

Structural & Fluid Analysis

Designing a Butterfly Valve: Structural Design



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Course: BEng Mechanical and
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Introduction

The task set is to use optimisation techniques that are used in relation with FEA software to optimise the composite construction of the butterfly valve plate, this to ensure that the product does not leak past the valve when it is closed while also using as little material as possible.

It is proposed that the plate is to be made from a unidirectional (UD) carbon fibre reinforced plastic known as (CFRP). The centre portion of the plate which is highlighted by the green segment on the image (fig 1) shown below is supported by the pin which is used to rotate the plate when opening and closing the value. The red portion of the plate is unsupported and subject to deformation and deflection from the forces placed upon it.

To satisfy the requirements of this task using the information provided in assignment 1. This specifying the butterfly is inserted into a pipeline that forms the outlet at the base of a 5m high storage tank which contains petroleum at atmospheric pressure. To follow on it is required to design the lay-up of the composite material to withstand the hydrostatic forces acting on the plate allowing a maximum deformation of 0.1mm to ensure a good seal between the plate and outer housing and using the least amount of material in achieving this.

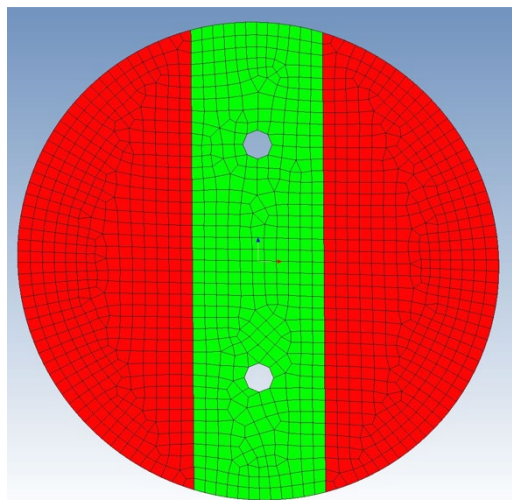


Figure 1

Task 1) Discuss FEA Optimisation Techniques

FEA uses computerised models and methods to essentially predict how a component/structure, will react to real world forces acting upon them, such as mechanical stress, vibration, and fluid flow. By using this technology it will allow to predict whether a product will fail through component failure, being exposed to excessive wear, degradation over time or work as intended when designed.

As FEA software is complex and its results are heavily dependent on user understanding and ability. Using optimisation techniques allows refining of the designed component/part to finer margins to test components to their limits and implement design changes to best suit the overall outcome.

There are a number of different optimisation techniques that are used all to best improve the design by carrying various alterations for the better. A selection of optimisation techniques are as follows:

- Topology optimisation
- Shape optimisation
- Size optimisation
- Topometry optimisation
- Topography optimisation

By incorporating these different techniques into your FEA analysis, it will drastically improve the overall design and outcome of the component being investigated.

Topology Optimisation

This type of optimisation is an algorithmic process of optimising a mechanical part/component usually through the reduction of material. This is done by calculations according to the mechanical stresses the part will be subjected to during its intended operation.

Topology optimisation can be regarded as a subfield of structural optimisation which would cover a number of subfields. Its main purpose is about performance and efficiency. It mathematically solves a major engineering problem. How to make a strong part while using

the least amount of material. This ultimately to reduce costs, for this reason it is widely used across many industrial sectors but aerospace being at the forefront as weight reduction is essential (Carolo, 2020).

Shape Optimisation

Shape optimisation, the main objective function is the structural mass of the component, and constraint functions are the structural compliance measures that are obtained from the topology optimisation and stress measures (Gary H. Koopmann, 1997).

The aim is to improve the performance of the structure by modifying its boundaries. This can be numerically achieved by minimising an objective function subjected to certain constraints. Every function is related to the design variables, which are some of the coordinates of key points in the boundary of the structure. With this method, you can optimise the boundary profile of your design shape to, for example, minimise the weight while satisfying constraints on the stress resulting from a range of loading conditions. (Gandomi, 2013)

Size Optimisation

Using sizing optimisation, engineers can compute optimal properties and parameters of a model to achieve a given a design objective such as a target weight reduction. Numerous properties such as cross-sectional areas, moments of inertia, layer angles and thicknesses, elastic moduli, Poisson's ratios, densities, and others can be considered to help engineers arrive at an optimum solution (Hexagon, n.d.).

In sizing optimization, the element cross-sectional dimensions are typically used as design variables. However, in finite element models, data is provided for properties (i.e., areas, inertias, etc.). To overcome this difference, in GENESIS and other commercial programs, such as MSC.Nastran, the user needs to create equations that relate design variables to the properties (Levia, 2013).

Topometry Optimisation

Topometry is a generalisation of sizing optimisation. Unlike size optimization, where all elements associated to a property data entry are designed with the same values, in topometry optimisation each element is designed independently. Topometry data uses sizing optimisation data. With sizing optimization data the user provides the information to the program of what relationship their designable properties (like areas and moment of inertia in bars in PBAR entry) and design variables have to follow. A new data in GENESIS, named DSPLIT, allows the user to select which sizing data will be used for topometry. Internally, the code splits the properties and creates all associated design data to create independent relationships between automatically created design variables and element properties (Levia, 2013).

Topography optimisation

Topography optimisation is a special case of shape optimisation. When optimising the program automatically generates perturbation vectors that are either perpendicular to the designable region or in a given direction.

This is particularly powerful for designing sheet metal parts. In this procedure, finite element grids are moved along normal to shell surface or user specified direction. Efficient algorithms are used to generate shape design variables based on bead dimensions, and to arrive at optimum shape (Hexagon, n.d.).

History

- The early stages of FEA dates back to the 1950s, analogue computers had been developed to process more complex structural problems. With the promise of more powerful computers to come (O'Donnell Consulting Engineers , n.d.).
- The basic concept of finite elements was born, although the process was still time consuming and limited. In 1960, Dr. Ray Clough coined the term “finite element.”

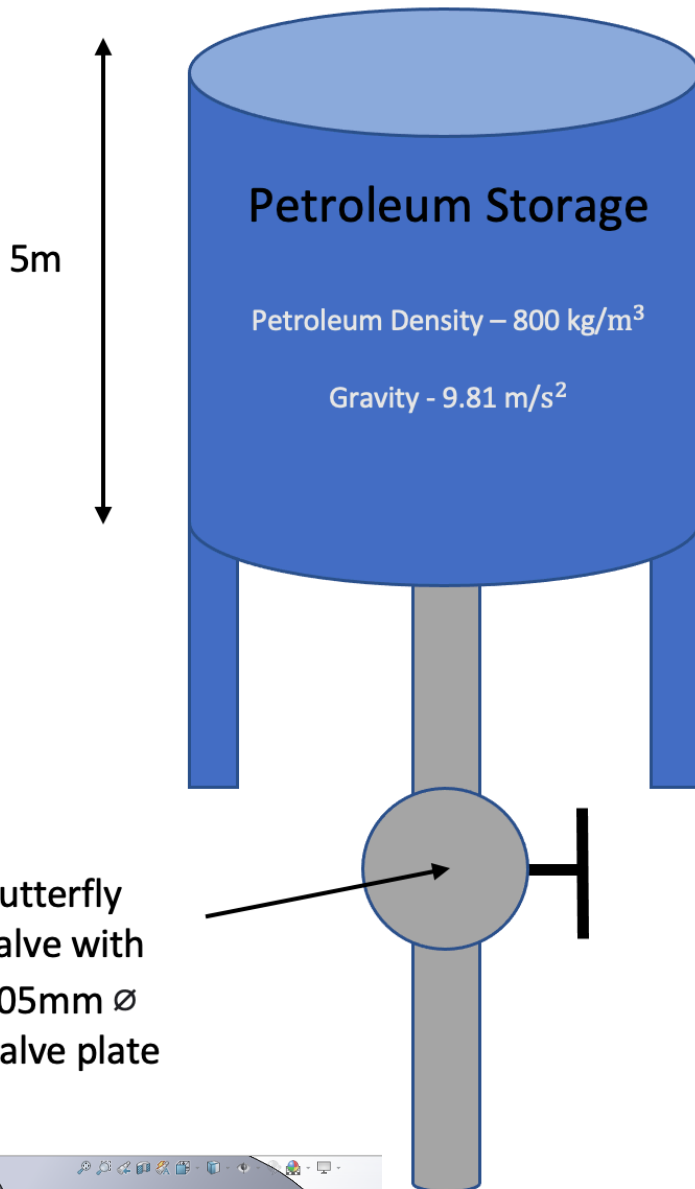
The 1960s saw the true beginning of commercial FEA as far superior digital computers replaced analogue (O'Donnell Consulting Engineers , n.d.).

- In the early 1960s, The MacNeal-Schwendler Corporation (MSC), was awarded a contract from NASA to develop a general purpose FEA code. This company, ensured the growth of commercial FEA by developing what is now known as NASTRAN (O'Donnell Consulting Engineers , n.d.).
- This original code had a limit of 68,000 degrees of freedom, which was believed to be larger than anyone would need. When the NASA contract was complete, MSC continued development of its software, called MSC/NASTRAN, while the original NASTRAN became available to the public (O'Donnell Consulting Engineers , n.d.).
- By the 1970s, minicomputers were developed, These were still considered complicated, these improvements continued into the 80s with colour stress contours this is where FEA was first considered for general product design main stream (O'Donnell Consulting Engineers , n.d.).
- In the late 1990s, the PC platform became a major force in high end analysis. Models with 1 million degrees of freedom were being run on “deskside” supercomputers capable of running 1 trillion operations per second (O'Donnell Consulting Engineers , n.d.).

The progression of FEA analysis and optimisation is remarkable and stems from the Nasa and the aerospace industry, this allowed for comprehensive simulation into structural behaviour into materials allowing for more effective and efficient designs. This eventually filtered through to different industries as the technology improved and costs reduced.

Task 2) Design Studio Model

Using the information provided from assignment 1, calculations can be carried out to satisfy the requirements needed for the tasks. These will be used to carry out product optimisation specifically relating to the structure given.



$$\text{Hydrostatic pressure (P)} = \rho \times g \times h$$

Where: P = Fluid pressure

ρ = Fluid density

g = acceleration due to gravity

h = Fluid depth

$$P = 800 \times 9.81 \times 5 = \mathbf{39,240N}$$

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

$$A = \pi \times 0.1025^2 = \mathbf{0.033m^2}$$

Force on plate: $P = \frac{F}{A}$ = rearranged to $F = P \times A$

$$F = 39,240 \times 0.033 = \mathbf{1294.92 N/m^2}$$

$$\text{Stiffness} = S = \frac{F}{\delta}$$

Where: F = Load

δ = extension

(This can be used further on to calculate stiffness of different plate deflections)

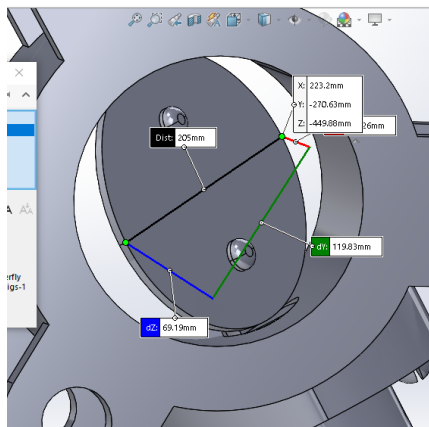


Figure 2, represents the CAD drawing of the butterfly valve to confirm valve plate dimension.

Using design studio software a FEA representation of the valve plate could be created to the parameters set. The following image (Fig 3) illustrates the material properties of the plate UD carbon reinforced fibre polymer (CRFP) and the material properties layers, (25 ply's of the UD. 5 at -90°, 5 ply's at -45°, 5 ply's at 0°, 5 ply's at 45° and 5 ply's a 90°).

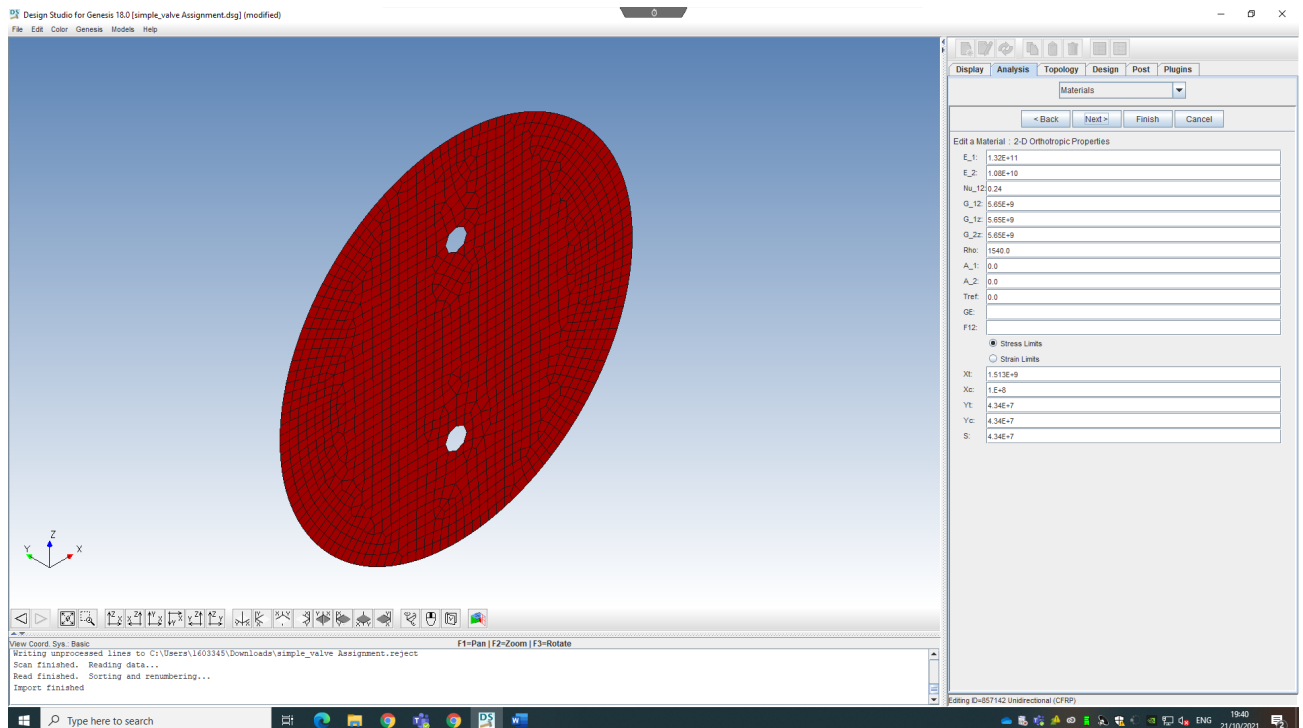
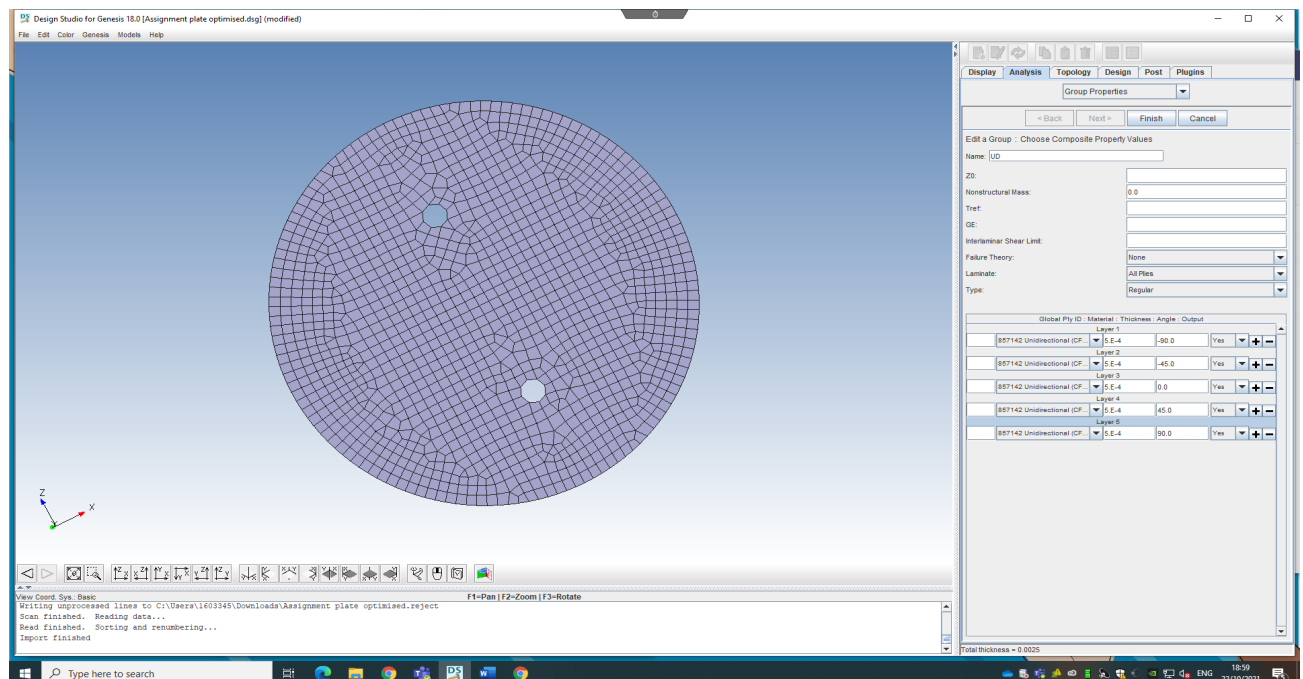


Figure 3



Task 3) Structure Optimisation

Optimisation is required to minimise the mass of the valve plate and meet the displacement constraints of a maximum of 0.1mm of deformation and provide the overall plate thickness. The software will enable results to be calculated based on the information inputted to provide a suitable CRFP valve plate within the set parameters.

The UD CFRP is set to each layer at 0.1mm thickness for each ply making each layer 0.5mm thick. With a total of 5 layers resulting in 25 ply's as represented in fig 4.

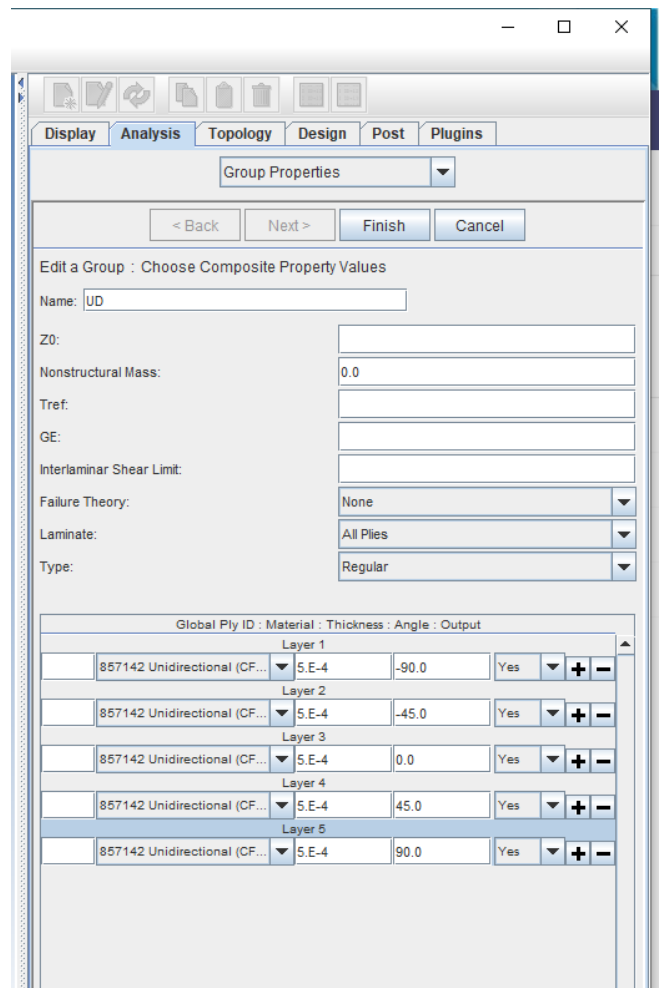


Figure 4

Using the calculations from task 2 the magnitude can be calculated to apply static load to the 1438 grids on the structure shown in fig 5. Using $F = 1294.92 \div 1438 = 0.9005 \text{ N/node}$

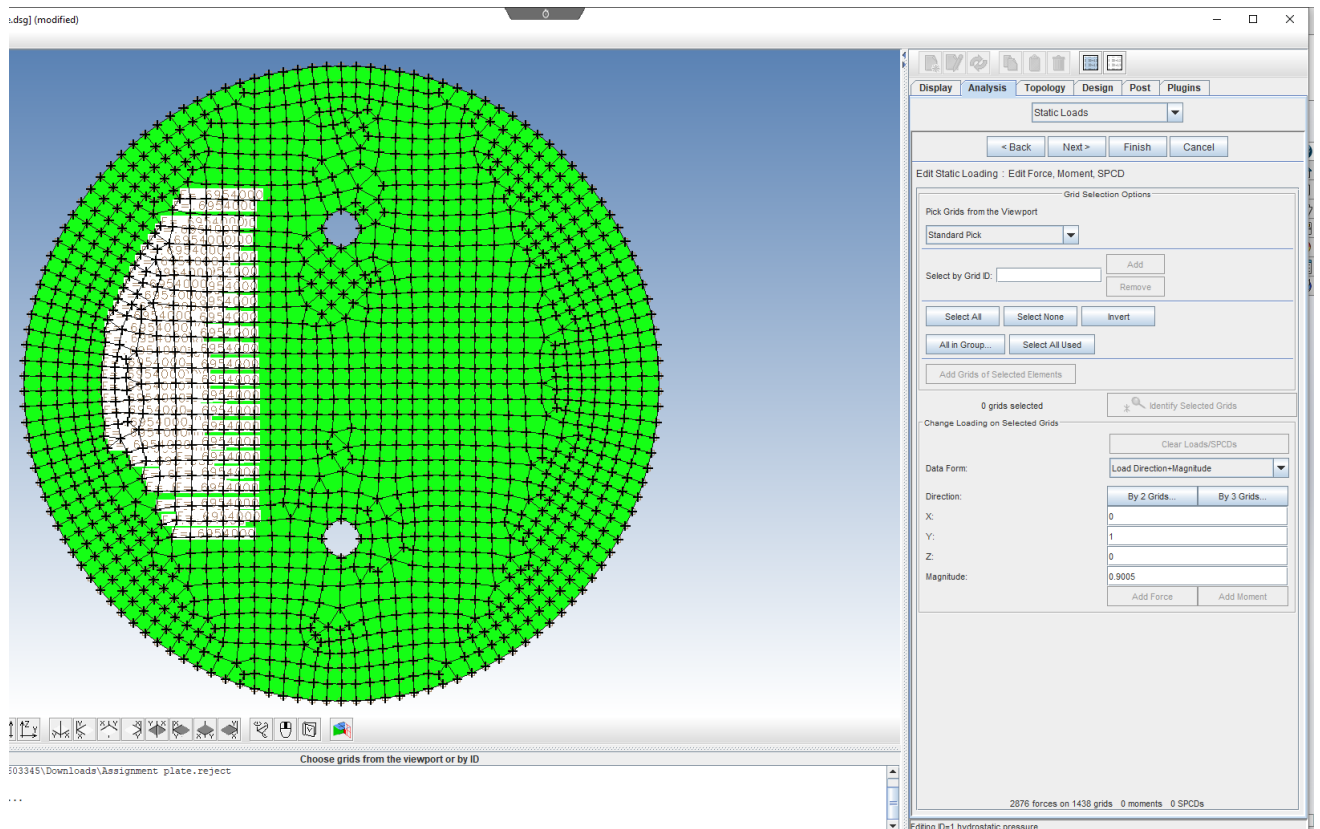
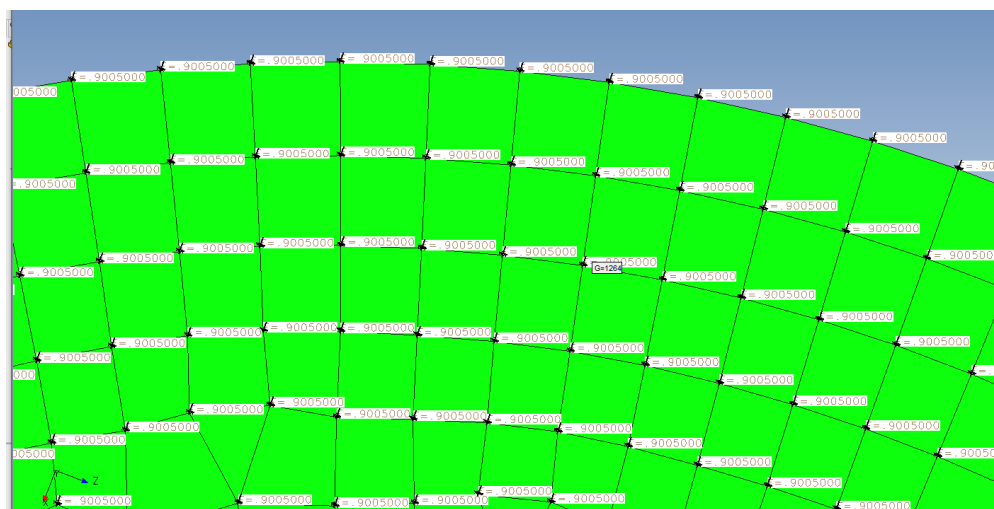


Figure 5



Design variables was set with lower boundary at 0.1mm thickness which is the smallest thickness possible for 1 ply and the upper boundary set to 10mm to ensure the optimisation cycle could run without being constrained giving the optimum results. Fig 6.

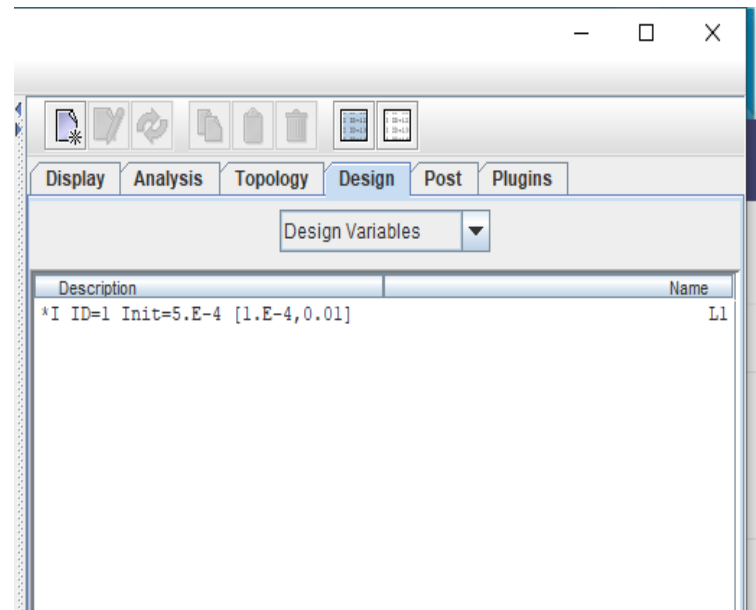


Figure 6

This is the first optimisation of the plate. It took a total of 12 cycles to find the optimum displacement constraint of 0.1mm. At the bassline cycle 0 the weight of the plate was at 126g but increased to 277g by cycle 12.

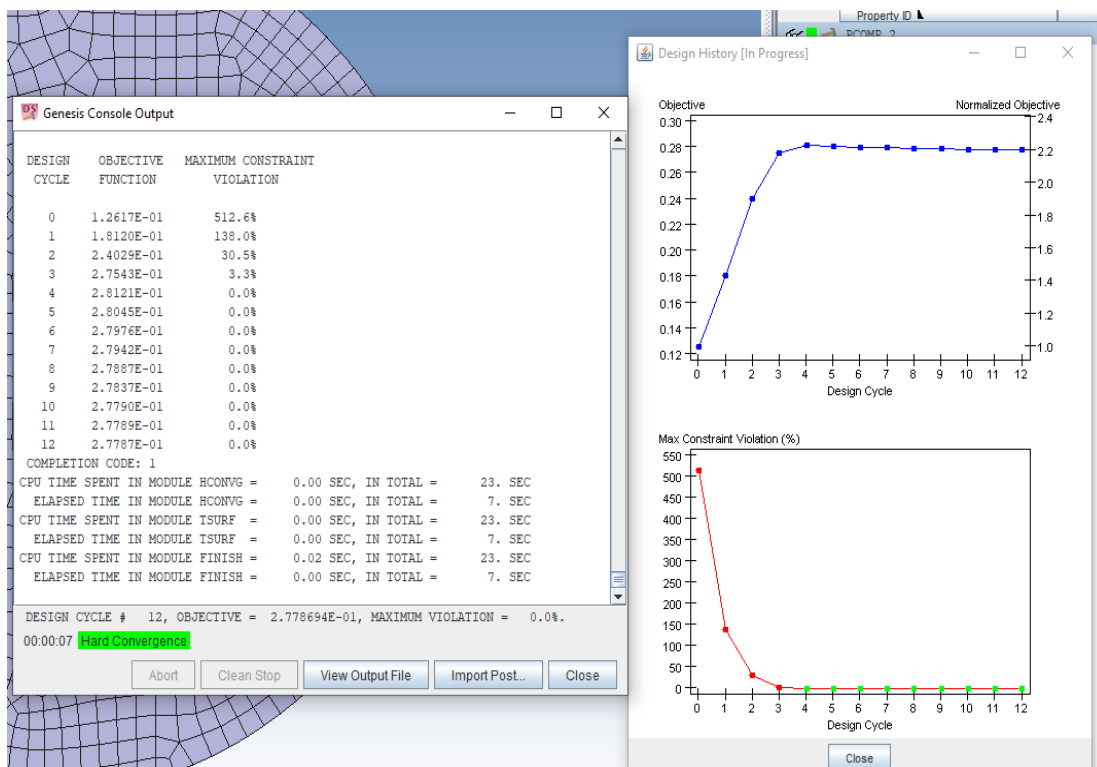


Figure 7

fig 8, represents each of the individual layer thickness as the each cycle optimised the component. As the cycles progressed layers 2, 3, 4 became thinner as layers 1, 5 increased thickness.

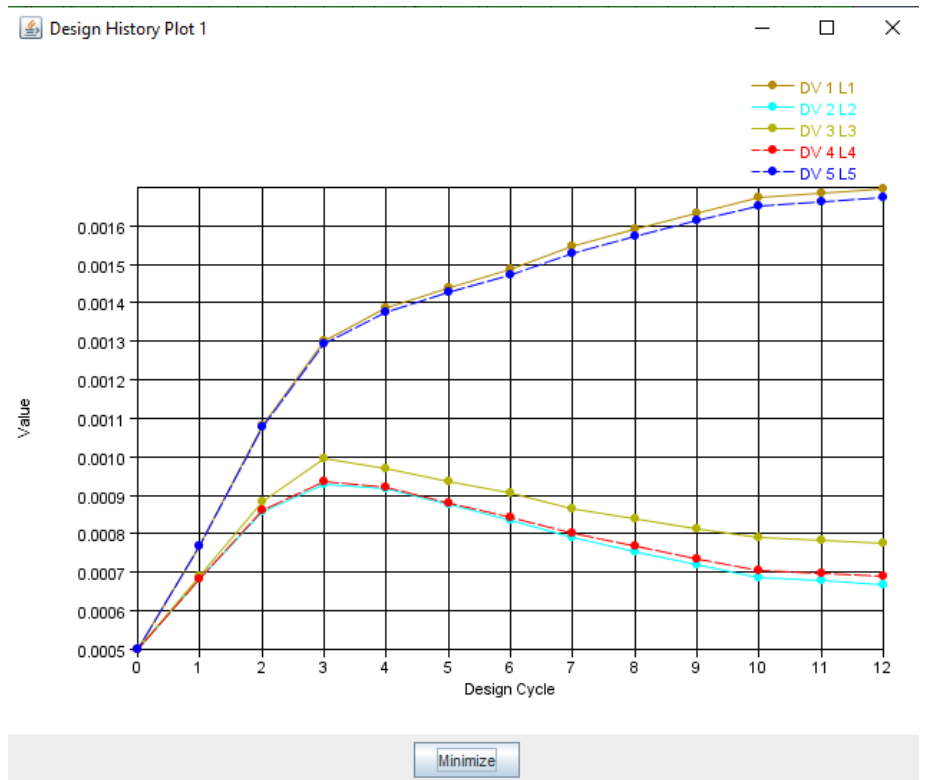


Figure 8

Design cycle 0 (Fig 9) showing a total of 1.1mm of deflection on the plate and design cycle 12 (Fig 9.1) meeting the criteria of maximum deflection of 0.1mm with a total of 0.095mm of total deflection.

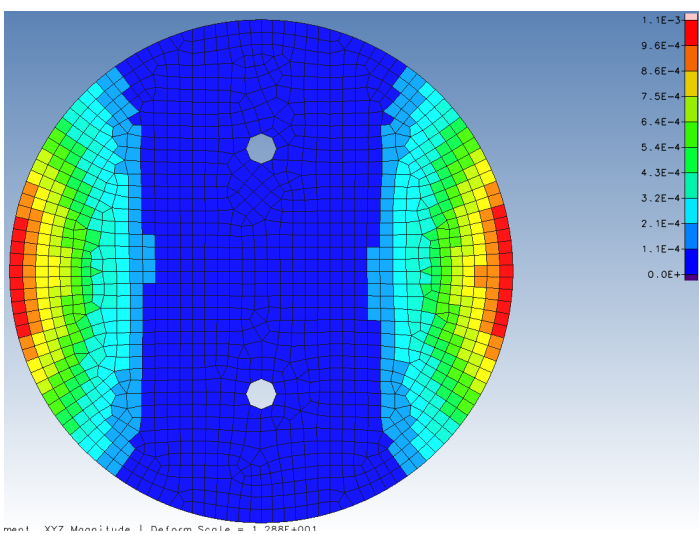


Figure 9

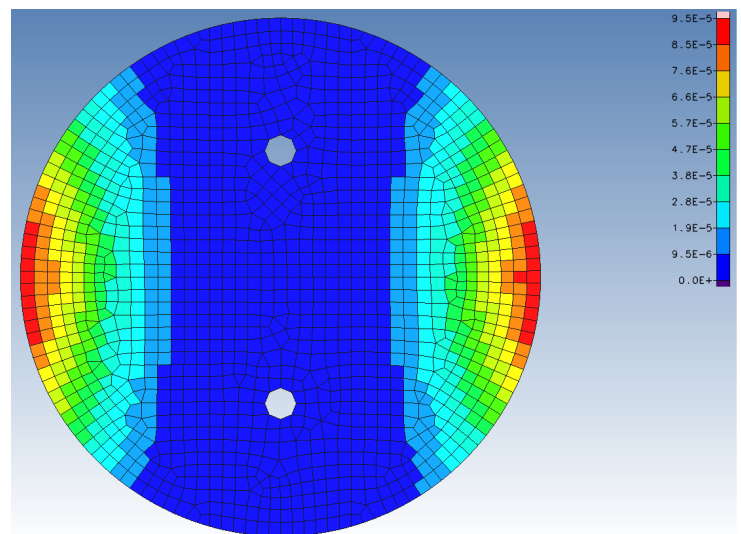


Figure 9.1

Design cycle 0 gave a total weight of 126g and a total of 2.5mm thickness (0.5 + 0.5 + 0.5 + 0.5 + 0.5)

DESIGN CYCLE # 0, OBJECTIVE = 1.261743E-01, MAXIMUM VIOLATION = 512.6%.		
DESIGN VARIABLE #	1 = 5.000000E-04	L1
DESIGN VARIABLE #	2 = 5.000000E-04	L2
DESIGN VARIABLE #	3 = 5.000000E-04	L3
DESIGN VARIABLE #	4 = 5.000000E-04	L4
DESIGN VARIABLE #	5 = 5.000000E-04	L5

Design cycle 12 gave an increased weight of 277g and a total of 5.51mm thickness (1.70 + 0.67 + 0.78 + 0.69 + 1.67)

This an increase of 3.01mm from the initial baseline cycle.

DESIGN CYCLE # 12, OBJECTIVE = 2.778694E-01, MAXIMUM VIOLATION = 0.0%.		
DESIGN VARIABLE #	1 = 1.697005E-03	L1
DESIGN VARIABLE #	2 = 6.688473E-04	L2
DESIGN VARIABLE #	3 = 7.767444E-04	L3
DESIGN VARIABLE #	4 = 6.890781E-04	L4
DESIGN VARIABLE #	5 = 1.673993E-03	L5

The parameters are altered to factor in component manufacturing using discrete valves. Ensuring results are given in 0.1 increments allowing for ease of manufacturing of the valve plate. Due to the 0.1 ply lay-up design.

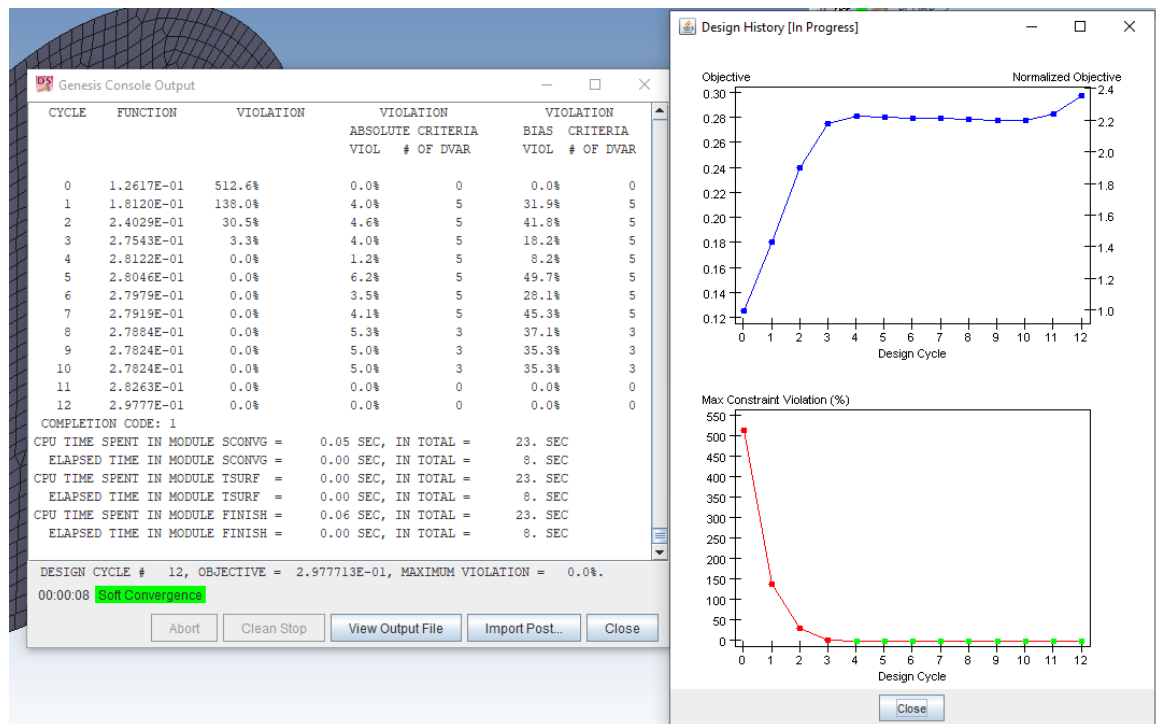


Figure 10

Fig 11, represents the fully optimised layers of the valve plate. It shows that the layer thickness of layers 2, 3 and 4 slowly decreased until cycle 9 which then reverses and increases as the software optimises the valve plate to the discrete valves.

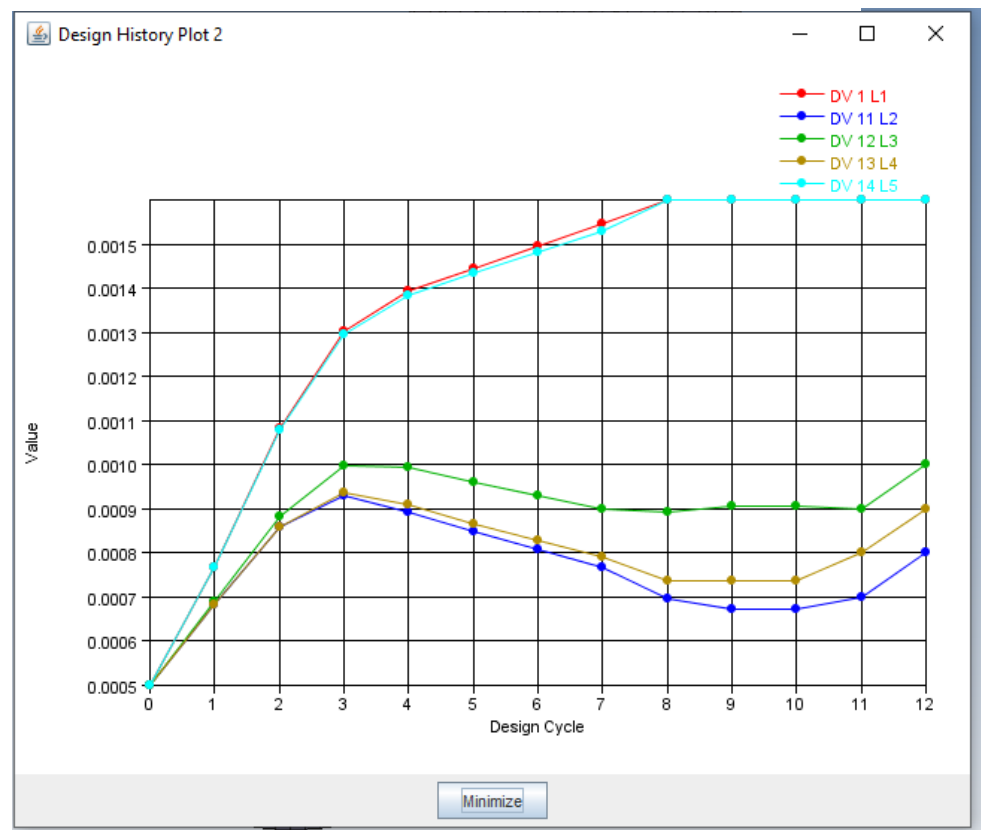


Figure 11

Fully optimised with discrete values, design cycle 12 gave a weight of 297g and a total of 5.9 mm thickness (1.6 + 0.8 + 1 + 0.9 + 1.6)

DESIGN CYCLE # 12, OBJECTIVE = 2.977713E-01, MAXIMUM VIOLATION = 0.0%.
 DESIGN VARIABLE # 1 = 1.600000E-03 L1
 DESIGN VARIABLE # 11 = 8.000000E-04 L2
 DESIGN VARIABLE # 12 = 1.000000E-03 L3
 DESIGN VARIABLE # 13 = 9.000000E-04 L4
 DESIGN VARIABLE # 14 = 1.600000E-03 L5

Comparison

Type	Material	Thickness	Ply's	Deflection	Stiffness	Mass	Load
Composite (cycle 0 initial)	CRFP	2.5mm	25	1.1mm	1177 N/mm	126g	1294.92 N/m^2
Optimised composite (cycle 12)	CRFP	5.51mm	55.1	0.095mm	13630 N/mm	277g	1294.92 N/m^2
Optimised (discrete)	CRFP	5.9mm	59	0.095mm	13630 N/mm	297g	1294.92 N/m^2

The results indicated that the theoretical plate is a superior constructed part due to the 20g less weight and 0.39mm reduction in thickness. But as this is theoretical, it is not practical in manufacturing of the component. Therefore the discrete results indicate the best possible solution for manufacture as the ply's are a standard thickness of 0.1mm

Task 4) Prototype Development

When a new component or product is designed, prototype development is a key element of understanding how the product behaves and reacts under the real world forces exerted on it. This allowing for a direct comparison to the research carried out in the design stage of the development. Although all the numbers from the analysis stage might meet the requirements in the development stage using the various CAD and FEA packages it is vital that this is compared and tested by prototyping. This is where alterations can be made based on the results and findings.

Firstly to carry out this task, it is critical the correct conditions are met to give the most reliable results. This replicating the forces exerted on the valve as calculated in the FEA and optimisation carried out. The nature of the valves running environment imposes various obstacles in accurately measuring the deflection of the valve plate under load. The brief states a maximum deformation of 0.1mm is seen, this ensure a good seal between the plate and outer housing. Therefore the key element of this valve is to create a good seal when in the closed position.

An option for this test is by using a butterfly testing jig as show in fig 12, this enables the valve to be set up as intended and place the correct load to the valve plate, simulating the force from the 5m high petroleum tank. Thus allowing for observations for any leaks, although this will indicate a good seal if no leaks are apparent it is not possible to measure the deflection of the plate if any.



Figure 12

(Metrus, n.d.)

Therefore it would be beneficial to create a specific testing set up allowing for deflection measurements. Fig 13 below is a basic representation of the set up to measure valve plate deflection.

- First step would be to replicate the given design as close as possible. Using a pressurised tank connected to a pipe with the butterfly valve mounted at the end. Enabling a controlled pressure source.

- Using a pressure gauge and isolation valve the pressure can be controlled and set at the calculated force.
- On the open end of the valve plate measurement sensors can be applied to the face of the valve located at pre-determined locations on the plate.
- The sensor can be moved to each pre-determined location and the test repeated taking measurements at the set points on the valve plate face.
- This allowing for a direct comparison to the FEA model giving real world measurements of the plates deflection under load .
- Additionally this setup will also allow for leak detection from the valve plate end monitoring how effective the seal created is when under load.

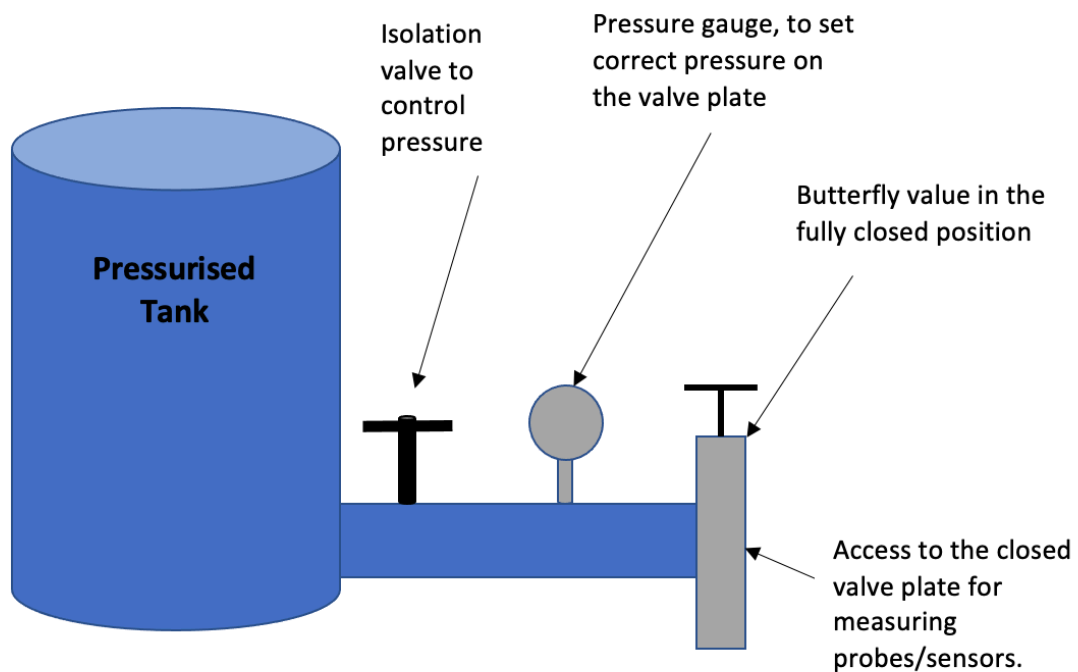


Figure 13

Task 5) Technical Literature And Standards

In the design and manufacture of parts and components it is important to ensure all designs are compliant with regulations and standards of the country of manufacture and the countries of intended use. This should be at the forefront of any design team's plans and factored in during the initial design stage, ensuring compliance.

With regards to the design of butterfly valves there are various British (BS), European standards (EN), international standards (ISO) and American standards (ANSI) that are currently in place and need to be considered. The following standards are relevant to the designing of a butterfly valve and all its associated components through material selection to testing requirements.

- BS EN 593:2017 (Industrial valves. Metallic butterfly valves for general purposes) this standard is initially a British standard which has been adopted by the European standards. This covers all aspects of the butterfly valve including areas directly related to the tasks. Areas listed below are of direct interest to the design of the butterfly valve in this task (BSI, 2017).
 - Operations tests (EN 12266)
 - Materials (EN 1503)
 - Design (EN 1092)
 - Testing and inspection (EN 12266)
 - Pressure test (in accordance to EN 12266-3)
- ISO 10631:2021 (Industrial valves – metallic butterfly valves) this document applies to metallic butterfly valves used for all industrial applications. 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) (ISO, 2021).

From the two standards listed above, relevant parts are highlighted from the BS standard in relevance to this task. For example under materials for the valve plate element “Materials

shall be suitable for the service conditions and fluid to be conveyed, e.g. type of fluid, pressure and temperature” . Pressure testing “ Each valve shall be capable of successfully undergoing shell strength, shell tightness, seat tightness” (BSI, 2017)

Conclusion

To conclude on this report it is clear the importance of the FEA software and optimisation techniques used in industry. Utilising the software's capabilities to create the best possible components strictly meeting design requirements. Therefore not over engineering components, which ultimately will incur increased manufacturing costs which is a key priority for manufactures to keep to a minimum.

The constant development of FEA software from its initial origins proves how powerful this can be in product design and product manufacture, initially used for aerospace development its use case is vital in today's industry. The array of benefits this has to organisations are key to successful and profitable projects.

The use of design studio allowed the valve plate to be made to the required dimensions, material properties and layup structure. Using the data regarding the petroleum storage tank and valve size, calculations could be carried out to find hydrostatic pressure, valve plate area and force acting on the plate. This could be utilised with the FEA software to input accurate findings to ultimately give the most accurate optimisation results. Thus satisfying the maximum deflection of 0.1mm and using the least amount of material possible to reduce manufacturing costs.

From the results it was apparent that the best plate was optimised without discrete values this required 12 design cycles to provide the best valve plate within the tolerance. Although this was the lightest and thinnest design it did not allow for ease of manufacturing, which is needed to ensure a high quality product whilst keeping costs to a minimum. Therefore the optimised plate with discrete values gave a total weight of 297g, thickness of 5.9mm with 59 ply's of CRFP material.

Once the theoretical model has been created it is important to verify these findings against a physical prototype. Although there are various butterfly valve test jigs available which can pressure test the valve these are unable to measure valve plate deflection.

To ensure this is possible to satisfy the design requirements, a set up was created allowing for a controlled pressure applied to the valve whilst measuring sensors are applied to the

exposed valve end measuring the deflection once the force is applied. This also allows for leak detection ensuring a good seal between valve plate and valve closing seat.

In the design and manufacture of components its vital these are designed in accordance to the current standards of the country of manufacture or intended use. Thus ensuring maximum operating efficiency and compliance to all relevant legislation.

Bibliography

BSI, 2017. *Industrial valves. Metallic butterfly valves for general purposes*. [Online]
Available at: <https://shop.bsigroup.com/products/industrial-valves-metallic-butterfly-valves-for-general-purposes?pid=000000000030339484>
[Accessed 24 10 2021].

Carolo, L., 2020. [Online]
Available at: http://www.mscsoftware.com/sites/default/files/ds_msc-nastran-optimization_ltr_pt.pdf
[Accessed 15 10 2021].

Gandomi, A. H., 2013. *Metaheuristic Applications in Structures and Infrastructures*. 1st ed. Amsterdam: Elsevier.

Gary H. Koopmann, J. B. F., 1997. *Designing Quiet Structures*. 1st ed. Massachusetts: Academic Press.

Hexagon, n.d. *MSC Nastran™ Optimization*. [Online]
Available at: http://www.mscsoftware.com/sites/default/files/ds_msc-nastran-optimization_ltr_pt.pdf
[Accessed 16 10 2021].

ISO, 2021. *Industrial valves - Metallic butterfly valves*. [Online]
Available at: <https://www.iso.org/standard/78331.html>
[Accessed 24 10 2021].

Levia, J. P., 2013. *Topometry Optimization: A New Capability to Perform Element by Element Sizing Optimization of Structures*. [Online]
Available at: <http://www.vrand.com/wp-content/uploads/2017/06/Man20859.pdf>
[Accessed 16 10 2021].

Metrus, n.d. *Butterfly valve test bench*. [Online]
Available at: <https://www.metrus.de/en/test-benches/butterfly-valve-test-bench/butterfly-valve-test-bench-36t-dn500>
[Accessed 20 10 2021].

O'Donnell Consulting Engineers , n.d. [Online]
Available at: <https://www.odonnellconsulting.com/what-we-do/expert-witness-forensic->

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[engineering/forensic-engineering-expert-witness/history-of-fea/](#)

[Accessed 17 10 2021].