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Designing a tanker propeller: Structural Design

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Introduction

I have been tasked with creating an optimal design for a steel propeller blade from a cargo ship. The blade material will need to be changed to carbon fibre reinforced plastic, or CFRP as well as optimised using FEA analysis to meet the design limits of this assignment. As well as using FEA analysis, I will explain the history surrounding optimisation techniques and the standards and regulations of manufacturing a CFRP propeller.

Part one

History

Trevor English, 2019, states that Finite Element Analysis, or FEA for short is a simulation which carries out a physical phenomenon using a numerical mathematic technique referred to as the finite element method, better known as FEM. The FEA process is commonly used in the mechanical division of engineering. It is also used when developing simulation software. The main reason for using FEM technology is to reduce the need for making so many physical prototypes, reducing time and cost surrounding projects as well as allowing engineers to optimise their designs.

Tom O'Donnell, (2020) explains that it's said that FEA first occurred in the late 1800's. John William Strutt Rayleigh developed a method for predicting the first natural frequency of simple structures. John Rayleigh assumed a deformed shape for a structure, then quantified the shape by minimising the disturbing energy in the structure. A man named Walter Ritz then expanded this into a method, this is what is known as the Rayleigh-Ritz method and used for predicting stress and displacement behaviour in structures.

O'Donnell (2020) informs us that the term 'Finite element' was first used in 1960's by Dr. Ray Clough, this was also the beginning of commercial FEA as digital computers replaced analog. A company called MacNeal-Schwendler (MSC) corporation ensured the growth of commercial FEA by developing NASTRAN. Once MSC had completed their NASA contract they continued to develop the software, the original version of NASTRAN became available to the public. MSC developed other software packages side NASTRAN, these include, ANSYS, MARC and SAP.

In the 1970's minicomputers were developed. These minicomputers were a lot more powerful than the mainframes. Even with the new technology, developing solutions were still too intense for casual users. Although in the 1980's developments in graphics processing left its mark on FEA as graphical 'pre' and 'post' processors became available and engineers could examine coloured stress contours. Really driving FEA systems into the public eye.

In the late 1990's the use of PC's became a major factor when examining high end analysis. Computers were developed that were able to handle 1 trillion operations a second, birthing the modern system that we use today.

History of Techniques

Dolf Broekaart, (2015), explains that the traditional way to optimise designs use FEA. Is to create a design, create and analysis and study how the design behaves and then determine whether or not the design will need to be optimised. The person looking to optimise their design will need to define what values would cause the design to fail from the original definitions. An example given by Broekaart (2015) is “*maximum allowable stress, maximum strain, maximum displacement, minimum volume, minimum Eigen frequency, etc.*”. The results from the initial analysis will allow further optimisation of the design. You can the change some parameters in the set up to try and get the numbers closer to the target needed. This is what is known as the manual approach or trial and error and has been used as the primary optimisation technique since the software’s birth in the 90’s.

Other Techniques Used

Parameter based optimisation

Broekaart, (2015) connotes that, parameter based optimisation software is a technique in which the traditional approach has been automated. This means you can create highly complex systems with a lot of parameters.

Topology based optimisation

Leap FEA Team, (2014), tell us that this technique is an optimisation capability which will allow the user to find the best distribution of materials. An optimal structure is generated by carving out material form a given design space, allowing for a given amount of material.

Shape optimisation

Leap FEA Team, (2014), informs us that shape optimisation is a capability which will allow the user to find the best shape possible for their design. The software will search for the best location of the finite element nodes, which define the shape of the structure.

Future of Optimisation

Bhaumik Dave, (2021). Tells us that FEA holds a ‘promising future’ for engineering product design is being increasingly refined to improve the solver capabilities when predicting the behaviour more accurately. Dave, (2021) further informs us that he believes that optimisation techniques will be more reliable and will eliminate the use of physical tests at many levels.

Part Two

A model of the blade in question was created and uploaded to Design studios. My main goal with this article is to significantly reduce the mass but allow the displacement to exceed no more than 100mm. For this to be possible the design will need to be first converted to carbon fibre reinforced plastic, or CFRP.

Below is the calculation used to find the total load upon the blade.

Assumptions.

- Assuming that my blade will be in the Pacific Ocean where the sea density is around 1030 Kg/m³ (Fred T. Mckenzie, 2012)
- Assuming that the sea temperature will be around 21 degrees Celsius. (Amy Tikkanen, 2015)
- Assuming that the blade length of the propeller is long and 3.15m wide.
- Assuming that the length from the top of the bottom of the hull to the water line is 30m (Jeanna Bryner, 2009)
- Assuming the propeller to be non-ducted
- The diameter of the boss is 0.6m
- I have an assumption that the propeller will be turning at 210 rpm or 20.16cpm. I have decided to stick with this number after carrying out research into the average propeller speed for a large shipping vessel. (Smita, 2019)
- The propeller will be full submerged within the water at a depth of 28.25m. Research carried out shows that the average hull depth of a cargo vessel is around 30m. It is recommended that the distance from the ship's hull to the centre of the propeller is 25% of the propeller's diameter. (Jeanna Bryner, 2009)
- I will assume that the blade a rectangle and flat when carrying out my force calculations. I have assumed this to ease the calculations as carrying out calculation on the shaped and curved blade require a degree of CFD software.
- I have assumed the density of the blade is too large to worry about buoyancy affecting my calculations.

Equation

$$F = PaA = PghaA$$

A = Area of submerged surface (m²)

Ha = Average depth (m)

P = Density (Kg/m³)

g = Acceleration of gravity (m/s²)

Calculation

$$g = 9.81 \text{ m/s}^2$$

$$\rho = 1030 \text{ kg/m}^3$$

$$h_a = 28.25\text{m} = \text{Average hull depth (30m)} - 25\% \text{ of propeller (1.75)}$$

$$A = \pi \times \text{Radius}^2 = 3.142 \times 3.515^2 = 38.82 \text{ m}^2$$

$$F = 1030 \text{ Kg/m}^3 \times 9.81 \times 28.25$$

$$1030(\text{kg/M}^3) \times 9.81 \text{ m/s}^2 \times 28.25\text{m} \times (2.97 \times 3.04) =$$

$$2577 \text{ kN}$$

When calculated with the number of nodes (2,577,000N / 4951). I received a figure of 520kN per node. This figure is too large for a propeller of these proportions.

After reviewing my research, I decided that the research was sufficient in giving me the correct values for my calculations. For the blade in question, I have decided to implement a UDL of 4.5kN. This value will give me a figure of 0.90kN per node. This figure will allow me to carry out an FEA analysis and gain more realistic results.

Steel blade Figures

Steel plate

$$\text{Stiffness} - k = f/x = 4951 / 0.22 = 22504\text{N/mm}$$

$$\text{Stiffness/weight ratio} - k/(mg) = 22504 / (646.7 \times 9.81) = 634\text{N}^2/\text{mm}$$

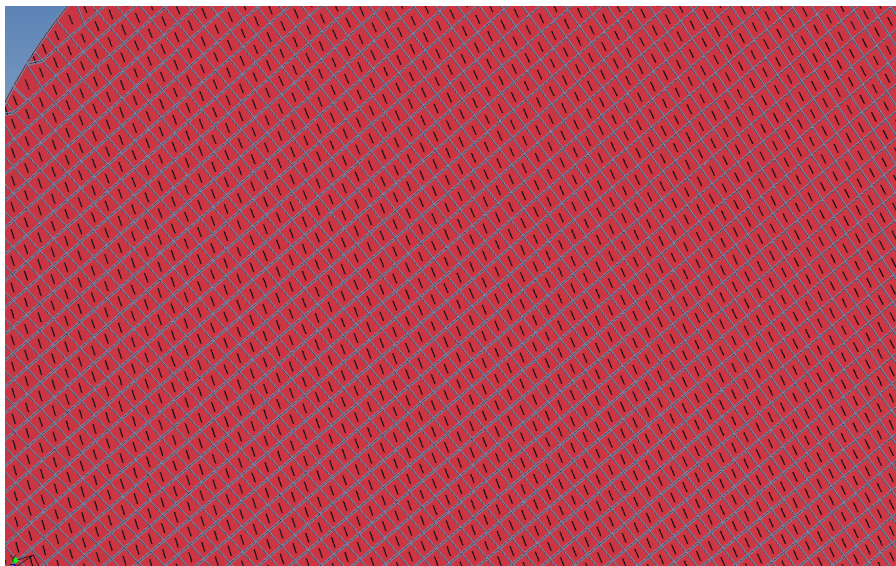
Mass	646.7
Stiffness	22504N
Stiffness/Weight Ratio	634N ² /mm (units)
Displacement	0.22m
Load	4.5KN

After uploading the steel blade to design studios, I adjusted the material properties of the blade. I added the values seen in figure 1. By doing this I created a unidirectional composite material. This is the chosen material to help us reach our goal with this project.

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 (ν_{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 (ρ):	1540 kg/m ³
Allowable longitudinal stress in tension (X_t):	1513 MPa
Allowable longitudinal stress in compression (X_c):	1000 MPa
Allowable transverse stress in tension (Y_t):	43.4 MPa
Allowable transverse stress in compression (Y_c):	43.4 MPa
Allowable inplane shear stress (S):	43.4 MPa

(Fig. 1)

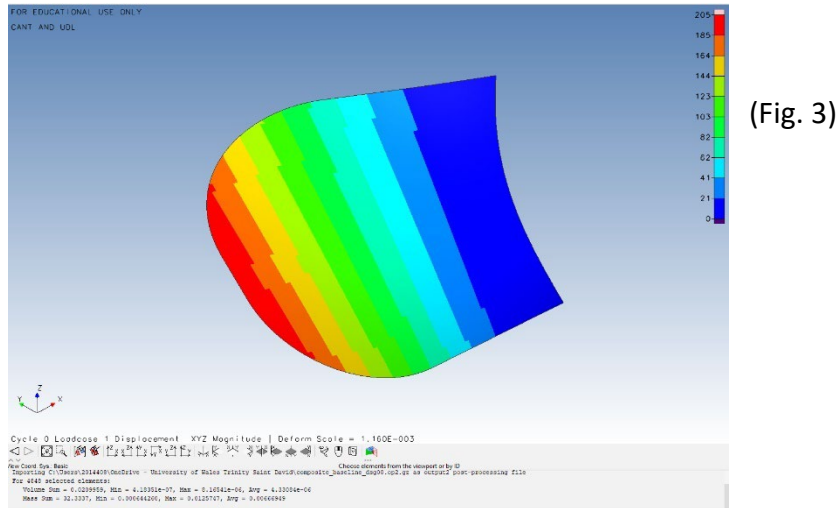
Due to the material properties changing. I needed to shift the directions of the elements. The reason for this is due to the natural bending of the blade changing due to the material change. I chose two grids in the 'X' axis. I chose this axis as this is the way water will flow over the blade deforming the blade on that axis. Figure 2 shows the flow of the elements over the blade after the position has been adjusted, as you can see, all elements are facing the same direction.



(Fig.2)

I adjusted the plies within the blades material, the blade consists of 25 plies in total. 5 at -90°, 5 at -45°. 5 at 0°, 5 at 45° and 5 at 90°. Each ply is set at a thickness of 0.5mm. This gives us an overall thickness of 2.5mm for the CFRP blade. The material is considered an isotropic material as it has the same material properties when tested in different directions.

I ran a single analysis on my blade once all these changes were made, the results are as followed. The mass drastically dropped to 32.3 Kg. This is a drop of 95% in overall weight of the blade. Although the weight dropped, the displacement slightly increased to 250mm and is still outside of our desired displacement of 100mm. This can be seen in figure 3.



CFRP Blade Figures

Stiffness – $k = f/x = 4951 / 0.25 = 19,804 \text{ N/mm}$

Stiffness/weight ratio – $k/(mg) = 19.804 / (32.3 \times 9.81) = 316.85 \text{ N}^2/\text{mm}$

Mass	32 Kg
Stiffness	19,804N/mm
Stiffness/Weight Ratio	316.85 (units)
Displacement	0.25m
Load	4.5KN

Conclusion

I have concluded that changing the material to CRFP and drastically reducing the weight of the blade has no advantage over the steel blade in terms of stiffness to weight ratio and displacement. To meet the displacement figure needed, the blade will need to be optimised.

Part Three

I have now proven that having converted the material to CFRP has no advantage over leaving the material as steel. The blade will now need to be optimised. Optimising is used to reduce material, prevent stress, and obtain desirable performance attributes.

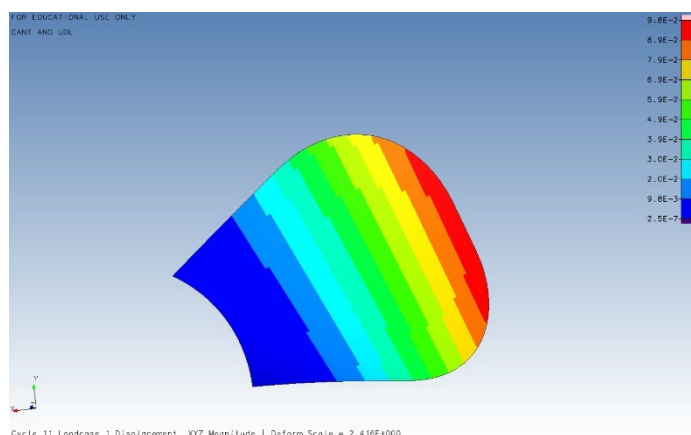
Before optimising our blade, I will need to add some values. When optimising, there are three values we must input before design studios will allow us to optimise our blade.

- **Objective** – First is our objective. In this section I will tell the software what our objectives are for our blade. In this case I'm looking to keep the mass to a minimum. I highlighted the 'min' to tell the software that the minimum possible mass should be achieved in the optimisation process.
- **Constraints** – In the constraints section, I adjusted the displacement. I put a maximum value of 100mm as well as setting the load to 4.5kN on all nodes.
- **Design Variables** – Finally, I set the design variables. In the design variables I inserted upper and lower bound thickness of each layer, placed mine between 0.1mm on the lower and 3mm on the upper. Once creating the first layer, I used copy and paste to create the other 4 and assigned each layer to a set of 5 plys.

Once all these values had been satisfied, design studios allowed for me to optimise my design. The results are as followed.

Optimisation 1

I adjusted the number of cycles that genesis will run to allow me to get the best possible results for my optimised blade. I set the amount to 100 cycles. Once the cycles had been set, I ran the optimisation programme, and my results are as followed. After the optimisation, the blade now has a weight of 219 Kg, this is significantly more than the CFRP blade but less than the steel blade. The displacement is less than the required 100mm, it lies at 98mm. This is shown in figure 3.



(Fig. 3)

Looking at our layer thicknesses, its apparent that I will need to add some discrete values. This means that the optimisation can only use certain values that I allow. The reason for needing to use the discrete values is due to one of the layer thicknesses being '1.274669E-02'. This value will be impossible to manufacture which makes the optimisation obsolete. This can be seen in figure 4.

```

65 DESIGN VARIABLE #      21 = 1.220626E-03   L4thk
66 DESIGN VARIABLE #      22 = 1.000500E-03   L5thk
67 DESIGN CYCLE #    11, OBJECTIVE = 2.165937E+02, MAXIMUM VIOLATION = 0.0%.
68 DESIGN VARIABLE #      1 = 1.000022E-03   L1thk
69 DESIGN VARIABLE #     19 = 1.000022E-03   L2thk
70 DESIGN VARIABLE #     20 = 1.274669E-02   L3thk
71 DESIGN VARIABLE #     21 = 1.000000E-03   L4thk
72 DESIGN VARIABLE #     22 = 1.000022E-03   L5thk
73 COMPLETION CODE: 1    258      0

```

(Fig. 4)

CFRP Blade Figures (Optimised)

Stiffness – $k = f/x = 4951 / 0.98 = 5,052 \text{ N/mm}$

Stiffness/weight ratio – $k/(mg) = 5,052 / (216 \times 9.81) = 2.38 \text{ N}^2/\text{mm}$

Mass	216 Kg
Stiffness	5,052 N/mm
Stiffness/Weight Ratio	2.38 (units)
Displacement	0.98m
Load	4.5KN

Optimisation 2

Due to the layer thicknesses given in the previous optimisation. I have now added discrete values to my optimisation variables. I placed a maximum layer thickness of 4mm and a lower value of 0.1mm with increased increments 0.1mm. Using these discrete values will allow me to receive layer thicknesses that are possible to manufacture. I ran the optimisation software, and my results are as followed.

My layer thicknesses have rounded out and are now possible to manufacture, this is shown in figure 5. The weight has increased to 219 kg, which is a 3 Kg increase, but the displacement has improved by 0.05mm and is now 0.93mm, which is within our limit of 100mm. This can be seen in figure 6.

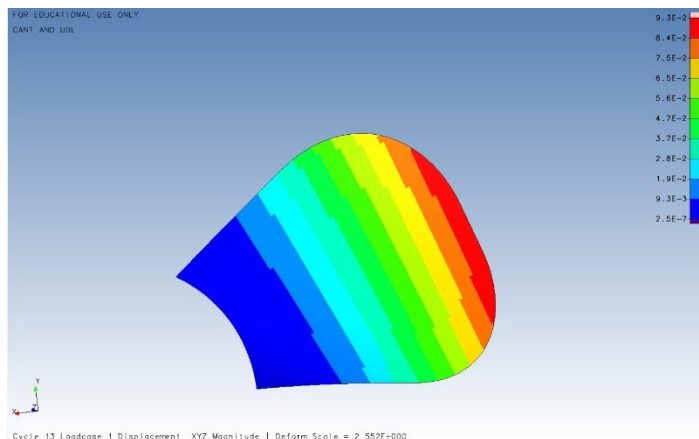
```

79 DESIGN CYCLE #    13, OBJECTIVE = 2.198690E+02, MAXIMUM VIOLATION = 0.0%.
80 DESIGN VARIABLE #      1 = 1.000000E-03   L1thk
81 DESIGN VARIABLE #     15 = 1.000000E-03   L2thk
82 DESIGN VARIABLE #     16 = 1.300000E-02   L3thk
83 DESIGN VARIABLE #     17 = 1.000000E-03   L4thk
84 DESIGN VARIABLE #     18 = 1.000000E-03   L5thk
85 COMPLETION CODE: 1    261      0
86

```

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(Fig. 5)



(Fig. 6)

CFRP Blade (Optimised with discrete values)

Stiffness – $k = f/x = 4951 / 0.93 = 5,323 \text{ N/mm}$

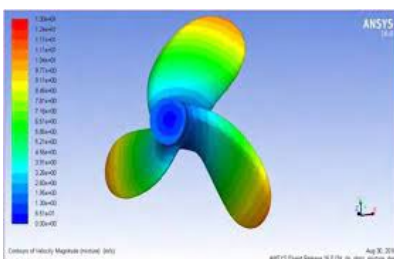
Stiffness/weight ratio – $k/(mg) = 5,323 / (219 \times 9.81) = \text{N}^2/\text{mm}$

Mass	219 Kg
Stiffness	5,323N/mm
Stiffness/Weight Ratio	2.48 N
Displacement	0.093m
Load	4.5KN

Optimisation Conclusions

Throughout the optimisation process, the weight of the blade has dropped by 67% and is now 219Kg. Although when changing the material to CFRP dropped the weight to 32.3 Kg. The displacement was still too large for our specifications. The displacement now lies at 0.093mm which is within our 100mm tolerance. I believe that this is the best the blade can be optimised and recommended that the blade is manufactured to this specification.

These results should be taken with a 'pinch of salt' as a blade fitted to a ship will not have a UDL across the whole blade. (James Noosomton, William Gunnuang, 2017), show us that the edges of the propeller blade has a larger force acting upon it compared to the sections of the blade which is closest the boss. This can be seen in figure 7. If you wanted more accurate results, you will need to add multiple forces along the blade, with a larger force on the outside and smaller force nearer to the propeller boss.



(Fig. 7, Noosomton, Gunnuang. 2017.)

Part Four

Blade construction

After the given results from the optimisation process a real-world blade will be constructed to the blade specifications from our discrete values. The blade will be made from a CRFP material with matching properties from our FEA analysis. If a material with isn't available matching properties, a replacement will be sourced with similar properties.

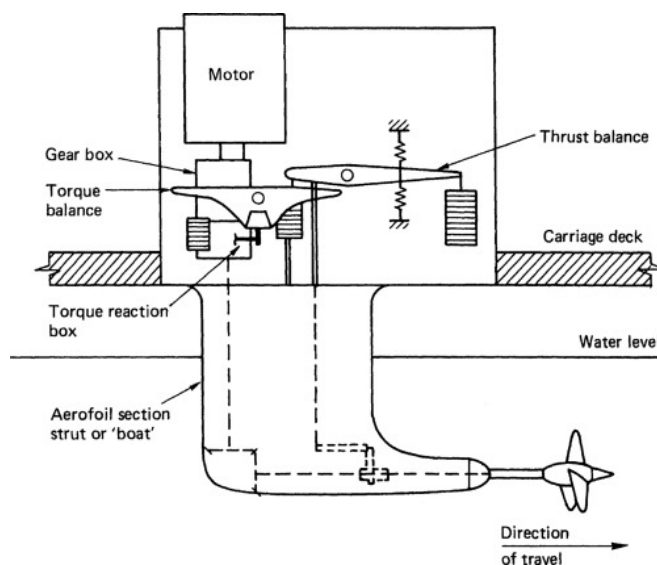
The blade ply thickness will be taken from the optimised design with the discrete values. The blade will be constructed to a 1:1 ratio to ensure accuracy throughout the project.

Intended outcomes

I will be looking to prove that my optimised design will withstand the force of 4.5 kN across all nodes and not displace over 100mm. According to my FEA analysis, this is possible. With a maximum displacement of 93mm.

Laboratory testing

I have decided to carry out open water testing with my propeller blade. Eric C. Tupper (2013) , explains that the open water test is carried out using a prototype of the propeller or an actual of the propeller to be fitted to the ship to derive its open water characteristics in order to estimate the displacement of the propeller blade. In this context, a prototype CFRP blade has been manufactured to the optimised model's specifications The propeller model is fitted on a horizontal driveway shaft and is moved through the water at an immersion of the shaft axis. A drawing of the supposed experiment is shown in figure 8. The load on the propeller is changed by either accelerating or decreasing the velocity that the propeller moves through the water.



(Fig. 8. Eric C. Tupper. 2013)

A series of sensors will be added to the backside of the propeller. These sensors will be constantly monitoring the displacement in each blade. This is how I will determine whether or not the figures from the FEA analysis are accurate. After the results have been taken from the open water test, they will be compared with the results given from the FEA analysis.

Conclusion and Comparison

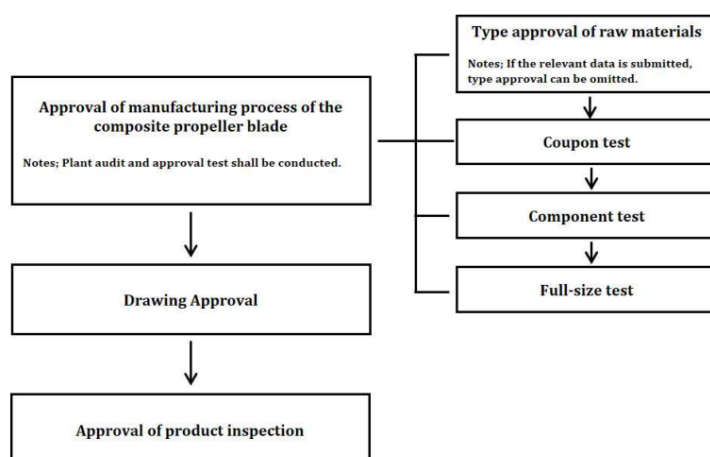
When comparing the results gathered from the laboratory experiment and the FEA there are many things that need to be considered. Although the viscosity and density of the water in the open water test can be calibrated there is still a chance that they can fluctuate. This will need to be considered when reviewing and comparing results.

When using the FEA analysis there is no consideration for variables such as water temperature, air temperature and manufacturing mishaps. Although each layer will be manufactured to meet the requirements of the FEA analysis there will still be micro discrepancies. For this reason, I feel as if the real-world testing is more accurate as it takes more factors into consideration. FEA analysis is a good baseline to start but I would now further develop the blade using open water testing.

Part Five

Korean Register, (2021), give us a guidance on what is needed when manufacturing CFRP propellers. They explain that before approval is given for the manufacture of a CFRP propeller the procedure seen in figure 9 will need to be followed before being granted with approval for manufacture.

After the approval of product inspection, an inspector will test the fibre volume fraction and glass transition temperature, carry out a visual and non-destructive inspection as well as a dimension measurement. Once the inspector is happy these standards have been met, the inspector will hand over a 'mark' which will show that the product has been approved by the society. Korean Register, (2021).



(Fig 9. Korean Register, 2021)

Regulations and Standards

Korean register, (2021). Lays out what standards and regulations need to be met when carrying out testing on a CFRP propeller. They are as followed.

<u>Test</u>	<u>Standard</u>	<u>Test orientation</u>	<u>Acceptance Criteria</u>
Tensile test	ISO 527-4, ISO 527-5	The test orientation is to be as deemed appropriate by the Society to confirm the mechanical properties of the laminates.	Manufacturer design value
Compression test	ISO 14126		Manufacturer design value
In-Plane shear test	ISO 14129		Manufacturer design value
Interlaminar shear test	ISO 14130		Manufacturer design value
Bending test	ISO 14125		Manufacturer design value
Seawater immersion test	After immersed in seawater at least 3 5°C for 28 days, tensile test, interlaminar shear test, in-plane shear test, and bending test shall be performed.		The property of the material should not be lowered by more than 25% compared to initial state before immersion.
Fiber volume fraction	ISO 3451, ISO 14127, ISO 1172, ASTM D3171, ASTM D2584, ASTM D5630. However, the thickness measurement method is excluded.		Manufacturer design value
Glass transition temperature	ISO 11357, ASTM D7028		Should be at least 10 °C above the design temperature

(Korean register, 2021)

Conclusion

Concluding this project, I was able to successfully optimise my propeller blade by converting the material to CFRP and adjusting the layer thickness to suit my displacement figure. By doing this the weight was drastically reduced by 67%. The optimisation techniques used will have a drastic impact on cost efficiency when developing components and makes the need for physical testing and prototyping almost obsolete.

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