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University of Wales
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Module: Structural & Fluid Analysis

Module code: ACMA6010

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Assignment title: Designing a butterfly valve: Structural design

Submission deadline: 29/10/2021

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Introduction

This assignment will be consolidating what has been discussed during classes, about what optimisation techniques can be used within Finite Element Analysis (FEA). This will include optimising the composite construction of the butterfly valve plate which will be made from a unidirectional carbon fibre reinforced plastic to ensure that the product does not leak past the valve when it is closed, using as little material as possible. FEA (Finite Element Analysis) is a common design tool that is used by design engineers in a range of industries to find and solve potential/existing structural or performance issues.

This assignment will start off by discussing FEA optimisation looking at how they have developed historically, how they may develop in the future and how they improve the design process. A model will then be created of the plate in design studios that meets all the requirements that have been set out in the assignment brief. The model will be created, trying to use as little material as possible to reduce the costs. On the other hand, there also cannot be too little material as it is a requirement for this task that when the hydrostatic forces are applied, a maximum deformation of 0.1mm can occur to ensure a good seal between the plate and outer housing. The proposal of producing a prototype to be tested will be looked at and discussed to understand the deformation of the valve plate when subjected to the hydrostatic forces. Then a discussion will be carried out into how this experiment should be carried out, how data can be obtained and how it can be compared to the simulation carried out. Any standards or technical literature that cover this component will be stated or referenced throughout the assignment.

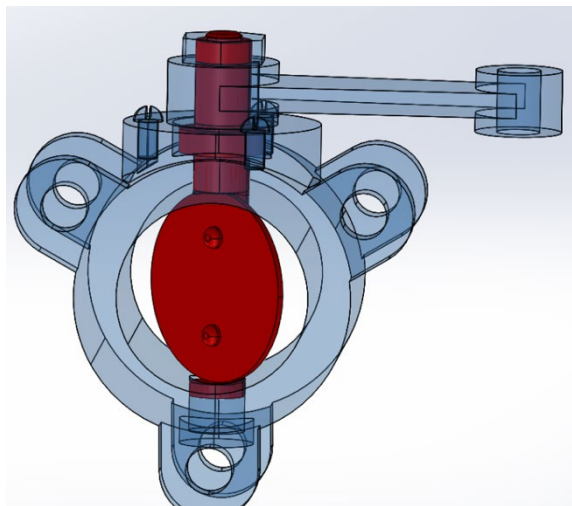


Figure 1. Butterfly valves plate highlighted red in this image

Task 1

Finite Element Analysis (FEA) is the simulation of a given phenomenon using a technique called Finite Element Method (FEM). It is used by engineers to reduce the number of physical prototypes and to optimize components when being designed so better-quality products will be produced, faster production and cost savings. **(SimScale, 2021)**. The FEA process starts by dividing up a chosen structure into small pieces, called elements because they are easier to analyse, and they all make up a mesh. As the number of elements increases, their size will decrease, which will then theoretically lead to the solution becoming more accurate. **(Donald, 2011)**.

FEA optimisation techniques and how they improve the design process

There are a range of optimisation techniques which are then used within FEA to test elements/parts to achieve the greatest degree or best result obtained or obtainable under specific conditions, by carrying out simulations rather than the need to undergo real life testing. Some examples of the optimisation techniques which are used are listed below.

- **Shape optimisation** - an optimisation capability which allows the user to find the best shape possible. The software finds the best location of the finite element nodes, which define the shape of the structure. **(team, 2014)**. Shape Optimization is a great tool especially when aiming to improve the structure locally. From analysis, local areas with high stresses can be recognized. These areas can be shape optimized to lower the stress levels acting on the element/part. **(Mansouri & Norman, 2009)**.
- **Size optimisation** - an optimisation capability which allows the user to find the best dimensions of any designable elements like bars, shells and composites (typically per group of elements). **(team, 2014)**. This could include the cross-sectional area, moment of inertia, thickness, and length of the design. In size optimisation the shape of the structure is known, and the objective is to optimize the structure by adjusting sizes of the components. **(Christensen & Klarbring, 2009)**.

- **Topography optimisation** – a special case of shape optimization. It allows the user to define the maximum height of the element offset, whether it is a normal or local direction, the width of a bead or swage that will be formed and active or inactive regions. It is 2D shell height mapping that can push elements out from a nominal surface to form beads or swages to increase bending stiffness and strength. (Abbey, 2016).
- **Topology optimisation** – the least constrained and most challenging technique which is used to create new designs with a layout which is optimized for a given load and by fulfilling given constraints previously established. (solutions, 2021). It is a valuable tool for the identification of the best design solution in the early phases of the design process, it will identify for you the best design whilst taking into consideration any design and manufacturing constraints. It is widely used in lightweight design of structures in automotive and aerospace industry, as well as in civil engineering, material science, and biomechanics. (Mariusz Bujny, 2016). Not only the shape and size of the structure, but also the connectivity of the structure changes during the topology optimization process. For such an optimization procedure, the three main elements are design variables, the cost function, and the constraints. (Inês P. Rosinha, 2015).
- **Topometry optimisation** – a generalization of sizing optimization. Unlike size optimization, where all elements associated to a property data entry are designed with the same values, in topometry optimization each element is designed independently. (Leiva, 2004). It can also be described as a 2D shell thickness mapping, which allows a free form distribution of thickness in a surface to vary stiffness and strength. It was generally known as free sizing optimization and the idea has been around for a long time. (Abbey, 2016).
- **Composite optimisation** – an optimization solution aimed at guiding and simplifying the design of laminate composite structures. The solution includes three phases: free size optimisation, size optimisation and ply-stacking optimisation. (Munoz, 2014).

How has FEA and its optimisation techniques developed historically

FEA was developed in the 1960s through the aerospace industry by Boeing and Bell aerospace in the US and by Rolls Royce in the UK. One of the authors which set up the method for FEA on paper and was published was Ray Clough, who was a professor at Berkeley. Due to this Berkeley soon became the centre of FEA research with a lot of early research into FEA development residing from here. In 1965, NASA funded a project to develop a more capable FEA program which then became NASTRAN. In the 1960s another FEA software made for nuclear reactor analysis was developed that became known as ANSYS. **(Tipton, 2017)**. In 1967 the first book on FEM was published by Dr O.C.Zienkiewicz and to this day remains a standard reference text for the basis of the FEM. **(Actis, 2021)**. Following on from this book in 1970 FEA modelling practices began. In 1991, Drs Barna Szabo and Ivo Babuska published Finite Element Analysis (FEA) which covered the fundamentals of linear theory of finite elements. Then in 2008, NASA released a standard for the development of models and simulations, so any FEA carried out would have to meet the requirements set out in this standard. **(Actis, 2021)**.

When looking specifically at the method of topology optimization, it was first implemented in the 1970s by Prager and Rozvany as Optimal Layout Theory. Topology optimization is much younger than size or shape optimization, however it is an ever-growing field within structural mechanics. The theory was an extension to beam systems, the fundamental principles of topology optimization established by Michell, an Australian inventor, in 1904.**(Roade, 2018)**. This theory was then generalized by Rozvany in 1972 and extended Michell's approach the beam systems, making the way for the optimal layout theory as the first general theory of topology optimization. **(Abdi, 2015)**.

How FEA and optimisation techniques may develop in the future

Even though over the years there has been constant development and improvement of FEA and its optimisation techniques there will always be ways to improve them like most things in life. One way in which they could be improved in the future is by them being able to reduce the amount of human error or reduce the possibility of human error occurring whilst using the software. The main problem with FEA is down to human error, as to get accurate results you will need to ensure all the data you have inputted into the software is correct. If the data inputted is incorrect then this can lead to the optimisation being wrong, which can then lead onto the part/component being manufactured, put in to use and then it not operating/functioning as it was intended to do so. This would then have the potential to cause safety issues as the part/component could fail and cause serious damage, injury or death which has occurred from FEA errors. **(Cyprien, 2016)**.

An area in FEA which is not accurate and could be improved in the future is stress concentrations. With stress concentrations there is a large stress acting on the material in a small area, this meaning stresses in the small area can go above the yield strength of the material. FEA struggles to accurately predict effects of the stress concentrations. So, in the future it could be looked at improving stress concentrations as currently they can only be dealt with by increasing the amount of material on these areas, but this is time consuming and would add to the cost of materials and manufacturing processes. **(Sparta, 2021)**.

Lastly, FEA optimisation software could also be improved in the future by making it simpler to use and quicker to obtain results. Even though it is relatively simple to operate, and results can be obtained within a fair amount of time, software like FEA can almost always be made more user friendly and easier to operate.

Task 2

To cover this task a model of the butterfly valves plate had to be created on solid works and then imported into design studios software. The butterfly valve then had to be set up with the correct material properties and correct number of plys at each layer. To show that the tasks set out were completed, print screen images of steps that were taken to create a model of the butterfly's valves plate are shown.

Print screen of the butterfly valve model

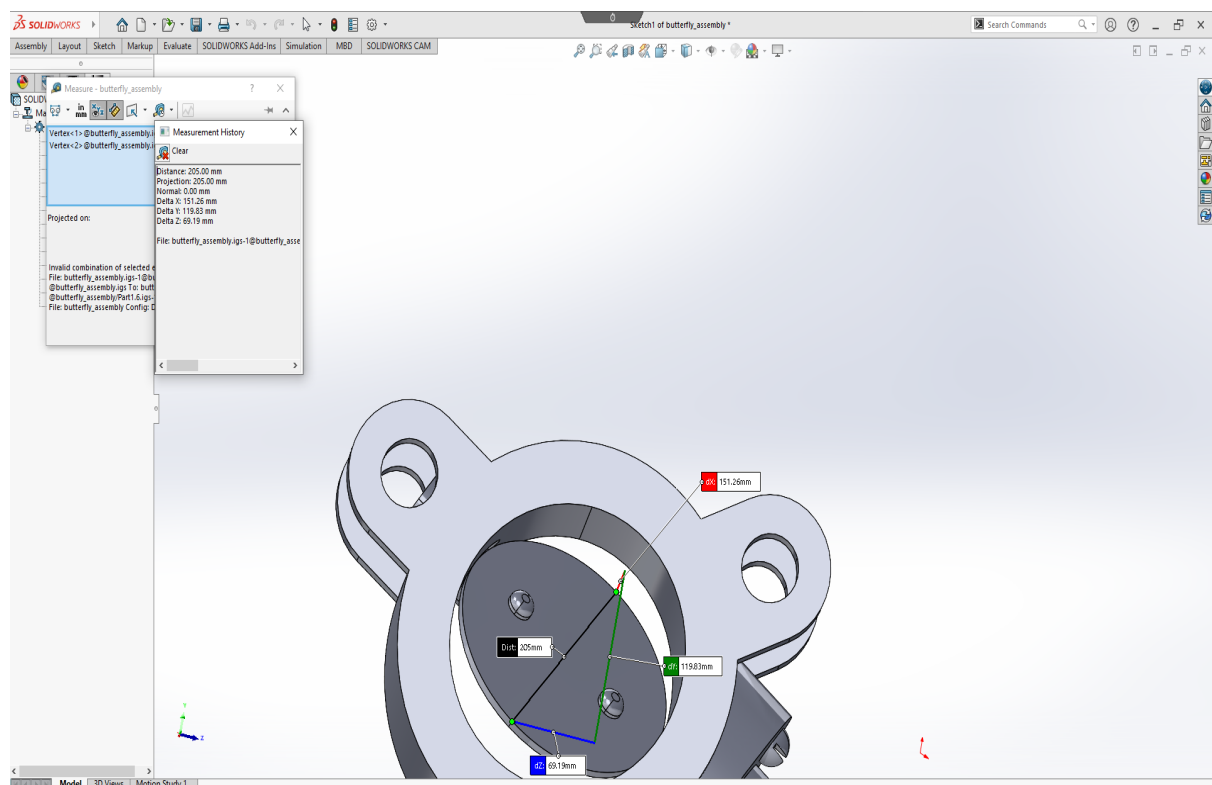
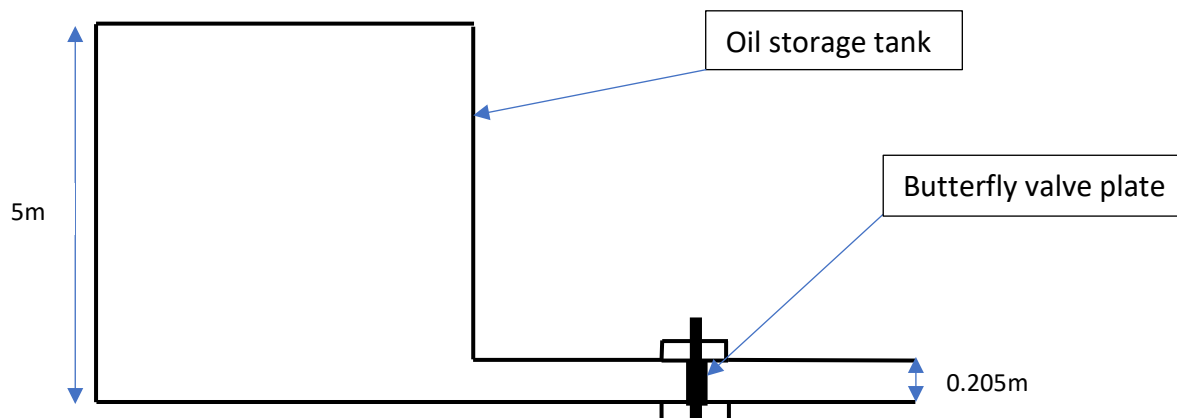


Figure 2. This print screen shows the butterfly valve model given out from the previous assignment with the diameter of the plate dimensioned, which can be used going forward in this assignment to create the plate and carry out calculations.

Calculations to work out the force acting on the butterfly valve plate



Density of petroleum = 800 kg/m^3 (Gindin, 2007)

Gravity = 9.81 m/s^2

Height of the petroleum(fluid) = 5 m

Diameter of the butterfly valve plate = 0.205 m

Calculations:

Hydrostatic Pressure, $P = \rho \times g \times h$

$$P = 800 \times 9.81 \times 5$$

$$P = 39240 \text{ Pa}$$

Area of the plate, $A = \pi r^2$

$$A = \pi \times (0.205 \div 2)^2$$

$$A = 0.033 \text{ m}^2$$

Force acting on the plate, $P = F/A \rightarrow F = P \times A$

$$F = 39240 \times 0.033$$

$$F = 1294.92 \text{ N}$$

Magnitude = Force $\div$ Number of Nodes

$$\text{Magnitude} = 1294.92 \div 1438 = 0.9005 \text{ N/node}$$

Stiffness calculations:

Original stiffness = F/δ

$$S = 1294.92 / 1.1$$

$$S = 1177.2 \text{ N/mm}$$

Optimised plate stiffness = F/δ

$$S = 1294.92 / 0.095$$

$$S = 13630.7 \text{ N/mm}$$

By optimising the plate, the stiffness has massively increased by almost 12 times.

The model of the butterfly valves plate created and set up

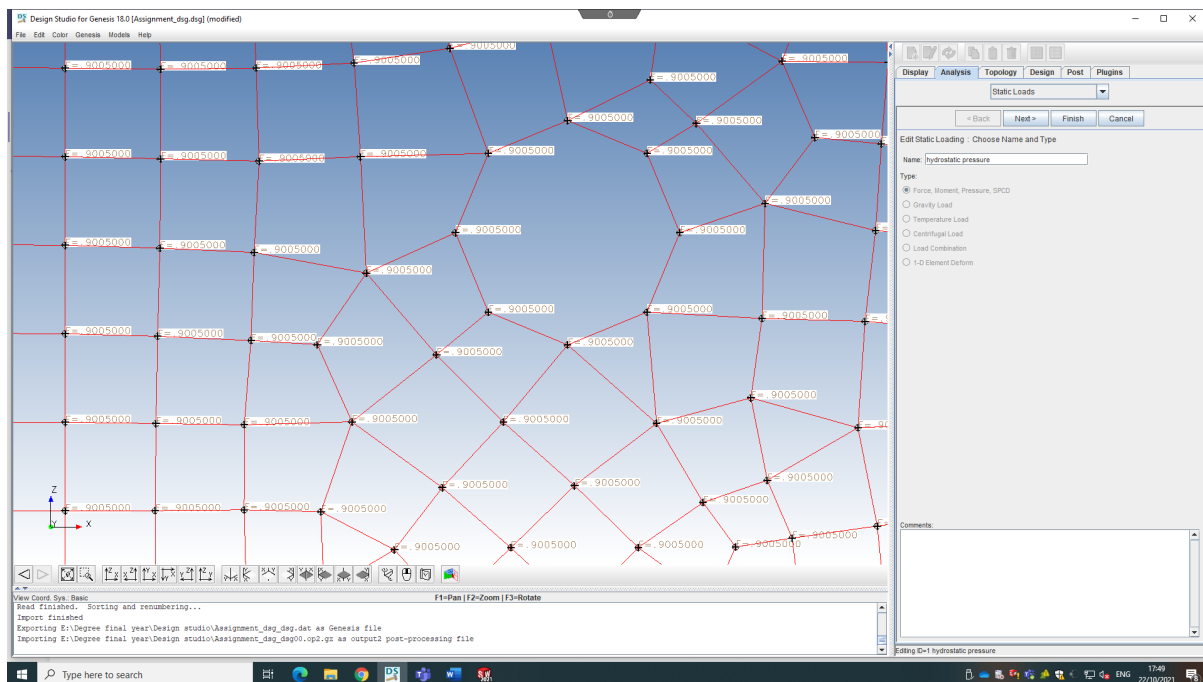


Figure 3. This is a close up shot of the plates mesh structure which shows the magnitude acting at each of the 1438 nodes in the structure. The force acting at each node is 0.9005N, this was calculated in the previous page and the method of how the magnitude value was obtained is shown.

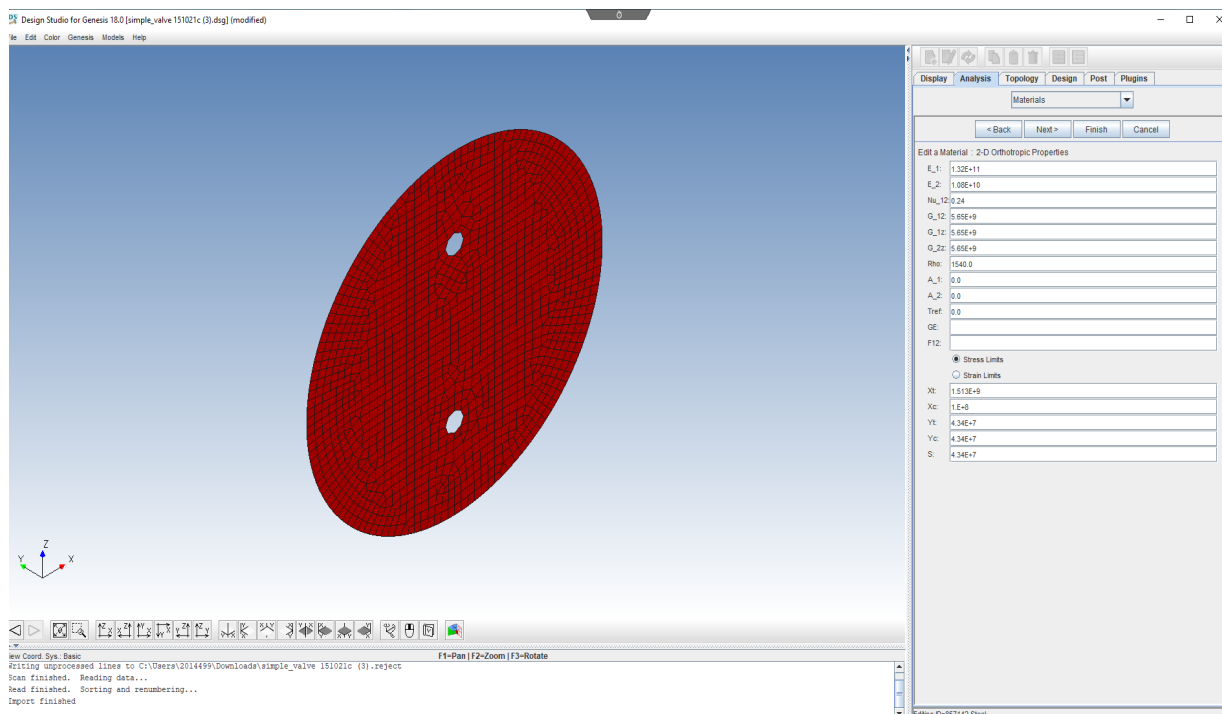


Figure 4. This image shows that the unidirectional CFRP material properties have been inputted into to the design studios model.

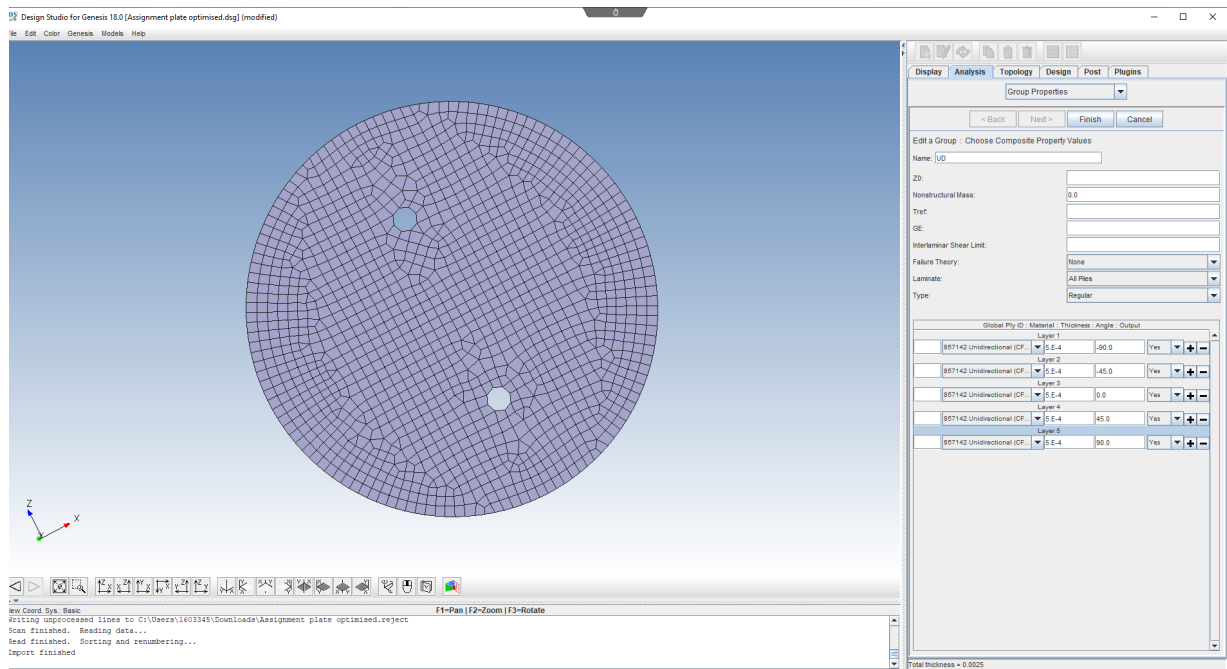


Figure 5. This print screen is showing that the 5 layers have been set up with 25 plies. There is 5 plies at each layer, 5 plies at -90 degrees, 5 plies at -45 degrees, 5 plies at 0 degrees, 5 plies at 45 degrees and 5 plies at 90 degrees. Each ply is 0.1mm in thickness so 5 plies total 0.5mm, with each layer then being 0.5mm in thickness.

Task 3

In this task there are print screens which show the steps taken to optimise the structure of the plate. Each print screen will be briefly described in the caption of the image and a summary of the progress/results included at the end of the task.

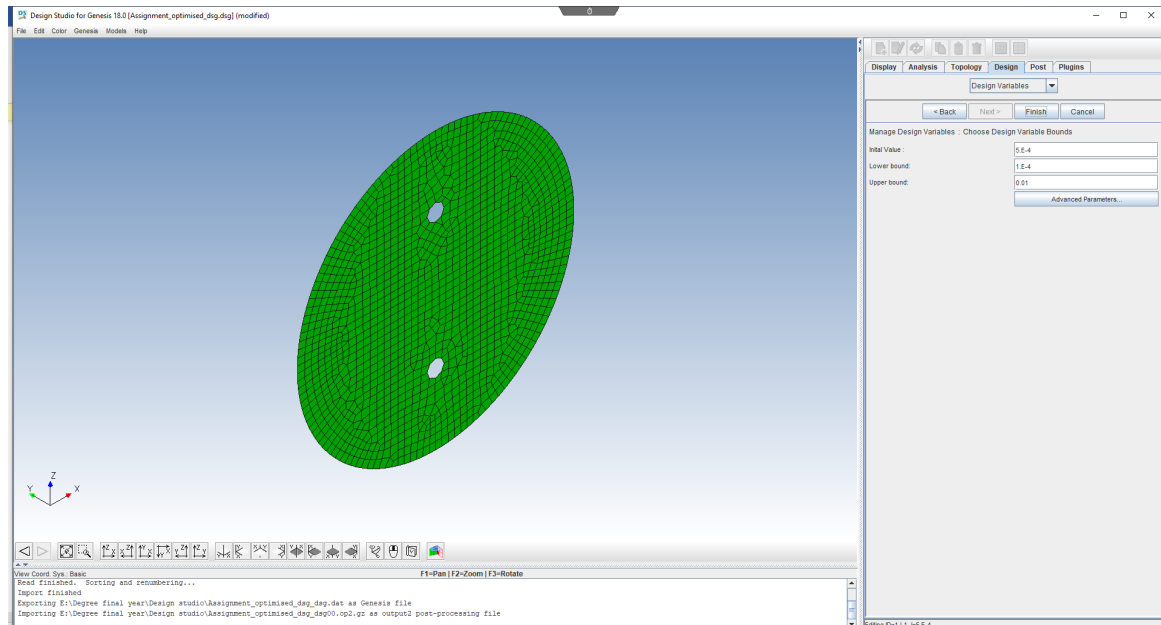


Figure 6. Constraints are set up with the initial value set at 0.5mm which is the total thickness of 5 plies at 0.1mm. The lower and upper bound constraints were set at 0.1mm and 10mm. The lower bound was set at the smallest thickness possible which was the thickness of 1 ply being 0.1mm and the upper bound was set at 10mm just so the upper bound limit would not be reached so that the plate could be optimised fully.

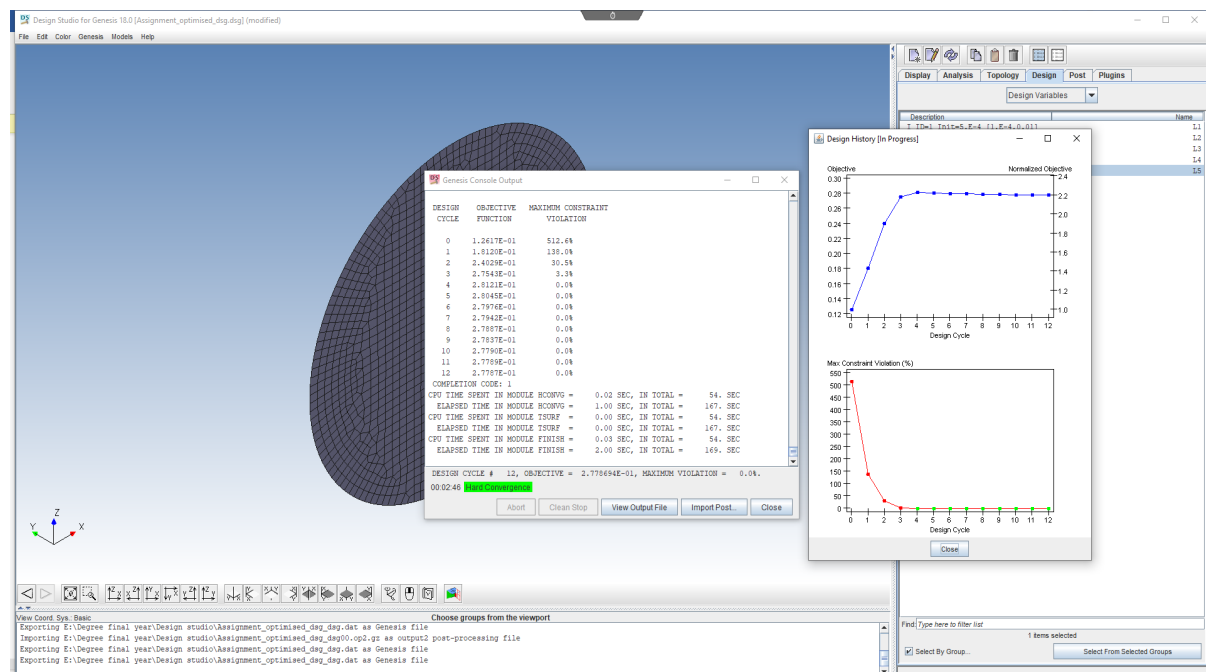


Figure 7. When Genesis optimisation was run, as you can see in the image, at cycle 0 (start) the constraint violation was 512.6% as shown in the bottom graph. At cycle 12 the constraint violation was by then reduced to 0%. This meaning that the displacement constraint of a maximum of 0.1mm deflection has been met. The graph on top with the blue points and line, then shows how the mass of the plate changes with every cycle completed, with the initial mass of the plate being 126.1743 grams and the final optimised mass at cycle 12 being 277.8694 grams.

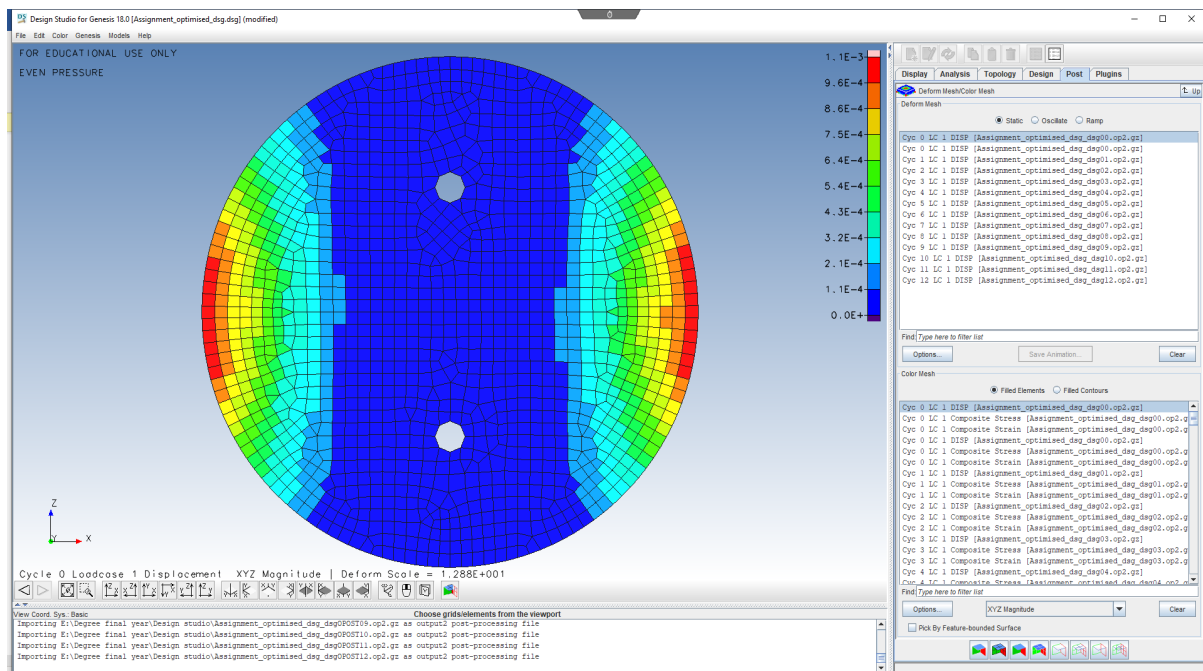


Figure 8. The plates deflection value of 1.1mm shown prior to undergoing optimisation. The max deflection can be seen to occur on the outer far edges of the plate, at the furthest point away from the centre pin on the plate.

Plate structure before any optimisation

Layer Number	Layer Thickness (mm)	Number of Plys
Layer 1	0.5mm	5 plys at -90 degrees
Layer 2	0.5mm	5 plys at -45 degrees
Layer 3	0.5mm	5 plys at 0 degrees
Layer 4	0.5mm	5 plys at 45 degrees
Layer 5	0.5mm	5 plys at 90 degrees
Total Thickness = 2.5mm		Total Number of Plys = 25 plys

- Mass of the plate = 126.1743 grams

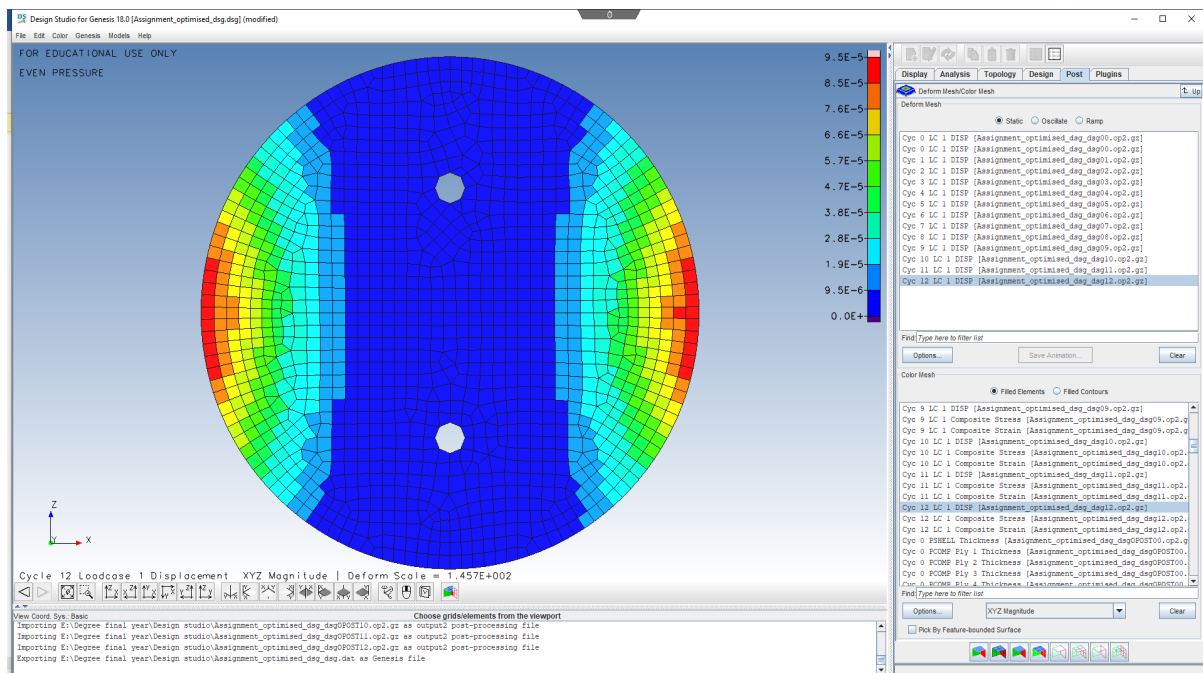


Figure 9. Cycle 12 of the theoretical optimisation of the plate gives the optimal thicknesses for each layer in which the plate will have a deflection no greater than 0.1mm at any point. It states the maximum deflection acting on the plate with this lay-up will be 0.095mm which is under the 0.1mm constraint set.

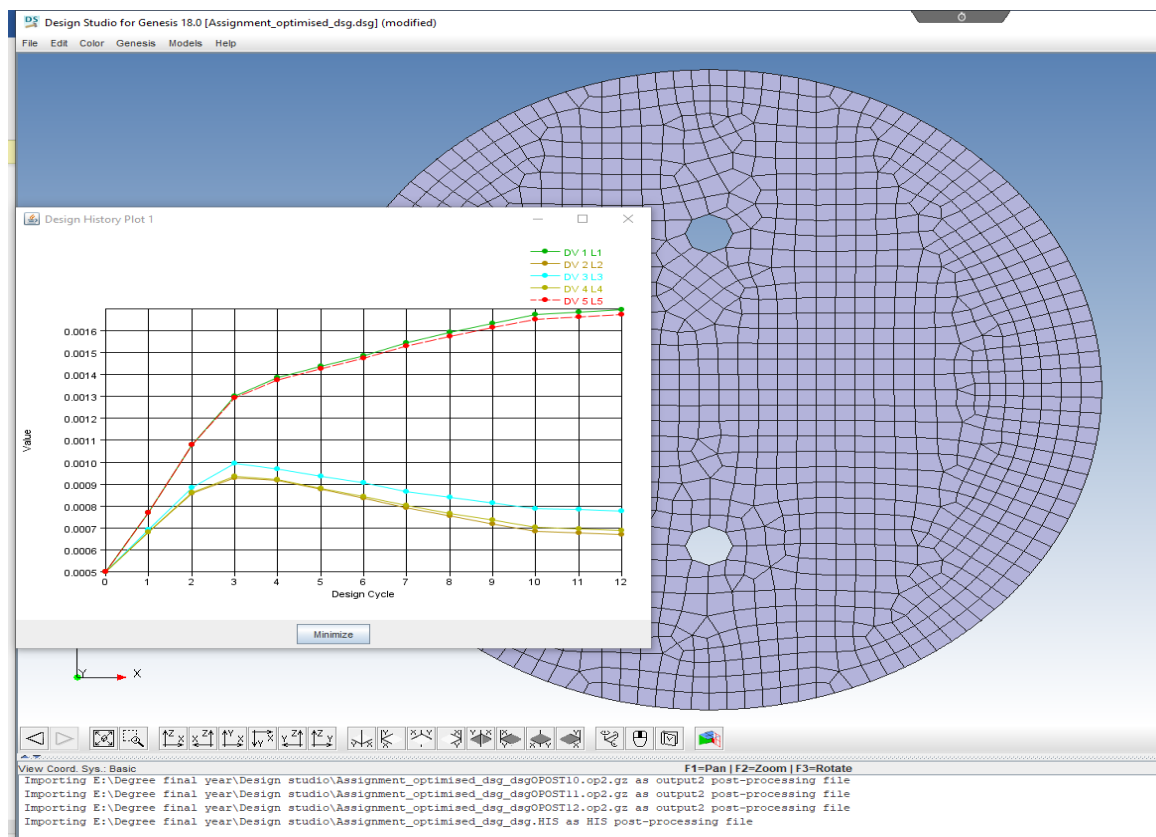


Figure 10. The graph shows the theoretical optimal thickness of each layer for the plate. It shows that layers 2,3 and 4 increase in thickness from cycle 0 up to cycle 3, after cycle 3 all layers are on a small decline in thickness up till cycle 12 where they reach their optimised thickness. When looking at layers 1 and 5 they constantly increase from cycle 0 all the way up to cycle 12, where the layer's optimised thickness is reached.

Plate structure after optimisation

Layer Number	Layer Thickness (mm)	Number of Plys
Layer 1	1.697005 mm	16.97 plys
Layer 2	0.6688473 mm	6.69 plys
Layer 3	0.7767444 mm	7.77 plys
Layer 4	0.6890781 mm	6.89 plys
Layer 5	1.673993 mm	16.74 plys
	Total Thickness = 5.5056678 mm	Total Number of Plys = 55.06 Plys

- Mass of the plate = 277.8694 grams

Plate structure after the discrete values used for the optimisation

Layer Number	Layer Thickness (mm)	Number of Plys
Layer 1	1.6 mm	16 plys
Layer 2	0.8 mm	8 plys
Layer 3	1 mm	10 plys
Layer 4	0.9 mm	9 plys
Layer 5	1.6 mm	16 plys
	Total Thickness = 5.9 mm	Total Number of Plys = 59 Plys

- Mass of the discrete optimised plate = 297.77 grams

Comparison between the initial and discrete value optimisations

By using discrete values instead of the theoretical best values, the total thickness of the plate increased by 0.3943322 mm. The total number of plys therefore also increased to 59 plys from 55.06 plys and the total mass of the plate increased by just shy of 20 grams. These increases in thickness, number of plys and mass are necessary as by the thickness of a layer being like the value of layer 2 (0.6688473mm), it would be practically impossible to manufacture the thickness of the plates layer to that degree of accuracy.

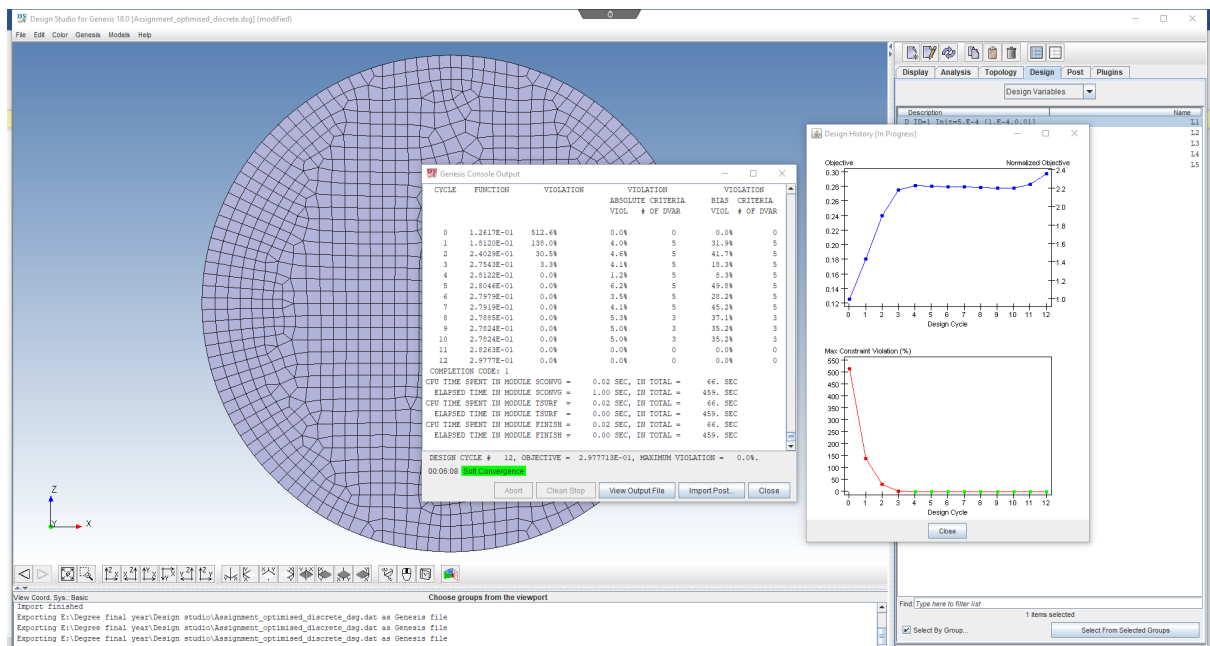


Figure 11. This optimisation still meets the constraint of a maximum of 0.1mm deflection but the plate now is slightly stiffer as discrete plys are used. The discrete optimised plate has a greater mass than the previous theoretical optimisation cycle carried out on the plate as this design cycle has an optimised mass of 297.77 grams and the previous design cycle had a mass of 277.8694 grams.

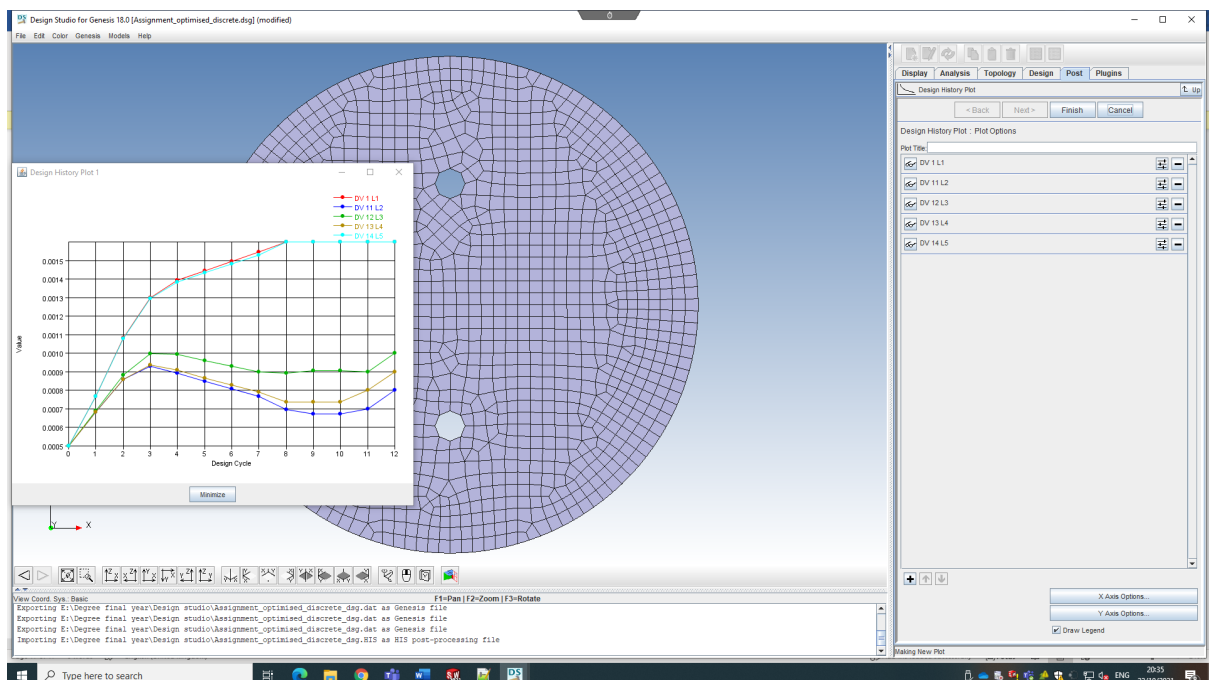


Figure 12. The graph produced shows the 12 optimisation cycles for the 5 layers of the discrete optimised plate, with all the layer's thicknesses starting at 0.5mm. From this graph you can see that layer 2, 3 and 4s thicknesses increase up to design cycle 3, then the thickness starts to decrease slowly before the optimisation increases the thickness of the 3 layers from cycle 10 onwards. With regards to layers 1 and 5 the thickness of the layers increases until cycle 8 before levelling off as they had reached their optimised thickness of 1.6mm by this point.

Summary of the plate's optimisation

When looking at the original part, it came out with results which violated the constraint of a deflection no greater than 0.1mm by a significant amount. With each layer being 0.5mm in thickness and an overall plate thickness of 2.5mm, there was a maximum deflection of 1.1mm. Comparing this to the optimised part when the discrete values were used, the maximum deflection on the plate was 0.095mm, which was less than the 0.1mm deflection constraint set. When comparing the mass of the original part and the optimised part using the discrete values the mass has more than doubled once optimised, as the original part had a mass of 126.1743 grams and the optimised part has a mass of 297.77 grams. Even though the mass has more than doubled the deflection on the plate has decreased to over 11 times smaller. Also, the optimised part has a much greater stiffness when compared with the original part, therefore, the optimised plate is much more efficient than the original plate.

The discrete values used for the second optimisation are required even though they result in the increase in the thickness of the plate, number of plys and mass. This is because by the thickness of a layer being like the value of layer 2 (0.6688473mm), it would be practically impossible to manufacture the thickness of the plates layer to that degree of accuracy. So, even though the optimisation using the discrete values isn't as efficient as the theoretical part, the optimisation using the discrete values is manufacturable unlike the theoretical part. Even with the added thickness and mass using the discrete optimisation it is still a great deal more efficient than the original part. The thickness the plate needs to be so it can be manufactured and be within the constraints is 5.9mm.

Task 4

For this task there will be an experiment procedure put forward, followed by a further detailed discussion, into how and why the experiment will be carried out using the procedure stated on a prototype of the butterfly valve system. It should be carried out in a way that will help engineers understand the deformation of the valves plate when it is subjected to hydrostatic forces seen. The results obtained from the prototype experiment should correlate to the simulation results obtained in task 3.

Experiment Procedure

The experiment steps which would be carried out on a prototype of the butterfly valve to be able to correlate these results with the simulation results in task 3 are as follows:

1. Fabricate a prototype of the butterfly valve and its plate out of CFRP to scale.
2. To test the prototype, use a butterfly valve testing machine like the one shown in figure 12.
3. When using the machine ensure all correct PPE is worn, safety barriers are all in place and all safety measures are adhered too.
4. The prototype should then be place in the machine, secured and locked in place.
5. Once in place the required force should be set.

The force acting on the valves plate was previously calculated for the optimisation; it was calculated to be 1294.92N.

6. Once the force reaches its target value of 1294.92N, leave this force applied to the valves plate for at least one minute and observe to see if any fluid leaks through the plate. (Inc, 2021).
7. After the minute is complete, release the force acting on the plate, release the butterfly valve from its clamps and measure the deflection on the butterfly valves plate using a digital DTI (Dial Test Indicator).
8. The DTI will be attached to a stand which will allow the DTI to run over the surface of the valves plate and display the deflection at different points across its surface.



Figure 13. Butterfly valve plate testing machine.
(YONGYE, 2021)

9. Record the amount of deflection displayed on the DTI at different points across the diameter of the plate. The highest amount of deflection should be measured, and this will be on the furthest point away from the centre of the plates surface.
10. The deflection measured on the plate should correlate with the results from the optimisation carried out in the previous task and have a deflection no greater than 0.1mm.



Figure 15. Digital Dial Test Indicator



Figure 14. Dial Test Indicator holder arm

Experiment discussion

The experiment procedure described step by step above, is a suitable procedure to follow, to gain the results required to correlate to the optimisation carried out in task 3. However, this procedure involves using a designated valve testing machine which would be very expensive to buy in or hire. If this is a one-off experiment then this wouldn't be a viable procedure to follow if the testing machine is not readily available, therefore, an alternative experiment can be looked at, but it may not give results that are as accurate. An alternative lower cost experiment could involve hanging the force which is 1294.92N (approximately 132kg), off the butterfly valve plate. This could be done using a webbing sling either side of the plates pin so the load would be relatively spread across the plates surface. The butterfly valve could then be slung to a crane hook so the 1294.92N of force could be hung on the slings slung on the butterfly valve plate. A load cell can also be used off the crane so the load being lifted on the crane would be known to ensure the force being exerted on the plate is correct.

Another potential issue with the experiment procedure stated step by step is that even though it can be seen if the plate deflects by fluid leaking through the valves plate the amount it deflects may be difficult to record. This is because even though a digital DTI can be used to measure the amount of deflection, when the butterfly valves plate is removed from the machine and set up to be measured, the plate may then not be deflected as much as when the force was being applied to the plate. Also, due to the small amount of deflection expected it could be difficult to get accurate readings using a DTI on small margins of deflection.

Task 5

This task covers the standards and any technical literature that is related to the butterfly valve model and its components, which are stated in the assignment brief. The standards related will be stated and explained and any related technical literature will be discussed.

Standards and technical literature related to the butterfly valve

Different countries across the world have different standards they require to follow, in the United Kingdom, the British Standards Institution (BSI) set out the British standards (BS) we require to follow. There are then international standards which are set out by the International Organization for Standardization (ISO), which are an independent organisation which ensures the safety, quality and efficiency of products and services worldwide.

- **BS EN 593:2017** – The standard for industrial metallic butterfly valves for general purposes. It specifies the minimum general requirements for butterfly valves which have metallic bodies and are used for isolating, regulating or control applications. **(standard, 2017)**. In this standard in section 5.1.1.2 it covers design and what is required specifically for the disk. It states that “The manufacturer shall publish dimensions showing the protrusion of the obturator (disk) in the open position beyond the faces of the valve”. In section 5.1.2.2 Obturator (disk) it states, “materials shall be suitable for the service conditions and fluid to be conveyed, e.g., type of fluid, pressure and temperature”. **(standardization, 1998)**.

This standard also states that when pressure testing the shell and seat of the valve the tests must be carried out in accordance with PREN 12266-3. For valves subject to European legislation on pressure equipment, EN 16668 applies. **(BSI, 2021)**.

Even though it is related to specifically metallic butterfly valves it will still be relatable to the CFRP butterfly valve component as CFRP material is up to ten times stronger so the standards should cover for metallic valves should cover it.

(Composites, 2021). There are also no current standards released specifically for CFRP butterfly valves, potentially because they are not produced for mass supply.

- **BS EN ISO 16136:2006+A1:2019** – Specifies requirements for the design, functional characteristics and manufacture of butterfly valves made of thermoplastics materials intended for isolating and control service, their connection to the pipe system, the body materials, and their pressure/temperature rating between -40 degrees Celsius and +120 degrees Celsius. It is also applicable to hand- or power-operated valves to be installed in industrial pipe systems, irrespective of the field of application and the fluids to be conveyed. **(institution, 2019), (BSI, 2021).**
- **ISO 527-5** – Defines the testing conditions and specimen geometry for tensile testing unidirectional reinforced plastic composites. The testing machine used to test the unidirectional fibre reinforced plastic composite must meet the standards set out in ISO 527-1. In this standard it states the testing machine is capable of a constant rate of extension, equipped with a load cell, an extensometer, and a force gauge. **(ISO, 2021).**
- **ISO 10631:2021** - Specifies requirements for design, materials (e.g., steel, cast iron, ductile iron, copper alloy), pressure/temperature ratings, and testing for butterfly valves having metallic bodies for use in general purpose flanged or butt-welding piping systems. Additional requirements given in the relevant application standards can apply to butterfly valves used for more specific applications (e.g., for the water industry, the chemical and petrochemical process industry, the oil, and gas industry). This standard also applies to butterfly valves that have the following pressure designations PN 2, 5, 6, 10, 16, 25, 40 and class 125, 150, 250, 300, 600. **(ISO, 2021).**

Conclusion

To conclude, throughout this report it is clear to see the importance of FEA and its optimisation techniques. From task 1 it defines the effectiveness of individual optimisation techniques and highlights clearly how over the years FEA has developed and greatly improved. FEA plays a massive role in the development of parts and components, it is there for all to see how effective it is and how useful the optimisation capability is by looking at tasks 2 and 3. These tasks confirm how effective the software is as the plate started with a mass of 126.1743 grams and had a deflection of 1.1mm. Once the part was optimised the mass had increased to 277.8694 grams, but the deflection had then decreased to 0.095mm which is almost 12 times smaller than the original deflection with a mass only just over 2 times greater.

Without FEA a prototype would have to be made and experiments carried out. In most cases this will cost a lot more for materials and is a longer process, it can be even more time consuming if a range of materials need to be tested when on FEA changing the material is a simple fix. In history when FEA wasn't available a lot of parts and components would have been over manufactured, this meaning they would have been manufactured with a greater thickness/mass when not required. By doing this, it is not cost effective, especially when mass producing parts the extra cost of material would add up. The experiment procedure discussed in task 4 highlights how a fairly accurate test on a prototype, would cost a great deal more than using the FEA software as the machine required in that procedure to be able to carry it out costs thousands of pounds on its own. Before FEA was available as well, when parts/components were manufactured, requirements that needed to be met weren't as strict as there were no standards released years ago and over time standards have added more requirements which need to be met. By more requirements being added to the standards it means parts will need to be produced with greater accuracy. When looking at FEA and experiments carried out on prototypes the best and most accurate results will come from FEA software.

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