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Structural and Fluid Analysis

ACMA6010

Designing a Tanker Propeller:

Structural Design

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Executive Summary

Structural analysis is critical for many industries ensuring structures perform their function optimally and safely. The idea of structural optimisation has been around since the 1800s but was introduced into software packages in the 1960s. They developed exponentially and grew with increased computing power.

There are many techniques for optimisation from topology which removes unnecessary material from a structure, whilst still providing structural support, to more advanced optimisation techniques recently introduced such as Generative Design which allows for an increase in design efficiency, by allowing an engineer to constrain the structure to many variables, from cost and materials to manufacturing methods, thus, decreasing design time whilst ensuring optimisation.

Within this report, a steel propeller loaded into optimisation software known as Design Studio has a Uniformly Distributed Load (UDL) of 5kN placed on it, to which the simulation states a deflection of 210mm would occur. With the dimensions and properties of steel, this indicates a stiffness-to-weight ratio of $3.75 \cdot 10^{-3} N^2/mm$.

Carbon Fibre Reinforced Plastic (CFRP) has been utilised for the same propeller. Without any optimisation analysis, the propeller would break with the same load added as the steel. However, when utilising a design specification thus limiting deflection to 100mm, the CFRP, shows a stiffness-to-weight ratio of $25.51 \cdot 10^{-3} N^2/mm$, indicating optimised CFRP has a 580.27% increase in strength-to-weight compared to steel.

Testing a CFRP propeller prototype would require innovative processes. A cavitation tunnel can be used, whereby Stereo Digital Image Correlation (S-DIC) is utilised to understand the deflection from a 5kN UDL, which can be compared directly to the simulation. Although many forces should be considered for real applications, only the thrust force is utilised, for simplification purposes.

Current technical literature shows that CFRP is being currently developed, with propellers under 2.5m compared to the almost 6m propeller in this report. However, the literature shows that CFRP properties far exceed those of current propeller materials, although further development is required, to not only meet current regulations but understand if this material has any disadvantages compared to traditional materials.

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1.0. Introduction

Structural analysis is crucial, ensuring structures perform their function optimally whilst conforming to safety regulations. Structural analysis establishes the distribution of internal forces, strains, stresses, displacements, and moments over the whole or part of the structure. Advancements in software packages are providing more efficient ways to find desired variables with precision, supporting traditional analysis and numerical calculations.

1.1. Report Purpose

This report investigates structural mechanics, which are applied to a propeller design, whilst outlining how material properties and their directional arrangements affect variables such as deflection. Considerations are made, to ensure the propeller meets specifications, manufacturing requirements and regulations.

2.0. Finite Element Analysis

Finite Element Analysis (FEA) allows one to solve Partial Differential Equations (PDEs) used within structural problems (Skotny, 2019).

FEA is a practical application of Finite Element Method (FEM), which creates a mesh from structural models, subdividing it into finite elements for analysis simplification. It solves PDEs, predicting the behaviours of each element, yielding results, to understand the models' structural variables, such as displacement when under a load (FEA in Structural Engineering, 2019).

2.1. FEA History

In the late 1800's John William Strutt Rayleigh developed a method for predicting natural frequencies of simple structures, which Waler Ritz expanded upon, creating the Rayleigh-Ritz method for predicting stress and displacement within structures (O'Donnell, 2022).

By 1940, numerical methods were developed, predicting general structure behaviours. By 1943, Richard Courant proposed breaking a system into triangle segments known as elements. This was the time of digital computing with 1950 obtaining analog computing for complex structural problems, with more powerful computers using matrix-based solutions. A manufacturing company, Boeing, within the same decade, utilised triangular stress elements for aeroplane wing stress analysis. The aerospace industry led the way for finite elements, with commercial FEA optimisation introduced in 1960, combining FEA with nonlinear numerical optimisation methods, creating Structural Synthesis, which has been continually developed, integrating techniques into modern design tools (O'Donnell, 2022).

O'Donnell (2022) states although NASA developed software like ANSYS and NASTRAN in 1960, microcomputers for complex problems were developed within 1970, with the 1980s developing coloured stress contours for structure analysis and optimisation techniques being utilised more in the late 1990s. Schramm (2020) supports these statements.

Conversely, Lógó and Ismail (2020, pp.101-102) state the 1870s developed the idea of optimisation with James Clerk Maxwell elaborating on the first techniques such as topology, whereby layout optimisation of trusses, known as minimum volume design of frames, was discovered, which Anthony Michell expanded upon in 1904, finding stress point loads on trusses to optimise structures. Mei & Wang (2021 pp.4-5) state that optimisation development is still relatively new with 73% of papers from 1970 to 2020, being published after 2010.

2.2. FEA Optimisation

FEA optimisation is crucial for design improvements, allowing companies to stay competitive. One technique is that of **Topology Optimisation**, shown in figure 1, which removes unnecessary material not required structurally for a given load, thus, reducing mass (ZHU et al. 2021, p.92).

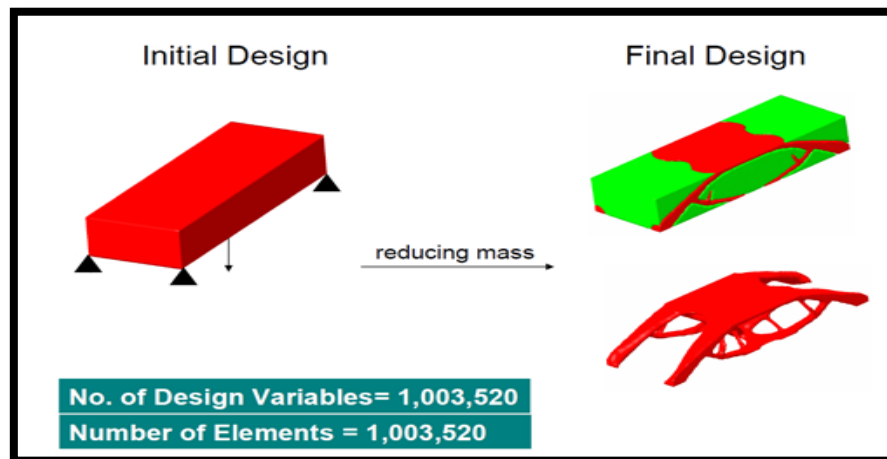


Figure 1. Topology Optimisation (Topological Optimisation with FEA, 2022)

Sizing Optimisation in figure 2 finds the best dimensions of a designable element, optimising elements for bars, shells, and composites, to perform a function effectively, such as reducing thicknesses or cross-sectional areas, whilst conforming to specifications or constraints (Mei & Wang 2021 p.2).

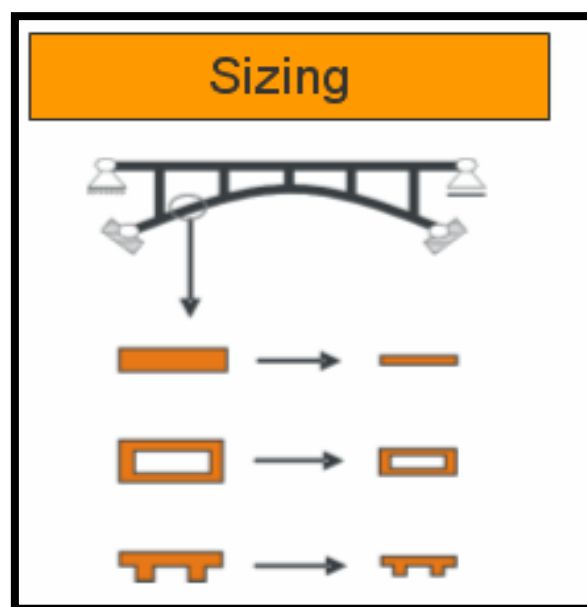


Figure 2. Sizing Optimisation (Michi, 2010)

Shape Optimisation in figure 3, finds the best shape for a given structure without compromising the specification, finding the best location of the finite element nodes, thus, defining the general shape of the structure (Mei & Wang 2021 p.2).

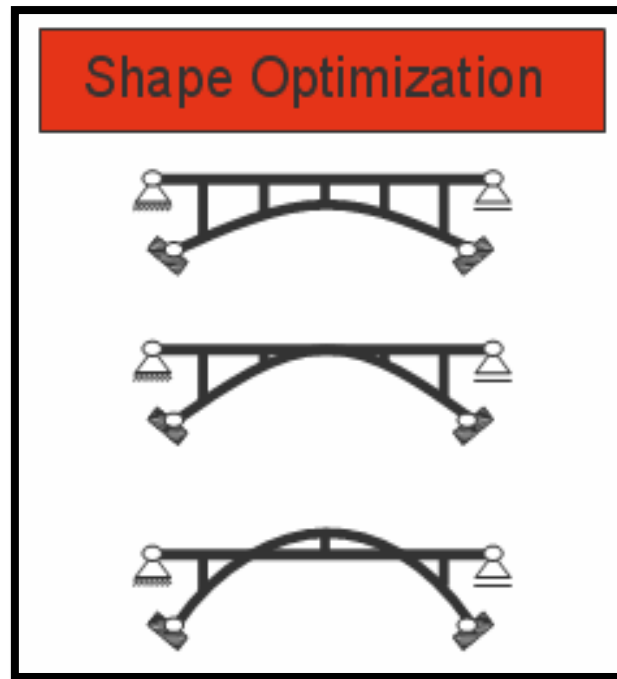


Figure 3. Shape Optimisation (Michi, 2010)

Topography Optimisation in figure 4 stiffens panel structures, whilst maintaining weight specifications, finding the location and shape of bead patterns, and optimising them without adding mass or manufacturing complexity, allowing engineers to design and optimise thin-walled parts (Carolo, 2020).

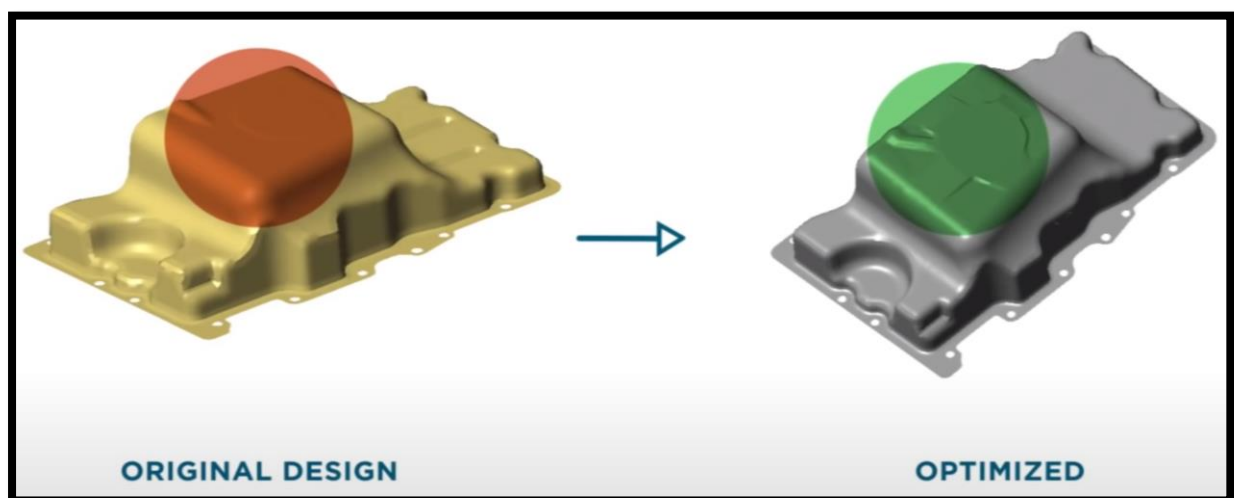


Figure 4. Topography Optimisation (Ponginan, 2021)

Topometry Optimisation in figure 5, finds the optimal distribution of sizing dimensions over the structure. It removes unnecessary material or adds material for strength and stability, thinning or thickening the structure element by element, defined by design variables (Ponginan, 2021).

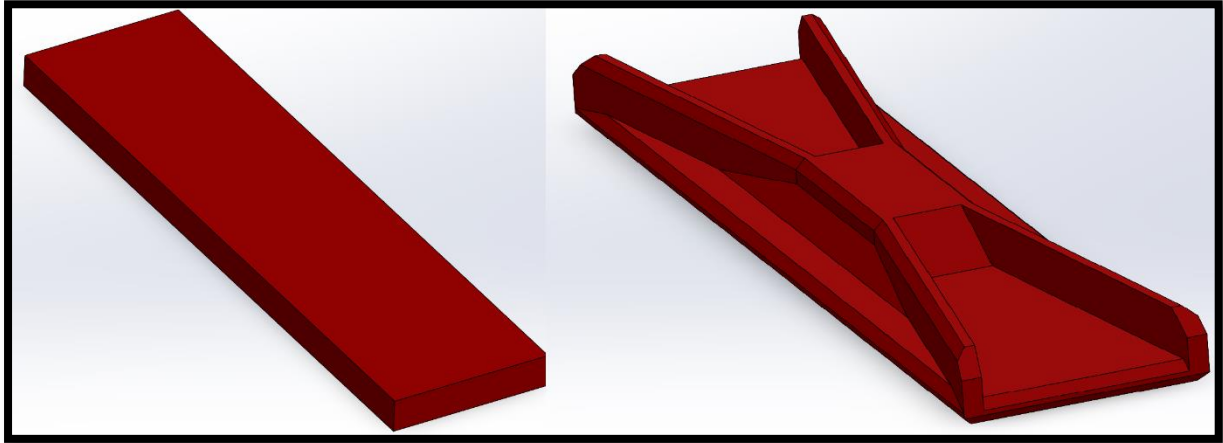


Figure 5. Topometry Optimisation

Freeform Optimisation in figure 6, finds the location and shape of rib patterns within a structure, stiffening them to ensure strength and stability, creating reduced mass compared to solid shapes. It can be used to find the best grid location within any structure type (Ponginan, 2021).

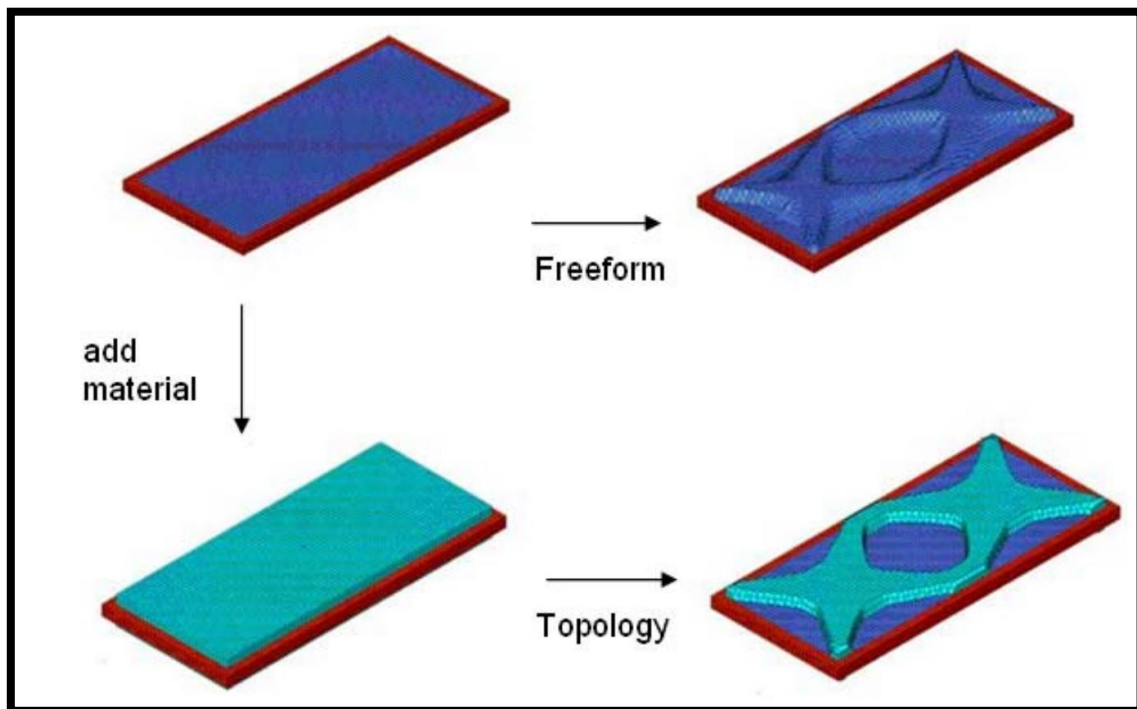


Figure 6. Freeform Vs Topology Optimisation (Leiva, 2010)

Generative Design (GD) in figure 7, can be utilised as a part of the initial design process. GD has goals and parameters imported into the software, such as material requirements or manufacturing methods and costs. It will then design and optimise the initial design in one package, based on the imported constraints, reducing time, cost and engineering resources. Table 1 shows a Topology and GD comparison (Baldota & Parmar, 2019).

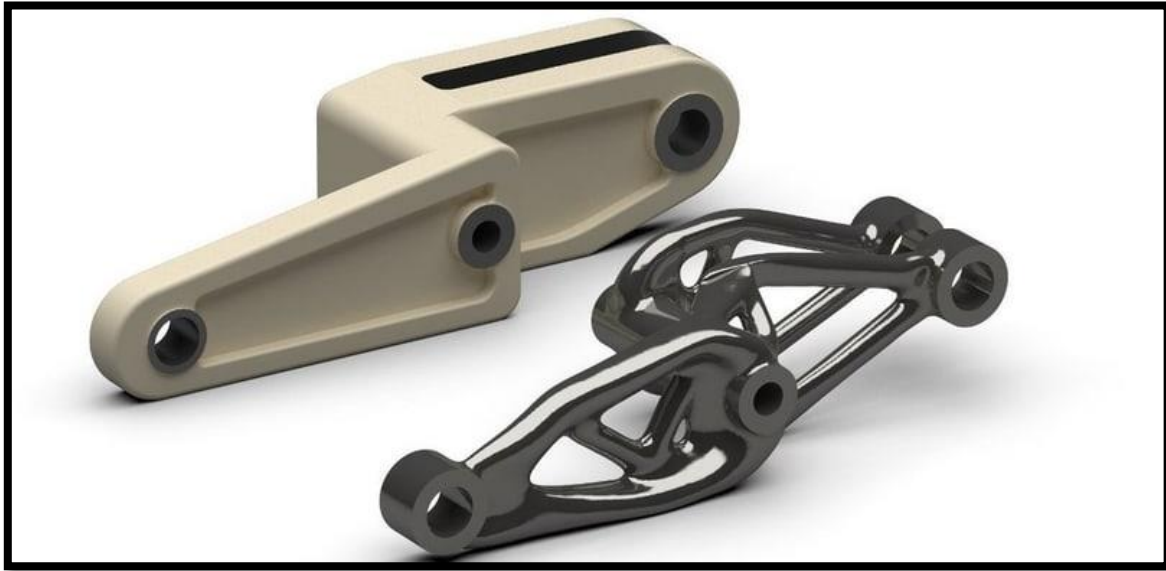


Figure 7. Generative Design (Baldota & Parmar, 2019)

Table 1. Topology Vs GD (Baldota & Parmar, 2019)

Topology Optimization	Generative Design
It uses an existing design to optimize it by removing material	It generates new optimized designs by growing the part as per the requirements
It gives you only one output	It gives you multiple outputs
It can be done on local computer	It is generally done on cloud but Siemens offers local solving also.
It can only be used in later phases of design where an initial design is already set	It is used in starting phase of the designs and it gives valuable feedback to engineers for initial design possibilities

2.3. FEA Design Influence

FEA and its' optimisation techniques improve efficiency, whilst reducing design time. Traditionally designs were made with prototyping phases to discover any design changes required. FEA allows for reduced lead times by optimising structures before manufacturing.

A **Standard Approach** in figure 8, allows analysis of a final Computer-Aided-Design (CAD) before making any changes. This iterative approach adds Non-Value-Added (NVA) tasks, thus, a **Modern Approach** reduces NVA tasks, providing a feedback loop at the early design stage to optimise the structure before a final design is made, improving efficiency (Berselli, Bilancia and Luzi, 2020).

It also removes an engineer's interaction time, allowing them to concentrate on more value-added tasks. However, FEA knowledge is still required to utilise the software effectively, considering manufacturing methods whilst anticipating how the optimised design will affect component features such as holes. However, GD allows the engineer to set more constraints to ensure feasibility and increase design efficiency at the initial stage (Velling, 2020).

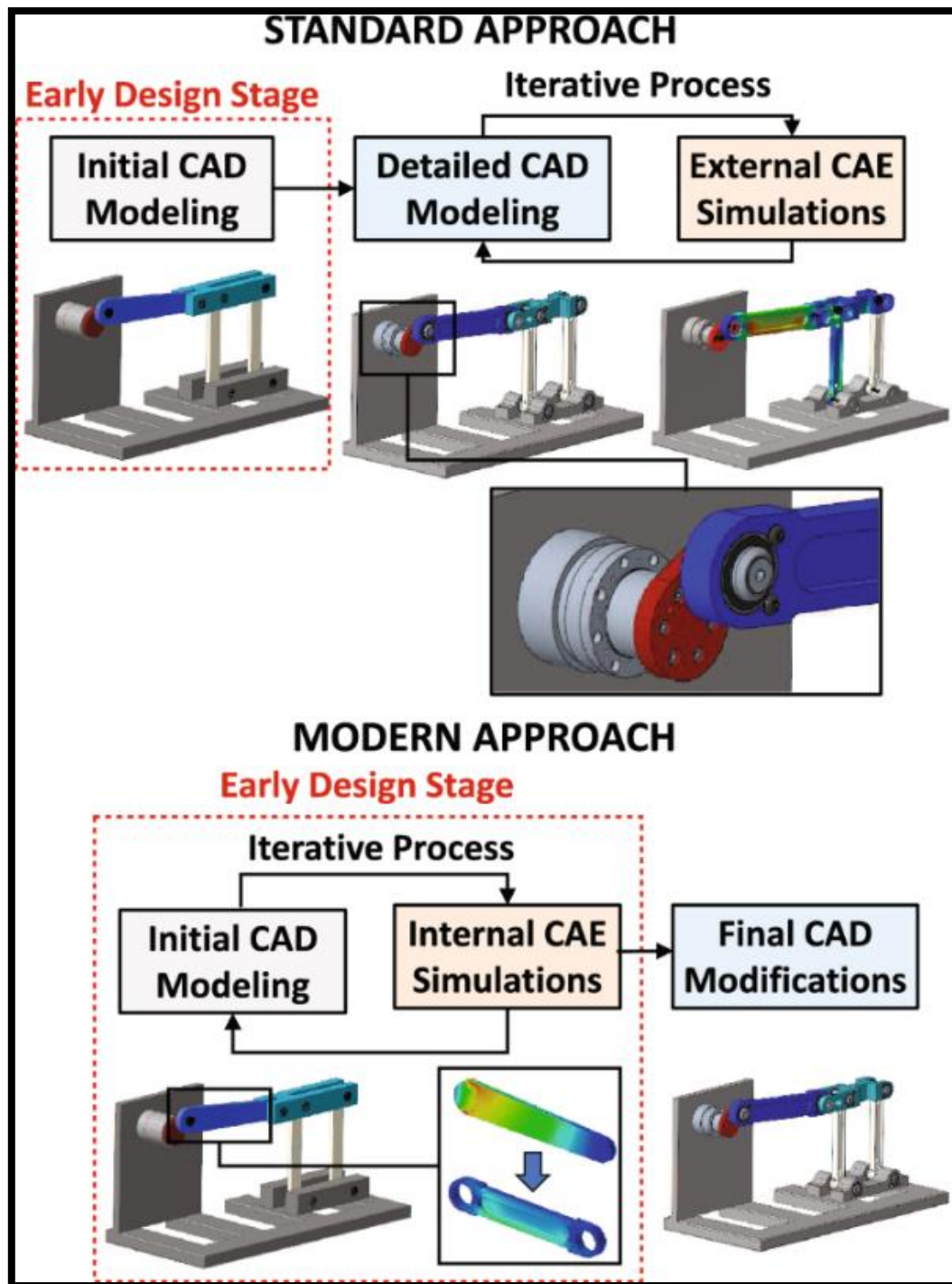


Figure 8. Standards and Modern Product Life Cycle (Berselli, Bilancia and Luzi, 2020)

2.4. FEA Future Developments

Current FEA optimisation requires an engineer's knowledge of manufacturing and constraint feasibility. Davim (2011, pp.201-239) states techniques like GD can be combined with Artificial Intelligence (AI), thus, AI-implemented constraints, manufacturing methods and budget constraints will automatically optimise structural problems.

Furthermore, current techniques like GD, do not consider Design for Assembly (DFA). Future optimisation may combine more effectively into design software, reducing design complexity with integrated optimisation features like DFA, thus, improving efficiency by mitigating mistakes made at assembly (Taylor-Smith, 2020).

FEA utilises mesh, analysing each element, whilst intertwining the results to understand their correlation. Engineers must understand the process for various geometries, with complex shapes requiring simplification. Roade (2020) states mesh-free software is being developed based on a Dirichlet Function variation which mathematically maps shapes, allowing boundaries to be set independent of nodes, allowing complex shape analysis without meshes, increasing accuracy and efficiency, which could also be implemented into design software packages.

Xu, Xu, Yang and Neumann (2019, pp.62-71) state that laser scanning combined with FEA increases accuracy through calibration systems. This could scan and optimise existing structures understanding modification requirements for safety and structural conformity from structural degradation. According to ZHU et al. (2021, pp.92-105) combined with advanced additive manufacturing, could provide fast and accurate components, which could also be utilised within medical applications such as prosthetics (Fey et al. 2009, pp.607-617).

3.0. Composite Propeller Model

This section utilises Carbon Fibre Reinforced Plastic (CFRP) within a propeller blade design, comparing it with traditional materials like steel.

3.1. Considerations and Constraints

Previous calculations have not been determined for load distributions, thus, the given 5kN Uniformly Distributed Load (UDL) will be utilised over one blade face as shown in figure 9, with dimensions shown in figure 10.

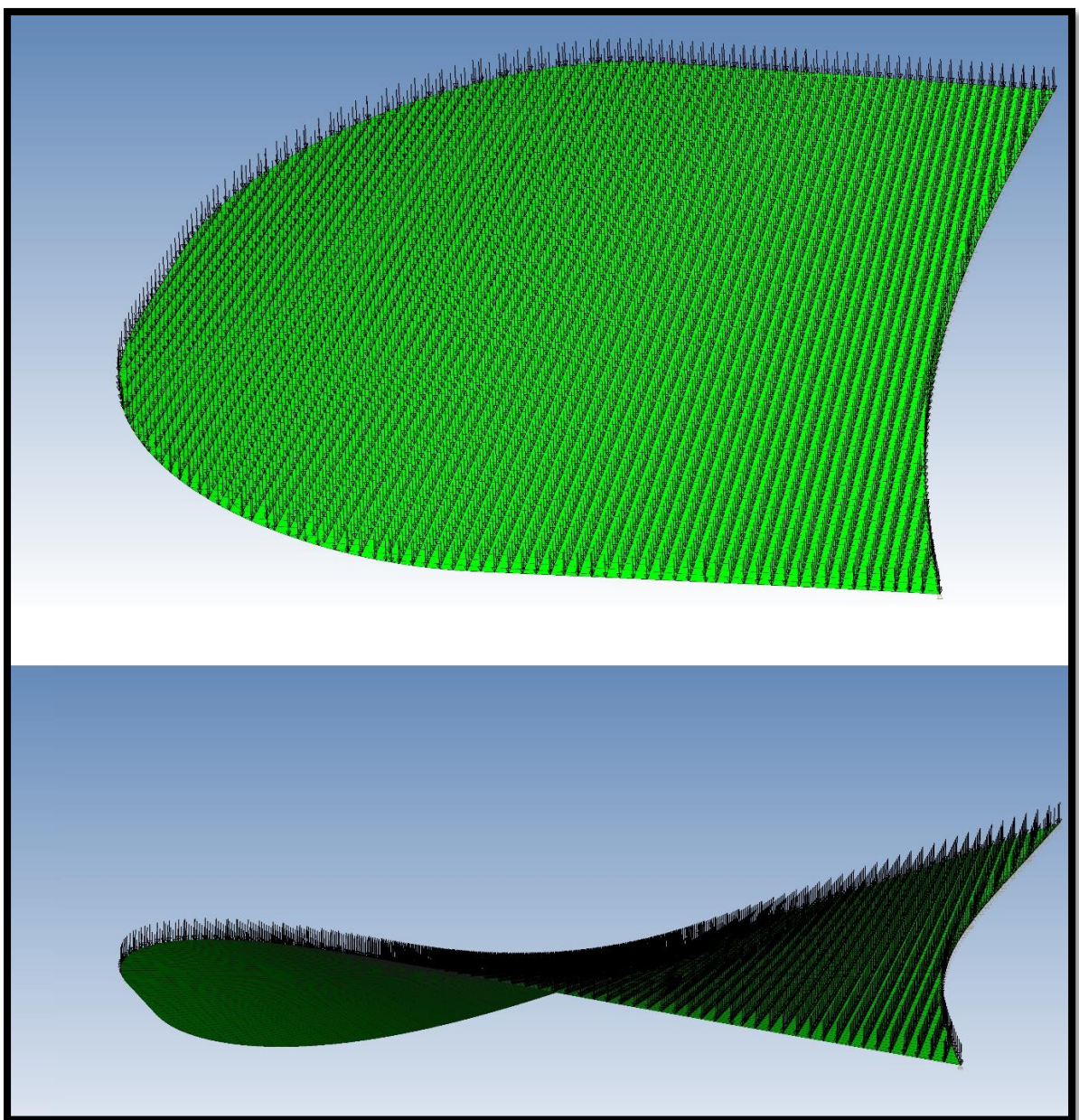


Figure 9. 5kN UDL over a Propeller Blade Face

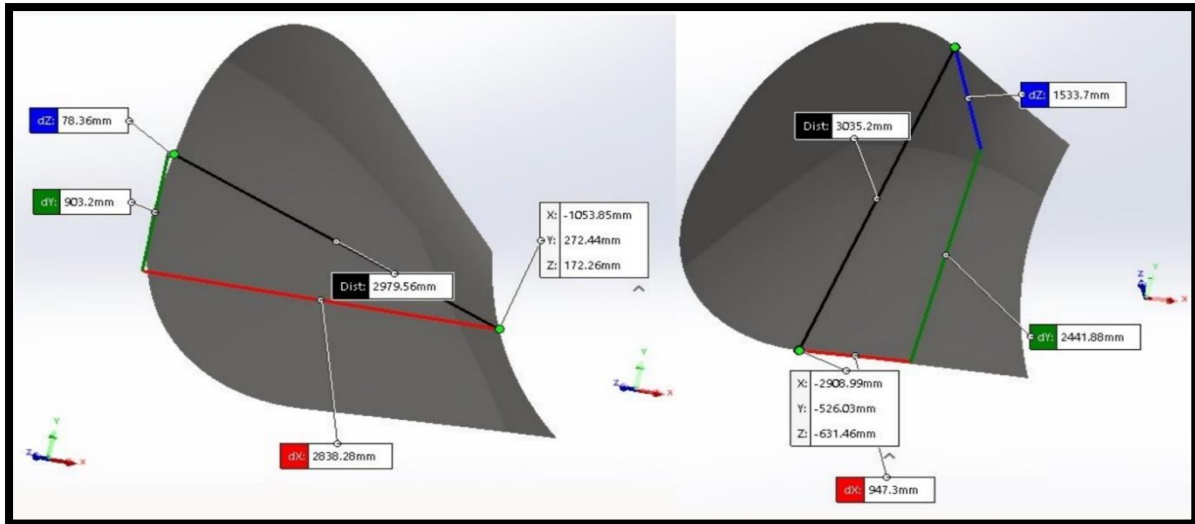


Figure 10. Propeller Dimensions

Submerged rotating propellers experience centrifugal forces, torque forces and varied load distribution due to varied fluid velocity, affected by Revolutions Per Minute (RPM), material friction coefficients and so on. Therefore, as these variables can change and require computational methods for accuracy, a UDL will be used whilst negating other forces, allowing for accurate deflection comparisons and optimisation for materials. These results will, therefore, differ from real-world results based on the variables. All assumptions are shown in table 2.

For simple analysis, all models are constrained with grid-component sets at the blade root, preventing 6-degrees of freedom. Although, mechanical tolerances may allow for some movement in real applications. These root constraints have been extended slightly towards to tip as figure 11 shows, which reduces moment forces. This simulates an attachment fillet to the hub, although, accuracy is limited due to software limitations.

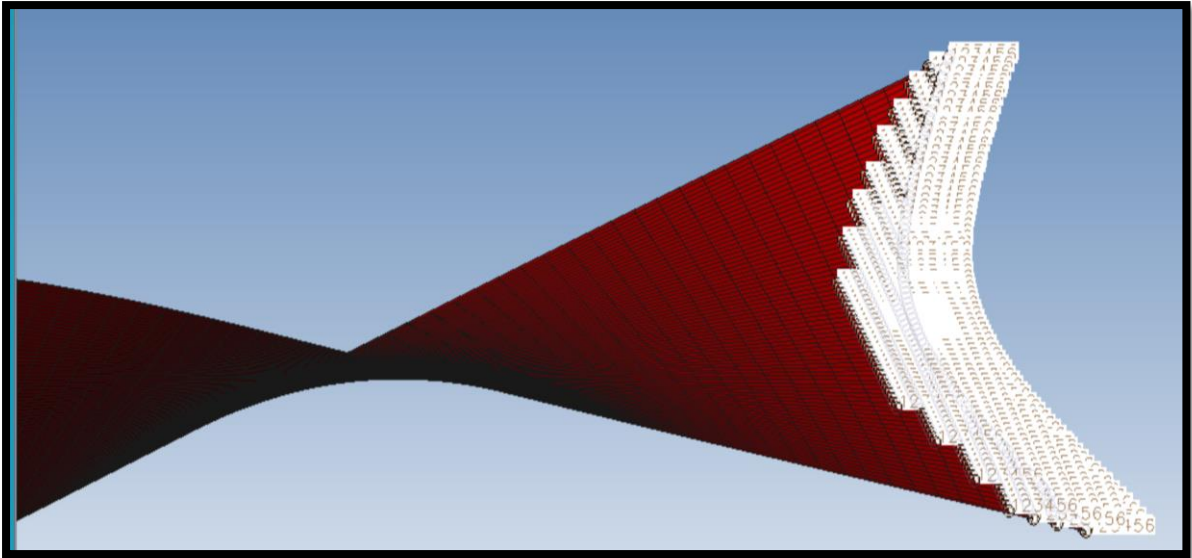


Figure 11. Grid-Component Sets

Polar coordinates should be used as zero degrees runs radially from the propeller centre. However, the software utilises cartesian coordinates, thus, elements are aligned parallel to one another from the root to the tip shown in figure 12. This alters the load case slightly from real circumstances.

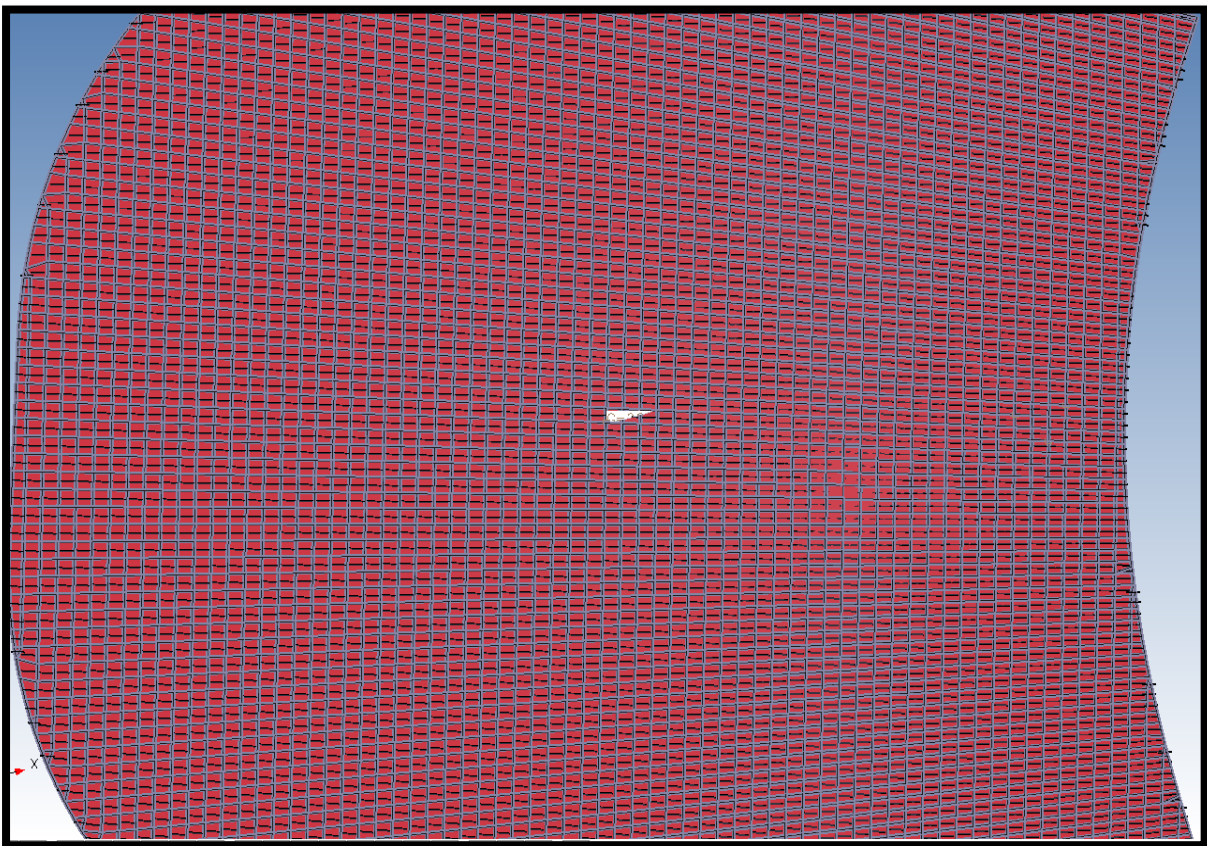


Figure 12. Element Direction

All assumptions and boundary conditions shown in tables 2 and 3 are made to simplify the analysis for greater design understanding, however, they may influence the results compared to real-world testing, such as torque forces causing additional blade stress, thus, altering deflection results.

Table 2. Assumptions

Assumptions
Material impurities are negated
Structural impurities are negated
Temperature is negated
Thrust force is in a condition whereby a UDL is applied
A fillet at the propeller blade root is applied to simulate a connection to the hub
Vibrational Forces are negated
Torque Force is negated
Centrifugal Forces are negated
The Materials' Coefficient of Friction is negated

Table 3. Boundary Conditions

Boundary	Condition
Attachments	Propeller root fixed with grid-component sets, preventing 6 degrees of freedom.
Attachments	Nodes along the propeller root edge are extended in the blade slightly and set for all varied analyses (Simulating a fillet)
Force	5kN applied as UDL
Force	Elements aligned parallel from root to tip

3.2. Steel Analysis

Applying the UDL to the steel blade shows a 210mm deflection, shown in figure 13. Table 4 is created from the analysis results with steel design properties in figure 14. Therefore this design does not meet the specifications. Grid-component sets impact deflection, increasing them reduces bending moments, thus, deflection, as figure 15 shows. However, original constraints will be used throughout for consistency.

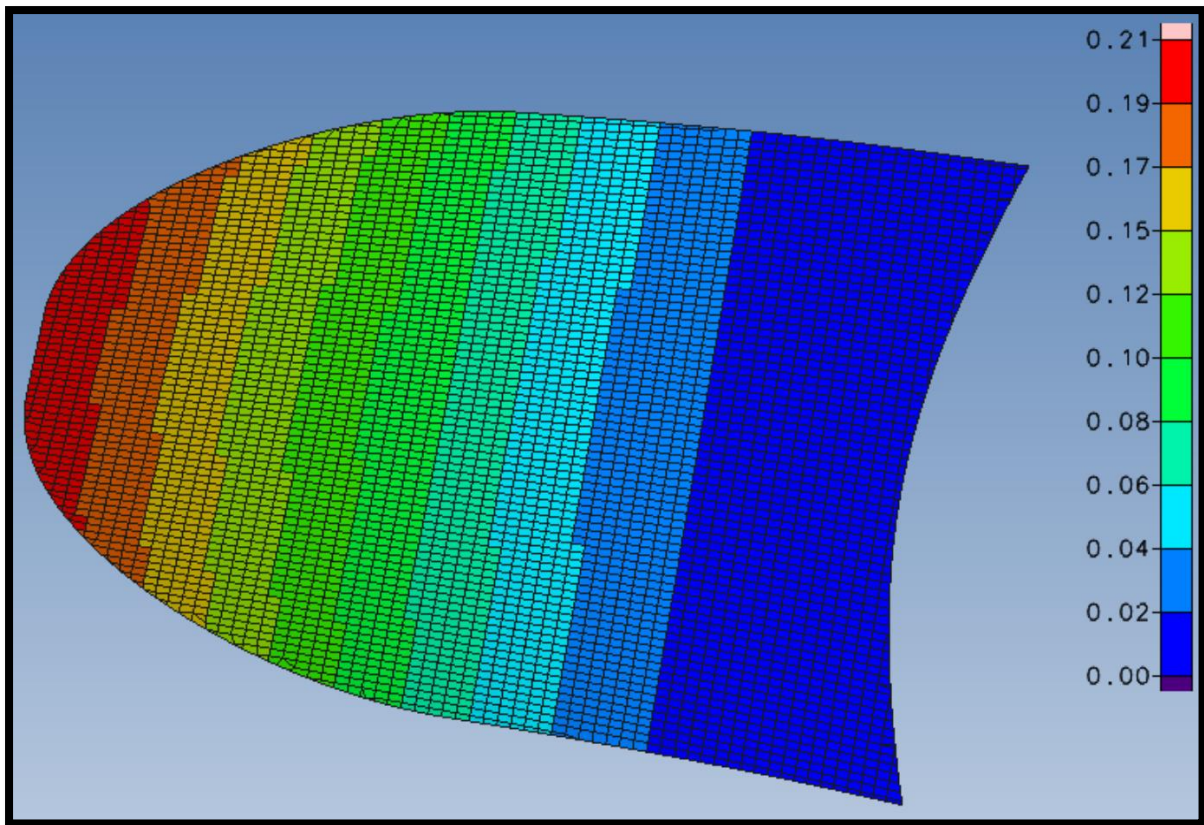


Figure 13. Steel Deflection

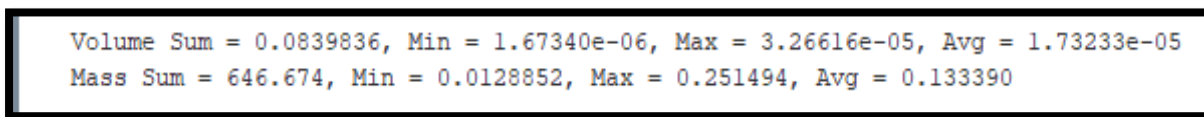


Figure 14. Steel Design Properties

Table 4. Steel Analysis Results

Run	Material	Thickness	Deflection	Mass	Load	Stiffness	Stiffness/Weight
Steel Baseline	Steel	10mm	210mm	647kg	5kN	23.81N/mm	$3.75 \cdot 10^{-3} \text{ N}^2/\text{mm}$

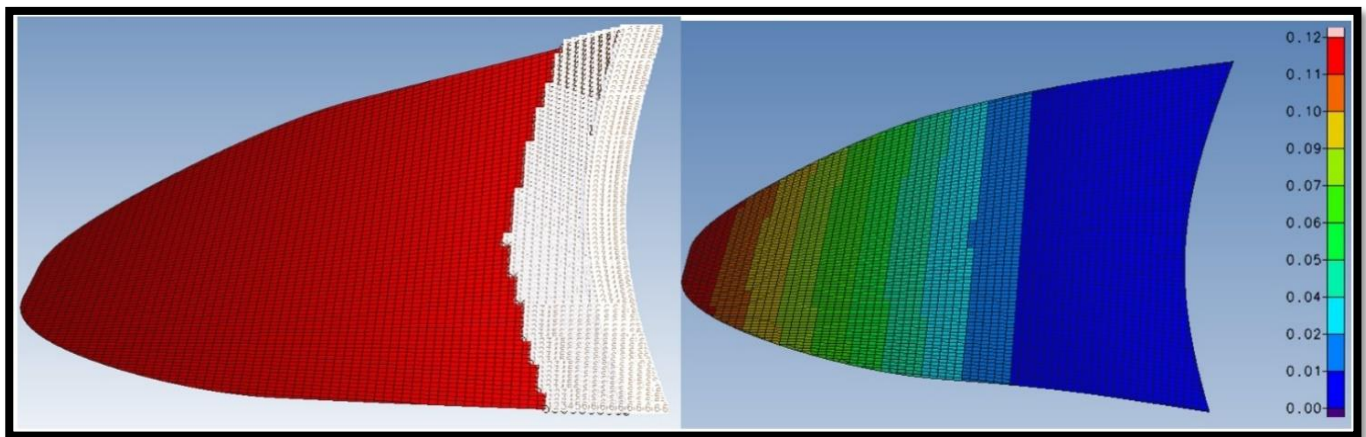


Figure 15. Grid-Component Sets Alteration Affecting Deflection

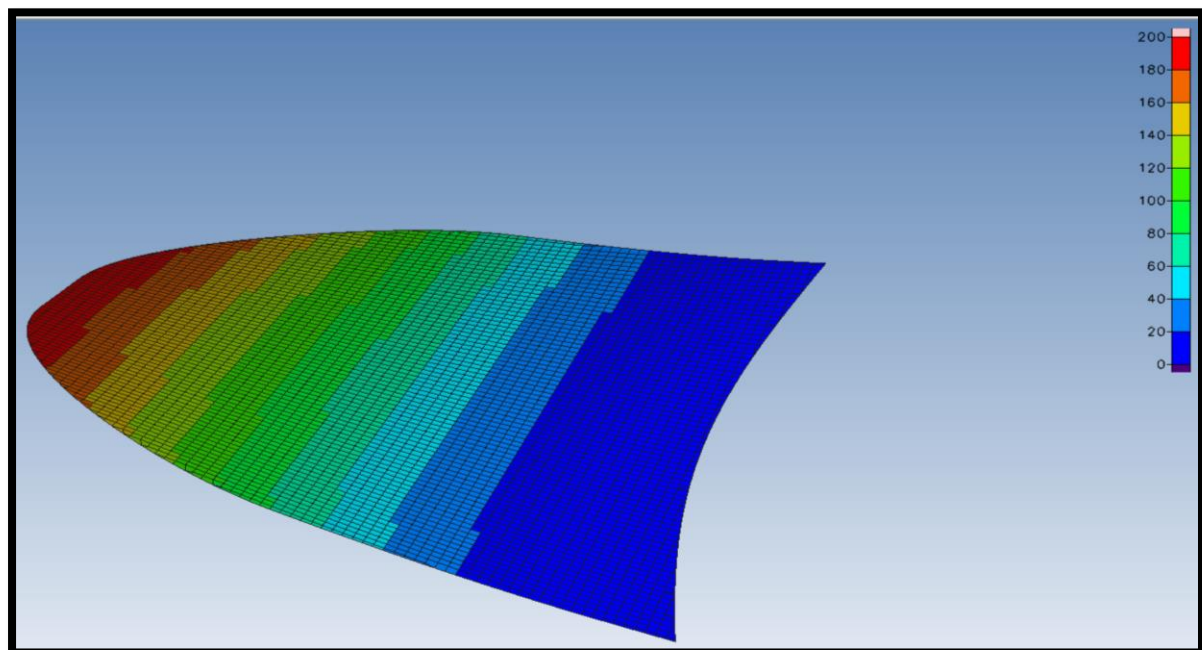
3.3. Composite Construction

The CFRP with properties shown in figure 16 is designed with 5 layers in the directions shown in figure 17, each made with 5 ply's of 0.1mm, totalling a 2.5mm thickness. Applying a 5kN UDL shows a 200-metre deflection, shown in figure 18. Combined with the design properties in figure 19, an analysis comparison has been completed, shown in table 5.

Edit a Material : 2-D Orthotropic Properties	
E_1:	1.32E+11
E_2:	1.08E+10
Nu_12:	0.24
G_12:	5.65E+9
G_1z:	5.65E+9
G_2z:	5.65E+9
Rho:	1540.0
A_1:	0.0
A_2:	0.0
Tref:	0.0
GE:	
F12:	
Xt:	1.513E+9
Xc:	1.E+9
Yt:	4.34E+7
Yc:	4.34E+7
S:	4.34E+7

Figure 16. CFRP Material Properties

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

Figure 17. Composite Layup*Figure 18. CFRP Baseline Deflection*

Volume Sum = 0.0209959, Min = 4.18351e-07, Max = 8.16541e-06, Avg = 4.33084e-06
Mass Sum = 32.3337, Min = 0.000644260, Max = 0.0125747, Avg = 0.00666949

Figure 19. CFRP Design Properties

Table 5. Steel and CFRP Comparison

Run	Material	Thickness	Deflection	Mass	Load	Stiffness	Stiffness/Weight
Steel Baseline	Steel	10mm	210mm	647kg	5kN	23.81N/mm	$3.75 \cdot 10^{-3} \text{ N}^2/\text{mm}$
Composite Baseline	CFRP	2.5mm	$200 \cdot 10^3 \text{ mm}$	32kg	5kN	0.025 N/mm	$7.96 \cdot 10^{-5} \text{ N}^2/\text{mm}$

Interestingly, although CFRP is approximately 20-times lighter than steel, its' stiffness-to-weight is 47-times lower than steel. However, a 200m deflection would indicate a break, as the software is linear, thus, the material would have passed its' Ultimate Strength, and thus, the stiffness-to-weight comparison is not completely accurate.

4.0. Optimised Propeller Model

Design optimisation is utilised to reduce mass, whilst constraining the model to 100mm deflection. It optimises it without breaking the limit, hence, a 99.9mm deflection is shown in figure 20. To achieve this, lower bounds were set to 0.1mm with upper bounds set to 10mm as figure 21 shows.

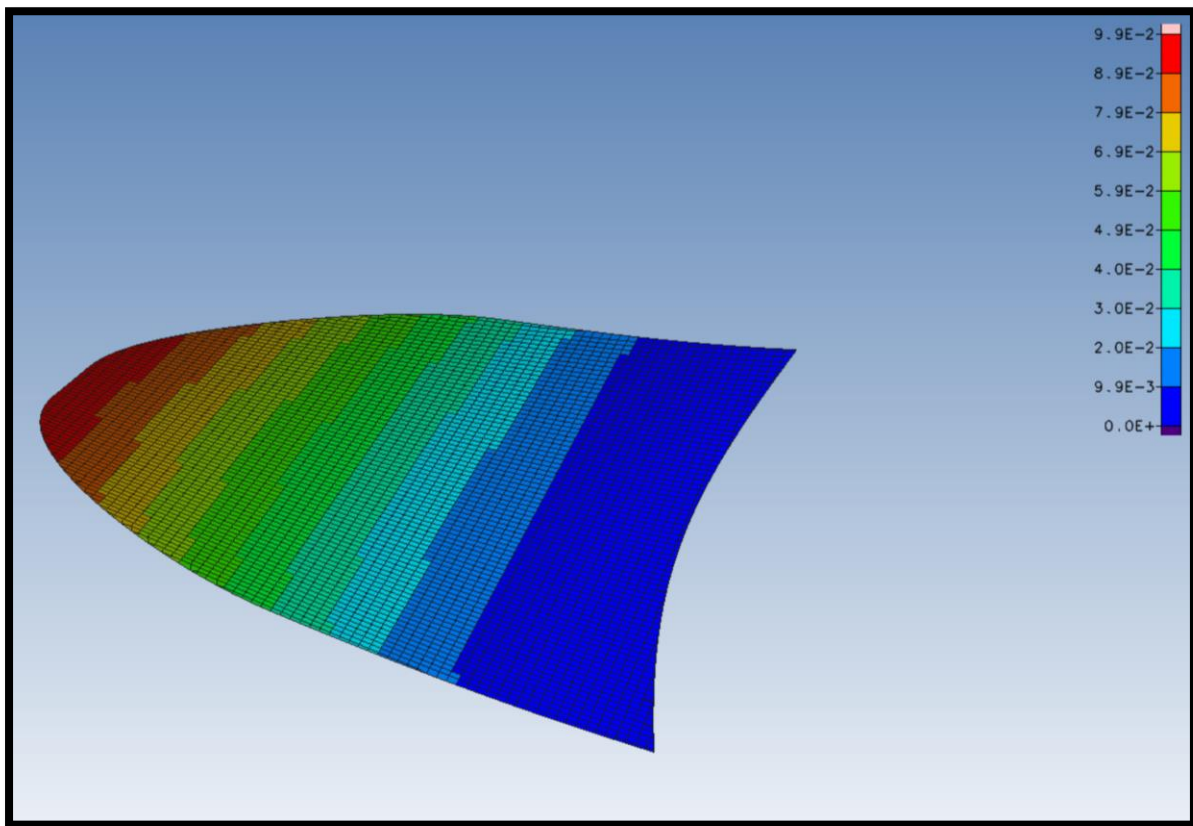


Figure 20. CFRP Optimised Deflection

Description	Name
I ID=1 Init=5.E-4 [1.E-4,0.01]	L1THK
I ID=2 Init=5.E-4 [1.E-4,0.01]	L2THK
I ID=3 Init=5.E-4 [1.E-4,0.01]	L3THK
I ID=4 Init=5.E-4 [1.E-4,0.01]	L4THK
I ID=5 Init=5.E-4 [1.E-4,0.01]	L5THK

Figure 21. Layer Design Variables

Figure 22 shows the design variables of each layer with a total mass of 340.7kg. This is almost half the mass of steel, whilst meeting specifications. Table 6 shows the layer breakdown, showing a thickness greater than steel at 28.741mm.

```

139 DESIGN CYCLE #    23, OBJECTIVE =  3.407356E+02, MAXIM
140 DESIGN VARIABLE #         1 =  2.307387E-04    L1THK
141 DESIGN VARIABLE #         2 =  8.250481E-03    L2THK
142 DESIGN VARIABLE #         3 =  9.999999E-03    L3THK
143 DESIGN VARIABLE #         4 =  7.598309E-03    L4THK
144 DESIGN VARIABLE #         5 =  2.657243E-04    L5THK
145 COMPLETION CODE: 1      553      0
146

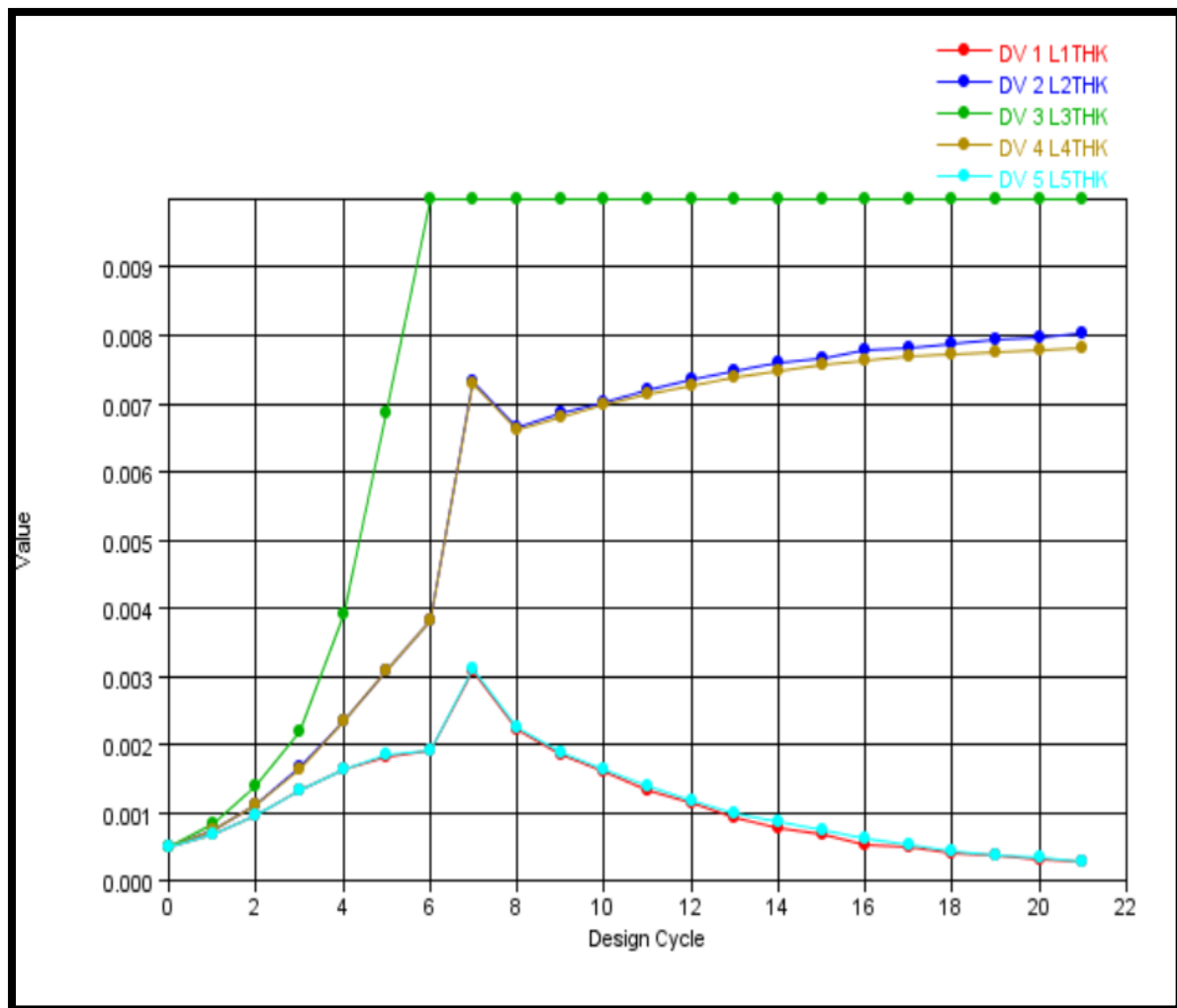
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Figure 22. Optimised Design Properties

Table 6. Layer and Ply Breakdown

Design Variable (Layer)	Thickness (mm)	Number of Ply's	Angle (degrees)
Layer 1	0.231	2.31	-90
Layer 2	8.25	82.5	-45
Layer 3	10	100	0
Layer 4	7.6	76	45
Layer 5	2.66	26.6	90

Graph 1 indicates layer 3 takes the majority of the load, maximising the 10mm upper bound limit. Allowing for an increased upper bound allows for better optimisation, as the other layers would not need to compensate for the layer 3 limits.

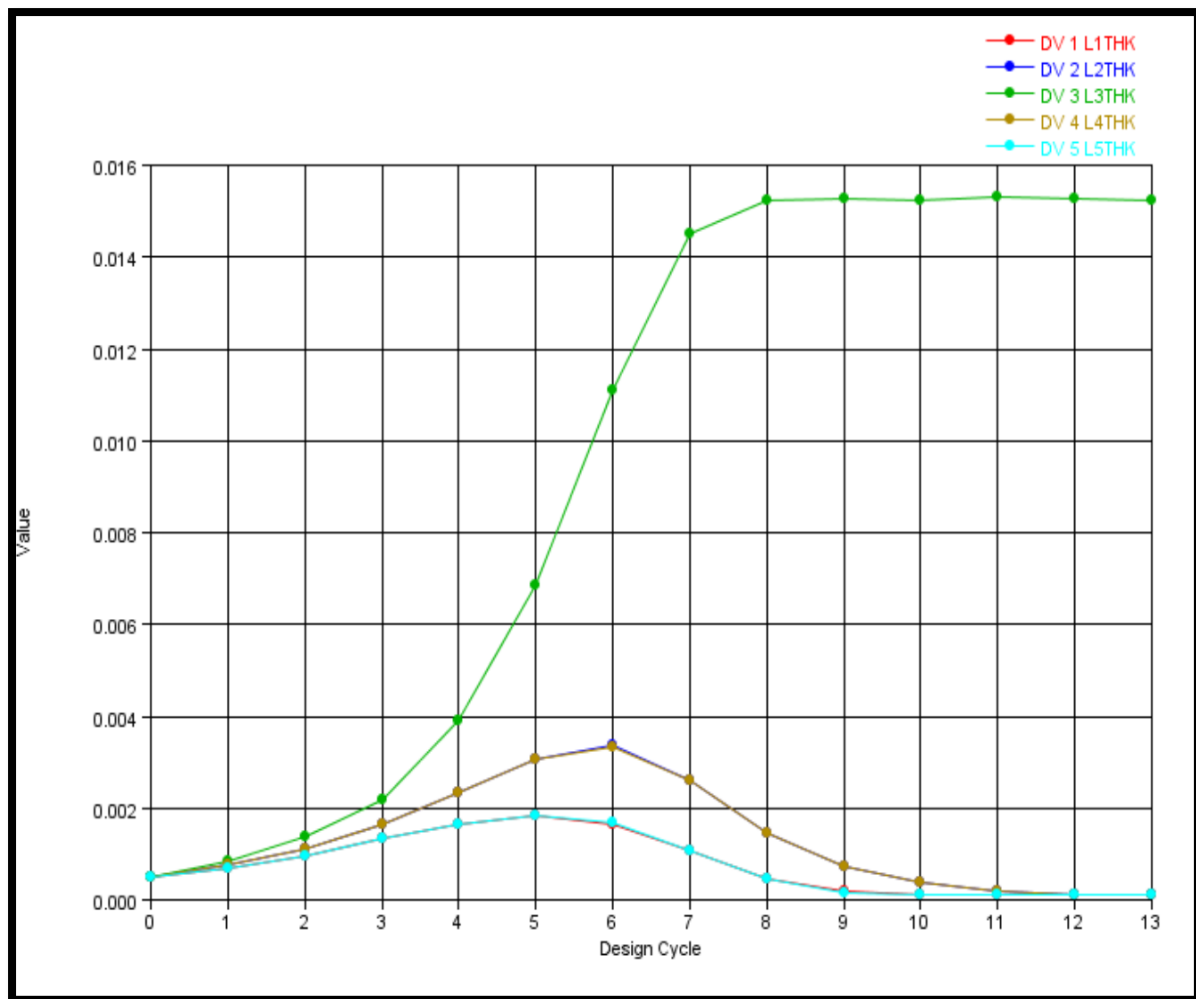


Graph 1. Optimised Layer Thicknesses

Increasing the upper bound to 20mm as figure 23 shows, prevent layer 3 from reaching its' limit which has prevented the other layers from compensating for the load as graph 2 shows.

Description	Name
I ID=1 Init=5.E-4 [1.E-4,0.02]	L1THK
I ID=2 Init=5.E-4 [1.E-4,0.02]	L2THK
I ID=3 Init=5.E-4 [1.E-4,0.02]	L3THK
I ID=4 Init=5.E-4 [1.E-4,0.02]	L4THK
I ID=5 Init=5.E-4 [1.E-4,0.02]	L5THK

Figure 23. Increased Design Variables



Graph 2. Further-Optimised Layer Thickness

As figure 24 shows, the new mass is 202kg whilst meeting the 100mm constraint. Table 7 shows the new layer and ply arrangement with a total thickness of 15.6mm.

79	DESIGN CYCLE #	13,	OBJECTIVE =	2.022474E+02,	MAXIMUM VIOLATION =	0.0%.
80	DESIGN VARIABLE #	1 =	1.000000E-04	L1THK		
81	DESIGN VARIABLE #	2 =	1.000000E-04	L2THK		
82	DESIGN VARIABLE #	3 =	1.523752E-02	L3THK		
83	DESIGN VARIABLE #	4 =	1.000000E-04	L4THK		
84	DESIGN VARIABLE #	5 =	1.000000E-04	L5THK		
85	COMPLETION CODE:	1	554	0		

Figure 24. Further-Optimised Design Properties

Table 7. Layer and Ply Breakdown

Design Variable (Layer)	Thickness (mm)	Number of Ply's	Angle (degrees)
Layer 1	0.1mm	1	-90
Layer 2	0.1mm	1	-45
Layer 3	15.2mm	152	0
Layer 4	0.1mm	1	45
Layer 5	0.1mm	1	90

Table 8 compares the optimised CFRP with that of the baseline CFRP and Steel. The results show a much higher stiffness for the optimised CFRP.

Table 8. Optimised CFRP, Composite Baseline and Steel Comparison

Run	Material	Thickness	Deflection	Mass	Load	Stiffness	Stiffness/Weight
Steel Baseline	Steel	10mm	210mm	647kg	5kN	23.81N/mm	$3.75 \cdot 10^{-3} \text{ N}^2/\text{mm}$
Composite Baseline	CFRP	2.5mm	$200 \cdot 10^3 \text{ mm}$	32kg	5kN	0.025 N/mm	$7.96 \cdot 10^{-5} \text{ N}^2/\text{mm}$
Composite Optimised	CFRP	15.6mm	99.9mm	202kg	5kN	50.05N/mm	$25.26 \cdot 10^{-3} \text{ N}^2/\text{mm}$

Therefore, although a CFRP mass of more than 6-times that of its' baseline has occurred, it now meets specifications with a stiffness increase from steel of 110.21% and a stiffness-to-weight increase of 573.6%.

However, manufacturing considerations are required. For example, when each layer is constrained to 10mm, partial ply's such as 2.3 ply's occurs, thus, not manufacturable. Therefore, discrete variables are required, preventing partial ply's. Discrete variables have been applied, therefore, figure 25 shows a new mass and layer arrangement, broken down in table 9.

187	DESIGN CYCLE #	31,	OBJECTIVE =	2.121090E+02,	MAXIMUM VIOLATION =	0.0%.
188	DESIGN VARIABLE #	1 =	5.000000E-04	L1THK		
189	DESIGN VARIABLE #	2 =	2.000000E-04	L2THK		
190	DESIGN VARIABLE #	3 =	1.530000E-02	L3THK		
191	DESIGN VARIABLE #	4 =	2.000000E-04	L4THK		
192	DESIGN VARIABLE #	5 =	2.000000E-04	L5THK		
193	COMPLETION CODE: 1	574	0			
194						

Figure 25. Discrete Variable (Manufacturable) Design Properties

Table 9. Discrete Variable Layer and Ply Breakdown

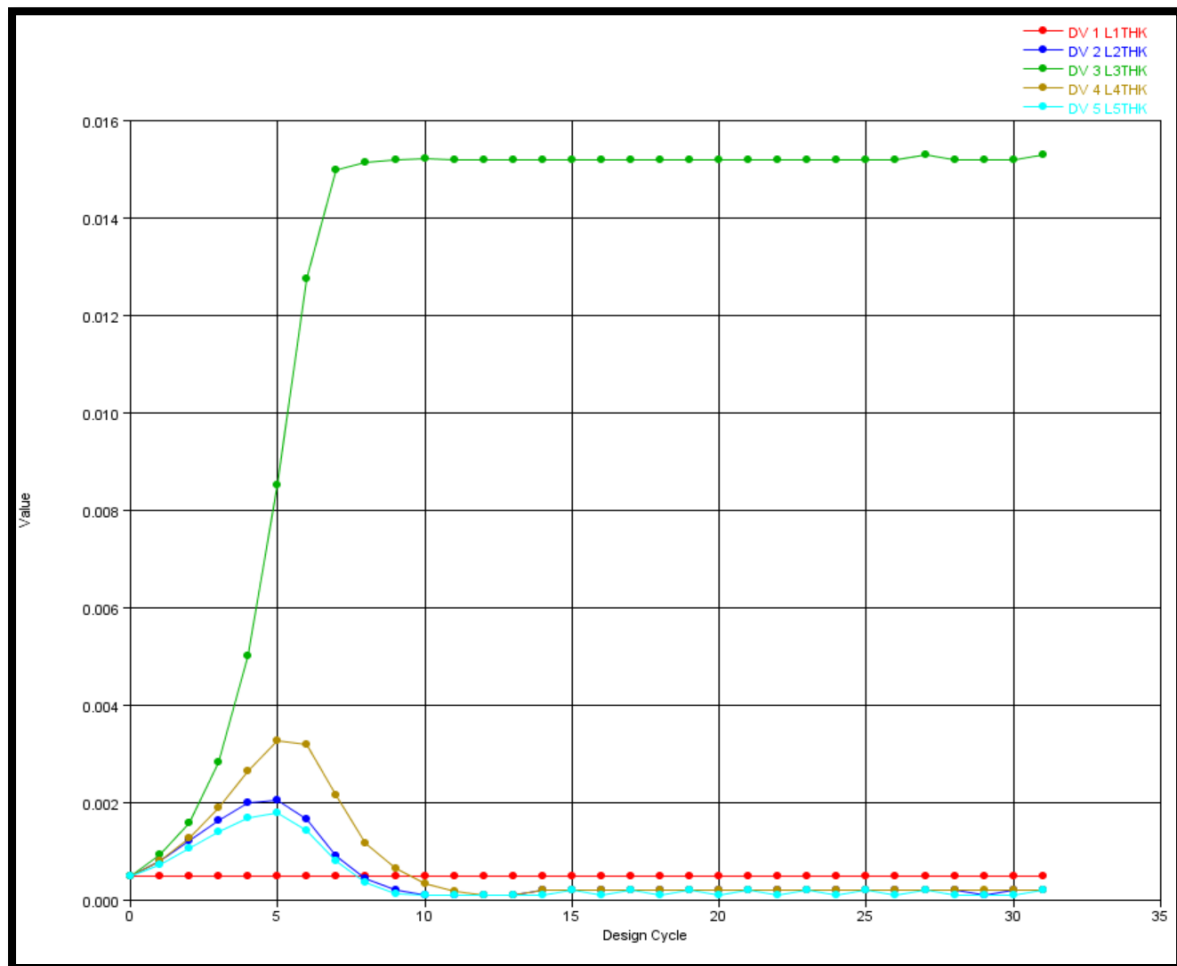
Design Variable (Layer)	Thickness (mm)	Number of Ply's	Angle (degrees)
Layer 1	0.5mm	5	-90
Layer 2	0.2mm	2	-45
Layer 3	15.3mm	153	0
Layer 4	0.2mm	2	45
Layer 5	0.2mm	2	90

Manufacturing considerations allow for increased success and accuracy. It has, however, increased the mass to 212kg, thus, a 4.71% stiffness-to-weight decrease occurs. Although, this still meets specifications, and is significantly higher than steel as table 10 shows.

Table 10. Discrete Optimised CFRP Comparison

Run	Material	Thickness	Deflection	Mass	Load	Stiffness	Stiffness/Weight
Steel Baseline	Steel	10mm	210mm	647kg	5kN	23.81N/mm	$3.75 \cdot 10^{-3} \text{ N}^2/\text{mm}$
Composite Baseline	CFRP	2.5mm	$200 \cdot 10^3 \text{ mm}$	32kg	5kN	0.025 N/mm	$7.96 \cdot 10^{-5} \text{ N}^2/\text{mm}$
Composite Optimised	CFRP	15.6mm	99.9mm	202kg	5kN	50.05N/mm	$25.26 \cdot 10^{-3} \text{ N}^2/\text{mm}$
Composite Discrete Optimised	CFRP	16.4mm	99.9mm	212kg	5kN	50.05N/mm	$24.07 \cdot 10^{-3} \text{ N}^2/\text{mm}$

Interestingly as graph 3 shows, layer 3 withstands the load due to it being loaded at 0 degrees, thus, with the rearrangement of layer angles, the design can be optimised further. Table 11 shows an optimised layer direction and how that affects the layer and ply arrangement, with figure 26 additionally showing the new mass.



Graph 3. Discrete Variable Layer Thickness

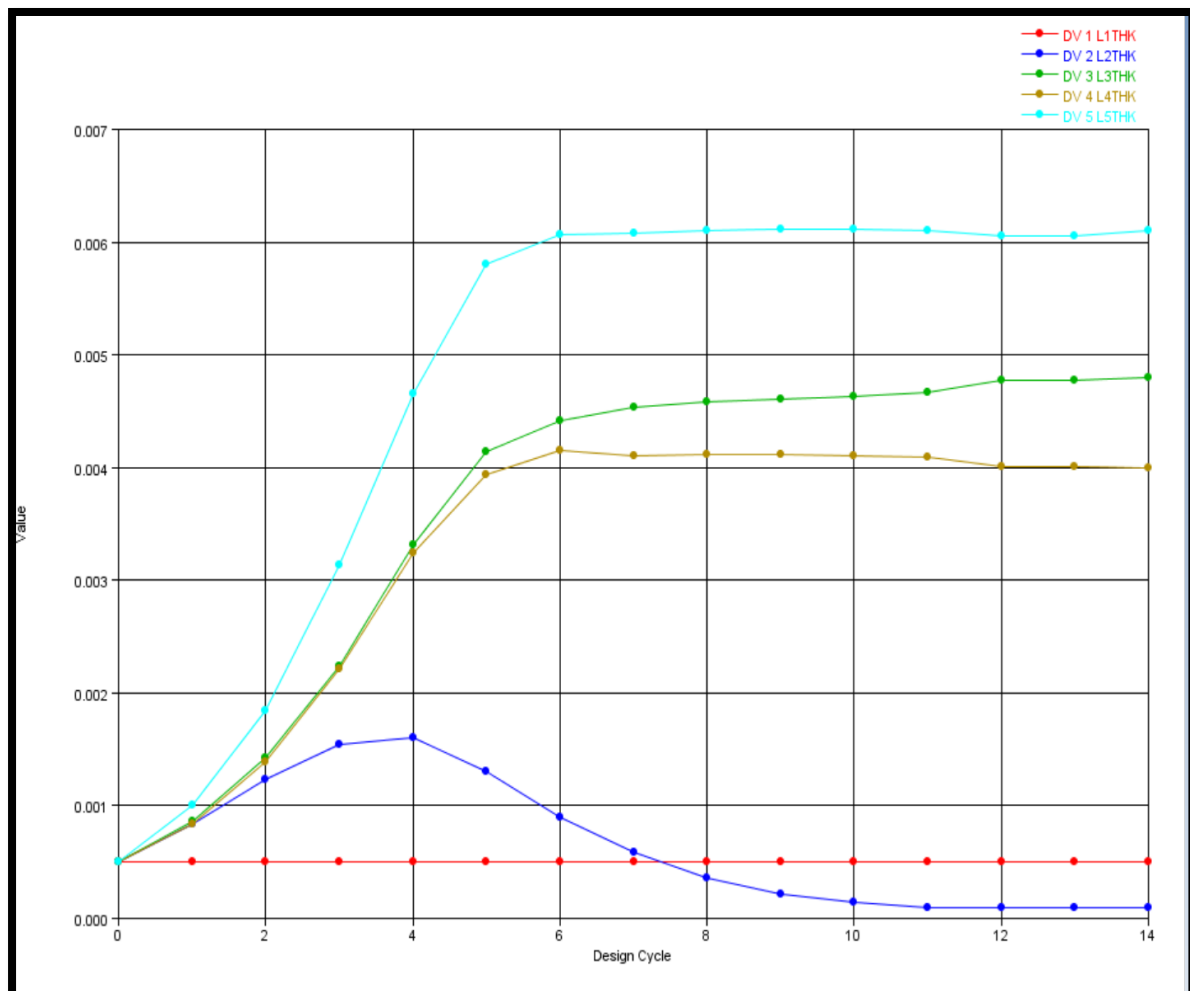
85	DESIGN CYCLE #	14,	OBJECTIVE =	2.004688E+02,	MAXIMUM VIOLATION =	0.0%.
86	DESIGN VARIABLE #	1 =	5.000000E-04	L1THK		
87	DESIGN VARIABLE #	2 =	1.000000E-04	L2THK		
88	DESIGN VARIABLE #	3 =	4.800000E-03	L3THK		
89	DESIGN VARIABLE #	4 =	4.000000E-03	L4THK		
90	DESIGN VARIABLE #	5 =	6.100000E-03	L5THK		
91	COMPLETION CODE: 1	557	0			
92						

Figure 26. New Layer Direction Design Properties

Table 11. New Layer Direction Layer and Ply Breakdown

Design Variable (Layer)	Thickness (mm)	Number of Ply's	Angle (degrees)
Layer 1	0.5mm	5	0
Layer 2	0.1mm	1	-45
Layer 3	4.8mm	48	0
Layer 4	4mm	40	45
Layer 5	6.1mm	61	0

Arranging the layer directions in this orientation ensures a more equal load distribution between layers, with 0 degrees supporting the majority, as graph 4 shows. This reduces layer thicknesses, thus, mass. The comparison is shown in table 12.



Graph 4. Layer Thickness for New Orientation

Table 12. Final Optimised Propeller Analysis Results and Comparison

Run	Material	Thickness	Deflection	Mass	Load	Stiffness	Stiffness/Weight
Steel Baseline	Steel	10mm	210 mm	647kg	5kN	23.81N/mm	$3.75 \cdot 10^{-3} N^2/mm$
Composite Baseline	CFRP	2.5mm	$200 \cdot 10^3 mm$	32kg	5kN	0.025 N/mm	$7.96 \cdot 10^{-5} N^2/mm$
Composite Optimised	CFRP	15.6mm	99.9mm	202kg	5kN	50.05N/mm	$25.26 \cdot 10^{-3} N^2/mm$
Composite Discrete Optimised	CFRP	16.4mm	99.9mm	212kg	5kN	50.05N/mm	$24.07 \cdot 10^{-3} N^2/mm$
Composite Layer Angle and Discrete Optimised	CFRP	15.5mm	99.9mm	200kg	5kN	50.05N/mm	$25.51 \cdot 10^{-3} N^2/mm$

Therefore, having considered manufacturing with discrete variables, and optimising the design with new layer directions, a total thickness of 15.5mm and mass of 200kg is achieved, increasing the stiffness-to-weight by 580.27% compared with steel. With new layer directions and without discrete variables, an even greater stiffness-to-weight would be achieved, but manufacturability may not be possible.

Therefore, with five 200kg propeller blades, negating other propeller components, a total mass of 1000kg is achieved. With steel being a total of 3235kg, CFRP is 3.235-times lighter than steel, whilst meeting specifications, which steel did not.

5.0. Testing

For accurate comparison to the simulation, the test must be carried out for thrust force, negating torque and centrifugal forces shown in figure 27. These forces, if not negated, will alter deflection, such as centrifugal forces increasing fluid velocity, or resistance deflection, with torque causing additional stresses. One must note, without propeller rotation, differential pressures on either side of the blade will not occur, thus, will further differ from real circumstances.

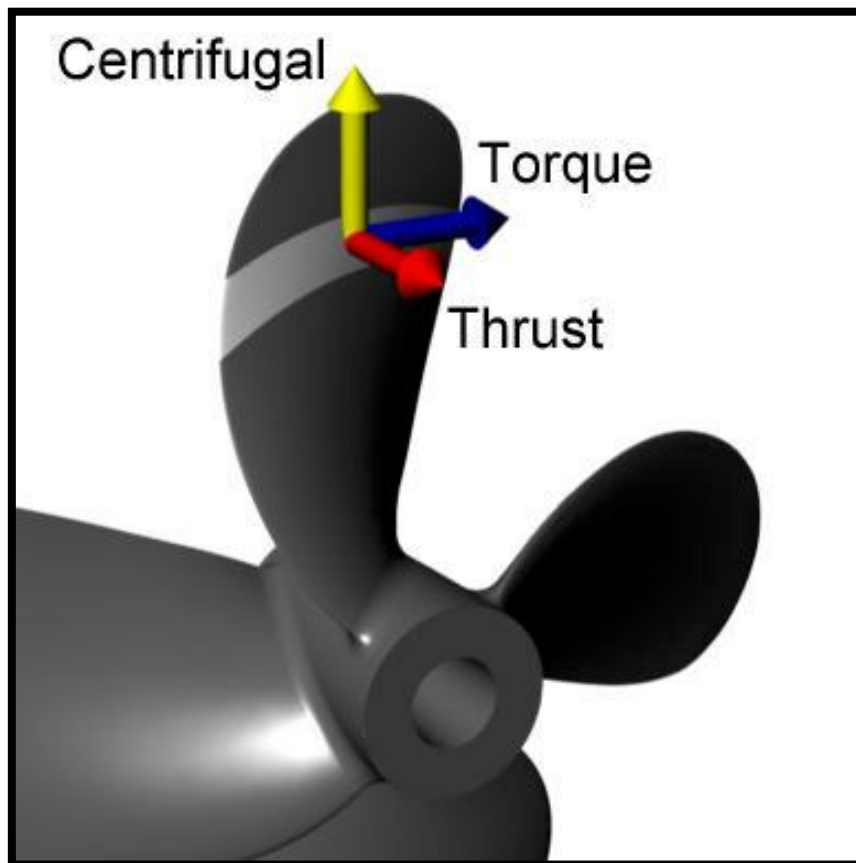


Figure 27. Typical Propeller Forces (HydroComp, 2022)

5.1. Prototype Testing

Manipulated variables must be constrained to that of the simulation. Regional standards are discussed in section 6.0. which state a cantilever-beam method can be used for deflection testing. Numerical calculations for this method utilise the formula:

$$y_{Max} = \frac{-WL^4}{8EI}$$

Table 13. Variable Descriptions

y_{Max}	Maximum Deflection [Metres (m)]
W	Force [Newtons (N)]
L	Length (m)
EI	Flexural Stiffness (Nm^2)

This is for a simple beam, thus, with a propeller's complex geometry, the regulations suggest bending moment calculations such as:

$$M_{th} = \frac{D \cdot Th}{2Z} (r_t - r_{root}) \cos \cdot \theta$$

Table 14. Variable Descriptions

M_{th}	Bending moment due to propeller thrust (Nm)
Th	Propeller thrust [N]
r_t	Radial location of resulting load [-]
r_{root}	Relative radius at root section (-)
θ	Pitch angle (degrees) at the root section
D	Entire Propeller Diameter
Z	Number of Blades

The calculation is for the entire propeller, with a derivation of deflection being required, thus, should be used for reference only (DNV 2015, p.18).

A cantilever method could be performed, attaching a blade to a hub, and evenly sectioning 5kN over the blade as figure 28 shows. Table 15 shows the boundary conditions.



Figure 28. Cantilever Loading Method (Kumar, Krishna and Subramanian, 2018)

Table 15. Cantilever Method Boundary Conditions

Boundary	Conditions
Length of Mass	5kN UDL over the entire length
Sections	An equal number of sections over the length
Mass	Each section will have the same calibrated mass equal to a total of 5kN
Propeller Support	The propeller will be supported allowing for the propeller to be horizontal, allowing for mass to act directly towards before deflection.

However, the cantilever method is difficult to produce an accurate UDL, due to each mass acting as a large point load. Also, the mass attachments may influence the stiffness of the blade, preventing accurate results.

Therefore, a Full-Scale Cavitation Tunnel shown in figure 29 is proposed, with the boundary conditions shown in table 16.

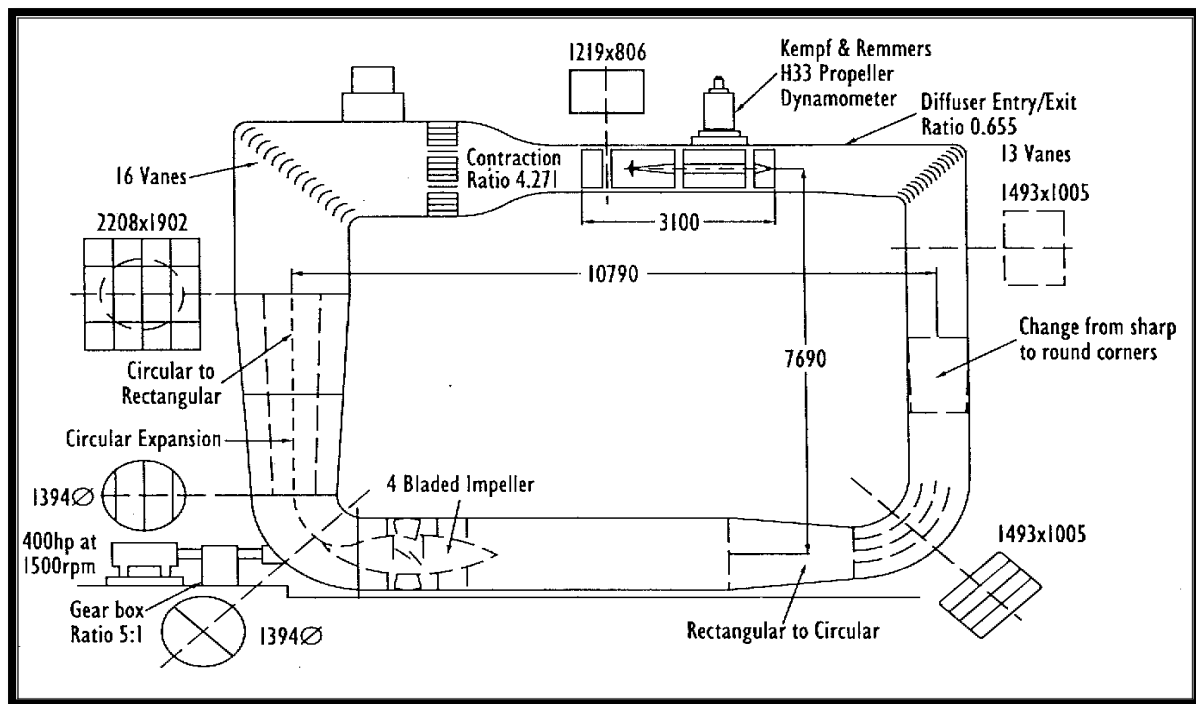


Figure 29. Full-Scale Cavitation Tunnel (SINTEF, 2022)

Table 16. Cavitation-Tunnel Method Boundary Conditions

Boundary	Conditions
Water Flow Rate (u)	Set and Constant (Based on Required Force)
Fluid density (ρ)	Set at Saltwater Density (1027 kg/m^3)
Fluid Temperature	Set and maintained at 10°C
Propeller Diameter	Fixed
Propeller Blade Length and Orientation	Fixed
Propeller Blade Pitch	Fixed with the face perpendicular to fluid flow
Material	Fixed material for Drag Coefficient
Propeller Rotation	Fixed

A full-scale tunnel prevents scaling errors, whilst forced fluid flow perpendicular to the blade face provides an accurate UDL. The tunnel will use an impeller, forcing fluid around the tunnel, creating fluid force on the blade face.

Contingencies must be considered for accuracy. Accurate fluid (water) force must be obtained to achieve 5kN. The formula for this is:

$$F = \frac{A \cdot C_d \cdot \rho \cdot u^2}{2}$$

Table 17. Variable Descriptions

F	Force (N)
A	Area (m^2)
C_d	Drag Coefficient
ρ	Density (kg/m^3)
u	Velocity (m/s)

This should be utilised for reference with more study done, due to complex propeller geometry. However, this would allow one to understand the rate of fluid flow required to generate 5kN. This combined with preventing propeller rotation will mimic the simulation without additional forces.

For reassurance, calibration can be carried out, by placing a 5kN UDL on a simply supported beam with similar dimensions to the propeller. A strain gauge attached to the beam will convert electrical current into a force measurement.

A similar beam with a strain gauge, calibrated on the cantilever beam (Newly manufactured to limit material fatigue) will be placed in the tunnel with fluid flow being increased until a reading of 5kN is achieved. Combined with the force formula, an accurate understanding of the flow rate can be achieved.

The propeller blade will be supported in the tunnel at the root, connected by a hub, with fluid flow producing the force required to achieve 5kN. Propeller deflection will be measured utilising Stereo Digital Image Correlation (S-DIC), shown in figure 30. This image-based, non-contact technique allows for data collection for object displacement and deformation which can be easily and accurately compared to the FEA model (Dong, Zeng and Pan 2019, p.4726).

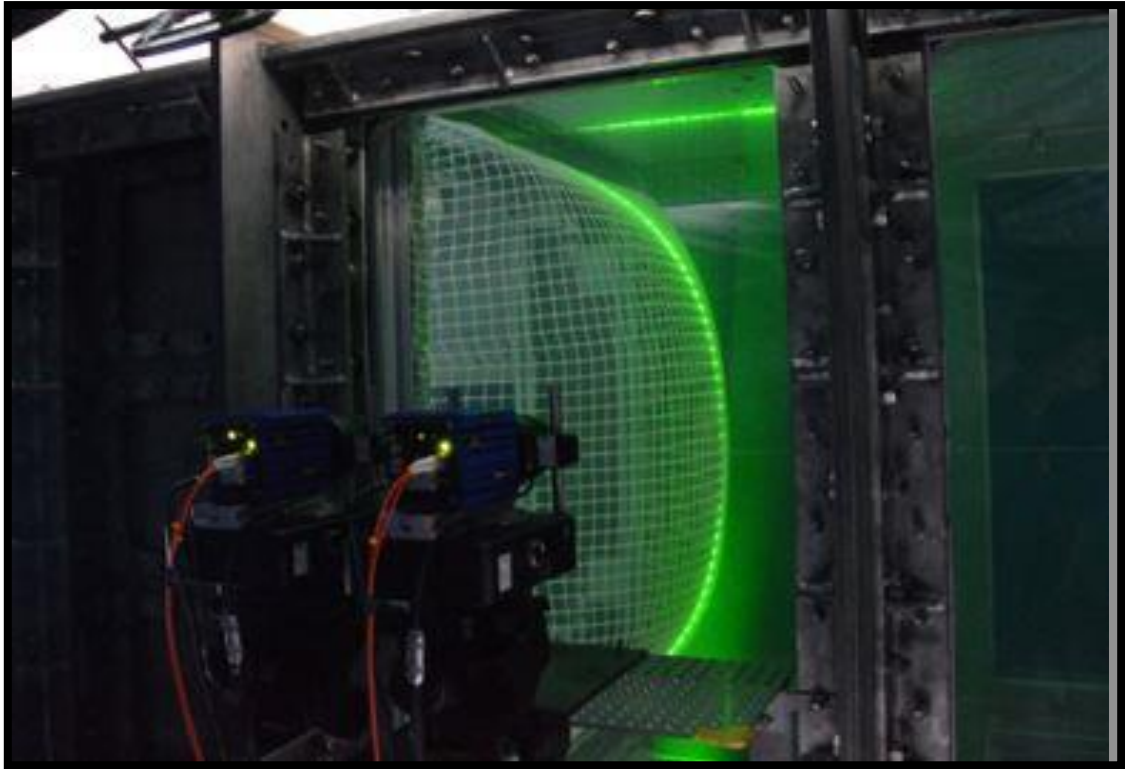


Figure 30. Stereo Digital Image Correlation (S-DIC) Testing Equipment (Cavitation Tunnel, 2022)

Some systems utilise reflective laser beams, allowing accurate deflection detection. Markers can also be used shown in figure 31, utilising imagery to compare set points across the blade, thus, analysing changes through computational methods with accuracies of 4 microns (Savio, 2015, pp.1-13).

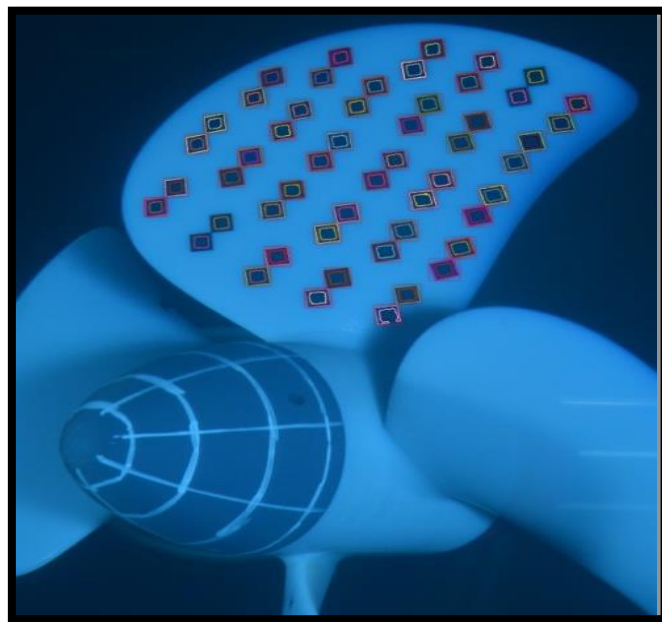


Figure 31. S-DIC Imaging Markers (Savio, 2015)

Further reassurance can be obtained from a strain gauge attached to the propeller, and compared with the calculation and cantilever method, with a standard deviation graph to create an accurate estimation of deflection. Both the strain gauge results and S-DIC results can be compared with the FEA through data analysis, comparing their stiffness-to-weight ratios.

Accuracy of mass can also be achieved within the tunnel, as one can utilise the displacement of water to calculate the propeller mass, however, the attachments must be negated.

Conversely, the cavitation tunnel can only be completed with enough time and resources, which is a limiting factor to this experiment, albeit more accurate. Furthermore, depth may impact the pressure on the propeller, thus, the test can be performed in multiple orientations to generate a further standard deviation, thus, allowing one to further incorporate this deviation into the results for increased accuracy.

6.0. Design Comparison

The International Organisation for Standardisation (ISO) set guidelines for which regional Maritime Standards are found. Safety Standards for propeller design and testing are within **Rules for Classification, Part 4, Systems and Components, Chapter 5, Rotary Machinery-Driven units** (DNV 2017, pp. 8-18). Propeller calculations are located under **Class Guidelines, Calculation for Marine Propellers** which are utilised for the design within this report, however, adapted for thrust force (Perpendicular to Blade Face) analysis only (DNV 2015, pp. 5-21).

Table 18 shows guidelines for propeller material properties. There are no standards for CFRP, however, it would likely meet regulations based on the guidelines set, with table 19 showing CFRP having greater properties compared with typical materials used for propellers.

Table 18. Typical Propeller Material Properties (DNV, 2017)

Material	Material constant U_1 [N/mm ²]	Material constant U_2 [-]	Minimum yield strength σ_y [N/mm ²]	Minimum tensile strength σ_B [N/mm ²]
Mn-Bronze, CU1 (High tensile brass)	55	0.15	175	440
Mn-Ni-Bronze, CU2 (High tensile brass)	55	0.15	175	520
Ni-Al-Bronze, CU3	80	0.18	245	590
Mn-Al-Bronze, CU4	75	0.18	275	630
Martensitic stainless steel (12Cr 1Ni)	60	0.20	440	590
Martensitic stainless steel (13Cr 4Ni/13Cr 6Ni)	65	0.20	550	750
Martensitic stainless steel (16Cr 5Ni)	70	0.20	540	760
Austenitic stainless steel (19Cr 10Ni)	55	0.23	180	440
Forged steel and other materials shall be especially considered.				

Table 19. CFRP Vs Typical Propeller Material Properties (Kumar, Krishna and Subramanian 2018)

MATERIAL PROPERTIES	CARBON FIBRE (Unidirectional)	ALUMINIUM ALLOY	NICKEL ALUMINIUM BRONZE	MANGANESE BRONZE
Youngs modulus (GPa)	120-220	68-72	122-130	110-120
Tensile strength (MPa)	800-1500	270-330	550-660	410-490
Density (gm/cm ³)	1.35-1.85	2.65	7.55	8.22
Thermal Conductivity (W/m.K)	20	117	42	80
Low coefficient of Thermal Expansion x10 ⁻⁶ (Inch/inch degree Fahrenheit)	-1 to 8	7-13	9	12
Poisson ratio	0.27	0.33	0.32	0.34

Within **Rules for Classification**, safety factors are required for propellers for given circumstances as table 20 shows (DNV 2017, p.14).

Table 20. Safety Factors (DNV 2017)

Application	Considered Section	Load condition		
		Static	Low cycle fatigue	High cycle fatigue
All propellers, exclusive tunnel thrusters	At root section	-	-	1.8
	At 0.6R	-	-	1.6
Reversible direction of rotation, exclusive tunnel thrusters	At 0.8R	-	1.5	-
Tunnel thrusters	At root section	2.2	-	-

The analysis within this report did not incorporate safety factors due to excessive optimisation. However, without safety factors, deflections greater than specified may occur, due to manufacturing defects, material impurities, additional forces like vibration and so on. Therefore, consideration is required, such as utilising a 2.2 safety factor, thus, the design would be constrained to 45.45mm or an applied UDL of 11kN would be utilised, and then optimised. Regulations state the design must conform to fatigue strength, whereby no deformation occurs before 10^7 cyclic loading at a bending frequency of no higher than 5Hz (DNV 2017, p.13).

The calculation for reference is:

$$U_1 = \frac{U_{E7}}{1.3} - 2 \cdot \sigma_{E7}$$

Table 21. Variable Descriptions

U_1	Fatigue Properties in Seawater
U_{E7}	Average Fatigue Amplitude (N/mm^2) up to 10^7 cycles with zero mean stress
σ_{E7}	Corresponding Standard Deviation (N/mm^2)

Nickel Aluminium Bronze (NAB), a typical material for propellers, has a strength of 255 MPa at 10^8 cycles. CFRP has a fatigue strength of 800-1500 MPa at 10^8 cycles, indicating this would likely meet regulation (DNV 2017, p.12).

Regulations state root fillets should be applied approximately 5% up the blade length as figure 32 shows. The software does not allow for accurate placement, thus, 5% cannot be guaranteed within this analysis, which may affect deflection results (DNV 2015, p.5).

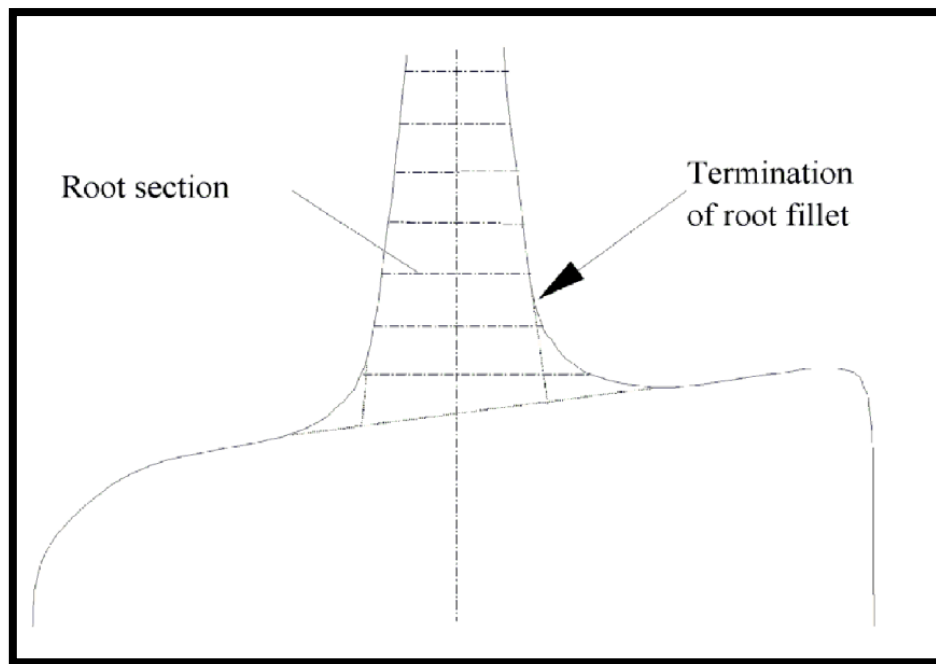


Figure 32. Typical Propeller Fillet (DNV 2015)

Dimensional requirements are stated within Tolerance Class ISO 484-1:2015 (en), however, they require financial purchase, therefore, the maximum and minimum thickness requirements for propellers above 2.5m cannot be stated. The propeller within this report is optimised to 15.5mm, therefore, further research is required. As the design meets specifications, it is likely to meet regulations, although a surveyor must be present when testing, with negated forces incorporated and safety factors included (DNV 2017, p.17).

The largest marine propellers in commercial use range from 4.7m to 9.1m, all made from metals. The propeller in this report is CFRP and approximately 5.96m in diameter. Large CFRP propellers are still under development without commercial use. **Fiberdyne** is developing large CFRP propellers that are yet ready for use. Pegorari (2018) and Kumar, Krishna and Subramanian (2018, pp.1-2) state CFRP properties exceed current materials, thus, have great industry potential. This report supports these statements, with CFRP optimisation exceeding steel.

Lin, Lai and Kuo (2010, pp.293-298) discuss optimum layer stacking angles, which Kumar, Krishna and Subramanian (2018, p.3) support, implementing 6 layers into a design at $0^\circ/-45^\circ/90^\circ/45^\circ/90^\circ/0^\circ$. Conversely, 90° is found to be the least optimal within this analysis, with 45° utilised to prevent layer separation whilst resisting some load. However, 90° directions are likely utilised for varied distribution of loads and forces such as centrifugal and torque,

therefore, further testing is required for these additional forces for deflection analysis differences based on layer directions.

Current technical literature focuses on CFRP Propellers less than 2.5m. Kumar, Krishna and Subramanian (2018) utilise a 0.125m propeller, where a 5.02mm tip deflecting occurs with a 483N UDL cantilever beam test. Their FEA simulation shows a 5.24mm deflection, indicating similar simulation and testing results. Their stiffness of 93N/mm is higher than 50.05N/mm in this report, however, their additional layer may cause this, although, ply thicknesses and quantity are not given, whilst mass is also not given; thus, stiffness-to-weight cannot be compared. Also, smaller propeller lengths reduce bending moment forces for the same total UDL, thus reducing deflection. However, results do not significantly differ, indicating the design within this report is similar to optimised designs in current literature.

7.0. Conclusion

FEA is valuable, advancing with computer power exponentially throughout history, allowing for advanced analysis and optimisation of structures, whilst conforming to specific constraints.

When optimised correctly, CFRP can be used for a propeller design, providing higher stiffness-to-weight ratios compared with traditional materials like steel. Constraints such as manufacturing methods must be included which alter these results, although proving to still have ratios 580.27% higher than steel.

Although being developed with small-diameter propellers, CFRP is yet to be utilised for large marine applications. Although its' properties exceed that of traditional materials, more investigation is required into propellers larger than 2.5m, expanding on this research, whilst understanding if they fully meet marine regulations.

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