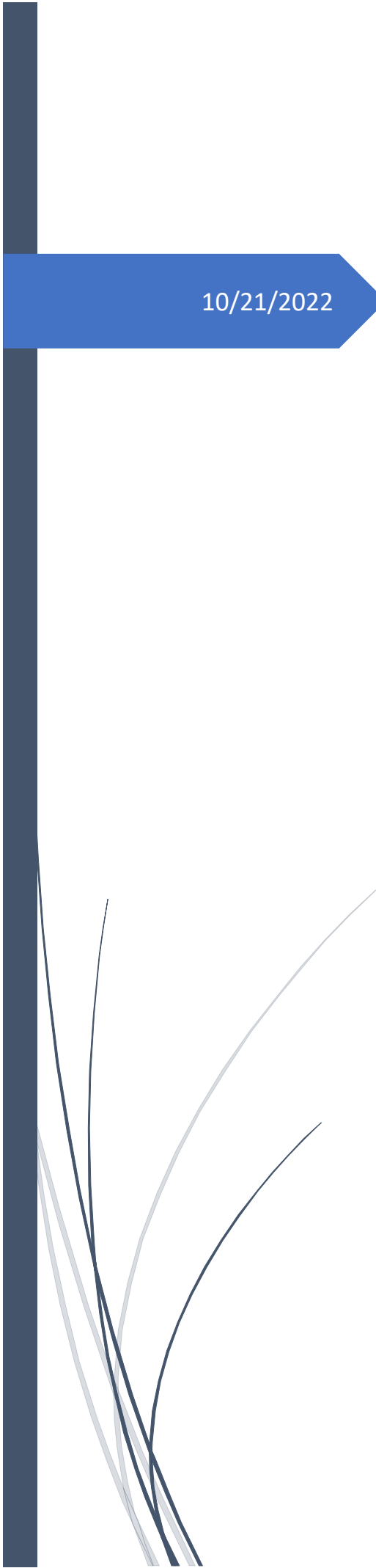


A thick dark blue vertical bar runs down the left side of the page. A blue arrow points to the right from this bar, containing the date. In the bottom left corner, several thin, curved lines in dark blue and light grey sweep upwards and to the right.

10/21/2022

Designing a tanker propeller

Structural Design

James Brearley (2110919)

UWTSD & THE DOW CHEMICAL COMPANY

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Introduction

This report is a follow up to the previous report (Brearley, 2022) which looked at the fluid flow around the tanker propeller, in this report the structural considerations are discussed, and the design of the propeller is optimized structurally to perform efficiently with the assumed forces.

FEA optimization and its history is discussed, followed by the process used to create an effective CFRP design of the propeller blade.

A real-world test method is then detailed to be used to determine the effectiveness and accuracy of the optimization process.

It should also be known that this report focuses purely on the axial forces that would be present on the blade, if this propeller were in operation there would be several other considerations that would have to be considered at the design process such as:

- The forces in the axial direction used in this report would be constantly changing due to ship speed, sea conditions (i.e waves & tides), the weight of the tanker, the constant pressure changes due to the rotating propeller.
- Centrifugal forces would be present due to the large rotating mass.
- The act of the blades forcing the water in order to propel the ship would also create torsional/twisting forces to the propeller.
- If the propeller is only partially submerged as is common for many tanker vessels, there would also be impact forces acting on the leading edge of the blades as they contact the water.
- With the propeller being 6.7m diameter there would be a differential pressure between the highest and lowest point due to the water pressures.

Task 1: FEA optimization

What is FEA (Finite element analysis)?

According to (PTC, 2022), “*Finite element analysis (FEA) is used to predict how a model will react to forces in the real world*”.

This methodology has become a crucial part of the design stage for effective modern components, by using FEA techniques and software, engineers can design their products to perform at the maximum efficiency within their intended purpose. During the optimization process for the propeller blade in this report, the aim was to make it as light as possible whilst meeting the deflection constraint whilst under load, this is one of the simpler tasks that can be achieved using FEA optimization, there are many other aims that can be achieved whilst designing a part such as minimizing vibration, meeting fluid flow criteria, optimal aerodynamics, easy machineability, and many more.

According to (NAFEMS, 2022), using FEA optimization during the design stage embraces the ideology of “right first time” using minimum design cycles.

History of FEA

The FEA optimization techniques and software that are widely used today have developed greatly since this methodology was first used.

It is widely accepted that the first method of FEA was used in the late 1800’s by John William Strutt Rayleigh, where he developed a process to predict the first natural frequency of basic structures by assuming a deformed shape and minimizing the energy distributed through it. This process was then enhanced by Walter Ritz which became known as the Rayleigh-Ritz method, used for predicting displacement and stress behaviour of structures. (Odonnell Consulting engineers, inc, 2022)

Whilst the late 1800s is noted as the beginning of FEA optimization, it was in the 1950’s where it really started to progress with the aerospace industry taking an interest. It was then that the likes of Boeing, Bell Aerospace and Rolls Royce started investing resources into its development.

According to (Tipton, 2017), one of the first papers to lay out FEA methods was written in 1956 by M.J. Turner, R.W. Clough, H.C. Martin and L.J. Top. It was Ray Clough, who was a Berkeley professor working for Boeing during the summer who wrote a second paper which was the first to use the term “finite elements”. He then became one of the world leaders in FEA research whilst working out of Berkeley.

Another fundamental paper for the development of FEA was joint written by Ray Clough and Edward Wilson, this paper was based on research carried out between 1957 and 1970, it details how FEA could be used to solve linear and non-linear problems such as creep, crack closing, heat transfer, flow of water, and many more. (Wilson, 1970)

The research carried out at Berkeley led to multiple programs being created which were made available worldwide for engineers to use.

Then in the early 1960s, NASA employed a small analogue computer manufacturer (MacNeal-Schwendler Corp) to develop a general-purpose FEA code which resulted in the creation of the NASTRAN deck. (Odonnell Consulting engineers, inc, 2022)

This code however had a limit of 68,000 degrees of freedom which was believed at the time to be more than anyone required, once the contract with NASA had finished, this software was made

available to the public, however it was extremely resource intensive and required super computers to run it, then in the 1980's, graphics cards were developed which allowed engineers to see colour mesh's (As used further in this report) which led to FEA becoming a standard resource in the development of products.

Then in the late 1990's, programs with 1 million degrees of freedom were developed which could be run at deskside via supercomputers, and from the until now the software and hardware has been developed so that FEA programs such as design studio can be run on readily available laptops and desktops.

Future of FEA optimization

The use of FEA during the development stage has become the norm for many manufacturing companies, as the software becomes more powerful and more affordable, even smaller companies who can't currently afford it could begin using it.

It's possible the objectives, variables, and constraints will begin to change to suit the issues with the modern world. Materials will be developed to use recycled waste, FEA will be used to make them cost effective, stiff, strong etc...

It's also possible FEA could be used to develop more efficient power generation methods that release little to no greenhouse gases, it could also be used to modify current technology such as gas turbines to reduce the harmful emissions associated with such processes.

One of the major advancements being seen today is the use of electric powered vehicles instead of internal combustion engines, it's likely this will also be seen in the aerospace industry with FEA being used to develop light and efficient aircraft suitable to be powered by electric means instead of fuel powered turbines.

There is also evidence where AI (artificial intelligence) algorithms have recently been used to design and develop components by employing FEA, an example of which can be seen below where a part for a jet engine was designed using an AI (artificial intelligence) algorithm and then 3D printed using Ti-6AL-4V powder.

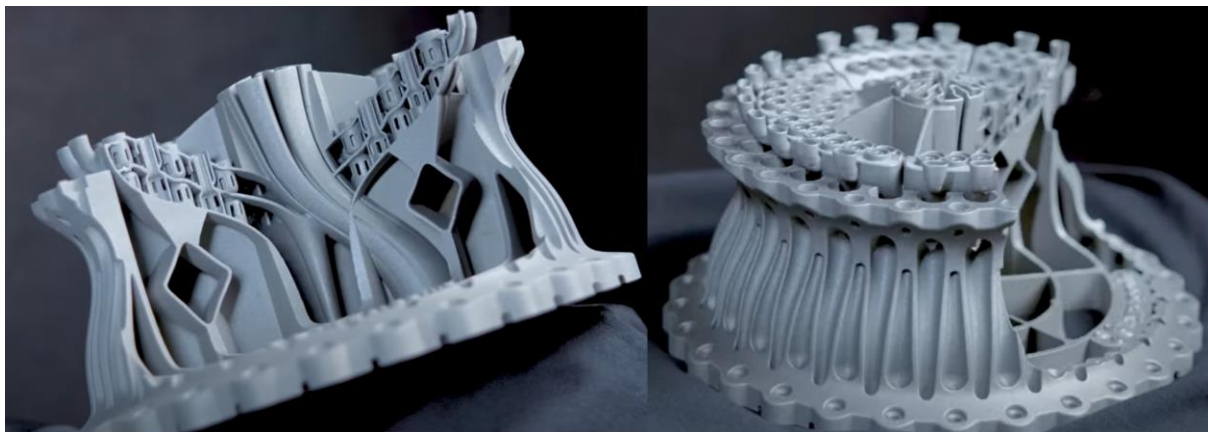


Figure 1 - (Titans of CNC, 2022) 3D printed part, designed by AI. (Cut out to show intricate internal design)

Task2: Creating a CFRP (Carbon fibre reinforced plastic) propeller

Steel blade baseline

In order to develop the propeller blade from CFRP, a steel model provided was used. The steel baseline was of the correct dimensions, however a 5KN UDL was present, this is unrealistic to real world conditions as from the previous assignment (Brearley, 2022), it was found that the pressure varies at different points of the blade, so the first step was to estimate a more realistic applied force.

A dynamic pressure was calculated using the velocity and fluid density values from assignment 1, as can be seen in figure 2 below.

Dynamic Pressure Calculator - SI Units
The default values below are for water with density of 1000 kg/m³.

ρ - density of fluid (kg/m³)

v - velocity (m/s)

- Dynamic pressure (N/m², Pa): **309690**
- Dynamic pressure (lb/ft², psf): **6468**
- Dynamic pressure (lb/in², psi): **44.9**

• 1 N/m² = 1 Pa = 1.4504x10⁻⁴ lb/ft² (psf) = 0.02089 lb/ft² (psf) = 1

Figure 2 - Dynamic pressure calculator.

As this figure of 309690N/M² is an assumption it was rounded down to 300KN for simplicity. The propeller blade had 4951 nodes, so this was calculated as 60.6N average force per node.

This was then applied to the blade with 70% of the load being applied to the selected points shown in figure 3, the remaining 30% was then applied to the remaining points.

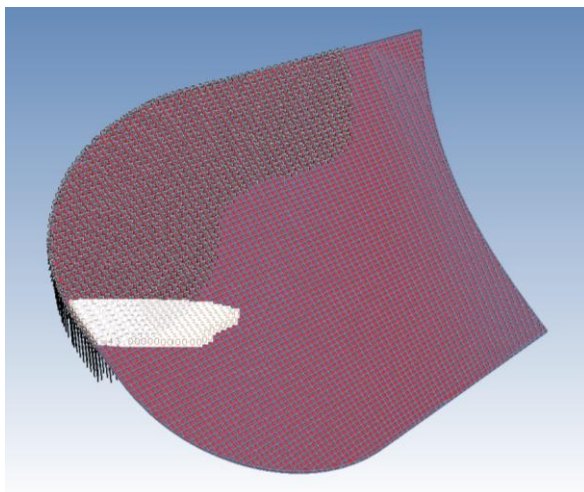


Figure 3-Screenshot from design studio showing the higher load area.

As several assumptions had to be made, it is likely that the actual figures for deflection can be inaccurate, this can't be helped without knowing exactly how much force is being applied to each individual node, however the assumptions made are based from assignment 1 and optimization could still be done successfully.

A single analysis was then run to simulate how much deflection would occur on the steel blade with the forces applied, from figure 4 below it can be seen that there was an apparent deflection of 6.3 meters. This means the blade broke, but design studio is a linear solver so won't know when the elastic limit of a part has been reached.

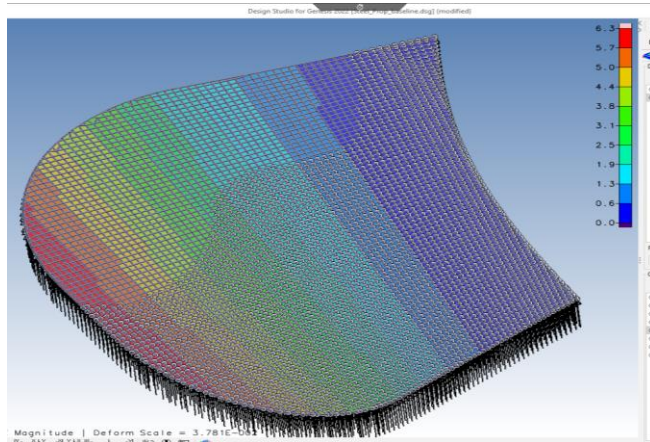


Figure 4- The deform mesh/colour mesh showing the deflection of the steel blade

For the purpose of future comparisons, the mass of the steel blade was calculated using design studio as 646Kg.

CFRP blade development

To create a blade from CFRP, the new material had to be created using the specification provided in the brief, this can be seen in figure 5.

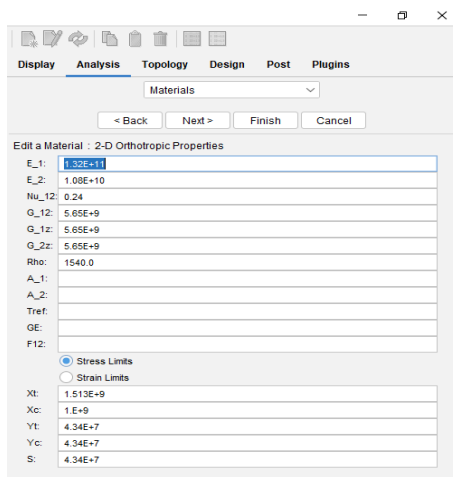


Figure 5- Material properties specified for the CFRP blade

The vectors and elements were then aligned from the centre of the hub outwards to the tip of the blade.

Setting up the layers

As specified in the brief, the blade is to consist of 5 layers of ply's, with a ply thickness at 0.1mm, and the layers set at -90 degrees, -45 degrees, 0 degrees, 45 degrees and 90 degrees. The baseline was then set at 5 ply's per each layer, as can be seen in figure 6.

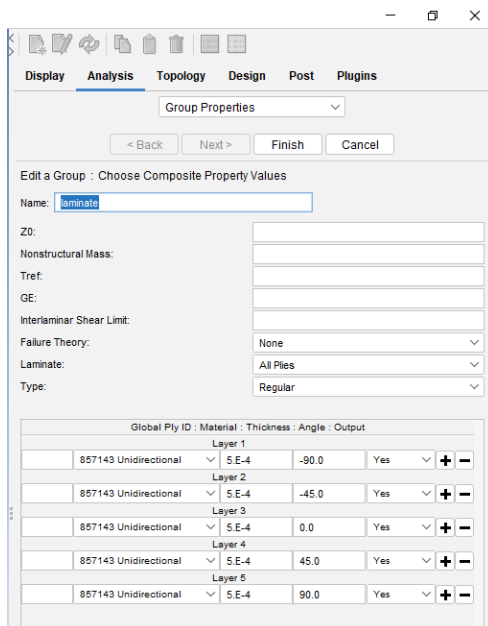


Figure 6- The 5 layers of 5 0.1mm ply's laid up as the baseline for the CFRP propeller blade

With the CFRP propeller baseline created, a single analysis was then completed to simulate the deflection, the results can be seen in figure 7.

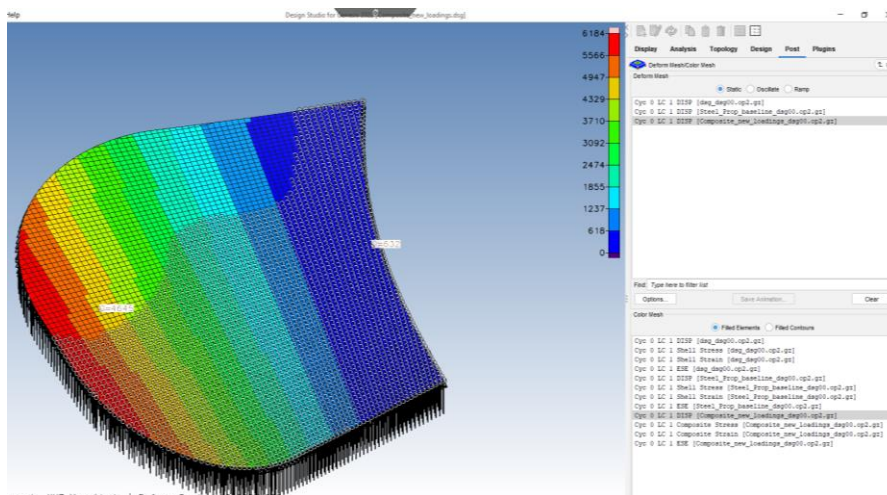


Figure 7- A simulated deflection of 6184 meters has been calculated.

As mentioned previously in this report, design studio is a linear solver, so will not recognise a breakage, but with a deflection of 6184 meters, it is safe to assume the blade has broken.

The weight of this blade was calculated as 32.3Kg.

Task 3: Optimization of CFRP blade

As can be summarised from the previous stages in this report, without optimising both the steel and CFRP propeller blades aren't fit for purpose as they both broke under the applied load. To create a suitable design in CFRP, the structure needed to be optimised.

The first step for FEA optimisation is to outline the design objectives, variables and constraints.

Objectives, variables and constraints

Objectives

The objective for the design is to be as light as possible, this was inputted into design studio as can be seen in figure 8, at the present stage the blade was calculated at 32.3Kg, however the blade broke under the forces, so this was expected to increase significantly along with the strength.

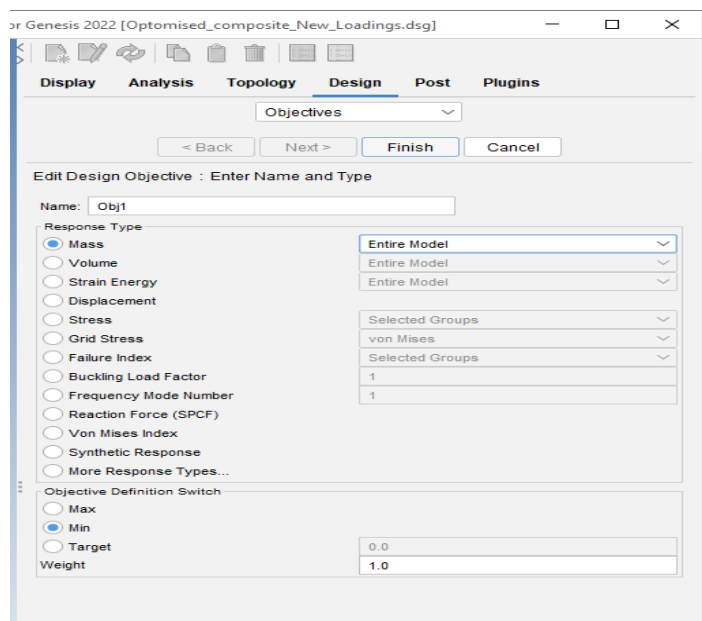


Figure 8 - Objective established in design studio to minimise the mass of the blade.

Variables

The variables, or the design factors that can be changed in order to meet the objectives and constraints, are the number of ply's that can be assigned to each of the 5 layers. The current model had 5X 0.1mm ply's for each of the 5 layers, giving a total thickness of 2.5mm. A minimum and maximum number of ply's was inputted so that design studio could simulate the most efficient way to populate the layers, the lower bound was set at 0.1mm (1 ply thick), and the upper bound was set at 100mm (1000 ply's). This can be seen in figure 9 below.

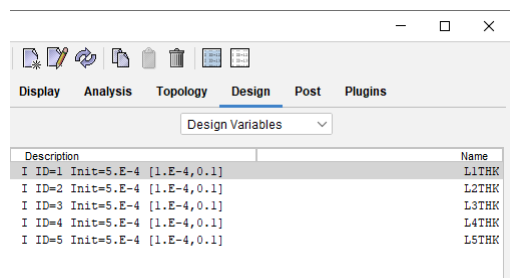


Figure 9 - Design variables set so each layer can be between 0.1mm – 100mm thick

Constraints

The constraint specified was given in the assignment brief, the blade deflection must not exceed 100mm, this was inputted into design studio as can be seen in figure 10.

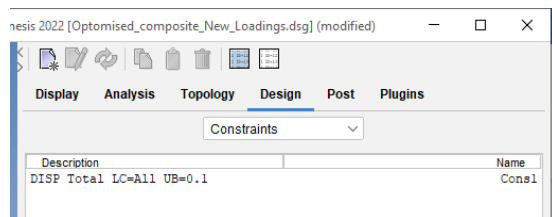


Figure 10 - Maximum allowable deflection of 100mm inputted into design studio

Optimization results

Once the objectives, variables and constraints had been inputted into design studio, the optimization process could begin. Figure 11 below shows the results of the optimization.

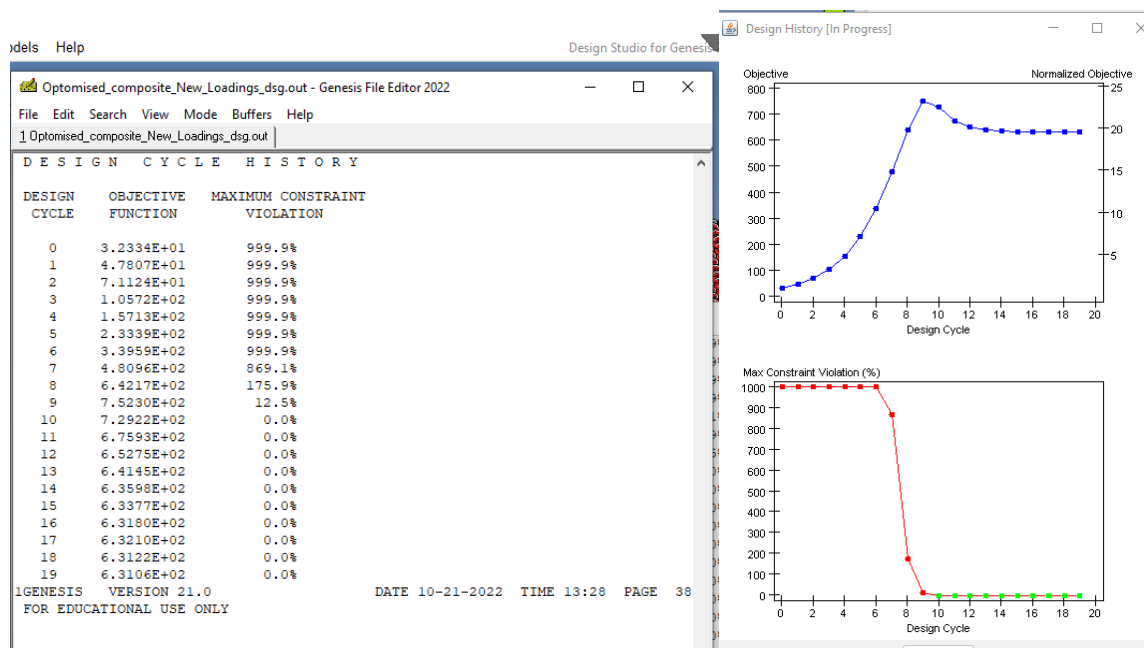


Figure 11 - Optimization results showing the design cycle history

As can be seen in figure 11, design studio ran for a total of 19 cycles, by design cycle 10 the constraint target (100mm max deflection) had been met, then from cycle 11 to 19 the variables (Layer thicknesses) were adjusted to minimise the weight of the blade. This shows the effectiveness of design studio very well, as at design cycle 10 the blade weighed 729Kg, but by the time it was fully optimized at cycle 19, it weighed 631Kg and still met the constraint.

Figure 12 (On the next page) shows the design variable history, illustrating the process taken by design studio to reduce the weight whilst still meeting the specified maximum deflection.

DESIGN VARIABLE HISTORY					
DESIGN CYCLE	DESIGN VARIABLE 1	DESIGN VARIABLE 2	DESIGN VARIABLE 3	DESIGN VARIABLE 4	DESIGN VARIABLE 5
	L1THK	L2THK	L3THK	L4THK	L5THK
0	5.0000E-04	5.0000E-04	5.0000E-04	5.0000E-04	5.0000E-04
1	6.7202E-04	7.5498E-04	8.3798E-04	7.4077E-04	6.9060E-04
2	9.2428E-04	1.1350E-03	1.3713E-03	1.0964E-03	9.7222E-04
3	1.2902E-03	1.6929E-03	2.1935E-03	1.6147E-03	1.3828E-03
4	1.8163E-03	2.5136E-03	3.4714E-03	2.3706E-03	1.9770E-03
5	2.5786E-03	3.7187E-03	5.4349E-03	3.4728E-03	2.8400E-03
6	2.9929E-03	5.2809E-03	9.7921E-03	4.7266E-03	3.4642E-03
7	3.1662E-03	6.9175E-03	1.7455E-02	5.8422E-03	3.8060E-03
8	2.7528E-03	7.7704E-03	2.9534E-02	6.0736E-03	3.5216E-03
9	1.7655E-03	6.6053E-03	4.2708E-02	4.7096E-03	2.3779E-03
10	8.1221E-04	4.0854E-03	4.7787E-02	2.6099E-03	1.0883E-03
11	3.7866E-04	2.4950E-03	4.7644E-02	1.3590E-03	3.8604E-04
12	1.4202E-04	1.5326E-03	4.7930E-02	7.1838E-04	1.4680E-04
13	1.0007E-04	9.5021E-04	4.8097E-02	3.4830E-04	1.0007E-04
14	1.0001E-04	5.5629E-04	4.8198E-02	2.1860E-04	1.0001E-04
15	1.0003E-04	3.8118E-04	4.8305E-02	1.1563E-04	1.0003E-04
16	1.0000E-04*	3.3654E-04	4.8214E-02	1.0000E-04*	1.0000E-04*
17	1.0267E-04	2.3567E-04	4.8324E-02	1.0764E-04	1.0315E-04
18	1.0036E-04	1.4951E-04	4.8354E-02	1.0102E-04	1.0042E-04
19	1.0003E-04	1.0356E-04	4.8389E-02	1.0007E-04	1.0003E-04

Figure 12- Design variable history showing the layer thickness for each cycle during the optimization process.

As can be seen in figure 12, at the start of the optimization process each layer was 0.5mm thick, by the final cycle, almost all the ply's were in layer 3, this was expected as layer 3 is at zero degrees which runs radially to the outer tip of the blade. The layer thicknesses in a clearer format for the final cycle are:

- Layer 1 -90° = 0.10003mm
- Layer 2 -45° = 0.10356mm
- Layer 3 0° = 48.389mm
- Layer 4 45° = 0.10007mm
- Layer 5 90° = 0.10003mm
- Total thickness of blade = 48.79269mm @631Kg

Optimization for manufacturing capabilities

Whilst at this stage, the blade was fully optimized, however it was only in theory as to be manufactured the layers must be in multiples of 0.1mm, this meant that design studio had to be instructed to optimize the blade further with discrete variables. Figure 13 shows the results of the optimization for discrete design variables.

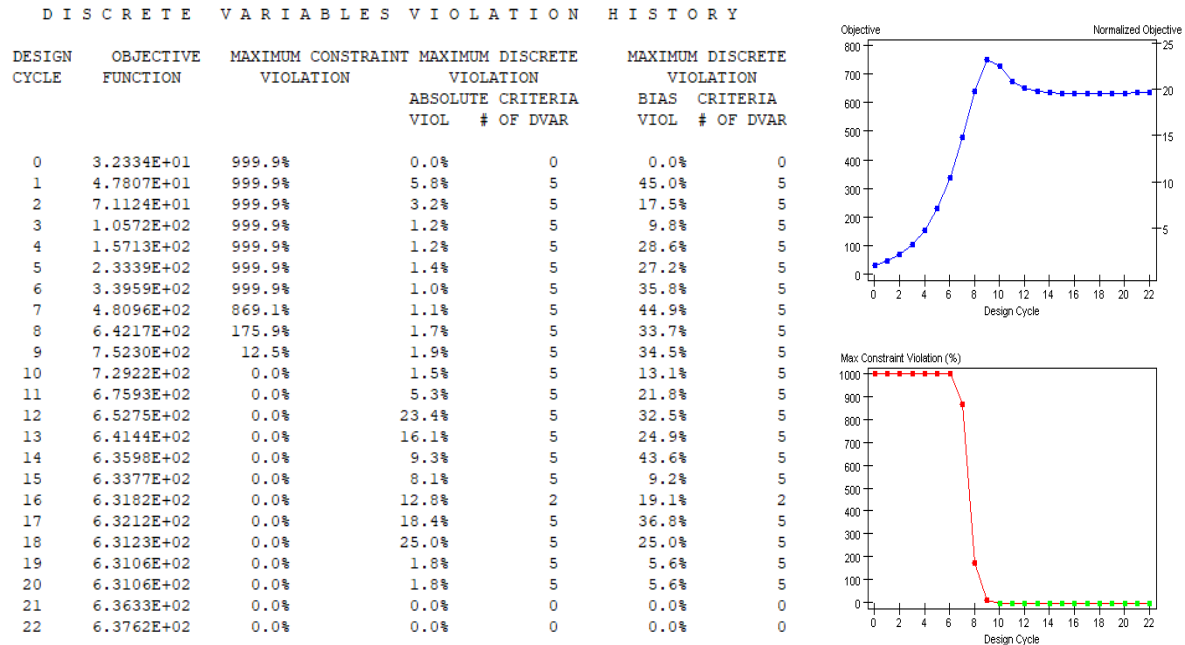


Figure 13- Design cycle history using discrete variables (layer thicknesses in multiples of 0.1mm)

Figure 13 shows that 22 cycles were ran in total, and that with the discrete variables the weight increased from the previous 631Kg to 637Kg, this was expected as it is impossible to create the most efficient design produced by the software, so to make it manufacturable and still meet the constraint, the layer thicknesses had to be rounded up to the nearest 0.1mm. This is still an effective design as a 6kg increase is less than 1% of the overall mass.

Figure 14 below shows how the thicknesses were adjusted during the 22 cycles.

D E S I G N V A R I A B L E H I S T O R Y

DESIGN CYCLE	DESIGN VARIABLE 1	DESIGN VARIABLE 2	DESIGN VARIABLE 3	DESIGN VARIABLE 4	DESIGN VARIABLE 5
	L1THK	L2THK	L3THK	L4THK	L5THK
0	5.0000E-04	5.0000E-04	5.0000E-04	5.0000E-04	5.0000E-04
1	6.7202E-04	7.5498E-04	8.3798E-04	7.4077E-04	6.9060E-04
2	9.2428E-04	1.1350E-03	1.3713E-03	1.0964E-03	9.7222E-04
3	1.2902E-03	1.6929E-03	2.1935E-03	1.6147E-03	1.3828E-03
4	1.8163E-03	2.5136E-03	3.4714E-03	2.3706E-03	1.9770E-03
5	2.5786E-03	3.7187E-03	5.4349E-03	3.4728E-03	2.8400E-03
6	2.9929E-03	5.2809E-03	9.7921E-03	4.7266E-03	3.4642E-03
7	3.1662E-03	6.9175E-03	1.7455E-02	5.8422E-03	3.8060E-03
8	2.7528E-03	7.7704E-03	2.9534E-02	6.0736E-03	3.5216E-03
9	1.7655E-03	6.6053E-03	4.2708E-02	4.7096E-03	2.3779E-03
10	8.1220E-04	4.0854E-03	4.7787E-02	2.6099E-03	1.0883E-03
11	3.7867E-04	2.4950E-03	4.7643E-02	1.3590E-03	3.8602E-04
12	1.4204E-04	1.5326E-03	4.7930E-02	7.1839E-04	1.4676E-04
13	1.0007E-04	9.5019E-04	4.8097E-02	3.4831E-04	1.0007E-04
14	1.0001E-04	5.5623E-04	4.8198E-02	2.1860E-04	1.0001E-04
15	1.0003E-04	3.8141E-04	4.8305E-02	1.1602E-04	1.0003E-04
16	1.0000E-04*	3.3756E-04	4.8213E-02	1.0000E-04*	1.0000E-04*
17	1.0266E-04	2.3634E-04	4.8324E-02	1.0761E-04	1.0314E-04
18	1.0036E-04	1.4976E-04	4.8354E-02	1.0102E-04	1.0042E-04
19	1.0003E-04	1.0358E-04	4.8389E-02	1.0007E-04	1.0003E-04
20	1.0003E-04	1.0358E-04	4.8389E-02	1.0007E-04	1.0003E-04
21	1.0000E-04*	2.0000E-04	4.8400E-02	2.0000E-04	1.0000E-04*
22	1.0000E-04*	2.0000E-04	4.8300E-02	2.0000E-04	1.0000E-04*

Figure 14- Design variable history with discrete variables inputted.

As can be seen in figure 14, using the discrete variables, by cycle 22 the layers are now made up of multiples of 0.1mm (1 ply), so the part can now be manufactured. The layer thicknesses with discrete variables are now:

- Layer 1 -90° = 0.1mm (1 Ply)
- Layer 2 -45° = 0.2mm (2 plys)
- Layer 3 0° = 48.3mm (483 plys)
- Layer 4 45° = 0.2mm (2 plys)
- Layer 5 90° = 0.1mm (1 ply)
- Total thickness of blade = 48.9mm @637Kg

Comparison of blade designs

To demonstrate the effectiveness of using FEA optimization for the design of this propeller blade, the statistics of the various stages are displayed in the table below.

Model	Material	Thickness (mm)	Deflection (M)	Mass (Kg)	Load (KN)	Stiffness (N/mm)	Stiffness/Weight (N ² /mm)
Steel baseline	Steel	10	6.3	646	300	47.61904762	0.007514138
CFRP Baseline	CFRP	2.5	6184	32.3	300	0.04851229	0.000153102
CFRP Optimized	CFRP	48.8	0.1	631	300	3000	0.484644053
CFRP Optimized (Discrete)	CFRP	48.9	0.1	637	300	3000	0.480079117

As mentioned previously, the steel and CFRP baselines would have broken under the load, but the 2 optimized models met the maximum deflection criteria, therefore the stiffness and stiffness/weight figures are significantly higher. The table also displays how the stiffness/weight ratio drops slightly once the discrete variables were generated, this is because the optimum design was impossible to manufacture using 0.1mm thick ply's, so the design has had to compromise slightly to meet manufacturing constraints.

Task 4: Prototype testing

It has been proposed that a prototype blade be created and tested to compare to the results obtained through the FEA optimization process and the simulations for the blade deflection.

Whilst it would be cheaper to manufacture a blade of a smaller scale, as suggested for the fluid flow experiment in assignment 1, only a single blade needs to be developed for this test as opposed to an entire propeller worth, so a full-sized blade should be used.

The following points detail the proposed set up for this experiment which can be seen in figure 14:

- The blade be mounted on the hub to be used for the propeller with the larger areas of the blade facing upwards and downwards, mounting it as it would be on the ship would present difficult challenges with applying the forces simulated in design studio.
- The forces to be applied can either be hung from the underneath of the blade or stuck to the top of the blade. Stuck to the top would be preferable as hanging from underneath would likely require drilling holes in the blade which would significantly weaken its strength. The weights used are to match the higher and lower forces used to simulate the pressure differences detailed previously in this report, 4951 weights can be used or less if the total weight equals 300KN.
- The blade is to be supported on its outer edge until displacement is being measured, the support will be removed so the blade is allowed to sag, using multiple calibrated laser distance measuring devices, the deflection at strategic points is to be measured.
- Strain gauges can be placed along the blade which can be used to compare the strain values given in design studio

Considerations to be made:

- The weight of the blade is calculated more than 600Kg, it is likely the blade will sag under its own weight, so the measurements may be higher those in design studio, this can be checked by removing the support whilst no weight is present on the blade and measuring the deflection, the measuring devices can then be zeroed so this is considered once the weight is applied. This won't be 100% accurate, but it will improve the accuracy compared to if this wasn't considered.

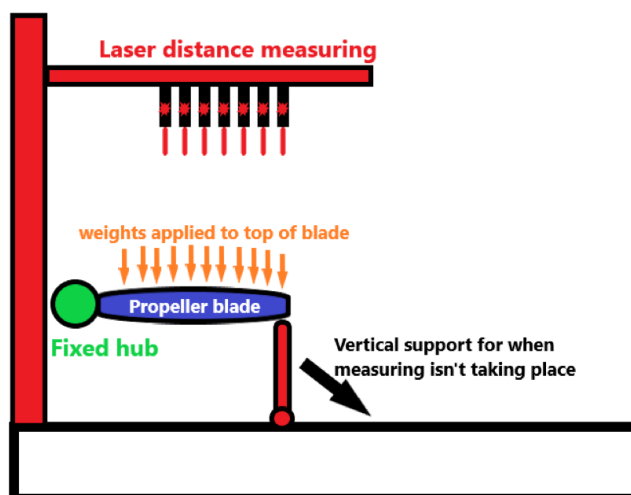


Figure 15- Diagram showing the test procedure described above

Task 5: Industry standards applicable

ISO standards applicable

While designing, manufacturing, and testing a ship propeller, there are several industry standards that must be considered, some of these were stated in the report for assignment 1 (Brearley, 2022):

- ISO 484-1:2015(en) - Shipbuilding — Ship screw propellers — Manufacturing tolerances — Part 1: Propellers of diameter greater than 2,50 m. (ISO, 2015)
 - This standard dictates the tolerances allowed during manufacturing for propellers of 2.5m in diameter and above
- Manufacturing accuracy, ISO 484/1 – 1981 (CE).

ISO 484/1 – 1981 (CE)

Class	Manufacturing	Mean pitch
S	Very high accuracy	+/- 0.5%
I	High accuracy	+/- 0.75%
II	Medium accuracy	+/- 1.00%
III	Wide tolerances	+/- 3.00%

(MAN

Energy solutions, 2019)

- ISO 19030-1:2016, Measurement of changes in hull and propeller performance
 - (ISO, 2016) states that this “*outlines general principles for the measurement of changes in hull and propeller performance and defines a set of performance indicators for hull and propeller maintenance, repair and retrofit activities.*”
- ISO 22554:2015, Propeller shaft revolution indicators — Electric type and electronic type
 - This standard sets out guidelines for how the RPM of a propeller shaft is measured and monitored
- ISO 22098:2020, Full-scale test method for propeller cavitation observation and hull pressure measurement
 - This standard sets out guidelines for measuring cavitation of the propeller and how it affects the ship’s hull
- ISO/DIS 23453, Guidelines for the design and manufacture of the hub cap with fins for a fixed-pitch marine propeller.
 - This standard is still under development so is likely to be released in the future, however its purpose is for a hub vortex device used on fixed pitch propellers to increase efficiency and energy savings.
- ISO 18352:2009(en), Carbon-fibre-reinforced plastics — Determination of compression-after-impact properties at a specified impact-energy level
 - This standard sets out guidelines for testing and monitoring the strength of CFRP after it has received impacts

HSE legislation to be considered

Considerations should also be made to legislation during the testing and manufacturing stages such as but not limited:

- Health and Safety at Work etc Act 1974 (HSE, 1974)
- Lifting Operations and Lifting Equipment Regulations 1998 (LOLER) (HSE, 1998)
 - To be considered in order to safely lift and handle the blades
- Provision and Use of Work Equipment Regulations 1998 (PUWER) (HSE, 1998)
 - To be considered in order to safely manufacture the components

Other guidelines available

The standards listed thus far are official documents that must be followed, there are also other guidelines available that would be helpful.

(Performance Composites inc., 2022) have created a complete design guide for the manufacturing and testing of composite materials such as CFRP. The guidance outlines:

- The specification of different grades of CFRP, including :
 - Stiffness
 - Strength
 - Density
 - Specific strength
 - Specific stiffness
- What grades are suitable for specific applications
- The process to be followed for manufacturing
- Tolerances for final products
- Electrical conductivity
- Corrosion resistance
- The tooling to be used for moulding

Conclusion

During this report, the effectiveness of FEA optimization during the structural design stage has been proven with the example of the ship propeller, whilst during the development of such a component there are many other factors that should be considered, but the process detailed in this report is proof of how effective a tool FEA is. The final design for the blade is lighter than the initial steel blade, but significantly stiffer and won't break under the forces detailed in this report and is also made up of discrete variables (Ply's) so can be manufactured.

Bibliography

Brearley, J., 2022. *Designing a tanker propeller - Fluid flow assessment*, Swansea: James Brearley.

Engineering toolbox, 2008. *Dynamic pressure*. [Online]

Available at: https://www.engineeringtoolbox.com/dynamic-pressure-d_1037.html

HSE, 1974. *Health and Safety at Work etc Act 1974*. [Online]

Available at: <https://www.hse.gov.uk/legislation/hswa.htm>

HSE, 1998. *Lifting Operations and Lifting Equipment Regulations 1998 (LOLER)*. [Online]

Available at: <https://www.hse.gov.uk/work-equipment-machinery/loler.htm>

HSE, 1998. *Provision and Use of Work Equipment Regulations 1998 (PUWER)*. [Online]

Available at: <https://www.hse.gov.uk/work-equipment-machinery/puwer.htm>

ISO, 2015. *ISO 484-1:2015(en)*. [Online]

Available at: <https://www.iso.org/obp/ui/#iso:std:iso:484:-1:ed-2:v1:en>

[Accessed 28 October 2022].

ISO, 2016. *ISO 19030-1:2016*. [Online]

Available at: <https://www.iso.org/standard/63774.html>

[Accessed 2 June 2022].

MAN Energy solutions, 2019. *Propulsion of 46,000-50,000 dwt MR Tankers*. [Online]

Available at: https://www.man-es.com/docs/default-source/document-sync/propulsion-of-46-000-50-000-dwt-mr-tankers-eng.pdf?sfvrsn=c58f03f3_0

[Accessed 28 May 2022].

NAFEMS, 2022. *Structural Optimization in Finite Element Analysis*. [Online]

Available at: <https://www.nafems.org/training/courses/structural-optimization-in-finite-element-analysis1/>

Odonnell Consulting engineers, inc, 2022. *HISTORY OF FINITE ELEMENT ANALYSIS*. [Online]

Available at: <https://www.odonnellconsulting.com/what-we-do/expert-witness-forensic-engineering/forensic-engineering-expert-witness/history-of-fea/>

Performance Composites inc., 2022. *Carbon Fiber Composite Design Guide*. [Online]

Available at: <https://www.performancecomposites.com/about-composites-technical-info/124-designing-with-carbon-fiber.html>

[Accessed 29 October 2022].

PTC, 2022. *Finite Element Analysis*. [Online]

Available at: <https://www.ptc.com/en/technologies/cad/simulation-and-analysis/finite-element-analysis>

Tipton, R., 2017. *Northern Lights Solutions*. [Online]

Available at: <http://nlsde.com/2017/01/04/a-brief-history-of-finite-element-analysis/>

Titans of CNC, 2022. *3D printing a titanium part created by artificial intelligence*. [Online]

Available at: <https://www.youtube.com/watch?v=hxKI4XBwBjU>

Wilson, R. W. C. & E. L., 1970. *Early finite element research at Berkeley*, Berkeley: University of California, Berkeley.

