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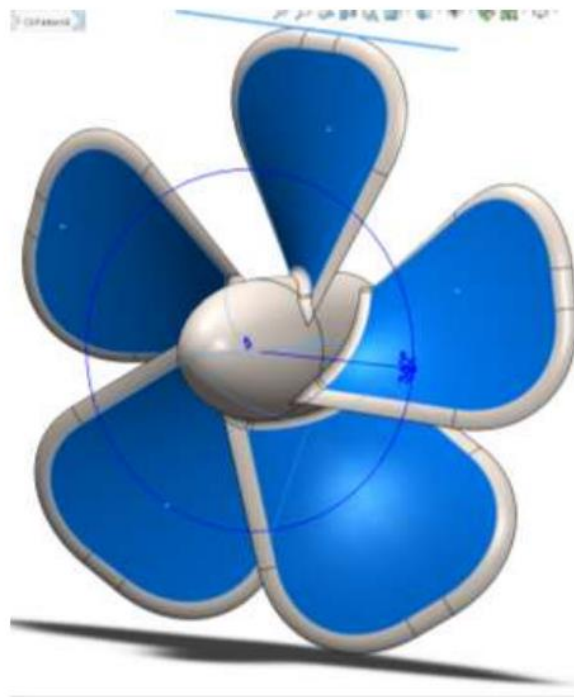
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University of Wales Trinity Saint David

School of Engineering

Designing a tanker propeller:

Structural Design



Structural & Fluid Analysis

ACMA6010

Assignment 2

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1 Introduction

Following the fluid analysis and design of the tanker propeller blade this report analyses the structural properties of the blade, specifically focusing on optimisation of the propeller blade using FEA software Design Studio.

A baseline steel structure had been created using Solidworks 3D, using the steel baseline design and geometry the propeller blade was converted to produce a unidirectional (UD) carbon fibre reinforced plastic (CFRP) version.

The design parameters were defined to optimise the blade, the aim was to minimise the mass of the structure whilst ensuring a maximum deflection of 100mm, the variables consisted of the number of ply's within each layer.

1.1 Aims

The aim will be to optimise the composite construction of the marine propeller blade, aiming to minimise the mass of the structure, whilst ensuring a maximum deflection of 100mm is maintained.

1.2 Objectives

The first objective was to ensure a maximum deformation of 100mm of the propeller blade.

The second objective was to reduce the weight of the propeller by using as little material as possible.

2 FEA Optimisation Techniques

2.1 NASTRAN

In the early 1960's NASA deployed engineers to develop their own FEA Optimisation Software to allow engineers to identify potential problems early in the design phase, these engineers came up with NASA Structural Analysis (NASTRAN) this was used to optimise early design of rockets such as the space shuttle. (Schmit, 1976) By 1970' NASTRAN was incorporated with MSC.

2.2 Early Design Optimisation

After the establishment of structural synthesis by the 1980's this had further developed into what was known as Multidiscipline Design Optimisation. This development lead to NASA investing a considerable amount into the research of the technology. (Schmit, 1976)

In the early 1980's optimisation began to find its way into commercial FE software including

- SDRC
- ANSYS
- RASNA
- MSC

By 1991 a structural optimisation program was released, this was called GENESIS.

It is now possible to solve structural problems far complex than previously imagined. Hundreds of thousands of design variables and millions of constraints.

2.3 Future of Design Optimisation Methods

Design optimisation and FEA will continue to support product design from a wide range of sectors. These methods are continuously improving and it is possible to predict behaviour with greater accuracy than ever before. Developments in high performance computer technology will promote better reliability in solving problems and may remove the potential for physical testing as the technology grows.

Design optimisation and FEA was originally only available to the likes of NASA to support the design of spacecrafts and associated components. this is now available and supports the design stages of many performance sectors including; aerospace, medical, marine, construction, defence, textile, & nuclear.

2.4 Optimisation Improving the Design & Engineering Applications

Optimisation techniques have been used within engineering to Improve performance of mechanical structures, systems & devices, design engineers are able to determine design parameters which leads to the best performance.

As the global economic problems continue to grow, the world starts to recognise the importance of conserving resources design optimisation techniques go a long way to support this. These techniques will continue to promote the design and production of innovative, highly efficient and more reliable products.

3 Steel Blade – Baseline Model

A single analysis was conducted on the steel baseline to assess its performance under loading with the deflection monitored.

- Force (f) = 5 KN
- Mass (m) = 646.7 KG
- Thickness (t) = 0.01 M
- Deflection (x) = .22 M

Stiffness, $k = f/x = 5000/.22 = 2272.27 \text{ N/M}$

Stiffness/weight = $k/(mg) = 2272.27/(646.7 \times 9.81) = 3.582 \text{ N2/M}$

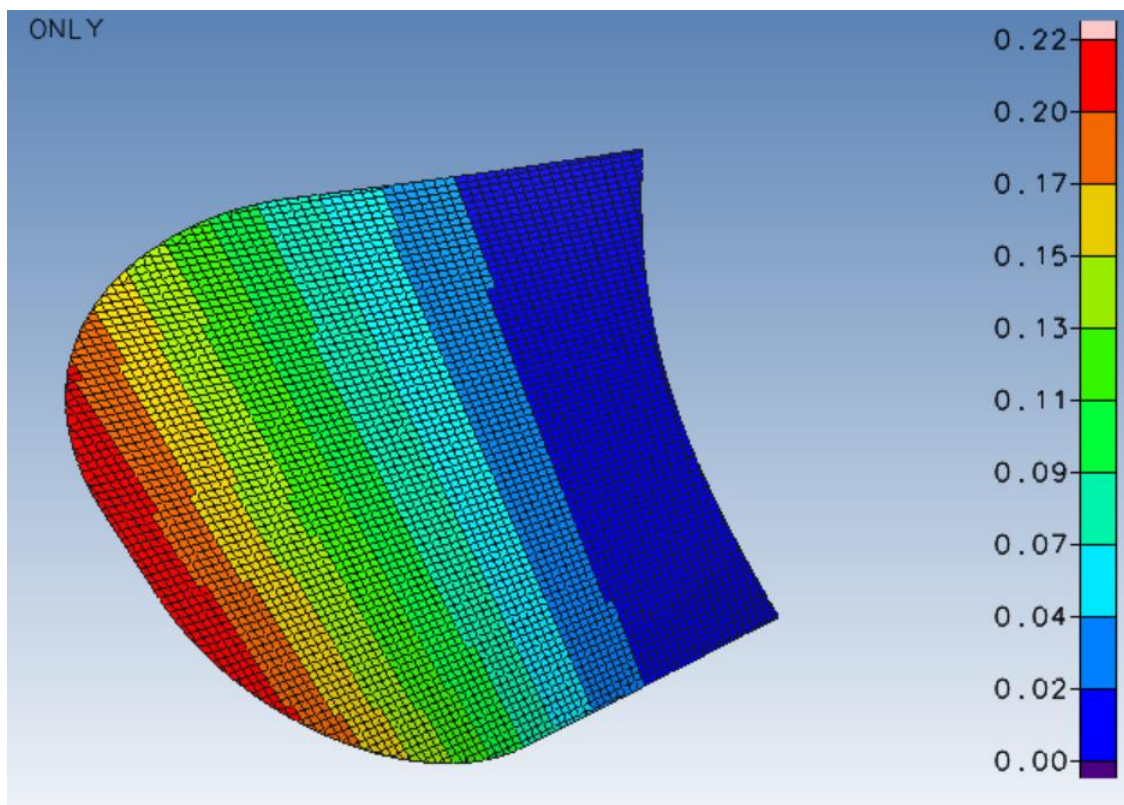


Figure 1: Steel Baseline - Deflection Under Load

4 Unidirectional CFRP Blade - Design Studio

4.1 Initial Actions

The steel baseline propeller blade was imported into design studio as a dat file. The initial actions was to create a new file and change the material properties form steel to carbon fibre reinforced plastic.

4.2 Material Properties - CFRP

The material properties of CFRP are different from metallic materials such as steel they have different mechanical properties in different directions this is known as Anisotropic Material as described in (Hong, 2021) it is vital that the material properties are correctly entered at this stage.

Table 1 below shows the properties entered.

Material Properties of CFRP	Values
Young's Modulus in the longitudinal direction (E_1):	132 GPa
Young's Modulus in the lateral direction (E_2):	10.8 GPa
Poissons Ratio (Nu_12):	0.24
Inplane Shear Modulus (G_12):	5.65 GPa
Transverse Shear Modulus (1-Z plane)(G_1z):	5.65 GPa
Transverse Shear Modulus (2-Z plane)(G_2z):	5.65 GPa
Mass Density (Rho):	1540 kg/m ³
Allowable longitudinal stress in tension (Xt):	1513 MPa
Allowable longitudinal stress in compression (Xc):	1000 MPa
Allowable transverse stress in tension (Yt):	43.4 MPa
Allowable transverse stress in compression (Yc):	43.4 MPa
Allowable inplane shear stress (S):	43.4 MPa

Table 1: Material Properties of CFRP

4.3 Vector Orientation

Once the CFRP material properties have been defined the elements needed to be orientated relative to the vectors. This is important as the material properties are no longer isotropic and are now considered anisotropic. Figure 3 below shows the vectors pre alignment and Figure 4 post alignment with vectors running zero degrees.

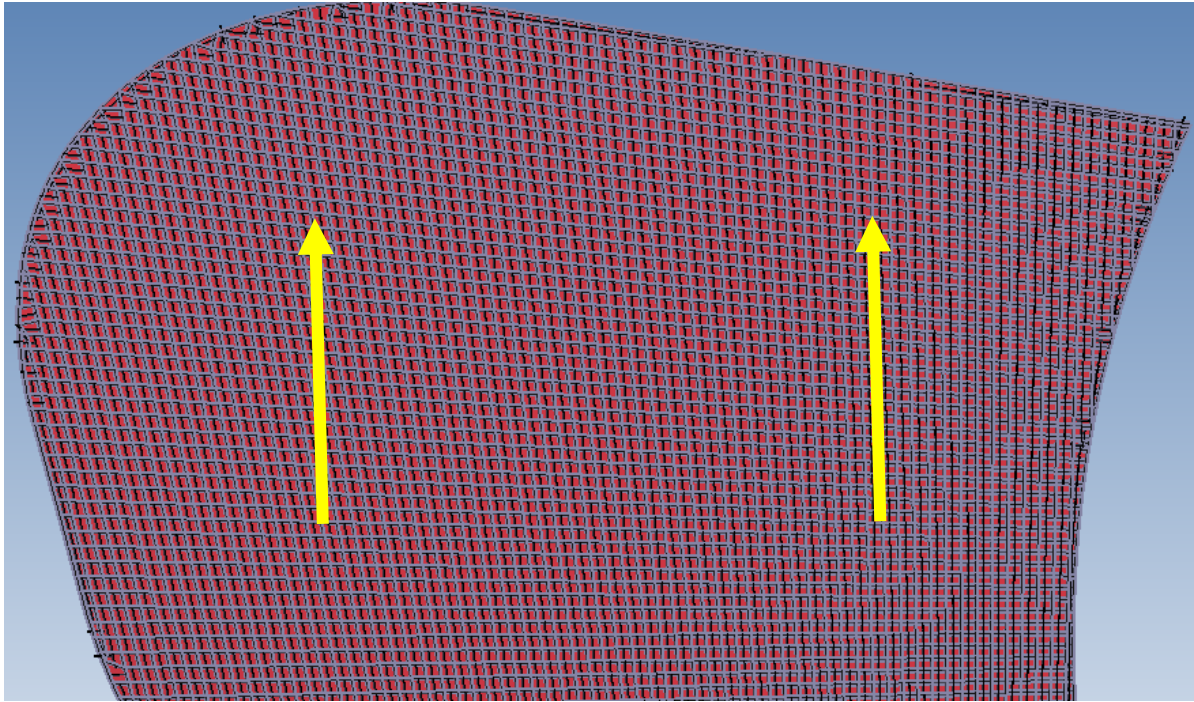


Figure 2: Original Vector Orientation

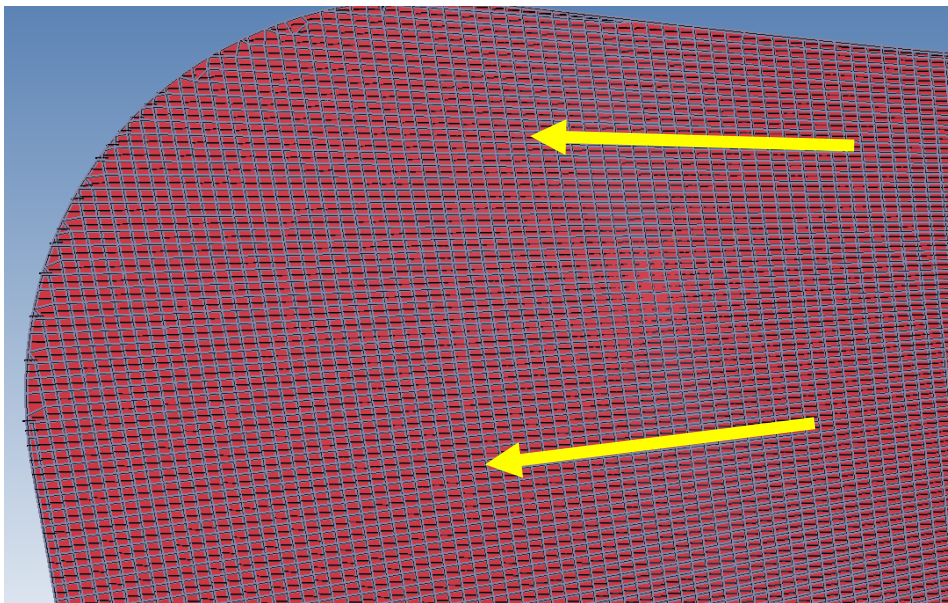


Figure 3: Vectors Running Zero Degrees As Defined

4.4 CFRP Layers

Once this had been defined the model layers were added. The layup consisted of 25 layers at 0.1mm thickness and the orientation of these layers consisted of 5 at -90 degrees, 5 ply's at -45 degrees, 5 ply's at 0 degrees, 5 ply's at 45 degrees and 5 ply's at 90 degrees.

Once this model had been fully defined and laid up the structure was tested to monitor the stress, strain and deformation of the CFRP propeller blade.

4.5 Results of Un-Optimised CFRP Blade

The newly laid up CFRP Propeller Blade delivered peculiar results firstly it was noted that the deflection of the blade amounted to a maximum deflection of 211 meters. The other results also concluded equally as dramatic results which initially caused confusion.

These results were difficult at first to understand, but important steps were taken to help understand what was causing the excessive deflection. When the CFRP Propeller Blade was laid up its total thickness of the 5 layers combined was 2.5mm and the load applied was 5000N. The high load on a thin propeller blade would simply cause the material to rupture as the yield point of the material has been passed.

As Design Studio is considered a linear solver, if the load passes the yield point of the material it will give an unusual/ inaccurate figure, but due to the scaling effect of the FEA it will still appear to be working. This issue highlighted the dangers of using such software, this lack of understanding could lead to catastrophic failures early in the design stages of new components.

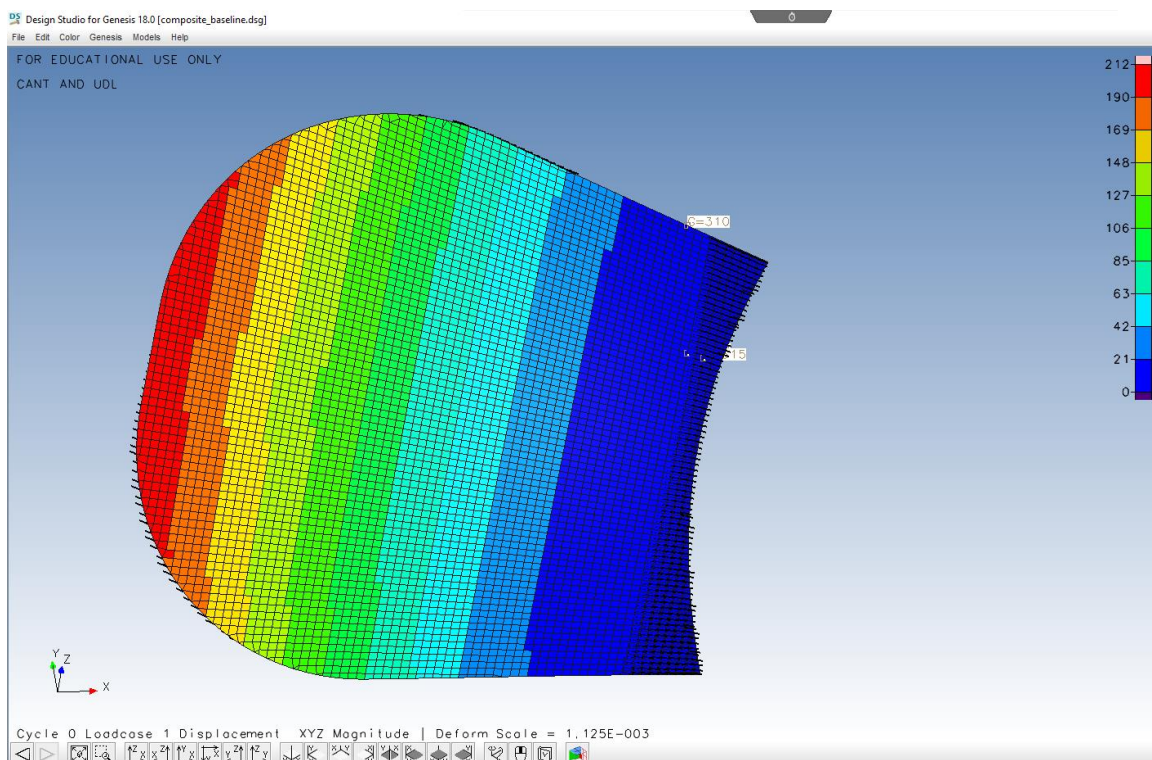


Figure 4: Maximum Deflection of Unoptimised CFRP Blade (212M)

5 Optimised CFRP Propeller Blade

5.1 Objectives, Variables & Constraints

When optimising a structure such as a propeller blade it is critically important to clearly define 3 parameters which include; Objectives, Design Variables, Constraints. For this investigation the parameters were defined as shown in Table 2 below.

Objectives:	Minimise the mass of the propeller blade
Variables:	Number of ply's in each orientation
Constraints:	Maximum deflection of 100mm

Table 2: Objectives, Variables & Constraints

A new file was saved of the CFRP blade structure calling it optimised, the optimised design parameters were then set within design studio.

A new design objective was set to minimise mass.

The constraint was set to displacement and the upper bound defined as 0.1M

And finally the design variables were set for each of the five layers, here it was defined that each of the layers could be made up to a 100mm in thickness this was to ensure that the model would be able to fully optimise without violating the constraints, by allowing 100mm thickness for each would mean that each layer could have 1000 ply's in each orientation.

Variable Name	Initial Value	Lower Bound	Upper Bound	Description
L1THK	0.5mm	0.1mm	100mm	Layer 1 thickness
L2THK	0.5mm	0.1mm	100mm	Layer 2 thickness
L3THK	0.5mm	0.1mm	100mm	Layer 3 thickness
L4THK	0.5mm	0.1mm	100mm	Layer 4 thickness
L5THK	0.5mm	0.1mm	100mm	Layer 5 thickness

Table 3: Design Variables of CFRP Propeller Blade

The structures objectives, variables and constraints had been defined at this point and was ready for optimisation.

5.2 Optimised Blade Analysis

Once the 3 parameters had been defined and set on Design Studio it was time to fully optimise the structure. On running the optimise function the mass of the blade increased rapidly as expected this is due to the FEA solver firstly ensures the blade doesn't deflect by 100mm it increases its layers to

increase the stiffness. The blades mass increased from an initial value of 32.3kg up to a maximum 272.1kg at this point the constraint violation was at 0% at cycle 7 which meant that the blade no longer deflects by more than 100mm. From this point the software worked to fully optimise the blade and reduced the mass to a minimum value of 207.3kg after 14 cycles. This action can be seen in Table 4 & Table 5 below.

DESIGN CYCLE HISTORY		
DESIGN CYCLE	OBJECTIVE FUNCTION	MAXIMUM CONSTRAINT VIOLATION
0	3.2334E+01	999.9%
1	4.7783E+01	999.9%
2	7.0963E+01	999.9%
3	1.0431E+02	999.9%
4	1.5095E+02	999.9%
5	2.1001E+02	305.6%
6	2.6423E+02	42.1%
7	2.7208E+02	0.0%
8	2.4298E+02	0.0%
9	2.2411E+02	0.0%
10	2.1461E+02	0.0%
11	2.1031E+02	0.0%
12	2.0856E+02	0.0%
13	2.0765E+02	0.0%
14	2.0745E+02	0.0%

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Table 4: Design Cycle Showing Mass Optimisation

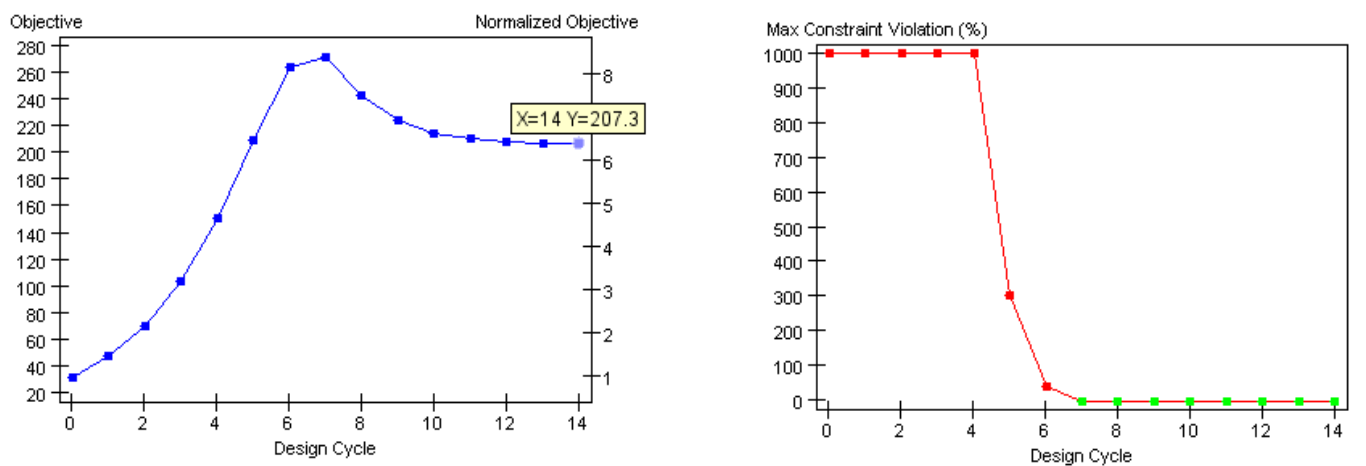


Table 5: Graphs Showing Design Objectives & Constraint Violation During Optimisation

5.3 Displacement – Optimised Blade

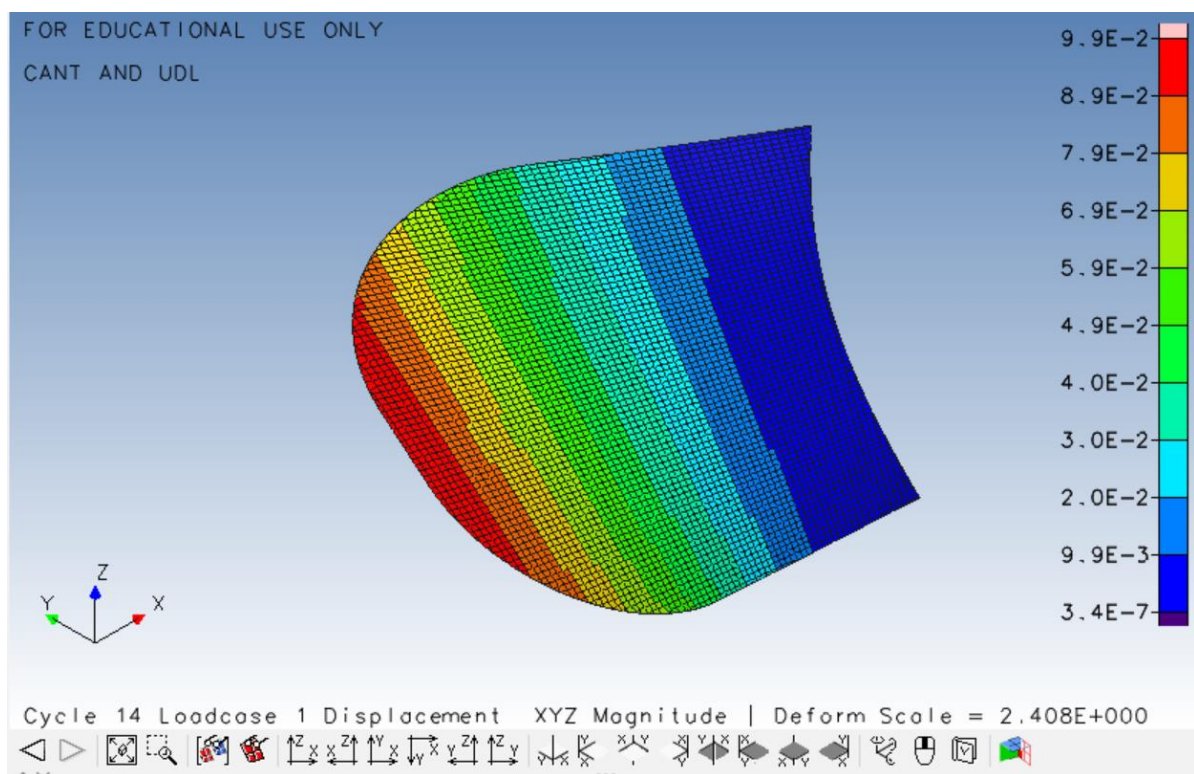


Figure 5: Displacement - Optimised CFRP

5.4 Stress – Optimised Blade

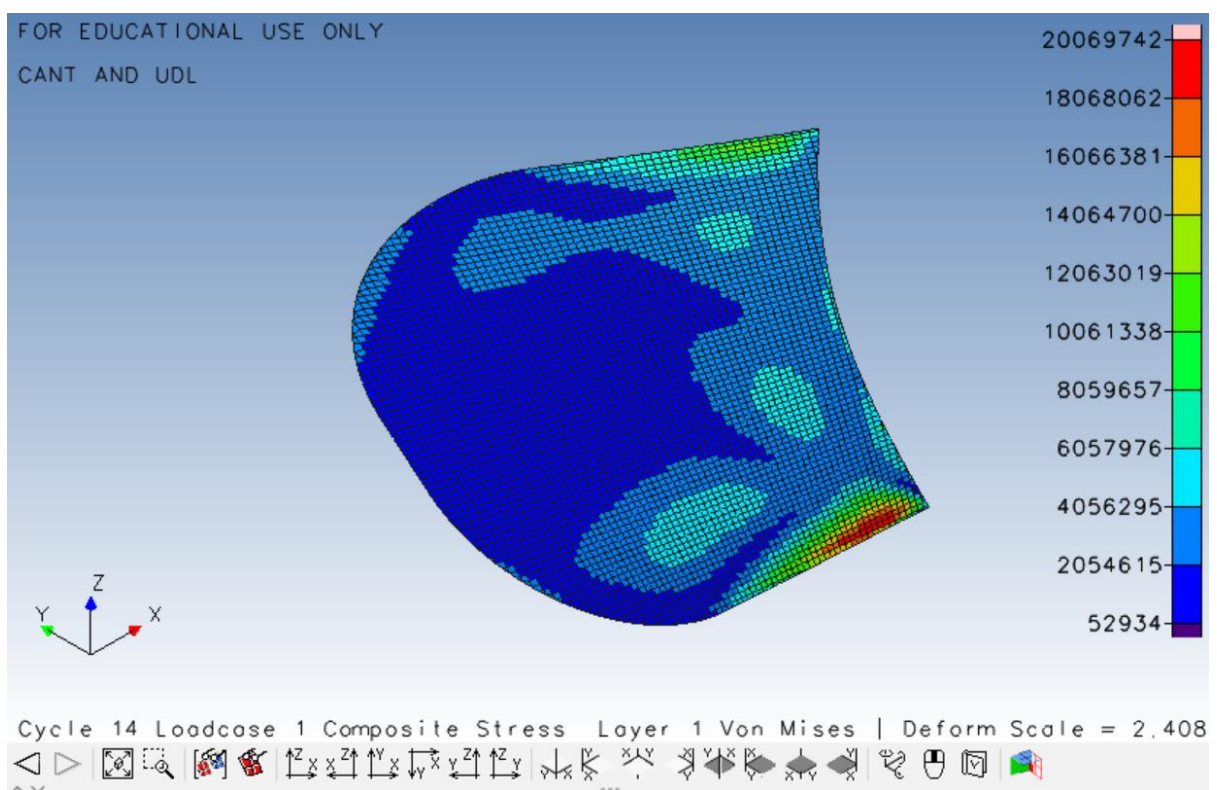


Figure 6: Stress - Optimised CFRP

5.5 Strain – Optimised Blade

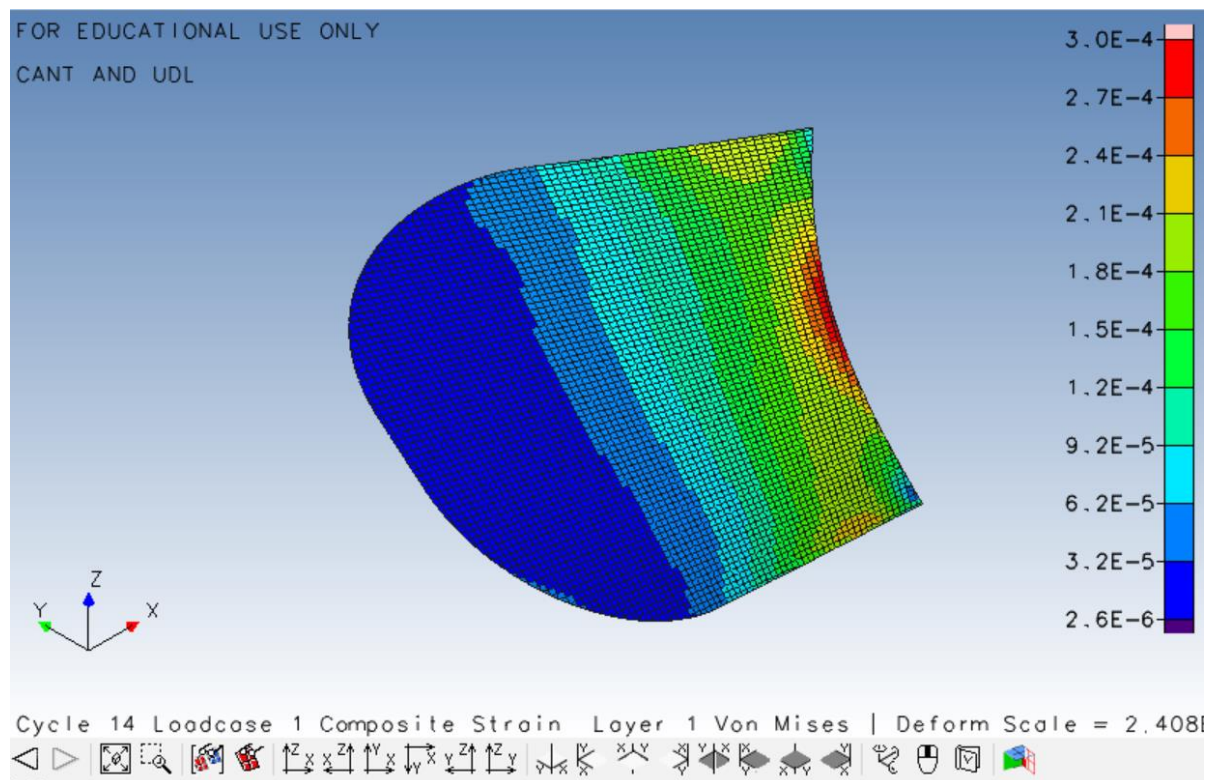


Figure 7: Strain - Optimised CFRP

5.6 Layer Thickness Optimised

The optimised Layers eventually as expected ran to a maximum on L1THK3 which in total amounted to 15.6mm the remaining layers ran to the minimum level which was set at 0.1mm. giving a total thickness of 16mm. The base of the blade connects to the centre so can be assumed to be a cantilever. This was predicted as the most strength from the UD CFRP comes from this orientation.

Table 6 below refers to the layer thickness of each blade for each cycle. It is worth noting that there is an increase to all layers before full optimisation has taken place, this explains why the mass of the blade increased to the maximum point. Eventually all layers bar L1THK3 run to the minimum allowable thickness as defined This can be observed in Table 7 below. We know this blade has been assumed to be a cantilever and the strength of the CFRP layers runs in the zero degrees hence why the layer thickness increased in this way.

DESIGN VARIABLE HISTORY					
DESIGN CYCLE	DESIGN VARIABLE 1 L1THK	DESIGN VARIABLE 2 L1THK2	DESIGN VARIABLE 3 L1THK3	DESIGN VARIABLE 4 L1THK4	DESIGN VARIABLE 5 L1THK5
0	5.0000E-04	5.0000E-04	5.0000E-04	5.0000E-04	5.0000E-04
1	6.6053E-04	7.6342E-04	8.3694E-04	7.3414E-04	6.9951E-04
2	8.9278E-04	1.1566E-03	1.3660E-03	1.0775E-03	9.9384E-04
3	1.0655E-03	1.7539E-03	2.4077E-03	1.5249E-03	1.3132E-03
4	1.1794E-03	2.5436E-03	4.2885E-03	2.0244E-03	1.6355E-03
5	1.1935E-03	3.4095E-03	7.4124E-03	2.4010E-03	1.8211E-03
6	9.6864E-04	3.7846E-03	1.1762E-02	2.2806E-03	1.6345E-03
7	5.7885E-04	3.0609E-03	1.4872E-02	1.5098E-03	1.0155E-03
8	2.9820E-04	1.9774E-03	1.5315E-02	7.3963E-04	4.5642E-04
9	1.3176E-04	1.1807E-03	1.5490E-02	3.3515E-04	1.9094E-04
10	1.0061E-04	6.5540E-04	1.5611E-02	1.2564E-04	1.0069E-04
11	1.0073E-04	3.7818E-04	1.5581E-02	1.0000E-04*	1.0068E-04
12	1.0000E-04*	2.1839E-04	1.5607E-02	1.0000E-04*	1.0000E-04*
13	1.0000E-04*	1.3294E-04	1.5622E-02	1.0000E-04*	1.0000E-04*
14	1.0000E-04*	1.0000E-04*	1.5640E-02	1.0000E-04*	1.0000E-04*

Table 6: Design Variable History

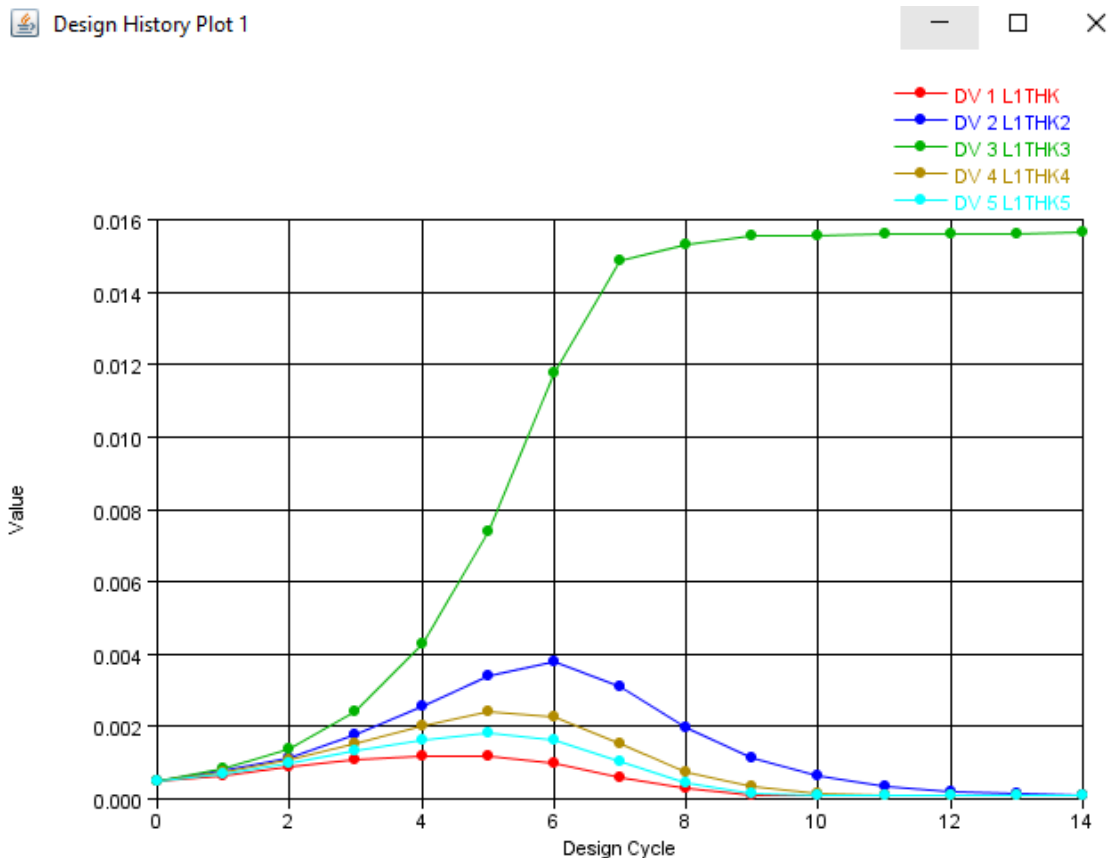


Table 7: Design Variable Graph Showing Optimised Layer Thickness

5.7 Mass Volume Optimised Blade

A single analysis was conducted on the steel baseline to assess its performance under loading with the deflection monitored.

- Force (f) = 5 KN
- Mass (m) = 207.3 KG
- Thickness (t) = 0.016 M
- Deflection (x) = 0.099 M

Stiffness, $k = f/x = 5000/207.3 = 2.412 \text{ N/M}$

Stiffness/weight = $k/(mg) = 2.412/(207.3 \times 9.81) = 0.00119 \text{ N}^2/\text{M}$

6 FEA Discussion

6.1 Grid Component Set

Despite engineers being able to yield accurate results that tend to be comparable with physical testing, there are some limitations which don't always compute with physical testing. Given this propeller blade as an example in this structure we have considered this to be infinitely ridged at the point at which the blade is secured. So what was considered here is that there will be no movement or minor deflection at the propeller fixing point. This is unlikely to be the case and we would expect that the edge of the blade to have some movement under loading albeit minor. Further to this the blade will require a mechanical device to secure to the propeller hub this will affect performance as there will be an increase localised stress.



Figure 8: CFRP Blade Secured at the Hub (ClasNK, 2021)

6.2 Vector Dislocations

Some of the vectors despite lining up with the zero axis have dislocated joints which don't run exactly true, this can have a minor effect on results but not excessive in this example because the line runs true through the centre and the maximum deflection will be based at the tip of the blade. These dislocations could be avoided and help yield better results if the number of elements were increased.

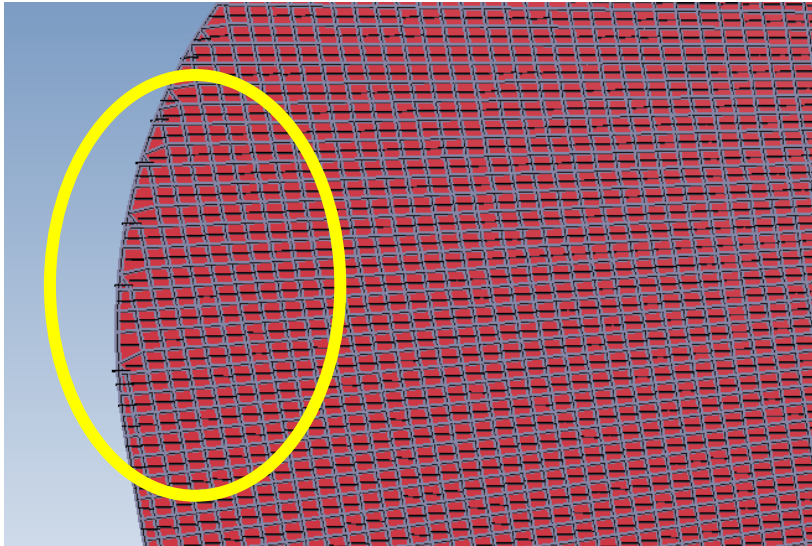


Figure 9: Vectors Aligned with Minor Dislocations on the Edges

6.3 Human Error Factor

During the experiment the wrong checkbox was selected when setting the design objectives, the maximum box was selected, this resulted in the objective rapidly rising to its maximum using as many layers defined as shown in Table 8. This error highlights some of the dangers with this software that despite its increase in popularity and more widely available it can result in poor results if poor use and application of FEA (Hearn, 1997).

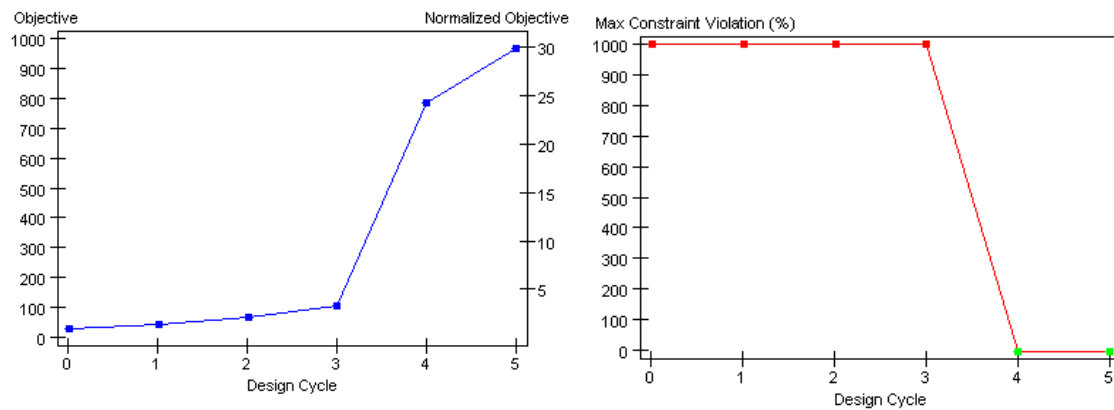


Table 8: Errors Made Setting Design Objective

7 Prototype Blade

7.1 Testing

It was proposed that after optimising the blade a prototype is produced and physical testing conducted to validate the performance of the FEA model.

The prototype blade was tested in laboratory conditions. There are several tests which could be performed to check overall performance but to help correlate the FEA model a static load test was deemed the most suitable to ensure full validation.

The load on the FEA Model is distributed over 4951 elements and 1N is applied to each node as seen in figure 8 and therefore it can be treated as a uniformly distributed load with a total load applied is 4951N.

The model was kept as a UDL to ensure the loading remained the same for verification purposes and to maintain testing standards however it would be expected that the load will not be perfectly uniformly distributed across the blade as it is known from assignment 1 that the blade distributes high pressure and low-pressure regions and we'd expect cavitation to form along the outer rear edge. It is known that the loading of marine propellers is over 1000 times greater than that of aircraft propellers due to the water density which increases loading (Lukas Mark, 2021).

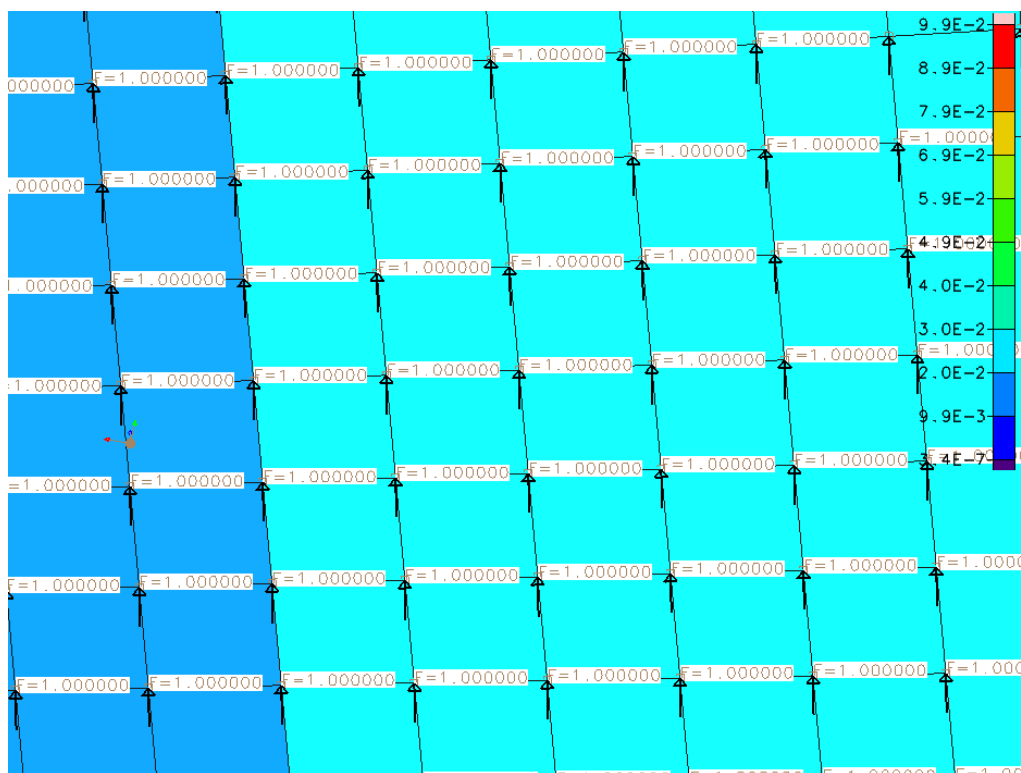


Figure 10: Force Applied to Each Node of the Propeller Blade - FEA Model

7.2 Prototype construction

To achieve the most accurate results on testing a full-size propeller blade was produced to reduce errors and simplify the calculations. The prototype was produced ensuring the orientation of the layers matched the Optimised blade on design studio. Ply's were arranged with visual inspection to ensure that the exact layup was produced. The Prototype propeller blade was constructed using a CFRP split mould. The model was scanned using a 3D scanner it is believed that this is the most reliable method to verify the geometry with the FEA. (Savio, 2017) To carry out the experiment the blade was mounted into a thick brass boss and supported horizontally in the X axis like a cantilever.

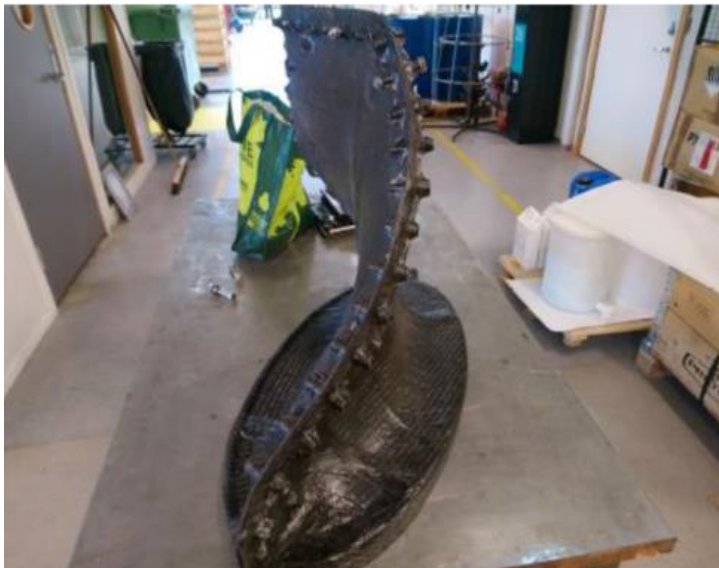


Figure 11: CFRP Split Mold (Lukas Mark, 2021)

7.3 Experiment Design & Data Acquisition

The node position was then overlayed onto the prototype and calibrated 1 Newton loads were applied to each location to mimic the FEA model load on design studio.

The prototype was then fitted with strain gauges and connected to a data acquisition device which sends the data to be displayed on the computer.

DIC cameras were fitted to monitor the displacement of the blade as the load was applied, for 3D imaging 2 DIC Cameras were fitted. This was the best method to monitor the displacement considering the size of the propeller blade. (Kurlov, 2013) This was also fitted a data acquisition device and relayed back to a computer. This method of non-contact monitoring will help reduce errors in testing. (Lukas Mark, 2021)

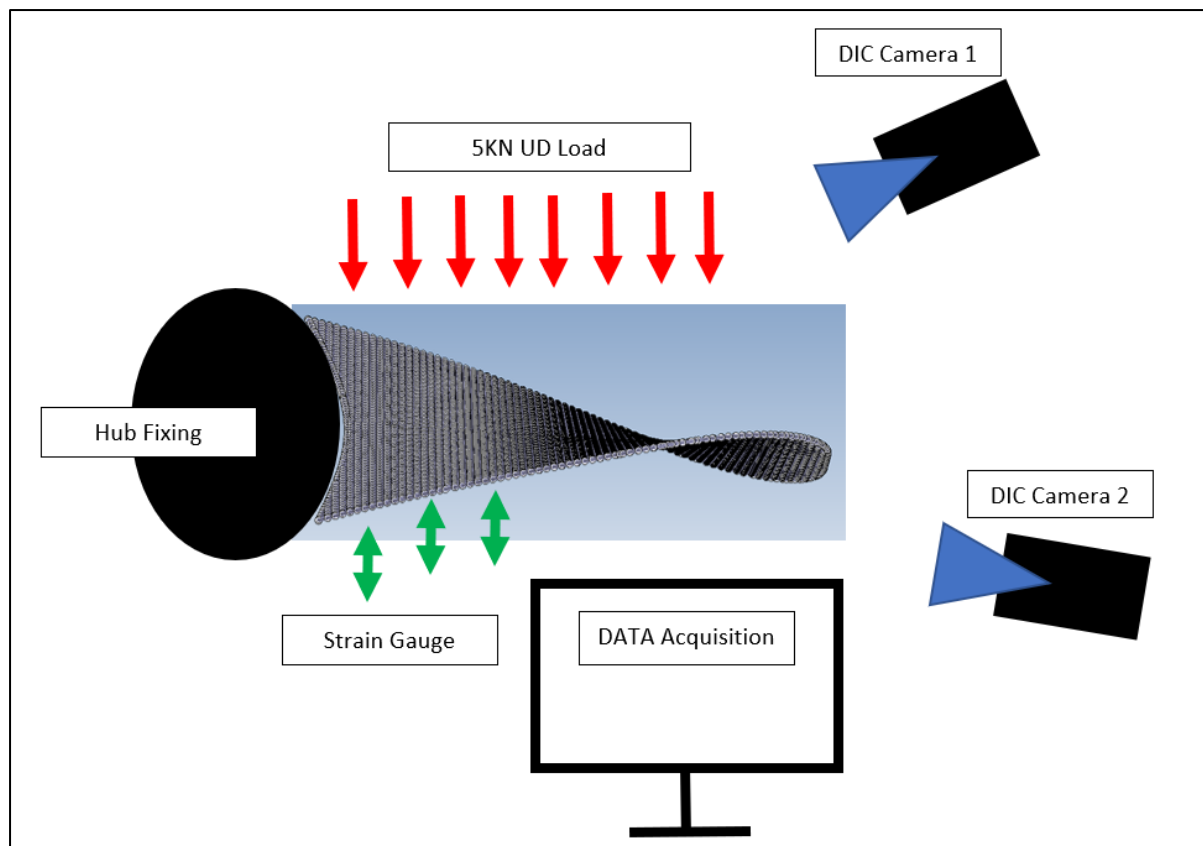


Figure 12: Prototype Test Method

8 CFRP Industry Standards

CFRP blades have advanced material properties which influence the efficiency, speed, cavitation reduction, reduced noise, damping and corrosion resistance. These properties make it an excellent choice for marine tanker propellers.

Composite material is susceptible to impacts and needs to maintain integrity on impact. It is known that marine propellers frequently collide with submerged debris such as ice, cables as well as collisions with the seabed and rocks.

During this experiment the propeller blade was optimised to reduce mass with a maximum deflection of 100mm. this was achieved but when considering other factors such as strength and impact resistance this would not be suitable for functionality as the layers are thick in zero degrees but thin in the other orientations, this would not be suitable for the marine environment, as the blades durability is a critical factor not just mass and deflection.

The impact behaviour of CFRP propellers is complex and are driven by many factors but for the design stage Layer thickness and stacking sequence is fundamental to the blade functioning. CFRP is prone to inter layer cracking which can lead to premature failures. It is said in Composites Part C Volume 8 the failure modes of composites are strongly dependant on stacking sequence and in particular. The inter ply angle. (Faisal Islam, 2022) The angle of the ply's strengthens the blade and allows more energy to be absorbed creating improved impact resistance.

The edge of the blade which is at most risk of damage can be protected by increasing the layer thickness of composite blades this improves impact resistance and offers better protection on the edge where delamination is most likely to occur on impact. (Faisal Islam, 2022)

There are many industry standards which ensure safety of marine propellers and ensures the delivery of high performing structures that are manufactured to the highest quality.

ClassNK have defined the requirements for all manufacturers of CFRP Propellers for the use in the maritime sector. They ensure that the blades meet the required standards. It covers many areas including material selection, testing requirements and manufacturing methods. This includes layer thickness and orientation. More information is found in The Guidance for the Approval and Type Approval of Materials and Equipment for Marine Use Part 4. (ClassNK, 2021)

Many other governing body including ISO, IMO and others influence the way marine propellers are produced and designers must ensure compliance with these if they are to be successful.

9 Conclusions

The first part of the report focused on the history of FEA and optimisation, the concept has been around for many years but under developed and limited by computational power. As computer technology develops design optimisation software will too. It will yield better results and further support design engineers, further promoting highly efficient and reliable components.

The initial experiment built understanding of what the software is capable of, when the blade was loaded with 5KN on a 2.5mm blade we simply couldn't solve this as design studio is a linear solver and cannot deal with non-linearity.

The blade was fully optimised, ensuring a maximum deflection of 100mm whilst minimising mass, further to this it is now understood that despite meeting these objectives other factors such as impact resistance and durability should be taken into consideration. It is now known that inter ply angle and thickness is crucial to developing a durable blade.

It is worth noting the human error aspect, it is known that if you put rubbish in you get rubbish out. These errors can be costly and is crucial that FEA analysis is conducted by highly skilled and experienced CAE engineers to avoid this.

FEA has a vital role to play in an ever-evolving world. Engineers and companies have a responsibility to reduce costs and improve efficiencies by making lighter stronger components using less material. As computational power is ever increasing with the availability of FEA software increasing there will be more reliance on FEA analysis and Optimisation techniques.

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