

Joel Lang

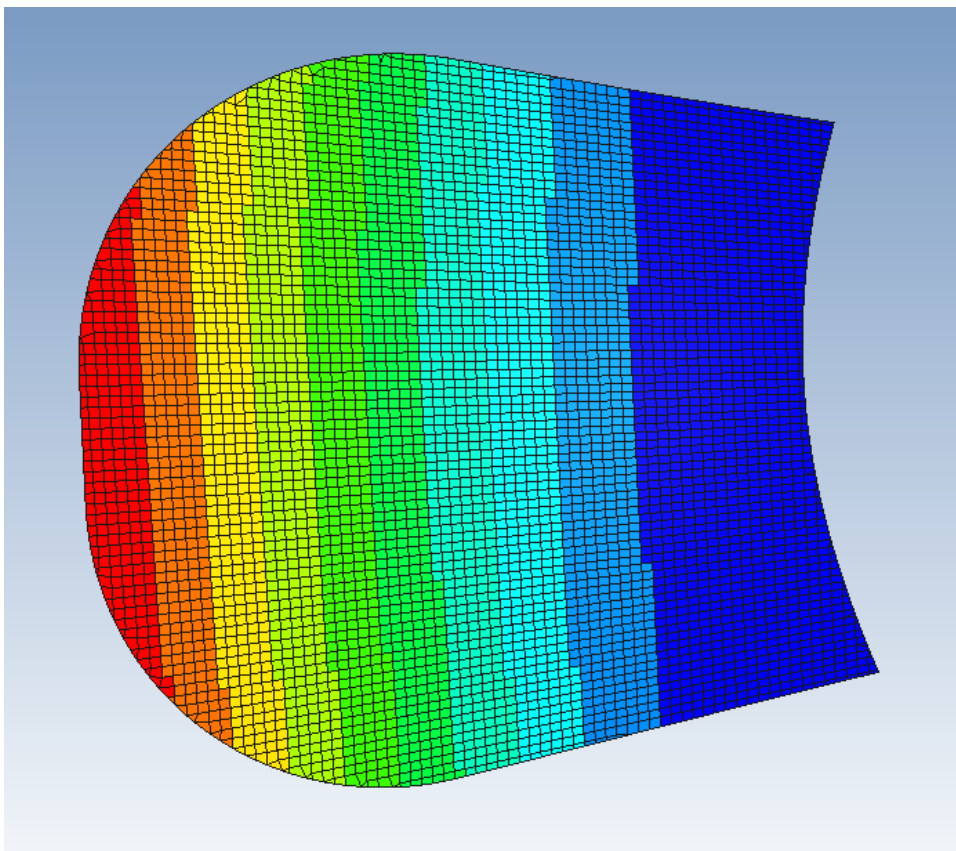
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Structural & Fluid Analysis

ACMA6010

**Assignment 2 – Designing a tanker
propeller: Structural design**

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Introduction

The purpose of this report is to investigate different methods of Finite element analysis (FEA) optimisation and to consider how FEA optimisation affects the design process. Furthermore, discussion with regards to historical and future development of FEA optimisation will take place.

Secondly an FEA study will be conducted followed by an optimisation process that aims to optimise performance of a marine propeller. A physical study will then be developed in order to compare theoretical data to practical data.

Lastly a review of technical literature will be carried out and any relevant information will be appraised and the implications of the new found information with regards to the propeller, will be considered.

1. Optimisation methods

Finite element analysis (FEA) is commonly used tool that is essential for understanding structural and fluid dynamics in many different engineering disciplines. In a mechanical engineering scenario FEA can analyse how components and assemblies will react and deform under a given load. (Heller, 2022)

The analysis can make a prediction for the stress and strain of a given component and identify areas of the geometry which will be subjected to the most deformation and is therefore likely to fail first. Highly useful information such as safe working loads and yield stress can be understood which gives an indication of the optimisation required to desired yield stress values. (Ogrodnik, 2020)

A variety of optimisation techniques are utilised in industry and depending on the problem, an engineer may select a particular method or collection of methods.

Topology optimization is a method that seeks to optimise how material is arranged within a given boundary, whilst maintaining the structural integrity of a given structure. (Inês P. Rosinha, 2015)

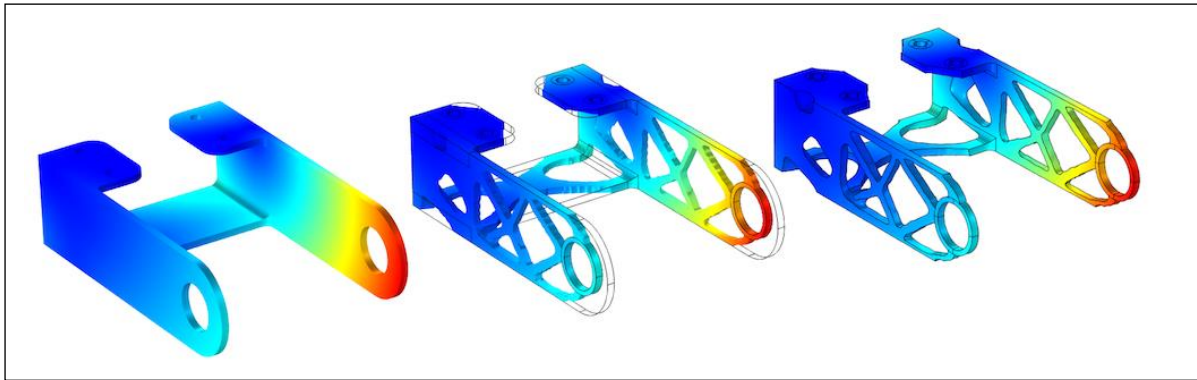


Figure 1: topology optimization (Jensen, 2019)

In Figure 1 the part has undergone topology optimisation and has resulted in the same mechanical strength whilst consuming less material. Which results in a lower manufacturing cost and lighter overall weight which can be particularly valuable in industries such as aerospace where weight is a critical property. (Jensen, 2019)

This method of optimisation is automated so the design process can be expedited by producing an ideal result first time without having to produce numerous iterations of designs and undergoing physical testing. Which is a time consuming and costly endeavour. (Querín, 2000)

Furthermore, the optimum solution may go undiscovered by engineers as bias and traditional practices have influence in the design process. Computer programs are not influenced by such things, allowing the ideal solution to be found. (Ereiz, 2022)

An alternative method is Topometry optimization. Whereas Topology optimisation is only capable of removing material within the boundaries of the material, Topometry is also capable of adding material in areas. This is due to its “element-by element method that allows users to design the dimensions of each element individually (Leiva, 2007)”. Developed in the early 2000’s, this method is relatively young within the scope of FEA optimization. (Leiva, 2007)

Other optimisation methods include

- Sizing optimisation

this method is used for finding the optimum values for key dimensions of parts, such as cross section of a tube or thickness of a bar.

- Shape optimisation

Capable of refining features of a part such as height, width, and radius of fillets in order to minimise the impact of high stress regions

- Topography optimisation

Optimises thin structures by finding ideal positions and patterns for bead structures, therefore strengthening the part where necessary.

(Leiva, 2017)

Historical developments

The discussed optimisation techniques arrived at different times during the history of this technology. The first form of optimisation was numerical optimisation which was developed in the early 1960's whereby optimisation was conducted via hand calculations. As FEA became more computer based, the more basic forms of optimisation such as Sizing emerged. Later giving way to more complex and sophisticated methods such as Topometry. (Hatfka, 2008)

Future development of FEA optimisation

As technology enhances, computers become more powerful. Current trends suggest more and more processes are being driven by artificial intelligence (AI) and machine learning (ML)

ML can “automatically generate a model using data from past experiences. (Badarinath, 2021)” Therefore, it has a wide range of applications in a variety of sectors. In recent times engineers have started researching its capabilities with respect to FEA. (Badarinath, 2021)

The models generated by ML algorithms will typically be far closer to the optimum solution than a human developed model. Therefore, FEA optimisation requires far less computing power when finding an ideal solution. Thus, reducing the cost of the FEA optimisation process. (Mohammed, 2021)

As this trend continues and algorithms become more capable, traditional FEA will play less and less of a roll in the optimisation process.

2. FEA analysis of a propeller blade

To estimate the force exerted on the propeller, the output force vectors are considered.

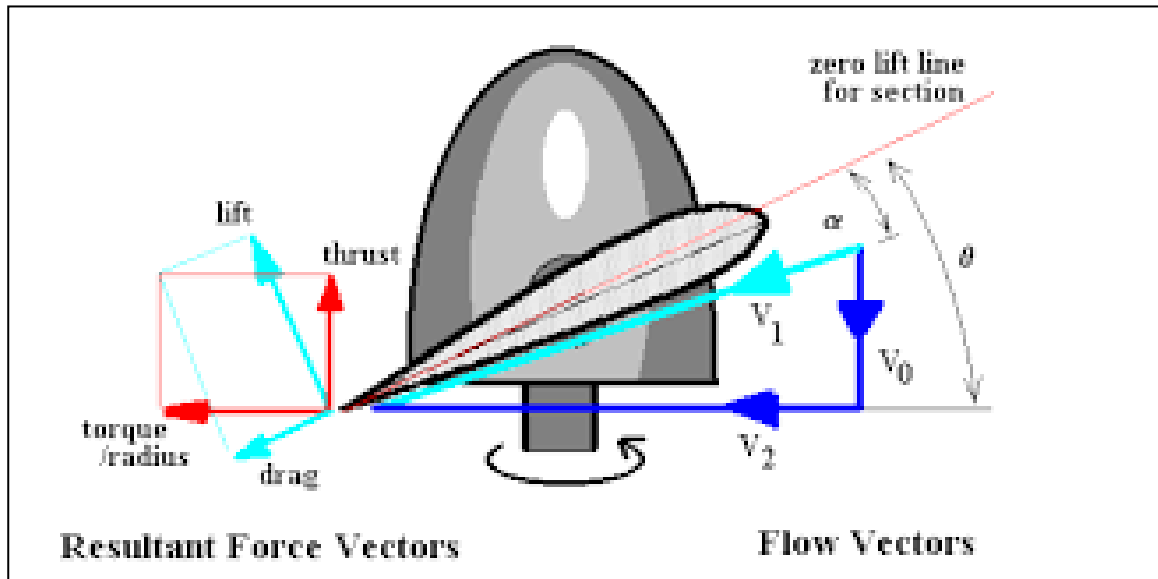


Figure 2 Force vectors of a propeller (University of Sydney, 2006)

Figure 2 Force vectors of a propeller shows that the force vector acting perpendicular to the propeller is Lift. Since Newton's third law states that "for every action (force) in nature there is an equal and opposite reaction. (NASA, 2022)" It can be assumed that the lift generated is equal to the force exerted on the propeller. (NASA, 2022)

Lift equation

$$L = C_L \times d \times \frac{V^2}{2} \times A$$

Where;

L = Lift

C_L = Lift Coefficient

d = density of fluid

V = Velocity of fluid

A = propeller Area

Lift coefficient

Lift coefficient is a value that is typically determined via experimental methods. This value depends largely on shape, size, and angle of attack of the propeller.

A 2017 study “Numerical study of marine propeller performance” analysed a similar propeller and determined that the lift coefficient (C_L) varies depending on the cross section of the propeller that was being analysed. The average value observed was 0.26 (unitless). Therefore, the value of this propeller is assumed to be 0.26 (Saha, 2017)

Density of fluid

The average temperature of surface seawater is 20°C, therefore the fluid is assumed to be 20°C. (Scripps institution of oceanography, 2014)

The density of seawater at 20°C is 1024 kg/m³.

Velocity of fluid

Figure 2 shows that the velocity of the fluid inflow (V_1) is the resultant of axial flow at the propeller disk (V_0) due to the forward motion of the vessel, and angular flow (V_2) due to the rotation of the propeller. (University of Sydney, 2006)

From fluid flow assignment.

“ V_2 - Rpm of typical tanker engines can range from 300 to 900 rpm. So, for the purpose of this report the rpm's is assumed to be 600.

The radius of the propeller is the distance from the centrepiece to the outside of the propeller blade. As per the drawings, the length of a propeller blade is 2838.28mm

I have assumed the centre piece of the propeller to be 750mm in diameter.

$$\text{Therefore, radius} = \frac{2838.25 + 750}{2} = 3213.25\text{mm}$$

or 3.21325m

$$v = \frac{2\pi r}{60} \times N, \text{ where } N \text{ is angular velocity (RPM)}$$

$$V_2 = 201.894 \text{ m/s}$$

V_0 -Average speed of an oil and chemical tanker is 13 to 17, so the velocity of the tanker is assumed to be 15 knots

$$15 \text{ knots} = 7.72 \text{ m/s. (Lang, 2022)"} \text{ (Lang, 2022)}$$

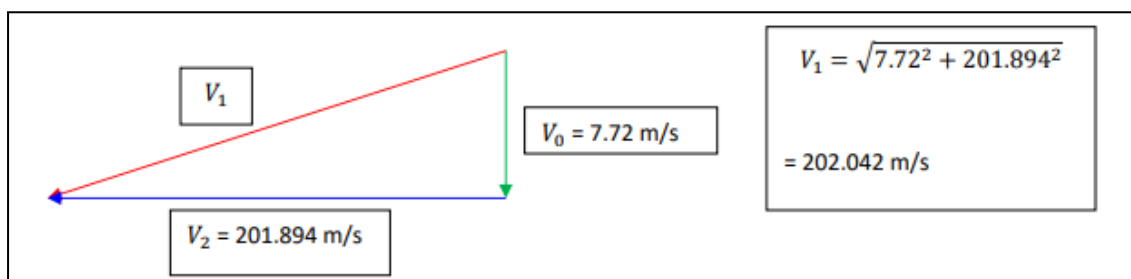


Figure 3 resultant velocity vector (Lang, 2022)

Area

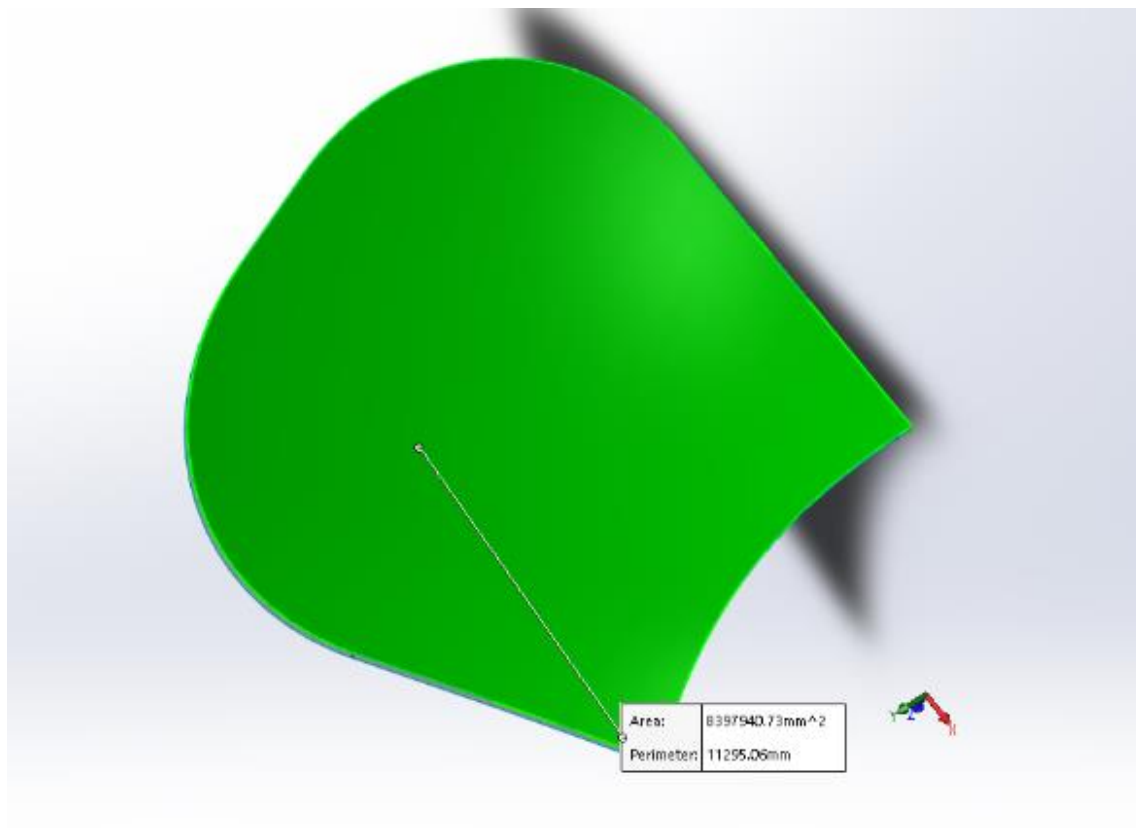


Figure 4 Area of propeller blade

From Figure 4 area of the propeller blade is 8397940.73 mm^2
 $= 8.40 \text{ m}^2$

Lift (force normal to propeller)

$$0.26 \times 1024 \times \frac{202.042^2}{2} \times 8.4 = 47,452,000 \text{ N}$$

or

47,452 kN

Load distribution

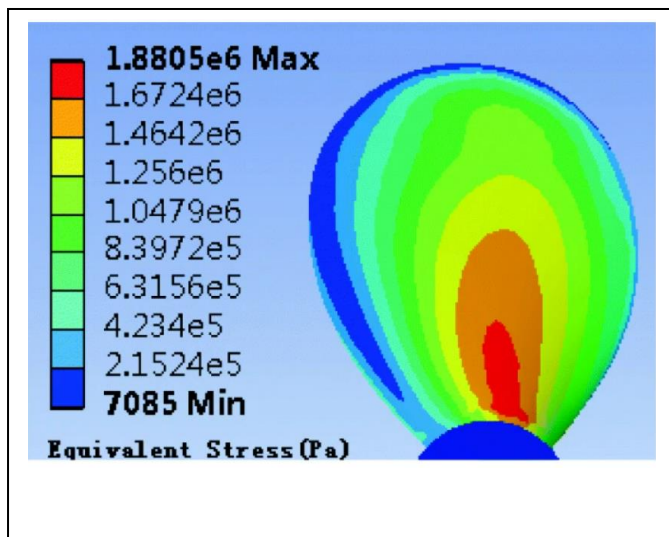


Figure 5 stress distribution example 1 (Yu, 2020)

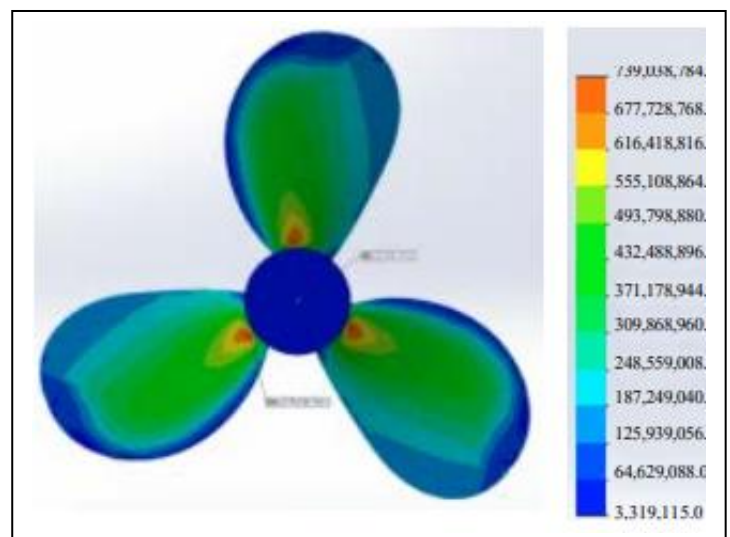


Figure 6 stress distribution example 2 (Yeo, 2014)

Figure 5 and Figure 6 are examples of independent computational fluid dynamics (CFD) studies regarding marine propellers. Each study shows that the highest stress regions are the regions at the centre of the propeller where the fluid inflows. This stress gradient decreases as the fluid moves away from this region.

To replicate this load distribution in a FEA model, Figure 5 was separated into 3 sections of high, moderate, and low load. The ratio of the force exerted on each section was used to model the load case for the FEA model of the CFRP propeller.

This model is a simplified version of the distribution in Figure 5 so is not a perfect representation but is sufficient for this model.

Table 1 Load distribution for CFRP propeller

REGION	NODES	STRESS ON FIGURE 5 (Pa)	% OF FORCE	FORCE PER REGION (N)	FORCE PER NODE (N)
HIGH	801	1.88E+06	0.262551659	12458601.31	15553.80937
MODERATE	1608	1.05E+06	0.146305708	6942498.436	4317.474152
LOW	2415	4.23E+06	0.591142634	28050900.26	11615.27961
TOTAL	4824	7162400	1	47452000	31486.56313

Table 1 details how the load distribution was calculated for each region highlighted in Figure 7. The stress values in Figure 5 were used to determine the ratio of force in each region. The ratios were then used to calculate a total force of each region. This value was divided by the number of nodes in each region so that the force exerted on each node was known.

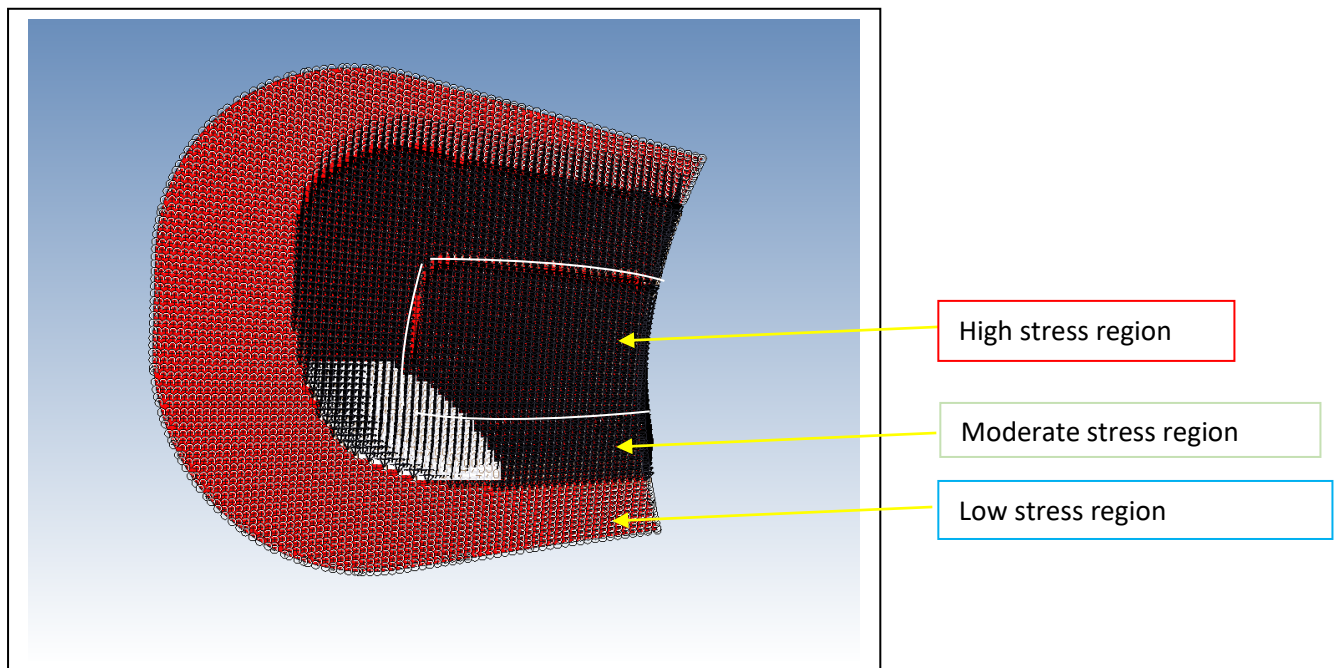


Figure 7 Load distribution of CFRP propeller

Fixed area

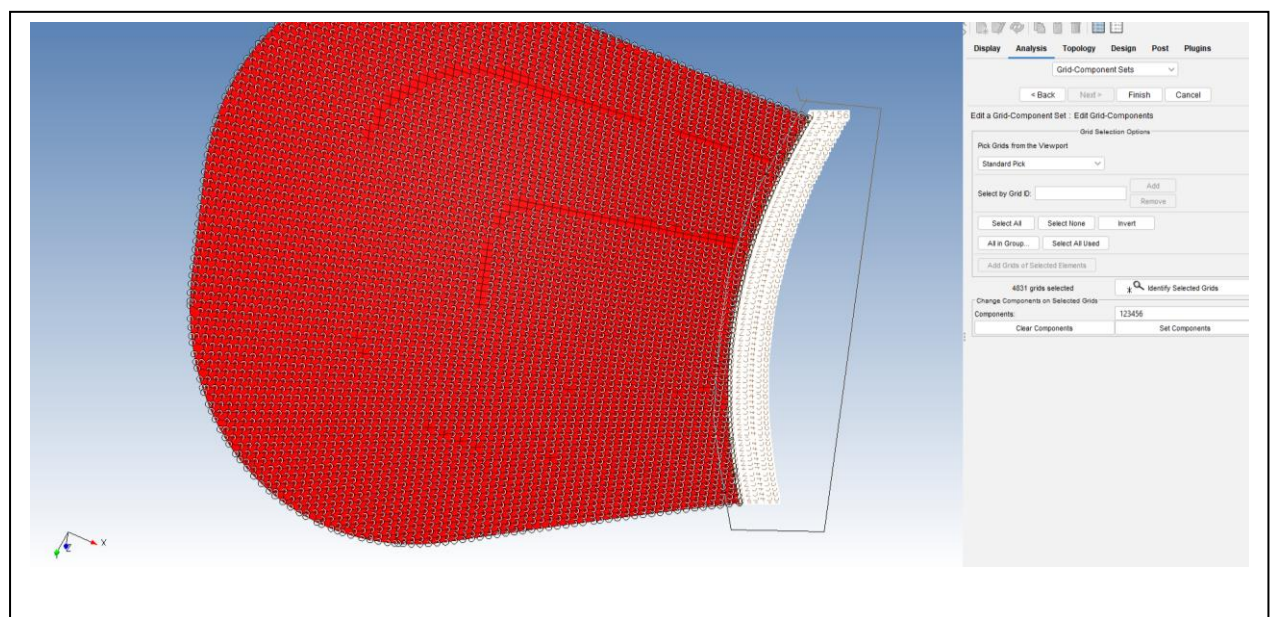


Figure 8 Fixed area of CFRP propeller

Figure 8 illustrates how an area was drawn around the base of the propeller in order to fix those nodes. This fixed area represents a weld bead that would be used to fix the propeller to the

Genesis single analysis

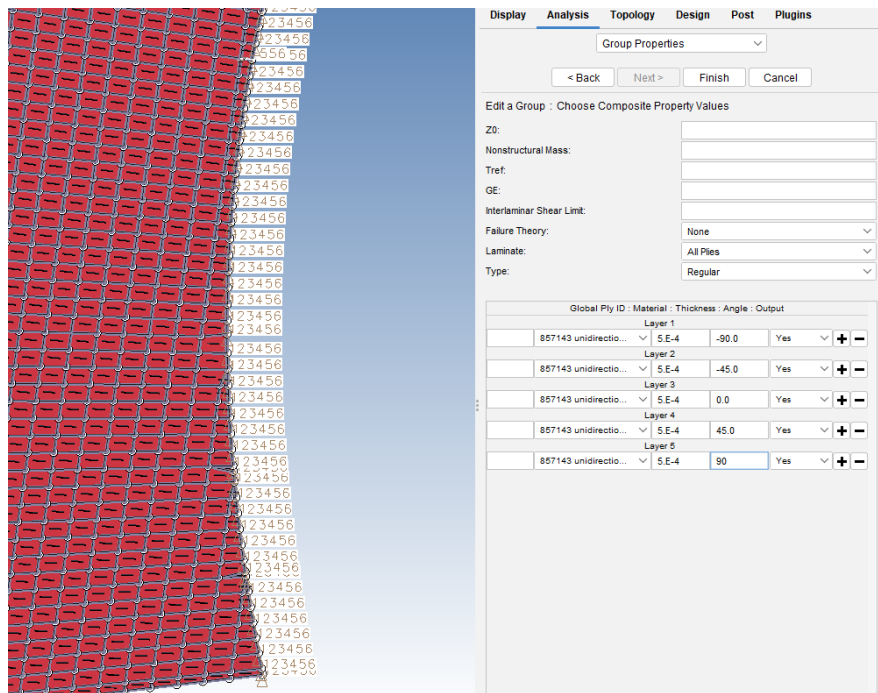


Figure 9 Layup and theta vectors

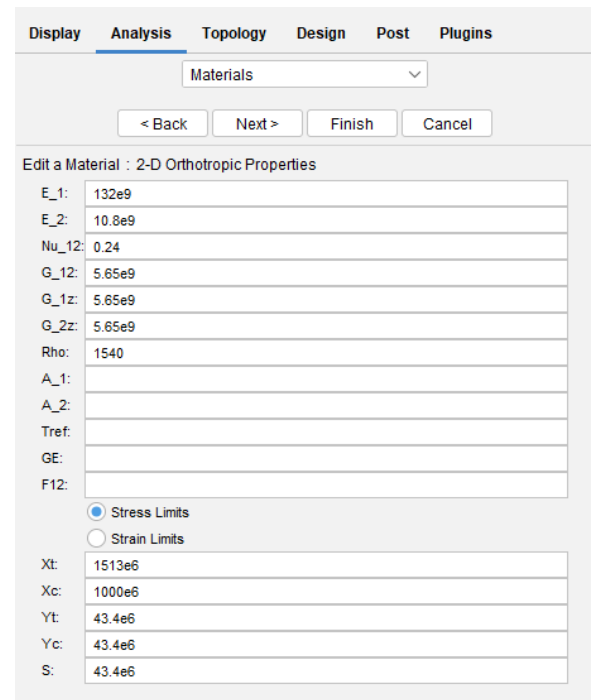


Figure 10 Material properties

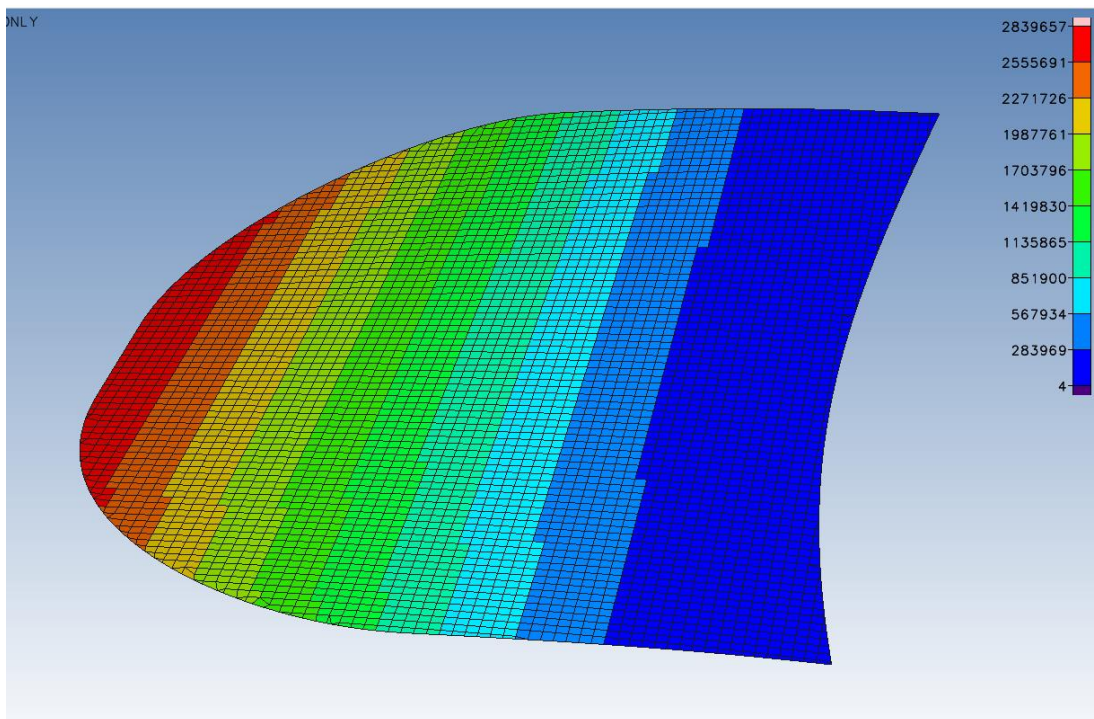


Figure 11 deflection of propeller

Table 2 CFRP propeller summary

Run	Material	Thickness(m)	Deflection (m)	Mass (kg)	Load (kN)	Stiffness (N/M)	Stiffness/weight (N/M ²)
Composite propeller	Composite	0.0025	2839657	32.3337	47452	16.71	0.057

3. optimisation of a composite propeller

Design rules

- Maximum deflection of 100mm
- Minimum possible mass

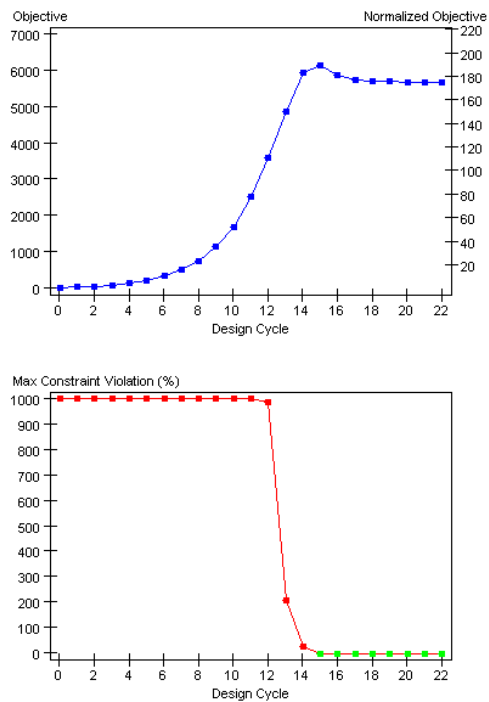


Figure 13 design cycles by weight and deflection respectively

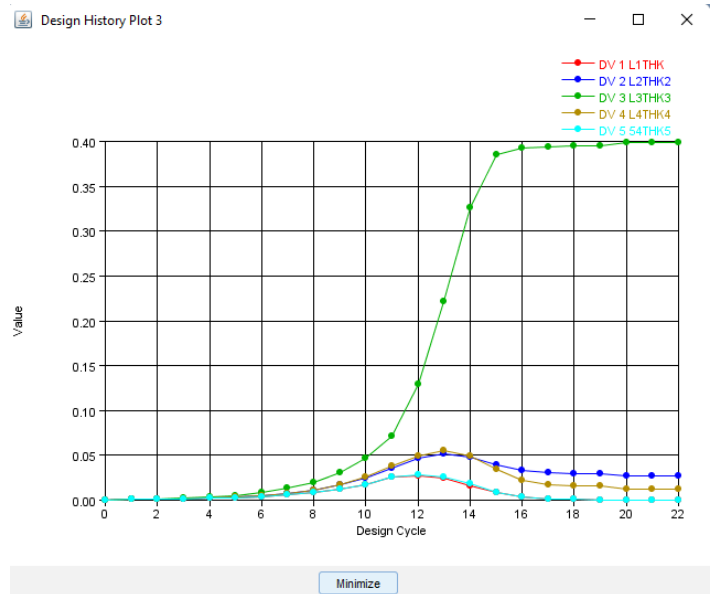


Figure 12 design cycle by ply thickness

Table 3 details the thickness of each layer after 22 design cycles.

Table 3 number of plies per layer

Layer	Thickness (m)	Thickness (mm)	Number of plies
1	2.00E-04	0.2	2
2	2.68E-02	26.8	268
3	3.99E-01	399	3990
4	8.30E-03	8.3	83
5	2.00E-04	0.2	2

Table 4 summarises the propeller properties after 22 design cycles.

Table 4 Optimised propeller summary

Run	Material	Thickness(m)	Deflection (m)	Mass (kg)	Load (kN)	Stiffness (N/M)	Stiffness/weight (N/M ²)
Composite propeller	Composite	0.0025	2839657	32.3337	47452	16.71	0.057
Optimised propeller	Composite	0.4367	0.099	5648	47452	4.79x10 ⁸	8645.14

4. Designing a physical test

Simulating conditions

The experiment should be carried out in a water tunnel. This allows conditions that the propeller would typically experience, to be replicated in a controlled environment.

The water tunnel can be configured to collect data to suit the needs of the experiment. This can be with regards to the fluid flow and the lift/drag generated when fluid passes over a physical object. Or in this case the behaviour of the physical object.

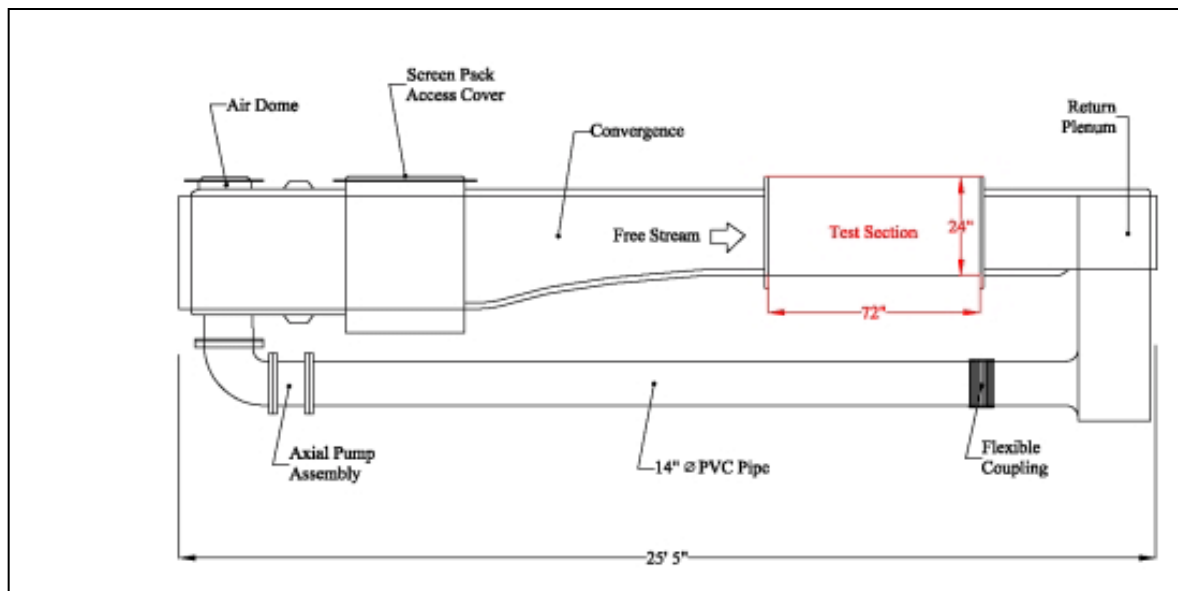


Figure 14 Water tunnel schematic example (Vlachos, 2022)

The size of the prototype that can be tested is limited by the size of the Test section on the water tunnel being used. The test section example detailed in Figure 14 is 72" (1828.8mm) in length and 24" (609.6mm) in width. therefore, in order to test the prototype in this tunnel, it would need to be scaled down significantly since its diameter of a full-scale prototype would be roughly 6.5m.

Similarity

Whenever scaling is used, it is critical that similarity considerations are taken in order to accurately represent the behaviour of the true scale model.

Different types of similarity that should be considered are;

- Geometric similarity
The prototype and the full-scale product identical in shape, the only difference being their size. (Subrata, 2005)
- Dynamic similarity
The force experienced by the model and the prototype differ by a scale factor that is consistent when multiple points are considered. (Jha, 2004)
- Kinematic similarity
"The velocities at 'corresponding' points on the model and prototype are in the same direction and differ by a constant velocity scale factor. (Jha, 2004)" (Jha, 2004)

Additionally, the prototype should be manufactured using the same material and manufacturing methods as the model.

To accurately represent the stress distribution experienced by a propeller the fluid flow would need to be representative of a real-world scenario.

To achieve this the fluid in the water tunnel will be flowing at a velocity that has been scaled with similarity in mind.

Furthermore, the propeller would be connected to a motor that rotates at an RPM that has been scaled with similarity in mind. This ensures the fluid will flow outwards due to the centrifugal force and will apply a representative stress distribution.

Measurement technique

An appropriate method to measure the deflection of the blade is via stereo imaging whereby the propeller blade would be marked with points that are identified by a camera system and their relative position to the camera is recorded and any change in that position is monitored.

By using a grid of points that ensure whole coverage of the propeller, software can then be used to visualise and quantify the deflection rate and maximum deflection of the propeller. (Savio, 2015)

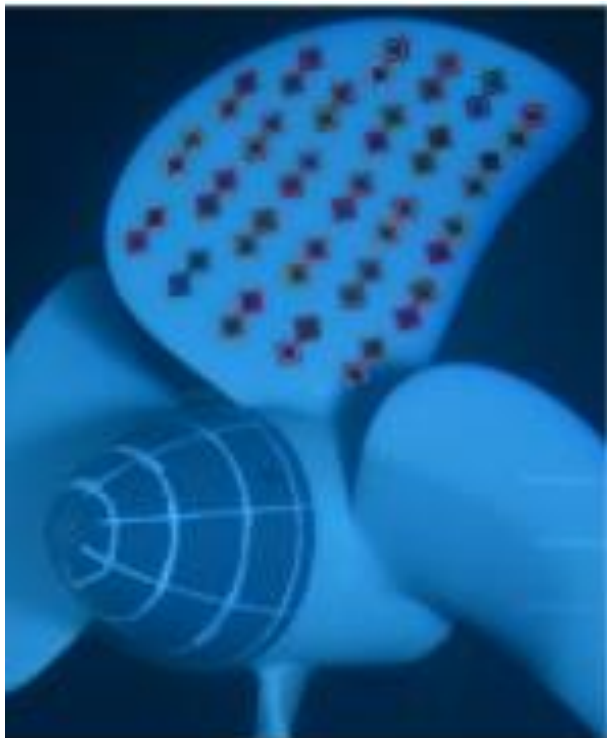


Figure 15 Marked propeller blade (Savio, 2015)

Figure 15 is an example of how a propeller can be marked for the purpose of movement tracking. The grid pattern is identified by two separate cameras that are positioned at different angles. Movement is recorded by the cameras and the images are overlayed in order to accurately determine the position of each reference point. (Savio, 2015)

In the human body, two images are observed via the eyes and are processed by the brain in order to create one image with depth perception. Figure 16 shows how a camera system can be set up to replicate this principle. (Sawano, 2001)

It is important that the tracking marks are embedded into the laminate and not embossed/debossed as this could affect the results of the experiment

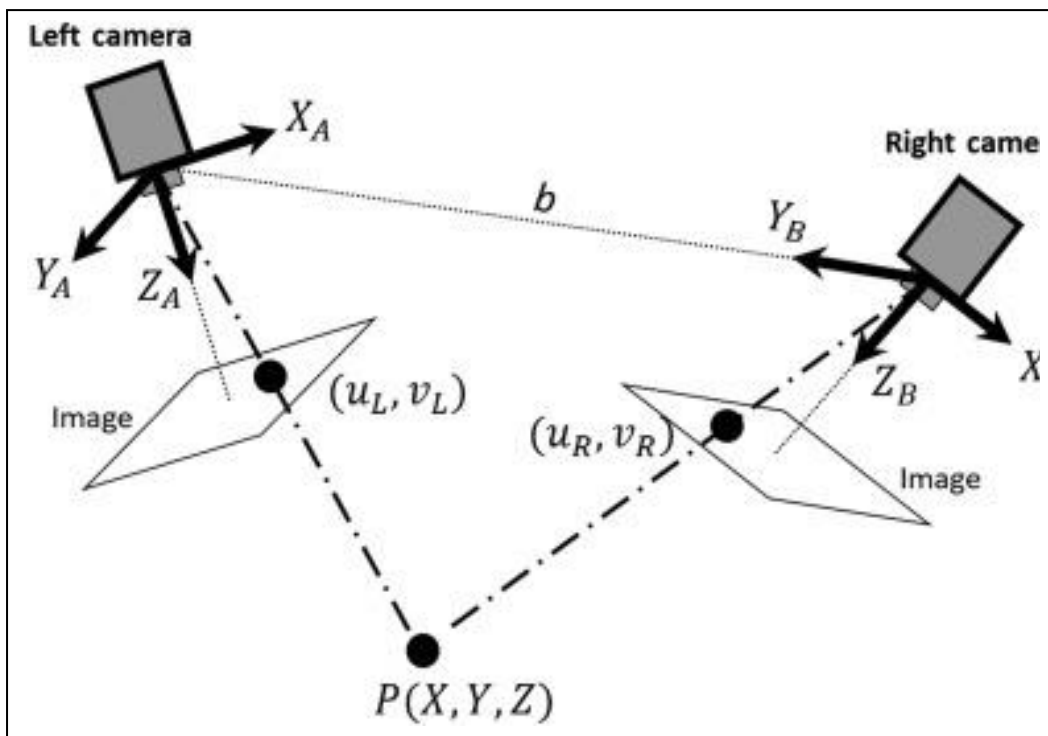


Figure 16 Stereo imaging setup (Gul, 2021)

Comparing data

The deformation recorded by the stereo imaging will be representative of the scaled model. In order to compare the results to that of the FEA analysis of the full-scale model, the data needs to be scaled up appropriately.

The experiment should be carried out multiple times to ensure the data sets are agreeable and are relatively similar. This ensures there is no anomalous data included in comparison to the FEA study. Therefore, allowing a greater degree of confidence in the results.

The results from the physical test can be compared to the FEA model to determine a margin of error. The lower the margin of error the more confidence can be had in the results. A Margin of error of less than 5% is desirable. (Deitz, 1995)

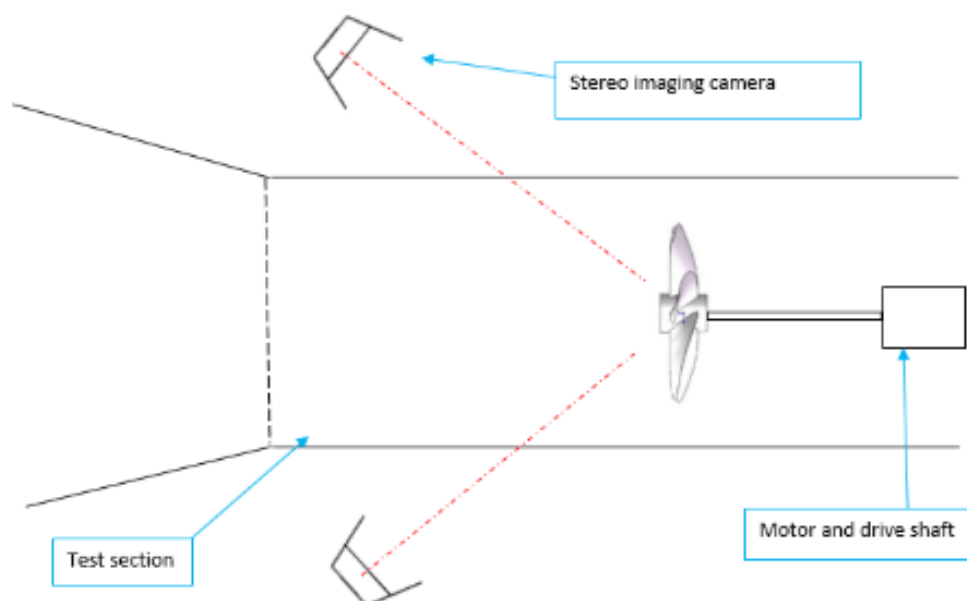


Figure 17 Schematic of test, top-down view

5. literature and standards review

Material selection

In recent history, marine propellers have traditionally been constructed using varying grades of Steel or Nickel-Aluminium-Bronze (NAB). However, this method of construction has become less prevalent in the last twenty years, Giving way to an era more focused on composite materials such as glass fibre, graphite fibre and in the case of the propeller in this report, carbon fibre reinforced polymer (CFRP). (Vardhan, 2019)

Table 5 Property comparison of propeller materials (Kumar, 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 (KG/M³)	1350-1850	2650	7550	8220
THERMAL CONDUCTIVITY (W/M.K)	20	117	42	80
POISON RATIO	0.27	0.33	0.32	0.34

Table 5 shows that CFRP has the highest Tensile strength whilst also recording the lowest density out of the materials considered. These properties make it a highly desirable material for structures such as propellers. Its unique advantage however, is its ability to elastically deform according to the static load exerted on it.

This is significant implications on performance as the propeller can deform and perform optimally over a range of rotation speeds. This contrasts with a traditional metallic propeller that has high rigidity and is designed to perform optimally at a certain speed. (Motley, 2011)

To meet the same thrust requirement as a metallic propeller, the CFRP propeller must rotate at a higher speed. This is as a result of the elastic deformation that alters the angle of attack of the propeller blade. However, this same feature is responsible for vast improvements in cavitation performance. This ability to deform depending on load is extremely beneficial in conditions that vary such as the open sea. (Motley, 2011)

However, with regards to the FEA model and physical tests, higher RPM's and therefore a higher load due to the increased fluid flow may be required in order to represent the behaviour of this material when operating at the target thrust.

A higher deflection would be expected resulting in a higher thickness of propeller once the optimisation process is repeated with this higher rotational speed considered.

Standards

BS ISO 484-1:2015

This standard covers “Shipbuilding. Ship screw propellers. Manufacturing tolerances – Propellers of diameter greater than 2.50m. (BSI, 2015)”. So is therefore relevant to the propeller that is the subject of this report since its diameter is roughly 6.5m (BSI, 2015)

This standard details manufacturing tolerances allowed on this propeller with regards to the pitch of the blades, the thickness of the blades and other relevant features. Guidance is also given on how to measure these tolerances and ensure the standard is adhered to. (BSI, 2015)

Should the pitch of the CFRP propeller need to be adjusted in order to comply with these standards. The force exerted on the propeller would change. Therefore, the optimisation process would need to be repeated with the new load case considered.

ClassNK

ClassNK is a global organisation that provides guidelines for the ship building industry with the view to promoting safety at sea and preserving the marine environment. (ClassNK, 2022)

In 2015 they released the first set of guidelines that explicitly address the use and construction of composite propellers. Some key points of the guidelines are that CFRP propellers must perform at least equal to aluminium-bronze composite propellers. To ensure the propeller that is the subject of this report meets this criteria, Re-optimisation may be necessary with new design rules that specify the performance of aluminium-bronze propellers as minimum targets for the CFRP propeller. (ClassNK, 2022)

Furthermore, the ClassNK guidelines details that the propeller must be manufactured with uniform quality. To ensure the CFRP propeller is compliant with this rule, the geometry of the propeller and the manufacturing method must be considered. It is possible that the current lay up of the propeller is not capable of being manufactured with uniform quality. In this case further optimisation may be required with new rules with regards to ply thicknesses that would ensure a uniform quality throughout. (ClassNK, 2022)

Conclusion

FEA optimisation has vastly improved the design process by eliminating time consuming manual design revisions. Instead, optimum solutions can be found via a semi-automated process. A variety of FEA optimisation methods are available to use, each with their own pros and cons that make them suitable for a variety of tasks.

Genesis design studio is a FEA software capable of analysing complex structures with complex load cases. Analysis that could take an engineer weeks or months to complete by hand can be carried out in a matter of hours. Highly useful information such as maximum displacement, stress and strain can be determined.

Where values such as maximum displacement are not acceptable, optimisation can be utilised. Rules can be dictated (e.g., max displacement of 100mm) and the software can carry out design iterations until the goals are achieved. This process is automatic once the rules and constraints have been inputted by the designer. Making this an invaluable time saving tool.

To ensure computer models are a reliable and credible source of information. Physical studies can be carried out in order to compare the sets of data and determine a margin of error. This helps to understand the level of confidence that can be placed in FEA models.

There are several standards that are required to be followed when designing components such as composite propellers. By being aware of these prior to the design process the product can be designed with these design rules in mind, therefore saving costly design and FEA resources. Furthermore, a vast amount of technical literature with regards to these components is available, it is advisable and beneficial to be aware of this as this allows the designer to be informed of latest advances in research and to therefore apply any concepts to their design.

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