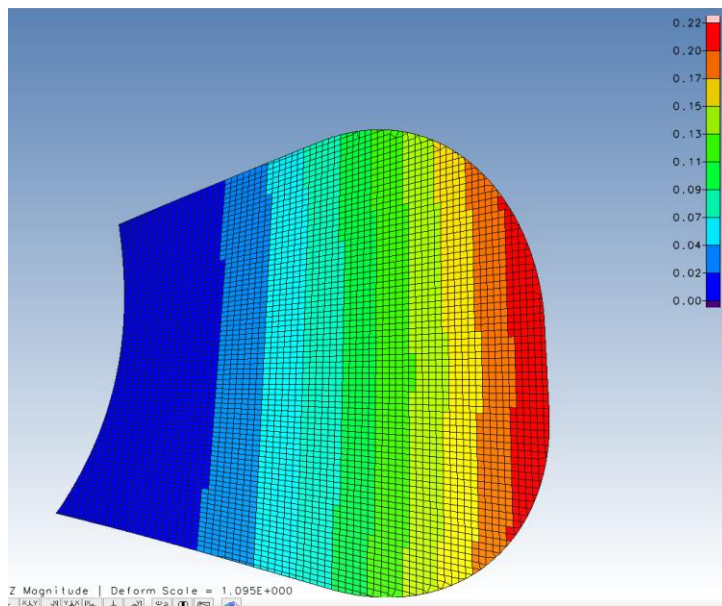




Mechanical and Manufacturing BEng

Structural & Fluid Analysis

Assignment 2

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Table of Contents

Table of Figures.....	2
Introduction	3
FEA Optimisation Techniques	3
Topology Optimization.....	3
Shape Optimization.....	4
Steel Blade	5
FEA Optimisation of Steel blade	7
Model Layup of CFRP	8
FEA Optimisation of CFRP blade	9
Results.....	10
Prototype	10
Technical literature	11
Conclusion.....	12
Bibliography	12
Appendices.....	13

Table of Figures

Figure 1-Space envelope of city bus	3
Figure 2- Topology Optimization of city bus.....	4
Figure 3- CAD representation and Hollow frame structure.....	4
Figure 4- Typical Shape Optimisation	5
Figure 5- Standard Steel blade.....	5
Figure 6- Standard steel blade mass.....	5
Figure 7- Pressure coefficient on marine propeller	6
Figure 8- 2N Load applied to the rest of the top section.....	6
Figure 9- 3N load applied to leading edge	6
Figure 10- Constrained elements.....	7
Figure 11- Standard steel blade deflection.....	7
Figure 12- Steel blade optimisation	7
Figure 13- Mass of optimised steel blade	8
Figure 14- CFRP Layers.....	8
Figure 15 - Composite material properties.....	8
Figure 16- CFRP Deflection.....	8
Figure 17- CFRP Mass before optimisation.....	8
Figure 18- Optimisation of CFRP	9
Figure 19- CFRP 9mm upper boundary	9
Figure 20- CFRP Optimised layers 1 & 2.....	13
Figure 21- CFRP Optimised Layer 5	13
Figure 22- CFRP Optimised deflection	13

Figure 23- CFRP Optimised layers 3 & 4..... 13

Introduction

Carbon fibre reinforced plastics (CFRP) are extensively used in the manufacturing of various structures like wingtips, stabilizer tips, antenna covers, flight controls and including marine propellers. The hydrodynamic aspects of the design of composite marine propellers have attracted attention because they are important in predicting the deflection and performance of the propeller blade.

The optimisation of these CFRP blades is critical to the vessels performance, as the design needs to be lightweight to increase the efficiency of the ship and reduce manufacturing costs. This report will look into the difference between steel and CFRP propellers and how the CFRP propeller can be optimised using FEA to make the design as light as possible while still meeting operating requirements.

FEA Optimisation Techniques

Topology Optimization

Topology optimization is a mathematical technique which spatially optimizes the distribution of a material with a defined domain. The pre-established constraints are broken down into the three main elements, design variables, the cost/function and the constraints of the design (Bendsoe, 2003).

This process was first introduced in 1988 by Bendsoe and Kikuchi, where they introduced a microstructure/homogenization approach to solve topology problems. This theory was further adjust by Bendsoe to then be called the “power law” or solid isotropic material with penalization (SIMP) approach (Bendsoe, 1989).

A research paper in 2004 by Mahdavi (Mahdavi, 2004) was created where they looked into this theory and why this technique isn’t as widely used as possible.

“With the major benefits that industries can gain by using this method in the conceptual design stage, the application of topology optimization to industrial problems is not yet widespread. The main reason is that, as an iterative process, topology optimization of large, real-world structures is computationally intensive.”

With limited technology available during 2000’s it made it difficult for companies to develop software which could calculate these equations quick enough to make the theory practical to

large companies. But as technology has advanced and computers becoming quicker, the theory is becoming wider spread throughout all industries.

The methodology over the last decade has become common into all types of engineering, especially



Figure 1-Space envelope of city bus

within the automotive industry. There is many examples within the automotive industry where material distribution has been applied to real world problems. A council looked into the design of their city buses and looked to create lightweight buses, so they hired Altair Engineering to look into the design of the bus to reduce the weight. This first thing they done was create a space envelope of the current busses shown in Figure 1, then topology optimisation was run then to find the optimal structure layout of the bus (Bendsoe, 2003).

Figure 2 shows the topology optimization of the city bus so this gave Altair a huge advantage on where the design needed to be strong. They changed these results into a CAD representation (c) and then performed sizing optimisation of the structure to hollow out these components (d) (Figure 3) to give them a strong lightweight design.

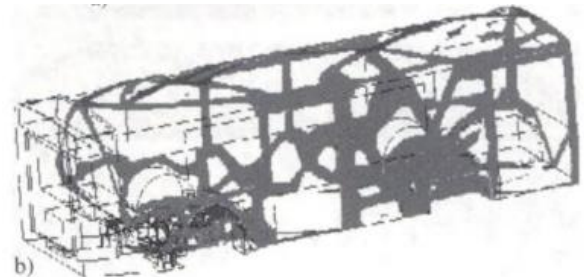


Figure 2- Topology Optimization of city bus

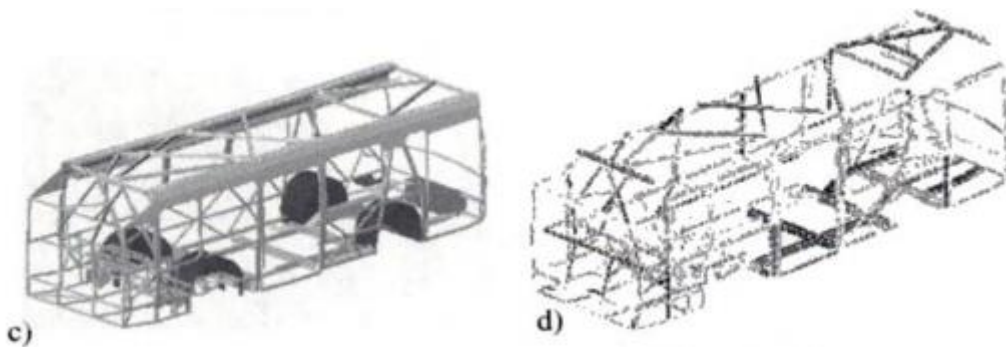


Figure 3- CAD representation and Hollow frame structure

As computers advance in the future and become more powerful it is believed that this theory will continue to grow and be used throughout every design based industry to optimise every design new or old to maximise the efficiency of that product. There is also the belief that the time taken to optimise these design will reduce as computational power doubles every two years according to Moore's Law, but with recent studies at Stanford it was found that artificial intelligence is doubling every 3.4 months (Saran, 2019) this meaning that artificial intelligence will start to be used in designs to optimise them and look at sustainable ways to create future projects.

Shape Optimization

Shape optimization refers to procedures that result in the prediction of a boundary (or shape) of the design domain of the structural/mechanical system to be optimized. Shape optimization is used in practice for cases where an initial shape already exists, but for a given a finite element mesh, nodes on the boundary are displaced in order to achieve an objective (like minimizing the stress on the surface for example).

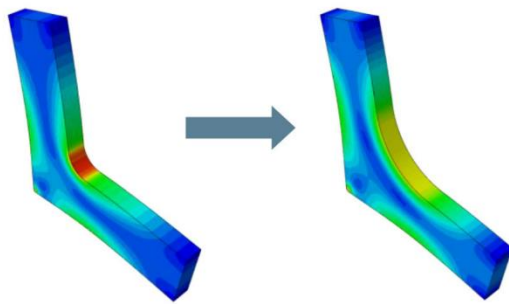


Figure 4- Typical Shape Optimisation

A typical shape optimization task could be to minimize the effective stress at some local regions. A parametric shape represents CAD parameters such as the radius of a fillet or the distance of a geometry section.

Most of the commercial CAD software uses parametric shape representation. However, the parametric shapes does not contain any explicit information of the geometry or the topology of

the boundary. Non-parametric shape optimization uses implicit parameters, these are defined from a set of chosen surface nodes from the FE model. The implicit parameters are defined as the scalar displacements along the optimization vectors belonging to the design surface nodes. The optimization vector is usually taken as the normal vector to the adjacent surface of the design node.

Steel Blade

A steel blade design has been modelled on solid works, this will be the baseline in which we can compare all of our analysis too. The steel blade was loaded in to design studio and analysis was run to find out the mass of the blade as this will be required as baseline target for CFRP. In Figure 5 & Figure 6 you can see the standard steel blade and the current mass of the propeller being 646.67Kg.

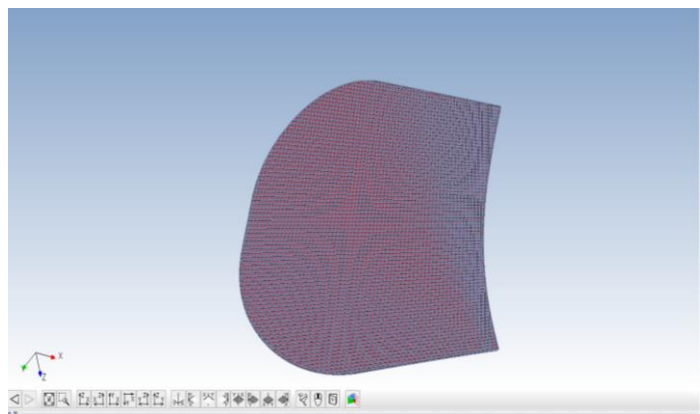


Figure 5- Standard Steel blade

View Coord. Sys.: Basic	Choose elements from the viewport or by ID
Mass Sum = 646.674, Min = 0.0128852, Max = 0.251494, Avg = 0.133390	
For 4848 selected elements:	
Volume Sum = 0.0839836, Min = 1.67340e-06, Max = 3.26616e-05, Avg = 1.73233e-05	
Mass Sum = 646.674, Min = 0.0128852, Max = 0.251494, Avg = 0.133390	

Figure 6- Standard steel blade mass

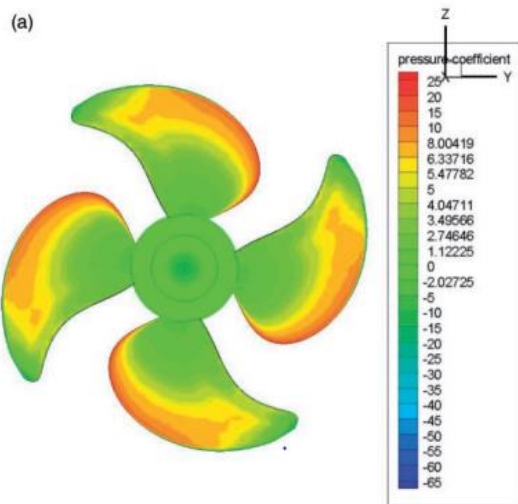


Figure 7- Pressure coefficient on marine propeller

For the load being applied to the blade it was critical to break down the load into three different sections as each part of the blade is exposed to different amounts of pressure due to the operation. In Figure 7 it shows that the pressure experienced by a propeller under heavy loads. A heavy loaded in this case is a boat with a 2.1m diameter propeller travelling at 4 knots (Gorji, 2022).

With the leading edge experiencing the highest pressure, to make the FEA analysis realistic a larger force of 3N per grid will be applied to the leading edge this can be seen in Figure 9. The remaining top section area then has a 2N load per grid space applied to it as this area is still going to experience some force but not to the same extent of the leading edge, shown in Figure 8. The remainder of the blade then has a force of 1.5N per grid applied to it as there is still some pressure applied to the blade surface from the sea water.

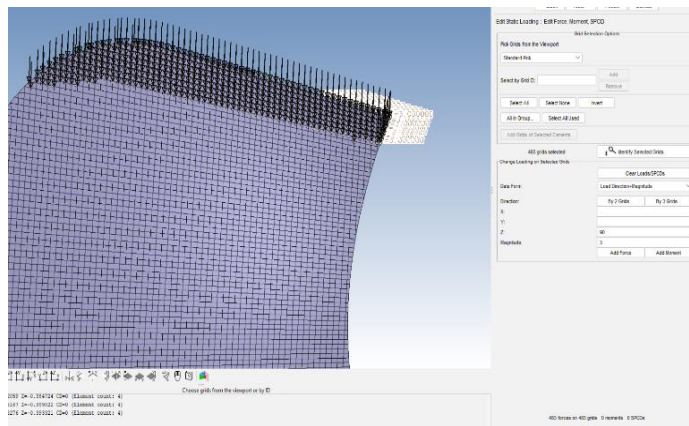


Figure 9- 3N load applied to leading edge

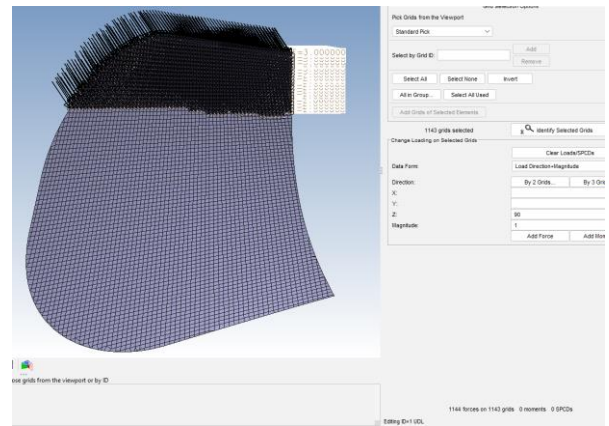


Figure 8- 2N Load applied to the rest of the top section

Area	Force per grid	Number Grids	Total force
Leading Edge	3N	483	1449N
Top section	2N	661	1322N
Remainder of blade	1.5N	3806	5709N
Total		4950	8480N

Table 1- Force applied to blade

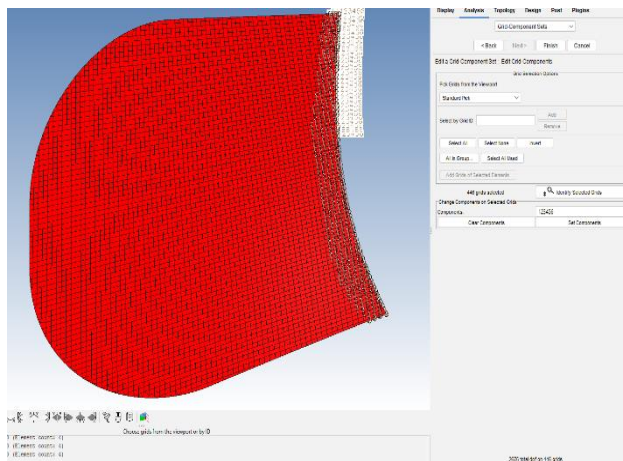


Figure 10- Constrained elements

The theta vectors were also adjusted on the propeller as we are assuming that the zero degrees runs radially out from the centre of the propeller. With the theta vectors adjusted the constrained elements needed to be updated, only the very edge on the propeller blade was constrained. In real life application it's more that like a large portion of the elements will be fully constrained due to the blade being welded onto the propeller hub, will leave a weld bead increasing the strength of the propeller and joint.

With all the parameters set out a single analysis was run for the standard steel blade and the deflection came back as 270mm (Figure 11) which is over double the requirement set by the manufacturer. The target set was for the CFRP to achieve was no more than 100mm in deflection as any more than this would have an effect of the propulsion and manoeuvring of the ships.

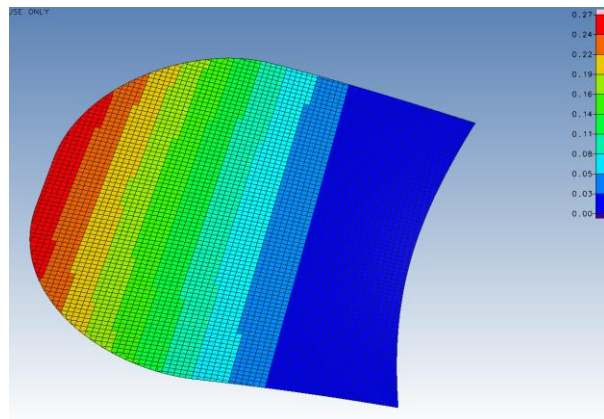


Figure 11- Standard steel blade deflection

FEA Optimisation of Steel blade

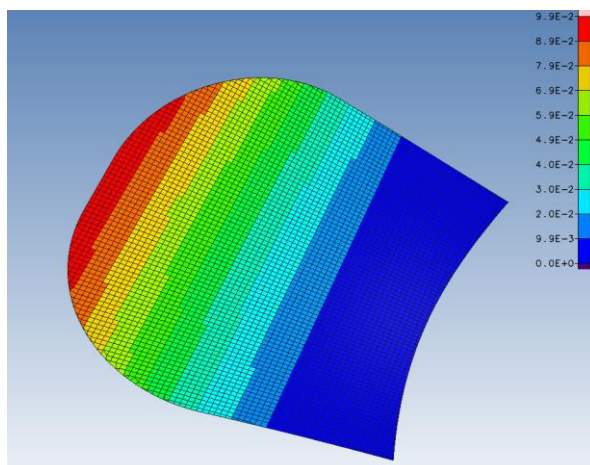


Figure 12- Steel blade optimisation

The blade needed to be optimised to get the deflection under 100mm this was done with trial and error by increasing the thickness of the steel until a suitable thickness was found. The steel now has to be 14mm thick to have a deflection rate of 99mm shown in Figure 12. The mass of the steel blade has now also increased giving it a total mass of 905.34Kg (Figure 13), giving us a numerical target for the CFRP to better.

For 4848 selected elements:
 Volume Sum = 0.117577, Min = 2.34276e-06, Max = 4.57263e-05, Avg = 2.42527e-05
 Mass Sum = 905.343, Min = 0.0180393, Max = 0.352092, Avg = 0.186746

Figure 13- Mass of optimised steel blade

Model Layup of CFRP

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

Figure 14- CFRP Layers

Figure 14 & Figure 15 show the properties, layers stack up and the angle of the proposed composite. Each ply is 0.1mm and because 25 layers is required each layer is set to 0.5mm.

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_13:	5.65E+9
G_23:	5.65E+9
Rho:	1540.0
A_1:	0.0
A_2:	0.0
Tref:	0.0
GE:	
F12:	
☒ Stress Limits ☐ Strain Limits	
Xt:	1.541E+10
Xc:	1.E+9
Yt:	4.34E+7
Yc:	4.34E+7
S:	4.34E+7

Figure 15 - Composite material properties

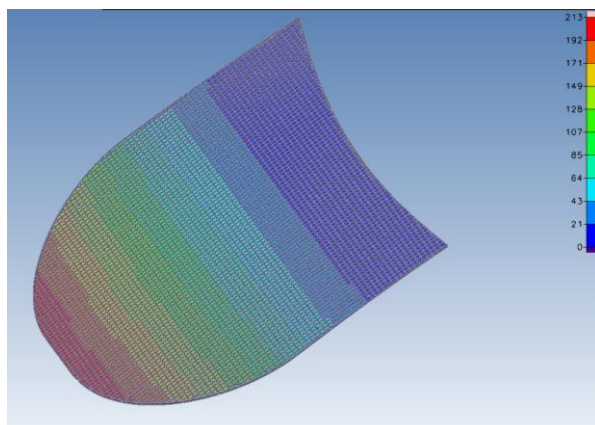


Figure 16- CFRP Deflection

Once the composite material properties and layers were created, another genesis analysis was run again and the results imported to review the displacement of the CFRP. In Figure 16 the results show that the blade would displace 213 meters, this obviously wouldn't be possible and the blade would break before it displaced this amount. As there is no upper boundary the software keeps on calculating the displacement until it achieves a mathematical answer.

View Coord. Sys.: Basic
 Importing C:\Users\2012414\OneDrive - University of Wales Trinity Saint David\Documents\ASSIGNMENT 2_dsg_dsg00.op2.gz as 'output2 post-processing file'
 For 4848 selected elements:
 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 17- CFRP Mass before optimisation

FEA Optimisation of CFRP blade

Optimisation begun on the CFRP blade there was a few factors which needed to be inputted, the maximum deflection set to 100mm, the objective set to minimum mass, layers upper boundary set to 10mm and finally the design cycles set to a maximum of 30 as any more would take too much time.

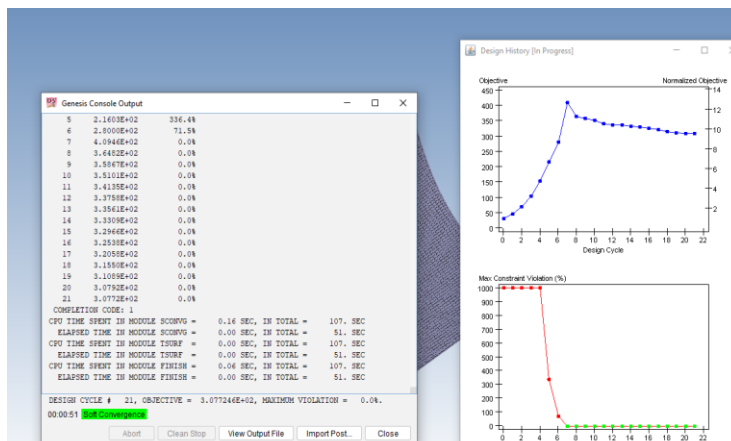


Figure 18- Optimisation of CFRP

Once all these factors inputted the optimisation was run and after 21 design cycles a soft compromise was achieved and the results came back as shown in Figure 18. The blade deflected 99mm shown in Figure 22 the same as the steel one, but the mass of the CFRP one is only 307Kg which is a huge difference compared to the steel one.

To try and further optimise the blade and reduce the mass of the blade, the upper boundary of the layers was reduced to 9mm with the theory being that with the layers being thinner but having more layers, would this further decrease the weight of the blade. So the optimisation was run again. After 28 design cycles this time a hard compromise was found shown in Figure 19. The results wasn't as expected and the mass of the blade came back as 360Kg which was heavier that previously with the same deflection rate.

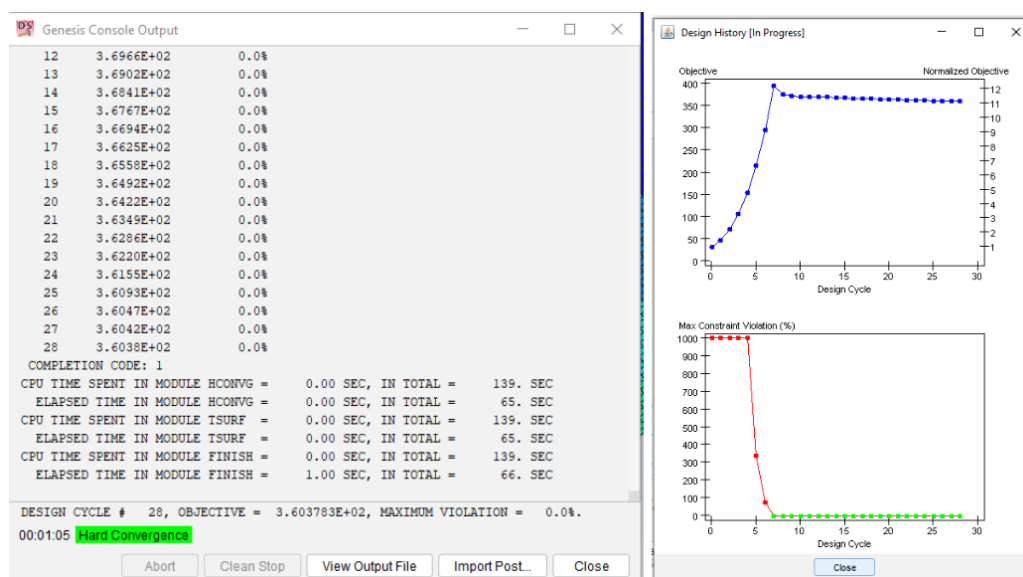


Figure 19- CFRP 9mm upper boundary

Results

The upper boundary was adjusted to try and achieve the lowest weight possible while still achieve the objective of 100mm deflection. Table 2 Shows the results achieved from the optimisation and the overall thickness of the blade.

Upper Boundary	Weight	Thickness
9mm	400.5Kg	25mm
10mm	388Kg	24.2mm
11mm	324.6Kg	22.6mm
15mm	275Kg	21.2mm
20mm	226Kg	17.5mm
25mm	226kg	17.5mm

Table 2- Optimisation of CFRP with boundary changes

	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
Thickness	0.2mm	0.202mm	16.7mm	0.2mm	0.2mm
Angle	-90 Degrees	-45 Degrees	0 Degrees	45 Degrees	90 Degrees

Table 3- CFRP Layers optimisation

	Thickness	Weight	Deflection
Steel	14mm	905.34Kg	99mm
CFRP	17.5mm	226Kg	99mm

Table 4- Comparison between Steel and CFRP

Table 3 shows the optimal thickness of each of the ply's and the angle in which they need to be layered for them to be the most effective. Table 4 is then a comparison between the steel blade and CFRP, with the later having a weight saving of 679.34Kg.

Prototype

In recent years there has been an increased focus on optimisation of composite propellers from both structural and marine engineer point of view. Most of the work which has been undertaken without experimental verification into whether the explored design are producible with the intended deformation. There has been some recent experiments looking into deformation characteristics of their produced prototypes, (Kumar, 2015) looked into full scale model prototypes and (Maljaars, 2017) looked at model scale prototypes both explored deformation by using point load experiments.

The point load static test has been considered to be the best kind of test, ideally the prototype blade would be loaded with the operational periodic load case and the resulting deformation measured. However the loading case was considered to be too complex to recreate.

Two point loads can be applied to the blade by hanging weights from the loading points, these loading points, can be located central to the areas which were highlighted in the FEA of the blade. The point load static test has been considered to be the best method as it would be applied in a manufacturing line for commercial composite propellers. The use of static load cases would be used to determine the quality and property checks at different intervals during the production of the composite propeller.

Once the static point loads are identified and drilled out, weights can be hung from the propeller in small increments and the displacement can be tracked. To measure the displacement of the propeller, digital image correlation (DIC) technology can be used. This works by painting the surface of the prototype white and adding black dot speckle which are 2-3mm.

With two cameras can be setup to track the displacement of the speckle pattern on the propeller blade surface. Using a software like Vic-snap 8, measurements can be taken and processes to calculate the deformation in the snapshots. Based on (Kumar, 2015) research it will be expected that we will find a comparable deformation between the FEA results and experimental methods.

Technical literature

The issue with CFRP is that it is a laminated composite, which means it has an unusual behaviour under impact, since damage which can be introduced it reduces the strength of the structure significantly (Abrate, 2001). During production of these CFRP propellers there is a chance that there may be some impacts produced which will cause deformations in a small zone surrounding the point of impact while larger impacts can cause deformations of the entire structure.

The process of creating these layups is time consuming and expensive as the materials needs to be layered correctly and to ISO standard 484-1:2015 which outlays the tolerances in which marine propellers have to adhere to (ISO, 2022). This time consuming task is sometimes questioned whether it is beneficial to the companies using this type of material, a study in 2007 (Burgoyne, 2007) found that *"The market for FRPs has not taken off as had been expected, largely because the FRP market has concentrated on trying to make FRPs look like the steel elements they are replacing."* So a lot of companies still wonder will all the cost implications and uncertainties the material brings is it worth the risk.

Delamination, burrs, and tearing are critical issues associated with the drilling of CFRPs, which are greatly affected by the wear extent of drill bits. This could be problem during the prototype experiment as any damage to the composite can have a great effect on the deflection of the blade. Any Excessive tool wear can lead to unacceptable inter-laminar

delamination, exit burrs, and surface tearing, all these issues account for a large proportion of composite part rejections during production (Xu, 2022)

Conclusion

To conclude this report we can say that using FEA analysis we are able to establish that CFRP would be considerably lighter (679.34Kg) than a steel blade in a numerical analysis. To confirm these results a prototype would need to be created and the experiment performed. It's difficult to just rely on numerical analysis for results as in real-life as details and operations the blade go through are difficult to impose. Any deviations in the manufacturing of the blade can cause big structural implications affecting any results which would be obtained.

The numerical analysis has given us a starting value to work with, so we now know from Table 4 that the CFRP is going to have to be at least 17.5mm to achieve the 99mm deflection. Without this data it would have been near impossible to come to this conclusion without doing trial and error with the prototype. This would have drove the price of the development of the blade astronomically high, leading to the business making a decision on whether the costs outweigh the benefits.

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Appendices

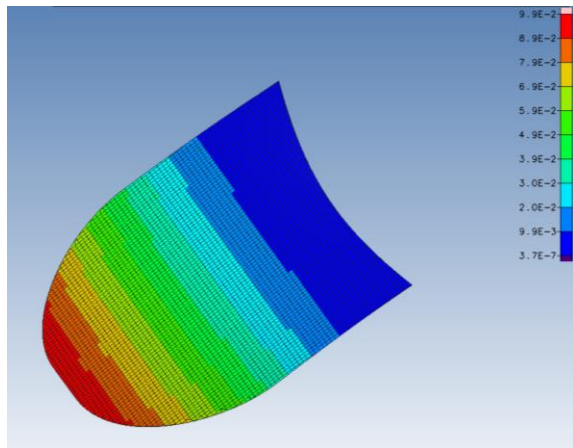


Figure 22- CFRP Optimised deflection

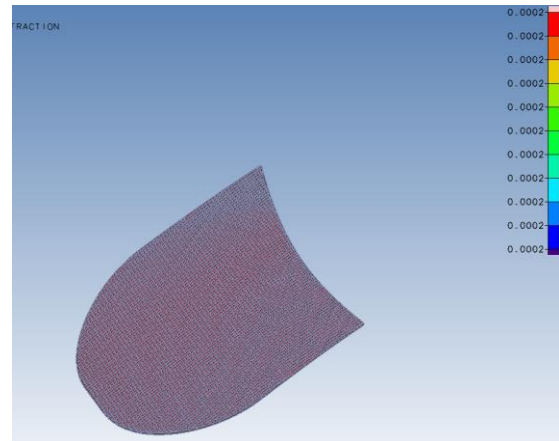


Figure 20- CFRP Optimised layers 1 & 2

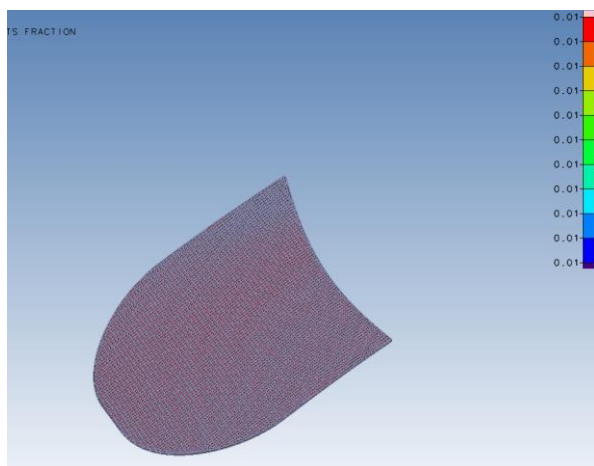


Figure 23- CFRP Optimised layers 3 & 4

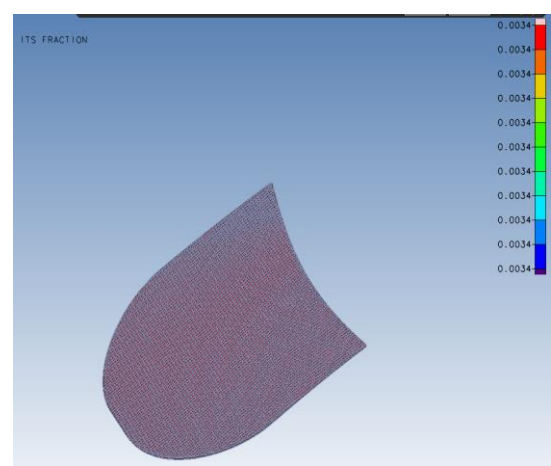


Figure 21- CFRP Optimised Layer 5