

Structural and Fluid Analysis ACMA6010

Designing a tanker propeller: Structural Design

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Abstract

In this paper, optimisation of tanker propeller using FEA analysis to determine efficiency of loaded structure. Optimisation techniques discussed, whilst meeting constraints within the manufacturing process of CFRP materials selected. Observing ply orientation and layer thickness to comply with maximum displacement of 100mm. Developing testing methods to acquire data and compare numerical and experimental results before manufacture, whilst considering standards and guidelines in the production of propeller blades.

1. FEA optimisation

As discussed in assignment one, optimisation of marine propellers, using composite materials can improve the fluid-structure interactions compared to that of a metallic blade [1]. Structural optimisation, using Finite element analysis (FEA) considers material selection that allows for optimal performance by obtaining the structural response to a set of boundary conditions for a given part [2]. Greater deflection when using composite marine propellers such as CFRP, has shown to optimise problems encountered with varying flows [3]. With the forces acting upon each blade section, deflection must be considered when optimising, so that deflection does not exceed design specification. Understanding the maximum deflection, weight of steel blade and forces acting on the steel blade, stiffness to weight ratio can be calculated. The greater the stiffness to weight ratio of material when optimising, the more efficient each blade section will be. The steel blade from assignment one has been optimised using FEA for minimal mass whilst meeting the displacement constraints, using CFRP material.

Finite Element Analysis (FEA) is a numerical solver to even the most complex structural designs [4]. When considering stress, strain and deflection, the use of finite element analysis can determine the properties and magnitude each material can withstand before exceeding constraints and failing from a structural design standpoint.

Similarly, to computational fluid dynamics (CFD) which simulates fluid flow around an object, FEA simulates the characteristics of a material subject to static and dynamic forces, this giving an opportunity to use FEA and optimise the component and improve its performance. It enables extensive simulation of computer aided design (CAD) drawings before the production of a prototype is finalised [5]. The engineering problem of displacement in solid mechanics can be hard to predict as it's an unknown. The finite element analysis procedure uses the CAD drawings and applies a finite number of elements which have approximated variable interpolation/shape functions, and these are called nodes [6]. Once elements and nodes have been selected, element properties are added to each element, FEA determines the response to the boundary conditions by solving equations at each node of the mesh. These responses could include values such as the amount of physical displacement or stresses caused by the loads on the part [2].

1.1 Optimisation techniques

The main advantage of using FEA is the ability to optimise the design following an analysis of the material performance under loading. FEA can deal with complex boundary conditions such as over constraints in solid mechanics and is insensitive to the complexity of given geometry of any material used when optimising [7]. Focusing on composite optimisation, as composite materials such as CFRP are sought after due to their strength to weight ratio. However, there are deficiencies in composites such as change in material properties, this can lead to delamination and debonding. To achieve high performance in different application, it's a must that composite structures are optimised. Ply orientations, number of layers and stacking sequence of fibers, including thickness of layers are examples of these effective boundary that can be used as variables in optimisation problems [8].

Optimisation techniques solve the structural design for minimum mass and maximum deflection, then stiffness of the material can be determined [9]. This can be done setting objective, constraints and design variables using FEA software. Optimising solves the best achievable values of the design variables set, operating within these constraints. Design variables describe configuration, dimensions, and sizes of elements. If the layers are made of composite ply's, the orientation of the fibers and their proportion can become additional variables [10].

When dealing with laminations and composites, stacking sequence optimisation is used to orientate the plies to determine optimal performance while also satisfying manufacturing constraints. The orientations of -90, -45, 0, 45, 90 are considered as the design variables [11]. Free size optimisation and the constraints would have to satisfy the upper and lower bound limits set for each individual ply or each layer consisting of a set number of plies. These can be applied locally on the structure through different element sets when perhaps a critical part of the structure should be considered [12].

1.2 History and future development of FEA

FEA originated as a method to analyse stress and structural mechanic problems in the design of aircraft and civil engineering applications back in the early 1950's. One of the earliest papers published explains the FEA method was developed for calculating stiffness influence coefficients for shell type structures, when stiffness of the complete structure is calculated through static or dynamic loading of each nodal point selected. Also, stating that with an increased number of nodes loaded you are likely to get more accurate results [13].

Following the release of the paper in 1956, Ray Clough developed a structural research analysis program which used triangular elements to solve several plane stress problems using. However, numerically calculating simple structures was time consuming using matrix algebra. It wasn't until 1960 that Ray Clough and Ed Wilson developed an automated finite element analysis program using the location of the nodes and the amount of nodes numbers where elements were then attached [14]. The term of the Finite Element Method (FEM) was introduced by Clough in the early 1960s and the application of finite elements analysis in mechanical structures is considered the key contributions in the development of the FEM [15]. At this point FEA was not feasible to run from a personal desktop computer, as the processing time constraints and the memory available to solve the complex problems in solid mechanics. Until recent decades the development of computers and software has made it an accessible program to use. FEA is now commonly uses to approximate solutions to a diverse scope of applications such as stress distributions, fluid flow, heat transfer and structural fluid interfaces [7].

Optimisation using FEA has continually developed for many years. However, there are drawbacks when using the program that can be developed further going forward. The limitations when calculating displacement is that it's a nonlinear solver. For example, when loading a composite structure of given length, the displacement when loading is applied will exceed this value substantially which is physically impossible. The software should state that this is not physically possible than spend time analysing a problem that cannot be solved physically. It's quite simple to get spurious results when defining material properties if an incorrect value is set. To save time, these values should be stored and embedded in the software not only to save time, but to avoid an error from the user.

Even though there are many tutorials to be found online, navigation of the software can be difficult to understand for a first-time user. Also, to display nodal loading when optimising the structure would also be a useful tool when reviewing the design. However, this function is not available. Once static loads have been defined and the structure has been optimised you are not able to change the loading following analyses and optimisation. Re calculating the load it's not as simple to amend the loading. The loading would have to be applied to the original structure again before analysing and optimising. These are all aspects that have been overlooked and could be addressed going forward in the development of FEA.

2. Defining propeller blade

The propeller blade was designed using solid works, then imported into design studio, where analysis was carried out. Initially, the steel blade was under a static load of 5KN. However, this is not the case from assignment one (analysing fluid flow around the blade) to determine whether flow was laminar or turbulent. What the Reynolds number showed is that the flow was turbulent.

When calculating Reynolds number, it was stated that the velocity of the blade at 0.7 of the cord length was 17.46 m/s. The force acting on the propeller blade can be calculated from dynamic pressure. It is commonly understood that $F = P \times A$. As the blade is moving through sea water with a density of sea water at 5°C is 1028Kg/m³ [16] dynamic pressure was calculated using the following equation.

$$\text{Dynamic Pressure} = \frac{1 \times \rho \times v^2}{2}$$

Dynamic pressure is equal to 156693.7 Pa. When considering the blade to be a flat rectangular plate and calculating the area from the longest distance in the x axis multiplied by the longest distance in the y axis. The area is calculated as follows, using the drawing from solid works.

$$A = 3.035 \times 2.979$$

The area is equal to 9.041M². From these calculations, discovered in assignment one, the force is calculated as;

$$F = P \times A$$

The force acting on this blade is calculated as 141.6KN. Understanding that the blade will not be subject to a UDL, this load was distributed predominantly on the leading edge and blade tip where the high-pressure region was discovered from CFD simulation in assignment one [17], using this the steel blade was loaded with a total of 141.6KN with a 70/30 split predominantly on the leading edge and tip. Refer to fig.1,2 for the loading of steel blade.

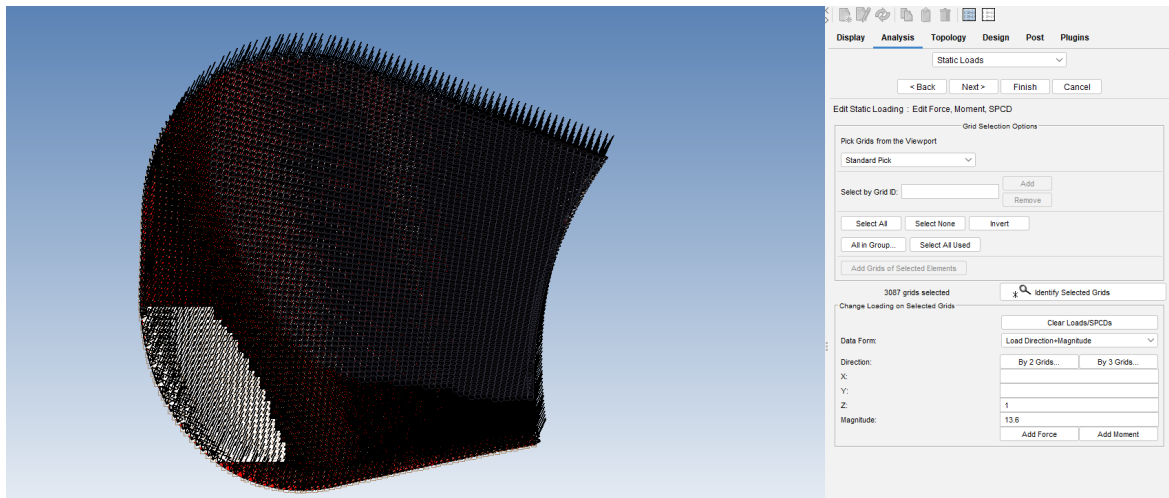


Figure 1: Loaded steel blade. Leading edge and blade tip loaded with a total of 99.1KN over 1864 nodal points. Each node loaded with a total of 53.11N. Trailing edge and back of the blade loaded with a total of 42.4KN over 3087 nodal points. Each node loaded with a total of 13.6N.

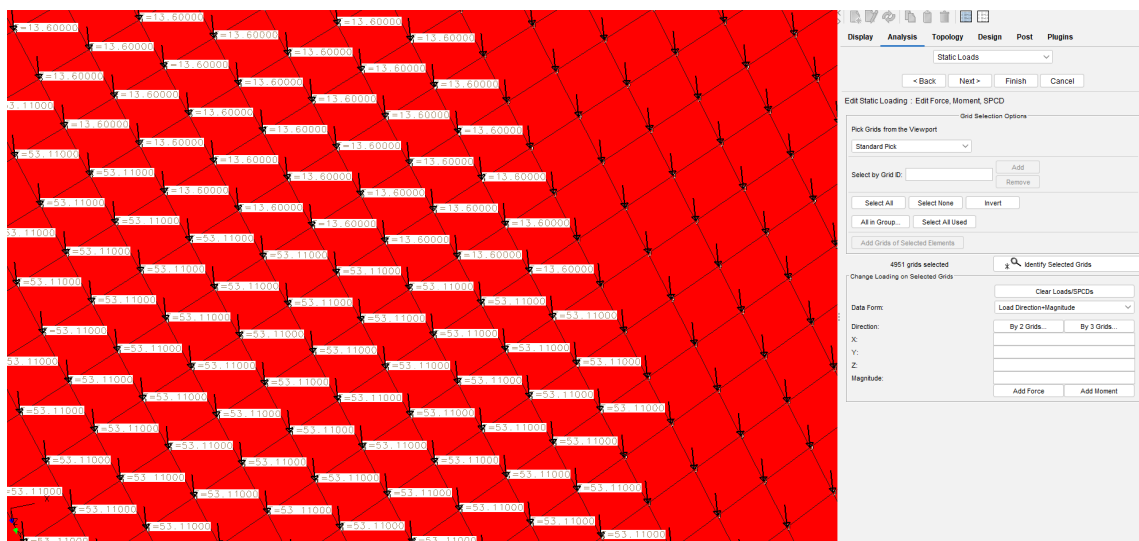


Figure 2: Loaded nodal points of steel blade. Shows the distribution of the loading and that it is not UDL. Each node carries a load which has been specified using the analysis tool in design studio.

Knowing that the blade had been loaded using reasonable and explained assumptions, single analysis could be run using design studio to illustrate the deflection of the steel blade under these conditions. Refer to fig.3.

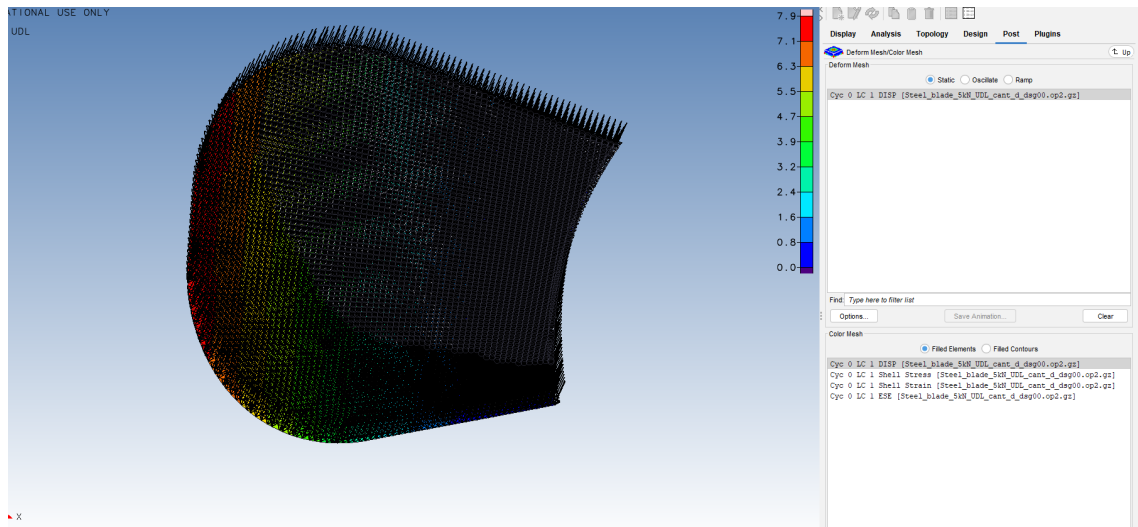


Figure 3: Displacement value of steel blade after loading using single analysis in design studio.

Following single analysis, the steel blade deflection was 7.9M which exceeded the maximum deflection required of 100mm. From this the stiffness to weight ratio was calculated as below in table 1.

$$\text{Stiffness (k)} = \text{force (f)} / \text{displacement (x)}$$

$$\text{Weight} = \text{mass} \times \text{gravity}$$

$$\text{Stiffness/weight} = \text{stiffness to weight ratio in N}^2/\text{M}$$

Table 1

RUN	MATERIAL	THICKNESS (M)	DELFECTION (M)	WEIGHT (Kg)	LOAD (N)	STIFFNESS (N/M)	STIFFNESS/WEIGHT (N2/M)
Steel Baseline	steel	0.01	7.9	6344.127	141667	17932.53165	2.826635035

To achieve the desired constraints and variables, the structure was designed from a composite material and the properties specified as suggested in fig.4

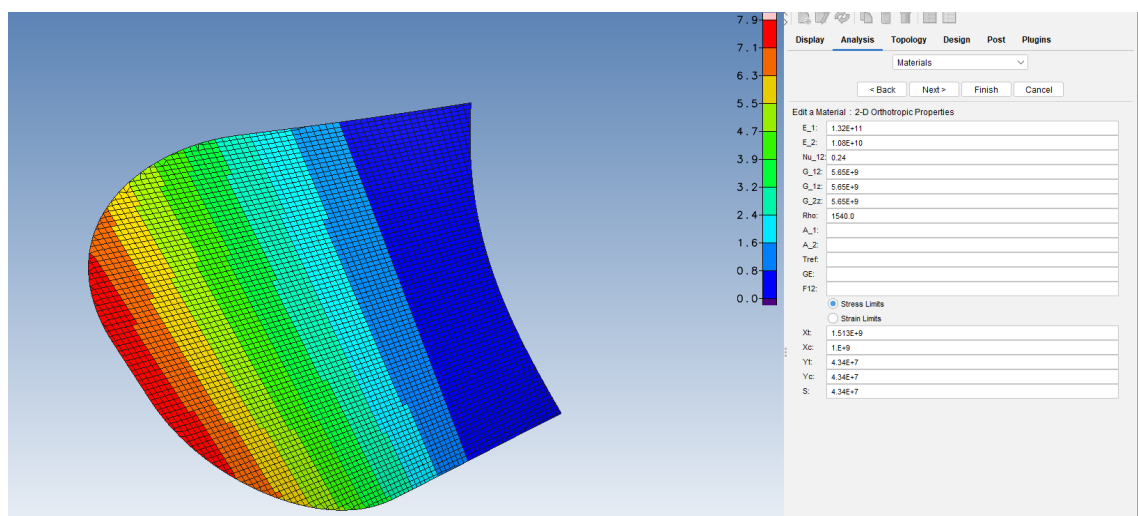


Figure 4: Composite material properties of CFRP marine propeller using analysis, materials, new, mat8

Assuming propeller blade to be cantilever and that zero degrees runs radially from the center of the blade all vectors are aligned to replicate this when loaded see fig.5.

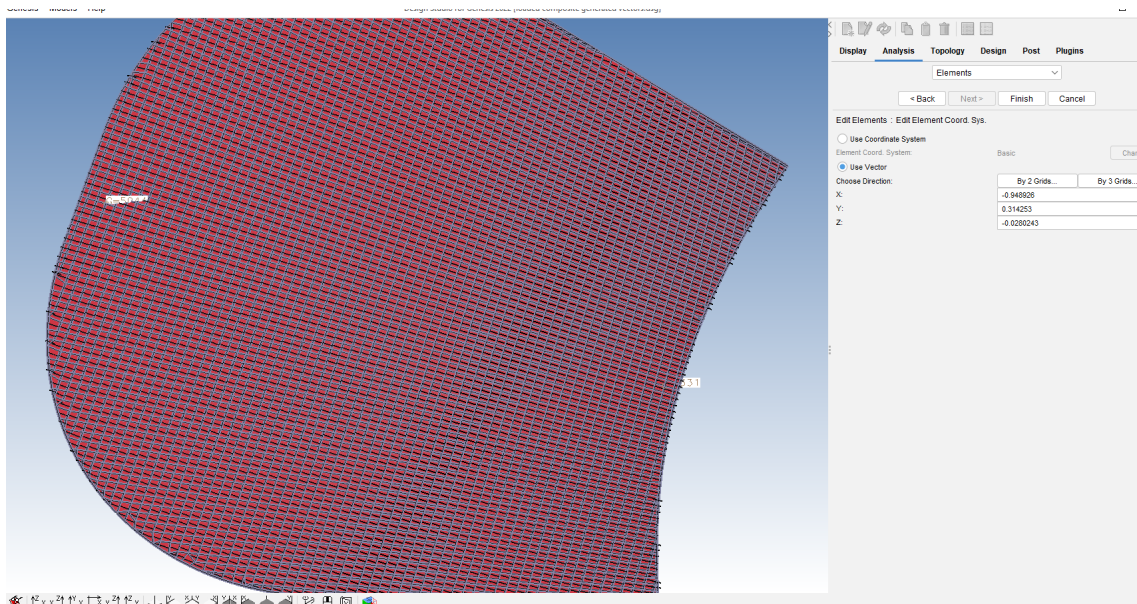


Figure 5: Vectors aligned radially from the center of the propeller

Following theta vectors generated, the PCOMP lay up of plies was generated see fig.6 and the displacement was seen in fig.7

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

Figure 6: ply orientation and thickness of each layer

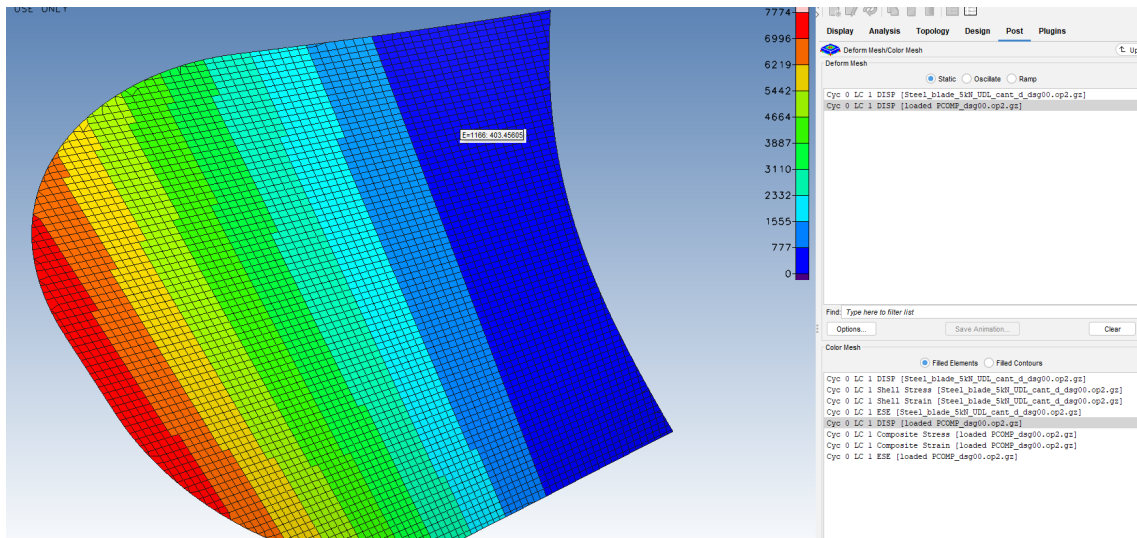


Figure 7: displacement following ply orientation and thickness of each layer

Displacement following PCOMP and lay up of plies at -90, -45,0,45,90 was found to be 7774M. FEA is nonlinear solver and has not predicted failure point. The stiffness to weight ratio was calculated in table 2 and compared with that of the steel blade.

Table 2

RUN	MATERIAL	THICKNESS (M)	DELFECTION (M)	MASS (Kg)	LOAD (N)	STIFFNESS (N/M)	STIFFNESS/WEIGHT (N2/M)
Steel Baseline	steel	0.01	7.9	6344.127	141667	17932.53165	2.826635035
Composite Baseline	composite	0.0025	7774	315.882	141667	18.22317983	0.057689833

The table shows that the mass was significantly reduced, this was based on the layer thickness and number of plies in each layer. It is stated that plies are 0.1mm and a total of 25 plies overall thickness. This was calculated at 0.5mm in each layer. However, this design did not meet the displacement constraint of 100mm. Also, this was not as efficient as the steel blade which was illustrated in the stiffness to weight ratio. So, the design was optimised further to meet the constraints set out. Minimum mass and maximum displacement of 100mm.

3. Optimising CFRP propeller blade

Design objectives were set to keep mass to minimum so that a more efficient propeller could be designed in terms of stiffness to weight ratio. See fig.8

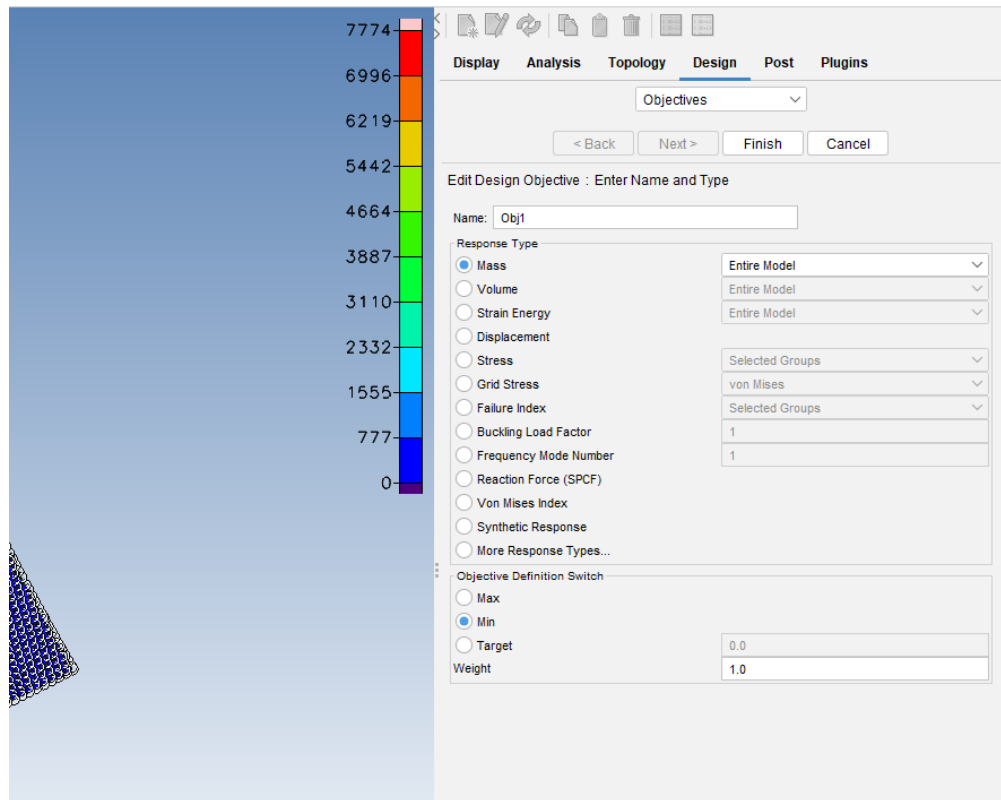


Figure 8: Design objectives are set to keep mass at a minimum during the optimisation of CFRP propeller.

The constraints of the design are to keep displacement less than 100mm. see fig.9.

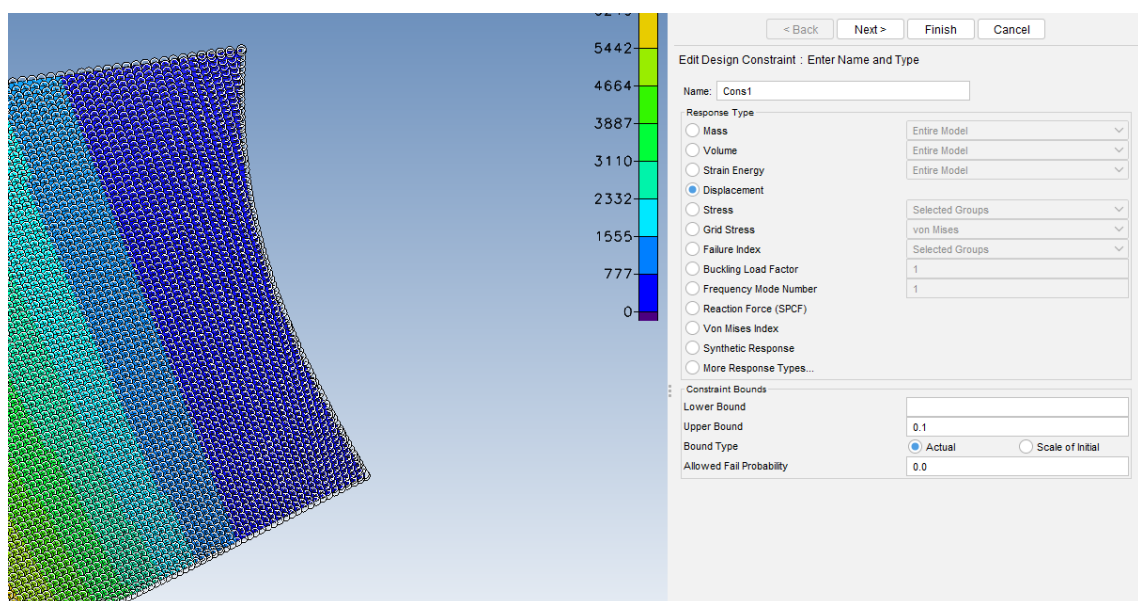


Figure 9: Displacement constraints set at 100mm upper bound limit.

Optimise the CFRP propeller, design variables of the different layer thickness were set using initial value of each ply, the lower bound limit, and the upper bound limit. What was found that restricting the upper bound limit, the displacement constraint was not achievable. To achieve the displacement, the upper bound limit was set as seen in fig.10.

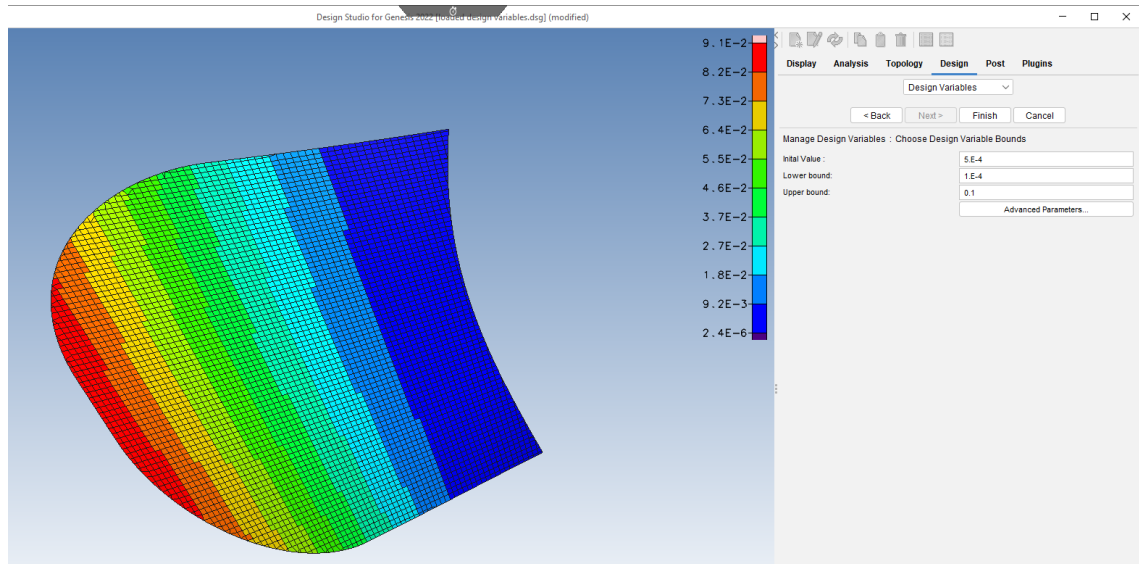


Figure 10: design variables set for each layer.

3.1 Optimised using design variables

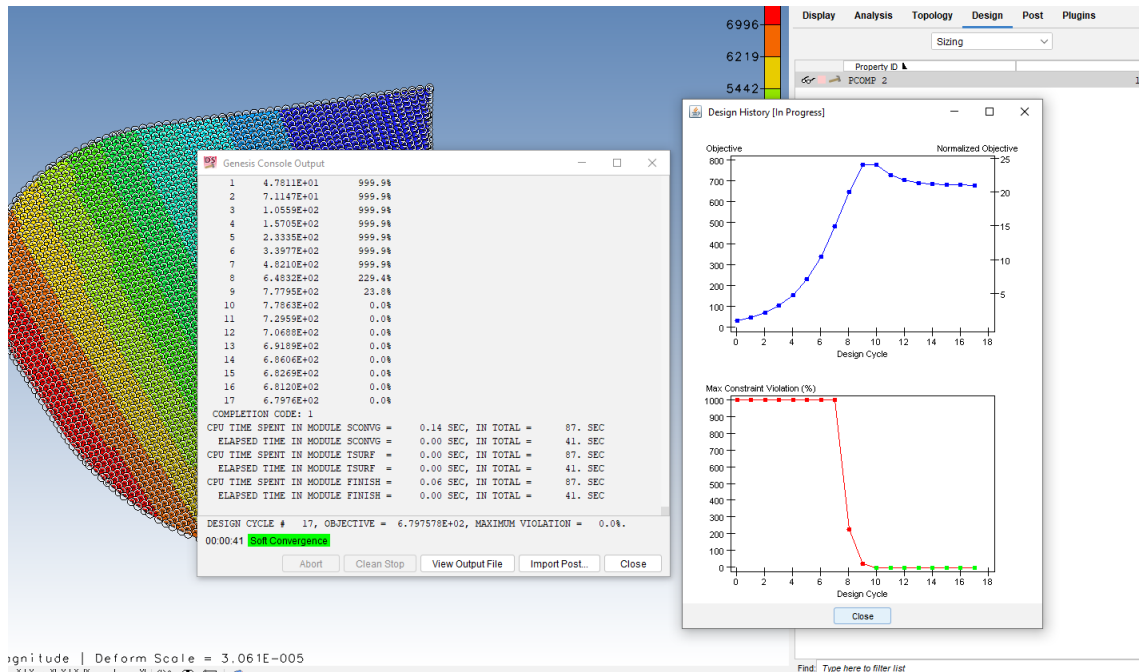


Figure 11: Optimised CFRP propeller blade stating design variable and upper bound constraints. Displayed is that by design cycle 10 the structure is meeting the displacement constraints.

The history plot fig.12, show the variables of each ply started at .01mm. The plies at 0 degrees increased to 52mm, this was a result of setting the upper bound limit to 100mm. Also, design studio has optimised the blade in this way as a result in the direction loading (running radially at 0 degrees from the base). This was where the strength was designed to be, to comply with the displacement constraints.

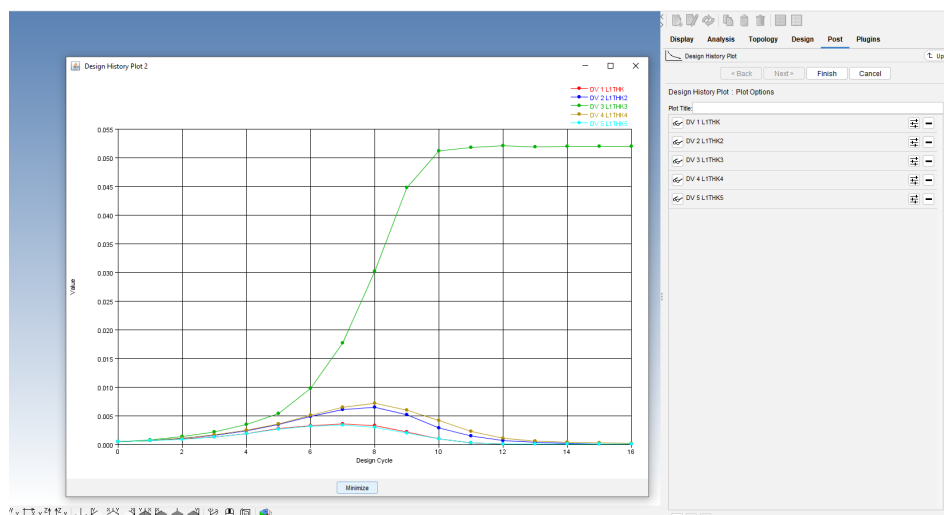


Figure 12: History plot of layers throughout design cycle. This illustrates the thickness of each layer in each orientation.

DESIGN CYCLE HISTORY					
DESIGN CYCLE	OBJECTIVE FUNCTION	MAXIMUM CONSTRAINT VIOLATION			
0	3.2334E+01	999.9%			
1	4.7811E+01	999.9%			
2	7.1147E+01	999.9%			
3	1.0558E+02	999.9%			
4	1.5705E+02	999.9%			
5	2.3335E+02	999.9%			
6	3.3983E+02	999.9%			
7	4.8233E+02	999.9%			
8	6.4905E+02	229.5%			
9	7.7857E+02	23.5%			
10	7.7770E+02	0.0%			
11	7.3735E+02	0.0%			
12	6.9997E+02	0.0%			
13	6.8787E+02	0.0%			
14	6.8386E+02	0.0%			
15	6.8167E+02	0.0%			
16	6.7993E+02	0.0%			
17	6.7912E+02	0.0%			
IGENESIS VERSION 21.0 DATE 10-21-2022 TIME 14:10 PAGE 348					
FOR EDUCATIONAL USE ONLY					
DESIGN VARIABLE HISTORY					
DESIGN CYCLE	DESIGN VARIABLE 1	DESIGN VARIABLE 2	DESIGN VARIABLE 3	DESIGN VARIABLE 4	DESIGN VARIABLE 5
	L1THK	L1THK2	L1THK3	L1THK4	L1THK5
0	5.0000E-04	5.0000E-04	5.0000E-04	5.0000E-04	5.0000E-04
1	6.8463E-04	7.4525E-04	8.3818E-04	7.4995E-04	6.7865E-04
2	9.5722E-04	1.1087E-03	1.3722E-03	1.1214E-03	9.4140E-04
3	1.3495E-03	1.6363E-03	2.1973E-03	1.6623E-03	1.3188E-03
4	1.9245E-03	2.4121E-03	3.4745E-03	2.4605E-03	1.8715E-03
5	2.7555E-03	3.5438E-03	5.4434E-03	3.6297E-03	2.6698E-03
6	3.3556E-03	4.8358E-03	9.7950E-03	5.0439E-03	3.2448E-03
7	3.6342E-03	6.0702E-03	1.7610E-02	6.4966E-03	3.4823E-03
8	3.2459E-03	6.4373E-03	3.0206E-02	7.1100E-03	3.1847E-03
9	2.1649E-03	5.0744E-03	4.4911E-02	5.8437E-03	2.2039E-03
10	9.9469E-04	2.9612E-03	5.1095E-02	4.0618E-03	1.0182E-03
11	3.4953E-04	1.4854E-03	5.1823E-02	2.1645E-03	4.1480E-04
12	1.1403E-04	7.3894E-04	5.1996E-02	1.1276E-03	1.4396E-04
13	1.0000E-04*	4.1812E-04	5.1847E-02	7.1995E-04	1.0000E-04*
14	1.0035E-04	2.1971E-04	5.1981E-02	4.7420E-04	1.0039E-04
15	1.0000E-04*	1.3850E-04	5.2063E-02	3.0467E-04	1.0000E-04*
16	1.0000E-04*	1.0909E-04	5.2075E-02	1.8668E-04	1.0000E-04*
17	1.0000E-04*	1.0009E-04	5.2086E-02	1.2259E-04	1.0000E-04*

* = DESIGN VARIABLE AT UPPER OR LOWER BOUND

Figure 13: Design cycle history of optimised structure displaying the following at each design cycle; mass, % constraint violation and thickness at each layer.

Detailed in fig.13, at design cycle 10 there was no violation of the displacement constraints. However, when observing ply thickness in each layer, it does not seem physically possible to manufacture each layer due to the thickness of each ply. It is stated plies are .01mm thick. There for by design cycle 17 it is not possible to manufacture layer 2, layer 3 and layer 4. Even though not manufacturable, table 3 show the optimisation has increased the efficiency of the CFRP propeller, now satisfying the displacement constraints. Strength to weight ratio significantly greater than both the previous design.

Table 3

RUN	MATERIAL	THICKNESS (M)	DELFECTION (M)	WEIGHT (Kg)	LOAD (N)	STIFFNESS (N/M)	STIFFNESS/WEIGHT (N2/M)
Steel Baseline	steel	0.01	7.9	6344.127	141667	17932.53165	2.826635035
Composite Baseline	composite	0.0025	7774	315.882	141667	18.22317983	0.057689833
Optimise Composite	composite	0.0525	0.099	6664.914	141667	1430979.798	214.7034152

3.2 Discrete variables

For manufacturing purposes, the structure must only have plies at .01mm thick. There for, discrete variable must be used to achieve this.

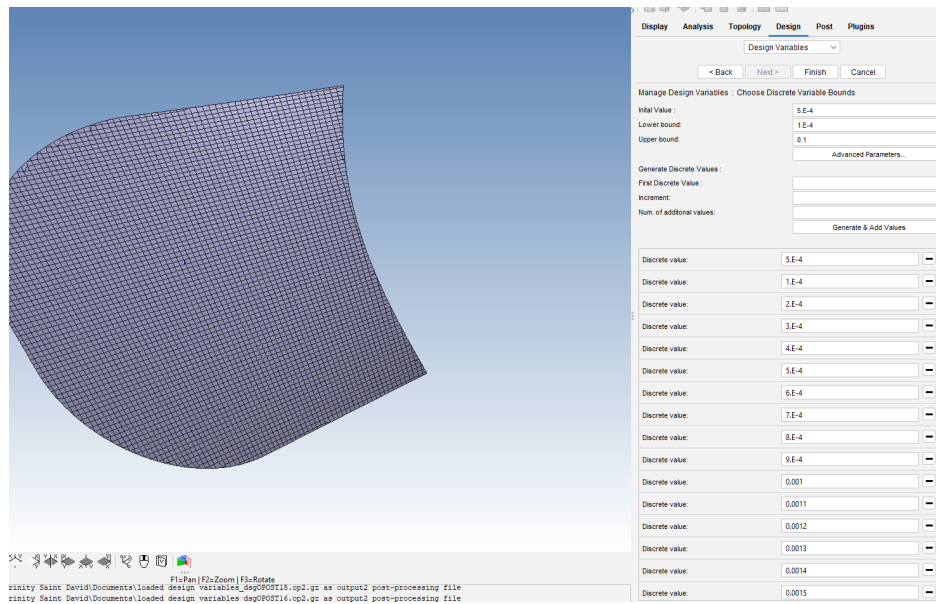


Figure 14: Discrete variable added for manufacturing purposes

Following this, the structure was optimised further. This time a total number of 22 cycles to optimise the structure and meet objective and constraints. Again, this was achieved by design cycle 10, from that point on the optimisation was aiming to reduce mass as specified in objectives.

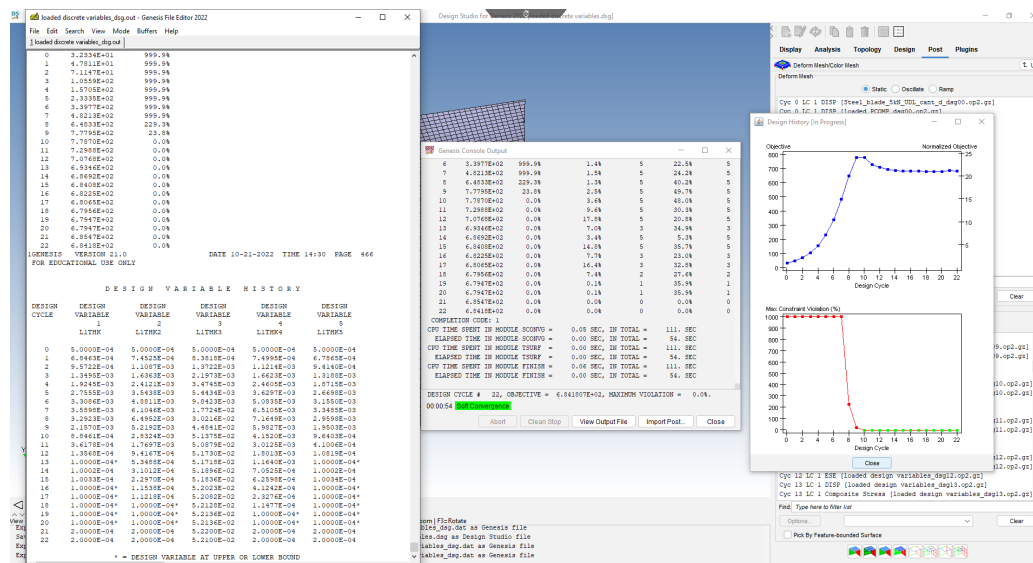


Figure 15: Optimisation following discrete variable and increments of .01mm plies only for manufacturing purposes.

On completion of the discrete variable optimisation, there was enough data to compare each of the run and discover which of the structure was the most efficient regarding strength/weight ratio. Refer to table 4.

Table 4

RUN	MATERIAL	THICKNESS (M)	DELFECTION (M)	WEIGHT (Kg)	LOAD (N)	STIFFNESS (N/M)	STIFFNESS/WEIGHT (N2/M)
Steel Baseline	steel	0.01	7.9	6344.127	141667	17932.53165	2.826635035
Composite Baseline	composite	0.0025	7774	315.882	141667	18.22317983	0.057689833
Optimise Composite	composite	0.0525	0.099	6664.914	141667	1430979.798	214.7034152
Optimise Composite (discrete)	composite	0.0529	0.099	6711.021	141667	1430979.798	213.2283296

Weight increases using discrete variable making the design not as efficient. This is the increase in thickness and overall mass. However, this can now be manufactured. Comparison of optimised and discrete optimised structures seen in table 5.

Table 5

	L1THK	L1THK	L1THK	L1THK	L1THK	TOTAL	Number of plies
composite baseline	0.0005	0.0005	0.0005	0.0005	0.0005	0.0025	25
composite baseline optimised	1.0000E-04	1.0009E-04	5.2086E-02	1.2259E-04	1.00E-04	0.05250868	525.0868
composite baseline discrete	2.0000E-04	2.0000E-04	5.2100E-02	2.0000E-04	2.00E-04	0.0529	529

4. Testing procedure

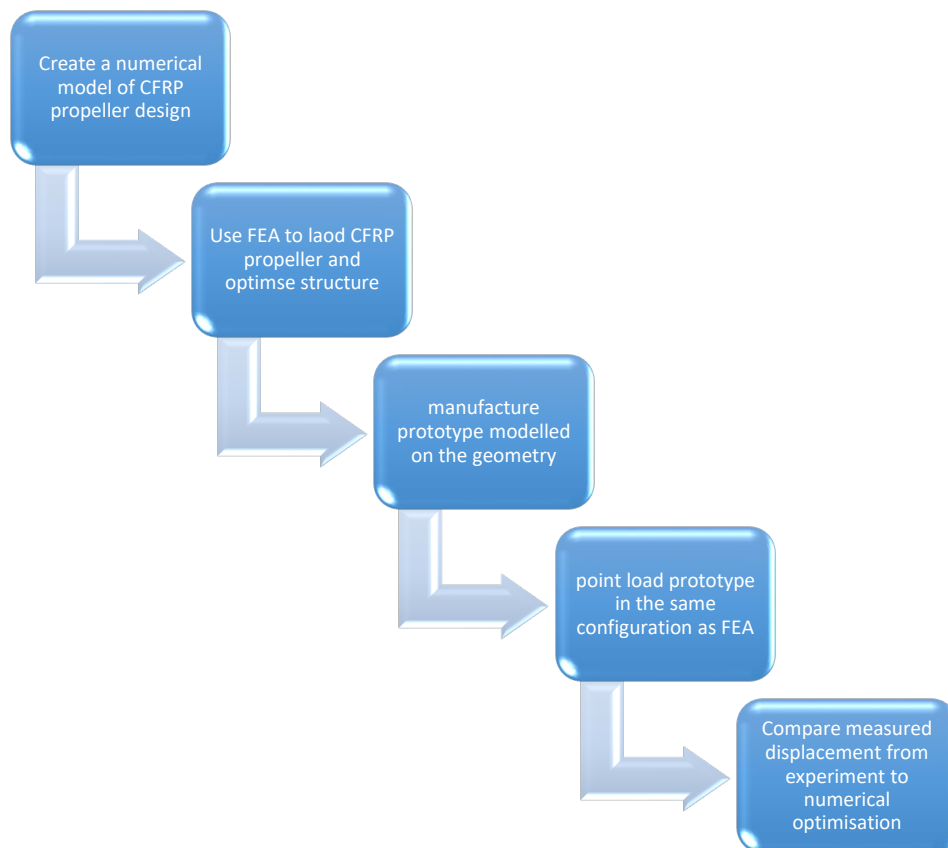
Cavitation tunnels can be used to understand the efficiency of the propeller, by creating a prototype using values of the material properties set in FEA to study its deflection around each blade. This is done by taking superimposed photography to study the deflection between pixels and measuring this can be quite difficult without this method [3]. Developments into detection systems are recently being used to improve accuracy using this method to measure deflection, rather than on the visual capacity of the tester which can allow for human error [18].

Cavitation tanks typically use scaled models, so the scaling would have to replicate the simulation in FEA. This can be difficult to get an accurate result and compared to FEA, as typically all simulations in FEA are approximated results and may differ from real life applications. There is also a possibility of using stereo imaging. An experiment into this new method discusses how the elasticity and deflection of composite propellers can cause problems with blade efficiency [19]. The blades' deflections are measured by tracking the displacements from a datum point placed on the blade surface. The datum is the propeller not subjected to any load. The displacements are computed as Euclidean distance between the locations of the points in the deflected and non-deflected case [20].

However, to truly replicate the predicted blade deflection, a point load static test would be the most suitable to gain a clear understanding and correlate both numerical modeling using FEA and experimental results. Using the methods discussed above (cavitation and stereo imaging), loading the propeller with a dynamic fluid is too complex to re-create on this prototype. The CFRP prototype would be modelled to match the geometry of the design in FEA, using the same ply orientation. The prototype would be mounted in a rig to replicate the cantilever as suggested in FEA. Given the difficulty to replicate individual nodal loading (4951 nodes) in FEA, the blade will be loaded using the 70/30 of 141kN split as described earlier. Deflection will be measured using strain gauges and DTI gauges to get an accurate result.

4.1 *Data acquisition on test methods detailed.*

Structural design and geometry of the propeller blade to be determined. To follow is analysis and optimisation under loading conditions using FEA. Then the manufacturing process and execution of the investigation around deflection is measured and compared to the FEA simulation.



Similar studies conducted indicate that that this experimental procedure and data acquisition of representative point load experiment were performed, and the experiment was staged physically with an equivalent FEA to verify that the prototype's FEA predicted properties were obtained. Comparison of experiments and FEA data found that the numeric model shows close to the expected deformation, indicating that the modelling captures the reality [21].

5. Manufacturing standards of propeller design

Considering the diameter of the propeller to be greater than 2.5 meters, manufacturing of this component must comply with the ISO 484-1. It must comply with tolerances on thickness of blade sections, tolerances on pitch angles, tolerances on rake, axial position and relative axial position of consecutive blades, surface finish and measuring equipment used [22]. During the manufacture of this propeller the surface finish of each blade section should have a surface roughness (Ra) measured in micrometers no greater than 3 at the hub, 6 at 0.3 of the radii, 12 at 0.4 of the radii and 25 at 0.5 of the radii.

ISO 20975-2 specifies the flexure test method for determining the through-thickness tensile properties of laminated carbon fiber-reinforced plastic (CFRP) composites, including strength, fracture strain, and modulus. Applicable to laminated CFRP composites with unidirectional reinforced laminate, namely unidirectional CFRP (UD-CFRP). This shows how tests specimens should be loaded in which direction of in plane fibers [23].

Rules and guidance published by ClassNK states for the approval of the manufacturing process of propeller casting must be designed in accordance with material grade, type of propeller and maximum diameter of manufacturing propeller [24].

- Analysis of chemical composition on ladles and separately cast are to be carried out.
- Tensile test: Tensile tests are to be carried out on the propeller castings and separately cast. Three each of test specimens from the propeller castings are to be taken from the position in the proximity of 0.2-0.35R (R is radius of the propeller) and the position in the section with maximum blade thickness.
- Micro-structure analysis: Micro-structure analysis is to be made on each tensile test specimen.
- Macro-structure analysis: Macro-structure analysis is to be made on the blade section in the proximity of 0.2-0.3R.

ISO 220298:2020 full-scale test method for propeller cavitation observation. The objective of the test is to investigate the propeller cavitation behaviour and its effects on the hull vibration problems. Cavitation is responsible for significant propeller performance

degradation and occurs at nearly all propeller [25]. This must be done following manufacture. As discussed, scaled prototype tests may not replicate full scale cavitation.

6. Conclusion

Initial analysis of steel blade structure under loading did not meet displacement constraints. However, the loading was calculated as a flat rectangular plate, so this may not replicate to the true loading. Even so, optimising the structure using FEA shows how material selection can improve efficiency. Using objectives, constraints and design variables, FEA illustrated how the structure was optimised after inputting the data specified. Analysis on composite material in the first instance violated these constraints, so only when variables of ply thickness and orientation were selected it was met. However, optimisation of design variables could not be manufactured, and so discrete variable were used to correlate the ply thickness of 0.1mm. The final optimisation of discrete variables is not as efficient but can now be manufactured. Testing methods researched have shown to correlate both numerical and experimental results, proving FEA optimisation is effective for real world applications.

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