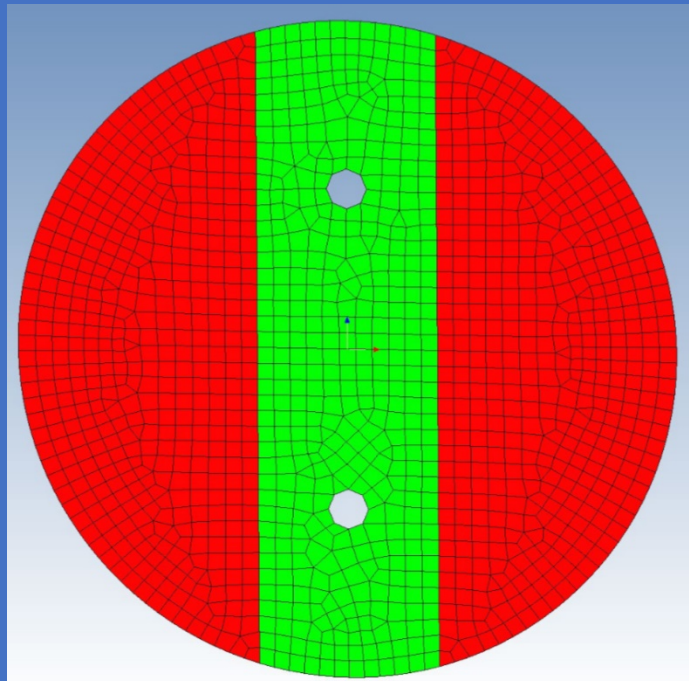


DESIGNING A BUTTERFLY VALVE: STRUCTURAL DESIGN



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ACMA6010 Structural and Fluid Analysis

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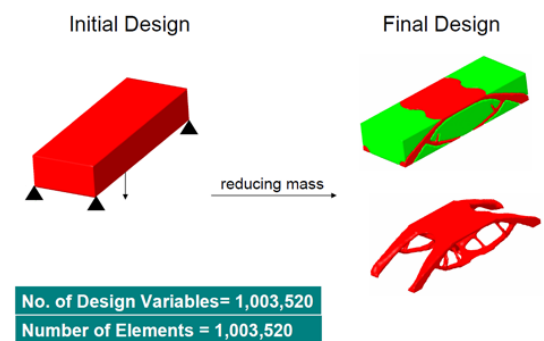
1. Introduction

The purpose of this report is to design and optimise the Carbon reinforced plastic butterfly valve plate with the use of design studio and genesis, running multiple cycles displaying, through the use of topology optimization software, what thickness each layer of CFRP plies should be to produce the strongest manufacturable component whilst also being the lightest. The component will go through 4 individual design phases to present the components evolution from a steel manufactured baseline component to a fully optimised and manufacturable carbon fibre reinforced plastic component which will be both stronger and lighter. However, before doing this it is important to outline what optimization is and how its is used throughout various different industries and how its has evolved into many different adaptations of itself. Also, how optimisation is used in many different project timelines, through CAD led design project processes vs Optimisation led Design project processes, outline the benefits of the latter design project process and finally, what it (FEA Optimisation) may develop into in the future.

Finally, continuing on with the development of the cfrp component, after the plate has been manufactured will be to explore how it would be real world tested. Exploring how real-world testing is carried out by manufacturers and governing standards and practices and how the component that has been optimized within this report should be tested. Also exploring how data is acquired and how it should be displayed and relating this back to the simulation produced in the Genesis software and creating valuable and reliable comparison between the two separate data acquisitions.

2. FEA Optimisation

Finite Element Analysis Optimisation is used throughout many different industries for predominantly the same thing, producing a final product that is the most efficient/lightweight or stronger than a designer or manufacturer requires and/or desires. “From its broadest definition, optimization is simply a process to make something as close to perfect as possible” (Gooch, 2021). FEA Optimisation can be done through hand calculations or through the process of computer aided optimization. Software packages such as ANSYS, Autodesk CFD, Solidworks & Design Studio all have some form of Finite Element Analysis available and are used by many different sectors. Before these packages were even readily available and accessible as they are now, all projects were basically produced and tested through “Trial and Error”. A project would go through the basic design phase into manufacture and then testing. This process would be repeated time and time again until complete component failure was not achieved, and the standards of the engineer had been met. FEA was first developed in the 1950’s by Boeing in the Aeronautical industry however the first free FEA software did not come about until the 1960’s (Tipton, 2014). The software that is used to display the results in this report is based on NASTRAN, the software developed by NASA in 1965 to aid in the space race.



More recently, in industry now, although the same packages and software is used, how they are used is very different, most will begin a new project through CAD led design and not through optimisation led design (Gooch, 2021). CAD led design as the name suggests is the process of running a project from the design stage into the computer aided analysis stage back into design stage, back into analysis stage and so on and so forth until the component is to the engineers desired strength, weight or whatever precise specification they may require, then progressing on to the manufacturing stage and then in nearly all cases the real-world testing phase and finally onto full scale manufacture (Gooch, 2021). This CAD led design process is much longer compared to Optimisation led design. Optimisation led design again is as the name suggests, contrary to CAD led, it is optimisation led. Optimisation led design process begins with finding the perfect form of the desired component and then moving onto the full design process (Gooch, 2021). It produces a much more efficient project as the time scale is a lot shorter as there is no need for redesign in cad and then a reassessment using the FEA software every time, this is already carried out beforehand (Gooch, 2021). FEA optimisation can only be carried out if we have three key features, a Variable, an Objective and Constraints. Without these three components then FEA software will not be able to carry out the optimisation required.

There are many different forms for optimisation, such as Topology optimisation, Shape optimisation and size optimisation. Each one will be explored as this report continues.

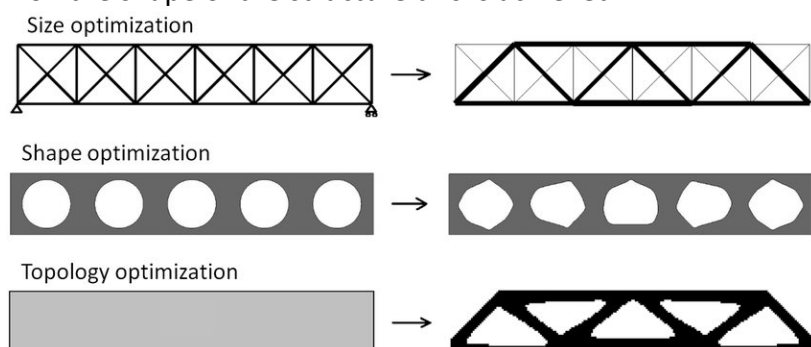
2.1 Topology Optimisation

Topology optimisation is the most prominent form of optimisation that is currently used throughout industry and is the type of optimisation that is used when analysing the component within this report. In its simplest form topology optimisation does not care about how a component or part may look, it simply is designed to find the most practical form that it may exist in to meet the required variables, objectives and constraints that has been inputted by whoever is carrying out the optimisation (Abaqus-docs.mit.edu. 2021). Topology optimisation will mostly produce results which are either extremely difficult or impossible to produce or are very expensive, for this reason topology optimisation is predominantly used as an early concept study to give the design team something to aim for but also make manufacturable. Topology optimisation will be primarily used to display a component in its strongest and lightest form. Due to progression in manufacturing software such as 3D printers, topology optimised structures are now more manufacturable to produce at a fraction of the previous costs. These progressions have meant that these structures are now used in areas such as medicine, 3D printed titanium surgical implants are now used to correct people's inherited deformities, as well as caused issues (Miacallef, 2016). Through the use of topology optimisation and CNC machines companies such as Novax DMA are able to produce medically safe implants which can be introduced to areas such as hips and skulls which are topologically optimized to be strong and also allow for integration from the natural bone growth around the implant (Miacallef, 2016).



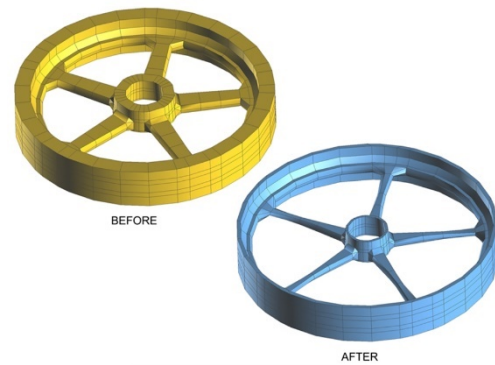
2.2 Shape Optimisation

Shape Optimisation is basing all optimisation on the shape of the structure this is achieved by controlling the boundary of the component. This is used in areas where strength needs to be high, but a certain shape needs to be adhered too. Also shape optimisation constraints are used to allow an optimisation package to change the size of components in areas to increase strength that the constraints have allowed it to and oppositely reduce them where the constraints have instructed the software too (Abaqus-docs.mit.edu. 2021). Shape Optimisation will be primarily done at the end of the design process.



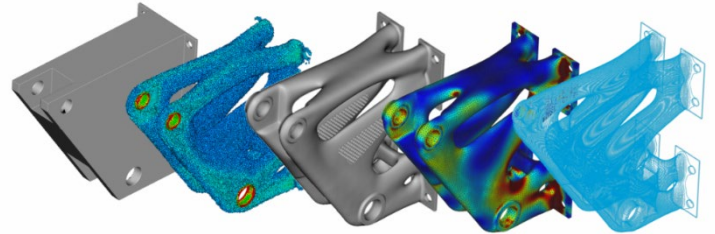
2.3 Size Optimisation

Alike shape optimisation, Size optimisation is very similar as it is based on the constraints that are implemented by the user instructing the optimisation software but instead of limiting the shape of a component it applies to the constraint of the size of the structure. This allows manufacturers to reduce on component size in areas that is simply not needed saving both size and also creating a more efficient product. Material is also saved as these components' sizes can be dramatically reduced saving costs on both materials and manufacturing (Abaqus-docs.mit.edu. 2021). Alike shape optimisation, size optimisation is also completed at the end of the design process.



3. The Future of Optimisation

FEA optimisation progression is forever expanding, the University of Melbourne published a paper titled “The Future of Optimization Technology” in this authors, Maria Garcia de la Banda, Peter J. Stuckey, Pascal Van Hentenryck and Mark Wallace, predict that the future of optimisation can only continue to progress if the language of optimization programming simplifies as the technology that runs the software and programs continues to become a lot more complex. With optimisation programs being written in NASTRAN files or MATLAB files and many other programming languages by minimising these differences and producing a one language system, this would allow all software to be run on all platforms that support it (Garcia de la Banda, M., Stuckey, P., Van Hentenryck, P. and Wallace, M., n.d).



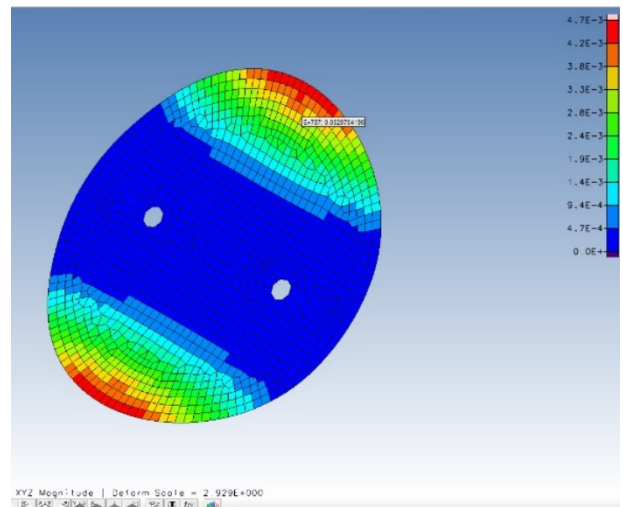
Optimisation could also be a contributing factor to industries becoming more sustainable as topology optimisation allows components to become more efficient this saves on both material and energy (Open Business Council. 2021).

4. Introduction of Genesis/Design Studio

To complete the optimisation of the butterfly valve plate in this report, the most suitable software to use is Design Studio and more specifically within design studio there is an optimisation software called Genesis. Genesis is what will be used to optimise the component. Firstly, in order to begin you first have to produce a fully constrained 3d model through the use of Solidworks. This model should be fully detailed to specify the material, the points of constraint and also the load. This has been predetermined for us however the only difference is the material that it has been modelled out of is steel. Once this is converted into a NASTRAN file it can be uploaded into Design Studio and Genesis is able to perform a single analysis to determine the displacement. In order for genesis to begin to optimize the structure it needs to know the variables, the objectives and the constraints. For the optimization of the CFRP component, the variable is going to be the number of plies in each layer, the constraint is going to be that we want genesis to keep the displacement the same if not better than the baseline steel component and finally the objective is going to be that we want the mass to be lower than the steel baseline component but also have a far lower deformation, remaining under 0.1mm as stated in the project brief.

4.1 Displacement of Steel Baseline Component

Once all constraints have been outlined in the Solidworks model, the butterfly plate is converted to a NASTRAN file and from there you are able to upload the file into Design Studio to begin a single analysis, to do this you simply click the “Genesis” drop down tab and click single analysis. This takes seconds and your first set of basic results is clear. From these results it states, the displacements in the baseline steel plate 0.47mm. This will not provide a tight enough seal between the plate and the outer housing according to ANSI/FCI 70-2-2006 standards for control valve leakage classification which states the valve must not have a higher leakage capacity of “0.01% of full valve open capacity”. Also, the mass of the valve is shown as 252g. The purpose of the objective is to get below this mass and have a far better displacement value.



4.2 Displacement of CFRP Baseline Component

Next part of the process is where the components profile and material structure changes to allow genesis to analyse the CFRP component. To do this you select analysis and add a new material. This material will be the CFRP Component. As the CFRP material is Orthotropic you must select a different material type. Call this new material UD. The new materials orthographic properties must show the orthographic properties given to you in the project brief, these are the properties for the CFRP. The orthographic properties of the components materials means that all properties are different in all direction's unlike isotropic materials. As this is the case, we need to ensure that all component fibres are facing the same way, so all properties run in the same direction. To do this you need to open analysis and "Generate Theta Vectors" and manipulate the fibres into running vertically down the component. Next it is crucial that all 5 layers are specified and layered up with 5 layers of 5 plies of 0.1mm of the UD,

Layer 1 – 5 Plys @ 0.1mm @ -90°

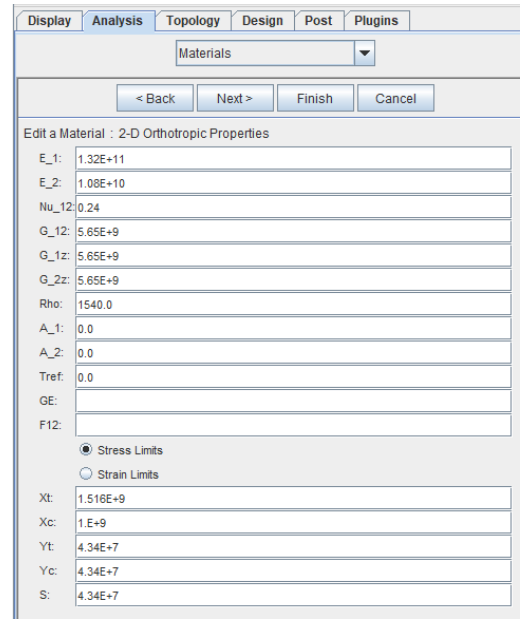
Layer 2 – 5 Plys @ 0.1mm @ -45°

Layer 3 – 5 Plys @ 0.1mm @ 0°

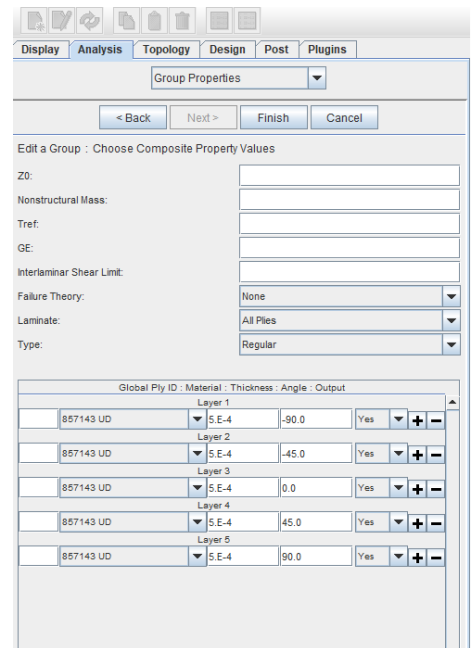
Layer 4 – 5 Plys @ 0.1mm @ 45°

Layer 5 – 5 Plys @ 0.1mm @ 90°

Now that all these constraints have been added you can now run a single analysis for the baseline CFRP component. The baseline CFRP component displaced by 0.74mm and had a mass of 126g. This shows the impressive stress/weight ratio of the CFRP compared to the Steel.

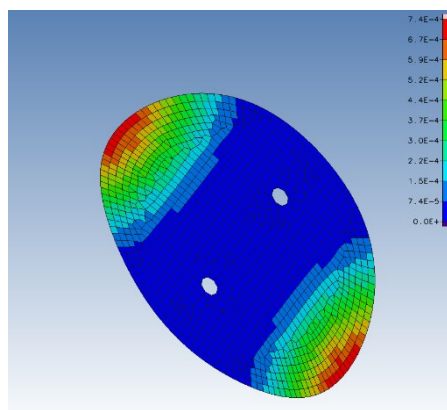


E_1:	1.32E+11
E_2:	1.08E+10
Nu_12:	0.24
G_12:	5.65E+9
G_1z:	5.65E+9
G_2z:	5.65E+9
Rho:	1540.0
A_1:	0.0
A_2:	0.0
Tref:	0.0
GE:	
F12:	
☒ Stress Limits	
☐ Strain Limits	
Xt:	1.516E+9
Xc:	1.E+9
Yt:	4.34E+7
Yc:	4.34E+7
S:	4.34E+7



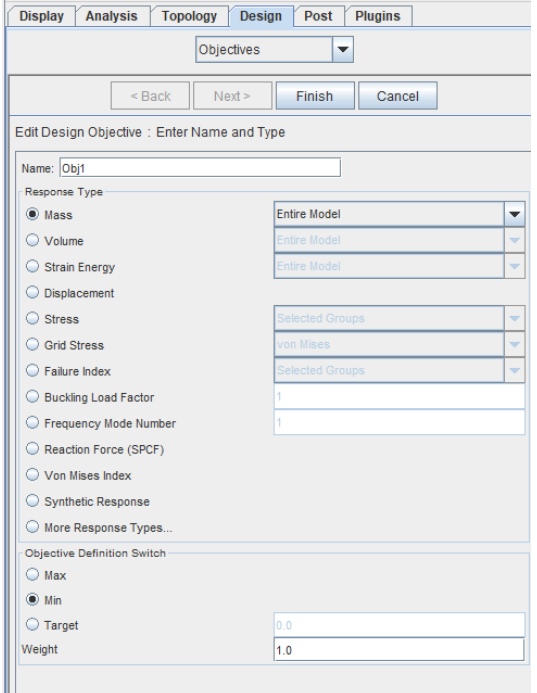
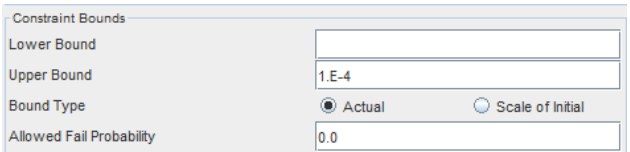
Z0:	
Nonstructural Mass:	
Tref:	
GE:	
Interlaminar Shear Limit:	
Failure Theory:	None
Laminate:	All Plies
Type:	Regular

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	+



4.3 Displacement of Optimised Baseline Component

Continuing on, previously it has been stated in order for the optimisation to occur then there needs to be 3 things stated in order for the software to run correctly. These three things are the variable, the constraints and the objective. Firstly, you should save off your work under a new title such as "cfrp_optimised_dsg.dat". Then you will begin the optimisation process by adding the objective, this is simply done by selecting the design drop down and selecting objectives. In this Design objective you simply want to specify that you want to decrease the mass. Next you must add the constraints. For the constraints you want to specify that the displacements upper boundary cannot be greater than 0.1mm. This is specified in the brief. Finally, Genesis is still unable to run an optimization sequence, this is because the required design variable has not been entered into the program, to do this you must enter an independent design variable, this states that each layer can be no more than 10 plies and no less than 1 ply. This must be repeated 4 times for the other 4 layers. However, once this is complete the program will still not run, you must assign all these design variables to their associated layers in order for Genesis to finally run. Genesis now has all the necessary data in order to run an optimisation sequence.

From the graph and results presented we now have a component which has met the variable and has still remained under the mass of the steel baseline component. Genesis has also only taken 3 cycles in order to meet our required specification even though my limited cycle range is at 50. Cyc 0 shows the component with the maximum displacement which has been programmed at the beginning of the optimisation process.

```

DESIGN CYCLE # 0, OBJECTIVE = 1.261743E-01, MAXIMUM VIOLATION = 338.1%.
DESIGN VARIABLE # 1 = 5.000000E-04 L1THK
DESIGN VARIABLE # 2 = 5.000000E-04 L1THK2
DESIGN VARIABLE # 3 = 5.000000E-04 L1THK3
DESIGN VARIABLE # 4 = 5.000000E-04 L1THK4
DESIGN VARIABLE # 5 = 5.000000E-04 L1THK5
DESIGN CYCLE # 1, OBJECTIVE = 1.776239E-01, MAXIMUM VIOLATION = 87.0%.
DESIGN VARIABLE # 1 = 7.596358E-04 L1THK
DESIGN VARIABLE # 2 = 6.651154E-04 L1THK2
DESIGN VARIABLE # 3 = 6.709521E-04 L1THK3
DESIGN VARIABLE # 4 = 6.649388E-04 L1THK4
DESIGN VARIABLE # 5 = 7.587736E-04 L1THK5
DESIGN CYCLE # 2, OBJECTIVE = 2.254656E-01, MAXIMUM VIOLATION = 17.0%.
DESIGN VARIABLE # 1 = 1.000000E-03 L1THK
DESIGN VARIABLE # 2 = 8.114279E-04 L1THK2
DESIGN VARIABLE # 3 = 8.438423E-04 L1THK3
DESIGN VARIABLE # 4 = 8.120745E-04 L1THK4
DESIGN VARIABLE # 5 = 1.000000E-03 L1THK5
DESIGN CYCLE # 3, OBJECTIVE = 2.519006E-01, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE # 1 = 1.000000E-03 L1THK
DESIGN VARIABLE # 2 = 9.956564E-04 L1THK2
DESIGN VARIABLE # 3 = 9.997077E-04 L1THK3
DESIGN VARIABLE # 4 = 9.957595E-04 L1THK4
DESIGN VARIABLE # 5 = 1.000000E-03 L1THK5
COMPLETION CODE: 1 1498 0
  
```

Examining the .HIS file for these results shows the layer thickness for each layer, in cycle 0 all layers are 0.5mm thick with 5 plys, however in Cycle 3 these numbers have drastically changed,

Layer 1 – 1.0mm – 10 Plys

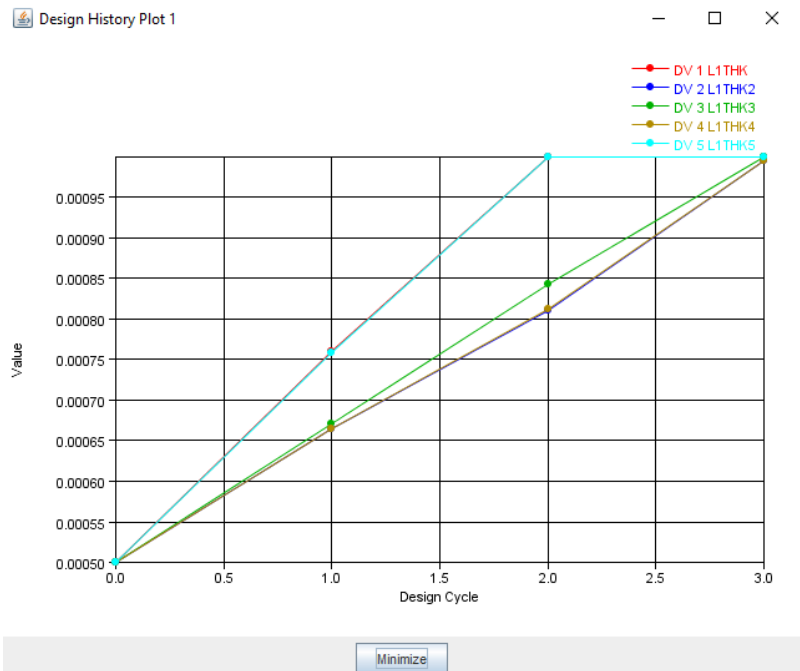
Layer 2 – 0.996mm – 9.96 Plys

Layer 3 – 0.999mm – 9.99 Plys

Layer 4 – 0.996mm – 9.96 Plys

Layer 5 – 1.0mm – 10 Plys

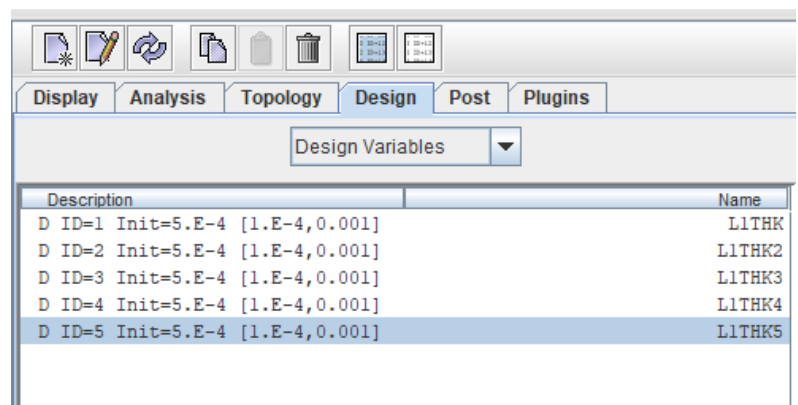
This is clearly shown in the graph that is produced from the .HIS file. The optimised cfrp component has a displacement of 0.095mm and a mass of 126g.



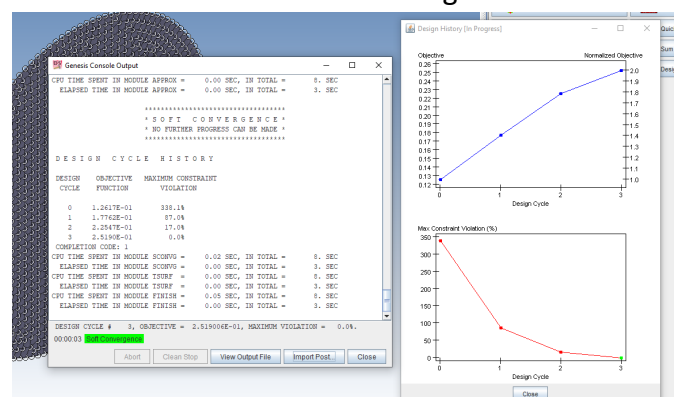
4.4 Displacement of Discrete Variable Optimised Component

The results above have been obtained using real world independent variables and not discrete variables meaning that the manufacturing process has not been taken into consideration. These real-world results on layer thickness would not be attainable through real world manufacturing processes, you would not be able to manufacture 9.996 plys of carbon

fibres. By adding discrete layers, it forces Genesis to provide attainable manufacturable results. Adding discrete variables isn't beneficial to the structure's stiffness to weight ratio but it produces a component which will be manufacturable and attainable. Notice how all design variables now have a "D" Instead of an "I" this is to show the user that all the design variables are now discrete design variables. By adding the discrete variables, Genesis has now had to run 2 more cycles, this is to ensure that our attainable layer thickness has been met.

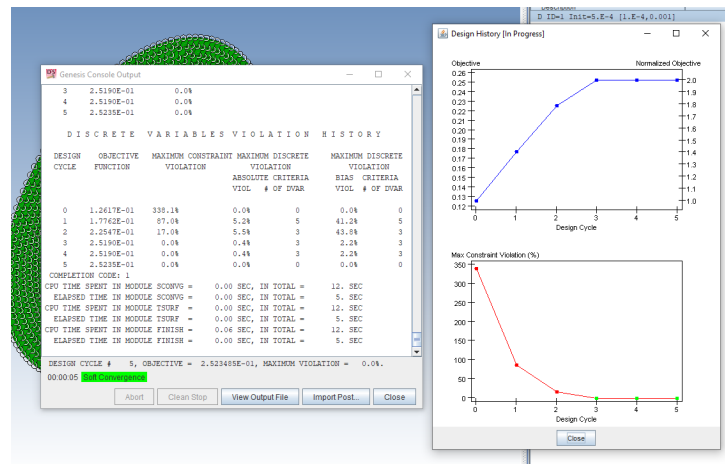


Description	Name
D ID=1 Init=5.E-4 [1.E-4,0.001]	L1THK
D ID=2 Init=5.E-4 [1.E-4,0.001]	L1THK2
D ID=3 Init=5.E-4 [1.E-4,0.001]	L1THK3
D ID=4 Init=5.E-4 [1.E-4,0.001]	L1THK4
D ID=5 Init=5.E-4 [1.E-4,0.001]	L1THK5



The discrete optimised CRFP component has displaced 0.095mm and once again measured at 126g in mass.

The results may be the same as previous for displacement and mass but as it is clear Genesis has had to run 2 more cycles. In these 2 extra cycles Genesis has had to think about the discrete variables and produce 2 extra readings with values that be attainable in manufacturing standards. Once again by examining the .HIS file it is clear to see this and is shown in the results and the graph below,



Layer 1 – 1.0mm – 10 Plys

Layer 2 – 1.0mm – 10 Plys

Layer 3 – 1.0mm – 10 Plys

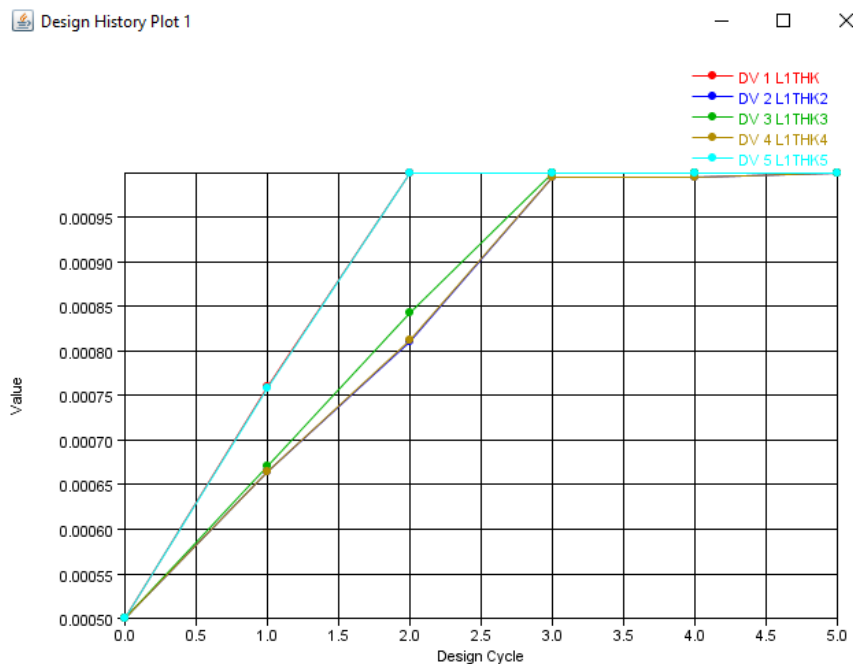
Layer 4 – 1.0mm – 10 Plys

Layer 5 – 1.0mm – 10 Plys

```

DESIGN CYCLE # 4, OBJECTIVE = 2.519006E-01, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE # 1 = 1.000000E-03 L1THK
DESIGN VARIABLE # 2 = 9.956564E-04 L1THK2
DESIGN VARIABLE # 3 = 9.997077E-04 L1THK3
DESIGN VARIABLE # 4 = 9.957595E-04 L1THK4
DESIGN VARIABLE # 5 = 1.000000E-03 L1THK5
DESIGN CYCLE # 5, OBJECTIVE = 2.523485E-01, MAXIMUM VIOLATION = 0.0%.
DESIGN VARIABLE # 1 = 1.000000E-03 L1THK
DESIGN VARIABLE # 2 = 1.000000E-03 L1THK2
DESIGN VARIABLE # 3 = 1.000000E-03 L1THK3
DESIGN VARIABLE # 4 = 1.000000E-03 L1THK4
DESIGN VARIABLE # 5 = 1.000000E-03 L1THK5
COMPLETION CODE: 1 1501 0
  
```

Genesis has shown by having a 10, 10, 10, 10, 10 Ply to layer structure produces a component that has the lowest displacement, lowest mass and is still manufacturable.



5. Real World Component Testing vs Design Studio Simulation

To ensure complete product complacency it is wise to perform real world product testing under full lab environment to ensure the results produced by genesis are both reliable and safe. This is carried out extensively throughout industry and valves, be it a butterfly valve or

a system control valve have to pass vigorous testing and meet seat leakage classification

standards. These classification standards are defined by the

ANSI/FCI 70-2-2006 or the

EU/International equivalent IEC 60534-4. However, as the butterfly valve in this report is purpose is to prohibit the flow of

light crude petroleum, the standards that it should be

tested too is the American Standard, ANSI/FCI 70-2 2006.

This is due to the fact that throughout the oil and gas industry all valves are still tested to American standards regardless of who is doing the testing (base nationality of company) (Contractorsunlimited.co.uk. 2021). The ANSI classification system is shown in the above table for classes 1-6. The CFRP Plate butterfly valve is classed as a class VI valve. Class VI valves are known as soft seated valves as "the shut-off disc is made from some kind of resilient material such as Teflon"

(Contractorsunlimited.co.uk. 2021). Therefore, in regard to testing the ANSI standards state that class VI valves should undergo "Test Procedure C". A copy of test procedure C is shown on the right of the page. Although the butterfly valve plate in question is manufactured from CARBON reinforced plastic not TEFLON as the previous quote states, the CFRP butterfly valve still comes under this class as it has a resilient material reinforcing the plate.

Now that the standards to what the butterfly valve should be tested to has been recognised and understood, the actual procedure for testing and data accumulation should be determined. From research conducted online, the most common test procedure used through industry is applying multiple pressure tests to the valve through both pneumatic pressure tests and hydraulic pressure tests, taking constant data readings if valve deformation both internally and externally has occurred to all areas such as the plate, the housing and the seat of the valve. These tests can be carried out using a Metrus Valve Test Bench (METRUS. 2018). These test benches are specifically produced to test butterfly valves both hydraulically and pneumatically. These test benches also take accurate data accumulation on component deformation and leakage. This data can be used to make a suitable comparison vs the results that genesis has produced.

Leakage Class Designation	Maximum Leakage Allowable	Test Medium	Test Pressure	Testing Procedures Required for Establishing Rating
I	x	x	x	No test required
II	0.5% of rated capacity	Air or water at 50 - 125° F (10 - 52°C)	45 - 60 psig or maximum operating differential whichever is lower	45 - 60 psig or maximum operating differential whichever is lower
III	0.1% of rated capacity	As above	As above	As above
IV	0.01% of rated capacity	As above	As above	As above
V	0.0005 ml per minute of water per inch of port diameter per psi differential	Water at 50 to 125°F (10 to 52°C)	Maximum service pressure drop across valve plug not to exceed ANSI body rating	Maximum service pressure drop across valve plug not to exceed ANSI body rating
VI	Not to exceed amounts shown in the table above	Air or nitrogen at 50 to 125° F (10 to 52°C)	50 psig or max rated differential pressure across valve plug whichever is lower	Actuator should be adjusted to operating conditions specified with full normal closing thrust applied to valve plug seat

5.4 Test Procedure Type C - Class VI

5.4.1 Test medium shall be air or nitrogen gas at 10-52°C (50-125°F).

5.4.2 Pressure of the test medium shall be the maximum rated differential pressure across the valve plug or 3.5 bar (50 psig) whichever is the least.

5.4.3 The test fluid shall be applied to the normal or specified valve body inlet, and the outlet connected to a suitable measuring device.

5.4.4 With the control valve adjusted to meet the operating conditions specified (see paragraphs 5.1.5 and 5.1.6) and with sufficient time allowance for stabilizing flow, the leak rate shall not exceed the values in Table 2.



6. Conclusion

To summarise, as stated at the beginning of this report, the intentions of this report was to design and optimise the CFRP component through the optimisation software genesis, modelling the basic plate, introducing the CFRP material properties applying the 5 ply, 5 layer system and testing this component and optimising this. This report has done this demonstrating through multiple cycles and with the addition of discrete variables a final manufacturable product which met the demands the project brief had outlined. Continuing on to how testing of this product would need to be conducted and what standards needed to be met. Whilst additionally exploring the different types of optimisations and the history and potential progression of the topic.

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