

ULA Rocket Hardware Design

ADVANCED COMPUTATIONAL METHODS

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1 ABSTRACT

The development phase of any product is the most critical part of the life cycle. This is where key elements such as mass, strength and manufacturing techniques are distinguished. With the use of computational tools, these elements can be optimized to reduce cost and time. This report is the first phase of the design stage of a boattail bracket used for the Atlas V rocket. The competition hosted by GrabCad for ULA had specified requirements to meet so a design can be used in their Atlas rocket. The boattail is a key part of the upper payload and needs to be as light as possible due to it has a direct effect on performance. A topology study has been carried out to eliminate as much mass from the boattail as possible. Recommendations based upon the results of load paths and structure have been shown with the next phased of design outlined with further design features.

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3 INTRODUCTION

In this report, a computational study of a boattail from the ULA Atlas rocket will be carried out. The boattail will meet the given specification from the ULA GrabCad competition taken place in 2016. An interpretation of the computational results will be explained and a conclusion will be made with regards to design and manufacturing techniques.

4 BACKGROUND

The design and component material is a key part of the industry of manufacturing sustainable and fit for use products (Dieter, 1991). With advancements in manufacturing techniques and computer-aided design, the ability to design a product based upon its conditions is now used more than ever. Tools such as topology and shape optimization are used throughout the component development phase to meet requirements such as strength and endurance (Groover, 2011). These tools will give the optimal component design based upon conditions and materials specified.

Topology optimization with regards to finite element analysis changes the connectivity of finite elements to meet the set objectives considering all the constraints (Koutromanos, 2018). This will remove unnecessary material to meet the set objectives, for example, meeting a required stiffness but reducing the volume. Topology is commonly based upon linear FEA solver to analysis material behavior thus the loads applied must be carefully selected (Zhang, et al., 2016) not to exceed the yield point of the material otherwise the study will be uncredible.

5 REQUIREMENTS

ULA has set a list of requirements that the boattail must adhere to be a viable option for the Atlas rocket. In the aerospace industry weight is a key contributing factor be reducing weight the rocket will be far more fuel-efficient (Zhu, et al., 2018).

This is one of the most important goals of the competition and will determine how the bracket is optimized to suit other requirements. The boattail support bracket will be used at the base of the payload fairing on the upper part of the rocket as seen in Figure 1. The boattail will be used as a support bracket for a platform in the days running up to the launch and will remain

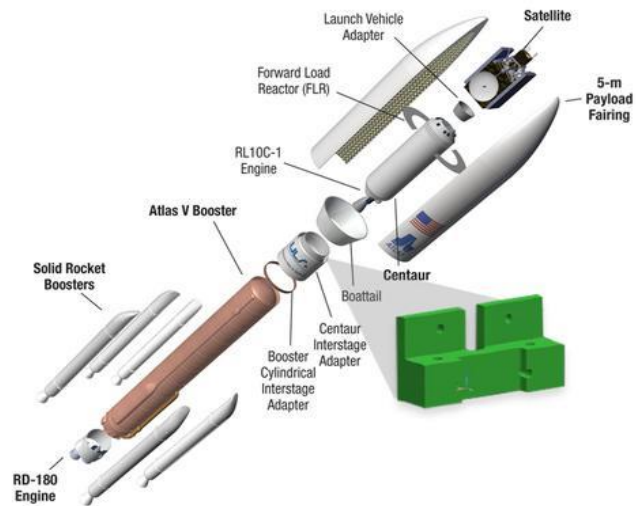


Figure 1 ULA Atlas V Boattail Location

on the rocket after launch. The boattail must have a maximum weight of 0.045 Kg with a load of is 2668.93 N uniformly distributed negative in the Z direction.

(ULA, GrabCad, 2016)

5.1 DIMENSIONS

The boattail bracket must not exceed the design envelope given as seen in appendix 1.

- Each fixing hole is a given dimension and must not be changed.
- The material around each fixing hole must be two times greater than the diameter.
- The wall thickness must be at least 1.016mm

(ULA, GrabCad, 2016)

5.2 MATERIAL PROPERTIES

The material which will be used is Ultem 9085 which has properties:

- Material strength: 31.026 MPa
- Specific gravity: 1.34
- Young's Modulus: 2240.798 MPa
- Poisson's ratio: 0.41

(ULA, GrabCad, 2016)

Ultem 9085 is a polyetherimide thermoplastic filament that is 3D printed using a fused deposition modeling printer (Stratasys, 2020).

6 LIMITATIONS

Manufacturing techniques are not considered as a constraint in the topology optimization, thus the results given may not be the most optimized solution or satisfy the requirements without further investigation and simulation. While the component used will be 3D printed due to Ultem 9085 being a fused deposition modeling (FDM) filament (Stratasys, 2020) this gives another problem that must be factored in. A 3D printed part tends to have different axial strengths due to the layered structure (Gibson, et al., 2015). Furthermore, the design space is a solid component in the optimization study while a 3D printed component due to it being FDM printed will not be a solid body (Gibson, et al., 2015).

7 METHOD

The computational method will be carried out in Autodesk Fusion 360. It will begin by creating the design space to which is specified in appendix 1. Once that is created, the boundary conditions can be set using tools such as to preserve region, constraining fixtures and direction loads. The objectives will be set to maximize stiffness and reduce mass. The maximum target mass is 0.046 Kg. Once the component is solved then an investigation of stress points and loads paths can begin and evaluate if the results can be made into a model and manufactured.

8 TOPOLOGY OPTIMISATION

The design space was designed in Fusion 360 to the specification in appendix 1. An Ultem 9085 material was created using data from Stratasys datasheet of the Ultem 9085 (Stratasys, 2020).

8.1 MASS

This allowed for the starting mass to be found which was 365.619g seen in appendix 2. The percentage of mass that will remain after the topology study must be then calculated (target mass/starting mass) x 100 - 100 = percentage of mass deducted to satisfy criteria. This calculated to be 87.7% however this is for the final design thus this will have to be further reduced in this stage of the design to allow for extra material to be added if needs be. Taking this into consideration the target mass reduction will be 92% which will leave 8% of the starting mass remaining.

8.2 CONSTRAINTS

The constraints that must then be set on each fixing point. The minimum edge distance around each hole is twice the diameter of the hole. This is calculated as 13.716mm for the fixing to the platform and 11.176mm for fixing to the vehicle interface. With a factor of tolerance, the platform will be 15mm and the vehicle interface will be 13mm. The minimum wall thickness is set at 1.016mm with a factor of tolerance the wall thickness will be set at 2mm (ULA, GrabCad, 2016).



Figure 2 Boattail Constraints and Loads

8.3 LOADING

The ultimate load that the boattail will experience is 2668.93N in the Z-direction this will be applied uniformly across the component at the platform fixing point. To give a round number a load of 2700 N will be applied.

8.4 MESH

Two topology optimization will be carried out with different first-order mesh sizes to compare the results. A mesh of 2mm and 1mm will be applied and solved, the 1mm mesh size should have more accurate results however will have a far longer solve time. The comparison will, therefore, show if the greater solve time is worth it based upon the results (Liu, 2013).

8.5 MATERIAL

The material will be created as a custom material into Fusion 360 as given by the specification sheet.

Material Properties: Ultem 9085

Material Strength Allowable: 4500 PSI – 31 MPa

Specific Gravity: 1.34 – 1340 Kg/m³

Young's Modulus: 325 KSI – 2240.8 MPa

Poisson's Ratio: 0.41

Non-Dissolvable support material

(ULA, GrabCad, 2016), (Stratasys, 2020)

9 RESULTS

To see if the results are useable we must compare the results against the required specification.

Maximum part weight: 0.045 kg

9.1 MASS

The target mass for the final component is 0.045 kg as seen in figure 3 the final mass of the first topology study was 0.029 kg which is far below the required mass. This will allow for further design as explained in section 6.1.

Based on the mass objectives the study satisfied that.

☐ Optimization Summary

Name	Value
Mass before	0.366 kg
Mass after	0.029 kg
Mass Ratio	7.91 %

Figure 3 Study Report Mass Data

9.2 GEOMETRY

To see if the topology study is credible now the geometry must be studied. As seen in figure 4 the component is now split into two bodies. The colour of the elements represents the load path of the structure. Red bares the highest amount followed by yellow then green

(Autodesk, 2017). While green is not necessary however, in this case, the green areas still satisfy the target mass thus will remain but bare very little load.

This indicates that the component can be further optimized.

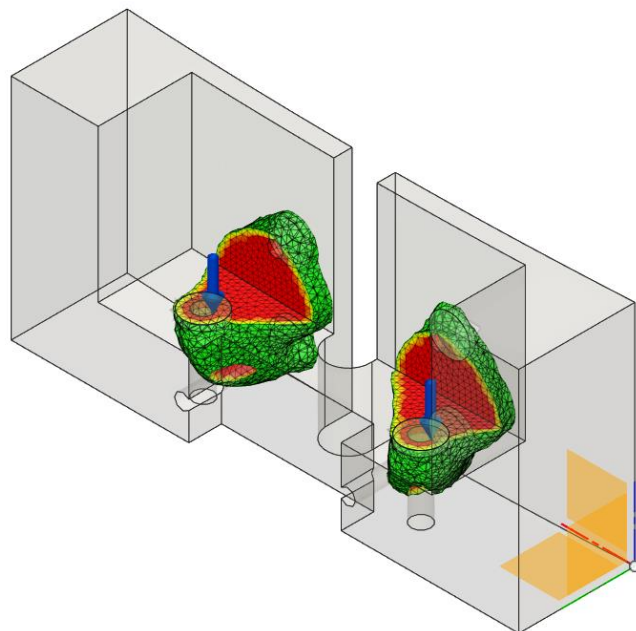


Figure 4 Study Results in ZY View

In figure 5 a top view of the study is shown. The remaining material is a clear indication that the load does not need to be spread over the original envelope and the study has optimized the design considerably. The material that remains is as expected. There is a gradual taper of material from the back edge to the platform fixing points.

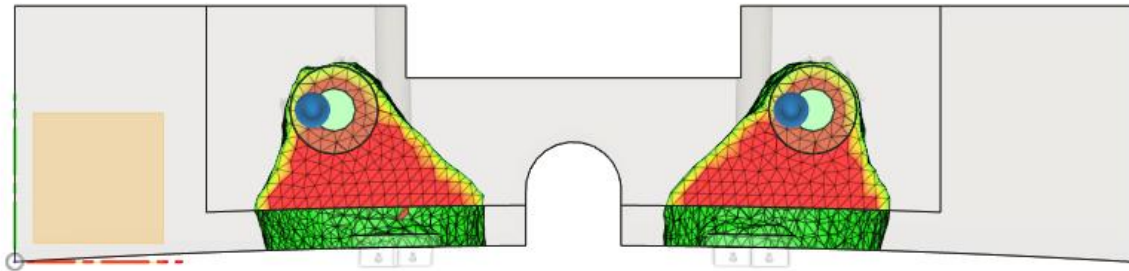


Figure 5 Study Result in Top View

However far more optimization could have taken place. In figure 6 there is a very sharp taper from the fixed geometry of the minimum edge distance and wall thickness to the front surface. The topology study has instead of reducing the width of the whole surface to be in line with the fixed geometry is has just reduced some material. Here is a clear indication that far more reduction is material is possible.

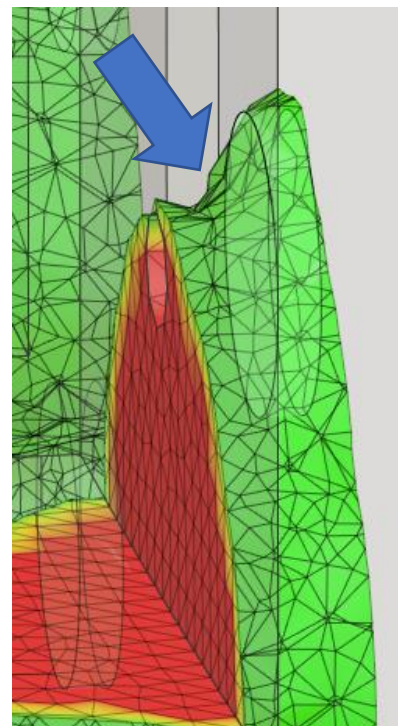


Figure 6 Study Results - Fixed Geometry

In figure 7 the back view is shown. The material around each hole is an indication of which vehicle fixing point has the highest load and how the load is dissipated to the loaded plane. The top hole has far more material around and has a more gradual taper this indicates that it will have the highest load when compared to the bottom hole.

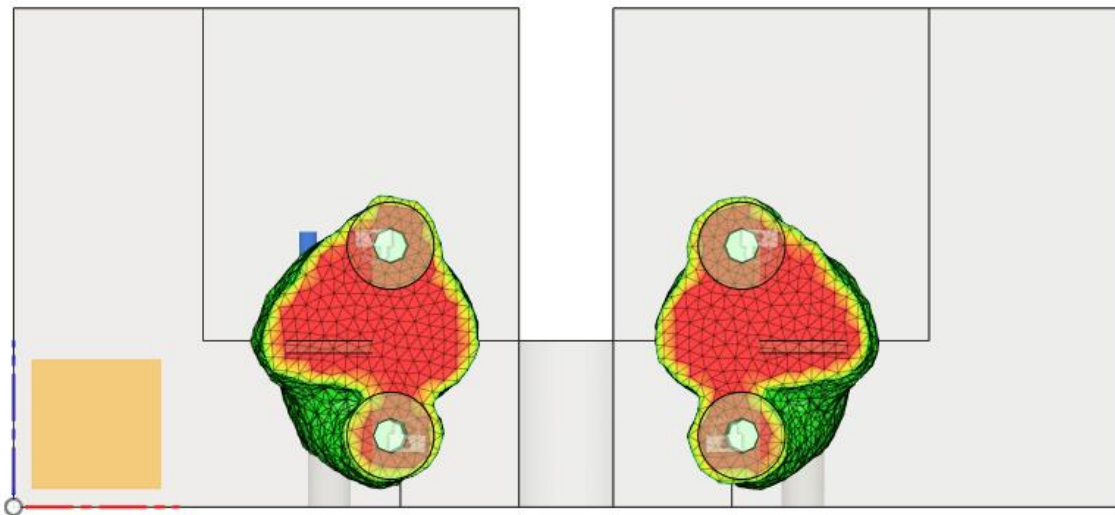


Figure 7 Study Results in Back View

In Figure 8 a cross-sectional area of each hole is shown. As expected there is very high loading around each hole and inside the body.

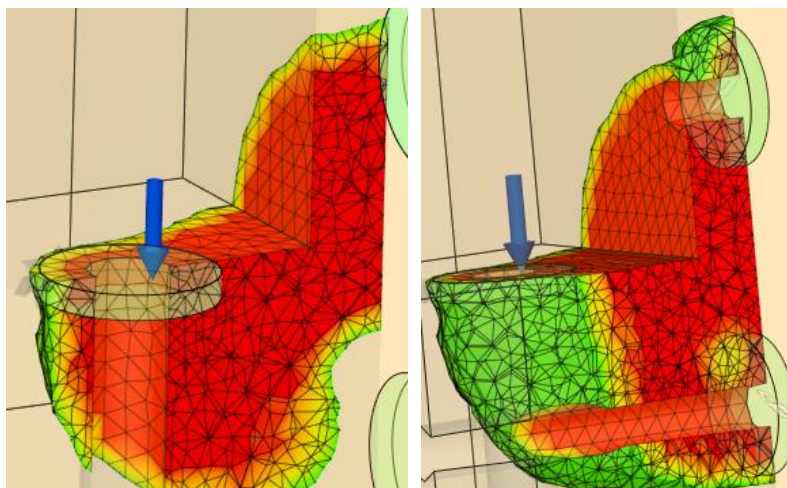


Figure 8 Result Study Cross-Sectional Area

10 ANALYSIS

This study should be used as the first stage of design it has indicated some key aspects that should be incorporated into the second phase. The minimum wall thickness and maximum edge size should be taken into consideration far more. There is too much material around these areas. Instead of using the volume of material as a way to disperse the load around these sections, features such as ribs and fillets could be used to make it far more effective. This will greatly reduce the mass of the part and possibly increase the strength. A static load analysis would be used to gain a better understanding of the stress paths of the part.

The geometry of the part of this study would be useless in the real world. There are no flat surfaces on the fixture holes for fittings such as bolts, nuts, and washers. This would be a key aspect taken into the second phase of design.

As seen in the study the part is now split into two bodies, this could have some implications. Twice as many parts would need to be manufactured, and fixed to the payload of the rocket. This could increase the cost and time taken to fit the part.

It should also be considered that the specification gives a design space with all the holes on a single body this would be an indication that the part should be one. A recommendation of a bridge between each body should be incorporated into the second phase design. The bridge could also distribute the load better and remove the high load path around the holes which could reduce the material around the holes.

In this topology study, no constraints of manufacturing are used. This could lead to serious implications further down the development. As discussed earlier 3D printing has axial strength, so when looking at the load paths inside the body the load paths will act very differently in real life

compared to this topology study. This is a high priority concern due to the part may lose its structural integrity and fail if not considered.

The two elements size that were studied had very little effect on the outcome of the study, each had almost identical load paths and gave the same data. Although the 1mm mesh time took far more time to compute even using Autodesk's cloud solver (Autodesk, 2017). Evidence of this comparison can be seen when comparing the reports of each in appendix 3, 4 and 5.

11 PHASE TWO OF DESIGN

The next phase of the design will need to consider all elements discussed in section 8. The next step should be to reduce the volume of mass around each hole with the addition of structural supports. A design such as seen in figure 9 has some of the added that are discussed. A topology study should be carried out again on this optimized part to see if further improvements can be made. Once that is completed then a static load analysis will give further insight into the stress and displacement the part is under. Further design changes will need to be carried out until the strength of the model does not meet the criteria.

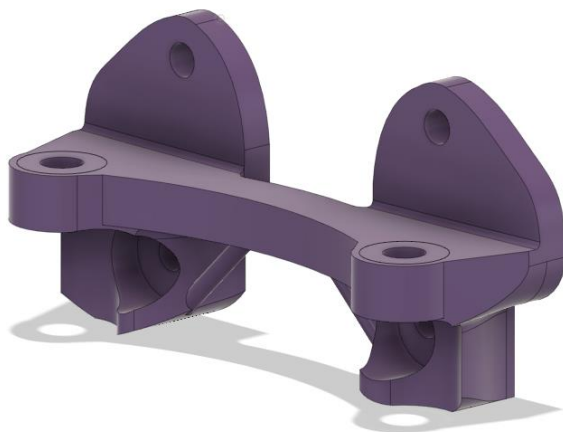
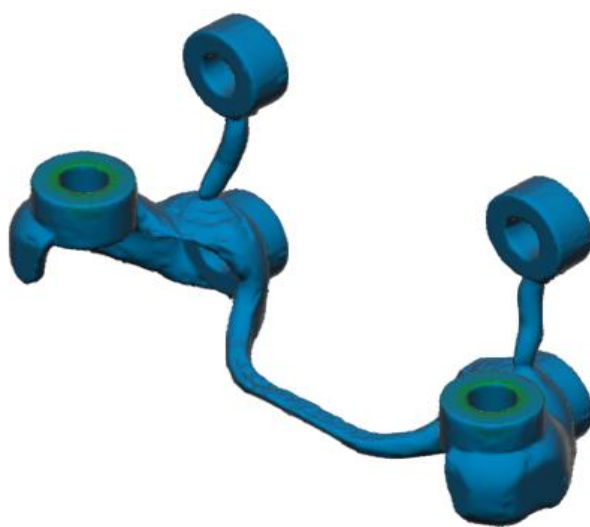


Figure 9 Second Phase Design

12 RECOMMENDATIONS

While topology is heavily used throughout the development of almost every part, advancements in technology in areas such as artificial intelligence have allowed for topology studies but in reverse (Autodesk, 2020). It is a technique called generative design and uses the same principles as topology with respect to constraints, preserved geometry and loading however this technique adds material to satisfy the study rather than removes it. Once all parameters are set generative design software will explore all permutations of the solution and display them as bodies (Francalanza, et al., 2018). A feature of the generative design that will greatly reduce the time of development is parameters for manufacturing that can be added. In the topology study of the boattail, this would greatly reduce the phases needed to design a part that meets the criteria.

Figure 9 is the generative design of the boattail is it clear to see that the part is optimized as possible. The minimum amount of material is used to disperse the load but keeping the structural integrity of the part. As can be seen, the mass of the part is 25g with max stress of 62.1MPa with a safety factor of 2. This will meet the criteria of the competition due to a safety factor not being required.



Estimated manufacturing cost	
Range (USD)	54 - 107
Median (USD)	75
Volume (mm ³)	9,198.71
Mass (kg)	0.025
Max von Mises stress (MPa)	62.1
Factor of safety limit	2
Min factor of safety	3.86
Max displacement global (mm)	0.01
Cost estimates powered by āPriori	

Figure 10 Generative Design of Boattail

13 CONCLUSION

To conclude the topology study taken place was the first phase of the development, the results to this phase are to aid the next phase. With a reduction of the material of 92%, it will give a good base to further the development of the boattail. A new design with features such as the example in section 9 would be a good start. The wall thickness of the material should be a further consideration.

As previously discussed the further investigation of how the part reacts under static loading will need to be carried out. With data from that and the topology study, a more calculated design can be made. This will allow for further optimization of the part and will exceed the requirements further.

If a different approach was taken as shown in section 10 there are far more efficient ways now to design such parts using tools such as generative design. Additive manufacturing is seen to be the future of manufacturing. However, using tools to design parts are from an age where volume and density equaled strength this will result in additive manufacturing not being used to its full potential. Generative design can now push the limits of additive manufacturing and give parts that would not be seen with the use of subtractive studies such as topology.

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[illegible]

(ULA, GrabCad, 2016)

Appendix 2Boattail Data - Fusion 360

(May-White, 2020)

15.3 TOPOLOGY REPORT OF 2MM MESH

Simulation Model 1:1

Study 2 - Shape Optimization

Study Properties

Study Type	Shape Optimization
Last Modification Date	2020-01-26, 13:35:42

Settings

General

Contact Tolerance	0.1 mm
Remove Rigid Body Modes	No

Mesh

Average Element Size (% of model size)	-
Solids	-
Scale Mesh Size Per Part	No
Average Element Size (absolute value)	2 mm
Element Order	Linear
Create Curved Mesh Elements	No
Max. Turn Angle on Curves (Deg.)	50
Max. Adjacent Mesh Size Ratio	1.5
Max. Aspect Ratio	10
Minimum Element Size (% of average size)	20

Materials

Component	Material	Safety Factor
Body1	Utem 9085	Yield Strength

Utem 9085

Density	1.134E-06 kg / mm ³
Young's Modulus	2241 MPa
Poisson's Ratio	0.41
Yield Strength	70 MPa
Ultimate Tensile Strength	68 MPa
Thermal Conductivity	2.4E-04 W / (mm C)
Thermal Expansion Coefficient	5.58E-05 / C
Specific Heat	1340 J / (kg C)

Contacts

Mesh

Type	Nodes	Elements
Solids	45937	235289

Shape Optimization

Criteria

Parameter	Expression	Value
Target Mass	< OR =	8 %
Stiffness	Maximize	

Results

Optimization Summary

Name	Value
Mass before	0.366 kg
Mass after	0.029 kg
Mass Ratio	7.91 %

Load Case1

Constraints

Fixed2

Type	Fixed
Ux	Yes
Uy	Yes
Uz	Yes

Selected Entities



Fixed4

Type	Fixed
Ux	Yes
Uy	Yes
Uz	Yes

Loads

Force14

Type	Force
Magnitude	2700 N
X Value	0 N
Y Value	0 N
Z Value	-2700 N
Force Per Entity	No

Selected Entities



Appendix 3 Report of Topolgy Study with 2mm Mesh

15.4 TOPOLOGY STUDY OF 1MM MESH

Simulation Model 1:1

Study 1 - Shape Optimization

Study Properties

Study Type	Shape Optimization
Last Modification Date	2020-01-26, 12:43:32

Settings

General

Contact Tolerance	0.1 mm
Remove Rigid Body Modes	No

Mesh

Average Element Size (% of model size)	
Solids	-
Scale Mesh Size Per Part	No
Average Element Size (absolute value)	1 mm
Element Order	Linear
Create Curved Mesh Elements	No
Max. Turn Angle on Curves (Deg.)	60
Max. Adjacent Mesh Size Ratio	1.5
Max. Aspect Ratio	10
Minimum Element Size (% of average size)	20

Materials

Component	Material	Safety Factor
Body1	Ultem 9085	Yield Strength

Ultem 9085

Density	1.134E-06 kg / mm ³
Young's Modulus	2241 MPa
Poisson's Ratio	0.41
Yield Strength	70 MPa
Ultimate Tensile Strength	68 MPa
Thermal Conductivity	2.4E-04 W / (mm C)
Thermal Expansion Coefficient	5.58E-05 / C
Specific Heat	1340 J / (kg C)

Contacts

Mesh

Type	Nodes	Elements
Solids	266510	1443911

Shape Optimization

Criteria

Parameter	Expression	Value
Target Mass	< OR =	8 %
Stiffness	Maximize	

Results

Optimization Summary

Name	Value
Mass before	0.366 kg
Mass after	0.029 kg
Mass Ratio	7.94 %

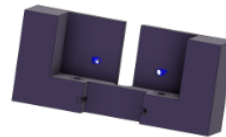
Load Case1

Constraints

Fixed2

Type	Fixed
Ux	Yes
Uy	Yes
Uz	Yes

Selected Entities

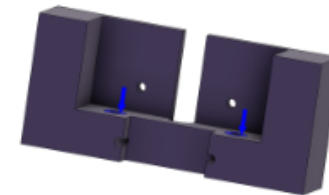


Loads

Force14

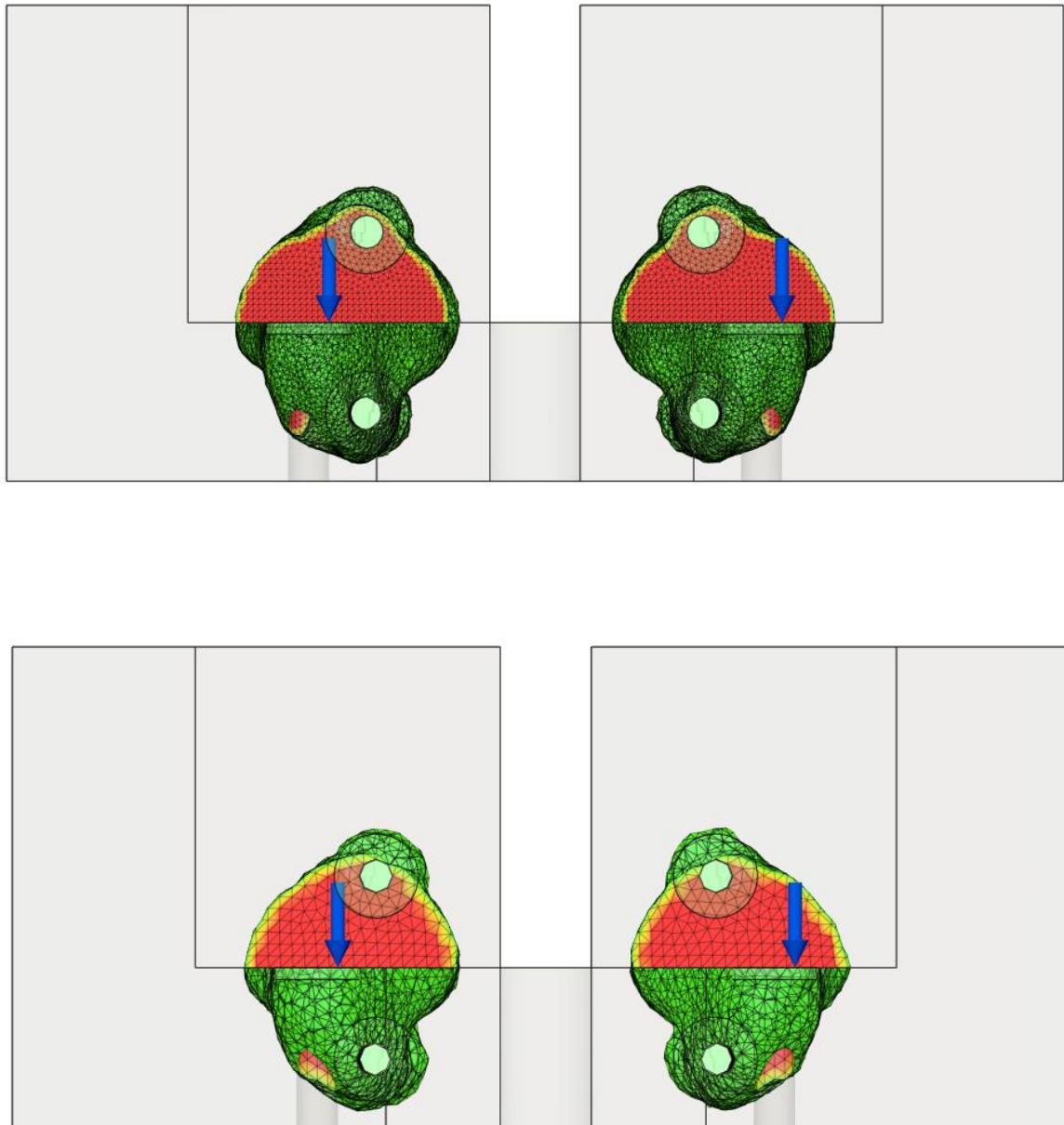
Type	Force
Magnitude	2700 N
X Value	0 N
Y Value	0 N
Z Value	-2700 N
Force Per Entity	No

Selected Entities



Appendix 4 Report of Topolgy Study with 1mm Mesh

15.5 1MM VS 2MM MESH



Appendix 5 1mm vs 2mm Mesh