

**Designing a tanker propeller:
Structural Design
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Task 1

Finite Element Analysis (FEA) is a computerised method of predicting how a real-world object will react to forces, vibration, heat, movement etc. There are many different FEA optimisation techniques used globally which will be considered below:

Topology

Topology often used in the aviation and automotive sector due to its advantages of weight reduction leading to increased fuel economy and power is used at the concept level of the design process.

Topology optimisation removes material from a structure while attempting to make it as strong as possible, thereby optimising the form to increase stiffness to weight ratio, illustrated in figure 1 (Introduction to Topology Optimization, 2017).

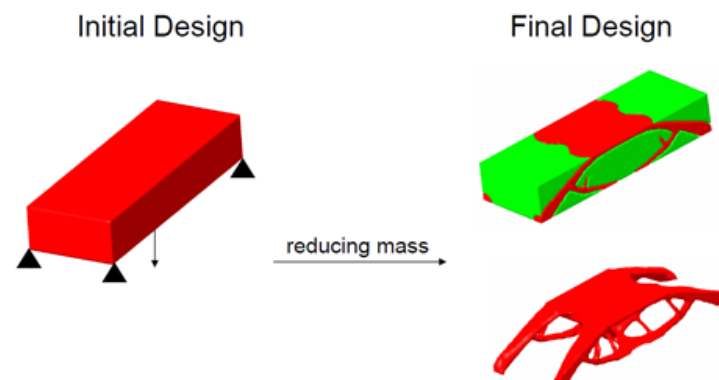


Figure 1 Topology Optimisation

One of the biggest advantages of topology optimisation is that it allows engineers to achieve an equilibrium between strength and affordability, influencing how to create a component that is significantly stronger using as little material as possible. This has added benefit to the environment by reducing the carbon footprint on the planet since less energy and material is used to manufacture the component. According to the Latin American Journal of Solids and Structures “based on topology optimization, the mass of the model is improved by a reduction of 36.5%” (Kong, 2016).

Futuristically topology development is a form of propagative design that removes many difficulties created by the traditional design process using software like computer aided design and 3D printing. The use and development of topology brings maximum performance in a short space of time, harnessing the developments of artificial intelligence and machine learning. Topology has the potential to significantly reduce time constraints whilst achieving complex structures whilst reducing cost and weight, improving sustainability and design outputs.

Topography

“Topography is an optimisation technique that can change the shape of a shell structure by layering stamped beads or swages for a better structural performance” (Pagadala, 2022). Topography is typically applied to thin structures to define swage patterns and is an advanced form of shape optimisation. Topography utilises shape variables instead of design variables. Optimisation is used to strengthen the structure of the component by applying bead parameters in the model, see figure 2.



Figure 2 Design space & Optimised shape

The benefits of topography are many, but primarily allows for a stiffer component without the need to adding mass, this is advantageous in the automotive industry; allowing for thin-walled parts to be made which subsequently reduces the mass of the car, improving its performance.

“Following topology, topography optimisation is used to fine-tune the topology-optimised model. Beads are added to the model to strengthen the stiffness of the structure. A topography optimised model can increase compliance by 27% compared with the sole topological optimized design” (Kong, 2016).

Developments in topography has allowed inroads into the arena of science, medical and mathematical world allowing the application and use of brain mapping using EEG (electroencephalography) topography, corneal topography to map the surface of the curvature of the cornea and in the field of mathematics to indicate patterns of features on any given distributed space (EEG topography, 2022).”

Topometry

Topometry is an element-by-element sizing optimisation method that allows users to design the dimensions of each element individually, as opposed to different sizing, where elements are designed in groups (Leiva, 2007).

Topometry is an alternative on conventional size optimisation and works on shell thickness (Juan, 2002). A section of shell elements is defined by the user which allows free-form variation in shell thickness. This allows each shell to be an individual design variable. However, the resulting distribution of thicknesses is not manufacturable. The outcome of topometry drives toward reducing or increasing a true objective function (Juan, 2002).

Topometry is not as efficient as topology since topology optimisation converges faster than topometry optimisation; topometry taking about 20% more design cycles, however this may be down to topometry optimisation is newer than topology and is still being developed.

A complex structure benefits from FEA optimisation since each has its own advantages and disadvantages, the complex structure may have several parts each suited better to either topology, topography or topomtery.

History of FEA

To meet popular demand and to comply with the environmental changes companies across the world now use FEA. However, this has not always been the case due to high cost and low belief in the software. FEA was first developed and researched by Boeing and Rolls Royce in the 1950's; Doctor Ray Clough first used the phrase *Finite element* in the 1960's whilst writing a paper on his findings in Berkley, which later become the centre for FEA research and early developments.

Furthermore, the first FEA program was developed by E. Wilson at Berkeley, and it very quickly become popular in industry as a freeware program. The FEA program continued to be developed and used for many more years.

Additionally in the 1960's NASA saw huge potential in FEA and poured a huge amount of money; 30 million pounds in today's day to fund, improve and further develop the FEA software program; initially it was still offered as freeware but later was commercialised and seen as an investment (Tipton, 2017). Moreover, after NASA had completed the project and contract came to an end, MSC resumed development of its software and called it MSC/NASTRAN, while the original NASTRAN became available to the public. The downside of the advancement of increased software packages was that computer power was limited.

By the 70's and 80's the development in microcomputers were becoming more popular in industry which allowed for vast improvement in graphic processing which transformed the FEA software. It allowed engineers and designers alike to examine colour stress contours instead of tabular output which has radically changed the way engineers and designers think and the way interact and incorporate FEA into the general product design process (K.K.Gupta, 1996).

By the 1990's FEA models were being run on supercomputers with 1 million degrees of freedom and capable of running 1 trillion operations per second: a world away from the original code of 68,000 degrees of freedom. FEA is a must for any serious design engineer seeking to improve and analyse any design process and without it we would be all the poorer in the engineering world (Tipton, 2017). (History of FEA, 2022)

One of the biggest advantages of finite element analysis (FEA) is design optimisation. By using FEA, designers and manufacturers alike can reduce material wastage, prevent stress concentrations, remove bottlenecks, and attain superior performance qualities.

Optimisation is achieved by taking a series of steps which include simplifying the model to only what is essential for analysis, that is, by removing unnecessary items and only analyse the structure and components that are used to define the analysis.

Secondly, adding boundary conditions, this step involves defining loads, constraints, and contacts, this is best done through experience to determine what constraints resemble reality and input them into the FEA software. The next step in optimising the design is to create and then refine the mesh; creating the first mesh depends on the complexity of the model however software packages like Genesis can generate a mesh automatically which makes it quicker (Emmetcosten, 2019).

Furthermore, once the mesh has been generated, a competent operator can refine the mesh in areas of difficult geometries such as edges and angles which typically have areas of higher concentrations of stress, in these areas a smaller mesh should be used which will allow for a more accurate calculation of stress analysis to take place, the downside of refining the mesh is the software will take longer to compute.

After the mesh is generated, it is up to the user to control the mesh and optimisation techniques, given it is inputted by the operator, it is essential that the operator is competent in their understanding of engineering and design to achieve the best results. For example, there is a higher concentration of stress where tight angles and rounded surfaces exist and therefore a smaller mesh is required. Once the mesh is generated, the model can be optimised (Emmetcosten, 2019).

Optimisation is a tool that advantages surpass its disadvantages since by optimisation allows for greater innovation, less waste, more confidence in production and efficiency and to meet and compete with industry today it is an essential tool.

Task 2

Initially a steel propeller approx. 3m in length and 2.9m in width and a thickness of 10mm steel model was subject to 3 unevenly distributed load of 25kN, 10kN and 5kN in different areas of the propeller. These loads have been estimated based of research carried out in assignment 1.

A new model of the blade was created, and material selection was changed from steel to carbon fibre reinforced plastic (CFRP); see the process below:

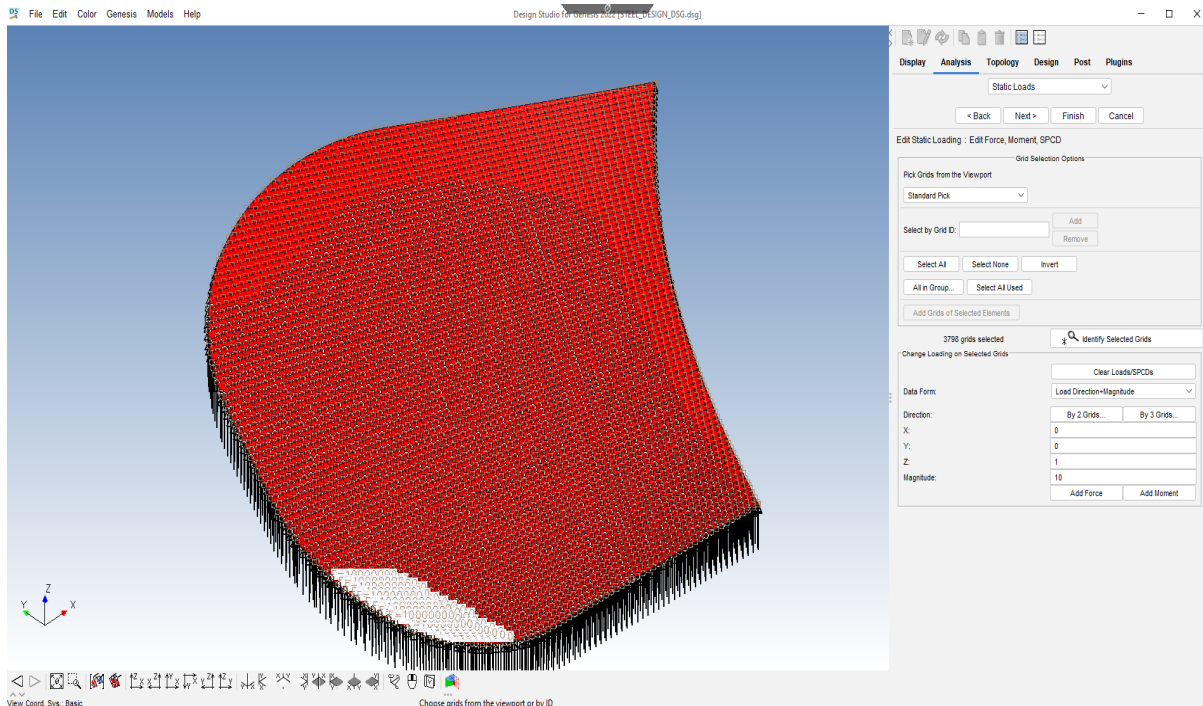


Figure 3 Steel Propeller

3 loads were applied across the steel propeller: A 25kN load was applied to the leading edge of the propeller; a 10kN load was applied across the entire length of the fixing from the propeller to the boss and a 5kN load was applied to the rest of the propeller. According to research the reason being, that the load applied on a propeller is not uniform would differ depending on the speed/velocity/density of the propeller and its environment.

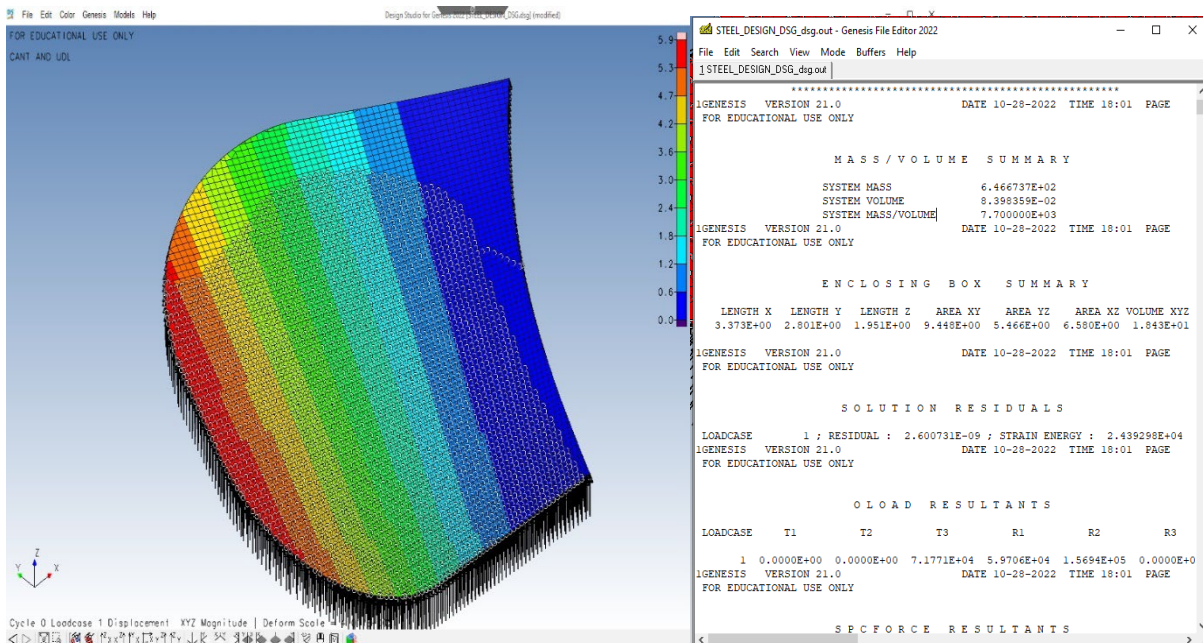


Figure 4 Distribution loads and deflection

Furthermore, the deflection of the blade with the above loads applied can be seen to be 5.9mm, however the mass of the propeller is nearing 650kg.

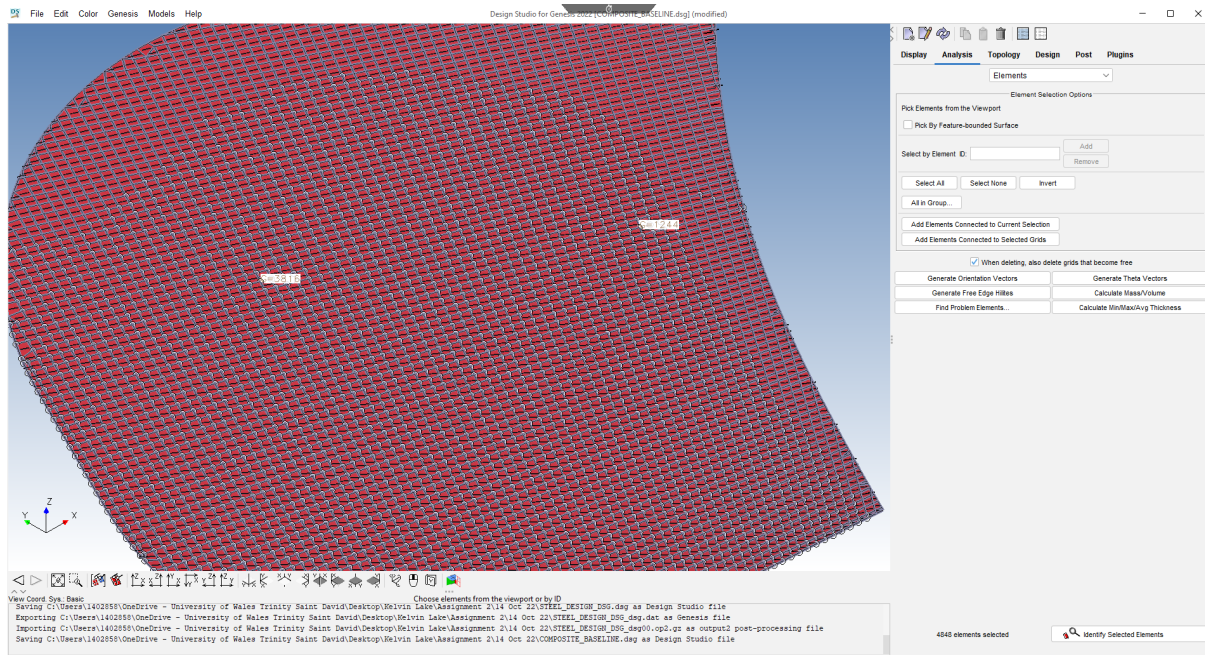


Figure 5 Element direction selection

Since the CFRP material has different material properties to the steel and is in different directions the orientation of the elements needs to correspond relative to the vector which the material property uses. Figure 5 shows the orientation of each element that has been automatically aligned with the x axis, which corresponds 0 degrees.

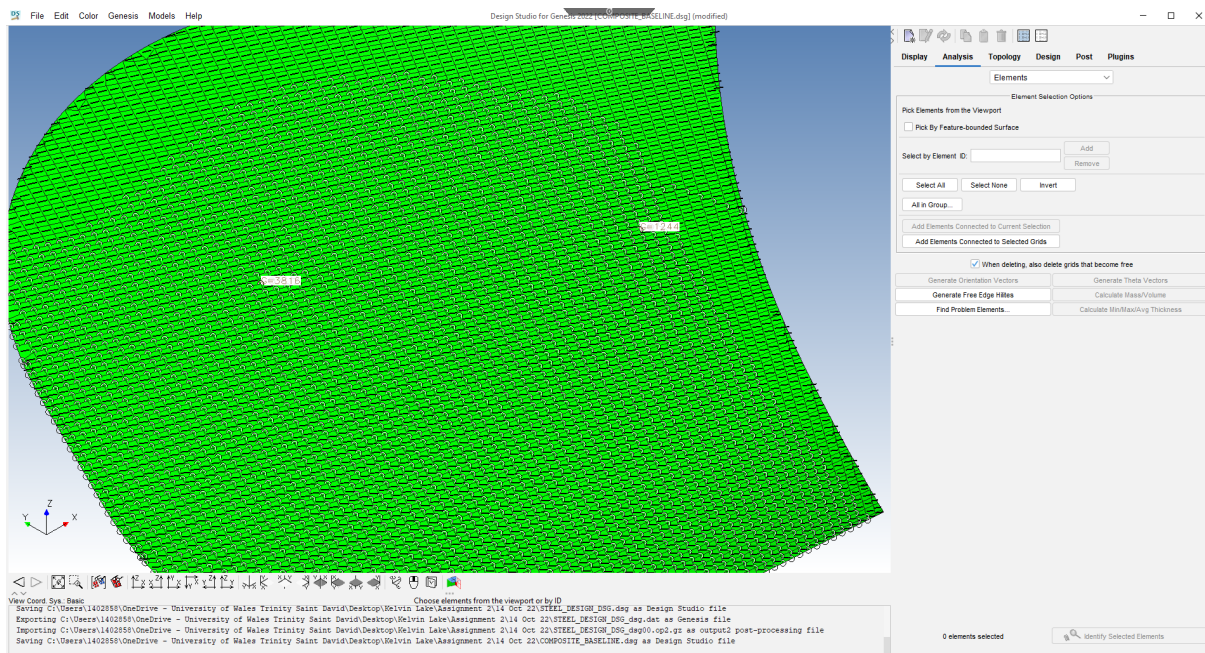


Figure 6 Element direction re-alignment

Figure 6 shows the vector realignment by selecting two points on the grind on the same axis. The vectors now follow on the y-axis which corresponds to the fluid flow over the propeller.

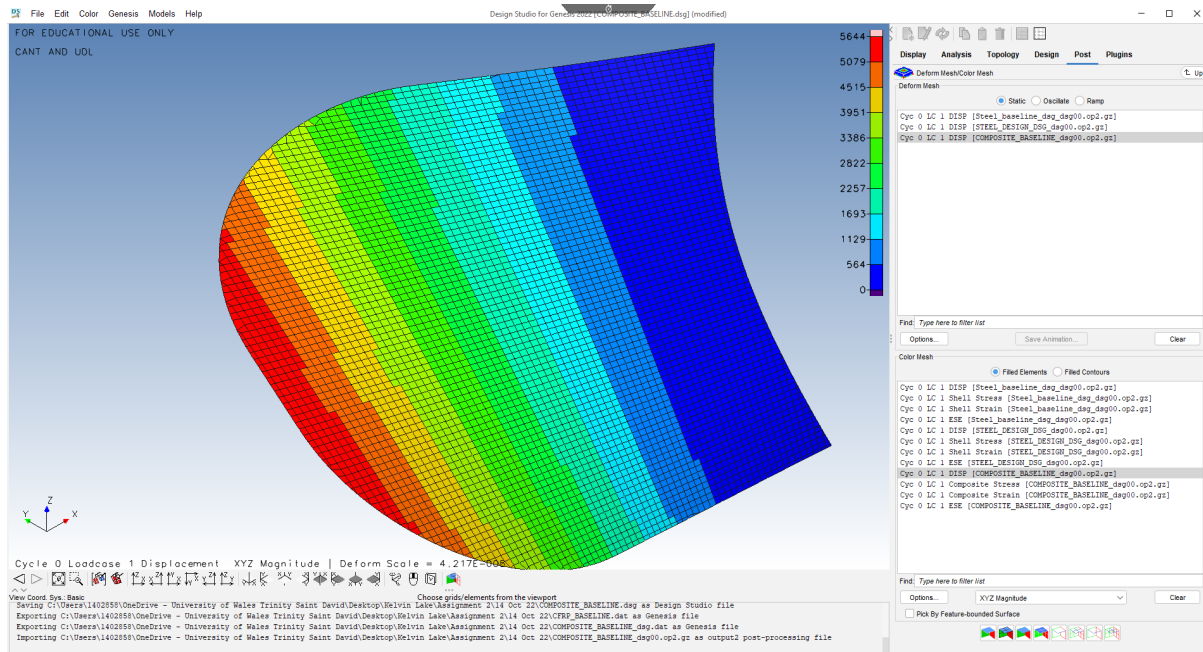


Figure 7 CFRP loading

The newly created propeller with manufactured from CFRP was subjected to the same force as the steel propeller and as the simulation in figure 7 shows, the propeller deflection was measured at 5644m meaning the current CFRP with 5 plys per layer with a layer thickness of $5.E-4$ at -90° to 90° snapped under loading.

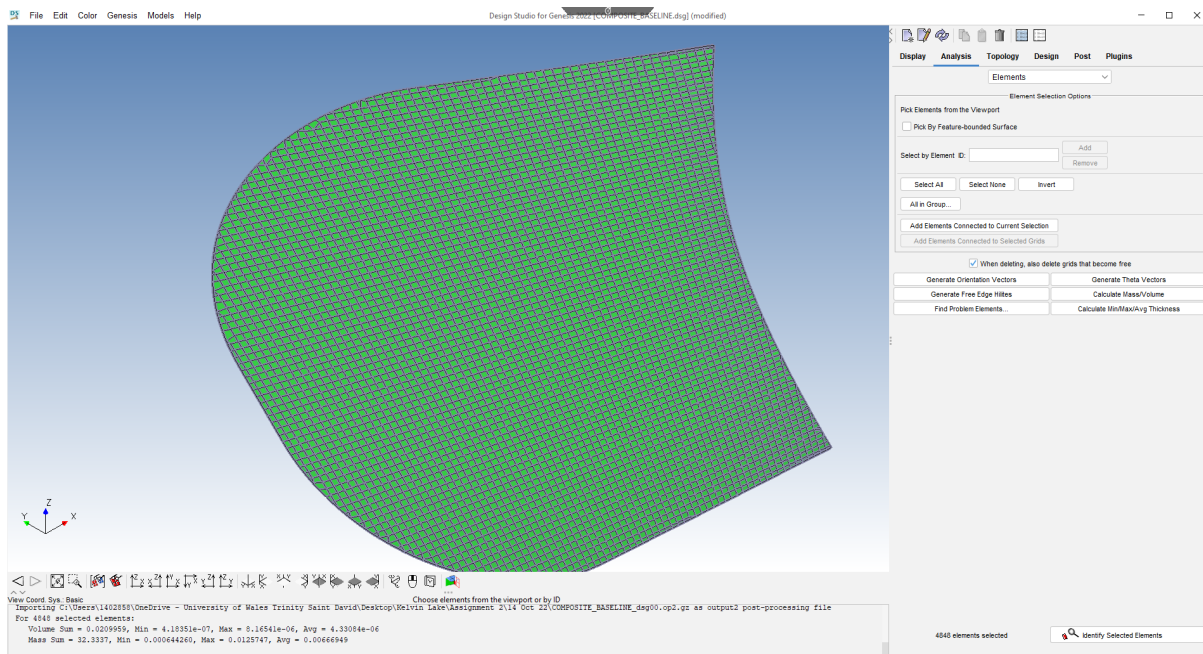


Figure 8 Mass of CFRP

However, even though figure 7 shows that under the loading the CFRP model snapped; it does prove that changing the material of the propeller from a steel structure to a CFRP model, significantly reduces the weight of the propeller but reduces the stiffness of the propeller.

Task 3

As we can see above in terms of stiffness/weight the composite part has NO advantage over the steel part.

We are now going to optimise the orientation of our composite layers and the thickness of these layers to achieve the same deflection as the steel structure at a reduced weight.

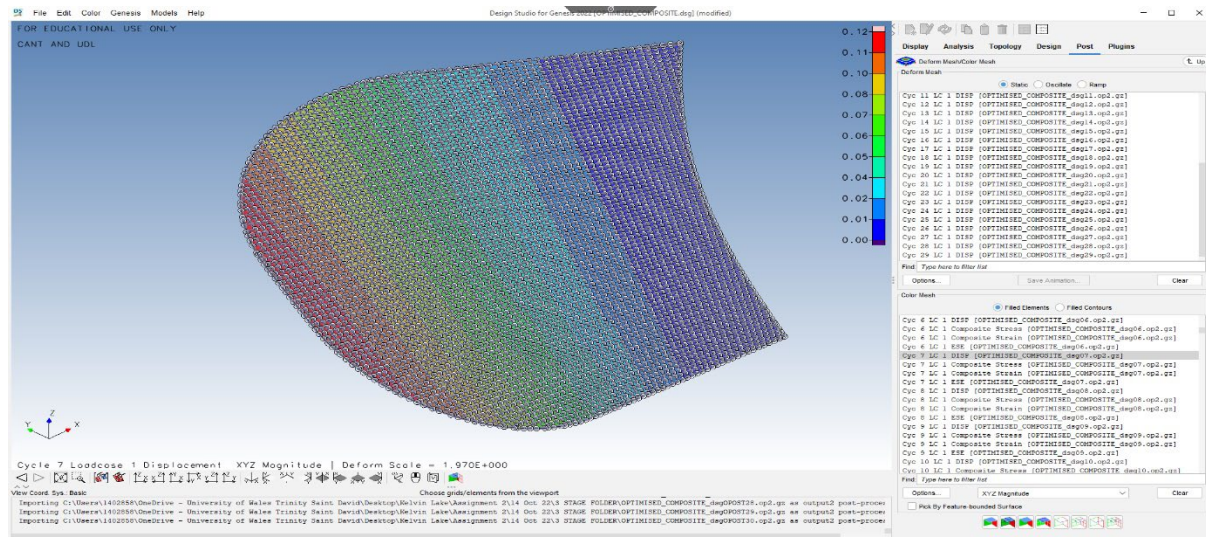


Figure 9 Deflection of CFRP model

As figure 9 view the displacement is now significant less than the first CFRP model with a displacement of 0.12m

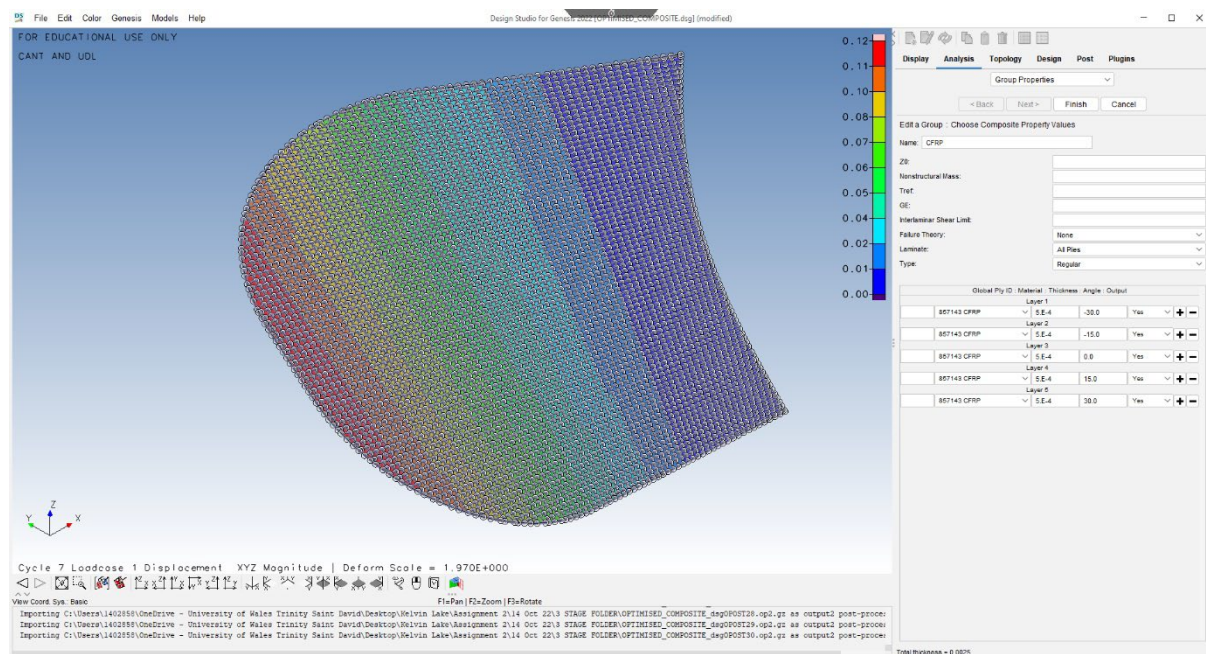


Figure 10 Layering of CFRP model

Furthermore, to decrease the displacement even more, I layered the plies at different angles where I thought the biggest concentration of stress would act on the propeller and ran the analysis again.

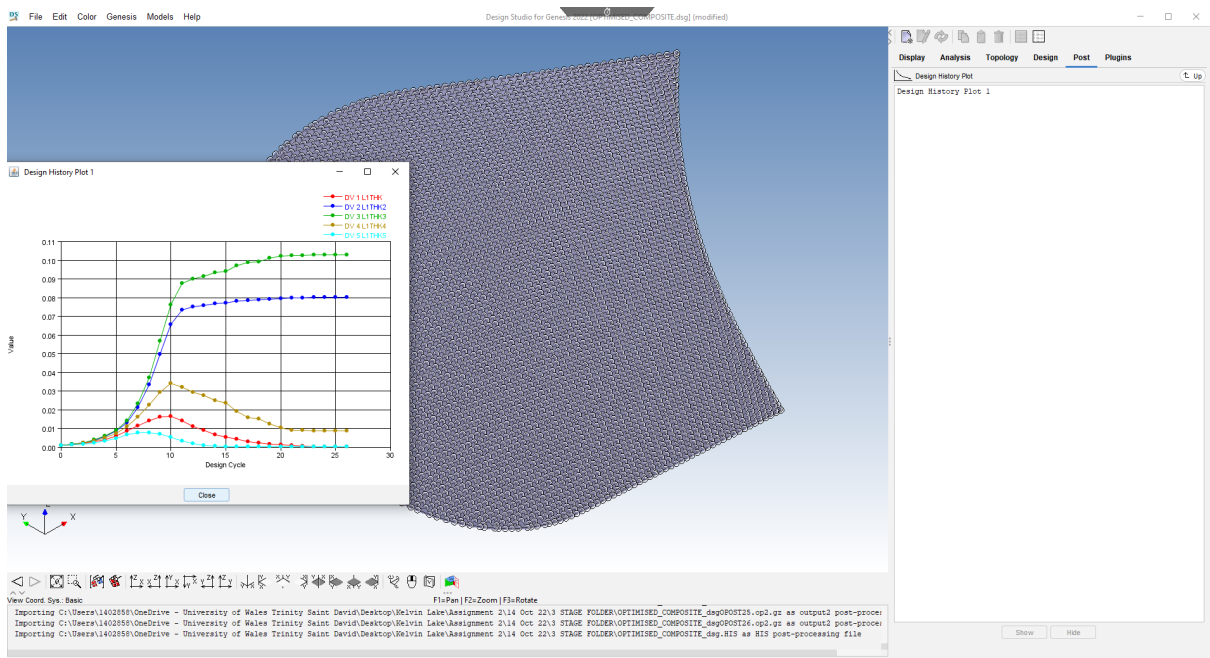


Figure 7 Variables changes of optimisation

As you can see all the variables started at 0mm (i.e. 5 plies). The plies closest to 0 degrees have increased to 0.10mm (the maximum) as you would expect, the plies at -30 and -15 have reduced to a minimum and the plies achieve the stiffness target.

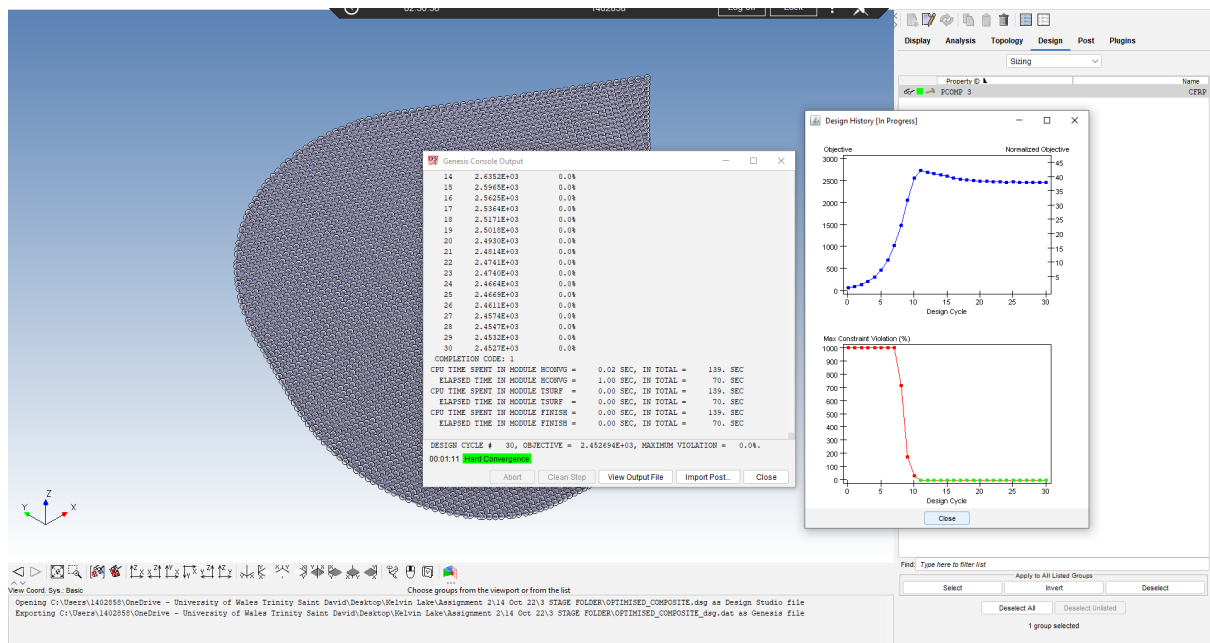


Figure 8 Run GENESIS software

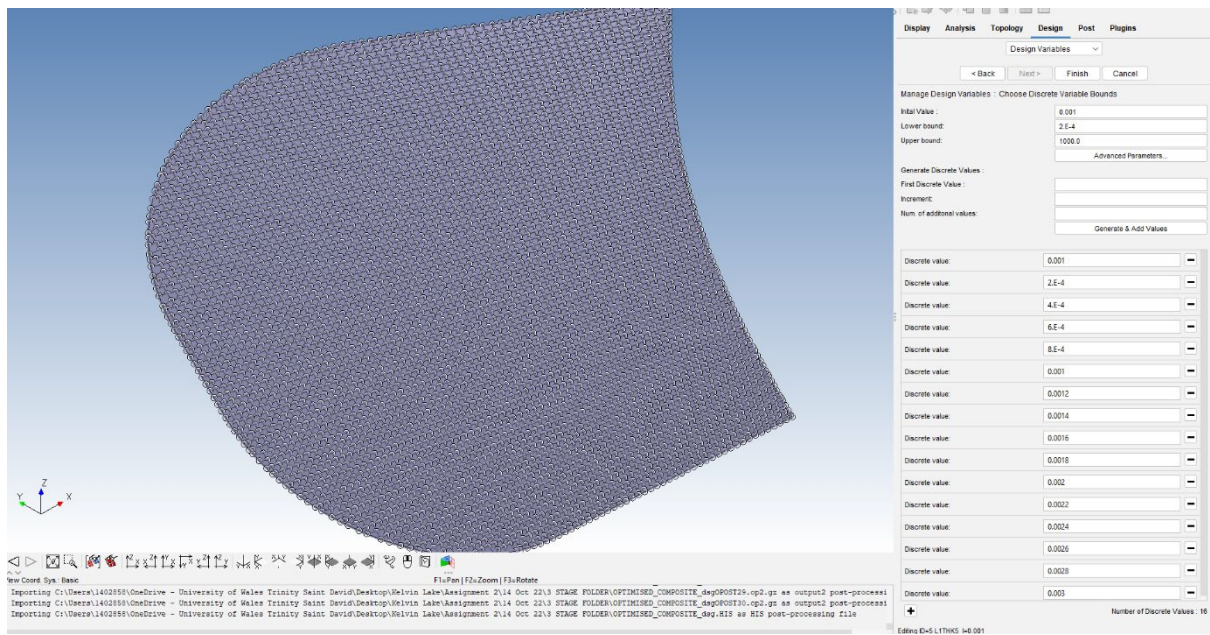


Figure 9 Discrete values

My first discrete value was set to 2e-4 and increasing in increments of 2e-4 and I added 100 extra points to allow for cycles to run.

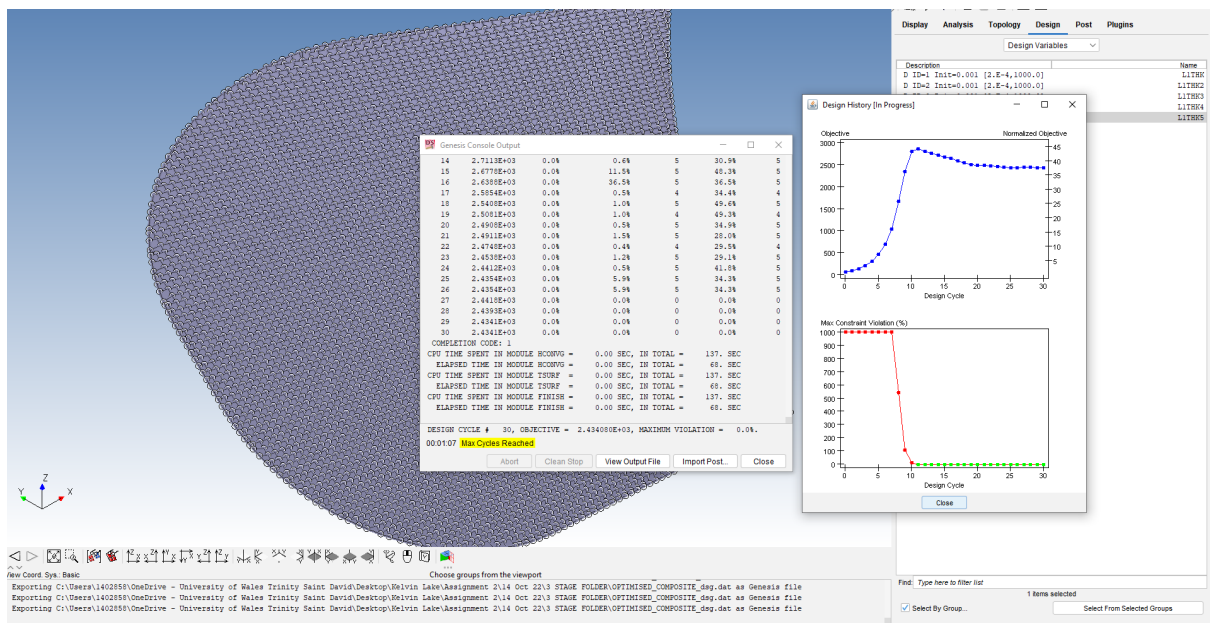


Figure 10 Design variables trend

Figure 10 shows the results from running the increased design variable cycle again.

To summarise

RUN	MATERIAL	THICKNESS	DEFLECTION	MASS	LOAD	STIFNESS
STEEL BASELINE	STEEL	10MM	5.9MM	650KG	40kN	6.8N/mm
CFRP BASELINE	COMPOSITE	15MM	SNAPS	220KG	40kN	SNAPS
OPTIMISED CFRP BASLINE	COMPOSITE	17MM	120MM	252KG	40kN	0.3N/mm

Task 4

Once an FEA model has been created and analysis taken place a prototype can be manufactured on a 3D printer. Similarly, to assignment 1 task 5; a scaled down prototype was manufactured using 3D printed carbon fibre reinforced plastic (CFRP) propeller, which replicates the material of the full-scale propeller.

As stated in assignment 1; geometric similarity can be achieved in a straightforward way through scaling of the full-scale ship dimensions and modelling it down to scale. However, the level of detail up to which geometric similarity can be achieved is limited. When further considering the boundary layer of the flow over a surface, the main problem of scaling becomes clear. Whereas geometric properties can straightforwardly be scaled, properties of the tank water like density, viscosity and vapour pressure are approximately the same as on full scale.

From research when undergoing a propeller test there are two main facilities of testing a prototype propeller in open water, meaning ideal flow conditions; a towing tank or a cavitation tunnel, however each has its own limitations. For this laboratory test a towing tank (see figure 11 below) was selected.

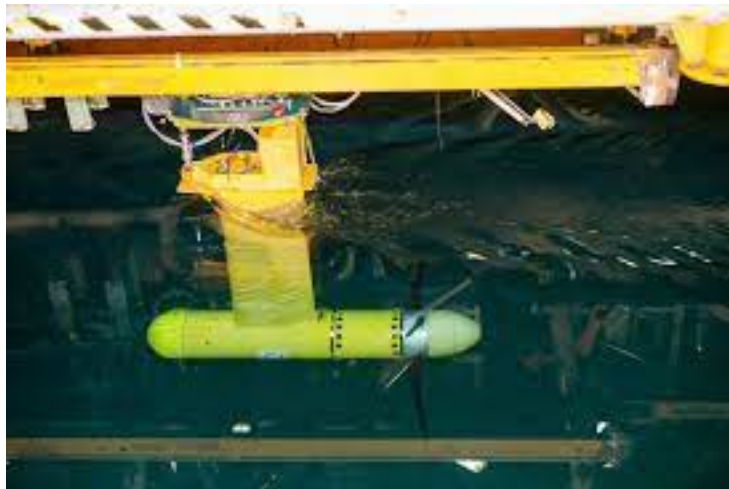


Figure 10 Towing tank and propeller

Test model: the propeller prototype is affixed to a rig in the water and rotates at a speed of 250 rpm (as described in assignment 1) and a water velocity of 35.62m/s, the load is applied by affixing the total weight of 25 newtons across the five blades at the leading edge of the blade as seen in task 2 when the load is distributed and applied.

Test device: the diameter and length of the tunnel in the working section was 0.8m and 3.2m allowing enough space around the propeller to see how it would respond. A series of DIC (digital image correlation) static images from the propeller and compared to 5 static images were taken at

different revolutions per minute from 0 to 250rp. This data was uploaded to a software package which allowed a comparison between 5 static photos, with that of the propeller rotating.

The DIC images were able to measure significant tip deflection of the propeller by comparing both the static and non-static images and measure accordingly.

Subsequently, another method used was to statically load the prototype propeller in linear fashion while it was fixed to a solid structure and apply hooke's law $f = kx$.

Equation 1 Hooke's Law

Although, it is unlikely that the load applied would be linear, it was a way to compare a linear and non-linear load on the propeller as a reference.

Task 5

CFRP propeller is a relatively new concept; assignment 1 touched on the history of manufacturing a ship propeller, however since the early 2000's many companies sought alternative ways to reduce cost but increase efficiency.

A company called Nakashima Propeller Co. did just this, in 2007 they carried out a feasibility study to determine whether CFRP was applicable to marine propeller and by 2011 Nakashima were conducting material evaluation tests, model tank tests and an actual ship test using a small boat. Their research and design concept were proved right, not only in theoretical but also in modelist terms. Their FEA deflection analysis corresponded with that of model tank test. In May 2014 Nakashima manufactured a world first 2,120mm, 4 blade propeller with an output of power rating of 735kW. Although it was larger than the steel propeller the weight advantage was 59% less than that of steel, weighing 422kg. Their open water testing proved that a CFRP propeller could compete with a steel propeller but by a significant amount less shaft power (Benefits of carbon composite marine propeller, 2007). The benefits of the composite propeller are well documented:

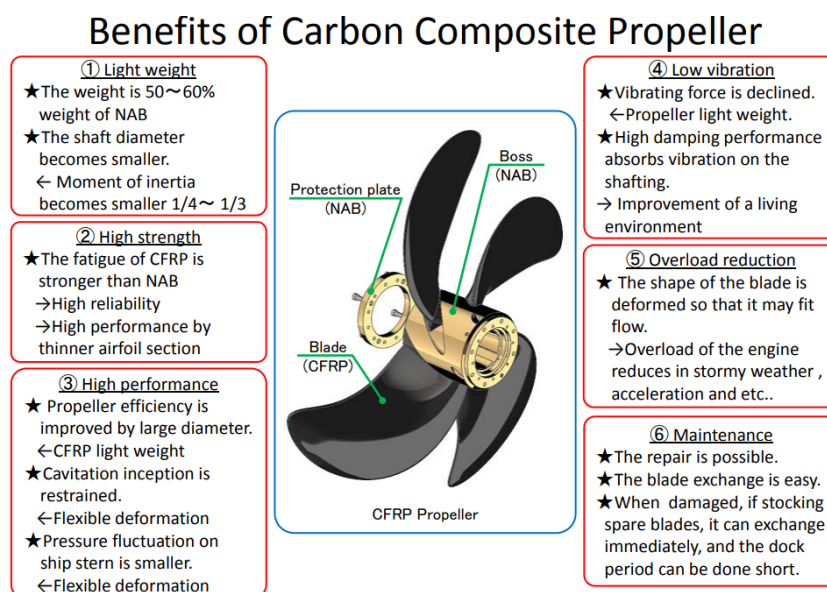


Figure 11 CFRP Propeller benefits

Because of this breakthrough by Nakashima, more and more companies are seeking and trialling similar things and thereby reducing the carbon footprint and increasing productivity.

Given the above, my design would change to align the layering of CFRP sheets with that of the Nakashima propeller since their results were more effective than mine. Further research has found that the elongation rate before failure is substantially smaller than that of a bronze or steel propeller meaning it is more brittle. This means if the propeller were to hit something hard it would damage

easier, however, this can be compensated since maintenance is less costly and individual blades can be replaced whereas this is not possible if the propeller is made using a mould and cast.

To compensate for this loss, some companies have already started to trial composite skins that have a band of metal or metal reinforced rods through the propeller structure which adds strength and durability. In concept this is a good idea to improve durability and brittleness, however the downside of this is that it adds mass leaving complications on the FEA optimisation side.

Bureau Veritas is the first inspection company to create legislation on composite propellers and state the following about testing procedures: "Prototype tests should be carried out on a blade or on a piece as much as possible representative of the type of propeller concerned. The objective of these tests is also to confirm numerical simulations by an experimental approach. The comparison with a Finite Element Model is mandatory by measuring stresses and displacement in two locations, $0,25.R$ and $0,6.R$ (where R is the blade radius) considering a load representative of 1,25 times induced bending moment and shear force (generated by maximum thrust and torque in continuous regime). (Veritas, 2020)". Given what Bureau Veritas have stated, I would change my method of FEA analysis to incorporate the measurement of stresses and displacement in at least two locations and increase loading to 1,25 times the induced bending moment and shear force.

Finally, one final control I would implement for control is to carry out some non-destructive tests (NDT) to verify the quality of the blade all at different stages of the manufacturing process, this would help as a reference for in service inspections, or the effects of life in service under the water.

Conclusion

This assignment discussed FEA optimisation techniques and considered the following 3 techniques adopted in industry today; Topology, Topography and Topometry all of which have their advantages however, from my research topology optimisation seems to be the industry standard since it's prime focus and function is to reduce material and maintain or even increase strength, this positively impacts the manufacture economically and ecologically since by reducing material less money is required but also there is less energy consumed. Furthermore, consideration was given to the development of FEA in general and how it has become industry standard across the world and development in the future to me looks like advancement in artificial intelligence and material selection.

Moreover, tasks 2 and 3 sought to show the benefits of FEA optimisation by comparing the results of a steel and CFRP ship propeller and thereby optimising the CFRP propeller to show just how advantageous it can be to implement a different material and increasing/decreasing the amount of plies used and layering them up in different orientations. The optimised CFRP model drastically improved the stiffness to weight ratio simply by changing material and laying up the plies differently giving the propeller better efficiency too.

Additionally, task 4 seeks to understand the benefits of prototyping before creating a full-scale model and to run tests and compare the results with that of the FEA calculations. For this, I suggested a towing tank with high-speed cameras, comparing a static, unloaded propeller with that of a loaded propeller. Also, if it is assumed the load is linear hooke's law could be applied, however, I do not propose the force is linear.

Finally, task 5 outlines technical literature in the form of a report from Nakashima detailing the research and implementation of a composite propeller. Bureau Veritas's guidelines were analysed and compared to that of my test method.

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