



ULA ROCKET HARDWARE DESIGN

Advanced Computational Methods

M6X00408

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1.0 EXECUTIVE SUMMARY

The following report aims to discuss and implement topology optimisation to a support platform bracket that is to be fitted to a rocket during its assembly stage to aid workers. The goal was to use the topology optimisation software to be able to reduce the weight of the bracket by 90%, without effecting the structural attributes of the component so that it still functions accordingly. This was achieved using Design Studio for GENESIS software with the report discussing the stages of the topology optimisation before analysis was carried out to show why certain problems were encountered, as well as the decisions made to overcome them to reach the goal set in. Recommendations were then drawn that could contribute to the final production of the component as this report was primarily focused on the optimisation side of things.

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3.0 INTRODUCTION

There are many aspects that must be accounted for when designing a new product or redesigning an existing one. These qualities and conditions may vary depending on the operational requirements of the product and will be a contributing factor to the overall success of the product in terms of practicality, sales, customer feedback etc.

This report aims to improve an existing component by redesigning it so that less material is used to make it, without drastically effecting the structural properties. As computer science and technology has developed over the years, certain design software programs can be used to design and develop complex shapes that will fulfil the same functions as a solid piece of material using less material.

For primary research purposes, an interview was conducted with Ford Motor Company Tinsmith - James Jenkins, an experienced and respected tradesman who is often tasked with creating and modifying various support brackets and structures. A transcript of the interview with Jenkins (2020) has been included in the report appendix.

3.1 TOPOLOGY OPTIMISATION

A topology optimisation consists of adding a load to a part via topology software and running a study to show the areas where stresses act on the part. The digital tool distributes material in the most appropriate manner within an existing part to ensure that it functions correctly under loading conditions. This involves changing some of the properties of an existing part e.g. weight or volume, by removing material that is not critical to the part while under loading conditions (Querin , et al., 2017). Certain constraints like increasing stiffness, reducing stress and displacement must be considered for this optimisation (Hassani & Hinton, 2012), as Bendsøe (2009) mentions that the removal of this excess material will reduce the stiffness and density of the component, having a first order effect on these factors. Bendsøe (2009) then goes on to say that the mass fraction of the topology study must be considered with these factors in mind so that the part can become lighter and still function accordingly. The topology software will repeatedly cycle, removing more material each time until the desired percentage of remaining material has been reached.

4.0 THE PART

As well as being able to function properly as a load bearing work platform, the weight of the bracket is critical in achieving the goal set in the report brief. Not only would the material required cost 1/10th of the price, but the weight saved would influence the take-off conditions, especially if there were multiple brackets fixed around the vehicle.

The mass of the rocket has a direct effect on the vertical motion due to Newtons 2nd law of motion; Force = mass x acceleration. Due to how the rocket is being propelled in the vertical direction, there will be an opposing gravitational force acting on it (ScienceLearningHub, 2017). Hypothetically, going off the figures shown in Table 1, if 5 brackets were required during the setup process and were not optimised, that would equate to 5 x 0.45kg = 2.25kg in additional weight. Compared to the optimised bracket weighing 1/10th of the original bracket, 5 x 0.045kg = 0.225kg. Due to the massive forces that are present during the take-off process of a rocket, this additional 2kg could cause problems. Considering a NASA rocket weighs around 400,000kg and accelerates at a rate of 8000m/s² in 8.5 minutes (NASA, 2020), the 2kg difference would increase the gravitational forces acting on the rocket slightly, but would still increase fuel consumption and costs.

Table 1 –Specifications for the optimised component (GrabCAD, 2019).

Condition	Value
Maximum part weight	0.045kg (0.1 lb)
Minimum wall thickness	1.016mm (0.040 inches)
Ultimate load (due to work platform)	272kg (600lbf) applied uniformly in the negative Z direction $F = ma$ $F = 272\text{kg} \times 9.81\text{m/s}^2$ $F = 2668.93\text{N}$
The minimum edge distance surrounding all bolt holes	2x diameter of hole

5.0 TOPOLOGY OPTIMISATION

5.1 MESH SELECTION

Meshing is a critical tool in design and optimisation software as it approximates the geometry of a component in one, two and three dimensions. This report focuses on a 3D component, so a solid mesh was used for the optimisation (Moldex3D, 2019). The mesh size used for the optimisation was 2.1mm and was determined by dividing the minimum point of thickness of the part by 3 (Lake, 2019). The detail of the mesh can be seen in Fig.1 and shows that the aspect ratio of 99.9% of the 217143 elements is below 3, indicating a high-quality mesh that is shown in Fig.2 to take 26 minutes to converge due to the degrees of freedom present with the elements.

Mesh Details	
Study name	Static 1 (-Default-)
Mesh type	Solid Mesh
Mesher Used	Standard mesh
Automatic Transition	Off
Include Mesh Auto Loops	Off
Jacobian points	4 points
Element size	2.1 mm
Tolerance	0.105 mm
Mesh quality	High
Total nodes	313369
Total elements	217143
Maximum Aspect Ratio	5.9864
Percentage of elements with Aspect Ratio < 3	99.9
Percentage of elements with Aspect Ratio > 10	0
% of distorted elements (Jacobian)	0
Time to complete mesh(hh:mm:ss)	00:00:10
Computer name	

Figure 1 – Mesh details of the 2.1mm standard solid mesh

Genesis Console Output		
* HARD CONVERGENCE *		
* SMALL PROGRESS BEING MADE *		

DESIGN CYCLE HISTORY		
DESIGN CYCLE	OBJECTIVE FUNCTION	MAXIMUM CONSTRAINT VIOLATION
0	1.8708E+01	0.0%
1	9.9369E-01	0.0%
2	3.4247E-01	0.0%
3	1.7187E-01	0.0%
4	1.1599E-01	0.0%
5	9.1598E-02	0.0%
6	8.5432E-02	0.0%
7	8.2415E-02	0.0%
COMPLETION CODE: 0		
CPU TIME SPENT IN MODULE HCONVG = 3.41 SEC, IN TOTAL = 3486. SEC		
ELAPSED TIME IN MODULE HCONVG = 3.00 SEC, IN TOTAL = 1616. SEC		
CPU TIME SPENT IN MODULE TSURF = 0.58 SEC, IN TOTAL = 3487. SEC		
ELAPSED TIME IN MODULE TSURF = 1.00 SEC, IN TOTAL = 1617. SEC		
CPU TIME SPENT IN MODULE FINISH = 0.19 SEC, IN TOTAL = 3487. SEC		
ELAPSED TIME IN MODULE FINISH = 0.00 SEC, IN TOTAL = 1617. SEC		
DESIGN CYCLE # 7, OBJECTIVE = 8.241512E-02, MAXIMUM VIOLATION = 0.0%.		
00:26:56 Hard Convergence		
Abort Clean Stop View Output File Import Post... Close		

Figure 2 – Convergence time

5.1.1 DRAFT QUALITY MESH

After more research was carried out and more knowledge about the subject was obtained, the decision was made to select a 'Draft quality' mesh. This type of mesh reduces the number of nodes present on the part to 42092 (See Fig.4) by eliminating the mid-side nodes (SolidworksHelp, 2019). This made it easier to insert the boundary conditions shown in section 5.2.1 and drastically reduced the time taken for the optimisation studies to compute. Considering each node saved can display up to 6 degrees of freedom, a massive number of nodes were eliminated for future studies, saving 22 minutes in total (See Fig.3).

Mesh Details	
Study name	Static 1 (-Default-)
Mesh type	Solid Mesh
Mesher Used	Standard mesh
Automatic Transition	Off
Include Mesh Auto Loops	Off
Jacobian points	4 points
Element size	2.1 mm
Tolerance	0.105 mm
Mesh quality	Draft
Total nodes	42092
Total elements	217143
Maximum Aspect Ratio	5.9864
Percentage of elements with Aspect Ratio < 3	99.9
Percentage of elements with Aspect Ratio > 10	0
Time to complete mesh(hh:mm:ss)	00:00:07
Computer name	

Figure 4 – Mesh details of the 2.1mm draft quality mesh

DESIGN CYCLE HISTORY		
DESIGN CYCLE	OBJECTIVE FUNCTION	MAXIMUM CONSTRAINT VIOLATION
0	3.1355E-01	0.0%
1	2.6486E-02	0.0%
2	1.1081E-02	0.0%
3	7.4054E-03	0.0%
4	5.4956E-03	0.0%
5	4.8303E-03	0.0%
6	4.7331E-03	0.0%
7	4.7279E-03	0.0%
COMPLETION CODE: 1		
CPU TIME SPENT IN MODULE HCONVG = 2.50 SEC, IN TOTAL = 237. SEC		
ELAPSED TIME IN MODULE HCONVG = 2.00 SEC, IN TOTAL = 204. SEC		
CPU TIME SPENT IN MODULE TSURF = 0.38 SEC, IN TOTAL = 237. SEC		
ELAPSED TIME IN MODULE TSURF = 1.00 SEC, IN TOTAL = 205. SEC		
CPU TIME SPENT IN MODULE FINISH = 0.03 SEC, IN TOTAL = 237. SEC		
ELAPSED TIME IN MODULE FINISH = 0.00 SEC, IN TOTAL = 205. SEC		
DESIGN CYCLE # 7, OBJECTIVE = 4.727929E-03, MAXIMUM VIOLATION = 0.0%.		
00:03:25	Hard Convergence	

Figure 3 – Convergence time reduction due to draft quality mesh

5.2 LOADING CONDITIONS

It is important that the loads and constraints that will be present on the component in real life circumstances are applied to the model for the topology optimisation. Doing so correctly will enhance the reliability of the study and provide digital results that replicate the real-life counterpart.

These conditions were applied and used for the topology optimisation using the Design Studio plug in feature for GENESIS Structural Analysis and Optimisation Software. This software was used to combine Finite Element Analysis (FEA) techniques to achieve and display the analysis for the optimisation of the boat tail (VR&D, 2020).

5.2.1 FIXED CONSTRAINTS

These constraints were applied to the model to imitate the use of the four bolts that would secure the part in place (See Fig.5). In real-life, there will be slight movement in the material around the holes where the bolt is inserted so there may be an increased stiffness included with this constraint

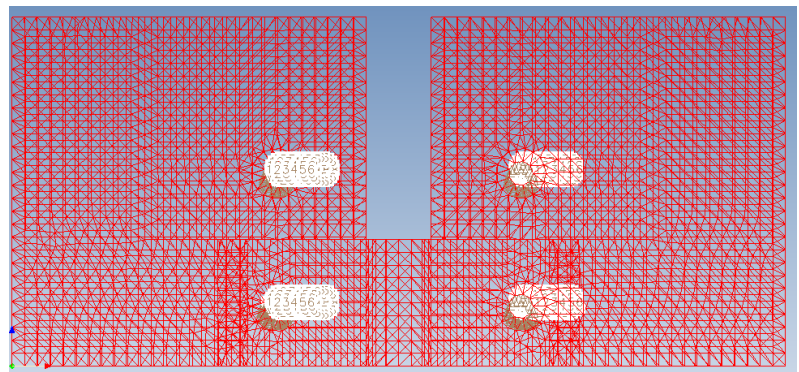


Figure 5 – Boundary conditions added to fix bolt holes in place

5.2.2 STATIC LOAD

This force of 2668.93N (See Table 1) was uniformly distributed across 455 grids (shown in Fig.6), meaning that a force of 5.87N would be exerted on to each grid in the -Z direction (Shown in Fig. 6 and 7). It was critical that only the top layer of grids that would touch the platform were selected to ensure more reliable results. The gravitational force acting on the part was discounted for this study as it was very small.

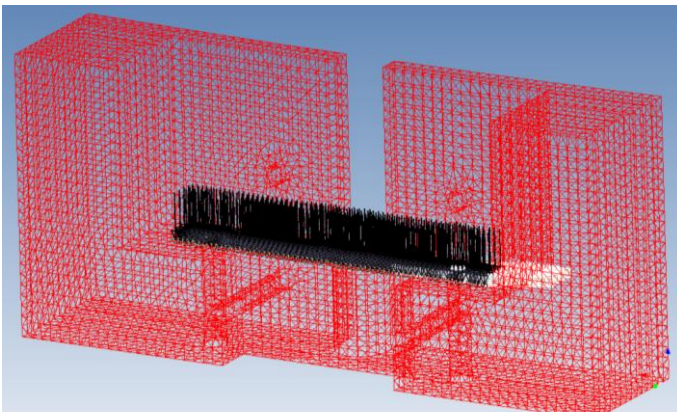


Figure 7 – Arrows indicating the direction in which the static load is acting

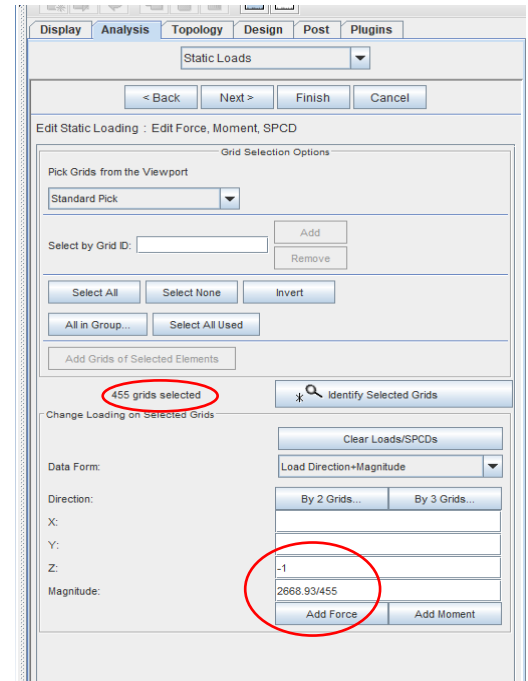


Figure 6 – Applying the conditions for the UDL

5.2.3 LOADCASE

The boundary conditions and static load addressed in sections 5.3.1 and 5.3.2 were combined to create a loadcase (See Fig.8). This means that both conditions will act on the part simultaneously, as they would in real life (Abaqus, 2019).

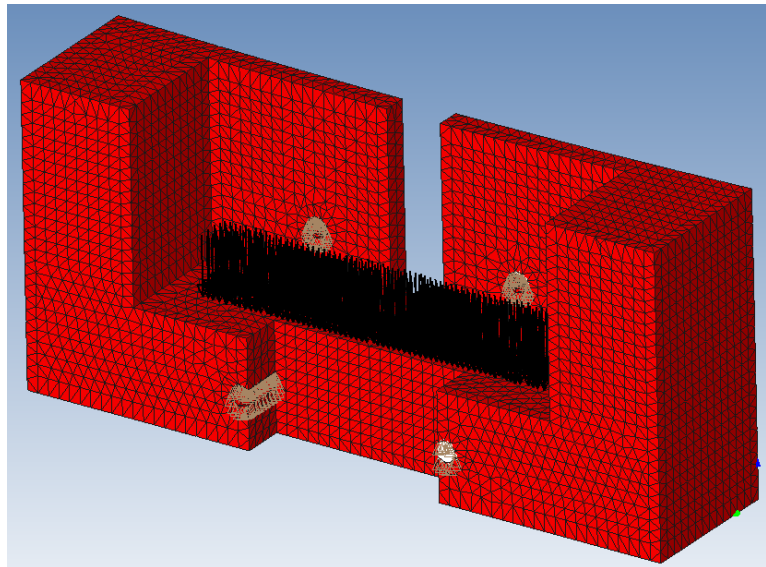


Figure 8 – Loadcase consisting of a static load and fixed constraints

5.2.4 MATERIAL PROPERTIES

The material that was to be used for the optimisation of the ULA bracket was listed in the report brief as Ultem 9085. Materialise (2020) describes Ultem as a “strong, lightweight and flame retardant” material that displays high levels of mechanical performance and strength to weight ratio. These characteristics are supported by Stratasys (2017). Both authors proceed to say how the material is manufactured in the form of Fused Deposition Modelling (FDM) 3d printing.

The following material properties for Ultem 9085 were obtained from Stratasys (2017) and by converting the figures given on the report brief to SI units. The material properties were:

Table 2 – Properties of Ultem 9085 (Stratasys, 2017).

Material Properties	Value
Material Strength Allowable	31MPa
Young’s Modulus (E)	2240MPa
Shear Modulus (G)	2050MPa
Ultimate Tensile Strength (UTS)	69MPa
Specific Gravity	1.34 g/cm ³
Poisson’s Ratio	0.41

These values were then imported into Design Studio so that the model bracket would display the same characteristics of the material, reacting to the topology study as if it were made from Ultem 9085.

5.2.5 TOPOLOGY CONDITIONS

Before carrying out the topology optimisation of the ULA bracket, the three requirements for any form of topology study were defined to ensure that the model was optimised accordingly. These were;

- Topology Regions – Initial mass fraction of the part was set to 0.1, this tells the software to use 10% of the material in the package space.
- Topology Objective – The loadcase was applied to the topology. Objective was to minimise strain energy to retain stiffness of the part so that it didn’t deform.
- Topology Constraints –The upper bound of the mass fraction was set to 0.1.

6.0 ANALYSIS OF OPTIMISATION STUDIES

To achieve the criteria in mentioned in Table 1, several topology optimisation studies were carried out on a trial and error basis. During a topology optimisation, the GENESIS software runs multiple design cycles that attempt to remove material until the target mass fraction has been met. A hard convergence was required as it shows that the software had successfully removed the desired amount of material after multiple cycles. A soft convergence occurred several times, but these were discounted as they signal the software had finished cycling without reaching the desired mass fraction.

Cross referencing Fig.10 with Fig.11 shows how most of the material was removed in the first optimisation cycle, with the remaining six gradually removing small amounts of material until the objective was met. Although Fig.9 shows that the mass is below the 0.1 target, this is due to the second element group that was added and is addressed in section 6.1.2.

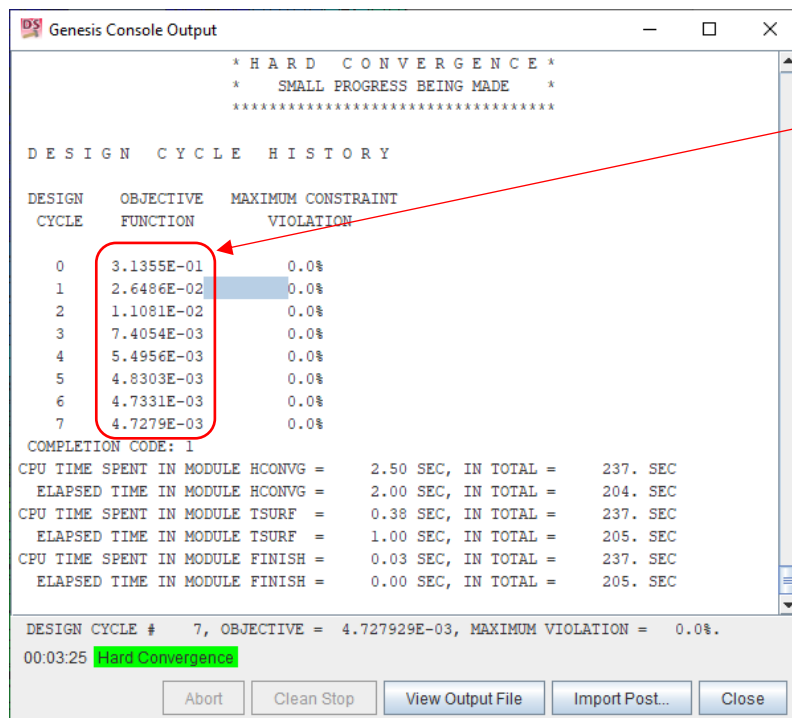


Figure 10 – Design cycle history displaying a successful hard convergence

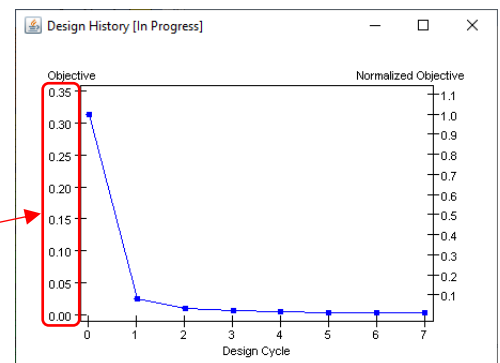


Figure 11 – Graph showing how the material was removed over 7 cycles

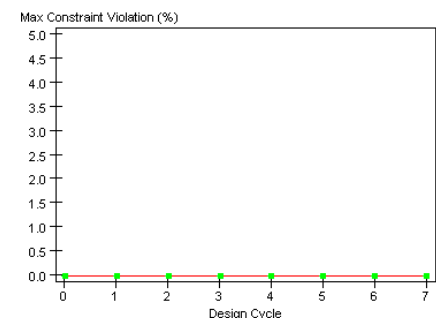


Figure 9 – Constraint behaviour graph

6.1 SIGNIFICANT STUDIES

This next section of the report highlights three of the more significant topology studies that played a part in achieving the target criteria. Each stage consists of the new feature that was implemented to improve the results and progress towards the finished product.

6.1.1 STUDY 1

The first successful optimisation was only able to deliver 16% of the material. This may have been due to the vagueness of the instructions input into the software as only one loadcase and the mass fraction were included. It is clear from Fig.12 that there is very little material surrounding the upper bolt holes meaning that it does not meet the criteria of the design brief.

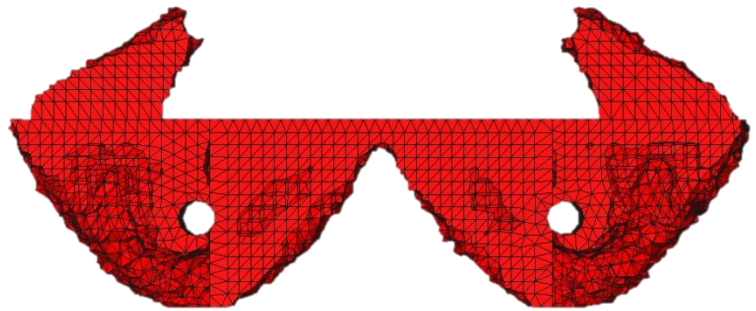
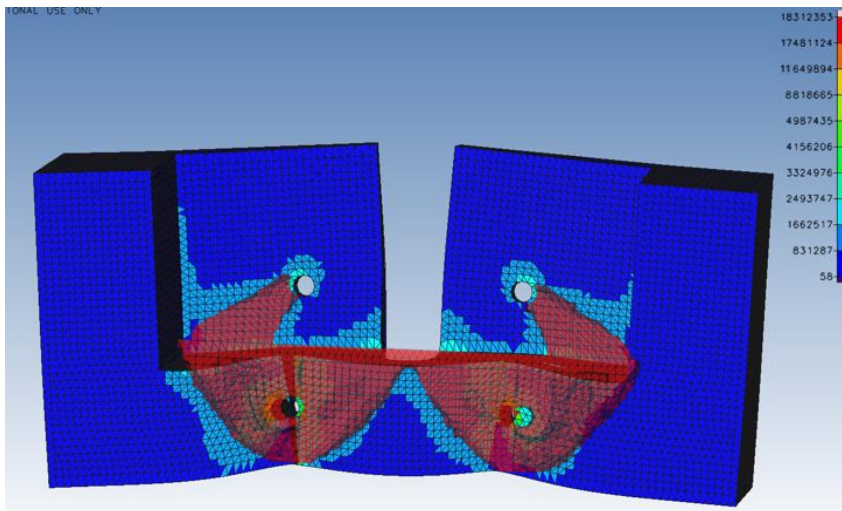


Figure 12 – First optimised bracket

Despite this study not meeting any of the targets, it was still a valuable step towards achieving them. Figures 13 and 14 show Fig.12 imposed on the stress and displacement graphs and shows that there is a clear relationship between the stresses that are exerted onto the bracket. This correlation implies that the topology optimisation is on the right lines but just needs some modifications to distribute material in the desired areas. It also supports what Jenkins (2020) said about the material on the sides of the bracket being wasteful (See appendix).



Stress

The scale in Fig.13 shows that the maximum stress of the component under loading conditions is 18MP which is below the material limit in Table 2.

Figure 13 – Optimised bracket projected onto the stress study

Displacement

Fig.14 shows that the maximum displacement values that act on the component are $4.1E-2m$ (Red) and have been scaled up on a deform scale to become visible to the user. Nearly all the material affected by these displacement values is removed during the topology study.

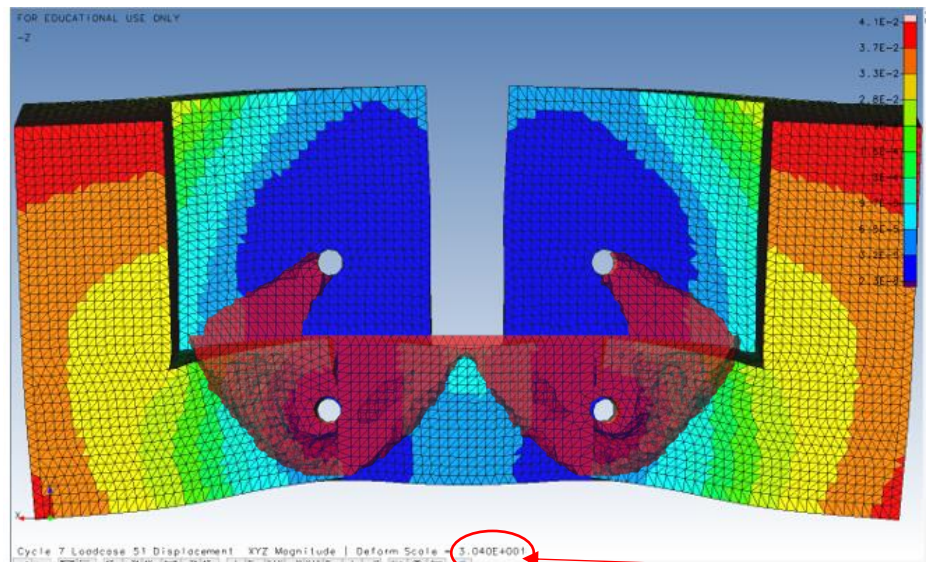


Figure 14 – Optimised bracket being projected onto the displacement study

Scale factor:
 $3.040E+001$

6.1.2 STUDY 2 – ELEMENT GROUPS

To increase the amount of material that would be distributed around the bolt holes, a second element group was added. This involved selecting an area of fixed geometry that would be excluded from the topology optimisation.

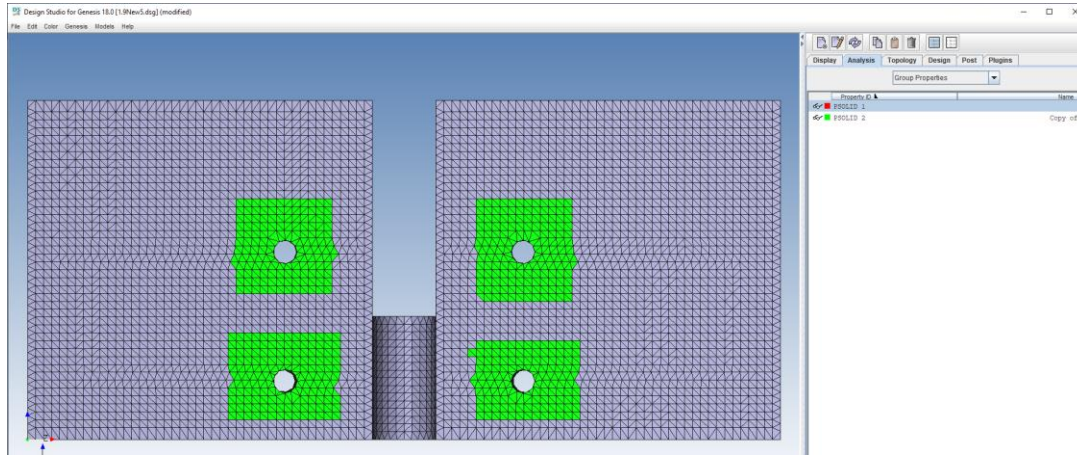
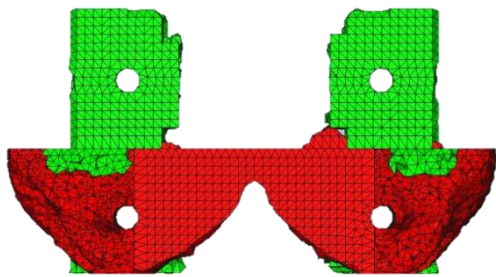


Figure 15 – Introduction of the second element group



With the addition of a second element group, it can be seen straight away that the model has improved. The shape of the topology matches the previous study, signalling that it still complies with the stresses and displacement acting on the bracket. The material around the holes is also thicker and now meets the requirements in Table 1.

Figure 16 – Optimisation results with second element group (View 1)

One problem with this study was the material distribution underneath that shelf as there seemed to be a section missing (See Fig.17). This could cause problems when the load is applied to the bracket as it is not structurally secure enough. Jenkins (2020) agreed with this, adding that “the groove in the material will want to close while under pressure from a load and will likely end up bowing or buckling.”

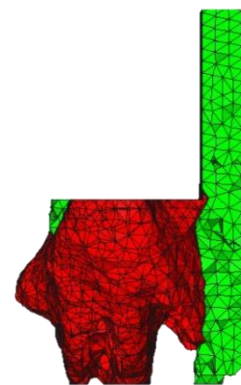


Figure 17 – Groove appeared underneath the platform

Part Weight

This model was converted to an STL and uploaded to Solidworks for further analysis to be carried out regarding the mass properties. On doing so, it was discovered that the new model was above the 0.1lbs (0.045kg) weight limit. The mass was calculated by using the volume obtained from Solidworks and the specific gravity value from Table 2.

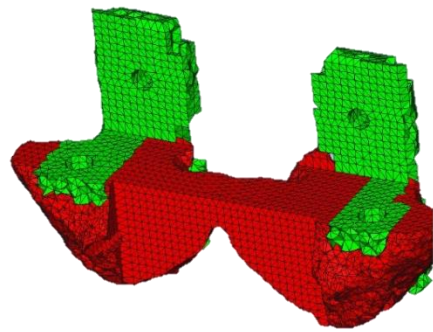


Table 3 – Calculating the mass of bracket – attempt 1

Figure 18 - Optimisation results with second element group (View 2)

Part Properties	Values
Volume	4.5e-5m ³ (Solidworks, 2020)
Density	= Specific gravity x 1000 = 1.34 x 1000 = 1340 kgm ³
Mass	= Volume x Density = 4.5e-5 x 1340 = 0.0603kg

6.2.3 STUDY 3 – MODIFYING CURRENT CONDITIONS

In order to achieve the mass target of 0.045kg, further topology studies were carried out with small changes being made to each one in a trial and error format.

Fixed Constraints

The fixed boundary conditions were adjusted so they did not apply right through the bottom two holes (See Fig.19). Instead they were applied approximately 1/3 of the way through from the back plate (See Fig.20). This caused the groove present in Fig.17 to disappear as the material had distributed towards the area that was now fixed, providing additional support to the platform.

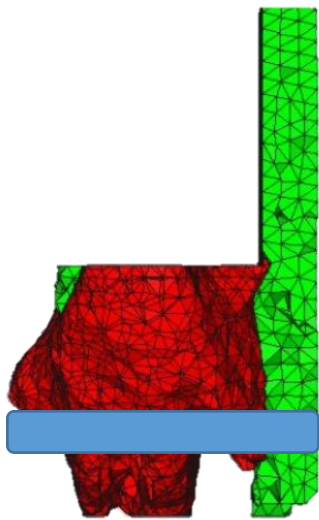


Figure 19 – Initial fixed grid position

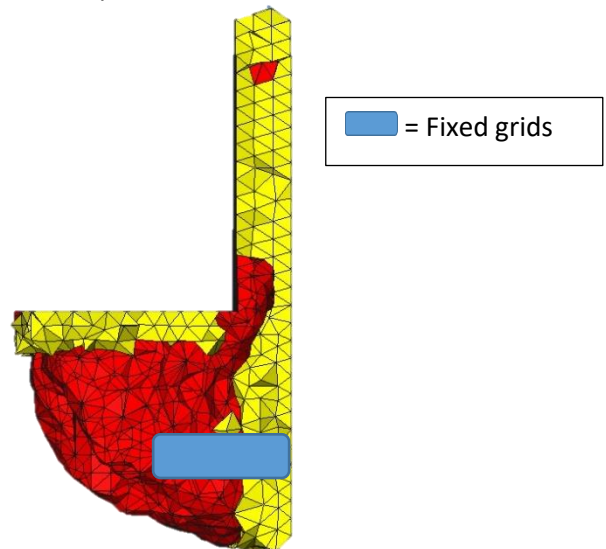


Figure 20 – Modified fixed grid position

Second Element Group Size

Considering the forces will be applied to the -Z direction, it did not seem feasible to require the additional material on the X axis. The element group was modified slightly so that the 2x hole diameter thickness requirement mentioned in Table 1 was only applied in the Z direction (See Fig.22). This modification only applied to the top two holes, as it was mentioned by Jenkins (2020) that these holes are being used to fix the bracket in place, as opposed to bearing the weight of the platform like the bottom holes.

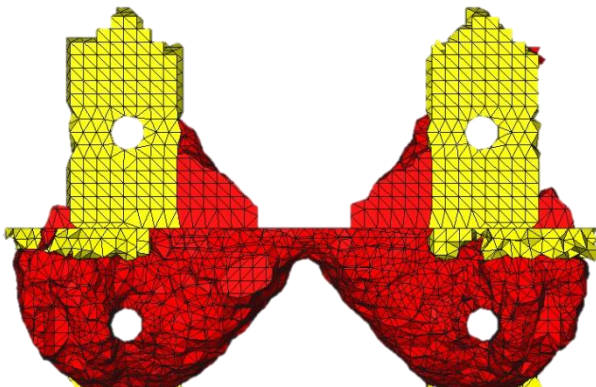


Figure 21 - Optimisation results with modified element group (View 1)

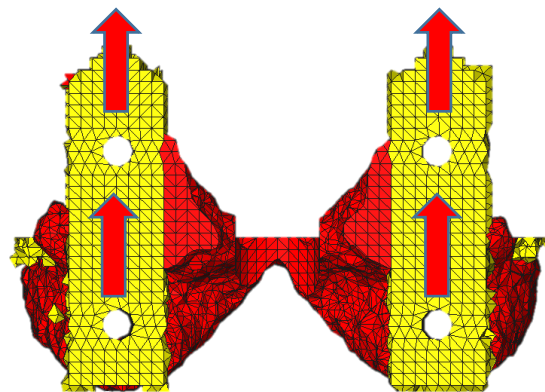


Figure 22 – Arrows indicating the force acting in the Z direction

Part Weight

The combined result of the two modifications that were made to the study shows that the model is now within the weight tolerance of 0.045kg (See Table 4).

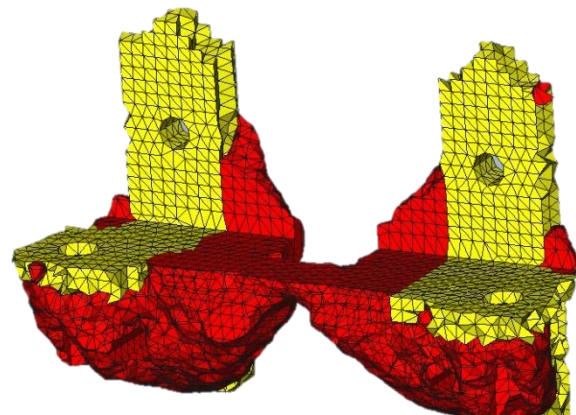


Figure 23 - Optimisation results with modified element group (View 2)

Table 4 Calculating the mass of bracket – attempt 2

Part Properties	Values
Volume	3.35e-5m ³ (Solidworks, 2020)
Density	= Specific gravity x 1000 = 1.34 x 1000 = 1340 kgm ³
Mass	= 3.35e-5 x 1340 = 0.045kg

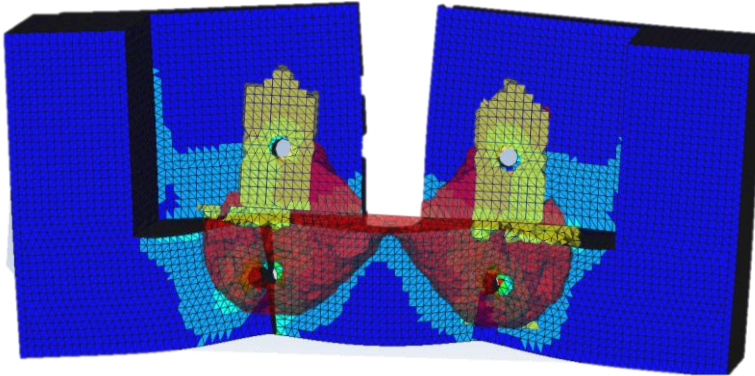


Figure 24 – Final optimised bracket projected onto the stress study

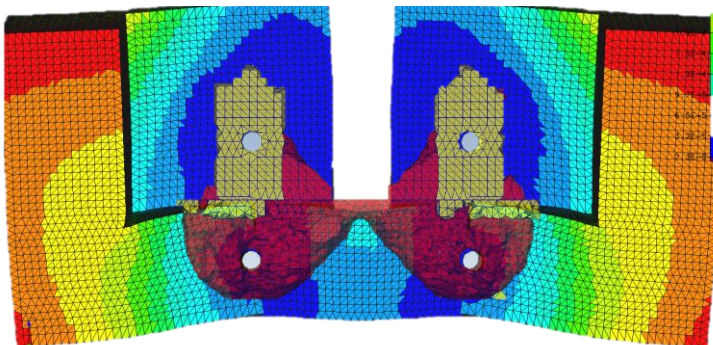


Figure 25 – Final optimised bracket projected onto the displacement study

Figures 24 and 25 show the final optimisation study imposed on to the stress and displacement studies. These figures support the accuracy of the topology optimisation as there is a clear relationship between the material removed and the forces acting on the bracket.

7.0 RECOMMENDATIONS

The objective of this report was to carry out a topology optimisation on an existing component and meet a certain criterion in doing so. While this was mostly achieved, there were several things that could be implemented to further improve the results of the optimisation.

Firstly, the optimised model could be converted to a CAD format so that some finishing touches could be added to improve the aesthetics as the final topology study has many jagged edges. Any areas of high stress concentration could be reduced by applying the appropriate fillets. These could also be applied to any corners as this material is not of purpose to the strength of the part Jenkins (2020). This would also give a better idea of how the finished product would look compared to the original.

Also, countersunk holes could be used for the top two bolt holes as a means of reducing any stress concentrations that may appear to form around those holes. Countersinking is commonly used in the aerospace industry and will increase the strength of a structure consisting of multiple pieces together (Reithmaier, 1999). Jenkins (2020) disagreed with this and stated that countersunk holes will take away material that is critical to support and should not be used unless the bolt caps are taking up too much room. However, SFGate (2020) suggests that a small chamfer could be applied to remove any rough edges or burrs and reduce the likelihood of a stress concentration from occurring from the hole.

Finally, a review of the material distribution could be carried out to ensure that the material is 2x the thickness of the hole diameter for the material surrounding each hole. The material could be taken from underneath the shelf as it was pointed out by Jenkins (2020) that there is an excessive amount of material located around the bottom bolt holes in the final study. (Jenkins, 2020) the goes on to say that a properly placed gusset would perform the same action with a fraction of the material being used, quite like in the winning design (See Fig.26)

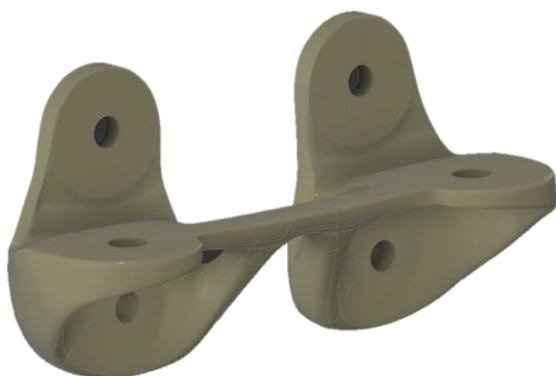


Figure 26 – Winning optimisation (GrabCAD, 2019)

8.0 CONCLUSION

It is clear from this report that topology optimisation can be a very useful tool for anyone tasked with redesigning an existing part. Knowledge and understanding of the subject are required however so that any obstacles that may be encountered along the way can be bypassed and rectified to meet the end goal. That was reflected in this report as the goal would not have been achieved if the study was not repeatedly analysed and modified on a trial and error basis so that the final optimisation study was of an adequate standard.

The analysis carried out was essential in creating the final study, with elements such as draft quality mesh, element groups and going back and modifying some of the conditions applied during the single analysis stage all contributing in the latter stages of the report to have a massive effect on the outcome.

APPENDIX

JAMES JENKINS INTERVIEW TRANSCRIPT

Q: What is your opinion on the original design?

A: "The thick sections of material on the sides of the original bracket is not relevant to the strength of the bracket so it is being wasted and should be removed. The same applies to the material above the top two holes that exceeds the minimum thickness around the hole limit."

Q: What is your opinion on the topology optimisation studies?

A: "The material around the bottom bolt holes should be thick as it is bearing the brunt of the weight applied to the platform. Also, the material underneath the platform is essential as it means that the shelf is less likely to bow or buckle. The groove that appears in the second study (See Fig.17) could cause the shelf to bow/buckle over time as the gap will gradually close. A gusset could be added to the final study in place of the material as it will do the same job if placed correctly. A brace angle of 45 degrees or more from the horizontal plane would produce a strong support feature for the job."

Q: What is your opinion on the winning design?

A: "The two fixing points (webs) located underneath the horizontal shelf of winning study are critical as they secure and strengthen the web. The positioning of them is essential to the strength of the component as they act as a gusset point so the design would fail if they were removed."

Additional comments:

"Rounding all corners of the part would reduce stress concentration and waste material. I make sure that I do this whenever I am tasked with modifying a support feature as the corner material is near enough redundant."

"For a material that is bearing a load, ideally you want as much material as possible around those holes. The bottom holes especially as they will be absorbing the most weight with the top two holes being used to fix the bracket in place. Countersunk holes may cause problems as they are essentially removing material that is needed as the holes are the more critical areas of a support bracket."

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