

OPTIMISING A BUTTERFLY VALVE DISC PLATE USING CARBON FIBRE REINFORCED PLASTIC WITH FINITE ELEMENT ANALYSIS

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1. Abstract

Primarily this report is to optimise a butterfly valve disc plate to achieve a maximum deflection of 0.1mm while trying to keep the weight as low as possible. The optimisation will be conducted through a finite element analysis software package. There are various parameters to be set up within the software to allow the design to be optimised efficiently. There will be careful considerations to the current British standards throughout the design and testing stage, especially with the accreditation of the valve to be PN2.5 rated. With the use of petroleum, careful consideration is made to ensure the valve is ATEX rated to withstand the risk of explosion. A prototype valve is to be tested with the data being acquired using the latest technology and compared to the theoretical analysis. This report will also investigate the different FEA methods and how these have developed over the years and how they can develop again in the future.

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5. Introduction

This paper will focus on the use of Finite Element Analysis to optimise a butterfly disc plate structure to meet a maximum deflection of 0.1mm. Butterfly valves can be used to start, stop, and regulate flow and are regularly used due to their low pressure drop through the valve (Menon, 2015). There will be comparison between steel and carbon fibre reinforced plastic (CFRP) to determine how efficient the design can be to determine the material selection for manufacture. The CFRP will initially be made from 25plys with 0.1mm thickness per ply. A ply is referred to the thickness of a CFRP layer which is then bonded together in a furnace to cure the epoxy to the carbon fibre to produce a light weight and incredibly strong material (F.Al-Mahmoud, 2018). The design will be optimised using a CAE software, Design Studio, to calculate the thickness at each orientation to show how the valve should be manufactured. This paper will discuss the different FEA optimisation techniques available and how FEA has developed over the years. The future of this analysis will be discussed and how it can be integrated with the current and future industrial revolutions. There will be a discussion on prototype testing and recommendations on how the test should be set up along with the acquisition of data and how the theoretical and physical analysis should be compared. Finally, the consideration of current British standards is considered within the design and testing phases to ensure compliance of the valve as well as receiving the relevant marking to be able to be used in British industries.

6. Finite Element Analysis Developments

6.1 Development of Finite Element Analysis

6.1.1 History of Finite Element Analysis

Over the last eighty years, the use of Finite Element Analysis (FEA) has become increasingly important as technology improves. The integration of FEA into FEM (Finite Element Method) was first adopted in the 1940's which allowed General Motors (GM) and IBM to develop a computer system called DAC-1 (Design Augmented by Computers) to facilitate the designs of cars (Crahmaliuc, 2020) (Moaveni, 1999). This led to NASA developing their own structural analysis solver tool called NASTRAN (NASA Structural Analysis). By the late 1960's the first commercially available version of NASTRAN which was known as the 'first generation of FEA software' (Actis, 2018). By 1999 this software was chosen to replace the current analysis tools for composite aircraft structures. This allowed NASA to implement standards for modelling and simulations which are still followed in the current industry codes of practice (Tipton, 2017) (Crahmaliuc, 2020). Historically, a concept design would be hand drafted and considerable time would be allocated for the designing. This would require appropriate tooling to be manufactured to allow the design to be produced (Dyi-Cheng Chen, 2018). Only once the design had been manufactured would it be subject to any testing, thus, only during this stage could errors be identified, which would lead to repeating this process until an optimised design was produced. This approach was very lengthy and a costly process as where the model '7 wastes' can be used to identify the wastes in this process to allow improvements to be made (A.Gnanavelbabu, 2014).

6.1.2 CAD Vs CAE Led Optimisation

This process was initially improved by being computer aided drawing (CAD) led in the design stage. This would entail a detailed 3D CAD model being modelled and then assessed using CAE. From the results of the CAE the design would be modified, and this process would be repeated until an optimised design was finalised (Zitzewitz, 2021). This design would be manufactured and testing to ensure its compliance. Compared to historical methods, this was seen as a major improvement for this process.

Finally, by being CAE optimisation led, a concept can be produced and optimised to meet the criteria of the customer before any manufacturing takes place. Once approved by the customer, the concept can be 3D modelled effectively which then can be manufactured, tested, and approved. This process has the greatest time saving affects, in return reduces the amount of costs occurred for this process due to the reduction in labour and tooling costs (Belhe, 2014).

6.1.3 Future of Finite Element Analysis

The future of FEA optimisation will be the integration to new industrial revolutions along with being able to be used in the additive manufacturing markets and utilising multi-materials. The ability to optimise a concept and 3D the concept could take as little as a day, depending on the size of the component, which will streamline the process even more than what it is today (Wood, 1992). The limitations that are currently not solved are multi-material topology optimisation, fluid-structure topology, and fluid-thermal topology. With the incorporation of these aeras, coupled with additive manufacturing (AM) the next generation and manufacturing using artificial intelligence is not far (Roade, 2020) (Gameros, 2015).

6.2 Finite Element Analysis Techniques

There are several CAE optimisation techniques available, however the most common is topology optimisation which is integrated within design studio which will be used to optimise a butterfly disc plate. Topology optimisation is a mathematical method to spatially optimises the distribution of material within a defined domain. The mesh created of the design space is analysed for stress distribution which informs how different sections of a design are exposed to different strain energies (Inês P. Rosinha, 2015). This process will create more efficient and cost-effective components. However, the manufacture of these components will be expensive due to additive manufacturing needing to be utilised (Velling, 2020). Alternatively, topography optimisation allows shapes to be optimised to improve structural integrity. Topography is a similar FEA method to topology where the major difference is the elements are offset from the components mid-plane whereas in topology the weight is altered at various sections. Both methods can include composite or steel materials to determine how their properties are affected when subjected to applied stress (Pagadala, 2015). The optimisation algorithm can be defined in *figure 1*.

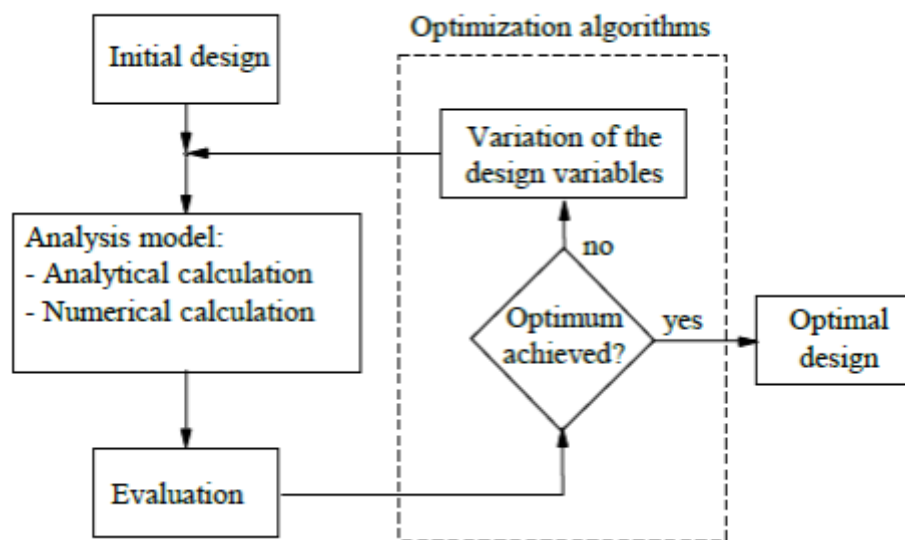


Figure 1 - Optimisation loop algorithm (Altair, 2015)

7. Creating A Baseline Model

7.1 Calculating the Force Required

To calculate the maximum deflection of 0.1mm occurring on the butterfly disc plate the maximum force of the fluid needs to be calculated. Considerations need to be made to ensure the valve complies with the current industry standards. The area (A) is calculated by multiplying pie (π) by the squared radius (r), which is seen in equation two. Thus, a pressure of 250,000 $\frac{N}{m^2}$ (2.5 bar) produced a maximum force equal to 8,250N. By using this pressure, the valve would be classed as 'PN2.5' where PN is the equivalent to bar which is recognised in the UK industry (Haihao, 2020). The full calculations for normal and maximum operating force can be seen in A.

$$\text{Hydrostatic Pressure } (P_h) = \text{Density } (\rho) \times \text{Gravity } (g) \times \text{Header Pressure } (h)$$

Equation 1 - Hydrostatic Pressure

$$\text{Area } (A) = \text{Pie } (\pi) \times \text{Radius Squared } (r^2)$$

Equation 2 - Area Equation

$$\text{Force } (F) = \text{Hydrostatic Pressure } (P_h) \times \text{Area } (A)$$

Equation 3 - Force Equation

7.2 Setting Up the Baseline Model Properties

Edit a Material : 2-D Orthotropic Properties	
E_1:	1.32E+11
E_2:	1.08E+10
Nu_12:	0.24
G_12:	5.65E+9
G_13:	5.65E+9
G_23:	5.65E+9
Rho:	1540.0
A_1:	0.0
A_2:	0.0
Tref:	0.0
GE:	
F12:	
☒ Stress Limits ☐ Strain Limits	
Xt:	1.513E+9
Xc:	1.E+9
Yt:	4.34E+7
Yc:	4.34E+7
S:	4.34E+7

Figure 2 - Material Properties for Carbon Fibre Reinforced Plastic

Within the NASTRAN deck provided, the fixed points were set along the centre of the disc plate spanning 56mm which is centralised as well as the material being set to steel. These material properties are required to be changed to represent carbon fibre reinforced plastic (CFRP). This can be achieved by defining a new material within the materials section. As CFRP is a composite material, it is defined as 'MAT8/PSHELL/PCOMP' which defines the algorithm for orthotropic materials. The properties for CFRP can be seen in *figure 2*. In *appendix B* an in-depth description of the properties can be found.

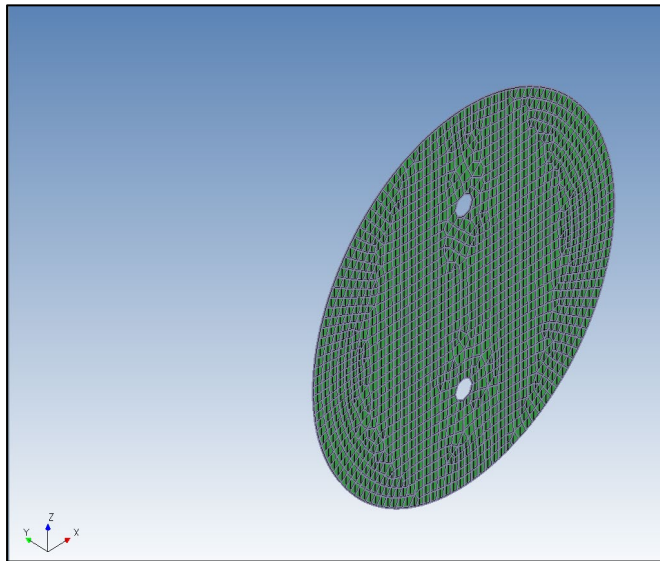


Figure 3 - Orientation of Vectors

To ensure the accuracy of results, it's important to ensure the element properties are in the correct orientation as per the requirement in the specification. This is done within the elements section which allows the elements theta to be changed to the Z plane, which can be seen in *figure 3* and *appendix C*.

< Back Next > Finish Cancel

Edit a Group : Choose Composite Property Values

Name: UD

Z0:

Nonstructural Mass: 0.0

Tref:

GE:

Interlaminar Shear Limit:

Failure Theory: None

Laminate: All Plies

Type: Regular

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

Figure 4 - Set up of layers

Another requirement is to set the correct thicknesses along with the different angles for the composite material, where the angles determine where the location of the material is distributed. The material is to be set up at -90degrees, -45degrees, 0 degrees, 45degrees and 90degrees to allow the material thickness to be constant throughout the disc plate baseline model. The thickness will be comprised of 25 plies where 1 ply is 0.1mm, which means there will be a total of 0.5mm at each angle, which is seen in *figure 4*. Thus, this disc plate will have a total thickness of 2.5mm.

With these parameters set, a single analysis operation can determine the deflection occurring based on the information applied, as well as the ability to calculate the mass of the disc plate. This allows the steel and CFRP baseline models to be compared to determine how the material properties impact deflection. In *table 1*, the baseline results show steel is nearly three times more efficient compared to the CFRP baseline. This is due to the thicknesses of the materials. Steel is roughly two and a half times thicker than the composite which results in the deflection being over three times greater in the composite. However, the composite is twelve times lighter than steel, which will allow CFRP to be optimised to reach the desired deflection.

Run	Material	Thickness (mm)	Deflection (mm)	Mass (g)	Load (N)	Stiffness (N/mm)	Stiffness/weight (N ² /mm)
Steel Baseline	Steel	6.00	0.190	1514	8250	43421	2924
CFRP Baseline	Carbon Fibre Reinforced Plastic	2.50	6.400	125	8250	1289	1050

Table 1 - Comparison of results between steel and CFRP baseline

In *figure 5*, a summary of the displacement is seen with the outer region of the disc plate experiencing the greatest deflection. This is as expected as the securing pins in the centre of the disc plate increase the stiffness at the centre region.

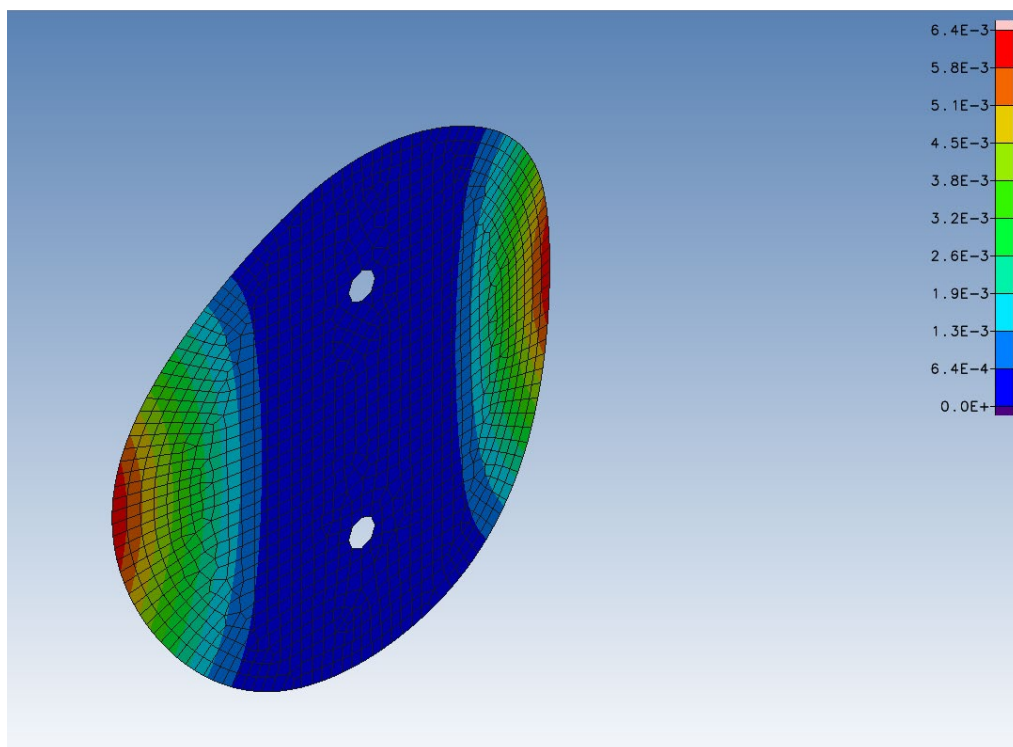


Figure 5 - Displacement of disc plate

8. Optimising The Disc Plate

Edit Design Objective : Enter Name and Type

Name:

Response Type

☒ Mass
☐ Volume
☐ Strain Energy
☐ Displacement
☐ Stress
☐ Grid Stress
☐ Failure Index
☐ Buckling Load Factor
☐ Frequency Mode Number
☐ Reaction Force (SPCF)
☐ Von Mises Index
☐ Synthetic Response
☐ More Response Types...

Objective Definition Switch

☐ Max
☒ Min
☐ Target

Weight:

Figure 6 - Objectives set up

Edit Design Constraint : Enter Name and Type

Name:

Response Type

☐ Mass
☐ Volume
☐ Strain Energy
☒ Displacement
☐ Stress
☐ Grid Stress
☐ Failure Index
☐ Buckling Load Factor
☐ Frequency Mode Number
☐ Reaction Force (SPCF)
☐ Von Mises Index
☐ Synthetic Response
☐ More Response Types...

Constraint Bounds

Lower Bound:

Upper Bound:

Bound Type: ☒ Actual ☐ Scale of Initial

Allowed Fail Probability:

Figure 7 - Constraints set up

Design Variables	
Description	Name
I ID=1 Init=0.001 [1.E-4,0.003]	L1THK
I ID=2 Init=0.001 [1.E-4,0.003]	L2THK
I ID=3 Init=0.001 [1.E-4,0.003]	L3THK
I ID=4 Init=0.001 [1.E-4,0.003]	L4THK
I ID=5 Init=0.001 [1.E-4,0.003]	L5THK

Figure 8 - Summary of variables

To be able to optimise the structure, there are three key parameters to define. These are objectives, constraints and variables must be set. The first objective to be set is the mass of the disc plate which requires to be as light as possible. This is reflected in figure 6 which shows the mass being set to minimum.

The constraint for this disc plate is a maximum deflection of 0.1mm. This constraint is added under the displacement section to set the 'upper bound' area to 1.e-4m and is seen in figure 7. The parameters used must be in international system (SI) units to ensure accurate results.

Finally, the design variables need to be established. The initial value is set to 1mm and with the thickness of the plys being 0.1mm this will be the lower bound parameter. The upper bound parameter is set to 3mm as this determines the maximum thickness. This can be seen in *appendix D*. This needs to be applied to the five thickness parameters being used. As seen in figure 8, the 'I' denoted in the description represents "Independent variables".

Run	Material	Thickness (mm)	Deflection (mm)	Mass (g)	Load (N)	Stiffness (N/mm)	Stiffness/weight (N2/mm)
Steel Baseline	Steel	6.00	0.190	1514	8250	43421	2924
CFRP Baseline	Carbon Fibre Reinforced Plastic	2.50	6.400	125	8250	1289	1050
CFRP Optimised	Carbon Fibre Reinforced Plastic	10.15	0.100	512	8250	82500	16411

Table 2 - Results from optimised analysis

Table 2 above shows the results from the optimised analysis compared to the CFRP and steel baseline. The results show the constraint has been achieved with the deflection being 0.1mm. However, to meet the constraint, the thickness of the structure has increased significantly (409%). The thickness of this structure is over four times greater than the CFRP baseline design and over one and a half times greater than the steel model. Although, this optimised structure is three times lighter than steel but twice as heavy as the CFRP baseline. Overall, the efficiency of this model is over sixteen times greater than the baseline model and just under six times better than steel. The model to show the deflection occurring on the disc plate can be seen in *appendix E (13.5.4)*.

Optimised – Independent Variables				
Design Cycle	Angle	Thickness (m)	Thickness (mm)	Thickness (plys)
12	-90	0.003	3	30
12	-45	1.33E-03	1.328118	13.28118
12	0	1.47E-03	1.470187	14.70187
12	45	1.36E-03	1.355	13.55
12	90	3.00E-03	3	30
Total		0.010153305	10.153305	101.53305

Table 3 - Optimised analysis thickness results

Table 3 above shows how the disc plate is to be constructed with the different thickness at different sections of the disc plate. As it can be seen, it is proposed the construction is to be manufactured with a total of 101.153305 plys, which isn't possible as the plys must have a whole number to be manufactured. These layers can be seen in *appendix E (13.5.1 – 13.5.3)* along with how the violation occurs per design cycle.

8.1 Discrete Optimisation

Although, the results show the targets have been met, there has been no manufacturing considerations, as seen in table 3. This means the design variables need to be changed from independent variable to discrete variables. The first discrete variables to be set is 1e-4m with an increment of 1e-4m. Within the design variables section, the summary of variables would show a 'D' instead of 'I' to represent discrete variables being active.

By optimizing the design with discrete values, more accurate values are produced in respect to manufacturing considerations. The only difference in this optimization is when the software realizes the discrete values are met. The optimized independent and discrete values are the same up until design cycle 12 where the independent variables stop, and the discrete variable get altered to consider the manufacturing aspect.

Run	Material	Thickness (mm)	Deflection (mm)	Mass (g)	Load (N)	Stiffness (N/mm)	Stiffness/weight (N2/mm)
Steel Baseline	Steel	6.00	0.190	1514	8250	43421	2924
CFRP Baseline	Carbon Fibre Reinforced Plastic	2.50	6.400	125	8250	1289	1050
CFRP Optimised	Carbon Fibre Reinforced Plastic	10.15	0.100	512	8250	82500	16411
CFRP Discrete	Carbon Fibre Reinforced Plastic	10.60	0.090	535	8250	91667	17466

Table 4 - Optimisation using discrete values

In table 4, the structure has been re-optimised to suit the manufacturing tolerance. This has resulted in the thickness and mass increasing slightly. The deflection shows it is just under the target meaning there is potential to reduce the thickness of the design. It also shows the efficiency of the design has increased with the stiffness to weight ratio increasing marginally, but roughly six times more efficient than steel. The full design cycle can be seen in *appendix F (13.6.4)* to show how the design violation and objectives are met per design cycle.

Discrete				
Design Cycle	Angle	Thickness (mm)	Thickness (mm)	Thickness (plys)
14	-90	3.00E-03	3	30
14	-45	1.50E-03	1.5	15
14	0	1.60E-03	1.6	16
14	45	1.50E-03	1.5	15
14	90	3.00E-03	3	30
Total		0.0106	10.6	106

Table 5 - Manufacturable thickness from discrete optimisation

Table 5 shows how the ply layers have adjusted to whole numbers due to the software considering the manufacture tolerances based on the information provided. The full design cycle for this thickness can be seen in *appendix F (13.6.1 – 13.6.3)*.

9. Prototype Testing

The purpose of carrying out prototype testing is to prove the performance of the disc plate against theoretical simulation to ensure it can meet the performance required and the valve is free from cracks, loose pores and slag which all affect the strength of the valve (Bradley, 2020) (Testing, 2020). As the flow has been calculated to be turbulent, this causes varying velocities through the pipe which different parts of the disc plate are subjected to different number of forces being applied.

Before conducting any testing, safety should be taken into consideration. As petroleum is being used, there are harmful risks involved such as skin irritation which means appropriate personal protective equipment should be used.

To acquire the amount of force required to certify the valve as PN2.5, ideally a replica of its intended purpose would be used. However, this wouldn't be feasible as the header pressure required would be 31m. There are two methods that can be used, pneumatic pressure testing or the use of pistons to hold fluid pressure in the line.

The use of pneumatic testing, normally in the form of compressed air can achieve very high pressures within a valve. However, this wouldn't be able to replicate how the fluid flow would behave and is also a costly option (Dey, 2014).

On the other hand, the use of pistons to hold the pressure within the valve will give the closest to a 'like for like' comparison. The fluid will be compressed in the valve using the piston. It is advised to have the valve in the closed position and then to pressure the system, with a blanking attachment on the other end of the valve. With the line pressurised, begin to remove the blank to see if any fluid is bypassing the valve (REGULA, 2019). This should be repeated several times with any fluid bypassed being recorded. A schematic of the set up can be seen in *figure 9*.

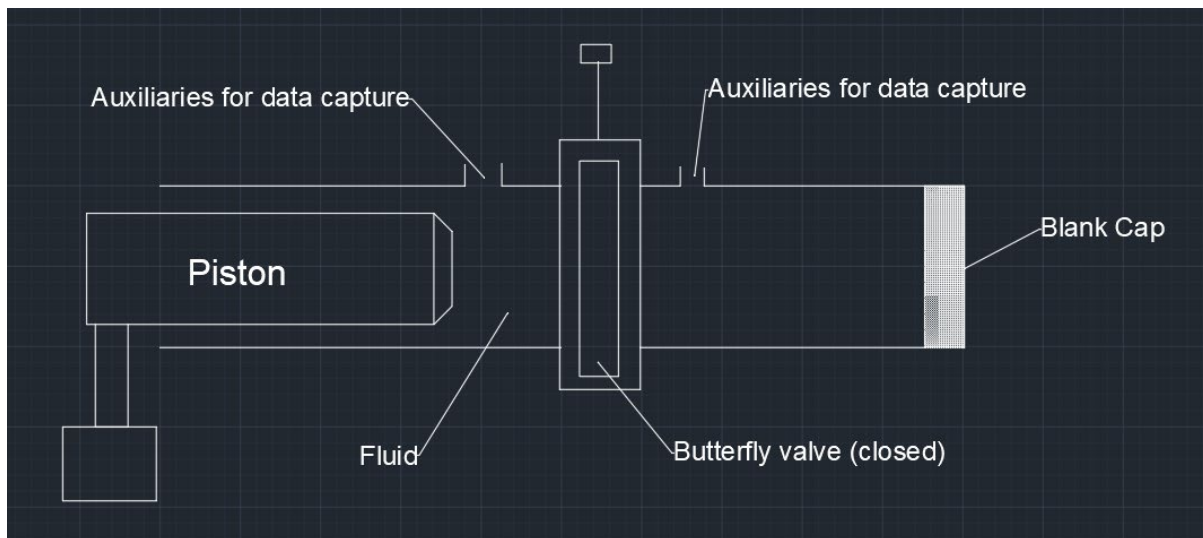


Figure 9 - Schematic of the test up utilising a piston

Secondly, a centrifugal pump with a tank of petroleum should be used to test the fluid flow through the valve. The reason for this test method is to conduct cyclic testing to understand how affective the valve isolation is when required to be open and closed repeatedly. This will give an indication of the wear on the plate. By closing the valve with fluid flowing through, it can demonstrate the disk plate can handle the forces that are generated during a sudden closure which may include the water hammer phenomenon (Conzen, 2019).

With the evolution for data capturing, there are various sensors and instrumentation that can be used compared to the conventional methods. By using sensors to capture data, it produces more accurate results as well as logging more data points and this is directly linked with industry 4.0. By using automation, it eliminates the time for manual data recording, which can be a lengthy process as well as human error. It is recommended that pressure transducers, flow and temperature sensors are used to log real time data which is relayed to a database by an electrical signal which will create meaningful data. The benefit of using sensors during testing is it allows prevention of significant failures by the sensors having warning sensors if the fluid is out of the set parameters (Kayer, 2019).

With all the data that has been gathered, the results from the prototype testing should be compared to the theoretical analysis to see if there are any differences between the simulation and the physical testing. If no problems are raised, then the prototype can be awarded its PN2.5 accreditation.

10. Legislation Compliance

As of January 1st, 2021, any manufactured component within the United Kingdom must conform to and be issued with the UK Conformity Assessed (UKCA) marking, which replaces the CE marking directive due to Brexit (Gov, 2020). This ensures the design and manufacture complies to the UK standards which is deemed safe for practice.

10.1 Chemical Environments

As the butterfly valve will have petroleum flowing through the valve, there is a risk of explosion due to the corrosive risk that is associated with petrol. This means the valve needs to be rated to withstand the resultant pressures if an explosion was to occur due to the ignition of the petroleum. Thus, the compliance with ATEX is required to allow the valve to always operate safely which the UK have implemented 'Directive 99/92/EC' (Commission, 2014) for the minimum requirements for protection. This directive was implemented through the 'Dangerous Substances and Explosive Atmospheres Regulations 2002 (DSEAR)'. To ensure these standards are being followed, the Petroleum Enforcement Authorities (PEAs) are responsible for enforcing the regulations as well as issuing certificates.

10.2 Design Standards

When it comes to designing butterfly valves, it is important to incorporate the relevant and current standards to ensure the safety when in operation. For the use in petroleum industries the following standards should be incorporated into the design. For general requirements such as material standards and thicknesses for a PN2.5 valve and the assumption the disc plate is concentric, BS EN ISO 10631:2021 requirements need to be met to ensure safe operation. This standard is very similar to BS EN ISO 593:2017 where the main difference between these standards is that the regulation states "*manufacturer technical documentation shall specify all necessary dimensions*" (BSI, 2017). Similarly, BS EN 558:2017 specifies the "face-to-face" (FTF) and "centre-to-face" (CTF) dimensions for PN designed valves. As this valve has been designed to PN2.5 this results in the surroundings of the valve needing to comply with this standard. Also, BS EN ISO 10423:2019 - (Under development) gives recommendations for performance, design, materials, testing and inspection. Within this standard, there are a range of classifications the valve must conform to. From the assumptions in the design of the temperature being around 22°Celsius, the temperature classification 'P' would be provided under this standard (BSI, 2019).

10.3 Testing & Performance

The testing of the valve is the most important sequence as this will highlight any failures in the design. BS EN ISO 12266-1:2012/ISO 9393-1/ ISO 9393-2 –Specifies the test requirements, procedures, and acceptance criteria. This standard was incorporated into the testing method in section nine of this report. Also, BS EN ISO 15848-1:2015 / AMD 1:2017 specifies the classification system and qualification procedures for testing valves. Although this standard is more suited to main line production, it is recommended the test procedure is in conformance with the prototype valve. The standard provides a recommended test procedure to ensure the valve is free from leaks. A certificate of conformance must be produced after a successful test period and state the results of the test.

11. Conclusion

From the data provided in this report, it is clear to see how important FEA is to engineering simulations. The development of FEA has accelerated over the years to improve the design cycle process to reduce the time associated with labour and reduction in tooling costs which results in the overall process being more cost effective when being CAE led. The future of this design cycle is exciting with the integration of industry 4.0 along with utilising additive manufacturing methods. It has also been proven how more efficient CFRP is compared to steel. CFRP was proven to be six times more efficient than steel due to the weight of CFRP being a fraction of steel. When comparing the optimised CFRP model to the steel baseline model, the thickness of CFRP was nearly doubled to that of steel. The importance of prototype testing when creating new models is key to understanding if there are any discrepancies from the theoretical calculations compared to the physical testing. By designing and testing the valve to 'PN2.5' this allows the figure to be engraved on the valve to show it complies to the British standards that are associated with the pressure nominal value. By acquiring data through industry 4.0 methods, it removes the human error factor for the data collection. It also allows for more data point to be recorded along with live data to be seen to prevent failures occurring. As this valve is to be used within petroleum environments, the valve should be ATEX rated to ensure the safety if an explosion was to occur. Further to this, the valve also needs to comply with the relevant British standards that cover the design, testing and acceptance of the valves disc plate.

12. References

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13. Appendix

13.1 Appendix A – Pressure, Area & Force Calculations

It is known that this butterfly valve would be inserted into a pipeline which is at the base of a 5m high storage tank which contains petroleum at atmospheric pressure. Using equation one, the hydrostatic pressure (P_h) can be calculated by multiplying the density (ρ) of the fluid by gravity (g) and by the height (h) of the fluid from the surface.

13.1.1 Working Hydrostatic Pressure

$$P_h = \rho \times g \times h$$

$$P_h = 800 \frac{kg}{m^3} \times 9.91 \frac{m}{s^2} \times 5m$$

$$P_h = 39240 \frac{N}{m^2}$$

13.1.2 Area of Disc Plate

$$A = \pi r^2$$

$$A = \pi \cdot (0.1025^2)$$

$$A = 0.033m^2$$

13.1.3 Working Force Applied

$$Force (F) = Hydrostatic Pressure (P_h) \times Area (A)$$

$$Force (F) = 39240 \times 0.033$$

$$F = 1295 N$$

It has been assumed the working head pressure will not exceed 5m as well as the temperature remaining constant at room temperature (22°C).

13.1.4 Maximum Applied Force (PN2.5)

$$PN2.5 = 2.5bar = 250,000 \frac{N}{m^2}$$

$$Force (F) = Hydrostatic Pressure (P_h) \times Area (A)$$

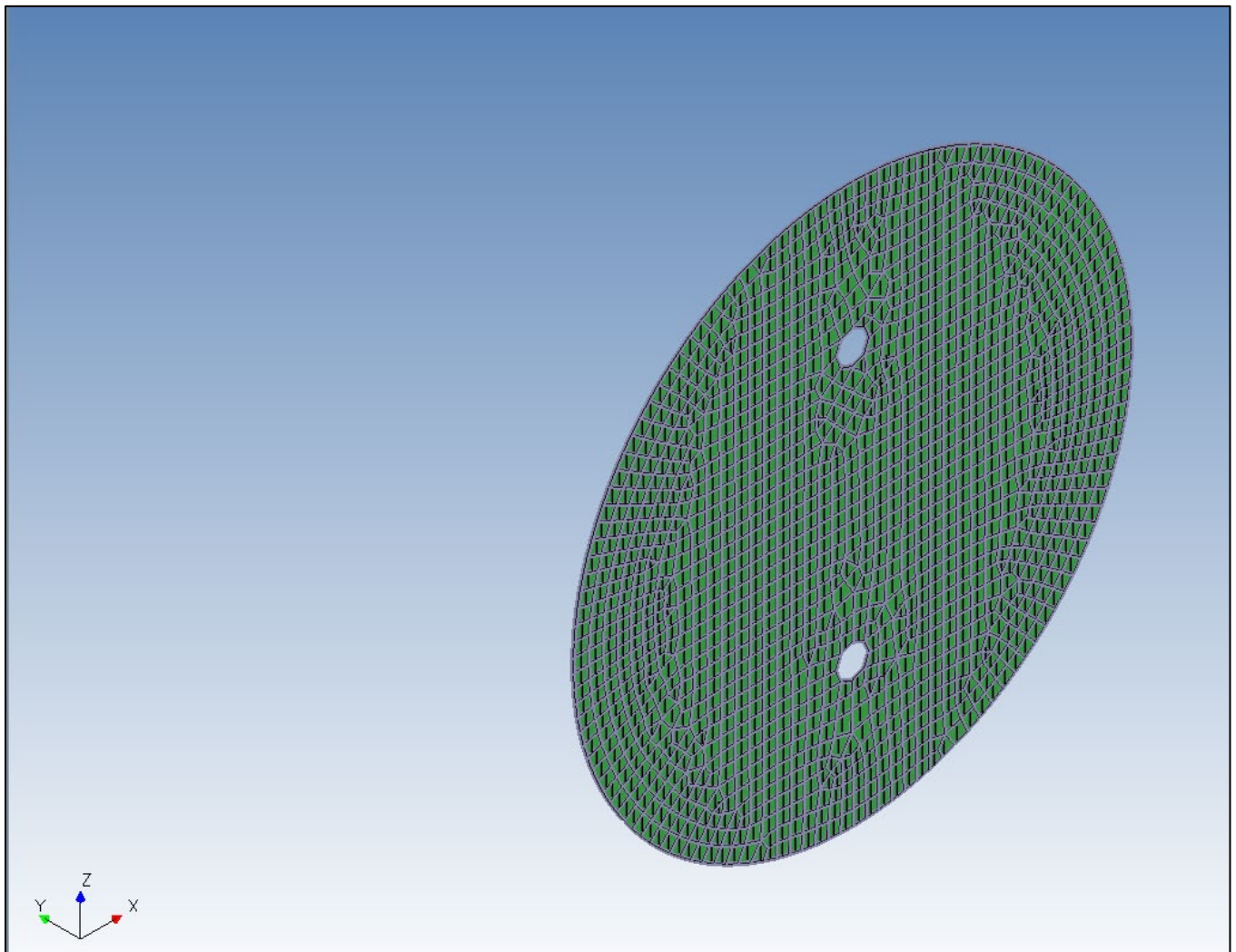
$$Force (F) = 250,000 \times 0.033$$

$$F = 8,250N$$

13.2 Appendix B – Carbon Fibre Reinforced Plastic Material Properties

(E_1) is the Young's Modulus in the longitudinal direction and (E_2) being the Young's Modulus in the lateral direction, which determines the stiffness across the disc plate. Poisson's ratio (ν_{12}) determines the ratio of change when being under uniaxial tension. The rigidity of the material is defined by In-plane shear modulus (G_{12}), transverse shear modulus (G_{1z}) and (G_{2z}) with the mass density being ρ .

13.3 Appendix C – CFRP Baseline Vector Orientation in the Z Plane



13.4 Appendix D– Design Variable Set Up

Design Variables ▼

< Back Next > Finish Cancel

Manage Design Variables : Choose Design Variable Bounds

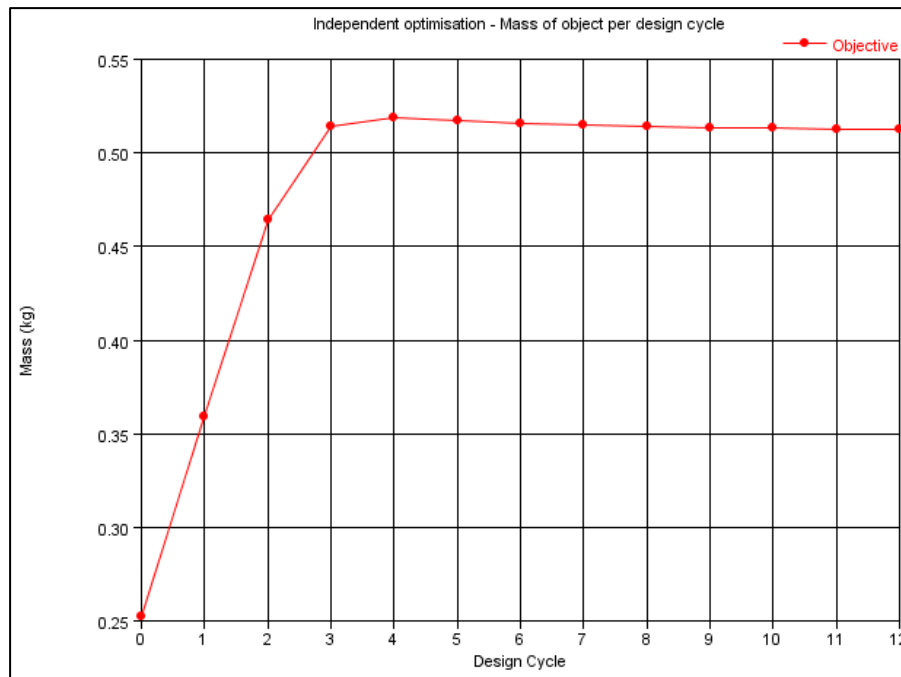
Initial Value :	0.001
Lower bound:	1.E-4
Upper bound:	0.003

Advanced Parameters...

13.5 Appendix E – Independent Optimisation

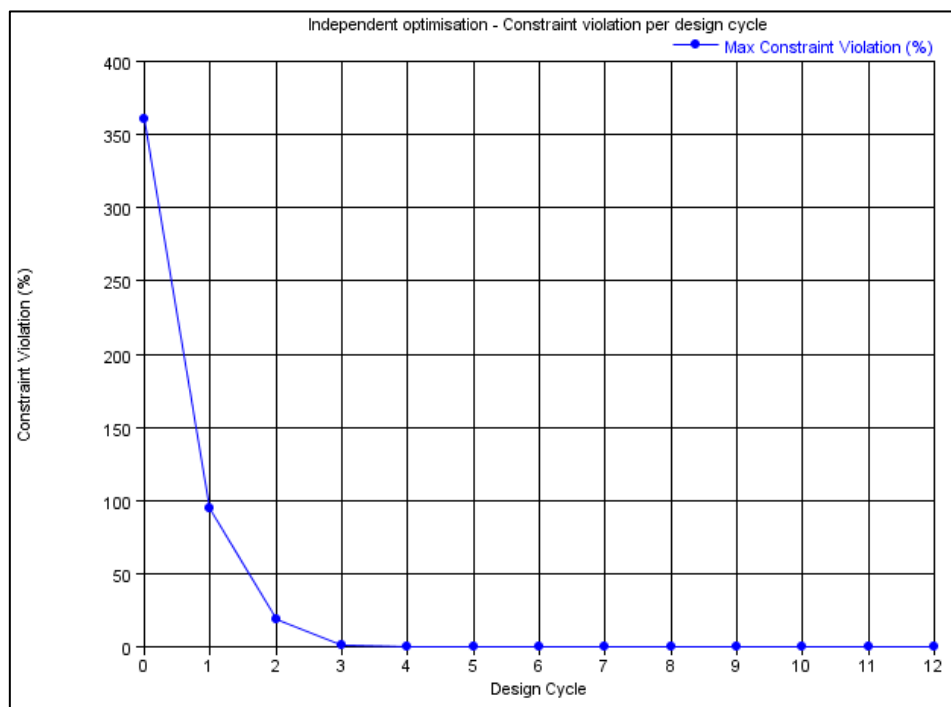
13.5.1 Objective – Mass Restriction

The below image is showing how the mass must increase to reach a maximum deflection of 0.1mm. In design cycle one, the mass is at its lightest (125g) and by design cycle 12 the mass is 512g.



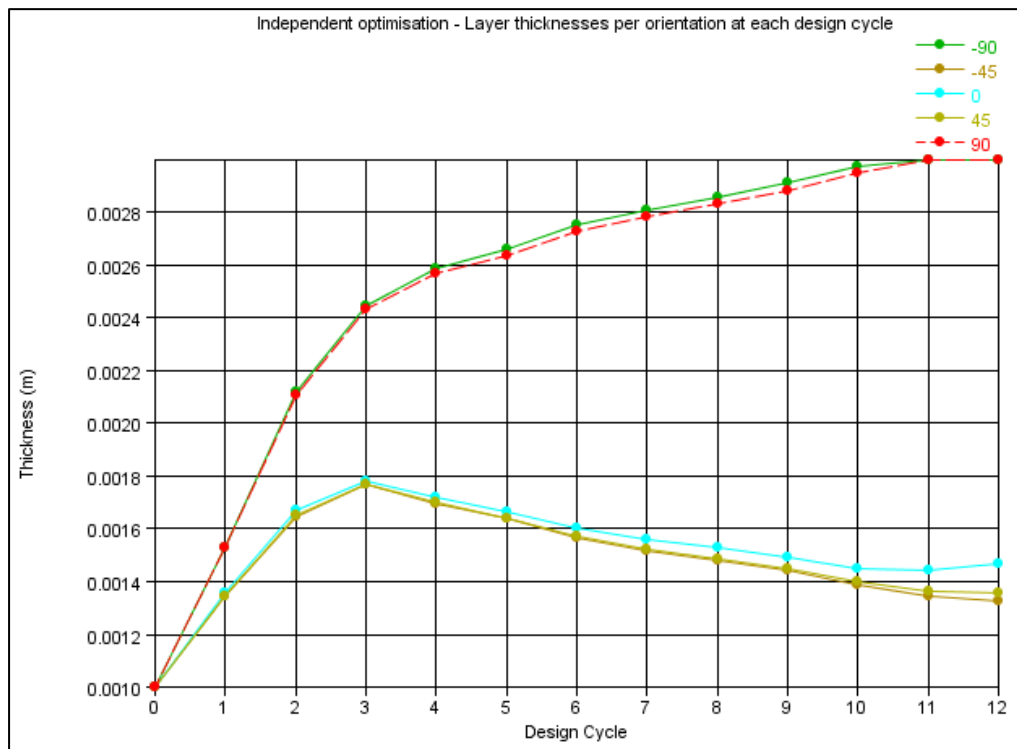
13.5.2 Constraint Violation

During the optimisation, the baseline structure was violating the constraint by 360.2% in design cycle 0. However, by design cycle 12 the violation was 0%.



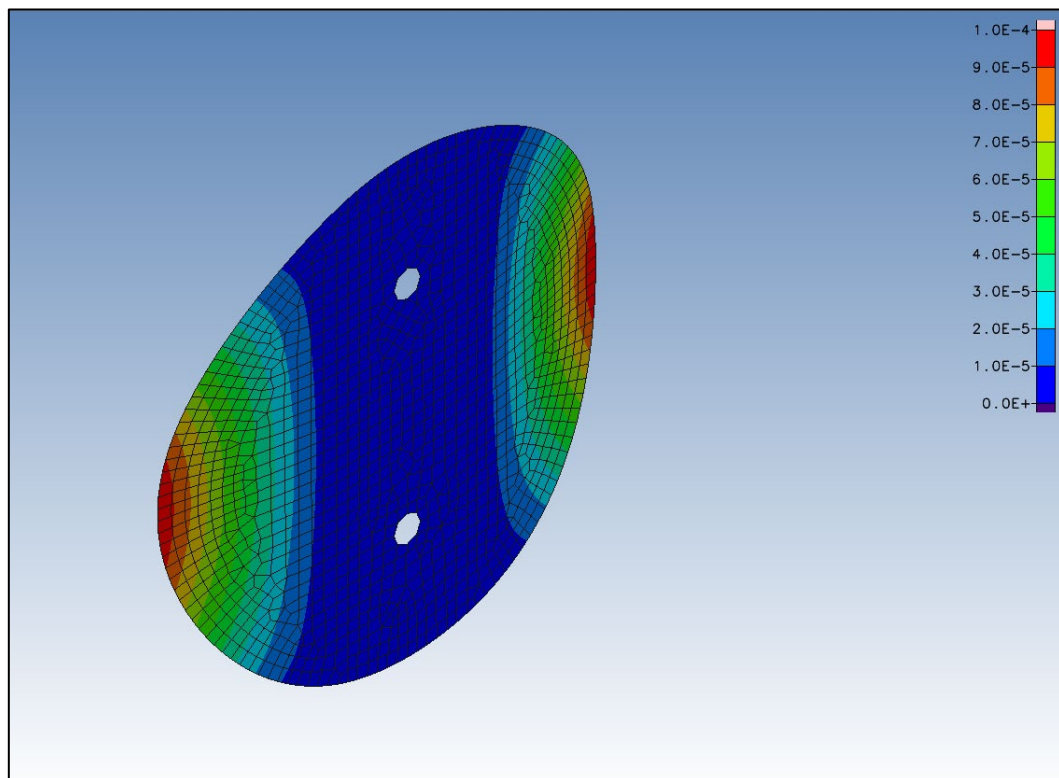
13.5.3 Independent Design Variables Thicknesses

As expected, the thicknesses have increased from 0.1mm to their desired thickness, with some being 3mm thick.



13.5.4 Deflection of Disc Plate During Independent Optimisation

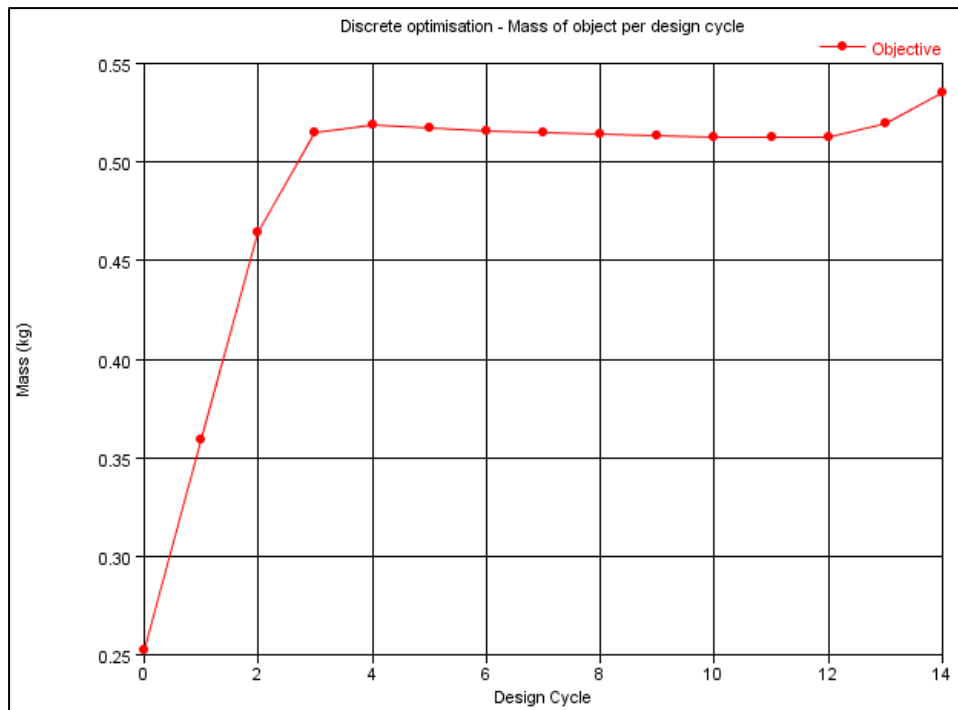
The below figure shows the deflection occurring on the disc plate. The goal of 0.1mm maximum deflection has been achieved.



13.6 Appendix F – Discrete Optimisation

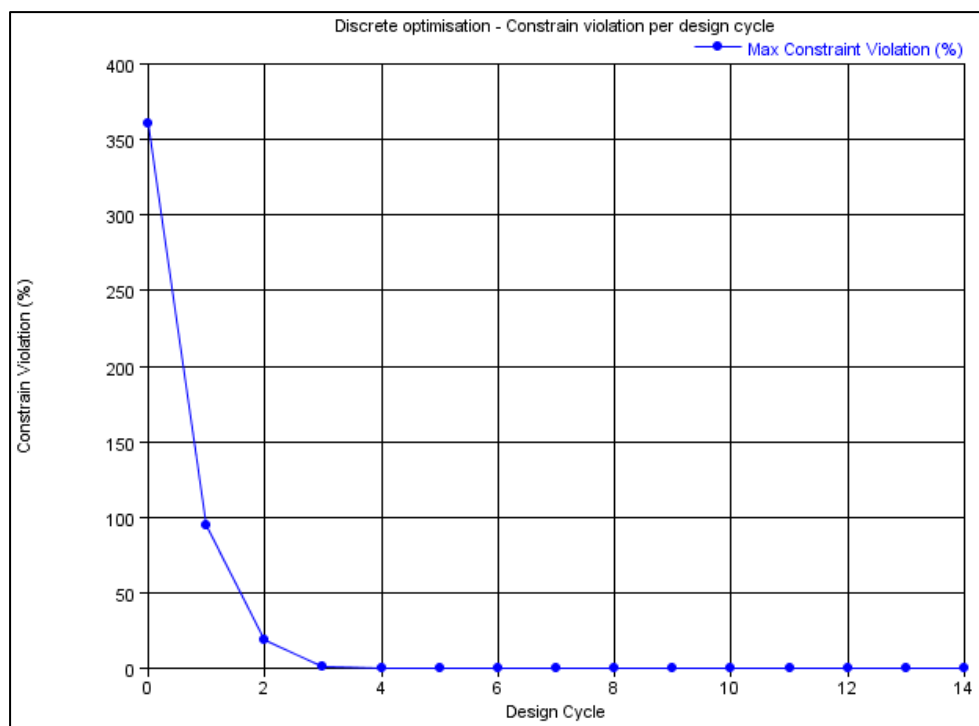
13.6.1 – Objective – Mass Reduction

This figure shows how two additional design cycles are required to consider manufacturing tolerances which increases the mass slightly.



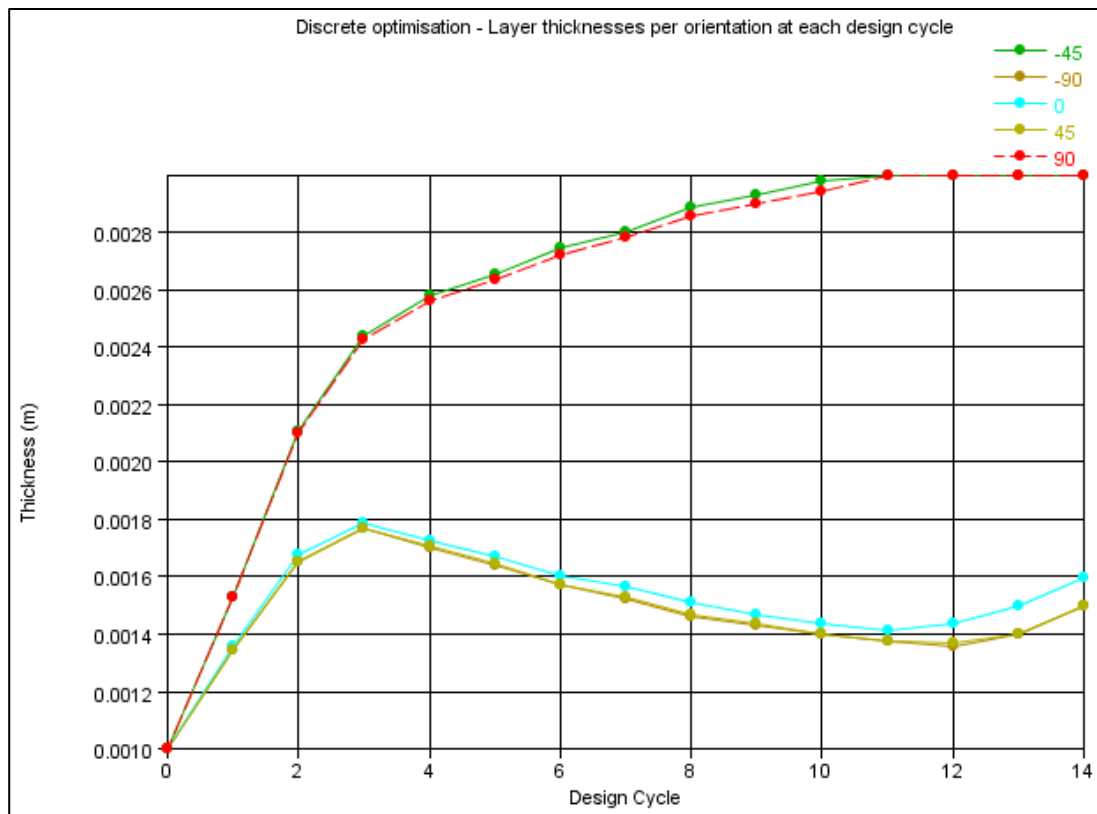
13.6.2 Constraint Violation

Although there are two additional design cycles, there is no further constraint violations.



13.6.3 Discrete Design Variables Thicknesses

There are no major thickness changes from the independent optimisation.



13.6.4 Deflection of Disc Plate During Discrete Optimisation

The maximum deflection occurring has dropped by 0.01mm due to manufacturing tolerances being considered. There is a potential the weight of the plate could be reduced.

