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Engineering HND | 17/10/2020

Structural optimisation of composite using
Genesis

Summary

This report will discuss many finite element analysis optimisation techniques available in today's industry and outline the benefits of utilising these optimisation techniques during the design phase. Secondly this report will optimise the skin of a wind turbine blade using optimisation software from a steel material properties into a composite material properties of the shell structure and highlight the benefits.

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1.0 Introduction

Optimisation techniques are being utilised in many industries and there are various types of optimisation techniques available to use. Structure optimisation can be classified into three main categories: Topology optimisation, shape optimisation and size optimisation. They can influence the design process massively and gain desirable results. Below will outline optimisation techniques available to an engineer.

2.0 Objectives

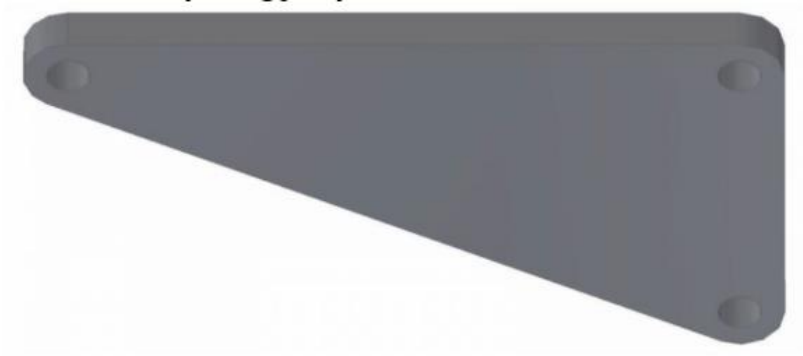
- Demonstrate competence in the application of suitable software packages to investigate engineering structural and fluid problems and cognitive skills in the formulation and analytical solution of a problem within the chosen engineering specialism.

3.0 Types of FEA optimisation

3.1 Topology Optimisation

A mathematical method that is used during the concept level of design phase, the goal of this method is to spread the material into critical areas of the model (optimal solid-void pattern) the design engineer will set specific boundaries conditions along with an applied load and limitation of space in the design. In its most basic understanding, topology optimisation takes the given 3D model and displaces and removes material to make the design the most effective it can be (maximum stiffness in structure with the least amount of material, minimising the strain energy to its lowest energy state) (Topological Optimisation with FEA | Finite Element Analysis (FEA) Blog – LEAP Australia & New Zealand, 2020). The objective of the function does not consider ease of manufacturing neither take into consideration the aesthetics of the finished geometry. (Topology Optimisation | Benefits & Disadvantages | Software, 2020).

Topology optimisation can focus on an entire component or elements of it. TO uses a finite element analysis to use a mesh on the design space. The model undergoes stress and strain analysis to find how the structure performs this allows the optimisation run to know where to put the material within the design space. With each iteration material is removed if this removal affects the stiffness the process will stop, and material will be retained in this area. A weight objective is set before the optimisation run is performed (e.g., 50%), other objectives and constraints can be set such as buckling, frequencies. (Topology Optimisation | Benefits & Disadvantages | Software, 2020).

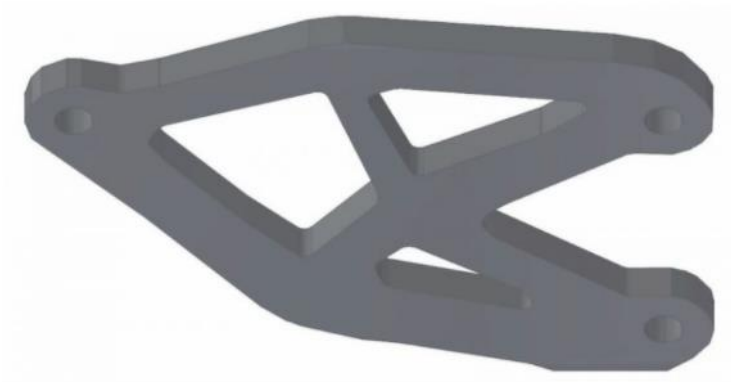


Fig(1) starting geometry before optimisation. (Topology Optimisation | Benefits & Disadvantages | Software, 2020)

The above shows the existing designed geometry before optimisation has been completed.

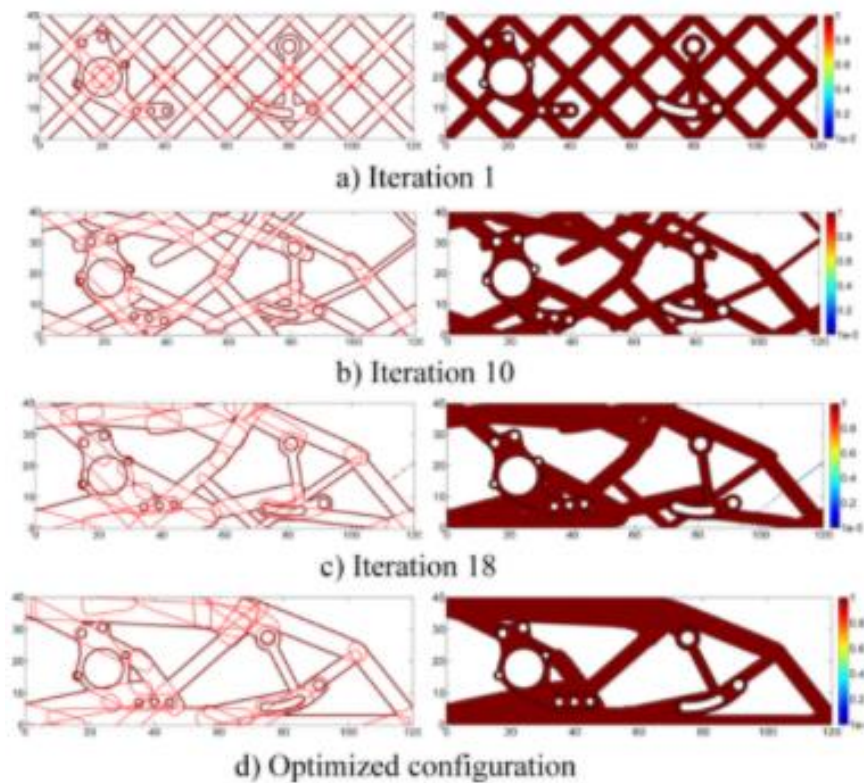


Fig(2) optimised geometry. (Topology Optimisation | Benefits & Disadvantages | Software, 2020)



Fig(3) final optimised geometry after post processing has been done. (Topology Optimisation | Benefits & Disadvantages | Software, 2020).

During the optimisation run the structure undergoes several changes, with each iteration the material is displaced into each critical location. The below shows this process.



Fig(4) Shows iteration 1 to 18 and the finished optimisation configuration. (Topological Optimisation with FEA | Finite Element Analysis (FEA) Blog – LEAP Australia & New Zealand, 2020).

3.2 Sizing optimisation

Sizing optimisation seeks for optimum geometry size of complex structures with various load cases, without changing the generalised shape it finds an optimum relation between stiffness and weight, sheet thickness is changed to find the dynamic behaviour of the given model (Systems, 2020). Sizing optimisation finds best dimensions for composites, shells, and bar elements. (Topological Optimisation with FEA | Finite Element Analysis (FEA) Blog – LEAP Australia & New Zealand, 2020).

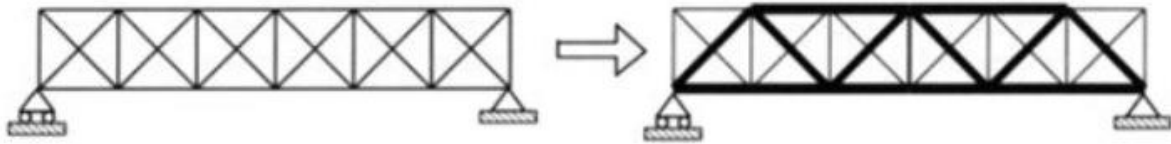


Fig (5) Sizing optimisation. (The-three-categories-of-structural-optimisation-a-sizing-optimisation-of-a-truss, 2020).

3.3 Shape optimisation

Shape 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. (Topological Optimisation with FEA | Finite Element Analysis (FEA) Blog – LEAP Australia & New Zealand, 2020).

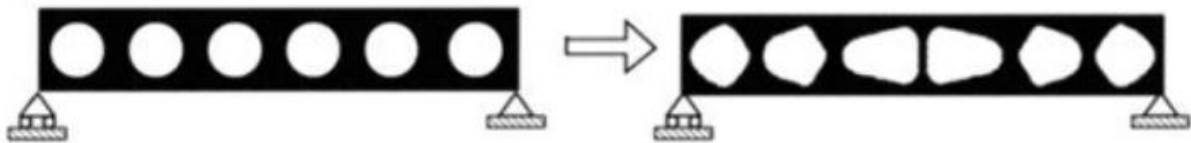


Fig (6) Shape optimisation. (The-three-categories-of-structural-optimisation-a-sizing-optimisation-of-a-truss, 2020).

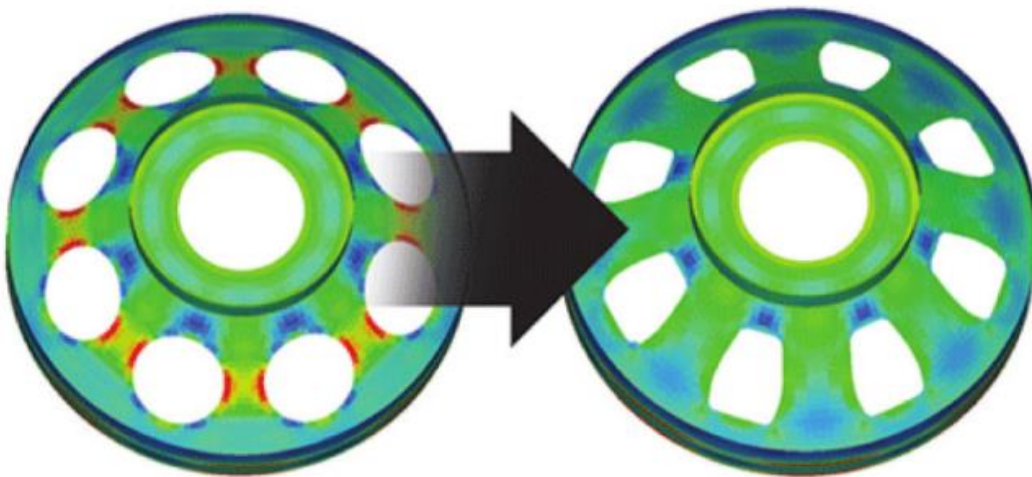


Fig (7) Shape optimisation of cut-outs in a thin-walled structure.

As seen in the above fig(7) the shape has been changed to mitigate the high stress regions observed (left side). The optimised shape (right side) has stress distributed evenly within the structure.

3.4 Topography optimisation

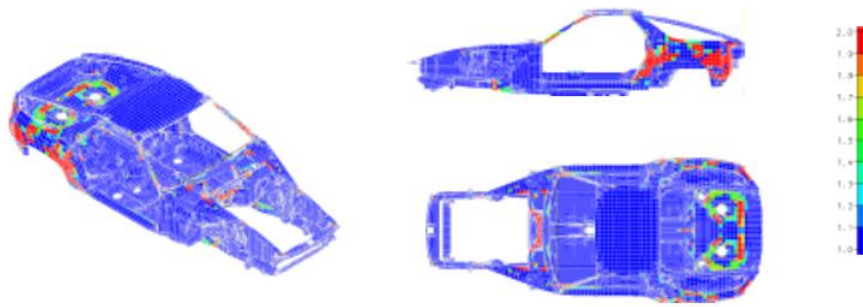
Topography Optimisation is a more advance form of shape optimisation is giving the engineer the capability of generating bead patterns and swages on the model these are used on panel/shell like structures(university, 2020). This is ideal because it will maximise the stiffness on the same overall geometry without increasing its mass, therefore gaining a lighter stiffer structure. It may also be utilised to maximize the frequency of the geometry; this is governed by the objective given by the user. (Structure > Run > Optimization > Topography Optimization, 2020).



Fig (8) Topography optimisation of sheet metal part. (Structure > Run > Optimization > Topography Optimization, 2020).

3.5 Topometry Optimisation

Topometry optimisation is a unique technique, it allows the engineer to find the optimum distribution of elements in the design space (Topometry Optimization: A New Capability to Perform Element by Element Sizing Optimization of Structures, 2020). Like topology this technique is used to take material out of the model, however unlike topology it can also add material to the design space, typically the user can define thicknesses of each element as a design variable. This technique can be utilised simultaneously with shape, size, and topography optimisation. (Topological Optimisation with FEA | Finite Element Analysis (FEA) Blog – LEAP Australia & New Zealand, 2020)



Fig(8) Thickness distribution, Topometry optimisation. (Topometry Optimization: A New Capability to Perform Element by Element Sizing Optimization of Structures, 2020).

3.6 Freeform Optimisation

Freeform optimisation is a new variation of shape optimisation it allows the user to find the best shape of rib patterns that allow structures increased stiffness, even within solid. Shape optimisation were performed whole vector whereas in free optimisation these vector are split so each grid or sets of grids can have their own single variable, this allow greatly flexibility within the optimisation to find an even more optimum shape. (Freeform Optimization: A New Capability to Perform Grid by Grid Shape Optimization of Structures, 2020). It has been given the name freeform optimisation this could be seen as a generalised version of topography as it can achieve the same results, however freeform optimisation can be utilised on shells, trusses, and solids giving it more freedom to be utilised however it needs to be, topography is mostly used with shell type geometry. (Freeform Optimization: A New Capability to Perform Grid by Grid Shape Optimization of Structures, 2020).

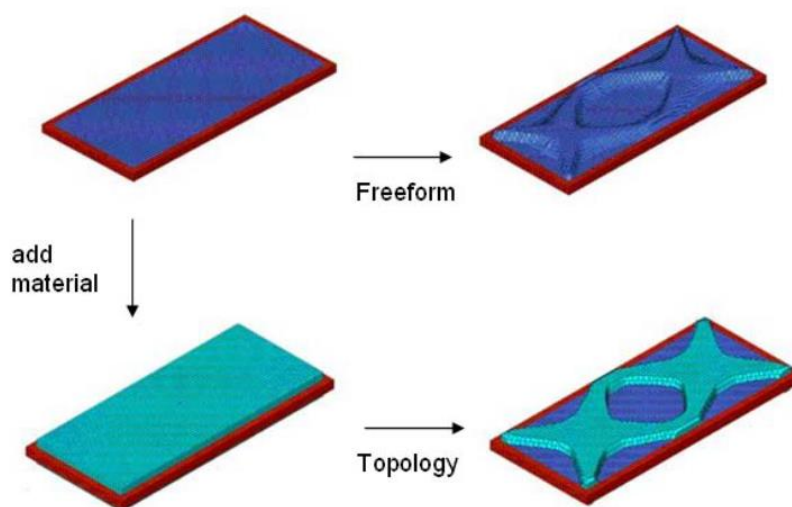
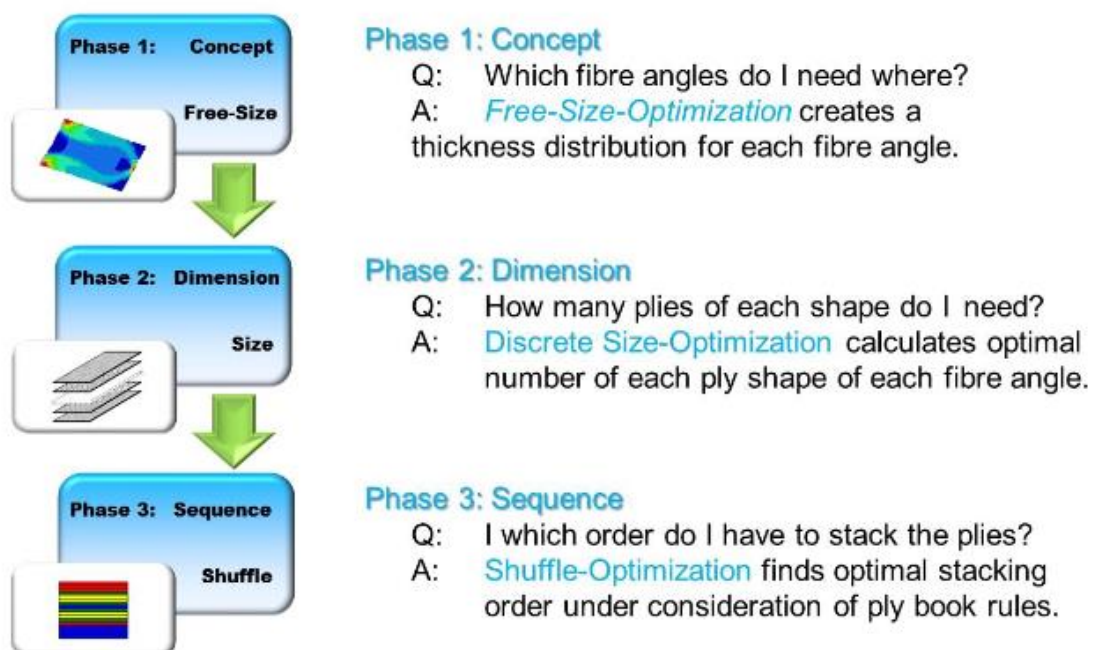


Fig (10) Freeform optimisation of sheet metal part. (Freeform Optimization: A New Capability to Perform Grid by Grid Shape Optimization of Structures, 2020).

As you can see by the above topology adds material into new shape whereas freeform will change existing geometry into a stiffer shape.

3.7 Composite Optimisation

Composite optimisation is being used in many area of engineering it offers high stiff and low mass, long fatigue life, it also has superior thermal properties and are corrosive resistance. Within composite optimisation optimum thickness for each layer can be obtained, optimum ply angles and optimum stacking of ply's. Below show possible routes for composite optimisation. (University, 2020)



Fig(11) shows composite optimisation routes. (University, 2020)

4.0 Benefits of using FEA optimisation

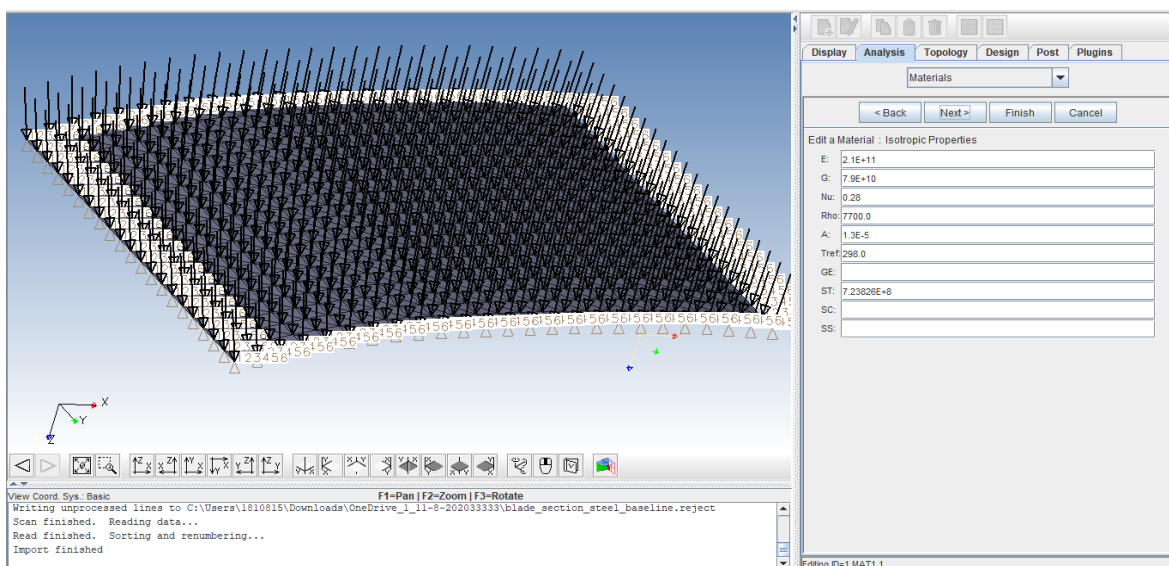
The benefits of using finite element analysis optimisation techniques during the design phase, can greatly influence the design process and gain desirable results needed in today industries.

- Reducing weight due to needing less material to achieve the same stiffness.
- Reduce cost due to these weight saving, without compromising on stiffness.
- Prevent stress concentrations within the model or mitigate them completely.

- Attain desirable performance attributes, such as frequency maximisation, stress, or displacement constraints. Using optimisation techniques will ultimately avoid huge amount of manual design iterations. (Xia, 2016)
- Remove bottlenecks.
- Can reduce engineering time during the design phase using optimisation techniques.
- Optimisation can lead to design geometry not thought off normally, very robust design can come to life due to a huge amount of design variable, so the user can explore the entire design space with several different optimisation techniques available. (Topological Optimisation with FEA | Finite Element Analysis (FEA) Blog – LEAP Australia & New Zealand, 2020)
- Increased sustainability due to less materials being used. (Querin et al., 2017).

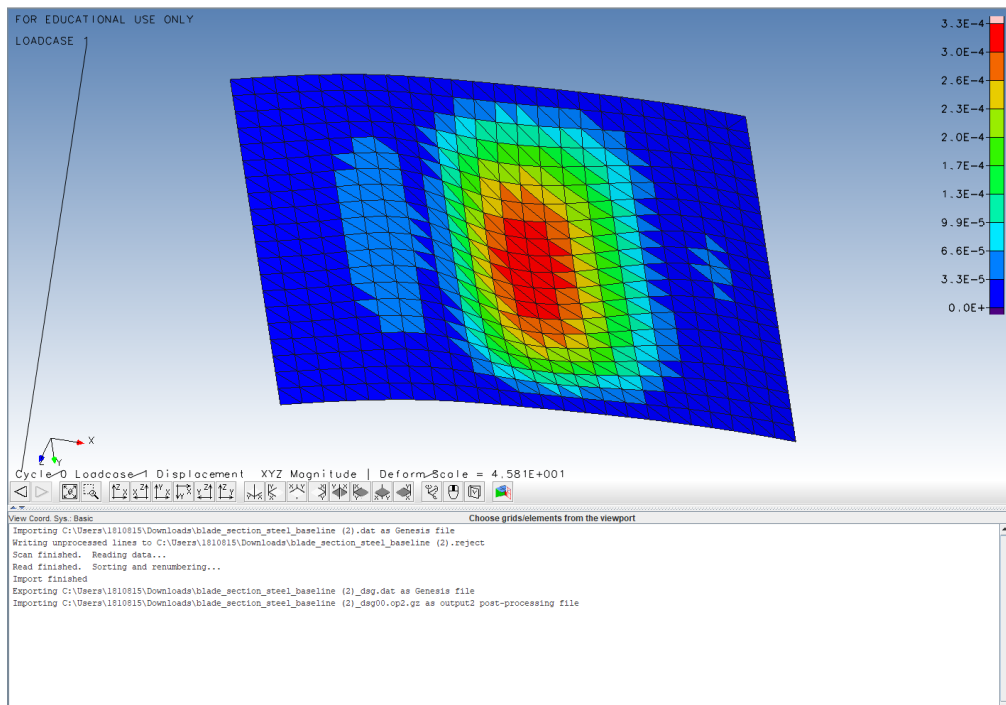
5.0 Optimisation procedure

5.1 Baseline geometry



Fig(12) Shows baseline material properties (steel) & Boundary conditions. (Genesis, 2020).

As the above shows current material properties on the right for the baseline structure, with boundary conditions on the structure restrained in 6 degrees of freedom, 3 rotational, 3 translational. This is the given assumption for the baseline structure.



Fig(13) Shows displacement of baseline material(0.33mm).(Genesis, 2020).

6.2 Baseline composite geometry

Fig(14) Shows material properties of composite. (Genesis, 2020)

The material properties have been inputted in design studio(shown above):

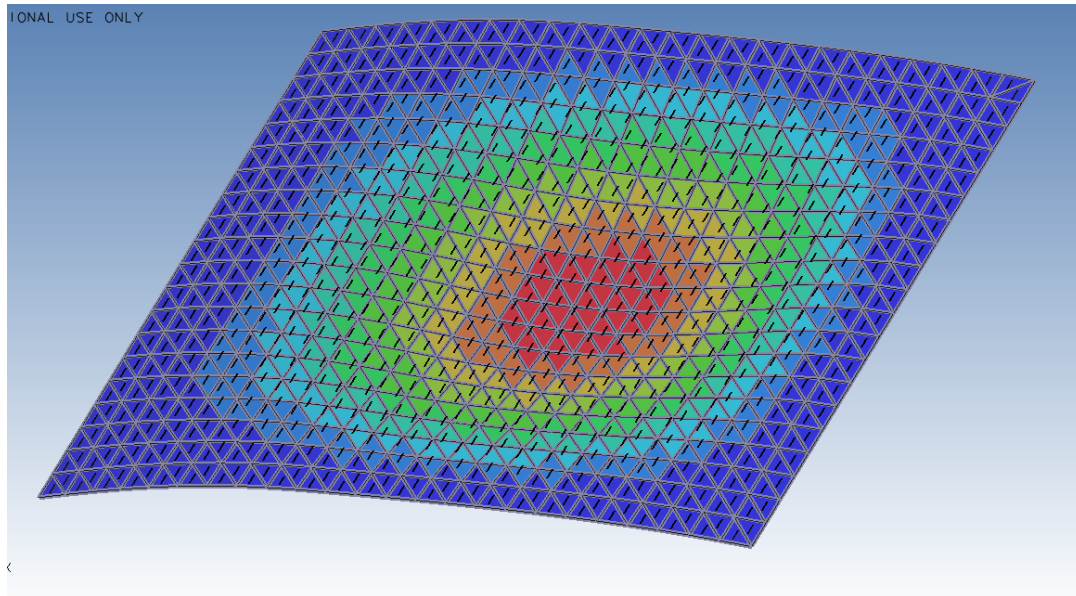


Fig (15) Shows theta value in the correct orientation. (Genesis, 2020)

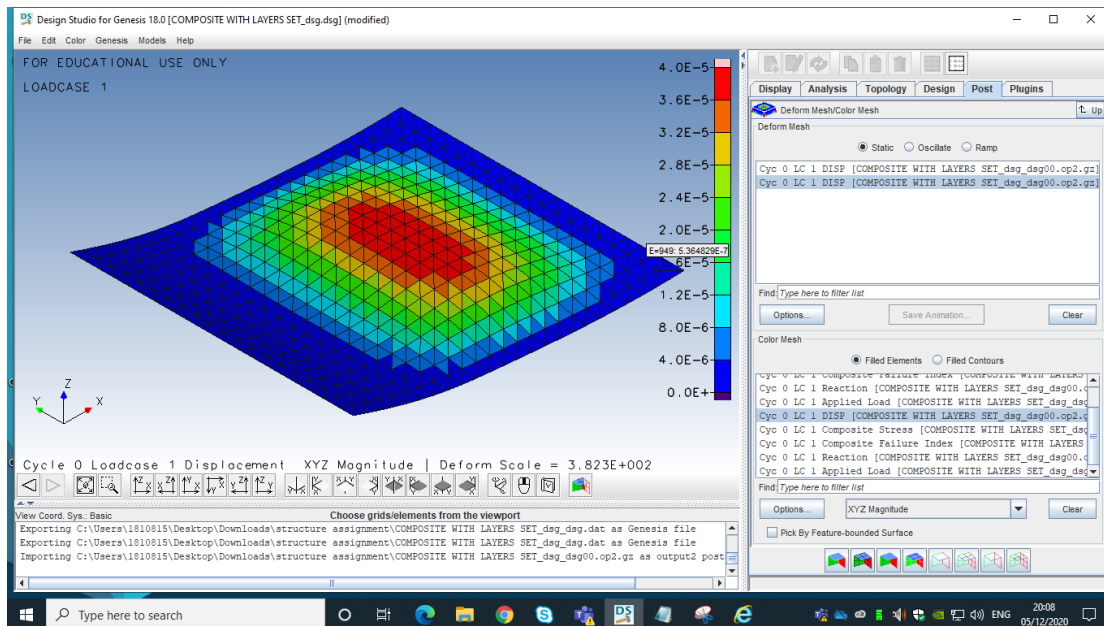
As stated the ply's at 0 degree should run longitudinally (0 degrees) down the length of the wind turbine blade as such the theta value needed orientation changed.

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

Total thickness = 0.0025

Fig(16) Shows layer thickness and angle layers are set.(Genesis, 2020)

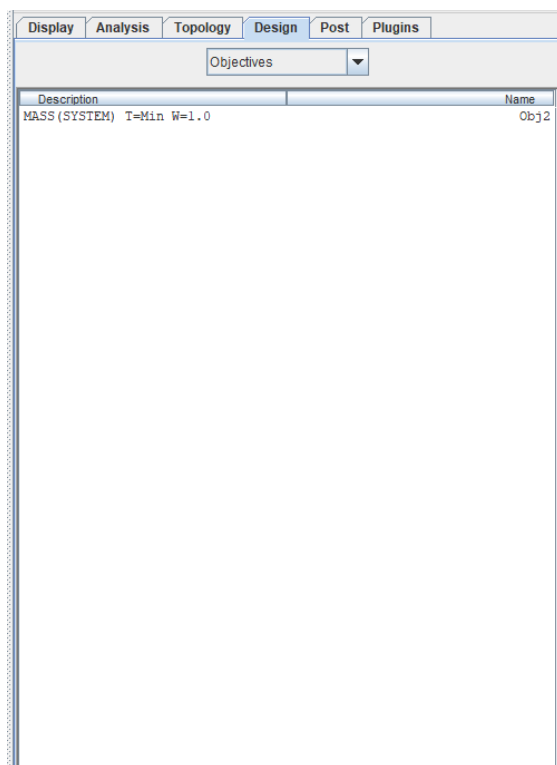
As required the correct layers have been assigned a total of 25 ply's of the Unidirectional. 5 at -90 degrees, 5 ply's at -45 degrees, 5 ply's at 0 degrees, 5 ply's at 45 degrees and 5 ply's at 90 degrees. Each layer is 0.5mm (5E-4). This is due to each ply being 0.1mm, each layer equal 0.5mm. Total thickness 2.5mm as seen in fig(16).



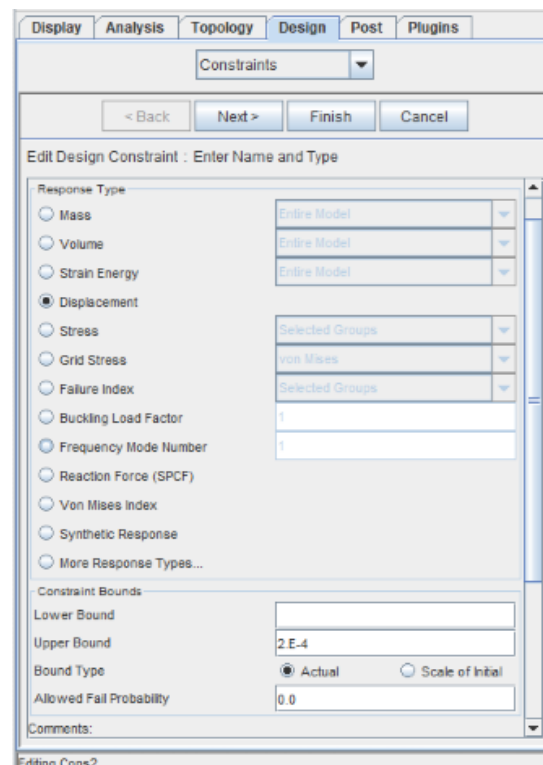
Fig(17) Shows deflections for composite material. (Genesis, 2020).

The above shows the deflection for the composite model, observed deflection was $4\text{e-}5$, compared to $3.3\text{E-}3$ for the steel material.

6.3 Setting up optimisation

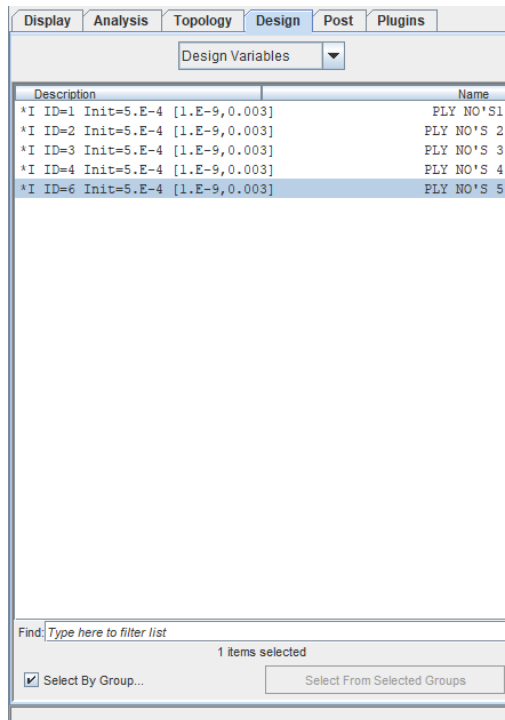


Fig(18) Setting objective to be lowest mass possible(left). (Genesis, 2020)



Fig(19) Design displacement constraint(right). (Genesis, 2020).

The above fig(18) shows mass being set up as an objective the be as minimum as possible.
The above fig(19) shows design constraints being inputted displacement not to exceed 0.2mm as state in assignment brief.



Fig(20) Design variables being inputted. (Genesis, 2020)

Initial value – 5E-4

Lower bound – 1E-9

Upper bound – 3E-3

So, the initial layer thicknesses are 0.5mm this is due to each layer having 5 ply orientated at directions during the laying up process each ply 0.1mm. Lower bound has been set to a very small value, and upper bound has been set at 3mm, this will allow the optimisation process freedom to choose the ideal layer thicknesses to achieve an optimum design.

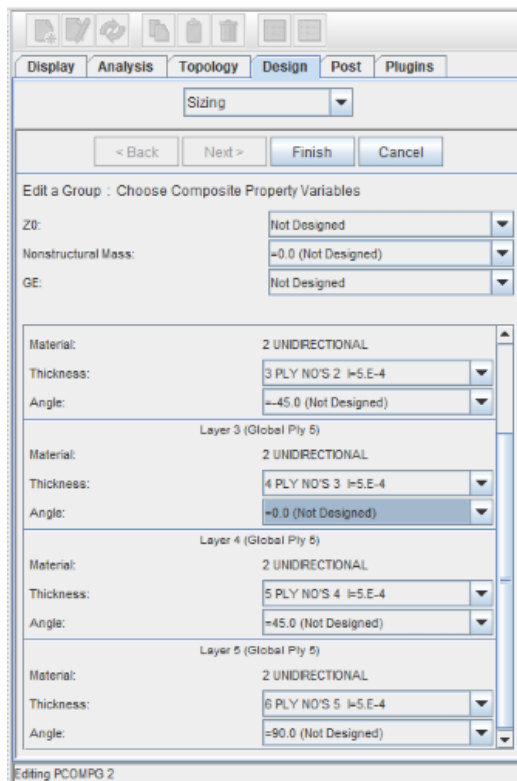


Fig (21) Variables assigned to correct material. (Genesis, 2020)

Each design variable has been assigned to each layer in material **PCOMPG** before optimisation can occur.

The below shows by design cycle 13 hard convergence has been obtained. The below shows each layer thickness. The displacement goal was achieved by iteration 5. A mass of 77.5 g has been achieved. (See appendix A for history file)

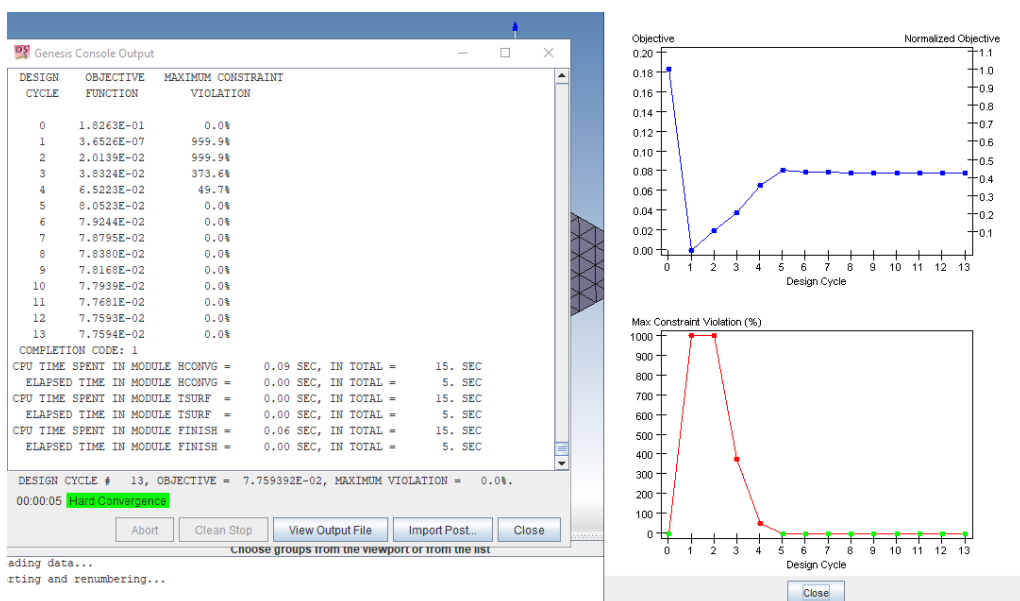
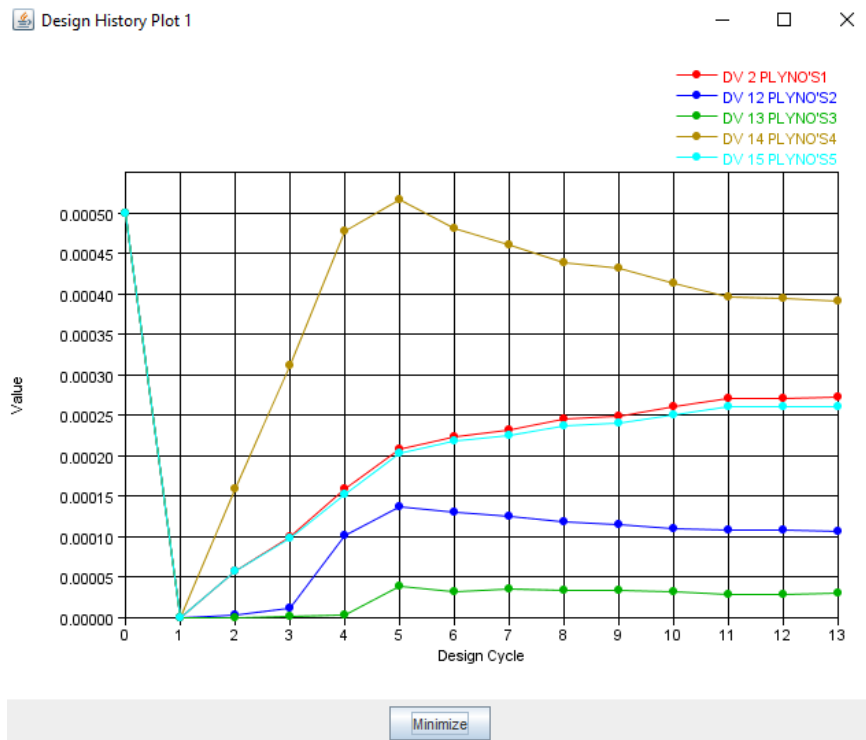


Fig (22) optimisation output .(Genesis, 2020).



Fig(23) shows design plot of each layer thickness achieved for each iteration.(Genesis, 2020).

Optimization runs showing each cycle, the part has now been optimised but it cannot be manufactured, fig(23) shows layer thickness achieved for each iteration. The part is not manufacturable due to each needing to be in step of 0.1mm. The new mass is 77.6 g.

DESIGN CYCLE # 13, OBJECTIVE = 7.759392E-02, MAXIMUM VIOLATION = 0.0%.

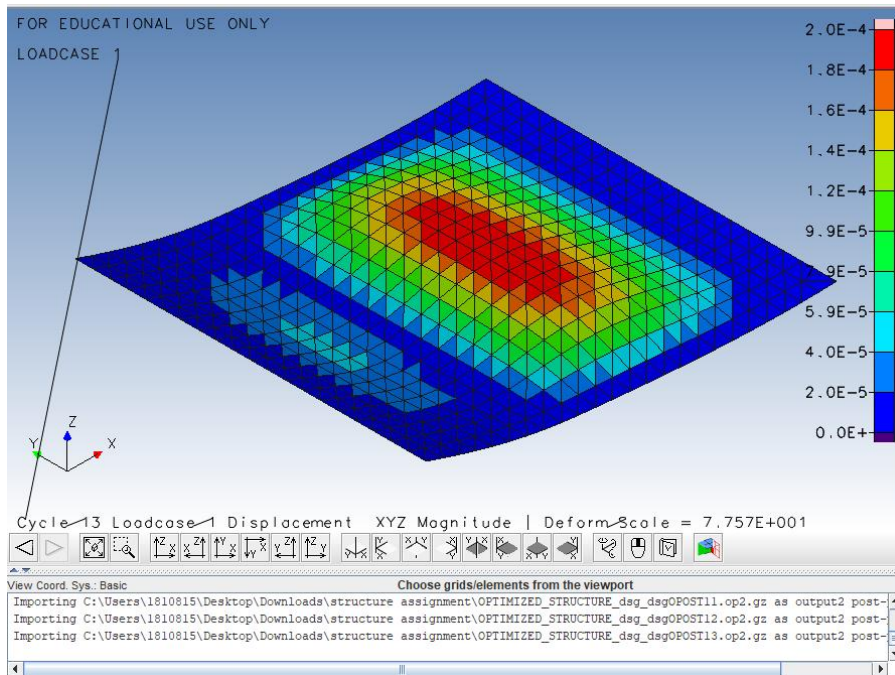
DESIGN VARIABLE # 2 = 2.719846E-04 PLYNO'S1

DESIGN VARIABLE # 12 = 1.071461E-04 PLYNO'S2

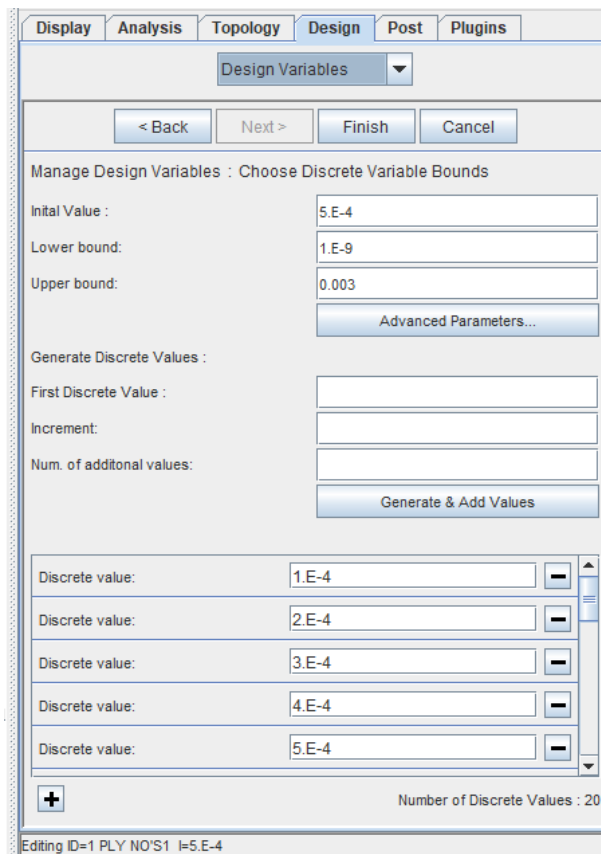
DESIGN VARIABLE # 13 = 3.030981E-05 PLYNO'S3

DESIGN VARIABLE # 14 = 3.916338E-04 PLYNO'S4

DESIGN VARIABLE # 15 = 2.611114E-04 PLYNO'S5



Fig(24) Shows displacement goal being achieved for composite part.(Genesis, 2020).



Fig(25) Shows discrete variables window.(Genesis, 2020).

Setting up discrete value to let know genesis these are the layer thicknesses allowed to be used during re-optimisation Fig(25).

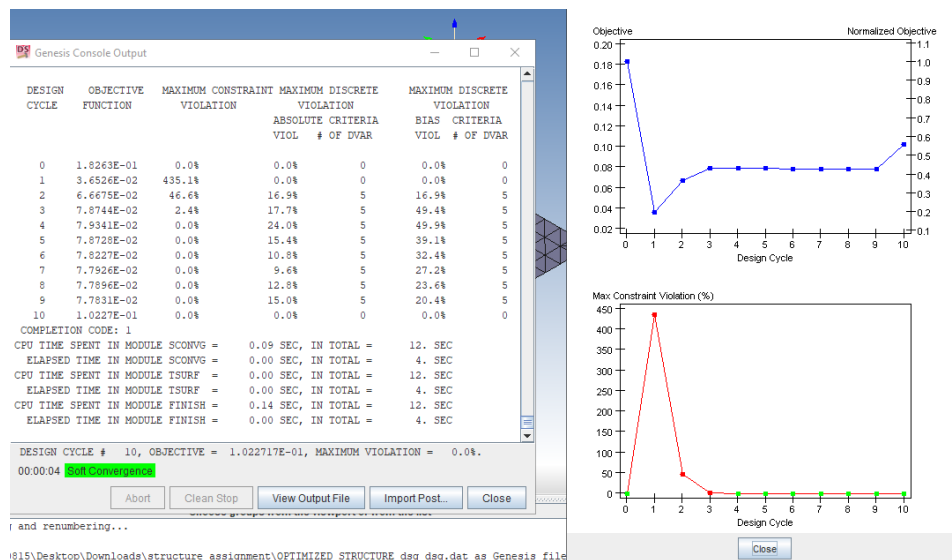
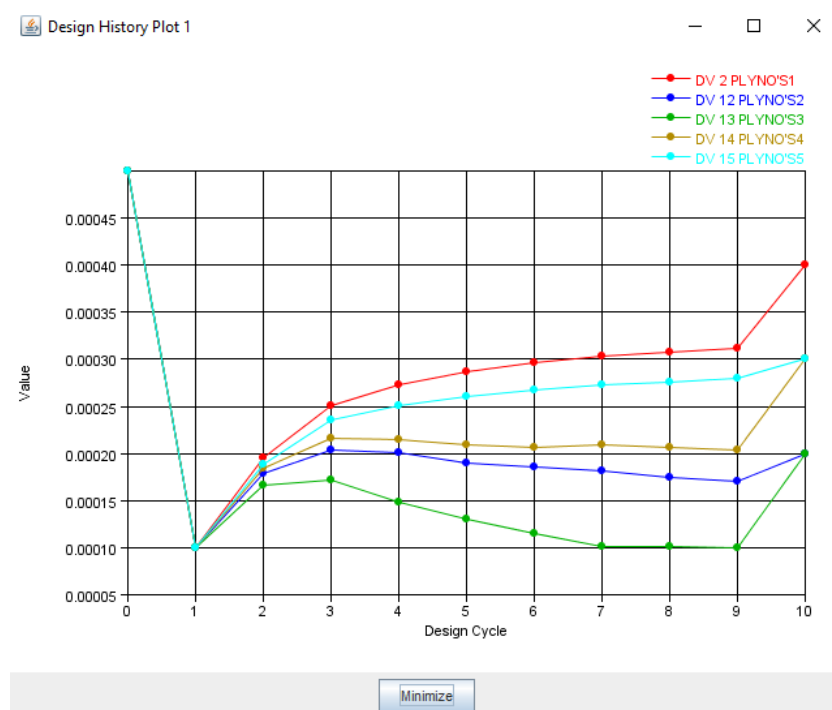


Fig (26) optimisation output of re-optimised structure .(Genesis, 2020).

(See appendix B for history file)



Fig(27) Shows layer thickness at each iteration.(Genesis, 2020).

Each layer thickness changing with each iteration with discrete values set. After optimisation as seen in fig (27) each layer has been given one of the inputted discrete values, which will allow this part to be manufacturable. However, this has led to the part increasing in mass (102g).

DESIGN CYCLE # 10, OBJECTIVE = 1.022717E-01, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE # 2 = 4.000000E-04 PLYNO'S1

DESIGN VARIABLE # 12 = 2.000000E-04 PLYNO'S2

DESIGN VARIABLE # 13 = 2.000000E-04 PLYNO'S3

DESIGN VARIABLE # 14 = 3.000000E-04 PLYNO'S4

DESIGN VARIABLE # 15 = 3.000000E-04 PLYNO'S5

6.0 Comparison of stiffness of each model and stiffness/weight ratio

Run	Material	Thickness	Deflection	Mass	Load	Stiffness	Stiffness/weight
Steel baseline	Steel		0.33mm	182g	200N	606 N/mm	339.41 N ² /mm
Composite baseline	Composite	2.5mm	0.04mm	182g	200N	5000 N/mm	2800 N ² /mm
1 st Optimised	Composite	1.24mm	0.2mm	77.5g	200N	1000 N/mm	1323 N ² /mm
2 nd Optimised	Composite	1.4mm	0.2mm	102g	200N	1000 N/mm	999 N ² /mm

Table 1 : comparison of each material.

As you can see in the above table of the observed variables during the optimisation process as you can see the mass has been greatly reduced but the stiffness has increase massively. This results in a lighter more robust and efficient structure due to the composite being optimised. The baseline composite structure has a high stiffness to weight ratio but offers no weight reduction, with our aim being the lightest structure possible, having used optimisation techniques the final optimised part is 3 times as stiff with almost a 50% mass reduction.

6.0 Conclusion

In conclusion finite element analysis optimisation techniques offer several benefits in the design process; these include reduced weight along with optimum stiffness, stress concentrations can be mitigated, optimum frequencies being obtained and optimum displacement constraints. Engineering time can be greatly reduced, Optimisation techniques can lead to desirable geometry being ascertained this leads to increased sustainability. Shape and sizes of geometry lead to increase performance within the model due to these optimisation techniques being utilised. All the above ultimately lead to superior part being

manufactured along with cost reductions. Composite optimisation is desirable due to the massive weight saving that can be made over metal parts, and composite offer an increase stiffness. Any weight saving that can be made will lead to increase performance and cheaper and faster production as well as a robust product.

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Element Sizing Optimization Of Structures. [online] Available at: <[http://www.vrand.com/wp-](http://www.vrand.com/wp-content/uploads/2017/06/Man20859.pdf)

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9.0 Appendix A

Optimised structure that cannot be manufactured history file.

DESIGN CYCLE # 0, OBJECTIVE = 1.826280E-01, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE # 2 = 5.000000E-04 PLYNO'S1

DESIGN VARIABLE # 12 = 5.000000E-04 PLYNO'S2

DESIGN VARIABLE # 13 = 5.000000E-04 PLYNO'S3

DESIGN VARIABLE # 14 = 5.000000E-04 PLYNO'S4

DESIGN VARIABLE # 15 = 5.000000E-04 PLYNO'S5

DESIGN CYCLE # 1, OBJECTIVE = 3.652559E-07, MAXIMUM VIOLATION = 999.9%.

DESIGN VARIABLE # 2 = 1.000000E-09 PLYNO'S1

DESIGN VARIABLE # 12 = 1.000000E-09 PLYNO'S2

DESIGN VARIABLE # 13 = 1.000000E-09 PLYNO'S3

DESIGN VARIABLE # 14 = 1.000000E-09 PLYNO'S4

DESIGN VARIABLE # 15 = 1.000000E-09 PLYNO'S5

DESIGN CYCLE # 2, OBJECTIVE = 2.013908E-02, MAXIMUM VIOLATION = 999.9%.

DESIGN VARIABLE # 2 = 5.681829E-05 PLYNO'S1

DESIGN VARIABLE # 12 = 2.749144E-06 PLYNO'S2

DESIGN VARIABLE # 13 = 1.000000E-09 PLYNO'S3

DESIGN VARIABLE # 14 = 1.592978E-04 PLYNO'S4

DESIGN VARIABLE # 15 = 5.681837E-05 PLYNO'S5

DESIGN CYCLE # 3, OBJECTIVE = 3.832432E-02, MAXIMUM VIOLATION = 373.6%.

DESIGN VARIABLE # 2 = 1.002288E-04 PLYNO'S1

DESIGN VARIABLE # 12 = 1.268539E-05 PLYNO'S2

DESIGN VARIABLE # 13 = 1.745514E-06 PLYNO'S3

DESIGN VARIABLE # 14 = 3.117708E-04 PLYNO'S4

DESIGN VARIABLE # 15 = 9.819233E-05 PLYNO'S5

DESIGN CYCLE # 4, OBJECTIVE = 6.522289E-02, MAXIMUM VIOLATION = 49.7%.

DESIGN VARIABLE # 2 = 1.584024E-04 PLYNO'S1

DESIGN VARIABLE # 12 = 1.008136E-04 PLYNO'S2

DESIGN VARIABLE # 13 = 3.864399E-06 PLYNO'S3

DESIGN VARIABLE # 14 = 4.778006E-04 PLYNO'S4

DESIGN VARIABLE # 15 = 1.519573E-04 PLYNO'S5

DESIGN CYCLE # 5, OBJECTIVE = 8.052263E-02, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE # 2 = 2.076931E-04 PLYNO'S1

DESIGN VARIABLE # 12 = 1.376738E-04 PLYNO'S2

DESIGN VARIABLE # 13 = 3.811562E-05 PLYNO'S3

DESIGN VARIABLE # 14 = 5.153415E-04 PLYNO'S4

DESIGN VARIABLE # 15 = 2.034529E-04 PLYNO'S5

DESIGN CYCLE # 6, OBJECTIVE = 7.924413E-02, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE # 2 = 2.230194E-04 PLYNO'S1

DESIGN VARIABLE # 12 = 1.302726E-04 PLYNO'S2

DESIGN VARIABLE # 13 = 3.266494E-05 PLYNO'S3

DESIGN VARIABLE # 14 = 4.812423E-04 PLYNO'S4

DESIGN VARIABLE # 15 = 2.175762E-04 PLYNO'S5

DESIGN CYCLE # 7, OBJECTIVE = 7.879522E-02, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE # 2 = 2.323964E-04 PLYNO'S1

DESIGN VARIABLE # 12 = 1.245657E-04 PLYNO'S2

DESIGN VARIABLE # 13 = 3.584490E-05 PLYNO'S3

DESIGN VARIABLE # 14 = 4.599702E-04 PLYNO'S4

DESIGN VARIABLE # 15 = 2.258531E-04 PLYNO'S5

DESIGN CYCLE # 8, OBJECTIVE = 7.838049E-02, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE # 2 = 2.452049E-04 PLYNO'S1

DESIGN VARIABLE # 12 = 1.186283E-04 PLYNO'S2

DESIGN VARIABLE # 13 = 3.326624E-05 PLYNO'S3

DESIGN VARIABLE # 14 = 4.382569E-04 PLYNO'S4

DESIGN VARIABLE # 15 = 2.375967E-04 PLYNO'S5

DESIGN CYCLE # 9, OBJECTIVE = 7.816759E-02, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE # 2 = 2.487565E-04 PLYNO'S1

DESIGN VARIABLE # 12 = 1.143806E-04 PLYNO'S2

DESIGN VARIABLE # 13 = 3.408644E-05 PLYNO'S3

DESIGN VARIABLE # 14 = 4.322461E-04 PLYNO'S4

DESIGN VARIABLE # 15 = 2.405690E-04 PLYNO'S5

DESIGN CYCLE # 10, OBJECTIVE = 7.793871E-02, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE #	2 = 2.604413E-04	PLYNO'S1
DESIGN VARIABLE #	12 = 1.106054E-04	PLYNO'S2
DESIGN VARIABLE #	13 = 3.249689E-05	PLYNO'S3
DESIGN VARIABLE #	14 = 4.123423E-04	PLYNO'S4
DESIGN VARIABLE #	15 = 2.510196E-04	PLYNO'S5

DESIGN CYCLE # 11, OBJECTIVE = 7.768123E-02, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE #	2 = 2.710667E-04	PLYNO'S1
DESIGN VARIABLE #	12 = 1.082630E-04	PLYNO'S2
DESIGN VARIABLE #	13 = 2.838846E-05	PLYNO'S3
DESIGN VARIABLE #	14 = 3.952294E-04	PLYNO'S4
DESIGN VARIABLE #	15 = 2.604334E-04	PLYNO'S5

DESIGN CYCLE # 12, OBJECTIVE = 7.759332E-02, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE #	2 = 2.712377E-04	PLYNO'S1
DESIGN VARIABLE #	12 = 1.076169E-04	PLYNO'S2
DESIGN VARIABLE #	13 = 2.919342E-05	PLYNO'S3
DESIGN VARIABLE #	14 = 3.936149E-04	PLYNO'S4
DESIGN VARIABLE #	15 = 2.605146E-04	PLYNO'S5

DESIGN CYCLE # 13, OBJECTIVE = 7.759392E-02, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE #	2 = 2.719846E-04	PLYNO'S1
DESIGN VARIABLE #	12 = 1.071461E-04	PLYNO'S2
DESIGN VARIABLE #	13 = 3.030981E-05	PLYNO'S3
DESIGN VARIABLE #	14 = 3.916338E-04	PLYNO'S4
DESIGN VARIABLE #	15 = 2.611114E-04	PLYNO'S5

10.0 Appendix B

Re-optimised structure that can now be manufactured

DESIGN CYCLE # 0, OBJECTIVE = 1.826280E-01, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE #	2 = 5.000000E-04	PLYNO'S1
DESIGN VARIABLE #	12 = 5.000000E-04	PLYNO'S2
DESIGN VARIABLE #	13 = 5.000000E-04	PLYNO'S3
DESIGN VARIABLE #	14 = 5.000000E-04	PLYNO'S4
DESIGN VARIABLE #	15 = 5.000000E-04	PLYNO'S5

DESIGN CYCLE # 1, OBJECTIVE = 3.652559E-02, MAXIMUM VIOLATION = 435.1%.

DESIGN VARIABLE # 2 = 1.000000E-04 PLYNO'S1
DESIGN VARIABLE # 12 = 1.000000E-04 PLYNO'S2
DESIGN VARIABLE # 13 = 1.000000E-04 PLYNO'S3
DESIGN VARIABLE # 14 = 1.000000E-04 PLYNO'S4
DESIGN VARIABLE # 15 = 1.000000E-04 PLYNO'S5

DESIGN CYCLE # 2, OBJECTIVE = 6.667535E-02, MAXIMUM VIOLATION = 46.6%.

DESIGN VARIABLE # 2 = 1.954915E-04 PLYNO'S1
DESIGN VARIABLE # 12 = 1.786492E-04 PLYNO'S2
DESIGN VARIABLE # 13 = 1.662946E-04 PLYNO'S3
DESIGN VARIABLE # 14 = 1.841137E-04 PLYNO'S4
DESIGN VARIABLE # 15 = 1.881720E-04 PLYNO'S5

DESIGN CYCLE # 3, OBJECTIVE = 7.874394E-02, MAXIMUM VIOLATION = 2.4%.

DESIGN VARIABLE # 2 = 2.506065E-04 PLYNO'S1
DESIGN VARIABLE # 12 = 2.041720E-04 PLYNO'S2
DESIGN VARIABLE # 13 = 1.713713E-04 PLYNO'S3
DESIGN VARIABLE # 14 = 2.163235E-04 PLYNO'S4
DESIGN VARIABLE # 15 = 2.354551E-04 PLYNO'S5

DESIGN CYCLE # 4, OBJECTIVE = 7.934139E-02, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE # 2 = 2.723494E-04 PLYNO'S1
DESIGN VARIABLE # 12 = 2.005144E-04 PLYNO'S2
DESIGN VARIABLE # 13 = 1.479737E-04 PLYNO'S3
DESIGN VARIABLE # 14 = 2.151746E-04 PLYNO'S4
DESIGN VARIABLE # 15 = 2.500948E-04 PLYNO'S5

DESIGN CYCLE # 5, OBJECTIVE = 7.872757E-02, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE # 2 = 2.863758E-04 PLYNO'S1
DESIGN VARIABLE # 12 = 1.901854E-04 PLYNO'S2
DESIGN VARIABLE # 13 = 1.308345E-04 PLYNO'S3
DESIGN VARIABLE # 14 = 2.094263E-04 PLYNO'S4
DESIGN VARIABLE # 15 = 2.608823E-04 PLYNO'S5

DESIGN CYCLE # 6, OBJECTIVE = 7.822731E-02, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE # 2 = 2.962285E-04 PLYNO'S1
DESIGN VARIABLE # 12 = 1.855307E-04 PLYNO'S2
DESIGN VARIABLE # 13 = 1.150434E-04 PLYNO'S3
DESIGN VARIABLE # 14 = 2.064496E-04 PLYNO'S4
DESIGN VARIABLE # 15 = 2.676040E-04 PLYNO'S5

DESIGN CYCLE # 7, OBJECTIVE = 7.792593E-02, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE # 2 = 3.034748E-04 PLYNO'S1
DESIGN VARIABLE # 12 = 1.808545E-04 PLYNO'S2
DESIGN VARIABLE # 13 = 1.009038E-04 PLYNO'S3
DESIGN VARIABLE # 14 = 2.087245E-04 PLYNO'S4
DESIGN VARIABLE # 15 = 2.727731E-04 PLYNO'S5

DESIGN CYCLE # 8, OBJECTIVE = 7.789611E-02, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE # 2 = 3.079804E-04 PLYNO'S1
DESIGN VARIABLE # 12 = 1.743380E-04 PLYNO'S2
DESIGN VARIABLE # 13 = 1.006661E-04 PLYNO'S3
DESIGN VARIABLE # 14 = 2.069776E-04 PLYNO'S4
DESIGN VARIABLE # 15 = 2.763603E-04 PLYNO'S5

DESIGN CYCLE # 9, OBJECTIVE = 7.783119E-02, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE # 2 = 3.121619E-04 PLYNO'S1
DESIGN VARIABLE # 12 = 1.699408E-04 PLYNO'S2
DESIGN VARIABLE # 13 = 1.000241E-04 PLYNO'S3
DESIGN VARIABLE # 14 = 2.037229E-04 PLYNO'S4
DESIGN VARIABLE # 15 = 2.795839E-04 PLYNO'S5

DESIGN CYCLE # 10, OBJECTIVE = 1.022717E-01, MAXIMUM VIOLATION = 0.0%.

DESIGN VARIABLE # 2 = 4.000000E-04 PLYNO'S1
DESIGN VARIABLE # 12 = 2.000000E-04 PLYNO'S2
DESIGN VARIABLE # 13 = 2.000000E-04 PLYNO'S3
DESIGN VARIABLE # 14 = 3.000000E-04 PLYNO'S4
DESIGN VARIABLE # 15 = 3.000000E-04 PLYNO'S5