

Considering Print Direction in Topology Optimization to Minimize Overhang Constraints

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Abstract

One of the main design aims in automated product design especially for additive manufacturing (also called 3D printing) is to obtain designs having no need for support structures with respect to overhangs as shown below.

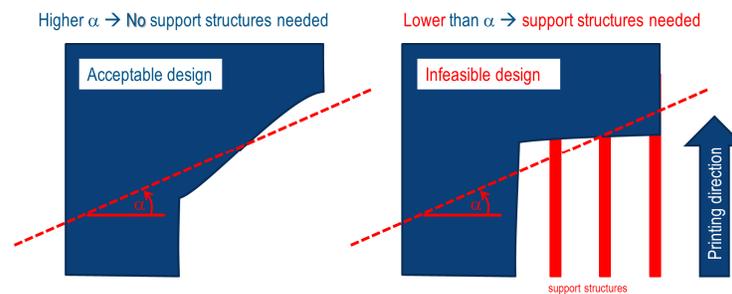


Figure 1: Obtaining optimized designs having no support structures for overhangs in the 3D printing process

Designers and makers as well as simulation specialists request the option to optimize and design structures using simulation and sensitivity based optimization having overhangs in the print direction which do not need any support structures. Typically, one geometrical design requirement is if the overhangs are over a defined angle α then support structures are not required for the additive manufacturing process. Designs manufactured with no support structures are cheaper to manufacture due to reduced production time, less material consumption and reduced post processing time since there will be no support structures.

In addition to considering print direction during optimization, taking manufacturing constraints into account such as choosing the right print direction to facilitate easy machinability after printing and modifying circular holes into diamond shaped openings to further reduce or eliminate the necessity of support material will contribute to creating self-supporting structures of good quality.

In this paper, the sensitivity-based topology optimization of an automotive door hinge was performed considering the print direction to be along the length of the hinge. Next, the optimized shape was reconstructed using various tools. Special considerations were made during the reconstruction to accommodate the review by AM manufacturing engineers before physically printing the part, in this case a Renishaw AM 500 machine. Subsequently, a static stress analysis considering the loads used for the optimization process was performed on the reconstructed shape.



Figure 2: Optimized Reconstructed final design



Figure 3: Physical printed part of optimized component

1 Introduction

Additive manufacturing, often called 3D printing, is a new and emerging technology which manufactures parts by depositing one material layer at a time. In the past, this technology was primarily used to create prototypes for parts which were manufactured using traditional manufacturing methods. This gave rise to the term Rapid Prototyping. However, with technological advancements over the years, this technology has evolved from just creating prototypes to manufacturing production-ready parts to series productions. Numerous companies in the aerospace, automotive, and life sciences industries have embraced this paradigm shift in manufacturing. Some examples of applications are jet engine nozzles with complex ducts, light-weighted brackets in airplanes, porous medical implant surfaces for osseous integration, and latticed parts for race cars, among many others have moved from functional prototypes to in-service usage. This has opened up possibilities to manufacture complex parts that cannot be manufactured using conventional manufacturing techniques. Although additive manufacturing opens up new manufacturing possibilities, the designs of the manufactured parts are often based on traditional and classic manufacturing methods.

To develop new and more complex designs that can be manufactured, a key simulation technology, Topology Optimization, is being leveraged in the shortened design cycle for additive manufacturing. Topology Optimization is a non-parametric optimization technique that identifies and removes areas of a design space according to design requirements defined by objectives and

constraints. This method determines an optimum material distribution in a defined design area (see Figure 4) while accounting for existing constraints for the design space. Some of these constraints are boundary conditions, fixations, pre-tensions, and external loads. With reduced manufacturing constraints, more organic structures with ‘holes’ and ‘openings’ are now possible designs using topology optimization. For the present work, robust general purpose tool for non-linear topology optimization is applied using Tosca Structure.



Figure 4: The general goal of topology optimization is the distribution of material in a given design space. For the basic optimization task, the target mass is the constraint. For a given mass (target volume or target weight) the stiffness is maximized

When manufacturing a part, often additional support material is required. The primary use of support structures is to restrain the part while manufacturing when the previous layers of material cool and contract. As a result, this will help in the completion of the build process. One of the other reasons why support material is important during a build process is that it helps defining a path for the heat to flow from the build plate thereby allowing effective conduction and convection between different layers. This will in turn reduce the residual stresses developed in the part.

Although support structures are vital for a part to be manufactured, manual post-processing techniques are necessary to remove support structures due to the sheer complexity of the structure. Usually, AM parts require supports which add to the cost of material and print overhead. Different ways to minimize the use of support structures are by reducing the overhang angles, build orientations optimization, and using parametric or non-parametric simulations to optimize support placement will ensure that you realize the cost benefits from topology optimization. Depending on the complexity of the manufactured part, the support removal process can be quite tedious. In addition, the appropriate print orientation needs to be considered to reduce the overall volume of supports as well as to facilitate easy removal of the part from the build plate amongst many other factors. Hence, a designer should consider factors like in-build residual stresses as well as other build defects to ensure that the manufacturing process completes as well as validate its structural integrity.

The hinge design was optimized using both threshold angles of overhanging surfaces as well as print direction to address this situation. To begin, the design space of the hinge was optimized using Abaqus Tosca considering an overhanging angle value of 45° and also the print direction, which is along the length of the hinge. The optimized design was then validated using Abaqus/Standard. Finally, the validated design was reconstructed into a surface model using subdivisional surfaces and then converted to a solid geometry. These tools are available in the Functional Generative Design application in the 3DEXPERIENCE platform.

2 Topology Optimization considering Overhang angles and Print direction

Tosca Structure can be used to create organic designs that use less material while satisfying all the functional requirements and constraints. A larger design space is chosen as the starting point (the gray area) and based on iterative non-linear finite element analyses using Abaqus, the locations of design space where the material is required is computed as shown in the right frame. In addition, Tosca now provides capabilities to reduce the number of overhanging surfaces in the optimized shape and also considers print direction during optimization.

2.1 Constraint Formulation

To obtain designs suited for the printing process the overhang criteria is included directly in the density-based topology optimization formulation in the form of a design variable constraint. This ensures that the optimized result will not contain critical overhangs with overhang angles lower than allowed. Various different approaches have already been suggested in research to realize this constraint [1, 2]. In the present work the method proposed by Matthijs Langelaar [2] has been modified and integrated in an industrial environment [3]. In this approach we ensure the overhang angle is not violated by checking each finite element for its support and penalizing all elements which do not fulfill the angle criteria. To decide whether an element has enough support we check a control volume in form of a cone lying underneath the element in terms of the given printing direction, see Figure 5:

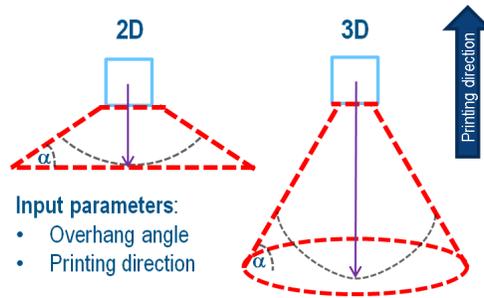


Figure 5: Control volumes (cones, red) for a design element (cone top, blue)

The control volume must contain at least one fully saturated element to completely support the element at the cone top. Langelaar therefore suggested a direct coupling of the density inside the cone top with the densities of the elements in the control volume with the following projection scheme:

$$DV_p = \min(DV_b, \max(DV_{p, \text{control volume}})) \quad (2.1.1)$$

The indices b stand for the blueprint design before applying the ALM-constraint and the indices p indicate that these are the values of the printable density field after the update of the constraint. By definition the DV_p field will not contain any critical overhangs. The formulation of the control volumes is independent of the used mesh type and therefore this approach can also be used for unstructured meshes (e.g. triangular and tetrahedral meshes). Additionally the overhang angle and the printing direction can be chosen freely by the user:

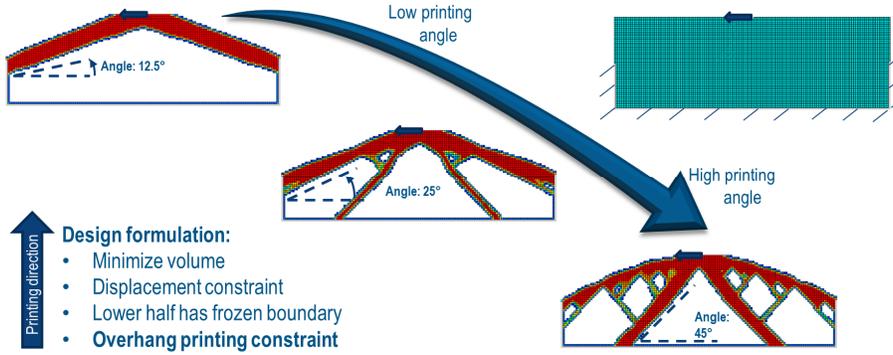


Figure 6: a) Influence of different overhang angles on the optimization result b) Bottom half of the design domain (shown in green) is frozen

2.2 Implementation

The ALM-constraint consists of two loops, one for the update of the design variable field and one for the update of the sensitivities. The first one is done from the bottom up in direction of the given printing direction. The values of the DV_p field are updated according to the projection scheme. The second one is done in the opposite direction, starting from the top, going layer to layer to the bottom. Sensitivity calculation is done by following the chain rule.

The min/max-functions are realized with pNorm approximation:

$$\min(\rho_b, \rho_p) = \frac{1}{2} \left[\rho_b + \max(\rho_p) - \left[(\rho_b - \max(\rho_p))^2 + \varepsilon^2 \right]^{\frac{1}{2}} + \varepsilon \right] \quad (2.2.1)$$

$$\min(\rho_p) = \left(\sum_{\text{control volume}} \rho_p^p \right)^{\frac{1}{Q}} \quad (2.2.2)$$

This approximation introduces a high non-linearity which has to be taken into account. To prevent checkerboard effects and to enable control over the minimum member size of optimized structures density filtering is done after the update of the ALM-constraint:

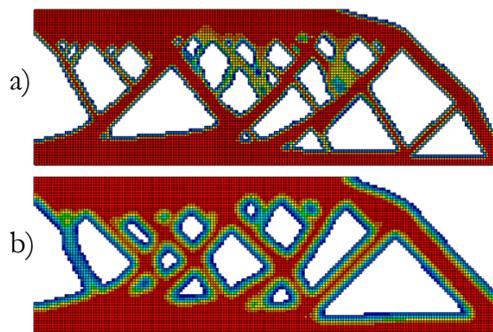


Figure 7: Influence of the density filter radius on the optimization results ($a < b$)

2.3 Model Setup

A topology optimization exercise was carried out with Renishaw PLC with the intent of printing the optimized design using the Renishaw AM 500 metal printer. The design that was considered was that of an automotive door hinge. Since the hinge is part of the door assembly, the interfacial areas are marked as frozen. By marking them as frozen regions, they are excluded from the design space.

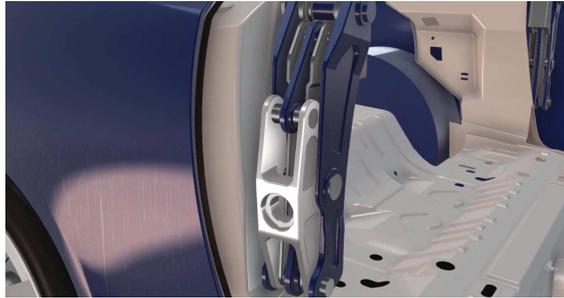


Figure 8: Automotive door hinge

Next, it is important to set a minimum member size for the optimization to account for the print resolution. By default, the minimum member size should be more than twice the mesh size. For metal printing process, the minimum member size can be much smaller. However, choosing a conservative limit can help avoid any manufacturing related defects (voids or cracks). In this case, a minimum member size of 6.4mm was chosen. Taking the above into account, multiple volume reduction constraints were chosen and a reduction constraint of 25% was chosen while proving most suitable for print, from a time, quality and material cost perspective.

Two additional critical constraints were enforced 1) Overhang constraint where the overhang angle was set to 45° and 2) Print direction was specified as a vector and the print direction was along the length of the hinge. This angle was chosen to vastly improve the likelihood of manufacturing it right the first time, thereby minimizing scrapped parts. This direction was chosen to avoid any complications with regards to part removal after manufacturing since the contacting surfaces with the build plate will be limited. The overall topology optimization process is summarized below.

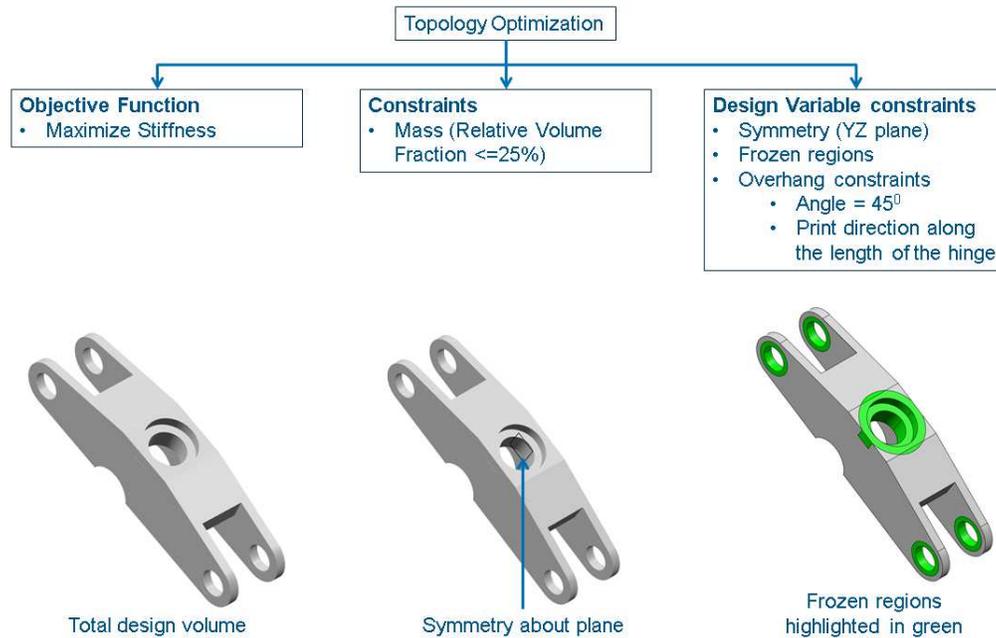


Figure 9: Topology Optimization setup

In addition to defining different constraints in the topology optimization process, all degrees of freedom of the central bore were fixed and a pressure load was applied to the top surface of the bore. In addition, four bearing loads were applied to the remaining four frozen regions. Four different load cases were generated and the optimization was performed. The following image is the result of the optimization.



Figure 10: Optimized shape of the automotive door hinge

3 Design Reconstruction

3.1 Subdivision Surfaces

The optimized shape from Tosca, with the appropriate settings, was exported as an OBJ file and was imported into the 3DEXPERIENCE platform. Upon import, this OBJ file translates into points and faces and can be readily manipulated using these points. These surfaces are typically referred to as subdivision surfaces. This approach of importing Tosca results into the 3DEXPERIENCE platform eliminates the use of STL files which can seldom be manipulated. This step drastically simplifies the reconstruction process, providing significant cost benefits as advanced surface modification tools in the CAD environment can be used to create organic shapes with vastly simplified facet information (reduced file size), true geometric features and parameters which lend themselves well to further parametric shape optimization studies.

The subdivision surface upon import was split from the design space thereby creating the optimized shape in the 3DEXPERIENCE platform. This solid shape served as a guide for the actual reconstruction of the design. While the frozen regions remained intact, the other parts of the hinge were constructed using the Tube Drawing tool within the *Functional Generative Design* app in 3DEXPERIENCE. This tool was used to design the members and struts of the hinge. If necessary, the shape of these members can be manipulated using control points. Using this method, the hinge was reconstructed and converted to a solid model.

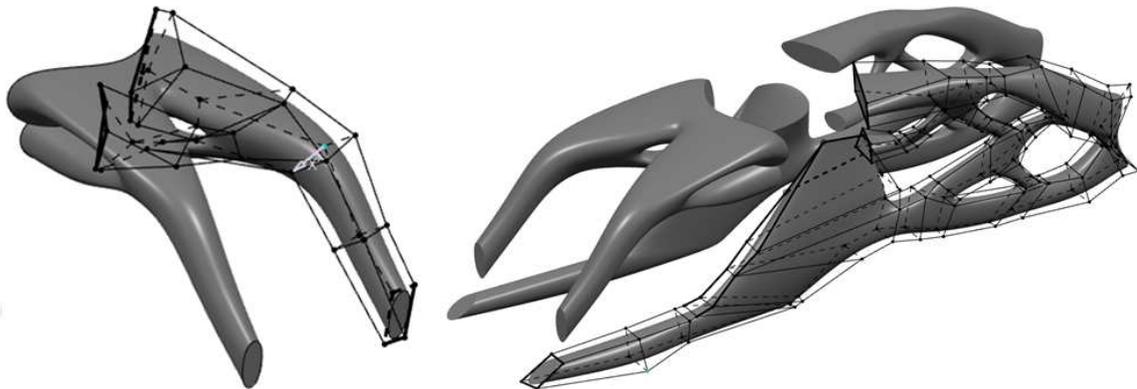


Figure 11: a) Subdivision surfaces with control points b) Subdivision surfaces for the entire hinge

3.2 Design Modifications

After completing the reconstruction of the part, further tweaks were made to the model by modifying the subdivision surfaces. This increased the angle of the struts and cross members to be more than 45° , thereby reducing the overall volume of supports required to manufacture the part. Another modification was that the sharp edges in the model were filleted to avoid any cracks due to thermal stress.

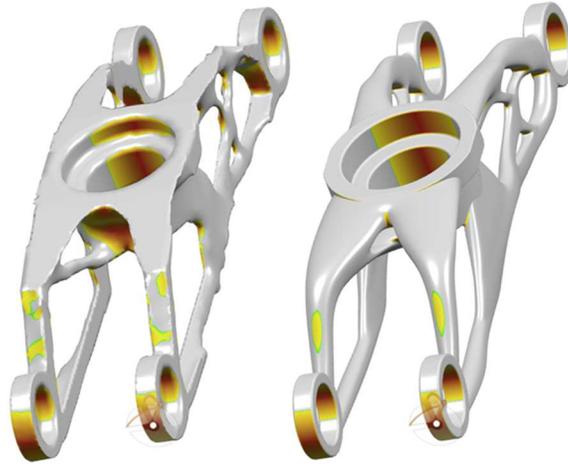


Figure 12: The ALM overhang analysis tool shows regions that require support material (highlighted in red and yellow) a) Initial Tosca output after importing into 3DEXPERIENCE b) Altered design to reduce overhanging surfaces/struts

In Figure 12, it is seen that the circular regions in the model also require supports. A more sophisticated technique was implemented by re-configuring the bores and the circular regions in the model to diamonds. This ensured that the regions were self-supporting and also increased the yield strength through reduction of possible support failure. Also, the material waste accounted for after machining the diamond regions into circular regions will be much lesser when compared to the material waste that will be accounted for by supports. Finally, the contacting surface between the hinge and the build plate was redesigned to be flat which would increase the robustness of the build. All the above listed modifications made the hinge self-supporting.

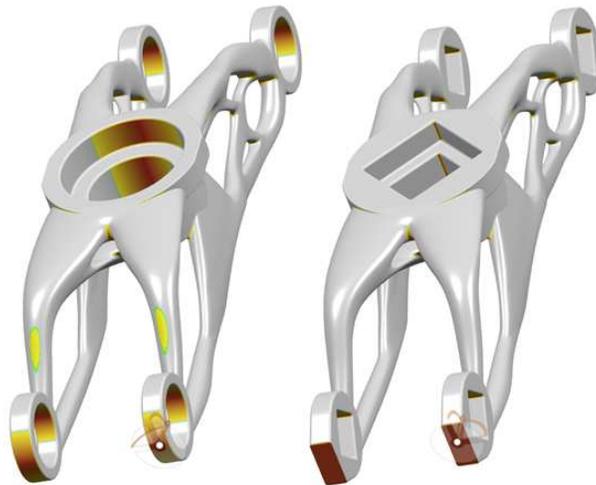


Figure 13: The ALM overhang analysis tool shows regions that require support material (highlighted in red and yellow) a) Hinge with circular regions b) Final design of the hinge with diamond regions, flat contacting surface and further modifications to struts to minimize supports

This design was printed using a Renishaw AM 500 printer with no additional support material.



Figure 14: Real printed part using the Renishaw AM 500 metal printer

4 Design Validation

To validate the structural integrity of the part, the loads and boundary conditions that were used for the optimization process were used for the validation. To perform a validation of the part, the diamonds have to be machined out such that the frozen regions are circular. In addition, surface finishing processes have to be implemented to make it ready for assembly. These operations will create machine induced residual stresses which need to be accounted for while validating the design.

In this paper, the validation is performed on the final shape without considering the above factors. Below shown are Von Mises stress results based on the different applied load cases.

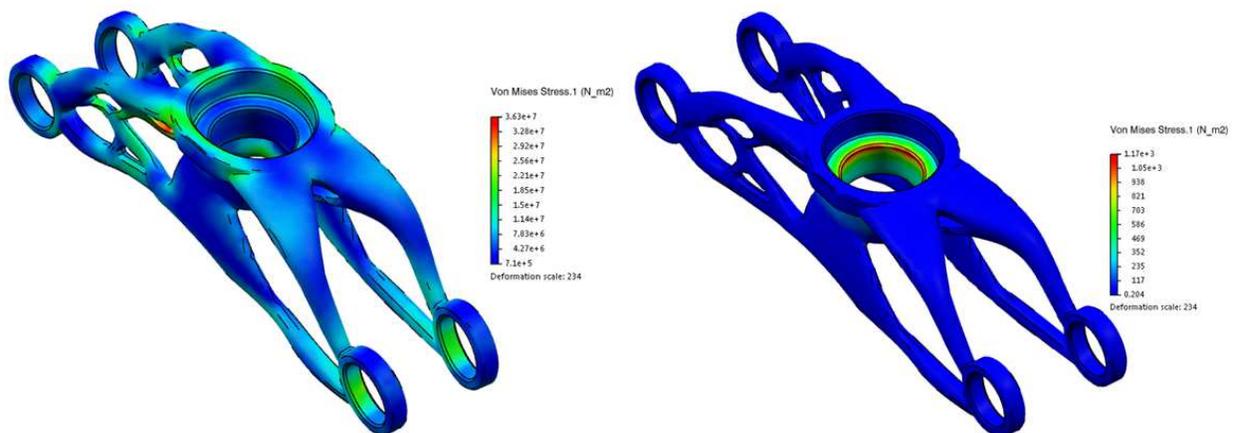


Figure 15 a) All loads are applied b) Only Pressure load

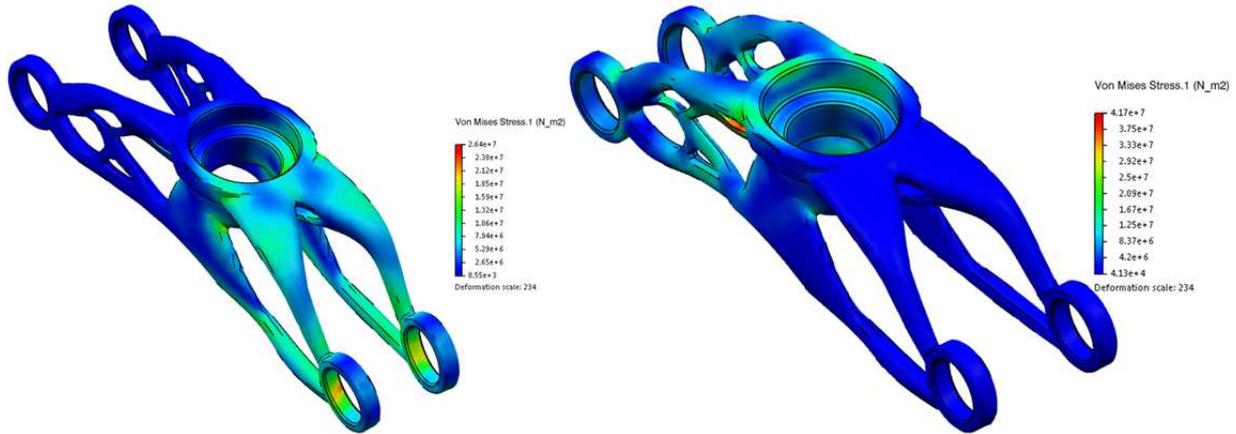


Figure 16: Pressure load and one bearing load is applied to the near end d) Pressure load and one bearing load is applied to the far end

5 Previous Hinge Design

5.1 Topology Optimization

The previous design of the hinge was a result of an optimization process (same loads and boundary conditions) with neither the angle constraint nor the print direction constraint in the design variable constraints definition. The design is shown below.



Figure 17: Reconstructed geometry of the previous design with overhanging members

In the previous design, there are a few overhanging members that will make the structure dependent on support material while manufacturing. The same manufacturing constraints were taken into consideration to change the circular regions into diamonds.

5.2 Support Structures

By comparing the two designs, it is expected that the old design will require more supports compared to the new design. Using Renishaw's preprocessing software QuantAM, the total volume of supports that will be required to manufacture both the designs can be computed and compared.

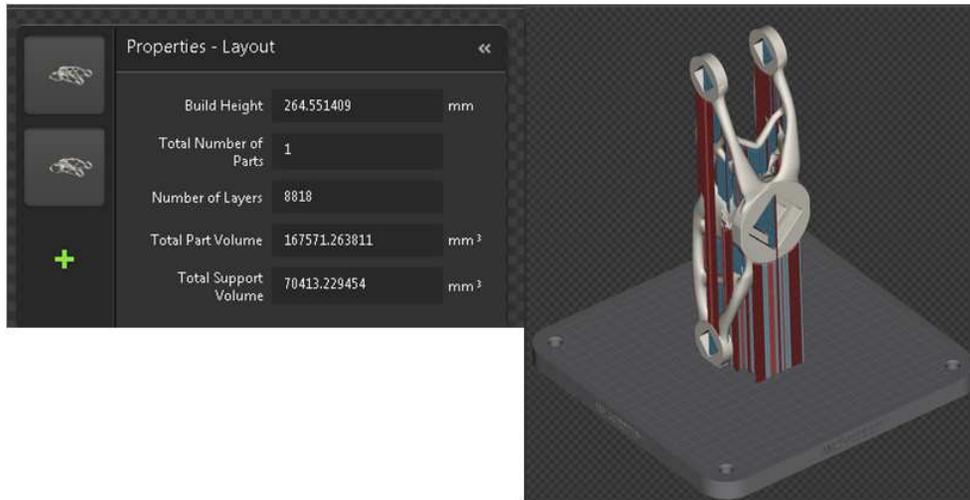


Figure 18: Support volume computed for the old (previous) design using QuantAM

In Figure 18, the support structures were computed based on a 45° constraint and the supports generated are circular in cross section. The total support volume was computed to be about 42% of the total part volume.

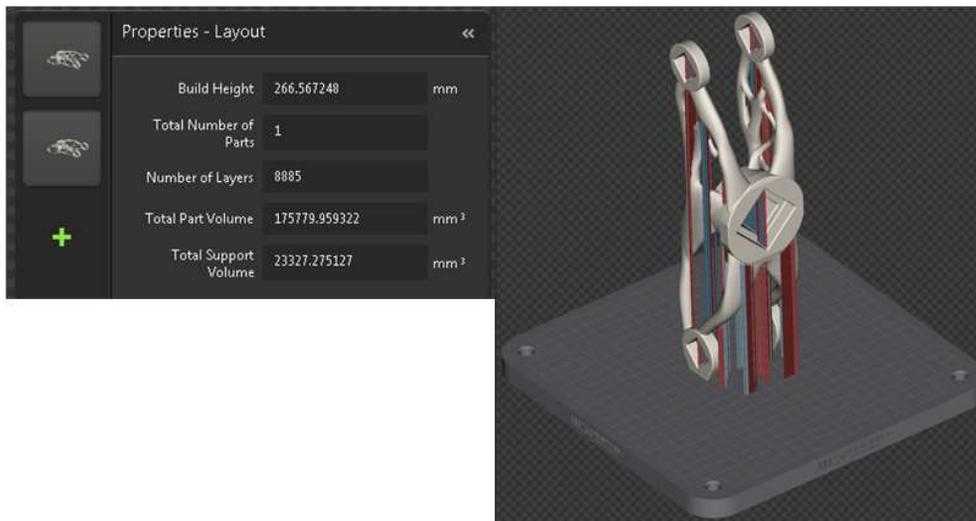


Figure 19: Support volume computed for the new design using QuantAM

In Figure 19, the estimated support volume for the new design was computed to be about 13% of the total part volume. Although supports were recommended for manufacturing the hinge, the metal powder acted as support material during the print process thereby eliminating additional supports.

5.3 Design Validation Comparison

The validation process is similar to the new design. Below is an image that compares the Von Mises stress of both the designs.

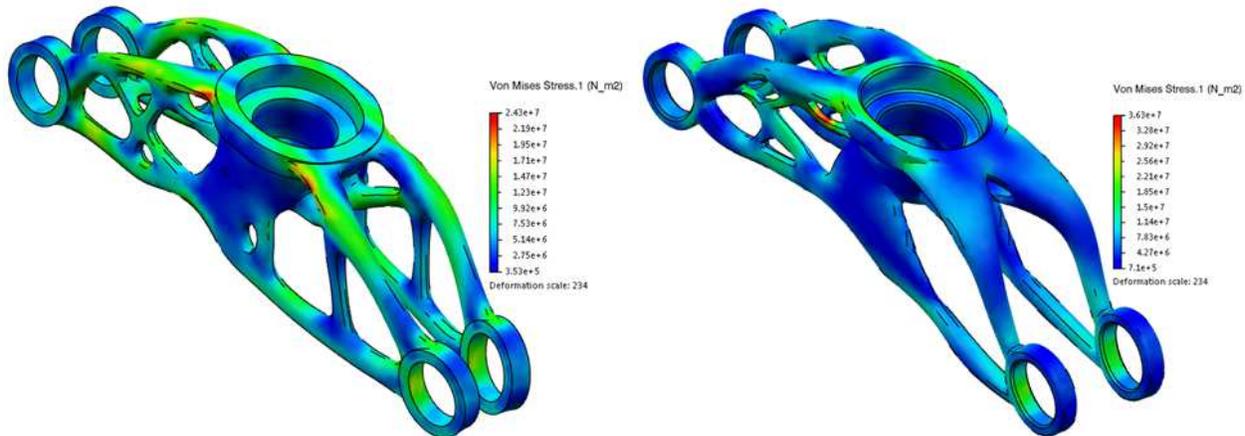


Figure 20: Von Mises stress a) Old design b) New design

6 Future Work

Next steps include performing the optimization with a displacement constraint in addition to the overhang and print direction design variable constraints and compare it to the current design of the hinge. Once the new design is reconstructed, stresses induced due to post processing will be included in the design validation process to have a more realistic comparison with the stresses developed during actual post processing.

7 References

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