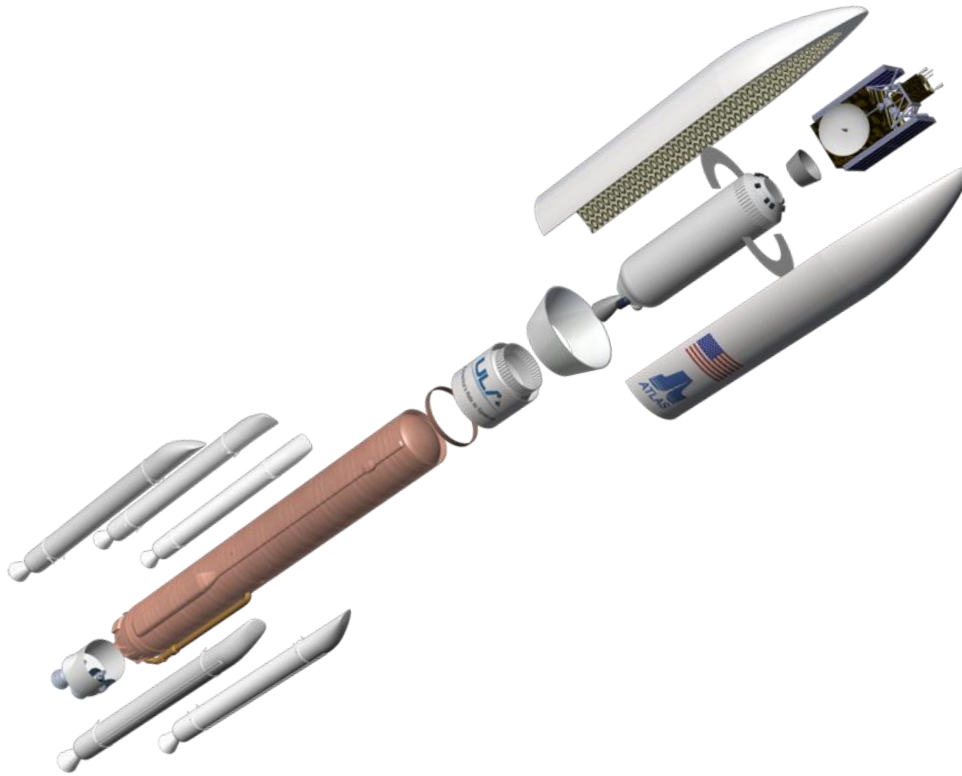




ULA Rocket Hardware Design

Advanced computational methods
BEng Mechanical and Manufacturing Engineering

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Faculty of Engineering

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Executive Summary:

The following document provides a conceptual topology optimisation study on an internal boat tail support bracket, which is located on the upper stage of the Atlas V rocket. The Atlas V is an expendable launch system which operates out of space missions. It was developed and manufactured under the authority of united launch alliance (ULA), whom also co-operated with the GrabCAD association to run a competition for the re design of the internal boat tail bracket seen in the document. Through the use of topology, informed decisions were made on optimising and redesigning the internal boat tail bracket to improve its current design and mass properties. Topology optimisation is a generative method which enables experimental testing of a component to be undertaken without the need for added design or manufacturing techniques.

This document outlines the methods undertaken during the topology study and explanations to any decisions made during that time. A full analysis was performed on the results obtained, and from the results and optimised component, decisions were made on the potential re design of the internal boat tail bracket.

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Introduction:

The aim of the report:

The following report has been undertaken to research and establish, how topology optimisation can be utilised to re-design a boat tail bracket located on the Atlas V rocket. The initial information provided, was extracted from the 3-2-1 lift off competition ran by GrabCAD, which was in association with the united launch alliance (ULA). The aim of the report was to further research the bracket and the information provided. A conceptual study was carried out using design studio for genesis, a topology optimisation tool. The topology results were interpreted and utilised for the redesign of the boat tail bracket. The parameters set out by the competition were adhered to during this process and the redesigned component was critically appraised and analysed, aiding in recommendations being made for future work.

The model:

The bracket was modelled on solid works from a drawing provided by GrabCAD, all dimensions were converted to SI units, the original drawing can be seen below. The component was also meshed in solid works and exported to genesis.

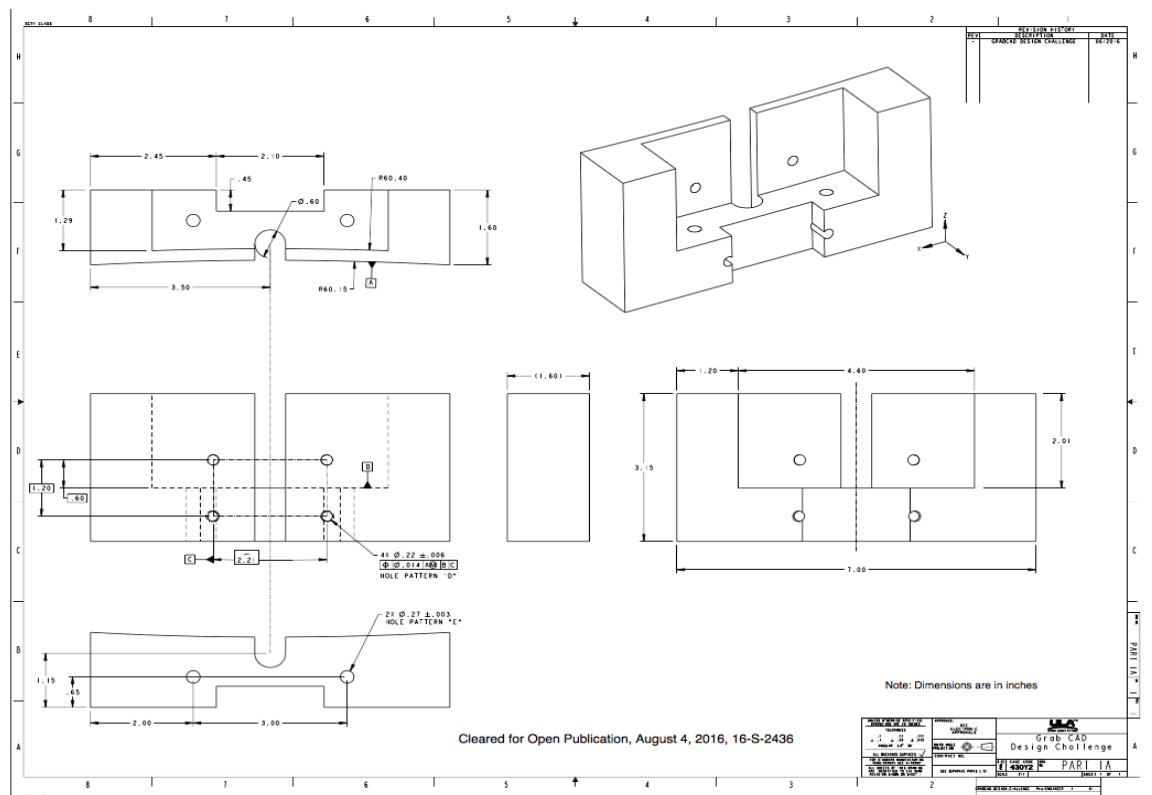


Figure 1: ULA Drawing of Boat Tail Bracket. (Alliance, 2016)

The Atlas V:

The Atlas V is a launch rocket utilised for space missions such as; manned and unmanned interplanetary missions, cargo transportation, ferrying astronauts to and from the space stations and releasing satellites into space orbit (Howell, 2018). The rocket is powered by two engines, the first is the lower stage engine and creates the thrust for deployment into space. The second is the upper stage engine and is attached to the centaur compartment which is surrounded by the payload fairing during deployment (Nasa, 2018). For the purpose of this report only the upper stage of the rocket is relevant as this is where the boat tail bracket is located and where the majority of the loading will occur. Below is a simplified drawing of the Atlas V components and the location of the boat tail bracket.

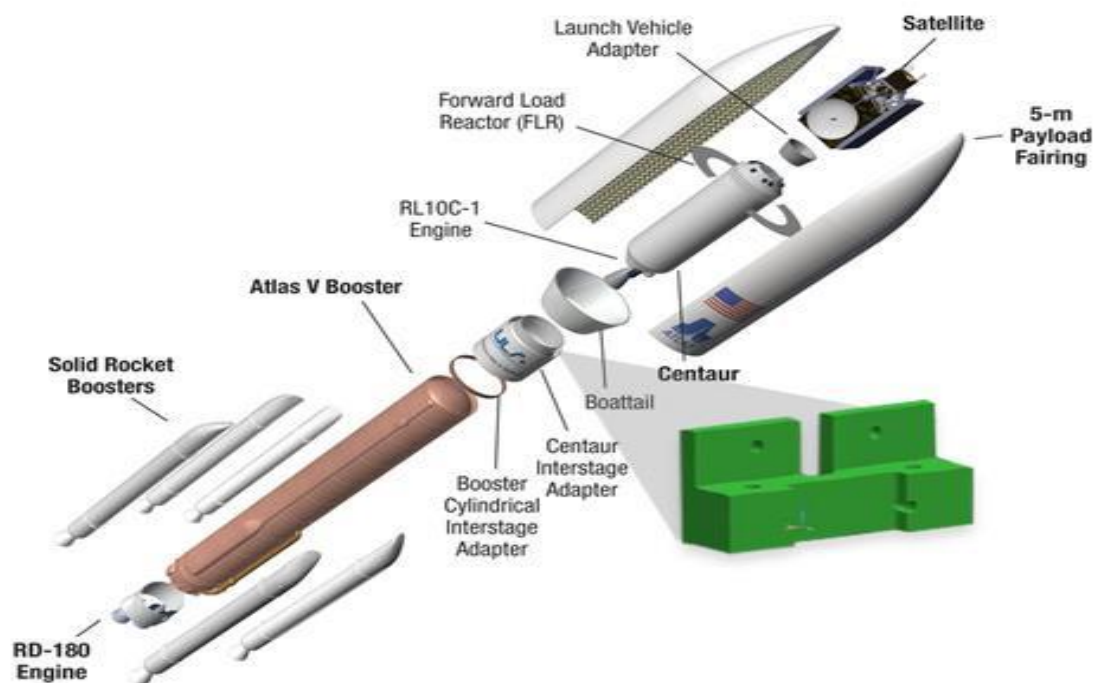


Figure 2: A Breakdown of The Atlas V components and The Location of The Boat Tail Bracket (Alliance, 2016).

Rocket boat tail:

The boat tail is a conical cylinder which aids in the overall stability of the rocket and assists in improving aerodynamic efficiency by reducing drag at subsonic speeds (Booth, 2015). (Calcara, 2016) also states that the slope of curvature must remain gradual to ensure no drag is incurred, therefore if the boat tail is designed correctly it will aid in the prevention of turbulent drag, whilst helping stability and security of the rocket and the centaur.

The payload fairing:

A payload fairing is a nose cone used to protect the rocket, it provides a safe environment for the space craft to ascend into space and minimises thermal damage to the cargo being transported (ULA, 2019). The payload consists of two independent expendable panels which are ejected off the cargo in space. The payload weighs from 7,769lbs to 9,654 lbs depending on nose length (Alliance, 2016) . A drawing of a short and medium payload can be seen below:

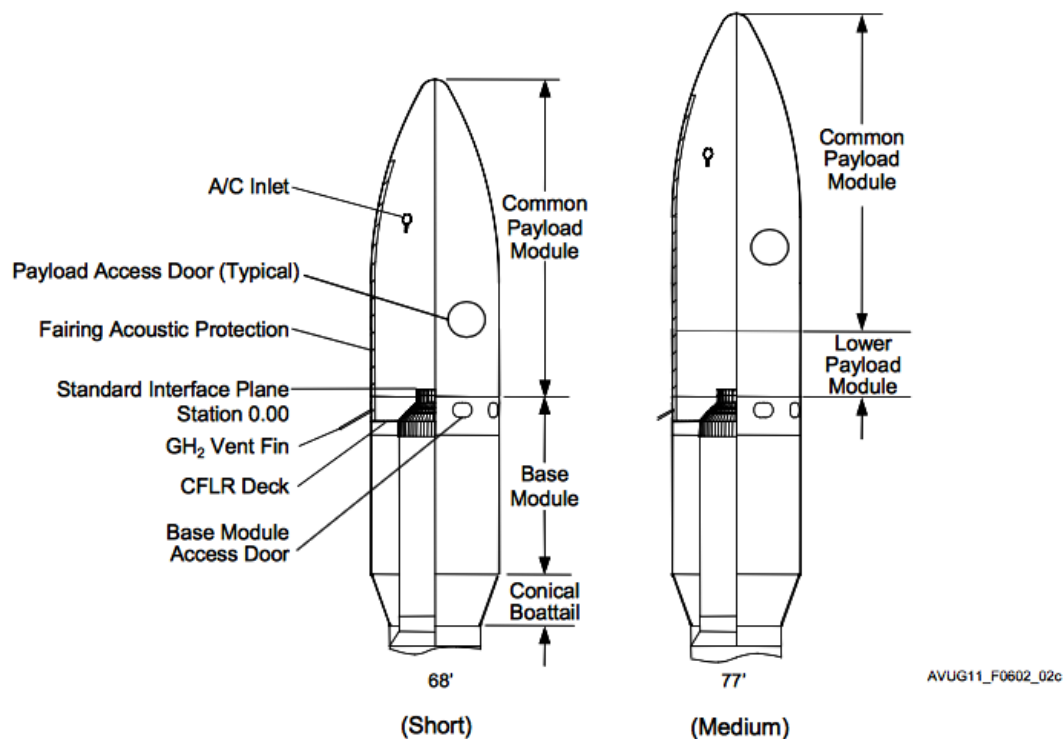


Figure 3: Image of short and medium length 5m payload fairing found on the Atlas V. (Alliance, 2016)

The function of an internal boat tail support bracket:

The boat tail bracket is used for support during ground processing at the base of the payload fairing and is also utilised around the upper section of the rocket for working platforms. The bracket is bolted to the boat tail using 4 bolts for security the component must be durable enough to endure all conditions. The bracket however, must remain as lightweight as possible, so the weight is restricted to 0.1lb. By reducing the weight of the bracket, it ensures the rocket remains as light weight as possible during deployment (GrabCAD, 2016).

The material of the support bracket:

Space launch components are manufactured from various materials such as aluminium alloys, wound composites, titanium alloys and high strength steels. (Henson, 2018). The information provided by GrabCAD states that the component is to be manufactured from Ultem 9085 (GrabCAD, 2016). Ultem is a strong, lightweight and flame-retardant thermoplastic, which incorporates high mechanical strength to weight ratio. Ultem 9085 is usually manufactured in resin form. The typical uses for Ultem are within the automotive and aerospace industry where it is utilised for reducing overall weight of components (Materialise, 2019).

The manufacturing of Ultem 9085:

The most popular manufacturing techniques for Ultem 9085 is 3D printing and injection moulding (Manufacturing, 2018). For aerospace components, a 3D printing technique called fused deposition modelling (FDM) is the preferred method, this is due to its ability to accurately produce solid intricate high strength components (SYS, 2017). The technique uses filament that is heated to its melting point and extruded layer by layer until the part is complete, however like with any technique there are limitations. FDM can sometimes lead to problems with warping and minor shrinking (Masood, 2014), therefore care must be taken when manufacturing a component, this can then lead to extended manufacturing times.

Topology optimisation:

Topology optimisation is a mathematical method that has the ability to systematically reduce a components size and design, until only the necessary material is present. Topology optimisation requires certain conditions to do this (Alonso, 2017). It requires loads, fixtures and boundary conditions to be added to the model. From those conditions, the software can determine what material to keep whilst developing the required load path. The model however, must be meshed, this is to enable the system to calculate the stresses and strains at each element and determine whether the reduction of that element may affect the structure (Peng, 2018).

Design studio by genesis:

Design studios by genesis is a topology optimisation tool which is based on the finite element method (FEM). The software allows users to easily create optimised design data and display the results. The system utilises FEM for “direct and modal frequency analysis, heat transfer analysis buckling calculations and normal modes” (VRandD, 2019). The system however cannot mesh the part and therefore a secondary software would be required to do that.

Methods:

As previously stated a conceptual study was carried out on the bracket. The bracket was modelled in solid works and then analysed and optimised using the topology software design studio for genesis. All the GrabCAD requirements were adhered to and can be seen in the Appendix A. The following section outlines information and explanations of the component set up in both solid works and genesis.

Solid works modelling:

The component was modelled in solid works. The dimensional data was derived from the drawing provided by the GrabCAD which was seen earlier on in the report. The component was meshed with a 1.9mm mesh, this is 1/3 of the thinnest part material and is recommended as it provides at least three elements per face. The model was exported as a NASRTN file into genesis the meshed model can be seen below.

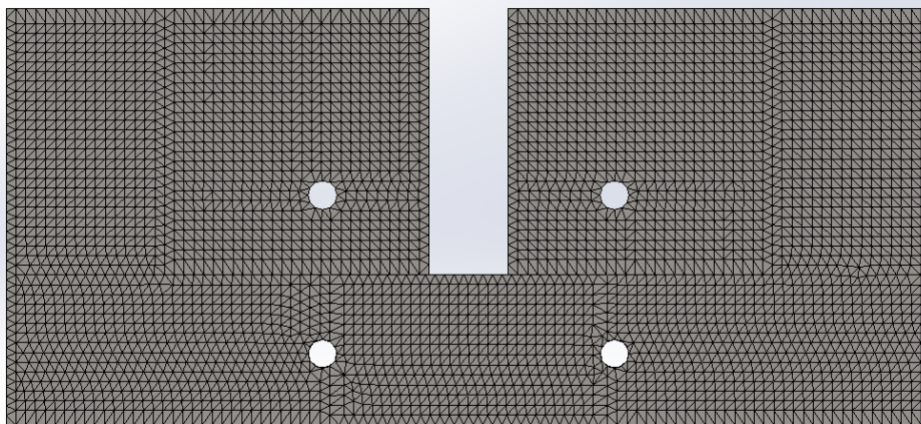


Figure 4: The boat tail bracket which was modelled and meshed in solid works, (Roberts, 2019).

Design studio for genesis topology set up:

The bracket was imported into Genesis where the topology was completed, certain parameters were required to be set up before the topology could continue. The parameter set up has been divided into two sections; section A for the single analysis and section B for the optimisation.

Material properties:

The ULA had previously specified the material in which the component was to be manufactured out of was Ultem 9085. The material properties were also given for Ultem 9085 and are shown in the table below:

Table 1: Information provided from GrabCAD of Ultem 9085 material properties.

Sub script value:	Meaning:	Value:	Sourced from:
E	Youngs modulus	325 KSI	(GrabCAD, 2016)
/	Specific gravity	1.34	(GrabCAD, 2016)
v	Poisson's Ratio	0.41	(GrabCAD, 2016)
ST	Material Strength allowable	4500 PSI	(GrabCAD, 2016)

The values however, were all imperial values. Genesis runs using SI units, therefore all values were converted to each standard SI unit. The converted units can be seen in the table below and hand calculations can be found in the Appendix B as equation one:

Table 2: Material properties for Ultem 9085 converted units.

Sub script value:	Meaning:	Value:	Sourced from:
E	Youngs modulus	2.2407 GPa	(Converters, 2020)
ρ	Density	1340 Kg/m ³ .	(Bansal, 2005)
v	Poisson's ratio	0.41	(GrabCAD, 2016)
ST	Material Strength Allowable	31.0247 MPa	(Tools, 2020)
G	Sheer Modulus	2050 MPa	(Stratasys, 2017)

The sheer modulus value was included. This allows the software to be aware of when the material would sheer and potentially provide more accurate results. The inputted values within genesis are below:

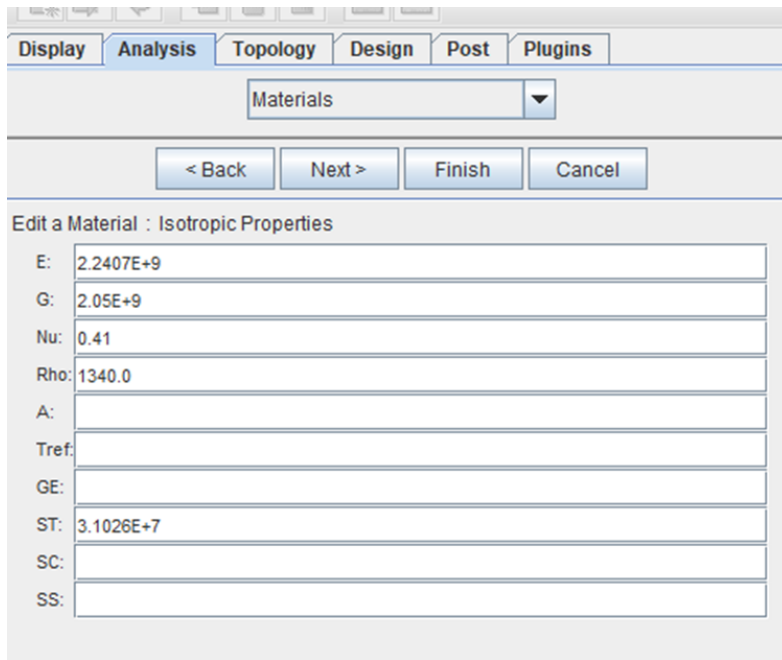


Figure 5: Converted material values inputted into genesis (Roberts, 2020).

Section A:

Setting grid components, elements, loads and load cases:

In order to accurately run the topology boundary conditions were set up within genesis. Grid set components were set, a load applied and elements selected, this enabled the software to recognise areas of material to be kept.

The brief outlined that the bracket was bolted to the boat tail using four bolt holes. Therefore, the bracket was constrained via the internal section of the four holes to eliminate the 6 degrees of freedom.

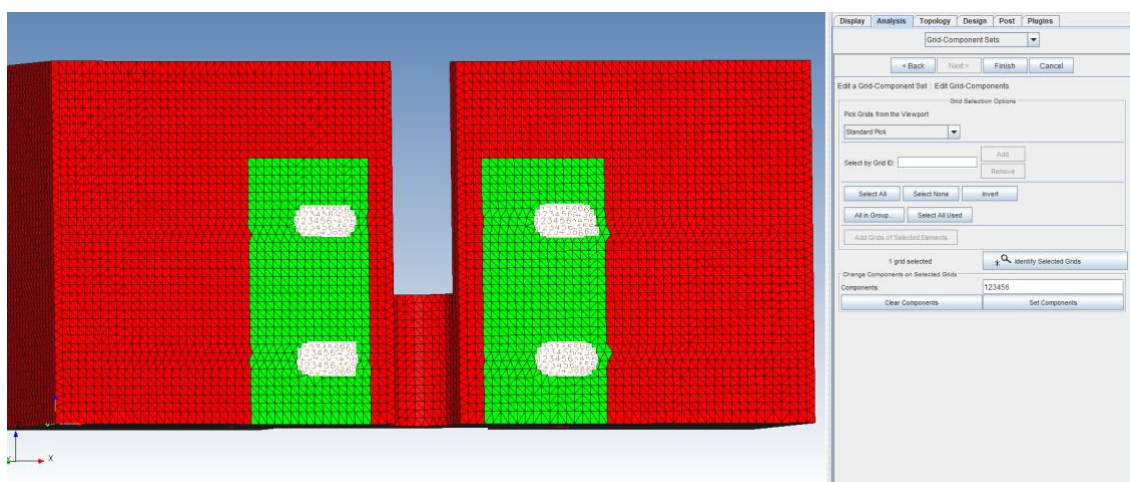


Figure 6: Example of how the boat tail bracket was constrained within genesis, (Roberts, 2020).

The elements selected to be kept were clustered around the fixed bolt holes as there must be at least two times the diameter material remaining around the holes on the bracket. There are typically three elements per diameter of the holes, therefore 6 elements each direction of the holes was selected to ensure the criteria was met and the elements were transferred into another area called Psolid 2.

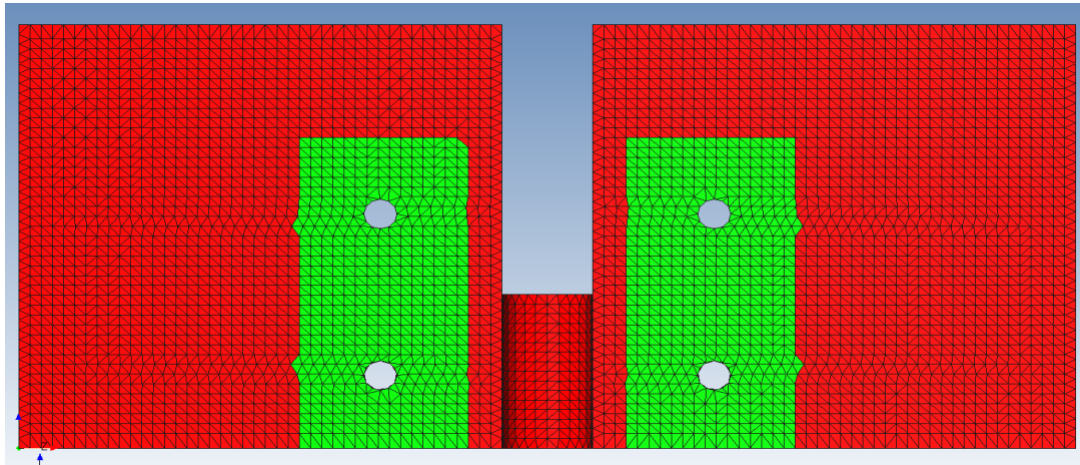


Figure 7: The elements to be kept in Psolid 2. (Roberts, 2020).

There is a work platform which creates a uniformly distributed load and is applied to the surface called datum B. The loading of the bracket was further researched, but no subsequent data was found to allude to another load being applied to the bracket.

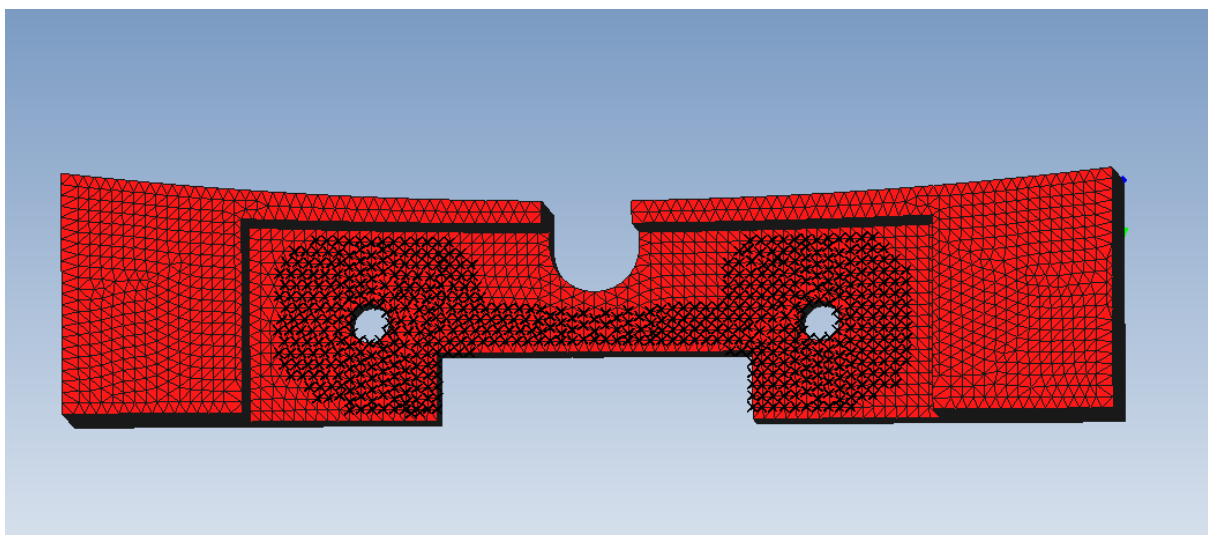


Figure 8: Top view of load applied to face, datum B, (Roberts, 2020).

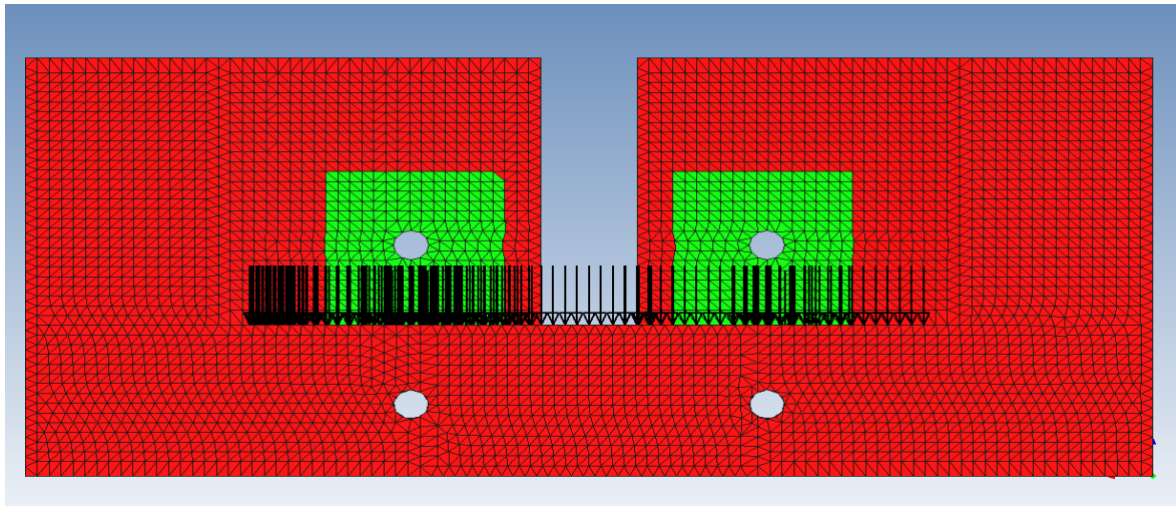


Figure 9: Front view of load applied to face, datum B, (Roberts, 2020).

The load was applied around the holes twice the diameter and thinly between both components to ensure the load path connected both sides of the bracket, ensuring the bracket remained one piece. The load was provided in the brief as 600lbf, but needed to be converted to SI units. Therefore, through a quick conversion (Units, 2020), the load was calculated as 2668.93N and was then divided by the grids selected, and set in the -z direction.

Static Loads

< Back Next > Finish Cancel

Edit Static Loading : Edit Force, Moment, SPCD

Grid Selection Options

Pick Grids from the Viewport

Standard Pick

Select by Grid ID: Add Remove

Select All Select None Invert

All in Group... Select All Used

Add Grids of Selected Elements

573 grids selected Identify Selected Grids

Change Loading on Selected Grids

Clear Loads/SPCDs

Data Form: Load Direction+Magnitude

Direction: By 2 Grids... By 3 Grids...

X: Y: Z: -1

Magnitude: 2668.93/573

Add Force Add Moment

Figure 10: Setting up load on genesis on datum face B, (Roberts, 2020).

A load case was set. The load case option can also allow multiple loads and fixtures to be added to the component for analysis.

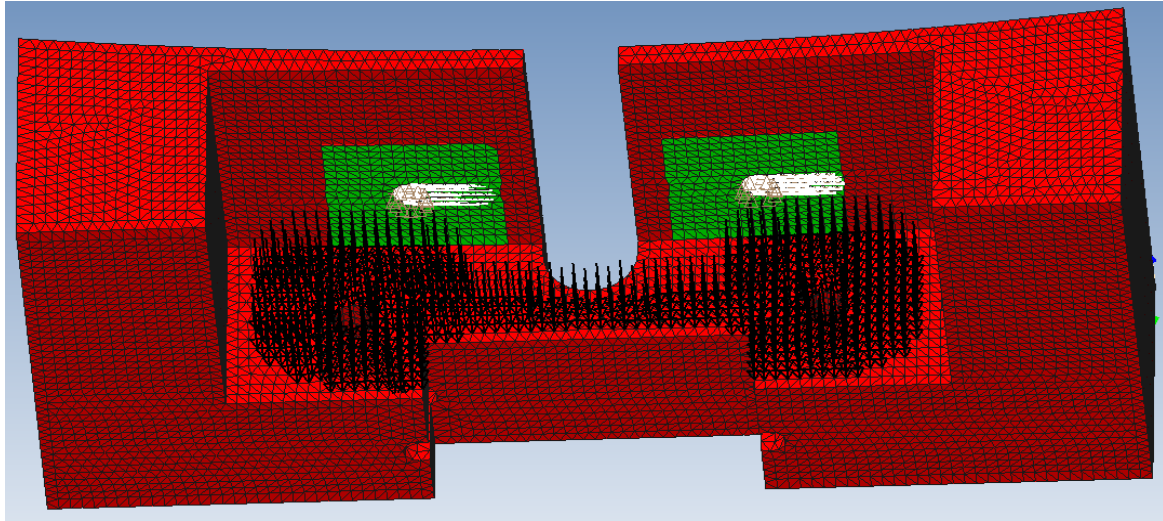


Figure 11: Image showing load cases being set to bracket. (Roberts, 2019).

Section B:

Setting up topology regions, objectives and constraints:

In order to run a full topology optimisation study, the topology conditions were set up. The first condition set was the topology regions. The topology regions are the areas which will be optimised, setting this up improves load balancing. The area to be optimised is Psolid 1 and the area to be kept is Psolid 2.

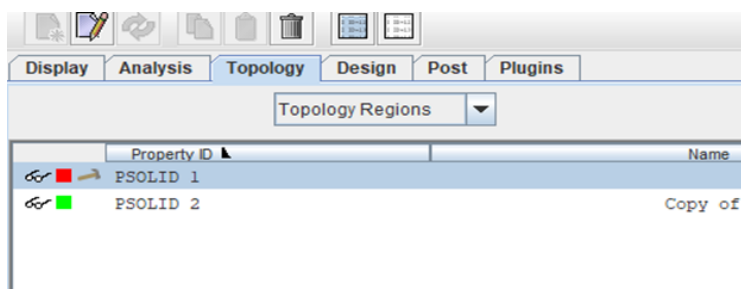


Figure 12: Image showing set up of Psolid's on genesis, (Roberts, 2020).

The initial mass fraction was set up in Psolid 1 as 0.1. This indicates the percentage of the material to be kept during optimisation. This was calculated and the calculations can be seen in the Appendix B, equation 2.

The topology region constraints were set up, constraint 1 mirrors about the YZ plane, this is to ensure that the part is symmetrical, the second constraint was to fill the y axis which would ensure there was no voids or missing areas in the part. The minimum size was 0.004 which is double the mesh, this ensures full integrity of the mesh.

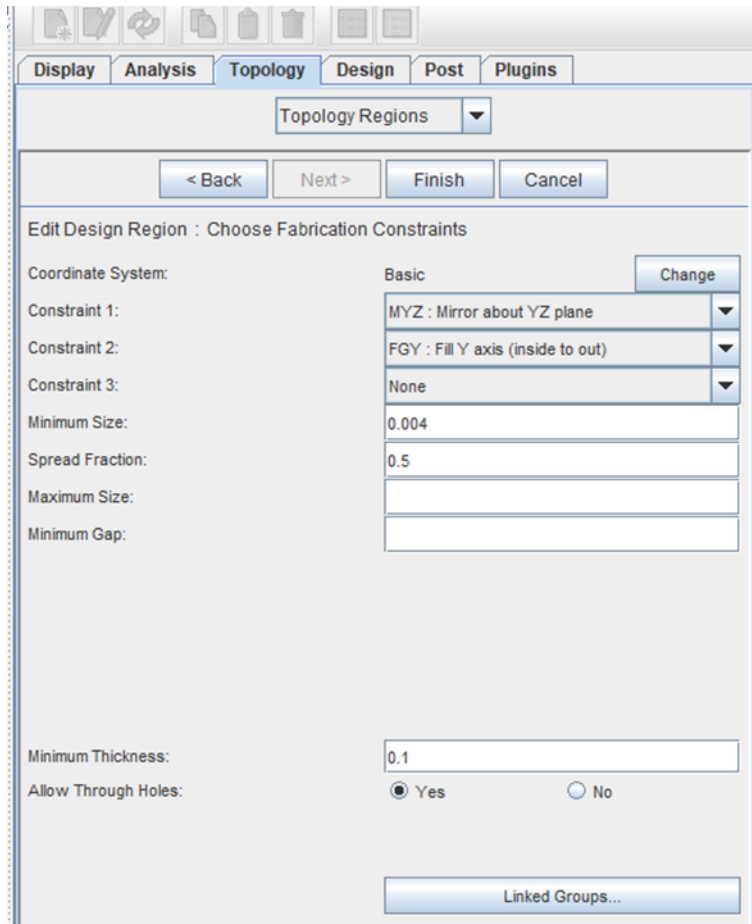


Figure 13: Setting up fabrication constraints on genesis, (Roberts, 2020).

The topology objectives ensure the stress, strain and displacement are observed in the component.

Results and Analysis:

The results and analysis are split into three sections; single analysis, optimisation results and the optimised bracket. The single analysis allowed an initial examination of the bracket's stresses and strains to be determined. The topology results enabled a better insight into a potential redesign of the part.

Single Analysis:

A table with the max and minimum values for each single analysis study is seen below:

Table 3: Single Analysis values:

Cycle No:	Type of Analysis:	Deform Scale:	Min Value:	Max Value:
0	Displacement, shown in figures 15 & 16.	1.228×10^3	0.0008mm	0.008mm
0	Stress, shown in figures 17 & 18.	1.228×10^3	40.11 MPa	400 MPa
0	Strain, shown in Figures 19 & 20.	1.228×10^3	2.2×10^{-5} Pa	2.2×10^{-4} Pa

The displacement seen in the bracket was very minimal when considering the magnitude of the load. The maximum and minimum stresses surpassed the required allowable stress of 31.02 MPa, the young's modulus was calculated (equation 3) as 18181 GPa and surpassed the required young's modulus of 2240 MPa, indicating to catastrophic component failure. This made the results questionable and would need to be further analysed for more reliable results. Images of the analysis results are below:

Displacement results cycle 0:

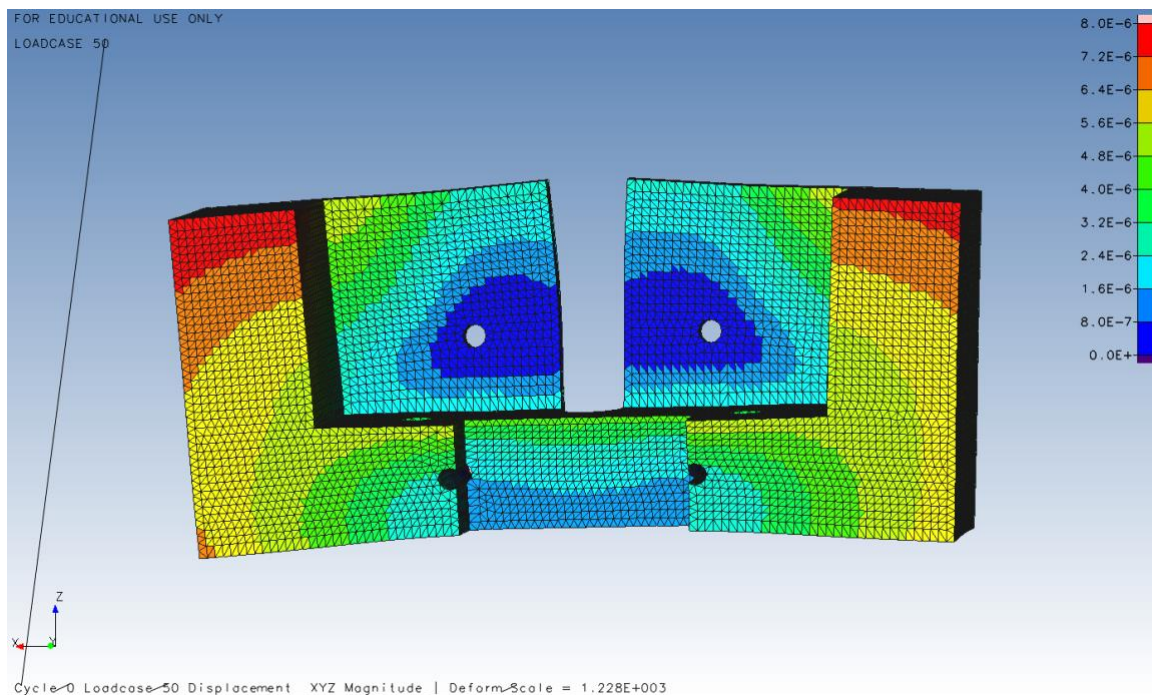


Figure 14: Bracket displacement at cycle 0, front view, (Genesis. Roberts, 2020).

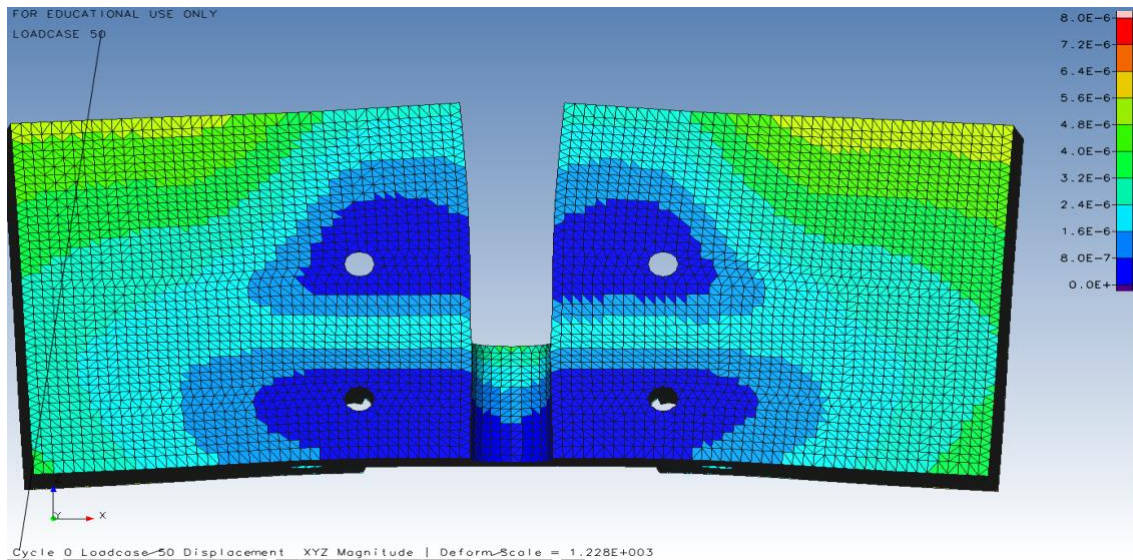


Figure 15: Bracket displacement at cycle 0, back view, (Genesis. Roberts, 2020)

The results show maximum displacement on the outer areas of the bracket, the displaced material is not required for the full function of the bracket so it should be removed to reduce displacement.

Stress results cycle 0:

There are elements internal of the holes which are highly stressed. The majority of stress was around the holes and lies in light blue to dark green stress regions. The bracket is constrained with the 4 bolts which reduces the six degrees of freedom, potentially creating stress concentrated areas shown in the images below:

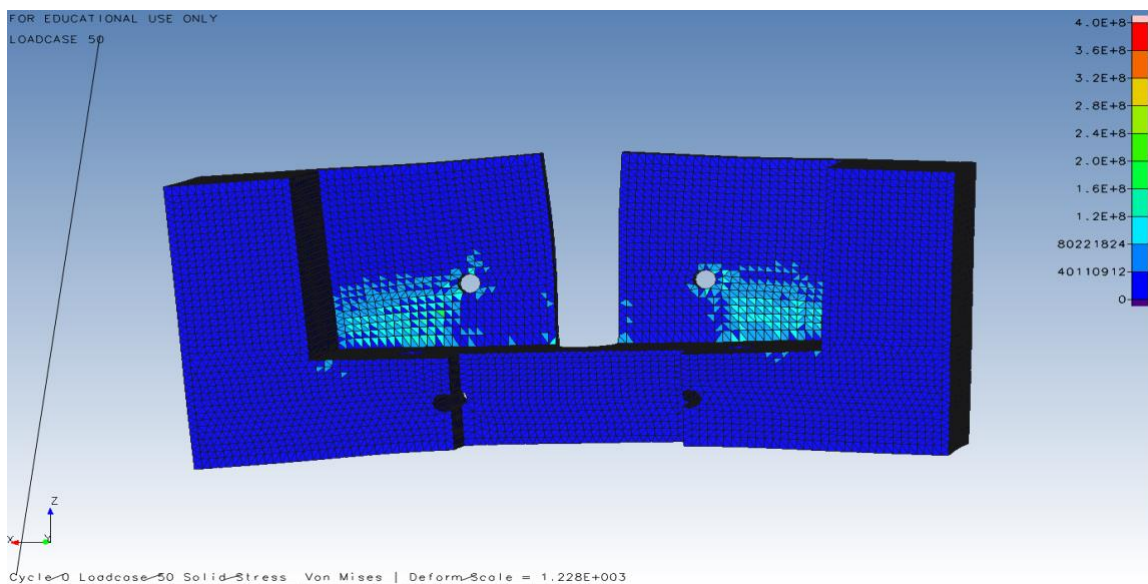


Figure 16: Bracket Stresses at cycle 0, front view, (Genesis. Roberts, 2020).

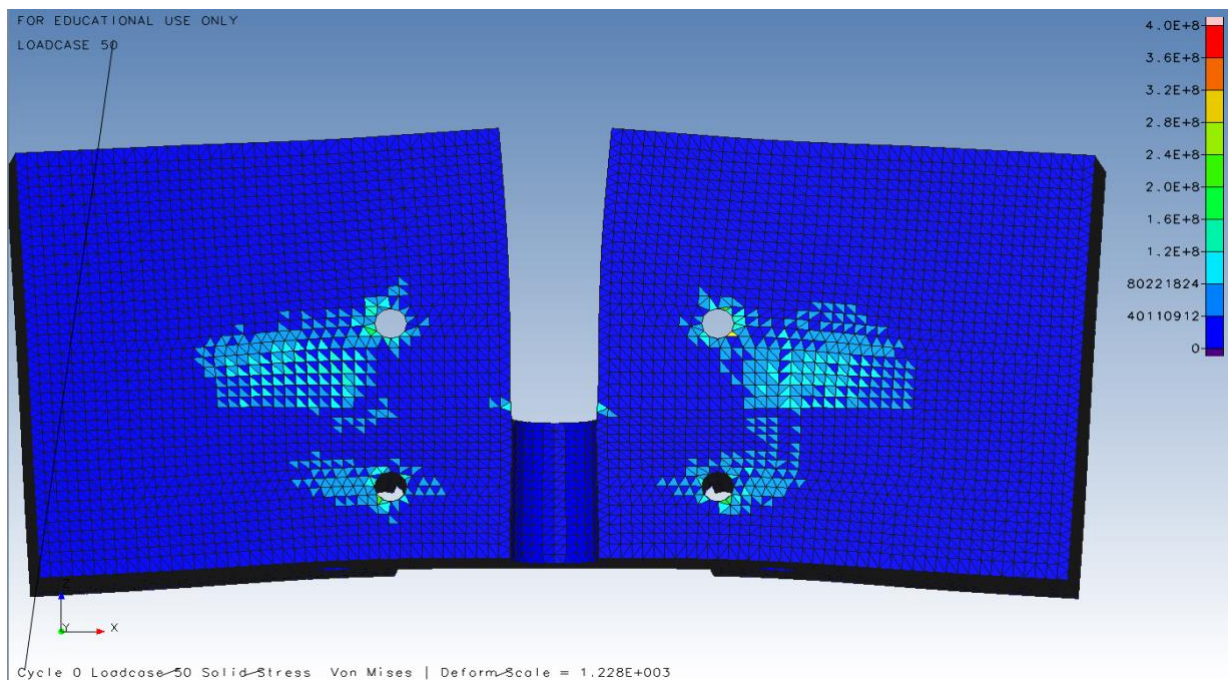


Figure 17: Bracket stresses at cycle 0, back view, (Genesis. Roberts, 2020).

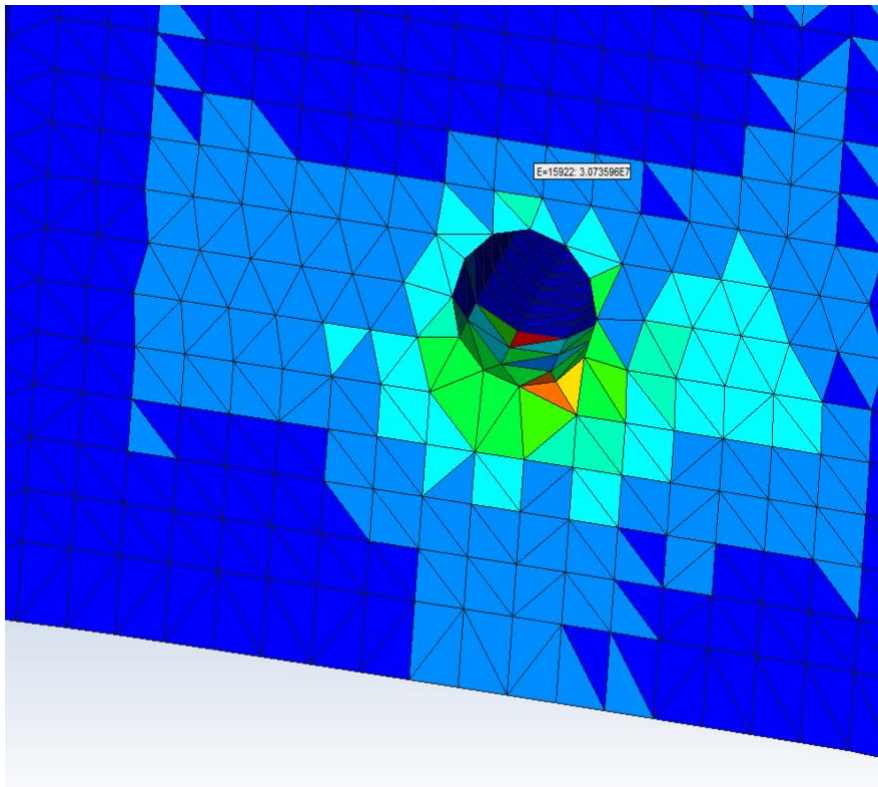


Figure 18: Stressed Elements in bolt holes, (Genesis. Roberts, 2020)

Strain results cycle 0:

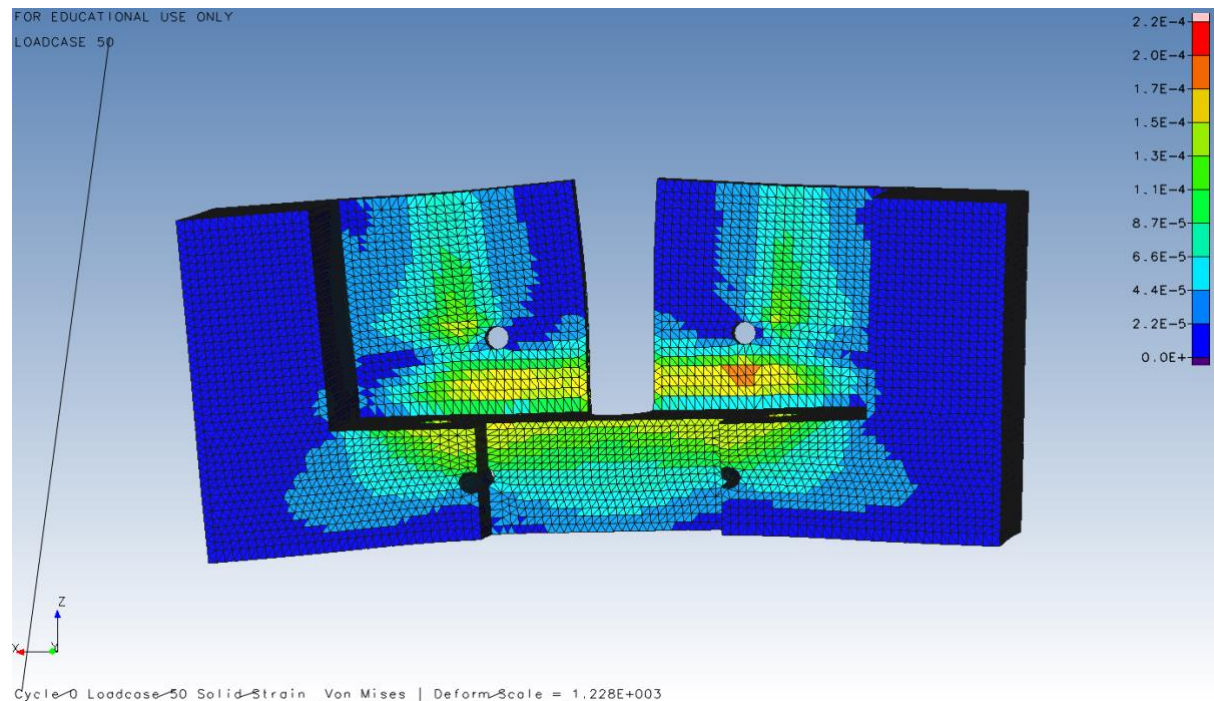


Figure 19: Bracket strain at cycle 0, front view, (Genesis. Roberts, 2020).

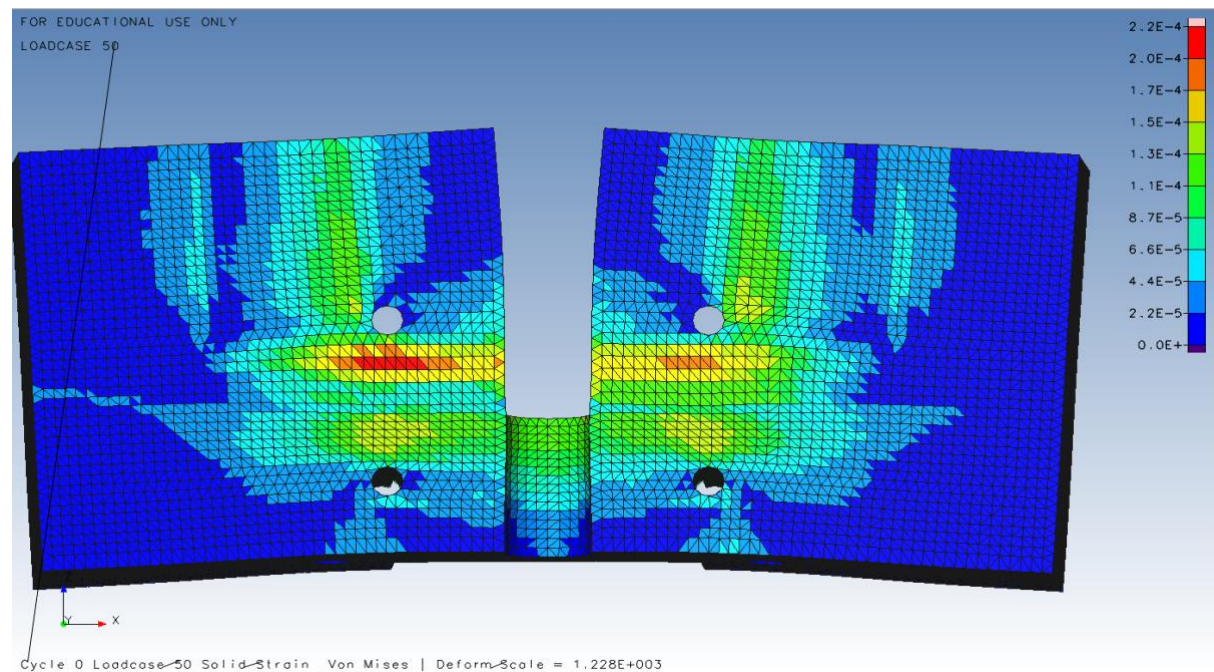


Figure 20: Bracket strain at cycle 0, back view, (Genesis. Roberts, 2020).

The highly strained areas are located below the holes, the fact that not all four holes are stressed in the same manner is questionable. This could be due to meshing/ modelling or element selection errors.

Optimisation results:

The optimisation ran 12 cycles and material was removed from areas deemed suitable. The results are shown in the table below:

Table 4: Optimisation result values:

Cycle No:	Type of Analysis:	Deform scale:	Min Value:	Max Value:
12	Displacement, shown in figures 22 & 23.	3.190	0.31mm	3.1mm
12	Stress, shown in figures 24 & 25.	3.190	7.2 MPa	72 MPa
12	Strain, shown in Figures 26 & 27.	3.190	7.9×10^{-3} Pa	7.9×10^{-2} Pa

The results show an increase in the displacement to 3.1mm which is due to the reduction in material. The maximum stresses in the component significantly decreased, but were still over double the maximum strength allowable of 31.02 MPa. The strained areas increased due to material reduction. The young's modulus of the component was calculated (equation 4) and improved to 911 MPa. This indicated the component did not fail but instead significantly deformed. A secondary optimisation would need to be carried out on the bracket and material would need to be added to the highly stressed areas. This should reduce the stresses, increase the bracket's stability which should reduce the displacement and strain.

Displacement cycle 12:

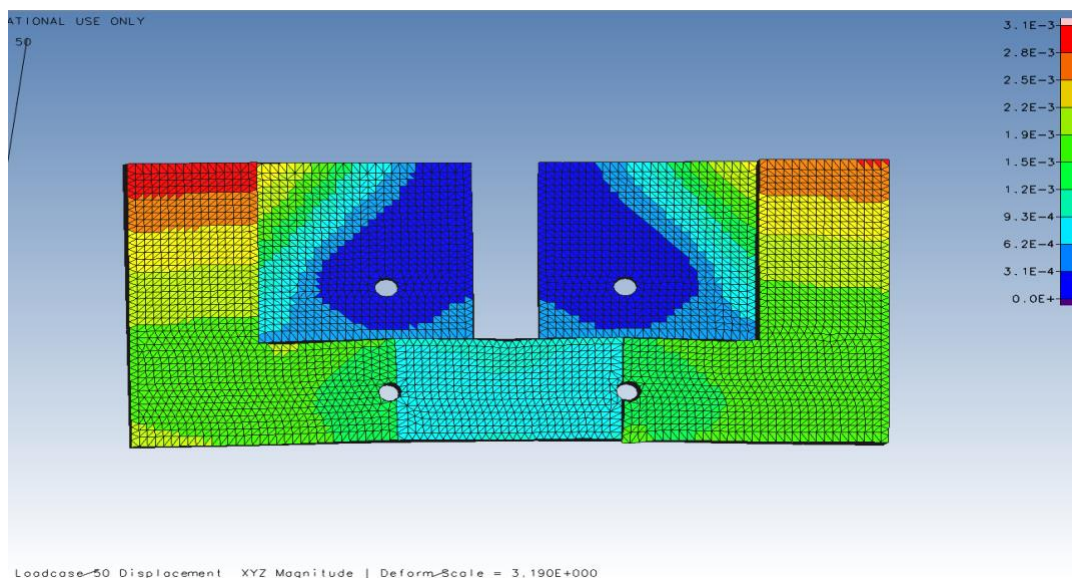


Figure 21: Bracket displacement at cycle 12, front view, (Genesis. Roberts, 2020).

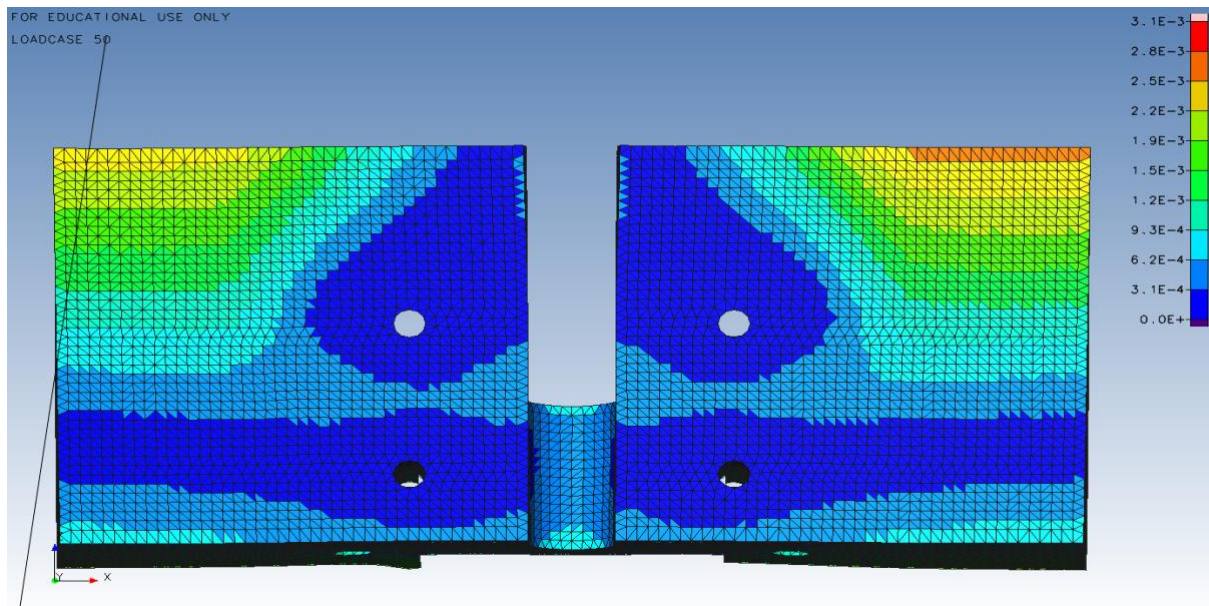


Figure 22: Bracket displacement at cycle 12, back view, (Genesis. Roberts, 2020).

The displacement is concentrated towards the front of the bracket directly beneath the load. Which typically is what should be seen.

Stress cycle 12:

The stress concentrations are reduced and located around the outer of the 4 constrained holes. Very few elements exceed 36 MPa, showing a successful topology.

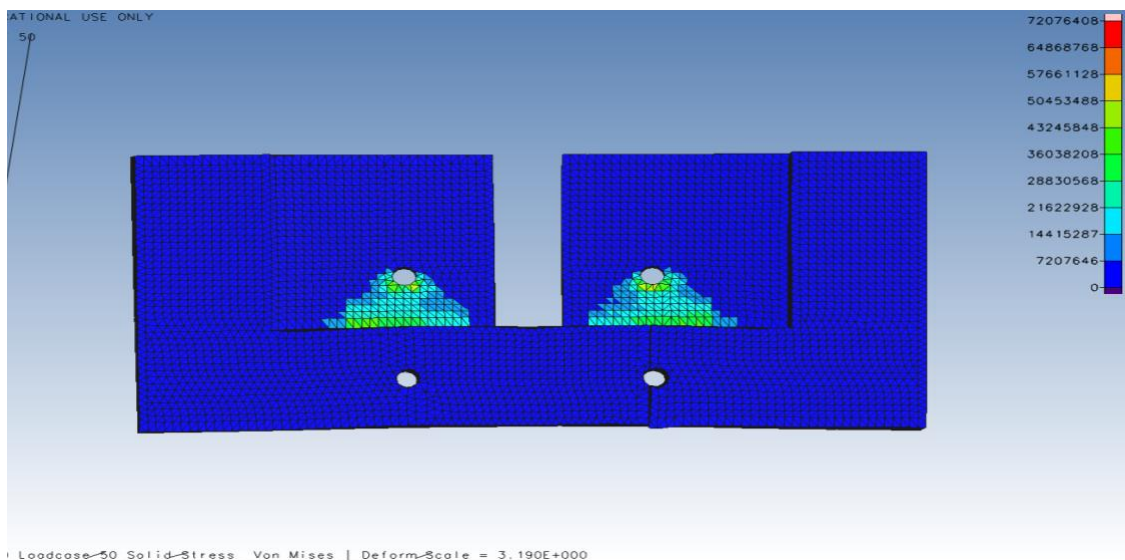


Figure 23: Bracket stress at cycle 12, front view, (Genesis. Roberts, 2020)

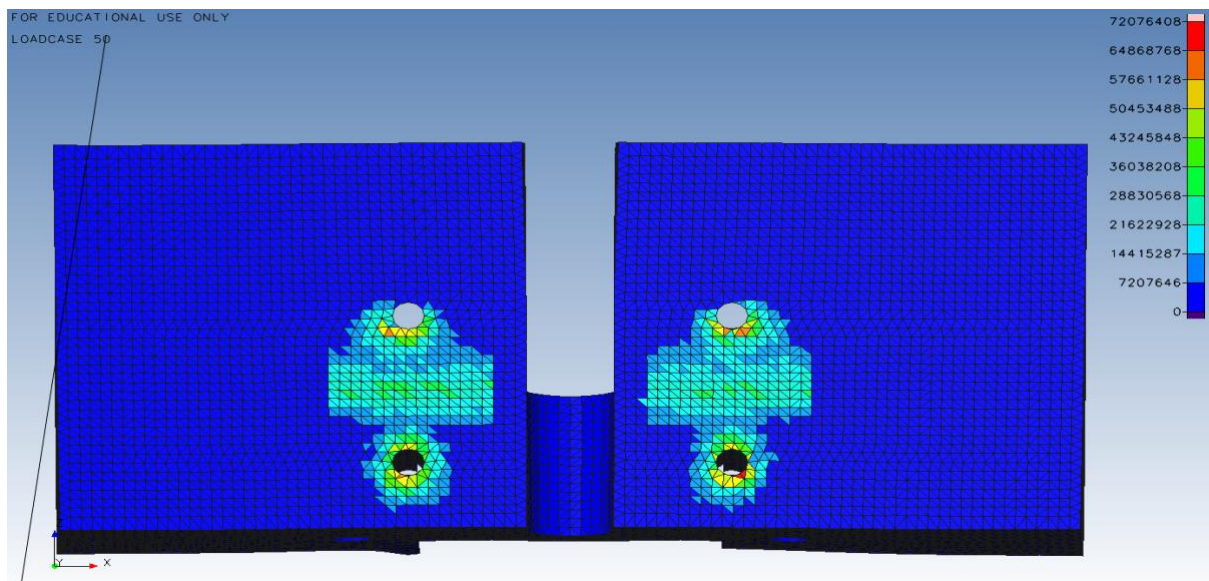


Figure 24:Bracke stress at cycle 12, back view, (Genesis. Roberts, 2020).

Strain cycle 12:

The strain has increased are around the four bolt holes, therefore would require more material.

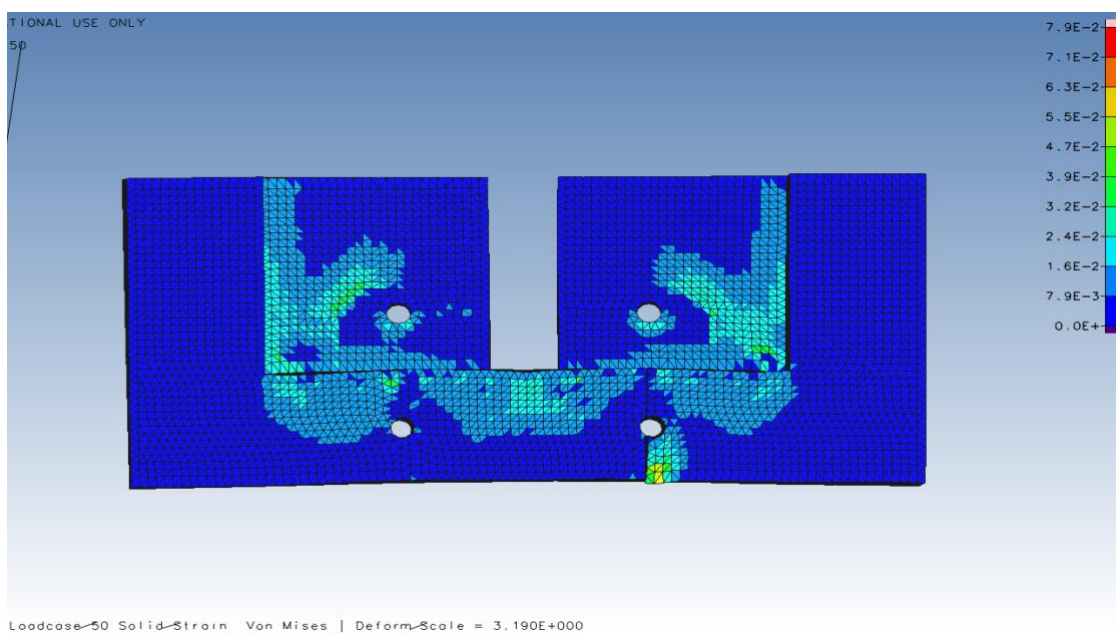


Figure 25:Bracke strain at cycle 12, front view, (Genesis. Roberts, 2020)

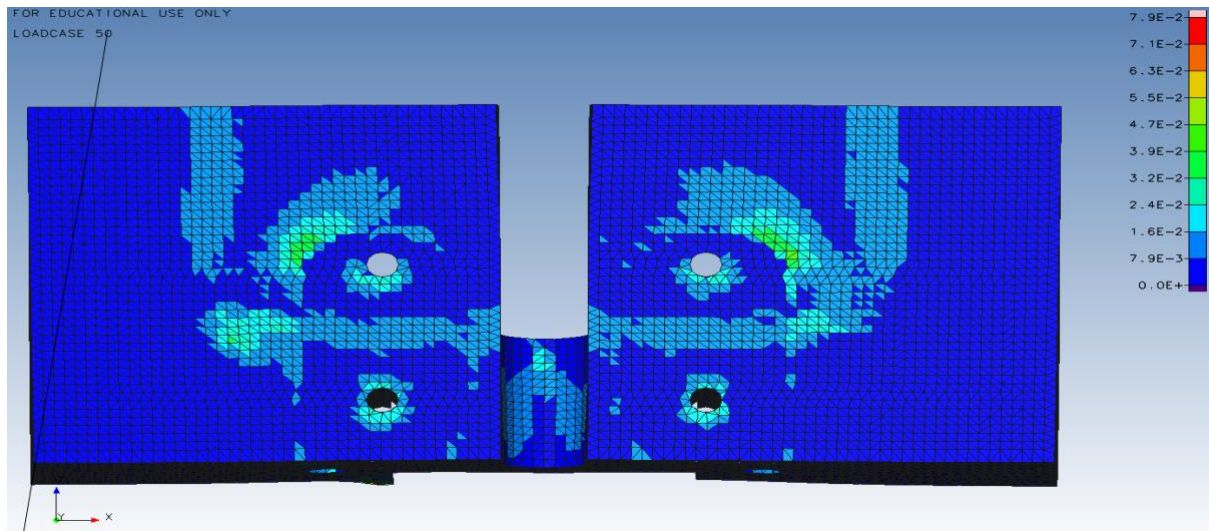


Figure 26: Bracket strain at cycle 12, back view, (Genesis. Roberts, 2020).

The optimised bracket:

A significant amount of material was removed from the bracket and the part was optimised to 0.042lb (equation 5) which is within tolerance of 0.1lb for maximum part mass. Twice the diameter material was left around the top two fixing holes. Material would need to be added to the bottom 2 fixing holes and datum b holes to follow the brief (see figure 28).

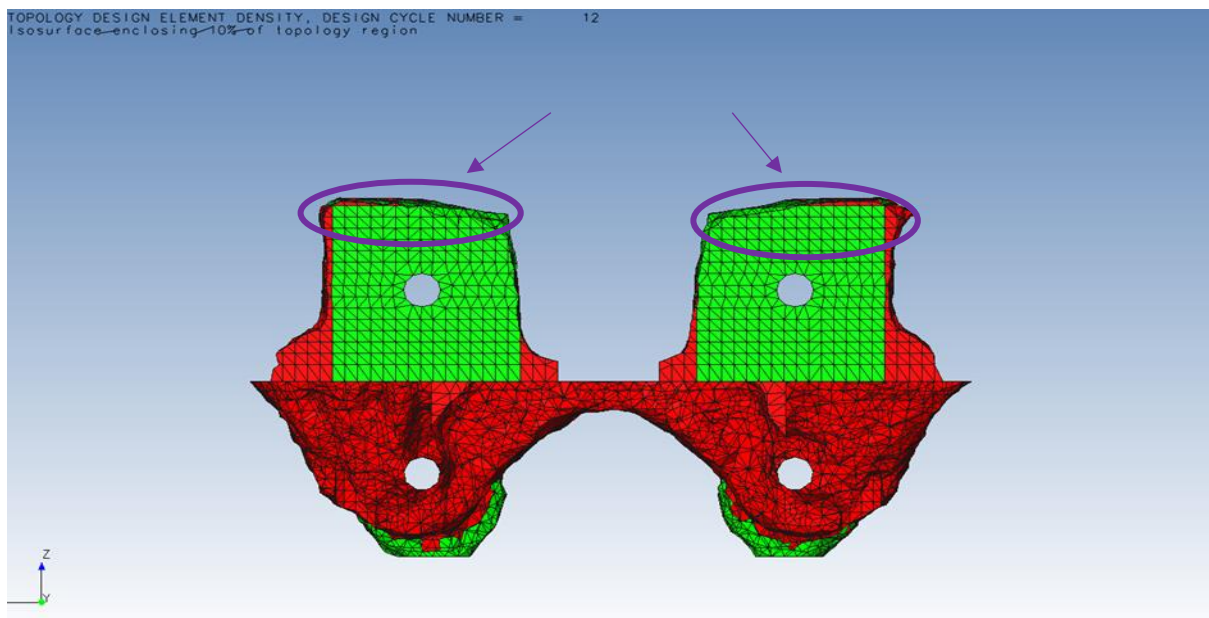


Figure 27: Front view of optimised bracket, (Genesis. Roberts, 2020).

Material should be removed from the top of the bracket. Where indicated on the image, to supply sufficient material around the other holes and stressed regions.

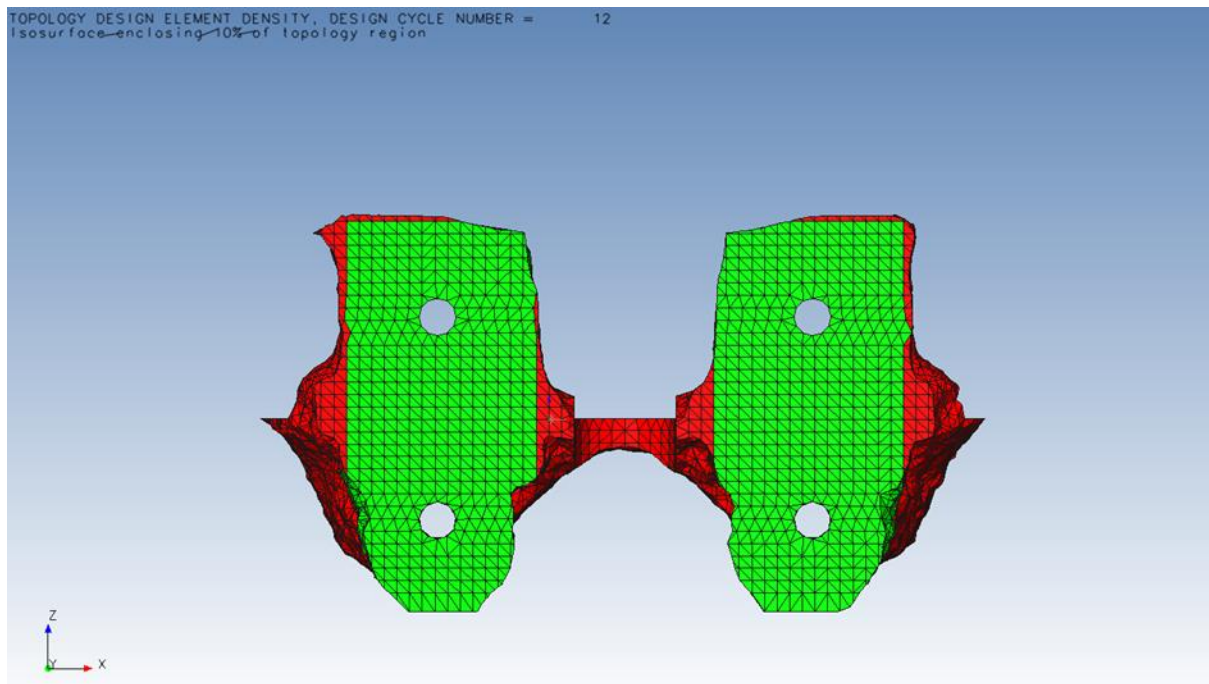


Figure 28: Back view of optimised bracket, (Genesis. Roberts, 2020).

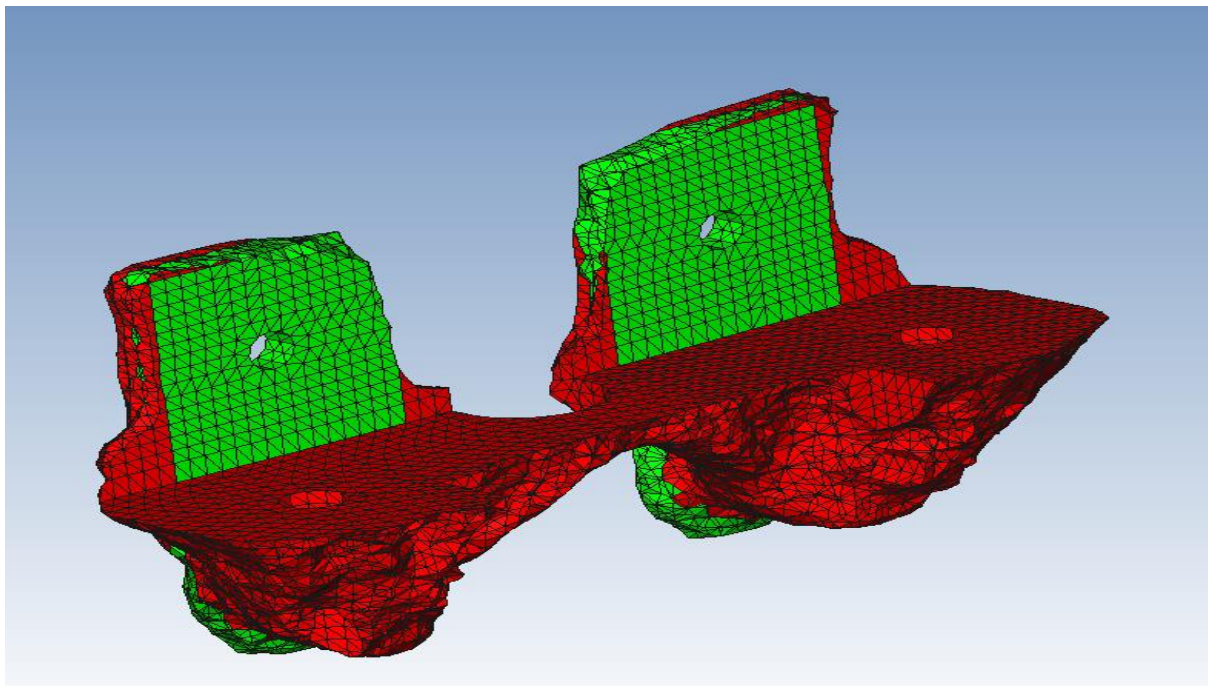


Figure 29: Angular view of optimised bracket, (Genesis. Roberts, 2020)

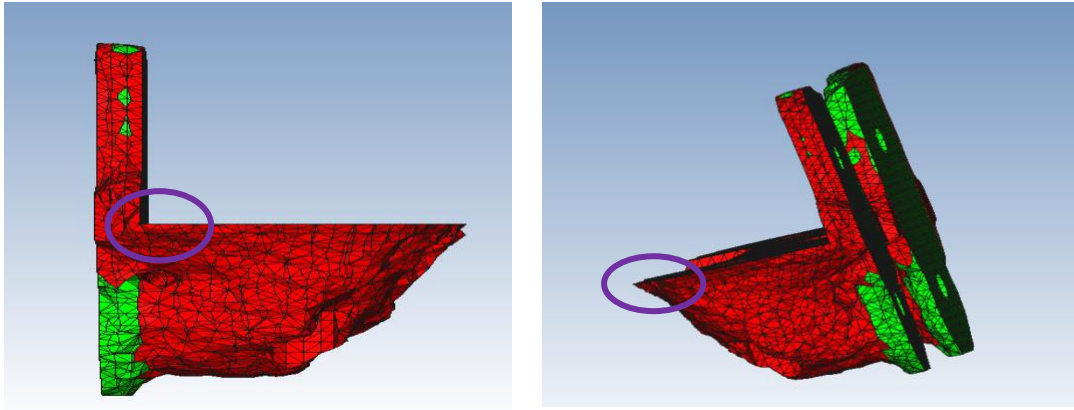


Figure 30: Side views of optimised bracket, (Genesis. Roberts, 2020).

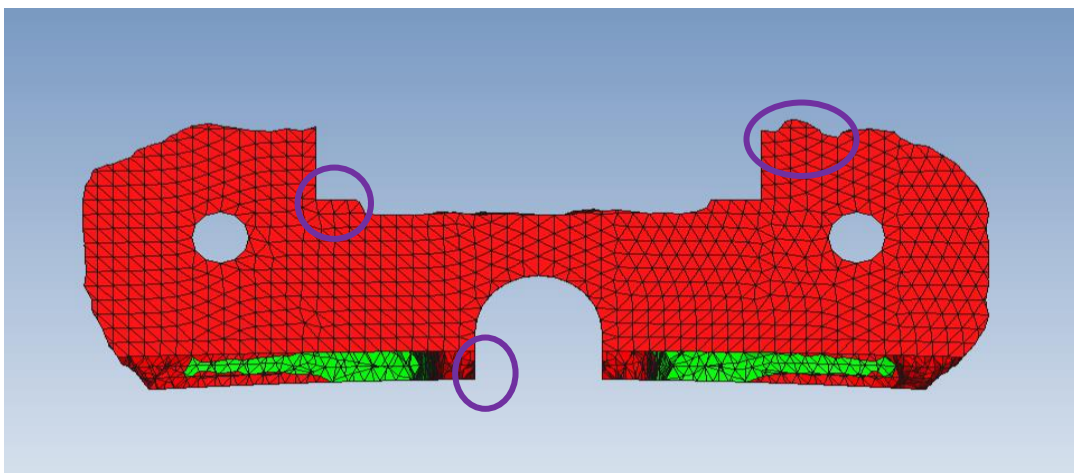


Figure 31: Top view of optimised bracket, (Genesis. Roberts, 2020) .

The platform holes need material added to the outer front face and radiuses added to the outer edges to reduce stress.

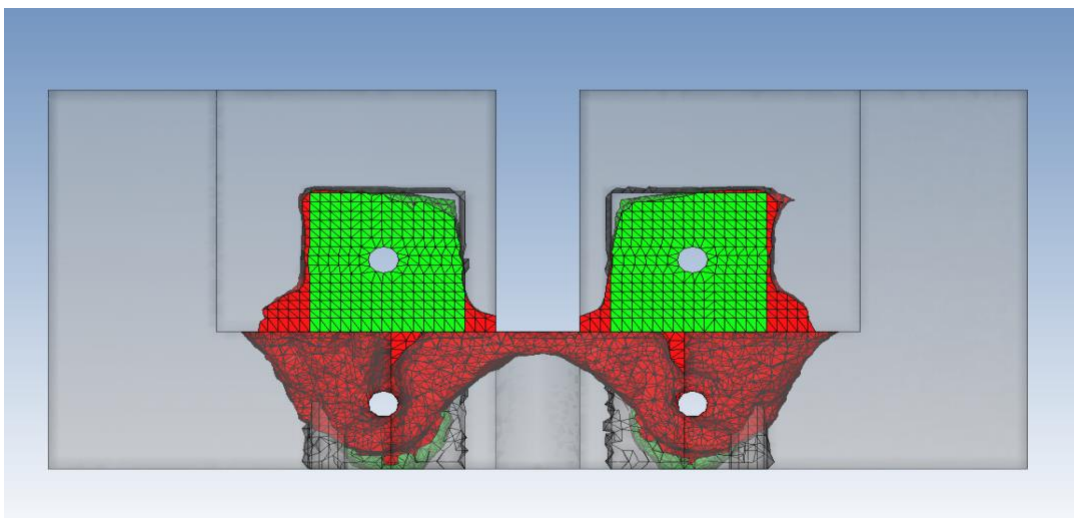


Figure 32: Optimised bracket inside original bracket, front view, (Genesis. Roberts, 2020).

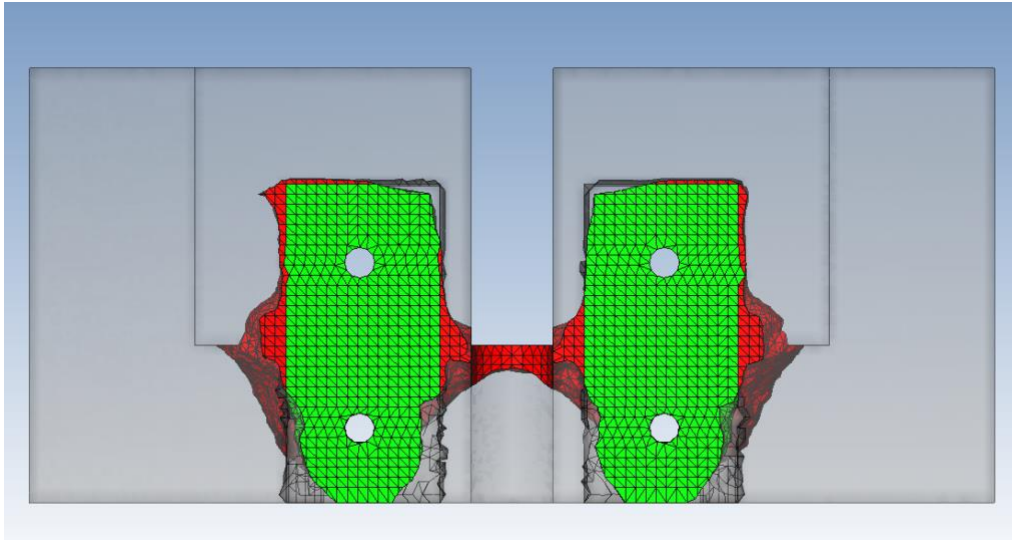


Figure 33: Optimised bracket inside original bracket, back view, (Genesis. Roberts, 2020).

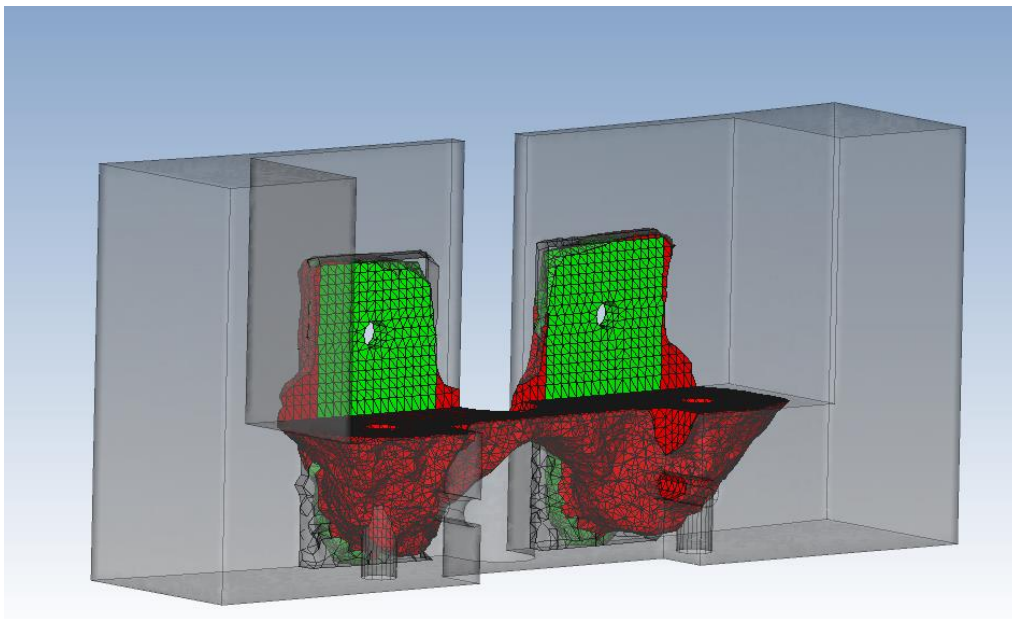


Figure 34: Optimised bracket inside original, side view, (Genesis. Roberts, 2020).

The topology study has created a strong, lightweight component. The reduction in the mass of the component reduces manufacturing costs, and also reduces fuelling costs for the rocket. To further reduce stresses, radiuses and fillets should be added accordingly to sharp internal and external areas, indicated in figure 30 and 31. The lower bracket should encompass triangular pockets and ribbed structures should be added for more strength and to further reduce the material, creating a more efficient component.

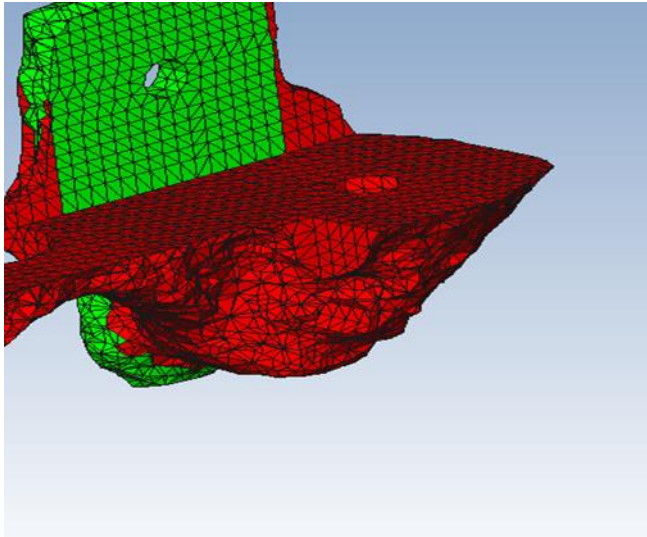


Figure 35: Pitted region on the lower of the bracket, (Genesis. Roberts, 2020).

The lower of the bracket has a pitted finish where limitations in the element arrangement can be seen in the image above. To enhance this region triangular structures and pockets should be added for increased strength and further reduction to the components mass. The structure should be kept symmetrical to ensure enhanced stability.

The end topology result was very similar to the winning component of the GrabCAD challenge, this further indicates a successful topology that the right avenue for re design is being undertaken. An image of the winning bracket is seen below:



Figure 36: Winning GrabCAD bracket, (Adams, 2016).

Critical Comments:

The optimised results were generally good, but attention should have been made to refine the stressed meshed areas to determine the actual stresses and strain incurred. The single analysis results are questionable as there is minimal displacement, but significant stresses, the results should correlate to some extent, as the displacement increases so should the stresses and strain. The green elements to be kept were excessive and would need reduction in order to gain material in areas where required and the pitted areas visually make it difficult to see the true orientation of the component.

The loading on datum B was influenced by the author, which subsequently influenced the topology on the component to fit the minimum requirements. If a true UDL was placed all continuously along datum B the results would of be different.

Conclusions:

A topology study was successfully run. Information on displacement, stresses and strain were analysed. From the results informed decisions were made on how the component potentially could behave and how the bracket could be improved to counteract the issues observed. The question asked was ‘whether the bracket was successfully optimised?’ and the answer was yes. Material was removed from various locations, which created a component within the specified tolerances and even resembled the winning component. However, additional optimisation and analysis would need to be under taken to ensure the required safety aspects were met.

As like any design processes, there must be a starting point and this was successfully achieved within the previous topology study.

Recommendations:

- Further investigation of the single analysis and topology results should be undertaken to make better informed design decisions.
- Further optimisation and topology studies should be done on the component to create a better structured component.
- Recommendations for the author: familiarise themselves with the software to a more competent level to enable them to utilise the software better.

References:

- Adams, N., 2016. *ULA internal boat tail support bracket*. [Art] (GrabCAD).
- Alliance, U. L., 2016. *GrabCAD Specification*. [Art] (ALA).
- Alonso, C. M. P. Q. O., 2017. *Topology Design methods for structural optimization*. Spain: Academic Press.
- Bansal, 2005. Properties of fluids : Specific Volume. In: *Fluid Mechanics*. Delhi: Laxmi Publications, pp. 1-10.
- Booth, H. F. M. P. T., 2015. Development and Test of an Experimental Hybrid Sounding Rocket. *Intercollegiate Rocket Engineering Competition*, 8(2).
- Calcara, L. F. G. H. T., 2016. *High Power Rocket Design Report*, Marymount: Digital Commons at Loyola Marymount University and Loyola Law School.
- Converters, U., 2020. *Unit converters*. [Online]
Available at: <https://www.unitconverters.net/pressure/ksi-to-pascal.htm>
[Accessed 18th January 2020].
- Genesis. Roberts, E., 2020. *Analysis results*. [Art] (University of wales trinity saint david).
- GrabCAD, 2016. *3-2-1 Liftoff! ULA Rocket Hardware Challenge*. [Online]
Available at: <https://grabcad.com/challenges/3-2-1-liftoff-ula-rocket-hardware-challenge>
[Accessed 16 January 2020].
- Henson, G. J., 2018. Materials for Launch Vehicle Structures. In: NASA, ed. *Aerospace Materials and Application*. America : American Institute of Aeronautics and Astronautics, pp. 1-35.
- Howell, E., 2018. *Atlas V: Reliable, Flexible Rocket*. [Online]
Available at: <https://www.space.com/40250-atlas-v-rocket.html>
- Manufacturing, A., 2018. *ULTEM & PEEK: the Ultimate Guide to High-Performance 3D Printing Materials*. [Online]
Available at: <https://amfg.ai/2018/07/09/ultem-peek-high-performance-3d-printing-materials-guide/>
[Accessed 16 january 2020].
- Masood, S., 2014. Advances in Additive Manufacturing and Tooling. *Comprehensive materials processing* , 1(1), pp. 3-24.
- Materialise, 2019. *Ultem 9085*. [Online]
Available at: <https://www.materialise.com/en/manufacturing/materials/ultem-9085>
[Accessed 16th January 2020].
- Nasa, 2018. *Atlas 5 Data Sheet*, United states America: Space launch Reports .
- Peng, X. S. Y., 2018. *Modelling, Solving and Application for Topology Optimization of Continuum Structures*. China: Butterworth-Heinemann.
- Roberts, E., 2019. *Fully modelled and meshed boat tail bracket*. [Art].

Roberts, E., 2020. *Genesis set up*. [Art].

Stratasys, 2017. *Ultem 9085*. [Online]

Available at: <https://www.stratasys.com/materials/search/ultem9085>

[Accessed 18th January 2020].

SYS, 2017. *3D Printed Aeroplane Parts for Airbus Using ULTEM 9085*. [Online]

Available at: <https://www.sys-uk.com/news/3d-printed-aeroplane-parts-airbus-ultem-9085/>

[Accessed 16 January 2020].

Tools, J. i., 2020. *Just in tools*. [Online]

Available at: <https://www.justintools.com/unit-conversion/pressure.php?k1=psi&k2=newton-per-square-meter>

[Accessed 18th January 2020].

ULA, 2019. *Atlas V*. [Online]

Available at: <https://www.ulalaunch.com/rockets/atlas-v>

[Accessed 16th January 2020].

Units, C., 2020. *Convert Units*. [Online]

Available at: <https://www.convertunits.com/from/pounds/to/Newton>

[Accessed 18th January 2020].

VRandD, 2019. *GENESIS Structural Analysis and Optimization Software*. [Online]

Available at: <http://www.vrand.com/products/genesis/>

[Accessed 16th January 2020].

Appendix:

Appendix A:

GrabCAD parameters:

- Minimum edge distance surrounding all bolt holes shall be 2 times the diameter of the bolt hole.
- Maximum part weight: 0.1 lb
- Minimum wall thickness: 0.040 inches
- Ultimate load (due to work platform): 600 lbf applied uniformly in the negative Z direction (illustrated on the envelope drawing).

Appendix B: Methods Equations:

Equation 1: Specific gravity to density equation.

Density = Specific gravity x density of water

Density = $1.34 \times 1000 = 1340$.

Equation 2: Mass calculations for bracket in solid works.

Mass = density x volume

Mass = $1340 \times 3.07 \times 10^{-4}$

Mass = 0.412 kg

Through a conversion it was calculated 0.1lb is 0.0453592 Kg, therefore the component must be 10% of its original mass.

Equation 3: Young's modulus calculation for single analysis bracket:

Young's modulus = Stress / Strain

= $400 \times 10^6 / 2.2 \times 10^{-4}$

= 1818.2 MPa

Equation 4: Young's modulus calculation for optimisation results bracket:

Young's modulus = Stress / Strain

= $72 \times 10^6 / 7.9 \times 10^{-2}$

= 911 MPa

Equation 5: Mass calculation for optimised bracket:

Mass = density x volume

Mass = 1340 x 3.15 x10⁻⁵

Mass = 0.412 kg