

DESIGNING A TANKER PROPELLER: STRUCTURAL DESIGN

ACMA6010 – Level 6

Structural and Fluid Analysis

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Part 1:

What is Finite Element Analysis?

Finite element analysis (FEA) is a software tool that allows you to review and simulate how a material/structure behaves under force and how fluid flows around the structure. The software can be useful when needing to visualise the aerodynamics of a structure and is commonly used by Engineers in businesses such as Formula 1 motorsport and the aerospace industry where fluid resistance and high stresses are extremely important and safety critical in most cases. FEA allows businesses to fully optimize their designs before prototyping, therefore since FEA has been introduced this has saved companies millions in time and money due to the reduction in prototypes required. (TWI, 2022)

History of Finite Element Analysis:

FEA development was first started in the 1950's by the following companies in the aerospace industry, Boeing, Bell Aerospace & Rolls Royce. In the early 1960's the first program was publicly released by a Professor E. Wilson at Berkeley university. This software was used by many universities due to it being freeware and it continued to grow and get developed rapidly for several years. In 1965, NASA funded a 3million dollar project to develop a more capable FEA software. This resulted in the program NASTRAN being created. Initially NASTRAN was released as freeware but soon after was commercialized.

(Tipton, 2017)

FEA Techniques:

There are a number of FEA optimisation techniques such as:

- Stress analysis for weight reduction – This is a technique used to design a component with a minimal amount of weight and material but still be able to achieve the strength required. This technique not only reduces waste but also reduces the cost of the component and can sometimes improve the components performance depending on its use. The technique has been developed over the years due FEA's optimisation tool becoming more advanced and accurate. For example, in design studios you can set a minimum mass objective.
- Topology optimization – This is an algorithmic process that gives you the most efficient design based on constraints and/or characteristics, this is often done by removing material from the design. Topological optimization techniques help users work around the limitations of pure shape optimization.
- Thermal gradient optimisation – Over the years engineers have realised the importance of the extension from structural finite element analysis to a thermal FEA solution isn't too different. In fact, there are direct analogies, displacement becomes temperature, then in the matrices stiffness becomes thermal conductivity.
- Shape optimization – Shape optimisation is a method used to also reduce mass but mainly ensure that the shape will achieve what is expected of it functional wise. For example, a bike frame has gaps between it, this is to reduce the weight of the bicycle along with reducing surface air which impacts air resistance. Both air resistance and mass directly impact the bicycles performance therefore this technique is extremely useful.

(Mechanika, 2022), (Autodesk, 2022), (Ananthasuresh, 2008)

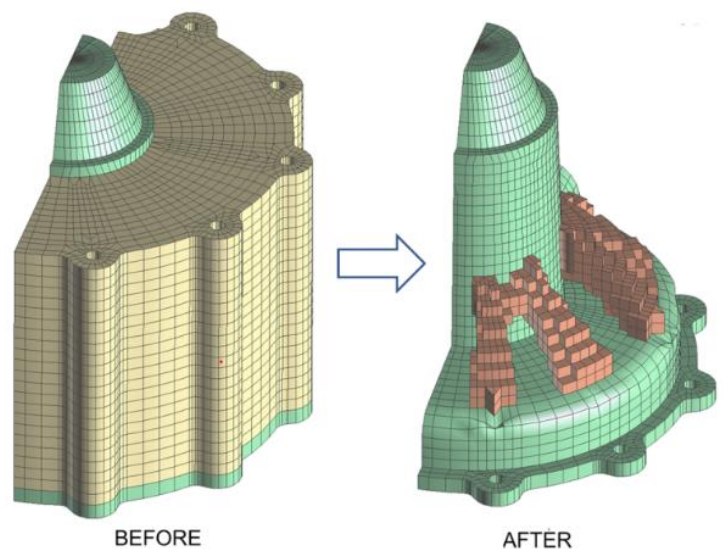


Figure 3a

Future FEA Development:

FEA software companies are now looking at merging their software packages with CAD to enable everything to be in one place for the user. In my opinion this will not only rise the price of the packages for their customers but could pose some risks to companies if a CAD draughtsman who is not competent with stress calculations was to carry out a stress calculation incorrectly on the FEA side of the software and design a structure which was too weak then it could be a potential danger. Another upgrade that FEA companies are looking into developing and expanding on is the way multiple structures interact with each other.

(Cuillière & Francois, 2014)

Impact FEA has on the design process:

Since the introduction of FEA within industries, design engineers have benefitted hugely. FEA allows the engineers to optimise their design fully before having to even step foot onto a machine factory floor or laboratory. The software allows the engineers to look at what effect sub-zero temperatures and levels of vibration have on the structure, along with a lot more properties such as stress, buckling, fatigue, creep, heat and so on. FEA not only speeds up the design process, but it saves on prototyping also.

(HAUGHTON DESIGN, 2022)

Benefits and advantages of FEA in design:

- Simulation of extreme scenarios that even the most expensive high tech equipment cannot simulate, meaning a more reliable design concept.
- Reduction in prototyping, therefore generating a cost saving.
- Reduction in material costs due to being able to slim down and optimise the structure to a minimum mass.
- Removes the risk of manual calculation errors in comparison to the old method of structural analysis.
- Speeds up the design process due to the structure being virtual with the ability to implement large changes in a matter of seconds rather than hours.
- Visualisation of the deflection, stress, strain.

(Marketing Indovance, 2021)

Part 2:

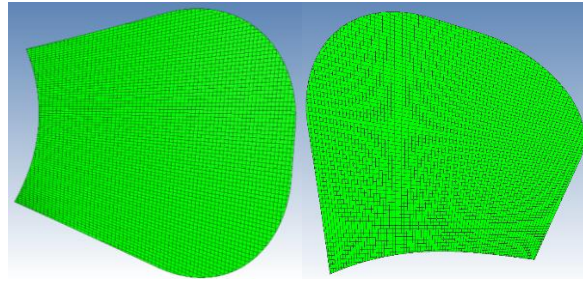


Figure 5a

Figure 5b

A model of a marine propeller blade was imported into the Design Studios from a given CAD model that had been drawn up on Solidworks (Figures 5a & 5b). Initially the blade was made from steel due to this being Design Studios default material. As you can imagine this made the blade quite heavy and inefficient for its design intention. As per assignment brief the material was then changed to unidirectional carbon fibre reinforced plastic (CFRP) by inputting the below material properties into the software (Figures 5c & 5d):

Property	Value
E_1	1.32E+11
E_2	1.08E+10
Nu_12	0.24
G_12	5.65E+9
G_1z	5.65E+9
G_2z	5.65E+9
Rho	1540.0
A_1	
A_2	
Tref	
GE	
F12	
☒ Stress Limits ☐ Strain Limits	
Xt	1.513E+9
Xc	1.E+9
Yt	4.34E+7
Yc	4.34E+7
S	4.34E+7

Figure 5c

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

Figure 5d

Due to the material having different levels of deflection in different directions I needed to orientate the elements relative to a vector which the material would flex the most in. I did this by going into elements, selecting all and then changing the theta vectors to be displayed in the X axis instead of the Y axis. This meant the vectors were travelling in the direction from the centre of the propeller to the tip of the blade.

The material was then laid up with 25 unidirectional plys. 5 ply at -90 degrees, 5 ply at -45 degrees, 5 ply at 0 degrees, 5 ply at 45 degrees and 5 ply at 90 degrees. The thickness of each ply was 0.5mm. Totalling an initial material thickness of 2.5mm. This weighed in at 32.33Kg. The reason this material has plys is because it is isotropic, meaning it has the same material properties when tested in different directions, this is due to it having multiple layers laid in different orientations. The group properties can be seen to the right in Figure 5e.

Global Ply ID	Material	Thickness	Angle	Output
857143 Unidirectional	5.E-4	-90.0	Yes	+ -
857143 Unidirectional	5.E-4	-45.0	Yes	+ -
857143 Unidirectional	5.E-4	0.0	Yes	+ -
857143 Unidirectional	5.E-4	45.0	Yes	+ -
857143 Unidirectional	5.E-4	90.0	Yes	+ -

Figure 5e

Next the constraints had to be added to the blade. A constraint was added to the side of the blade that connects to the boss (centre of propeller) this can be seen below in Figure 6a:

The highlighted region was chosen as a completely fixed constraint, therefore having 0mm movement capability within its 6 degrees of freedom. This is due to this section of the blade being connected to the boss of the propeller, I chose a thicker region rather than just the end nodes because most propeller blades are welded on, and the weld will have a thickness that constrains more than just the end nodes of the blade.

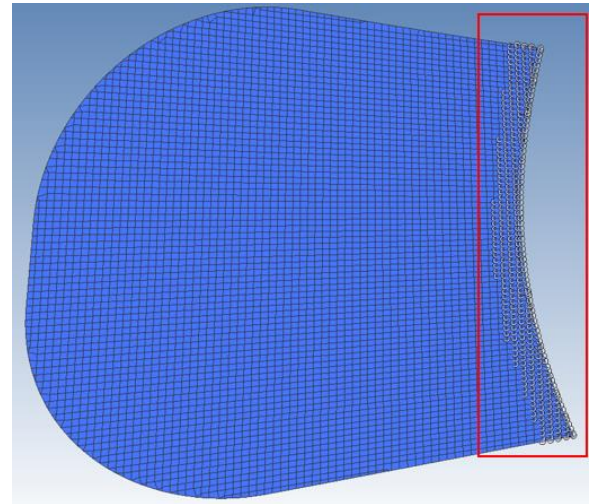


Figure 6a

A displacement constraint was set so that all nodes on the blade could only deflect a maximum of 100mm in any direction. This was a target deflection set in the assignment brief. Below in Figure 6b shows all of the nodes that the constraint applied to:

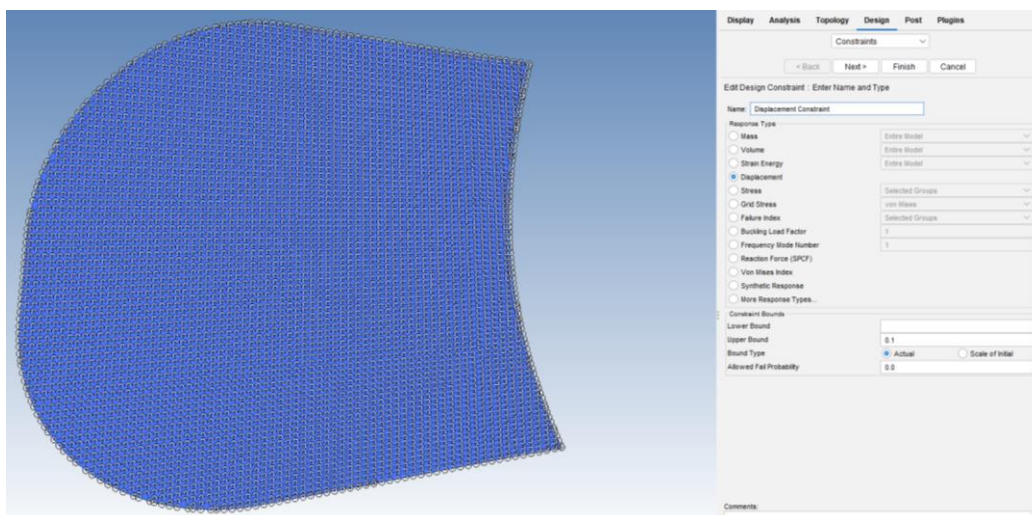


Figure 6b

Due to wanting to minimise the mass I set this as the objective when optimising.

In the below table you can see my initial statistics for both Steel and CFRP before the optimisation:

Initial Mass CFRP (Kg)	Initial Mass Steel (Kg)	Initial Displacement CFRP (mm)	Initial Displacement Steel (mm)	Initial Thickness CFRP (mm)	Initial Thickness Steel (mm)	Initial Stress(KN/m ²)/Strain CFRP	Initial Stress/Strain Steel (Units)
32.33	646.67	16200	140	5mm	10mm	810,000/0.023	130,000/0.00043

Comparison between how the Steel and CFRP blade acted:

As you would expect, the mass of the 10mm thick steel blade is a lot greater than 5mm CFRP blade due to its density and light material properties. Looking at the displacement of each blade, it performed just how I would have expected it to with the thicker and heavier steel blade deflecting less than the CFRP. Thicknesses were determined by the standard default steel thickness and the assignment brief layer thicknesses. The stress and strain on both blades were seriously high due to the blade displacing by a huge unrealistic amount, in the real world this would have broken and snapped the blade.

Calculating the force acting on the blade -

The formula to calculate force acting on a surface submerged in a liquid is:

$$F = p_a A$$

Formula breakdown and symbol meanings:

$$F = p g h_a A$$

F = Force (N)

p_a = Average pressure on a surface (Pa)

ρ = Density (Kg/m^3)

g = Gravity (m/s^2)

h_a = Average depth (m)

A = Area of submerged surface (m^2)

(Engineering ToolBox, 2011)

Assumptions:

- The blade will be submerged in sea water (salt water). Having done research, the approximate density of sea water is $1030 \text{Kg}/\text{m}^3$.
- The sea water will be at 21 degrees Celsius, this is based off an average sea temperature of the Atlantic ocean.
- The dimensions of the propeller blade are the same as the given propeller model in assignment 1 (see Figures 7a & 7b). The diameter of the propeller therefore is 7.03 metres. This is presuming that the boss is approximately 18% of the blades span, which is 1.07 metres in diameter. I made the presumption that the boss diameter is 18% of the blades span by looking at dimensioned drawings of propellers and taking an average ratio.

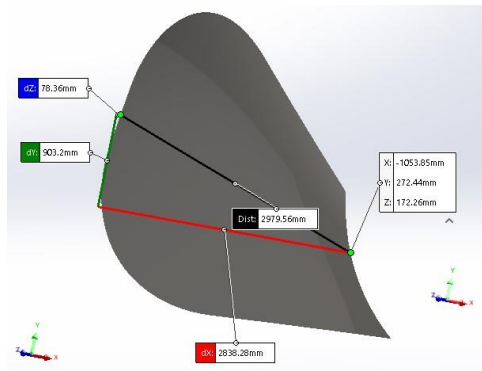


Figure 7a

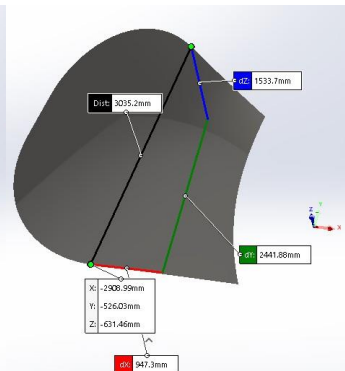


Figure 7b

- The blade will be submerged fully in the water at the depth of 28.25m. This is based off some research which follows: The average hull depth of a cargo boat is around 30m deep. It is recommended that the centre of the propeller is around 25% of the propeller diameter in length away from the boats hull.
- The propeller is turning at the velocity of 170rpm - $17.8024 \text{rad}/\text{s}$. This number is based on an average speed that is typical for a large commercial propeller to spin at, due to them rotating at a range of speeds between 90 to 250rpm.
- I have presumed that the surface of the blade will be flat and rectangular in shape for ease of calculation purposes, and due to not being able to accurately calculate the force on a curved surface without having CFD software availability. I understand that this will leave the force result I retrieve from the calculation below with a small degree of error due to the area not being accurate.
- Due to the density being so large the buoyancy would be so small it is not worth considering, therefore I am assuming that the buoyancy is zero.

(LaValley, 2002), (SeaTemperature, 2022), (Garrido, 2019), (WÄRTSILÄ, 2022)

Calculations:

Force acting on the propeller blades face

$$F = 1030(\text{Kg/m}^3) \times 9.81 (\text{m/s}^2) \times 28.25(\text{m}) \times 9.04(\text{m})$$

$$F = 2580.44\text{KN}$$

Centrifugal force acting on propeller blade

$$F_c = mv^2/r$$

m = Mass of blade

v = Velocity of propeller

r = Radius of the propeller (length of blade)

$$F_c = 32.33 \times 17.8024^2 / 2.980$$

$$F_c = 3438.32\text{N}$$

(Get Education Skills, 2021)

Conclusion of calculations:

My first calculation above concludes that there should be a UDL of 2580.44KN on the blades face. Due to the face having 4951 nodes within design studios this would mean that each node would have a load of 521.19N. I realized that this figure was too great of a load for such a thin propeller and therefore reviewed my calculations. I confirmed that I was working in SI units and justified my figures again below:

Gravity – Known Value - 9.81m/s²

Area – Length x Width of given blade dimensions – 9.04m

Density of sea water – Researched - 1030Kg/m³

Depth of propeller – Researched – 28.25m

After reviewing I was happy there were no errors, but to be able to get a more realistic result and simulation I decided to use 0.6N load on each node (2.97KN in total). This would also give me a more realistic thickness and therefore weight result when optimising.

My second calculation gave me an overall centrifugal force value of 3438.32N. Meaning there would be a centrifugal force of 0.694N on each node which seemed a reasonable amount of force to expected therefore I decided to stick with this result.

In order to test the stress, strain and deformation of the blade a load was required. I carried out some research and calculations which can be found above. I came out with a UDL of 2.97KN (0.6N per node) and a centrifugal force of 3438.32N (0.694N per node). See Figure 8a below on how each node was loaded.

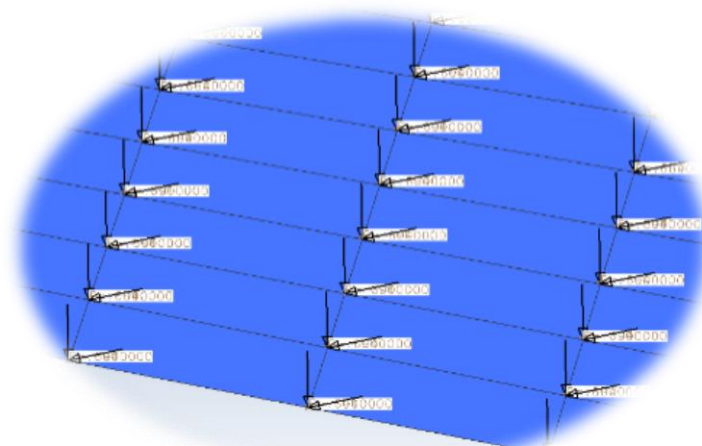


Figure 8a

Part 3:

The results from the optimisation can be seen below in Figure 9a. As you can see the structure does not conform to the displacement constraints set until optimisation cycle 5. The software understands that to reduce deflection it needs to add mass to the structures layers, this is why when the displacement constraint is not met on cycles 0 to 2 (max's out on the bottom graph in Figure 9a) it starts to throw mass at the structure rapidly to reduce the displacement. You then see the change in displacement on cycles 3 & 4 where the bottom graph decreases very abruptly. Then, on cycle 5 when the structure is within its constraint limit of 100mm deflection (0% constraint violation), the software begins to focus on minimizing the mass while keeping within constraints. As you can see on the top graph in Figure 9b the mass reduces steadily from cycle 5, then starts to flatten out by cycle 12. At cycle 12 the software is still looking to reduce mass although it has already optimized the structure fairly accurately, I allowed the process to continue for a further seven cycles before stopping it to ensure the mass was at its minimum.

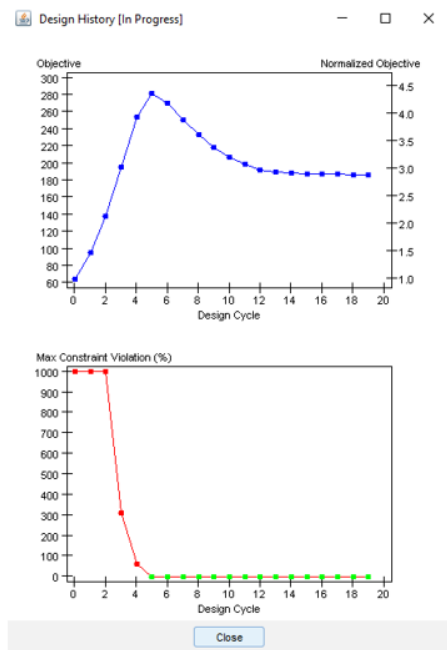


Figure 9a

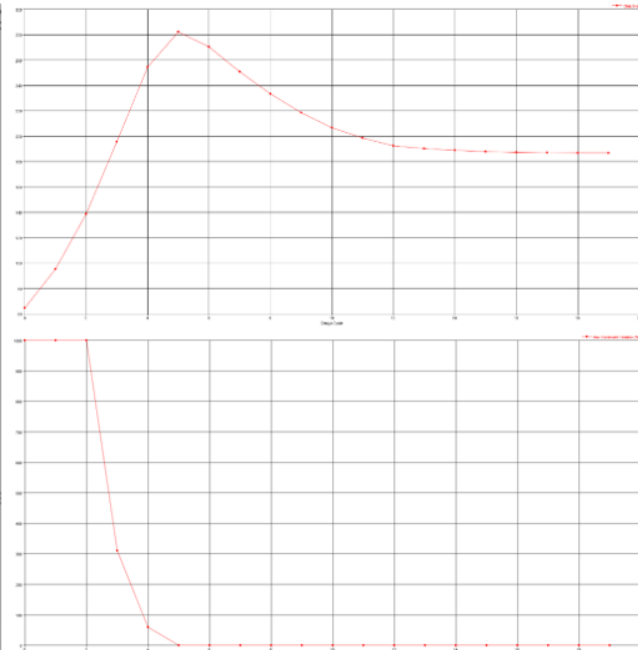


Figure 9b

Looking into the breakdown of each layer thickness after the optimisation was complete (see Figure 9c) I could see that the middle layer was the thickest by far with a thickness of 14mm. This makes sense due to the middle layer having to flex the most out of all the layers. For it to be able to flex this much and withstand the forces acting on it without failing it needs to be the thickest and most pliable layer.

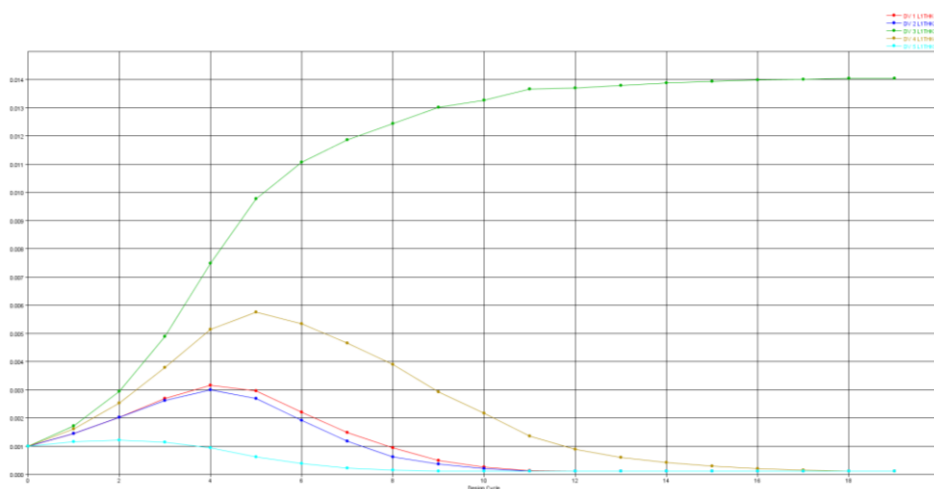


Figure 9c

Comparison between initial and final statistics on CFRP:

Initial Mass CFRP (Kg)	Final Mass CFRP (Kg)	Initial Displacement CFRP (mm)	Final Displacement CFRP (mm)	Initial Thickness CFRP (mm)	Final Thickness CFRP (mm)	Initial Stress(KN/m ²)/Strain CFRP	Final Stress(KN/m ²)/Strain CFRP
32.33	64.67	16200	99	5mm	14.4mm	810,000/0.023	37260.76/0.0001

The change in mass was expected due to the overall thickness of the blade more than doubling after optimization. The change in displacement was also predicted to be in the high nineties as my constraint said the blade could not deflect more than 100mm, therefore the software brought the blade just within that specification to allow the blade to meet the criteria but also be as light as possible as per objective set. The thickness increased due to the software having to throw mass at the structure to add stiffness.

Stiffness to Weight Ratio:

Stiffness = Force x Displacement = 2970 x 99 = 294030N/mm

Stiffness/Weight = Stiffness / (Mass x Gravity) = 294030 / (64.67x9.81) = 463.468N²/mm

The stiffness to weight ratio reflects on the sizing and optimization of the structure.

Below are the visualisations of displacement, stress and strain after the software optimized the CFRP:

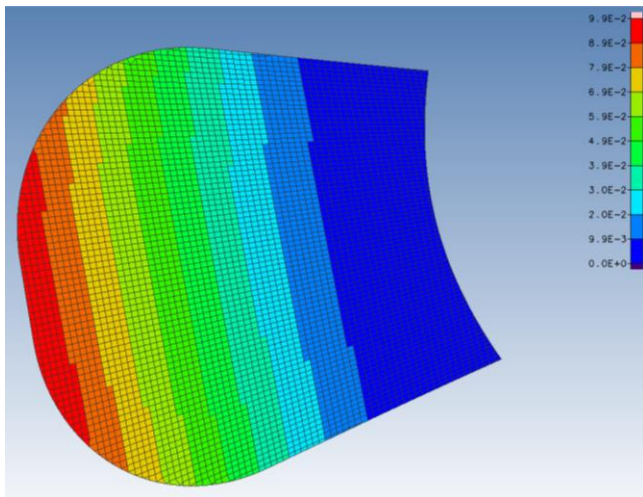


Figure 10a – Displacement

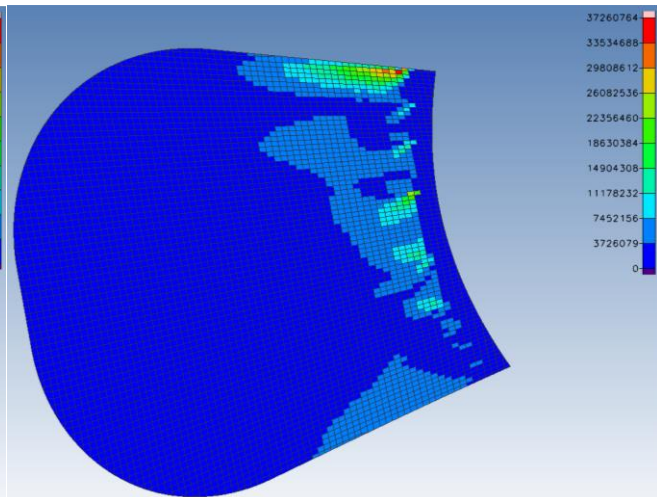


Figure 10b – Stress Results

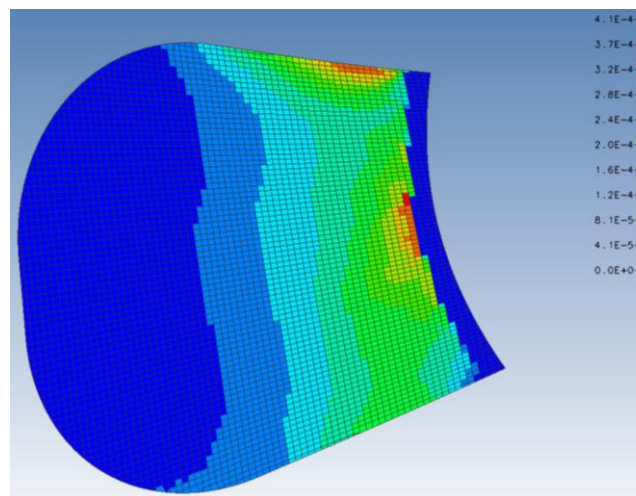


Figure 10c - Strain

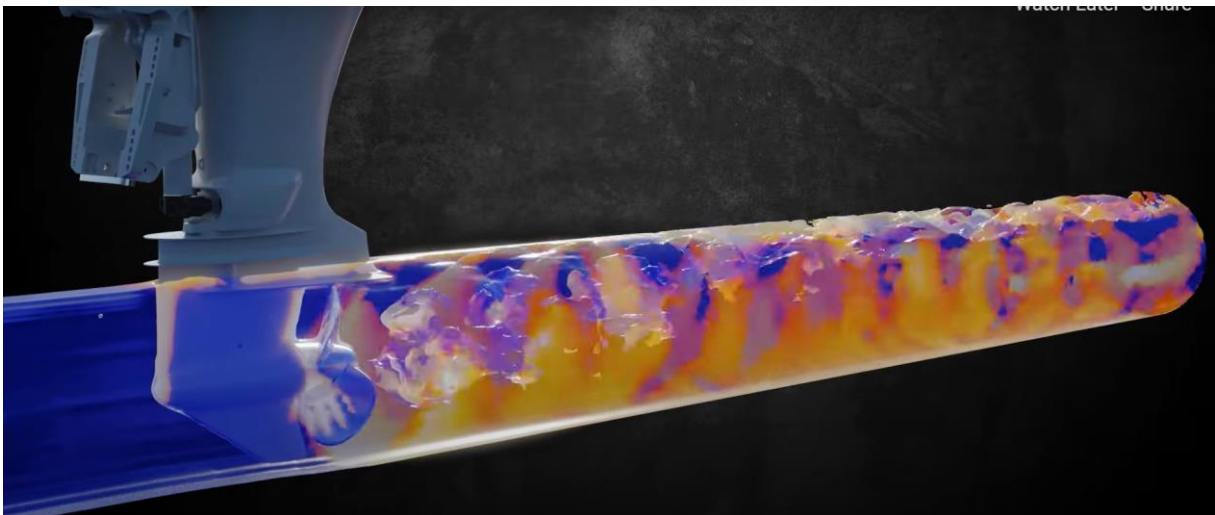
Part 4:

Having researched the typical testing that propellers blades undergo during the prototype phase. I would suggest that the blade is firstly manufactured from the same material as the intended blade that is going to be created is as this ensures that it has the same core material properties. I would also suggest that the blade is machined in the same fashion as small surface defects can make all the difference under high stresses. It would also be sensible to get the blade manufactured to scale so that the same amount of force is acting on it compared to the final blade.

My research shows me that the most common testing carried out on propeller blades is wind and hydro tunnel testing. This makes perfect sense as it not only allows you to test the structural strength of the blades, but you can also assess the fluid flow around the structure. By testing in a tunnel, you are simulating a real world scenario which is fully relatable to the blades intended use. Due to the blade that we have been instructed to assess in this assignment being a marine propeller then I would lean more towards hydro tunnel testing it, as then the density of the fluid is comparable to what forces the blade would see in the ocean.

The mass of the blade and its dimensions are known, therefore when the marine propeller is spun at a typical max speed the velocity and its centrifugal force will also be known. If the blade is then measured after a certain cycle time at that velocity, you will be able to calculate the creep in the blade and whether it is feasible to withstand the centrifugal force for the lifespan required. Displacements in the blade can be monitored with underwater lasers. The blade can also be monitored thermally with a thermal imaging camera.

Below you can see a hydro tunnel in action, carrying out the initial experiment with the propeller running at a maximum velocity. The colours you can see are the different levels of pressure and heat transfer within the tunnel:



(Chessa, 2022)

In comparison to the FEA software, you cannot measure anything to anywhere near the accuracy in the hydro tunnel. This is mainly due to the software having nodes spread across the surfaces less than a millimetre apart from one another. FEA is a lot more accurate than any physical measuring system you may use in a hydro tunnel, although with the software you run the risk of setting the simulation up incorrectly, resulting in false results. Most hydro tunnels are full of fresh water, whereas with FEA you can input the correct density of salt water to improve accuracies when analysing. It is likely there will be a slight difference in results due to tolerancing of the propeller itself, the hydro tunnel measuring system and the FEA mesh calculations used to gain the readings. Overall, you would expect fairly similar results due to both being quite reliable methods of testing within the industry.

Part 5:

From research I have carried out into carbon fibre blades I have found that the majority of the time they are coated in polyurethane foam filling and a glass fibre reinforced resin aerofoil shell covered with a tough polyurethane coating to protect them from erosion. Dowty Aerospace also states that further protection is given on propeller blades by using a replaceable leading edge strip. The propeller blade needs to be well protected as it is a primary component, and no structural failures are permissible. Due to the blades having such a large impact on a tanker's functionality, all stages of the manufacturing process have to be closely controlled. The manufacturing method involves the use of special tooling and a resin injection process specifically developed to produce composites with high fibre volume fractions and correspondingly optimum structural properties.

(LMK Thermosafe Propeller Blades, 2022)

Due to the propeller blades requiring a protective surface and edge beading this will impact the thickness and therefore the mass and stress of the blade including the strain/stiffness. If I was manufacturing the said blade, this thickness and material would have to be accounted for within the FEA software to be able to get more realistic results. The replaceable edge beading is fitted to the edge of the blade to strengthen it and ensure the layers of laminate do not separate over time as if the plies were to separate the blade would lose its material properties and strength.

Conclusion:

To conclude, carbon fibre reinforced plastic is a much more efficient material to design a marine propeller out of compared to steel. The reasons for this are due to the material properties of carbon fibre. Carbon fibre is layered and is an isotropic material unlike steel, meaning it has the same material properties in every direction. Due to this the layer thicknesses can be optimised to give you a much higher stiffness to weight ratio. This benefits the propellers design as it not only reduces the mass added to the tanker but also requires less force to drive the propeller rotation. The downfall to carbon fibre is that it is costly and can be fragile if it isn't manufactured or coated in protective polymers correctly. If I were to review a marine propeller in future I would ensure that I add a polymer layer on the blades surface to get a more realistic figure for the mass and displacement.

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