1.754525E-01, MAXIMUM VIOLATION = 0.0%.	DESIGN CYCLE # 15, OBJECTIVE = 1.690936E-01, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE # 1 = 1.065637E-03 thickness	DESIGN VARIABLE # 1 = 1.199084E-03 thickness
DESIGN VARIABLE # 2 = 6.814173E-04 thickness	DESIGN VARIABLE # 2 = 6.010267E-04 thickness
DESIGN VARIABLE # 3 = 4.927941E-04 thickness	DESIGN VARIABLE # 3 = 2.241663E-04 thickness
DESIGN VARIABLE # 4 = 3.812298E-04 thickness	DESIGN VARIABLE # 4 = 1.223194E-04 thickness
DESIGN VARIABLE # 5 = 1.151359E-03 thickness	DESIGN VARIABLE # 5 = 1.499282E-03 thickness
DESIGN CYCLE # 5, OBJECTIVE = 1.740996E-01, MAXIMUM VIOLATION = 0.0%.	DESIGN CYCLE # 16, OBJECTIVE = 1.694115E-01, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE # 1 = 1.096088E-03 thickness	DESIGN VARIABLE # 1 = 1.195388E-03 thickness
DESIGN VARIABLE # 2 = 6.553187E-04 thickness	DESIGN VARIABLE # 2 = 5.870628E-04 thickness
DESIGN VARIABLE # 3 = 4.467144E-04 thickness	DESIGN VARIABLE # 3 = 2.246502E-04 thickness
DESIGN VARIABLE # 4 = 3.384036E-04 thickness	DESIGN VARIABLE # 4 = 1.137289E-04 thickness
DESIGN VARIABLE # 5 = 1.206823E-03 thickness	DESIGN VARIABLE # 5 = 1.521710E-03 thickness
DESIGN CYCLE # 6, OBJECTIVE = 1.730923E-01, MAXIMUM VIOLATION = 0.0%.	DESIGN CYCLE # 17, OBJECTIVE = 1.693136E-01, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE # 1 = 1.120668E-03 thickness	DESIGN VARIABLE # 1 = 1.197763E-03 thickness
DESIGN VARIABLE # 2 = 6.462887E-04 thickness	DESIGN VARIABLE # 2 = 5.889311E-04 thickness
DESIGN VARIABLE # 3 = 4.088814E-04 thickness	DESIGN VARIABLE # 3 = 2.090904E-04 thickness
DESIGN VARIABLE # 4 = 2.958688E-04 thickness	DESIGN VARIABLE # 4 = 1.101588E-04 thickness
DESIGN VARIABLE # 5 = 1.249983E-03 thickness	DESIGN VARIABLE # 5 = 1.534500E-03 thickness
DESIGN CYCLE # 7, OBJECTIVE = 1.723427E-01, MAXIMUM VIOLATION = 0.0%.	DESIGN CYCLE # 18, OBJECTIVE = 1.692087E-01, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE # 1 = 1.138426E-03 thickness	DESIGN VARIABLE # 1 = 1.199715E-03 thickness
DESIGN VARIABLE # 2 = 6.278641E-04 thickness	DESIGN VARIABLE # 2 = 5.905268E-04 thickness
DESIGN VARIABLE # 3 = 3.779644E-04 thickness	DESIGN VARIABLE # 3 = 1.936849E-04 thickness
DESIGN VARIABLE # 4 = 2.597667E-04 thickness	DESIGN VARIABLE # 4 = 1.070402E-04 thickness
DESIGN VARIABLE # 5 = 1.301552E-03 thickness	DESIGN VARIABLE # 5 = 1.547221E-03 thickness
DESIGN CYCLE # 8, OBJECTIVE = 1.714969E-01, MAXIMUM VIOLATION = 0.0%.	DESIGN CYCLE # 19, OBJECTIVE = 1.906872E-01, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE # 1 = 1.149070E-03 thickness	DESIGN VARIABLE # 1 = 1.300000E-03 thickness
DESIGN VARIABLE # 2 = 6.186671E-04 thickness	DESIGN VARIABLE # 2 = 7.000000E-04 thickness
DESIGN VARIABLE # 3 = 3.481555E-04 thickness	DESIGN VARIABLE # 3 = 3.000000E-04 thickness
DESIGN VARIABLE # 4 = 2.387305E-04 thickness	DESIGN VARIABLE # 4 = 2.000000E-04 thickness
DESIGN VARIABLE # 5 = 1.332763E-03 thickness	DESIGN VARIABLE # 5 = 1.600000E-03 thickness
DESIGN CYCLE # 9, OBJECTIVE = 1.712308E-01, MAXIMUM VIOLATION = 0.0%.	DESIGN CYCLE # 20, OBJECTIVE = 1.813853E-01, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE # 1 = 1.163723E-03 thickness	DESIGN VARIABLE # 1 = 1.200000E-03 thickness
DESIGN VARIABLE # 2 = 6.182497E-04 thickness	DESIGN VARIABLE # 2 = 6.000000E-04 thickness
DESIGN VARIABLE # 3 = 3.267400E-04 thickness	DESIGN VARIABLE # 3 = 3.000000E-04 thickness
DESIGN VARIABLE # 4 = 2.124164E-04 thickness	DESIGN VARIABLE # 4 = 3.000000E-04 thickness
DESIGN VARIABLE # 5 = 1.360536E-03 thickness	DESIGN VARIABLE # 5 = 1.500000E-03 thickness
DESIGN CYCLE # 10, OBJECTIVE = 1.706500E-01, MAXIMUM VIOLATION = 0.0%.	
DESIGN VARIABLE # 1 = 1.170058E-03 thickness	
DESIGN VARIABLE # 2 = 6.100964E-04 thickness	
DESIGN VARIABLE # 3 = 3.025186E-04 thickness	
DESIGN VARIABLE # 4 = 1.993571E-04 thickness	
DESIGN VARIABLE # 5 = 1.387165E-03 thickness	

