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Designing A Tanker Propeller: Structural Assessment

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Introduction

In this Report it will be looking over FEA optimisation techniques and discussing what they are, how have they been developed historically, what future development is install for them and how they help improve the design process. As work has been referenced from appropriate sources from a wide range. This report will then delve into an example of how FEA optimisations can be used to improve a tanker blade. The goal in mind to create to blade out of a composite layup material and to achieve a deflection no more than 100mm when a load is applied while reducing the weight as much as possible. An experiment is then proposed on how a physical prototype of the blade will be done in a laboratory with discussion on how the results will be collected and compared. Finally, the blade design will then be compared to technical literature and standards.

Finite Element Analysis (FEA)

Finite Element Analysis (FEA) is an engineering software that provides engineers the ability to simulate any given physical phenomenon through a numerical technique known as Finite Element Method (FEM). Using FEA software engineers can minimise the number of physical prototypes and testing, while being able to improve component designs during design stages using optimisation techniques. Therefore, increasing quality of product and saving time and money.

To fully understand and quantify the behaviour of structure/fluid in a physical phenomena's, mathematics must be introduced. The process demands the use of Partial Differential Equation (PDEs). For a computer to solve PDEs, numerical techniques such as optimisations must be used. (Simscale, 2022)

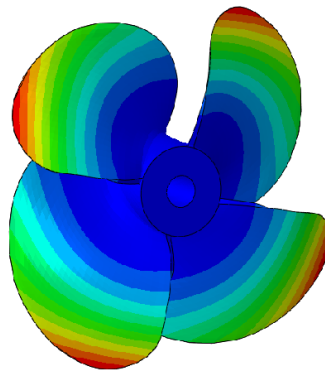


Fig.1- FEA Propeller, (Rao, Mohan, & Kumar)

Optimisation techniques

Background/history

In recent decades engineers have been able to use software to improve mechanical designs through what is known as an '*Optimum design*' (Altair, 2021). This is where a software can optimise a design and therefore direct engineers in the direction to produce the best design from a given specification including design variables, objectives, and design constraints. Doing so eliminates conventional methods which can be very tedious and involve a lot of redesigning (Altair, 2021). Traditionally design optimisation involved manually identifying the right combination of boundaries, this can be very time consuming and requires a step-by-step approach. The method requires experience/judgment of engineers to predict the structures behaviour and determine if any optimisations could be implemented to prevent failure. This can limit the exploration scale of solutions therefore providing a sub-optimal design and preventing potential significantly better designs. As mentions it is a step-by-step approach also known as Iterative optimisation loop (trial and error) (Broekaart, 2015). The industry was then introduced to Parameter-based optimisation, this is where parameter-based optimisation software would automate the traditional trial and error loop method for the user. This allowed for more complex systems, explore the design space, and interact to analyses the design better. (Broekaart, 2015)

Historical development

The first recorded analytical work on structural optimisation goes back to 1869 by Maxwell and Mitchell in 1904. Their work had proven great insight into structural optimisations problems and the design processes. (Vanderplaats, 1982)

In 1988 Martin Philip Bendsøe and Noboru Kikuchi, proposed a method of homogenization optimisation. This meant structures are optimised in a form of '*perforated microstructure*', which means it is constantly changing the density and orientation to proposing what is known as a Solid-Isotropic Material with Penalization (SIMP) (Rozvany, 2001). Years after in 1993 Xie and Steven introduced Evolutionary structural optimisation (ESO) which is a technique that identifies low stress material (inefficient) and there for removes or redistributes the material to achieve the most efficient structural organisation results (Gernaey, Huusom, & Gani, 2015). Both SIMP and ESO are techniques of Topology and use mathematical method to calculate the equivalent density for every element and which of the node are needed or not to deliver a structure meeting required objectives while maintaining its set constraints and variables. (Velling, 2022)

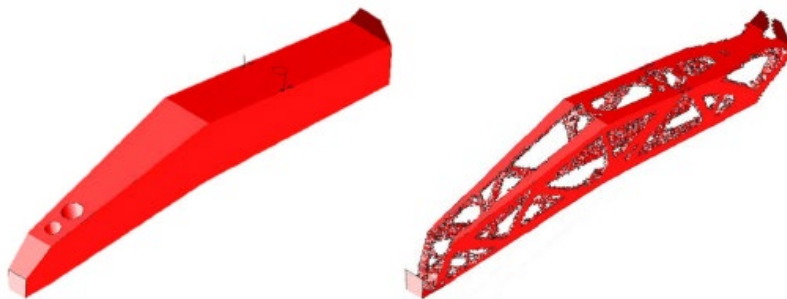


Fig.2- Topology optimization design of the Airbus A350 pylon (Zhu, Zhang, & Xia)

Topology within Additive Manufacturing and future development

Topology has shown great benefits in current and future developing methods of manufacturing. Additive manufacturing (AM) is rapidly growing and due to the complexity of shapes produced within Topology optimisation, conventional methods such as casting, and moulding has proven difficult to manufacture (Plocher & Panesar, 2019). AM processes thrives under the constrains given by Topology with the only limiting facture of its minimal wall-thickness (Femto, 2022). Actions for future development surrounding topology optimisation process for AM could be a hard-kill element elimination approach. This is where the removal of elements that been left at a low modulus over several optimisation iteration to reduce the finite element number. Another implementation could be using iterative remeshing to allow only refining where required and coarsening where fine mesh is not required. (Brackett, Ashcroft, & Hague, 2011)

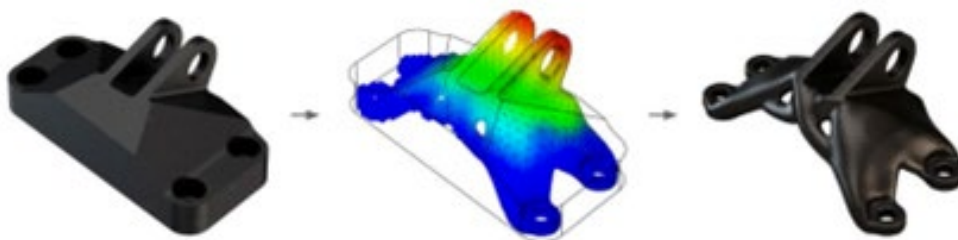


Fig.3-Typical TO Design step, (Design)

Topology's impact on design process

Techniques such as topology within a design process can help to improve the process as mentioned above, through early stages of concept and unlocking designs that are not usually thought of. It has taken away a lot of the unnecessary conventional methods such as trial and error strategy, which has proven time consuming and costly. Research suggest that design processes cannot fully be mathematical formalised. But, through using techniques such as topology it provides greater mathematical design models and helps further understanding the limitations surrounding a given complex design including its automating. (Braha & Reic, 2003) It is a great tool as current time requires a fast competitive market where new designs are being made faster and more efficient.

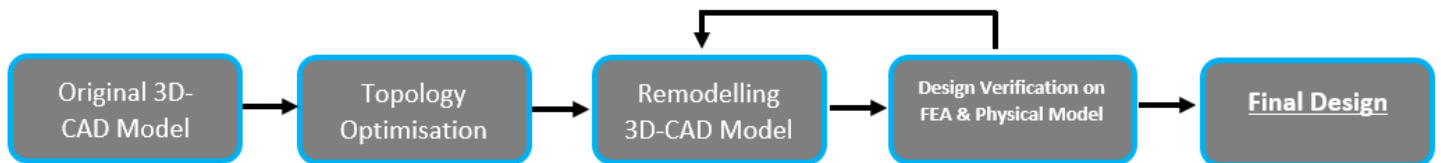


Fig.4- Topology Design Process

Other techniques involve Size, Shape and Topography. Due to a lack of literature surrounding these techniques this report focus was around Topology as Size, Shape and Topography all play a part in how topology optimisation works. In many literatures defined that Topology was usually 'paired' up with either size or shape and due to the complexity of Topography, topology is heavy used within its development over the years. (Liu, Cho, Takezawa, Zhang, & Kitamura, 2019)

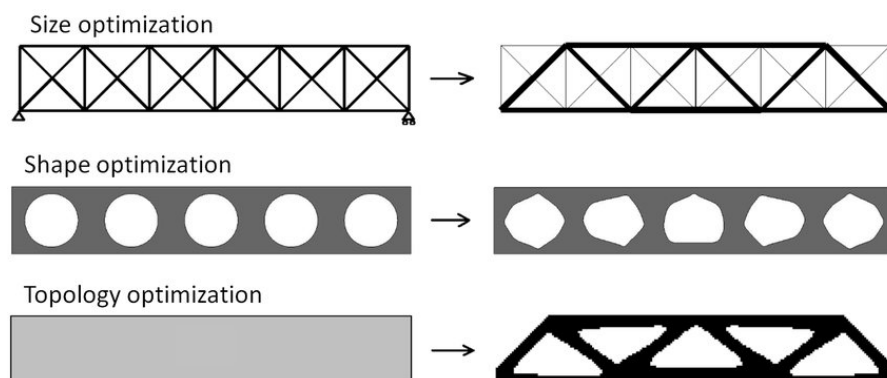


Fig.5-Different Optimisations, (Hendrik & Haertel)

Size

This optimization has been developed to predict a structural layout and size optimal stiffness. Sizing ensures correct distribution of material to improve structural dynamics, stability, and static performance. Sizing can target/modify several factors within the structure such as element thickness, cross sectional area, stiffness, and mass to satisfy requirements. Size optimization could even help identify material choice (ErsilioTushaj & Lako, 2017)

Shape

This technique is used when engineers identify high stress concentrations on a component, through using shape optimisation the shape can be changed to reduce the stress concentration to prevent failure. This can be achieved by enhancing its geometry (height, length, or radius) to morph the stress more evenly. This process requires knowledge to achieve high results. (Bakhtiari, 1996)

Topography

This optimisation technique is mostly found applied onto thin wall structures as a method of reinforcing it. Due to a thin structure being prone to noise and vibration on impact, the use of topography creates patterns/shapes to help minimise its effect on the structure. This technique uses shape variables over density variables much like topology. Through using topography, it can generate awkward patterns that provide better results that many designers cannot simulate without a lot of experience. (P.Sahoo, 2011)

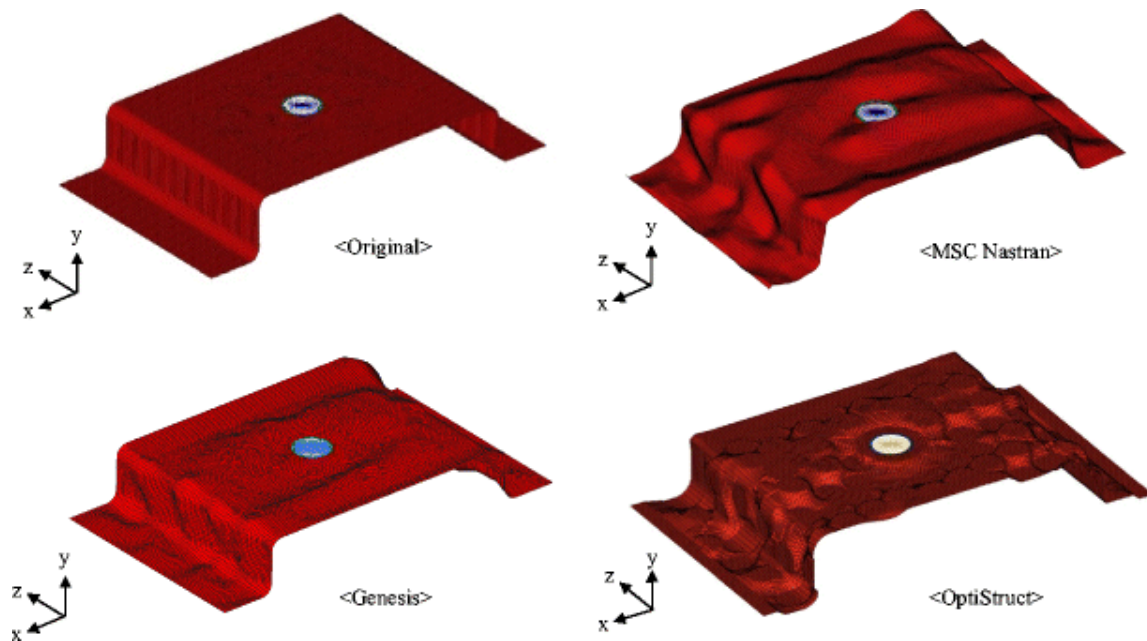


Fig.6-Types of Topography, (Choi, Kim, & Park)

Create Carbon fiber Reinforced Plastic Blade

In this report section DESIGN STUDIO GENESIS is used to create a model of the blade using a lay-up composite material such as Unidirectional (UD) Carbon fibre reinforced plastic (CFRP), rather than the original selection of steel. The Composite material will then go through optimisation to reduce the weight of the blade while ensuring the deformation does not exceed 100mm when forces are applied. During the initial research a calculation was made to determine the load acting on the blade, a force value of 1449.16kN was given from the assumptions made within the first assignment along with the following formula.

$$F = \rho ghA$$

$$F = 1030\text{Kg/m}^3 \times 9.81\text{m/s}^2 \times 15.83\text{m} \times 9.06\text{m}$$

$$F = 1449.16\text{kN}$$

After some consideration this value was deemed too high and even with secondary reflection on the assumptions made there was no clear indication why? Therefore, the original load given by the Steel UDL (5000N) was used. This load will still demonstrate the difference in both material and how the composite characteristics change after optimisation.

Steel blade

The Blade model is first created on SOLIDWORKS it is then imported onto DESIGN STUDIO GENESIS using a NASTRAN Deck program which contains steel properties.

Assignment 1 did not consider rotational forces (Centrifugal force). Therefore, force will only be considered on a stationary blade. **Fig.7** taken from assignment 1 displays how forces on the leading edge are greater due to its smaller area, this has been replicated on **Fig.8** and **Fig.9**.

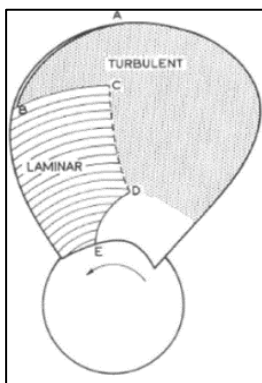


*Fig.7- Schematic Blade,
(Baltazar, Melo, &
DouweRijpkemab,
2020)*

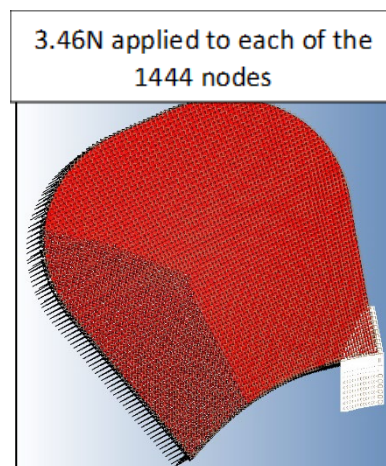


*Fig.8- Load on Leading-edge,
Design Studio*

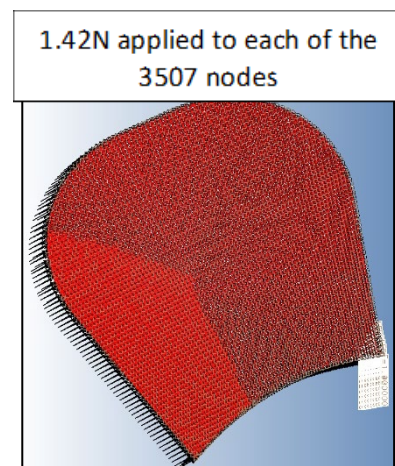


*Fig.9- Load on trailing-edge,
Design Studio*

When solving structures on the software it takes in all the given information such as geometry, elements, material, thicknesses, constraints, and loading to interpreted what would happen to the structure if this load was to be applied. It does this though the use of matrix algebra, as a result it could provide an 'OP2 file' which can then be read into design studio as shown below **Fig.10** the displacement of the elements on the steel blade (0.6m).

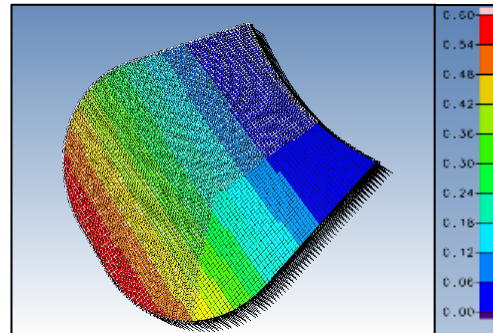


Fig.10- Colour Mesh Deflection on steel blade, Design studio

Stiffness to weight ratio can be calculated using $\frac{(load/ displacement)}{(mass\ of\ blade \times Gravity)}$. The mass of the blade can be found in the information windows **Fig.11** once calculated seen below.

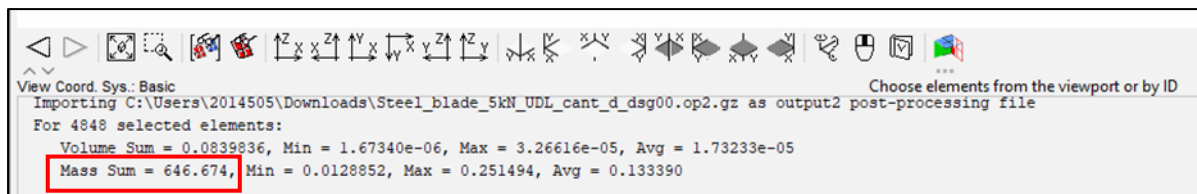


Fig.11- Mass of steel in Information Window, Design Studio

CFRP Blade

Instead of creating a new file the same file was used to maintain consistency with the loading formation. Therefore, a new material was created using an orthotropic with material the given properties **Fig.12** from the brief.

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

Fig.12- Material Properties, Assignment Brief

The composite (CFRP) is compiled of 5 unidirectional layers, each layer comprised of 5 plies (0.1mm thick) in orientations of -90, -45, 0, 45, 90 degrees shown in **Fig.13**. Thus, giving a total of 25 plies with a total thickness of 2.5mm.

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

Fig.13- Composite lay-up, Design studio

Due to CFRP being a composite material (Orthotropic) the material properties (Stiffness) E1 and E2 values are known but are not directionally defined. Design studio has a mesh algorithm that creates orientations vectors associated with those elements which have been generated from the order of nodes. The assumption made that the fibres would run along the blade in the X-Orientation. Theta Vectors demonstrated below **Fig.15**.

Edit Elements : Edit Element Coord. Sys.

☐ Use Coordinate System

Element Coord. System: Basic

Change

☒ Use Vector

Choose Direction:

By 2 Grids...
By 3 Grids...

X: 1
Y: 0
Z: 0

Fig.14- Set up Vectors, Design Studio

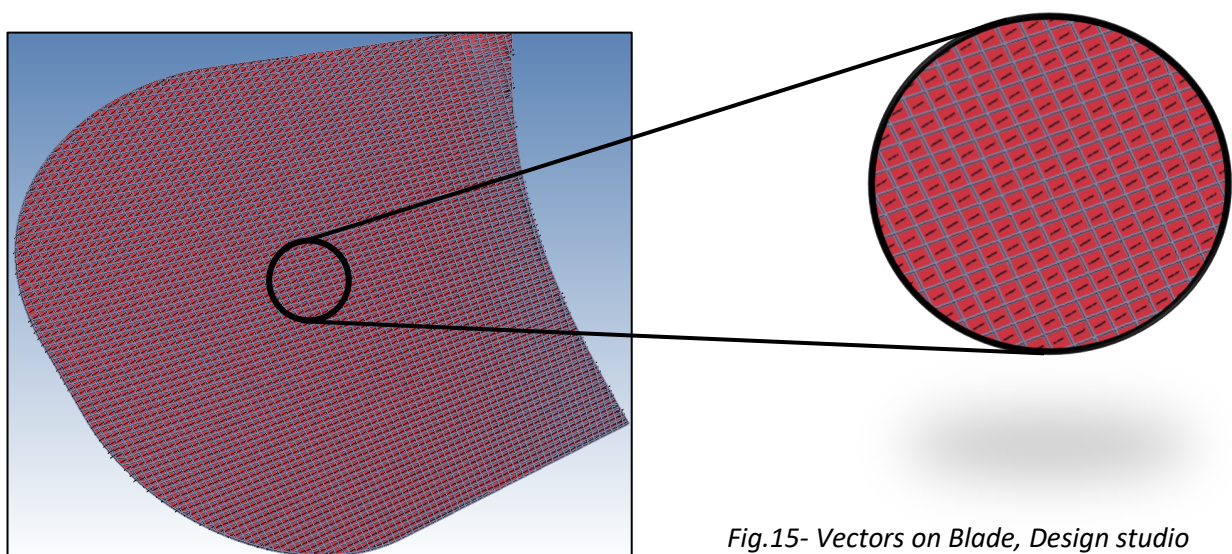


Fig.15- Vectors on Blade, Design studio

By exporting the blade program, the modified NASTRAN DECK **Fig.16** will display the blade as a PCOMP with all the new material properties and all elements will correspond with CFRP.

```

28 $ STRESS = ALL
29 BEGIN BULK
30 $
31 $ Parameters
32 $
33 $
34 $ Property definitions
35 $
36 $HMNAME COMP 1 "Blade"
37 $HMCOLOR COMP 1 1
38 PSHELL 1 8571421.0000-2 857142 857142
39 $HMNAME COMP 2 "CFRP"
40 $HMCOLOR COMP 2 2
41 PCOMP 2
42 + 8571435.0000-4-90.0000 YES 8571435.0000-4-45.0000 YES
43 + 8571435.0000-4 0.0 YES 8571435.0000-445.00000 YES
44 + 8571435.0000-490.00000 YES
45 $
46 $ Material definitions
47 $
48 $HMNAME MAT 857142 "Steel"
49 MAT1 8571422.100+117.900+10.28000007700.000130000.0298.0000
50 7.2333+8
51 $HMNAME MAT 857143 "CFRP"
52 MAT8 8571431.320+111.080+10.24000005.6500+95.6500+95.6500+91540.000
53 + 1.5130+91.0000+94.3400+74.3400+74.3400+7
54 $
55 $ Load definitions
56 $
57 $HMNAME LOADCOL 1 "UDL"
58 FORCE 1 5124 1.420000 0.0 0.01.000000
59 FORCE 1 5123 1.420000 0.0 0.01.000000
60 FORCE 1 5122 1.420000 0.0 0.01.000000
61 FORCE 1 5121 1.420000 0.0 0.01.000000
62 FORCE 1 5120 1.420000 0.0 0.01.000000

```

Fig.16-NASTRAN DECK, Design studio

The new structure made from CFRP is them analysed **Fig.17**, generating its maximum deformation of 547m with a mass of 32.33Kg (**Fig.18**).

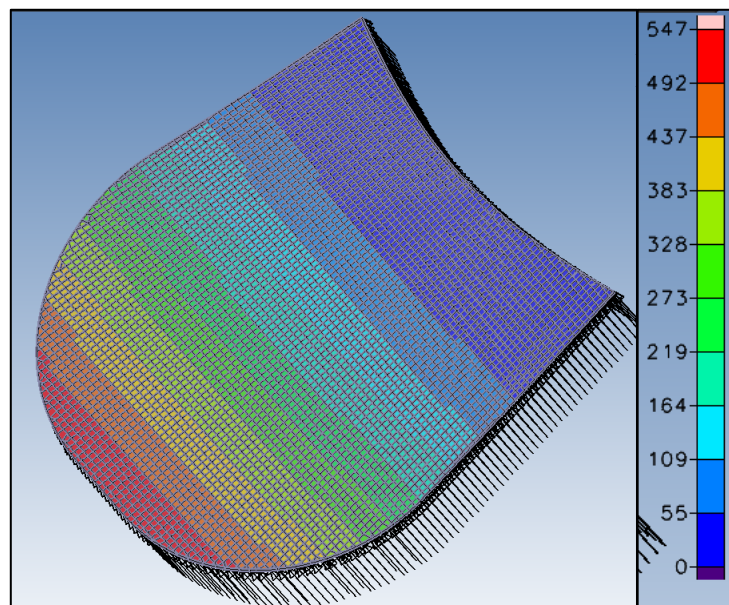


Fig.17- Colour Mesh Deflection of CFRP blade, Design studio

Fig.18- Mass of CFRP in Information window, Design studio

View Coord. Sys.: Basic

Importing C:\Users\2014505\OneDrive - University of Wales Trinity Saint David\Steel_blade_5kN_UDL_cant_d_dsg00.op2.gz as outp

For 4848 selected elements:

Volume Sum = 0.0209959, Min = 4.18351e-07, Max = 8.16541e-06, Avg = 4.33084e-06

Mass Sum = 32.3337, Min = 0.000644260, Max = 0.0125747, Avg = 0.00666949

Below is a table comparing the Steel with the Composite Blade.

Run	Material	Thickness	Deflection	Mass	Load	Stiffness	Stiffness/Weight
Steel blade	Steel	0.01m	0.6m	646.67kg	5000N	8333.3 N/mm	1.31N ² /mm
Composite blade	CFRP	0.0025m	547m	32.33kg	5000N	9.14N/mm	0.03N ² /mm

Fig.19- Table comparing Steel and CFRP blades

As can see from the table above **Fig.19**, both materials have the same load applied, steel thickness is 4 times that of the composite blade, which was layered up with 5 layers each having 5 plays (0.1mm) resulting 2.5mm total. The mass of steel is measured 646.67kg while the composite only weighted 32.33kg which is a huge difference in weight. But because of that the steel deflection is only 0.6m while the composite is 547m, they both are way out of requested design specification of 0.1m. After calculating the load and displacement, stiffness of steel is 8333.3 N/mm while stiffness composite is 9.14N/mm. This carries over to stiffness/weight ration to give 1.31N²/mm for steel and only 0.03N²/mm for composite which would easily break on impact and so no benefit other than weight to change.

Optimisation of CFRP Blade

Following this result, to achieve the task goal of limiting the blades deformation to while reducing the weight of the blade using a layup composite, an optimisation is carried out on the structure.

Within the Optimisation it will define how many plies is required in each orientation of the composite to reduce the deflection from 547m to 0.1m. To do this the following must be considered.

- **Objectives**-To make the blade as light weight as possible.
- **Variables**-Will be the number of plies in each layer. Through using the optimisation, it will advise how many plies is required at each layer to be able to achieve the constrains put in place this case 100mm.
- **Constrains**-Will be the displacement over the entire blade structure in 6-degrees-of-freedom(Translation magnitude). Note:The lower bound is left out to prevent over constraining, but an upper bound value is entered to achieve that 100mm or stiffer displacement.

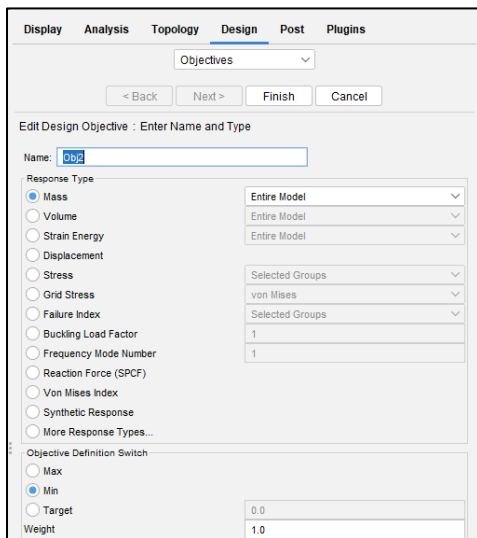


Fig.20- Objective setup, Design studio

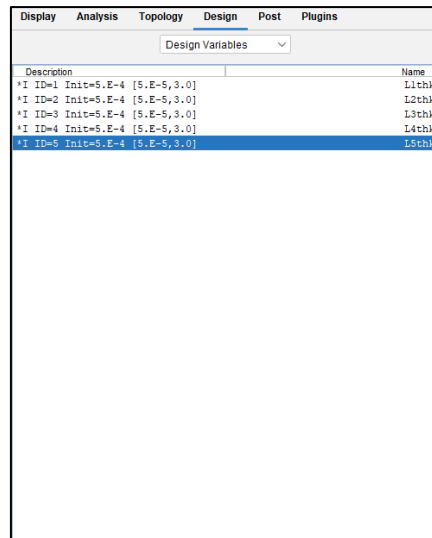


Fig.21- Design Variables setup, Design Studio

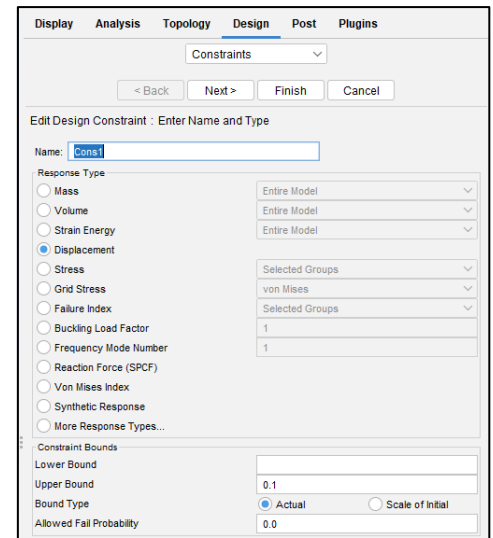


Fig.22- Constrain setup, Design studio

After imputing all considerations (Ensuring variables have been linked to the physical property and therefore not displaying *) An optimisation is carried out show below **Fig.23** of the console and design history graph.

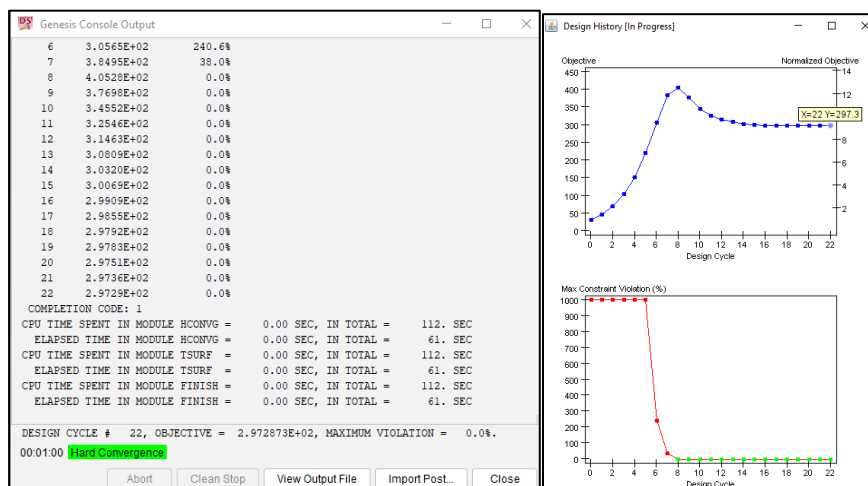


Fig.23-Single Analysis with graphs, Design studio

For greater visual representation of all the cycles carried out and use of history graphs the post process files (**Fig.24**) were inputted into Design studio

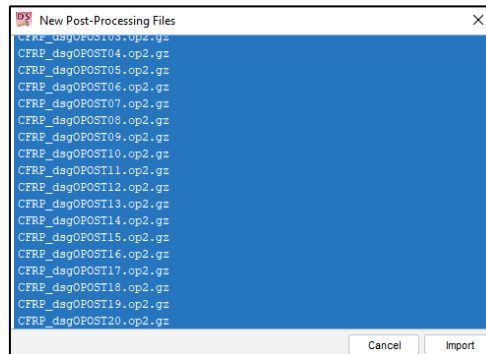


Fig.24- Post-Process Files, Design studio

This allowed to display how each cycle behaved during the optimisation and the required deformation of each ply thicknesses. Cycle-20 was the last to run and therefore investigated to be able to compare with CFRP original layup structure.

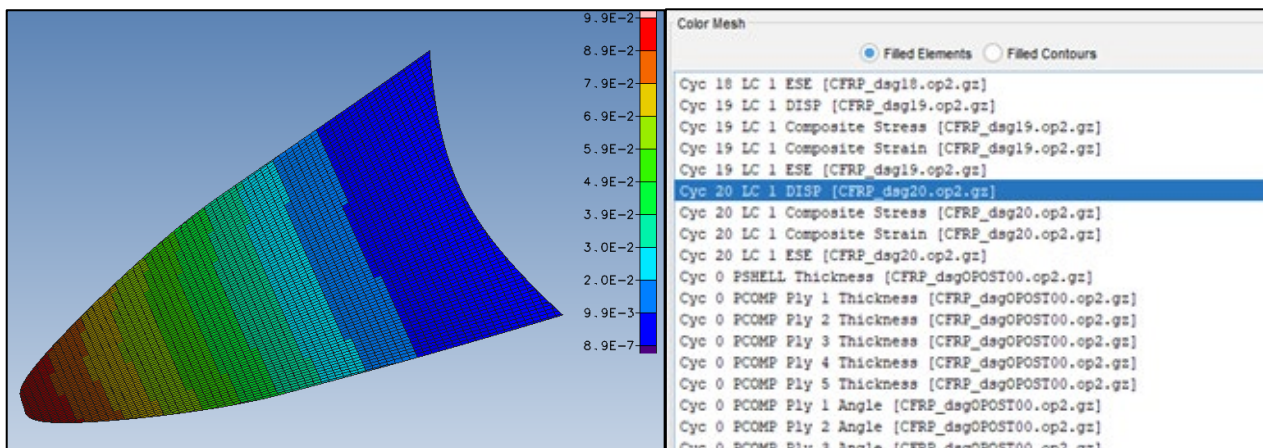


Fig.25- Colour Mesh for Optimised CFRP, Design studio

When opened in 'HIS' file both cycle 0 (**Fig.26**) and 20 (**Fig.27**) can be compared to see how the optimisation has changed the structures requirement to meet design constrains.

1	DESIGN CYCLE #	0, OBJECTIVE = 3.233368E+01, MAXIMUM VIOLATION = 999.9%.
2	DESIGN VARIABLE #	1 = 5.000000E-04 L1thk
3	DESIGN VARIABLE #	2 = 5.000000E-04 L2thk
4	DESIGN VARIABLE #	3 = 5.000000E-04 L3thk
5	DESIGN VARIABLE #	4 = 5.000000E-04 L4thk
6	DESIGN VARIABLE #	5 = 5.000000E-04 L5thk

Fig.26- History File Cycle 0, Design Studio

121	DESIGN CYCLE #	20, OBJECTIVE = 2.979226E+02, MAXIMUM VIOLATION = 0.0%.
122	DESIGN VARIABLE #	1 = 5.010612E-05 L1thk
123	DESIGN VARIABLE #	2 = 5.010612E-05 L2thk
124	DESIGN VARIABLE #	3 = 2.271094E-02 L3thk
125	DESIGN VARIABLE #	4 = 1.737459E-04 L4thk
126	DESIGN VARIABLE #	5 = 5.010612E-05 L5thk

Fig.27- History File Cycle 20, Design studio

As can see **Fig.26** the original 5 plys in 5 layers has violated the constraint by 999.9% therefor no good. When looking at cycle-20(last cycle) **Fig.27** it has dramatically changed the design resulting in 0% violation but requires a total thickness of 0.02344m which weights 297.92kg, nearly x10 the original weight which is still over 3 times lighter than the steel blade which displaces 6 times as much.

Run	Material	Thickness	Deflection	mass	load	stiffness	Stiffness/weight
Steel blade	steel	0.01m	0.6m	646.67kg	5000N	8333.3 N/mm	1.31N ² /mm
Composite blade	CFRP	0.0025m	547m	32.33kg	5000N	9.14N/mm	0.03N ² /mm
Optimised composite	CFRP	23.03m	0.099m	297.92kg	5000N	50505.05N/mm	17.28 N ² /mm

Fig.28- Table comparing Steel, CFRP and Optimised

As seen from the second table above **Fig.28** a new row has been added where the original Composite material has now been optimised to meet design constraint. This has been done through using independent design variables, The optimisation has calculated that for the constraint of 100mm to be met the number of plys used must increase totalling the thickness to 23.03m which as a result increased the mass to 297.92kg. When calculated the stiffness using the same 5000N it gives a value of 50505.05N/mm and a ratio of 17.8N²/mm which is much more desirable and beneficial for the application compared to the previous designs.

Unfortunately, when the investigated the HIS file the design Variable (Number plys in each layer) it displays **Fig.29**. The issue is the blade needs to be able to be manufactured and therefor requires whole numbers which using independent variable as mentioned above does not consider and only produces best results regardless how its made. For example, 5.010612E-05 is not manufacturable.

Design Variable #	1 = 5.010612E-05	L1thk = 0.5 at -90
Design Variable #	2 = 5.010612E-05	L2thk = 0.5 at -45
Design Variable #	3 = 2.271094E-02	L3thk = 501 at 0
Design Variable #	4 = 1.737459E-04	L4thk = 1.73 at 45
Design Variable #	5 = 5.010612E-05	L5thk = 0.5 at 90

Fig.29- Table showing size of Plys and number of plys per layer

The table can also be read in a form of a graph shown below **Fig.30** highlighting the thicknesses of each layer, with layer-3 extremely higher compared to the other 4 layers.

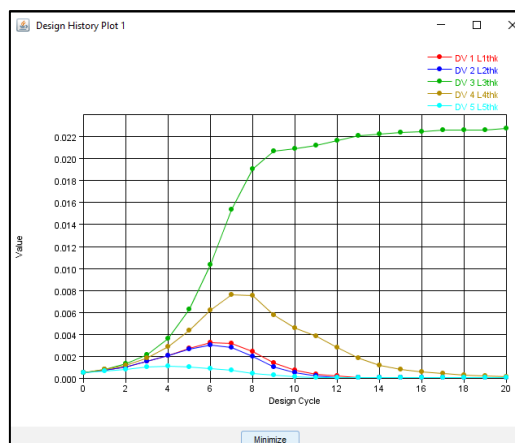


Fig.30- History Graph of Design variables, Design studio

Discrete Optimisation CFRP blade

To achieve useful manufacturable values the independent values much change into descret variable within the design **Fig.31**, this is to rescript design studio freedom to focus its choices down. In this case Number of additional values of 1000 from 5.E-5 were added **Fig.32** to esnure maxium-violation had a chance to come to 0%.

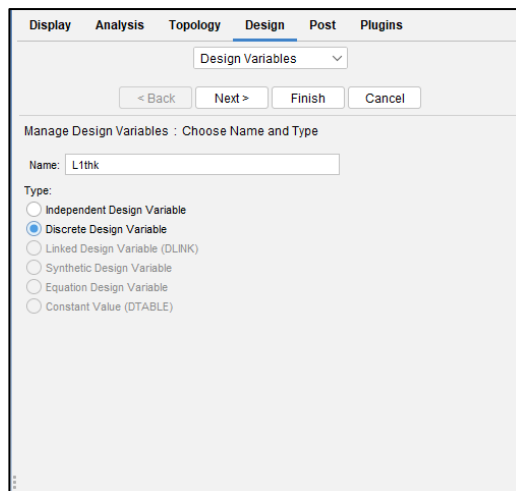


Fig.31- Changing to discrete variables, Design studio

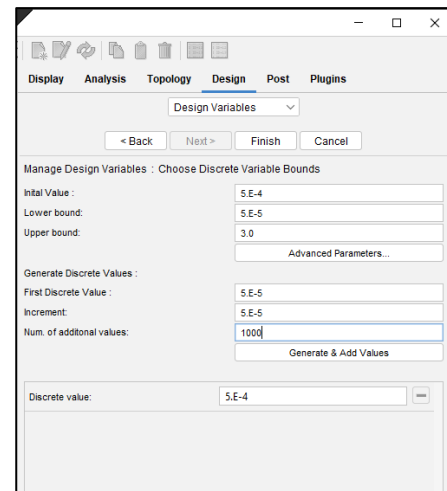


Fig.32- Setup Discrete Variables, Design studio

Notice **Fig.33** when optimised the discrete variables at cycle-20 the values are the same but as it continues through the cycles its backtracking and realising the valvies are not discrete valvues and therefore adjusts to meet requested variables.

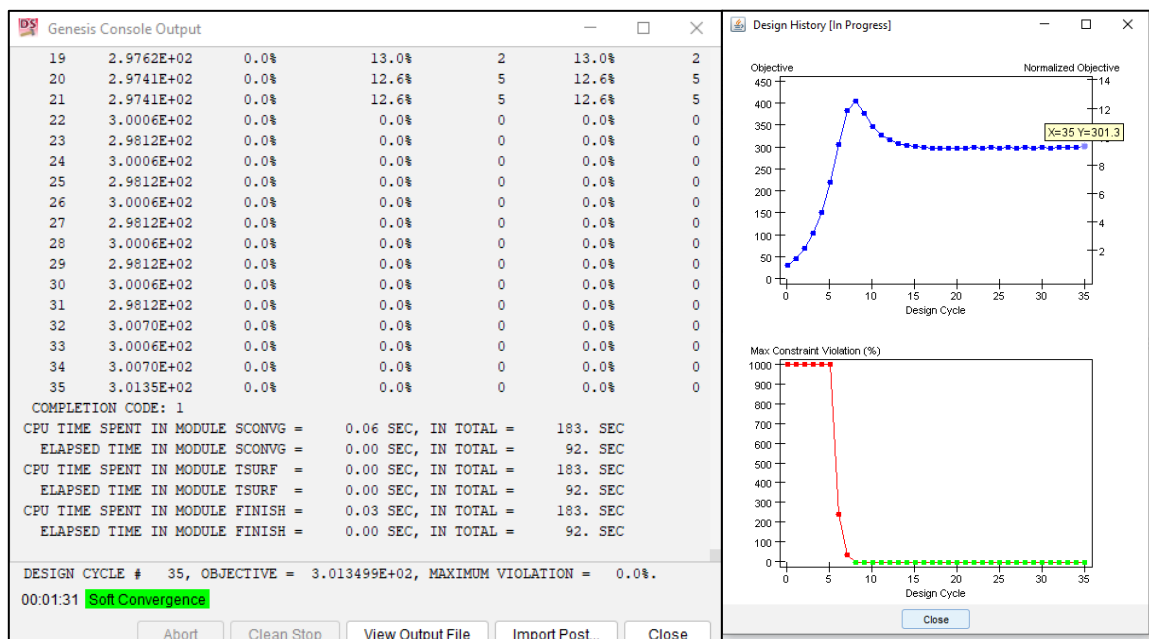


Fig.33- Single Analysis for Discrete Optimised CFRP, Design Studio

Can now import file to read on His file and Graphs, shown below **Fig.34**.

211	DESIGN CYCLE #	35,	OBJECTIVE =	3.013499E+02,	MAXIMUM VIOLATION =	0.0%.
212	DESIGN VARIABLE #	1 =	1.000000E-04	L1thk		
213	DESIGN VARIABLE #	2 =	1.000000E-04	L2thk		
214	DESIGN VARIABLE #	3 =	2.270000E-02	L3thk		
215	DESIGN VARIABLE #	4 =	3.000000E-04	L4thk		
216	DESIGN VARIABLE #	5 =	1.000000E-04	L5thk		
217	COMPLETION CODE:	1	272	0		

Fig.34- History File Cycle 35 on discrete CFRP optimisation, Design Studio

As can see from the text file **Fig.34**, the numbers in cycle-35 have now changed to discrete whole values which would be suitable for manufacturing the blade. The graphes (**Fig 35,36 and 37**) are a bit difficult to tell the difference as they are zoomed out but as can see the design cycle stretches to 35 cycles. The maximum violation remains 0% but the mass of the object increases to 301Kg which is 4Kg heavier do to the variable change.

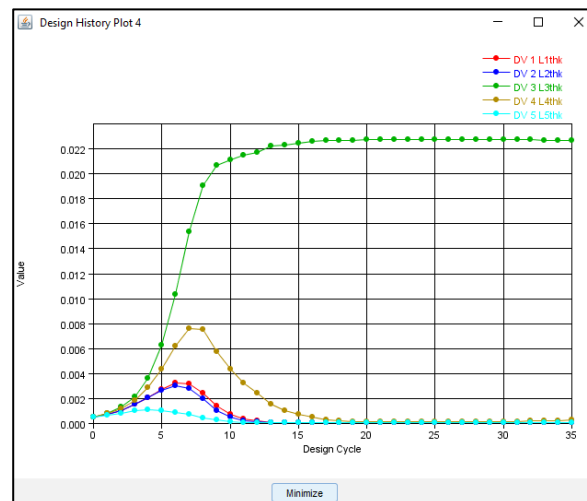


Fig.35- History Graph of Discrete Design variables, Design studio

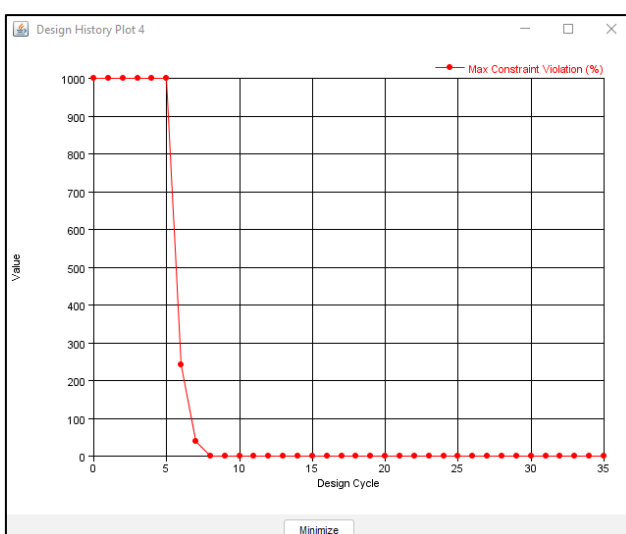


Fig.36-Constrain history graph for Discrete design variables, Design studio

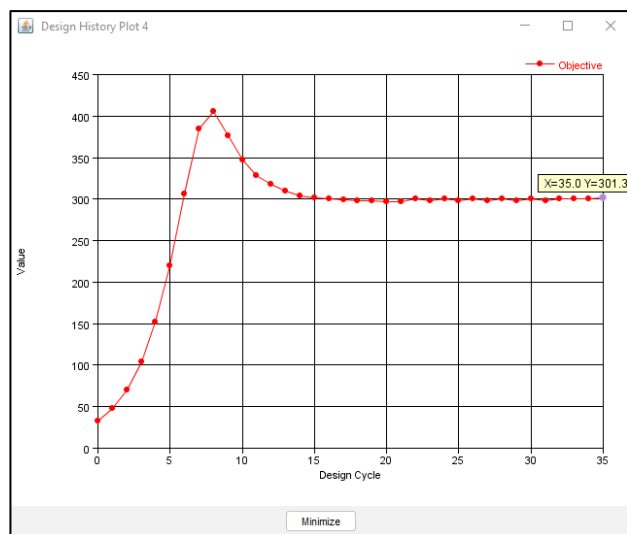


Fig.37- Objective history graph for Discrete design variables, Design studio

$-90\text{Degrees} = 0.0001 = 1\text{Ply}$

$-45\text{Degrees} = 0.0001 = 1\text{Ply}$

$0\text{Degrees} = 0.0227 = 227\text{Plys}$

$45\text{Degrees} = 0.0003 = 3\text{Plys}$

$90\text{Degrees} = 0.0001 = 1\text{Ply}$

Total = 0.0233m = 233plys

Run	Material	Thickness	Deflection	mass	load	stiffness	Stiffness/weight
Steel blade	steel	0.01m	0.6m	646.67Kg	5000N	8333.3 N/mm	1.31N ² /mm
Composite blade	CFRP	0.0025m	547m	32.33Kg	5000N	9.14N/mm	0.03N ² /mm
Optimised composite	CFRP	0.02344m	0.099m	297.92Kg	5000N	50505.05N/mm	17.28 N ² /mm
Optimised composite (Discrete)	CFRP	0.0233m	0.097m	301.35Kg	5000N	51546.39N/mm	17.44N ² /mm

Fig.38- Table comparing Steel, CFRP, Optimised CFRP, Discrete Optimisation CFRP

Summary

To summarise the final Optimise composite shown in **Fig.38** has 3.43Kg more weight than the Optimise composite but as a result is thinner in size, achieve a 0.002 greater deflection(Bypassing the required 100mm deflection),1041.34N/mm additional stiffness and a 0.16N²/mm higher stiffness to weight ratio. Most importantly manufacturing the blade is possible.

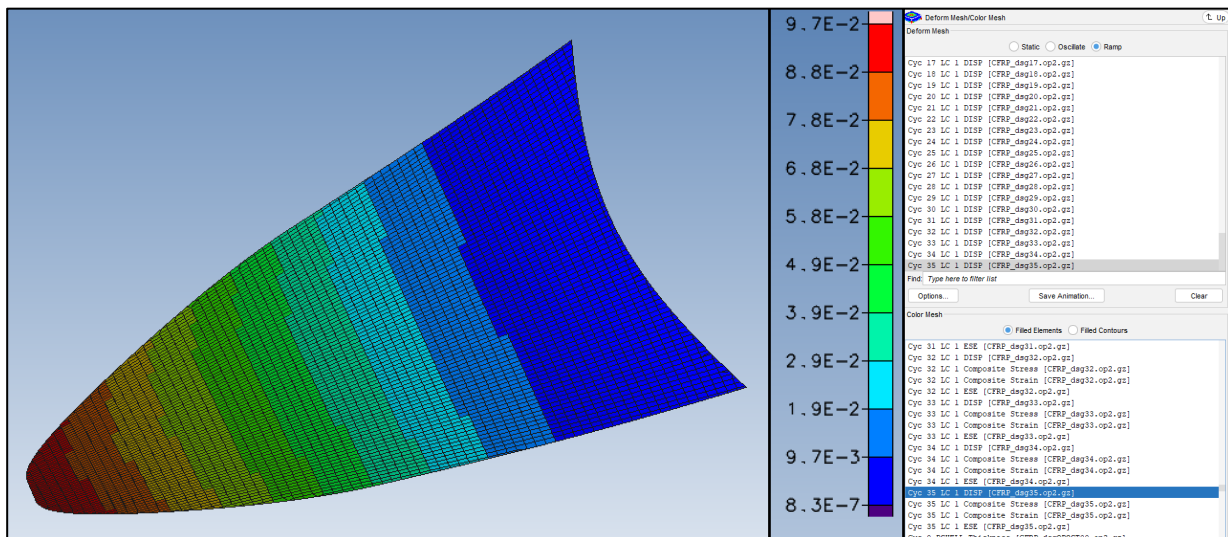


Fig.39- Colour Mesh on discrete Optimised CFRP, Design studio

Physical Prototype Experiment

In this section it will discuss a physical experiment is done on the blade in a laboratory to determine its deformation (change in pitch angle under operational load) which can then be compared to the FEA design results. Shown below **Fig.40** is a Process Flow Chart showing the procedure to compare the results.

Process Flow chart

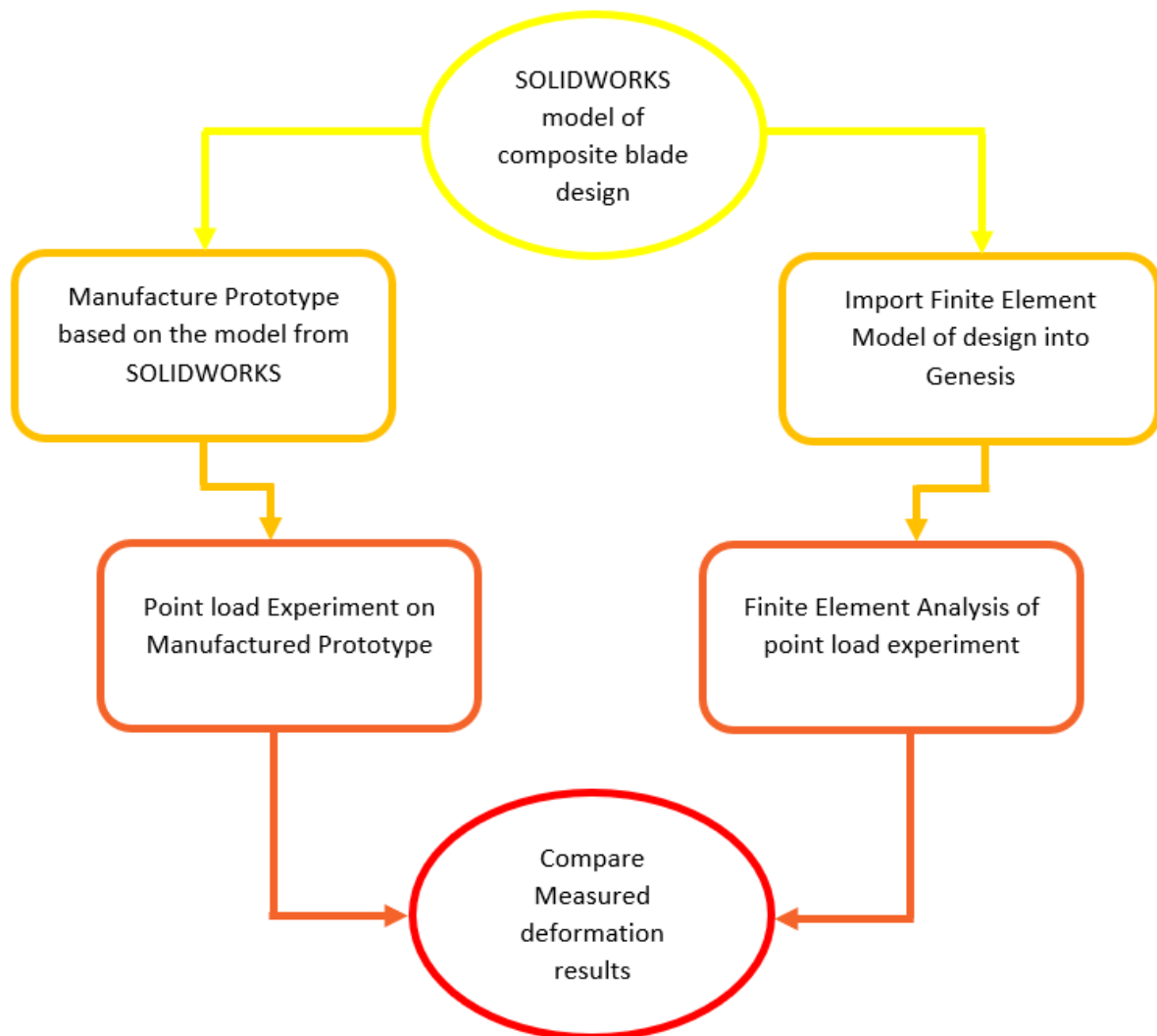


Fig.40-Process Flow Chart for Prototype and FEM

In a perfect world the prototype blade would be loaded with the operational periodic load case to provide measurements for resulting deformation. However, by loading the blade with an operational fluid load case would result in a very complicated. Therefore, a point load case experiment was the sensible choice. Initially the prototype blade was scanned using Atos-5[High-precision 3D-scanners that measure with digital image correlation (DIC) technology] before the experiment took place. This allowed a 3D-model of the prototype to be compared to the original 3D-model. Using drilled holes on the root of the cast the blade would be mounted onto a rigid steel test rig at 20° to imitate its most loaded position. The method used to apply load onto the blade was done by hanging weights from the point load position. The weight would hang on the end of a climbing rope which had been fed and knotted to prevent falling through a drilled hole. As the knot could have added potential stress the blade a plastic washer was added between the two to minimise the possibility.

The use of strain gauges was used though out the experiment to constantly logging data onto a software displaying its behaviour. The weights would be added incrementally onto the point load by hand. The precision 3D-scanners were not only used at the start but used through out the experiment taking snapshots after every incremental load was added, to measure the occurring deformation. To ensure accuracy of Scanners the blade had to have a distinct marking for the cameras to focus on to be able to take snapshots of its start and end position including each time weight was added. So, to do this the blade surface was painted white and a black dot was added using black paint.

The data was then gathered from both the scanners and strain gauges. The first comparison is through DIC and FEA measurements, these measurements can be presented in full alongside producing a load max displacement graph, deformation characteristics and the blades bending and twisting deflection. The second comparison is using the strain measurements and numeric predictions was given to judge the materials response in both experiment and FEA. See **Fig.41** for visual.

Schematic of Experiment

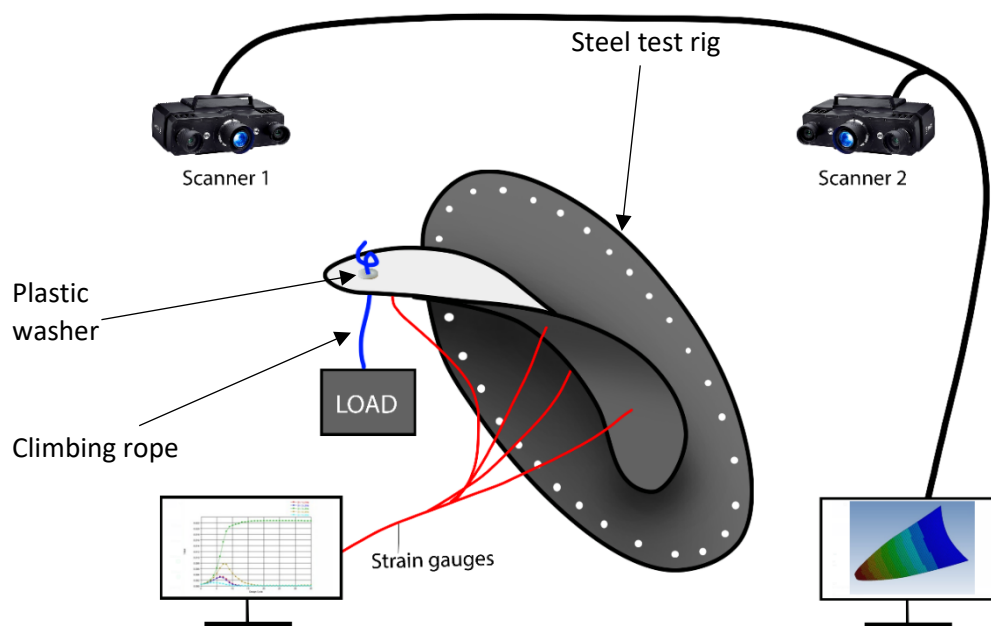


Fig.41-Schematic of Blade Experiment

Relate Design to Technical literature and standards

To relate the design created in this report, primary research was carried out. The first piece of relation technical literacy found was surrounding Stacking sequences, work done by (Lin, Lai, & Kuo, 2010) discusses how they optimised a blade with a stacking sequence of 6 layers oriented at $[0, -45, 90, 45, 90, 0]$ whereas this reports design is stacked with 5 layers at $[-90, -45, 0, 45, 90]$. Another paper done (Kumar, Lal Krishna, & Anantha Subramanian, 2018) followed (Lin, Lai, & Kuo, 2010) design and went on to test it in a controlled room environment and compared result with a FEM.

During operation of blades cavitation is a problem design engineers try to solve as it creates erosions, noise, vibration and even thrust breakdowns. (Koko, Shahin, Akpan, & Norwood, 2012) discusses as a ship moves it produces non-uniform wake at the rear, results in inflow variation of the blades which generate unavoidable cavitation. By designing propeller blades relatively thin in comparison to the blades area it limits the extent of cavitation.

As a ship propeller is operating the blade is exposed to cavitation, because of this it caused the material on the blade to erode resulting in damage and ineffective propeller blade. This occurs on the leading-edge of the blade as the cavitation is greater. This is demonstrated in the reports blade design (force acting on the blade leading-edge greater than the trailing-edge). (Yamatogi, Murayama, Uzawa, Kageyama, & Naoko, 2015) has tested and found that material such as aluminium bronze (NAB) has a greater erosion resistance than CFRP due to its material properties.

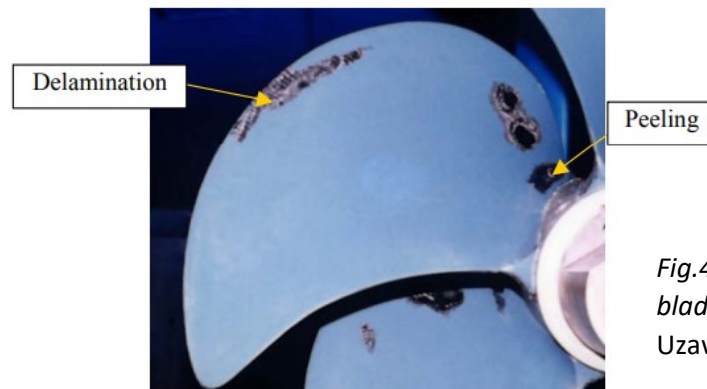


Fig.42- Post Erosion on Propeller blade, (Yamatogi, Murayama, Uzawa, Kageyama, & Naoko, 2015)

A Document on Machinery requirements for a polar class ship (IACS, 2007) discusses how the material exposed to sea water temperatures must meet specification to be considered. For example, propeller blades shall not exceed a given value for elongation. It also states that withing blade design the blade stresses are to be calculated using backwards and forwards loads. This can be considered done on the report design as the blade is assumed symmetrical and therefore when loaded on one side the results will be the same on the other. It then requests that the stresses on the blade shall not exceed the allowable stress which has been defined within the report design constraints.

Conclusion

To conclude there was a lot of study surrounding Topology optimisation and how its future development is bright with the rise in AM. The composite lay-up blade was a success after changing the material and running two optimisations the last being discrete. The results gained were positive through using design studio with a 97mm deflection and a total weight of 301Kg which both are massive improvements over the original steel blade while having no limitations of its manufacturability. A process map along with a schematic was drawn out to help illustrate how a physical prototype would be carried out alongside design studio and how data would be collected to compare the two. Finally, technical literature and standards were researched into to relate to the design blade within the report. A number of relative literatures were used, unfortunately not a lot was found as blades are varied for several applications and there wasn't a great deal around that could be related to the design made in this report.

References

- Altair. (2021). *Practical Aspects of Structural Optimization with Altair OptiStruct™*. Michigan, USA: Altair Engineering, Inc.
- Bakhtiary, N. (1996). A New Approach for Sizing, Shape and Topology Optimization. *SAE transactions*, 745-761.
- Baltazar, J., Melo, D., & DouweRijkemab. (2020). *Analysis of the blade boundary-layer flow of a marine propeller using a RANS solver, Ocean Engineering*. Lisbon: Marine Environment and Technology Cent.
- Brackett, D., Ashcroft, I., & Hague, R. (2011). *TOPOLOGY OPTIMIZATION FOR ADDITIVE MANUFACTURING*. Austin: International Solid Freeform Fabrication Symposium.
- Braha, D., & Reic, Y. (2003). Topological structures for modeling engineering design processes. *Research in Engineering Design*, 185-199.
- Broekaart, D. (2015). What does it take to optimize your designs with the use of FEA?
- Choi, W.-h., Kim, J.-m., & Park, G.-j. (n.d.). Toporaghy Optimisation . *Comparison study of some commercial structural optimization software systems*. Hanyang Univeristy, Seoul.
- Design, E. P. (n.d.). *Typical TO Design step*.
- ErsilioTushaj, & Lako, N. (2017). Review of structural size optimization techniques applied in the engineering design. *International Journal of Scientific & Engineering Research*.
- Femto. (2022, Setptemebr 30). *Topology Optimisation* . Retrieved from Femto.eu: <https://www.femto.eu/stories/topology-optimization/>
- Gernaey, K. V., Huusom, J. K., & Gani, R. (2015). 12th International Symposium on Process Systems Engineering and 25th European Symposium on Computer Aided Process Engineering. *Parts A, B and C. Elsevier*.
- Hendrik, J., & Haertel, K. (n.d.). Comparison of size optimization, shape optimization, and topology optimization based. *Design of Thermal Systems Using Topology Optimisation*. Technical Univerity of Denmark, Denmark.
- IACS. (2007). *Machinery Requirements for Polar Class Ships*. IACS.
- Koko, T. S., Shahin, K. O., Akpan, U. O., & Norwood, M. E. (2012). *Review of Composite Propeller Developments and Strategy for Modeling Composite Propellers using PVASt*. Halifax: Defence Research and Development Canada.
- Kumar, A., Lal Krishna, G., & Anantha Subramanian, V. (2018). Design and analysis of a carbon composite propeller for podded propulsion. *4th International conference on ocean engineering (ICOE2018)* (pp. 203-215). Chennai: Indian Institute of Technology.
- Lin, H. J., Lai, W. M., & Kuo, Y. M. (2010). EFFECTS OF STACKING SEQUENCE ON NONLINEAR HYDROELASTIC. *Journal of Mechanics*, 293-298.
- Liu, Z., Cho, S., Takezawa, A., Zhang, X., & Kitamura, M. (2019). Two-stage layout–size optimization method for prow stiffeners. *International Journal of Naval Architecture and Ocean Engineering*, 44-51.

- P.Sahoo. (2011). Surface topography. In J. P. Davim, *Tribology for Engineers: A Practical Guide* (pp. 1-32). Woodhead Publishing.
- Plocher, J., & Panesar, A. (2019). Review on design and structural optimisation in additive manufacturing: Towards next-generation lightweight structures. *Materials & Design* 183, 108164.
- Rao, R. S., Mohan, S., & Kumar, G. (n.d.). displacement on Propeller Blade. *Determination of Fatigue Life of Surface Propeller by Using Finite Element Analysis*. International Journal of Engineering Science.
- Rozvany, G. (2001). *Structural and Multidisciplinary optimization*, 90-108.
- Simscale. (2022, September 20). *What is FEA | Finite Element Analysis?* Retrieved from SIMSCALE: <https://www.simscale.com/docs/simwiki/fea-finite-element-analysis/what-is-fea-finite-element-analysis/>
- Vanderplaats, G. (1982). Structural Optimization-Past, Present, and Future. *AIAA journal*, 992-1000.
- Velling, A. (2022, September 25). *Topology Optimisation*. Retrieved from Fractory: <https://fractory.com/topology-optimisation/#:~:text=Topology%20optimisation%20is%20a%20mathematical%20method%20used%20at,load%2C%20and%20space%20limitations%20to%20create%20a%20design>
- Yamatogi, T., Murayama, H., Uzawa, K., Kageyama, K., & Naoko. (2015). *Study on Cavitation Erosion of Composite Materials for*. Japan: School of Engineering, The University of Tokyo.
- Zhu, J.-H., Zhang, W.-H., & Xia, L. (n.d.). Topology optimization design of the Airbus A350 pylon. *Topology Optimization in Aircraft and Aerospace Structures*. Engineering Simulation and Aerospace Computing (ESAC) Northwestern Polytechnical University, Shaanx.