IOP Conf. Series: Materials Science and Engineering **276** (2017) 012026 doi:10.1088/1757-899X/276/1/012026

A case study on topology optimized design for additive manufacturing

A W Gebisa* and H G Lemu
Department of Mechanical and Structural Engineering and Materials Science, University of Stavanger, Stavanger, Norway

*Corresponding author: aboma.w.gebisa@uis.no

Abstract. Topology optimization is an optimization method that employs mathematical tools to optimize material distribution in a part to be designed. Earlier developments of topology optimization considered conventional manufacturing techniques that have limitations in producing complex geometries. This has hindered the topology optimization efforts not to fully be realized. With the emergence of additive manufacturing (AM) technologies, the technology that builds a part layer upon a layer directly from three dimensional (3D) model data of the part, however, producing complex shape geometry is no longer an issue. Realization of topology optimization through AM provides full design freedom for the design engineers. The article focuses on topologically optimized design approach for additive manufacturing with a case study on lightweight design of jet engine bracket. The study result shows that topology optimization is a powerful design technique to reduce the weight of a product while maintaining the design requirements if additive manufacturing is considered.

1. Introduction

Topology optimization is a mathematical tool to make optimized material distribution in a part to be designed. By doing so, it gives us a part topology that is more natural and more complex. There are different topology optimization approaches developed during the last three decades. For instance, set level approach, homogenization method, SIMP method and density approach are among the main topology optimization techniques [1, 2]. The initial topology optimization developments considered the conventional manufacturing techniques that are either subtractive or formative. These conventional manufacturing systems have limitations in producing complex shape geometries as they have different manufacturing constraints. The birth of additive manufacturing gave another bright future opportunity for topology optimization as with additive manufacturing (AM) technologies; producing complex shape geometry is achievable. This is because, in AM, the systems do not require any tooling for producing a part. For this and other similar capabilities of the technologies, topology optimization and additive manufacturing are considered ideal couples.

To implement AM technology in production of functional parts, advances in materials technology and design optimization are considered as the key areas of current research. Regarding the last-mentioned research challenge, a design approach that can directly transfer the design concept of the engineer to a produced part without any due consideration for manufacturing constraint and enable optimum utilization of the part under loading is sought. If proper and efficient algorithms are developed, topology optimization techniques can play a key role in the future development of AM technology. This

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case study article is intended to explore the role of topology optimization in AM to design a lightweight product.

The article is structured as follows. Section 2 discusses the basics of topology optimization with its benefits and the formulation of topology optimization problems. In Section 3, topology-optimized design for additive manufacturing is discussed considering lightweight product design. Section 4, elaborates the case study considered in the project followed by Section 5 that ends the report by drawing some conclusions.

2. Topology optimization

In mechanical design problem, there came to exist a structural optimization concept in which the size, shape and topology of a product are optimized separately or simultaneously. These concepts are very important to find an optimal size, shape and material distribution during the product development process. As shown in Figure 1 [3], size optimization deals with the optimization of size of an object (length, width or depth); whereas shape optimization is to find optimal shape of a part or openings in a part; while topology optimization deals with optimizing the whole geometry of the part including both size and shape. In this section, the concept of topology optimization with its benefits and formulation of topology optimization problems are discussed.

2.1. What is topology optimization?

Topology optimization is one of the structural optimization techniques that optimizes the distribution of material within a specified design space for a given loading and boundary conditions while fulfilling the performance requirements of the product. Most of the topology optimization techniques are carried out by collective use of Computer Aided Design (CAD) concept, Finite Element Analysis (FEA) concept and different optimization algorithms in consideration of different manufacturing techniques as shown on the topology optimization process on Figure 2 [4]. The use of CAD in topology optimization is to make a rough/initial model of the product to be optimized, whereas FEA is used to see the distribution of stresses and displacements throughout the product. The topology optimization is performed to remove the areas of the part that are not sufficiently supporting the applied loads and not undergoing significant deformation and thus not contributing to the overall performance of the part.

Based on the design problem requirement, different optimization algorithms are used to remove the portion of the material in the product that are not supporting the applied load. Moreover, the topology optimization is done to satisfy certain design objectives and maintain the design constraints. Based on the problem at hand, the objectives might be to minimize the compliance of the part, i.e. to maximize the stiffness of the part, as compliance is the inverse of the stiffness; the constraints could be the maximum allowable deformation, the maximum mass fraction and so on. The topology optimization tools generate a complex natural shape that shows the removal of materials based on the objectives and constraints set in the design problem. The design is then finalized on CAD software to get smooth and manufacturable part following the shape generated from the topology optimization process. Ultimately, the final optimized design is validated using FEA tools to satisfy the design requirements so that the product meets its overall performance.

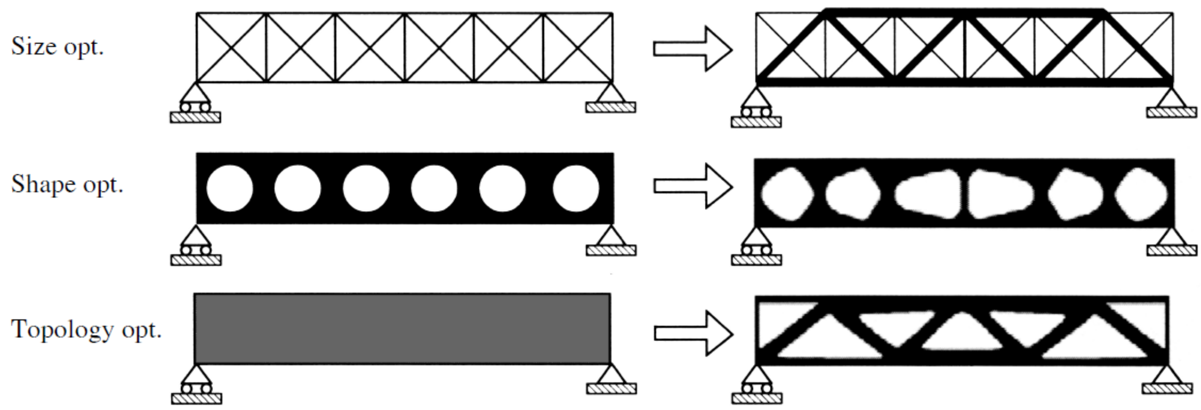

Figure 1. Comparative illustration of size, shape and topology optimization

Structural optimization, in general, has huge potential benefits in product development process. Topology optimization in particular has the following benefits in the design process

- Creating lightweight structures
- Creating ready to manufacture design
- Reducing time-to-market
- Saving huge amount of material
- Reducing physical test
- Saving large amount of processing energy
- Reducing physical prototype build

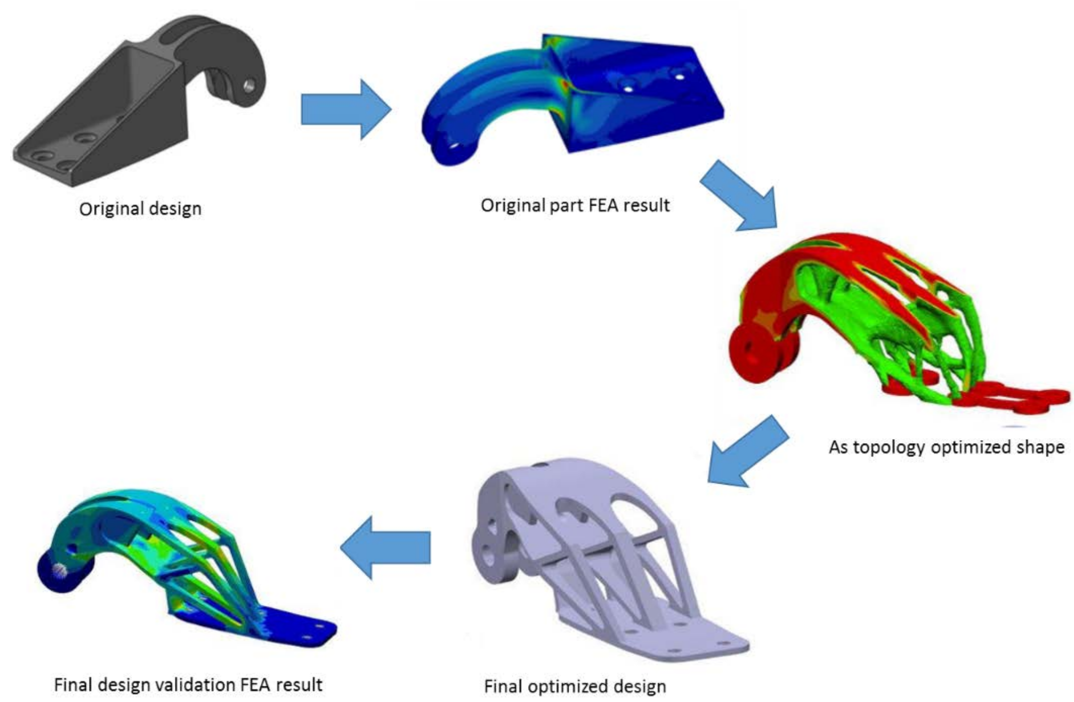

Figure 2. Topology optimization process

2.2. Formulation of topology optimization problem

The formulation of topology optimization problem has to be made very carefully as the best solution is obtained only if the problem is formulated in a proper way. The following five steps are used in the formulation of design optimization problem [5].

1. *Develop topology optimization problem statement:* In this step, the design goal, what to accomplish by the optimization and set of criteria will be clarified.
2. *Data and information collection:* In this step, all the necessary information are collected.
3. *Identification/definition of design variables*: In this step, the design variables that describe the system are identified and defined.
4. *Identification of a criterion to be optimized:* The criteria to evaluate and stop the optimization process has to be clarified. These criteria are called objective functions, which have to be maximized or minimized depending on problem requirements.
5. *Identification of constraints:* The restrictions on the problem are identified at this stage. They are extracted from the resources and performance requirements.

Mathematically the optimization problem can be formulated as in equation (1) [6]:

$$\begin{aligned} \text{Minimize}: &\quad f(\mathbf{x}) \\ \text{Subject to}: &\quad g_i(\mathbf{x}) \le 0, \quad i = 1,\ m \\ &\quad h_j(\mathbf{x}) = 0, \quad j = 1,\ p \\ &\quad \mathrm{x}_k^{\ell} \le \mathrm{x}_k \le \mathrm{x}_k^{\mathrm{u}}, \quad k = 1,\ n \end{aligned} \tag{1}$$

where f(x) is the objective function to be minimized whereas g(x) and h(x) are inequality and equality constraints respectively. The m and p are the number of inequality and equality constraints respectively; x is the vector of design variables; n is the total number of design variables; and x^l_k and x^u_k are the lower and upper bounds of the k^{th} design variable x_k, respectively.

3. Topology optimized design for additive manufacturing

Topology optimization is a powerful design approach to save time, material and energy that are not economically achievable with any other manufacturing process if explored to its maximum by considering additive manufacturing. Additive manufacturing (also referred to as 3D printing) is an emerging manufacturing technology that has the potential to outpace or replace the conventional manufacturing approaches. AM is defined as “process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies ” [7]. Additive manufacturing technology has unique capabilities; shape complexity (produces any shape that can be designed), materials complexity (processes multi-material products), hierarchical complexity (products internal structure ranging from mesoscale to macroscale) and functional complexity (produces multiple parts as a single functional product) [8]. Topology optimization has started long time ago with consideration of the existing manufacturing techniques. However, the existing techniques did not benefit sufficiently from this design approach because there are manufacturing constraints for the optimized designs. The optimized topology could not be produced, as there are limitations on the geometric complexity to produce with the existing manufacturing techniques.

In product development process, lightweight design has huge benefits including reduction in material consumption, reduction in processing and energy consumption. The potential approach to reduce the weight of a product is to use the topology optimization with additive manufacturing techniques as reported elsewhere [9-19]. Topology optimization can be employed for new product design or redesigning of an already existing product so that lightweight product can be obtained while maintaining its functional requirements. Topology optimized lightweight design can be realized by using different materials internal structures: solid structures or cellular structures. Topology optimization with additive manufacturing is considered to redesign a bracket to reduce its weight from 70 gm to around 42 gm, which is about 40% reduction [20]. A similar opportunity in re-designing a bracket with more lightweight that was manufactured using laser additive manufacturing is reported in [21]. These kinds of geometries are very difficult to manufacture using the traditional techniques but they can be realized with additive manufacturing.

Designers at ARUP in Netherlands have also explored the opportunity of topology optimization for additive manufacturing by redesigning a steel node for a tensegrity structure [22]. In their research, they found out that the topology-optimized design for additive manufacturing could enable the weight reduction of the node from 20 kg to 5 kg (75% reduction) without compromising the functional and structural performance of the product. Lightweight topology optimized automotive control arm design with lattice structure is investigated as another opportunity to be produced using additive manufacturing [23].

It is also reported [24] that, a hip joint implant interior part is topologically optimized and fabricated using additive manufacturing. The implant part has interior pore that makes it much complex and unachievable with conventional manufacturing techniques. However, the part is produced with additive manufacturing since the technology made the geometry complexity free. Moreover, it was not possible to find porous implants that allow the ingrowth of bone and cells if design optimization and additive manufacturing were not implemented together in the product development process. OptiStruct and Altair product design team helped RUAG Space Switzerland Zurich to topology optimize an existing antenna support arm to be produced using additive manufacturing that resulted in half weight reduction from the old version [25]. Topology optimized cargo sling with 15% volume reduction thus weight reduction is also another research that demonstrated the potential of topology optimization to make lightweight design [26].

Figure 3 shows topology optimized design process. First, the original CAD design is drawn in a 3D-CAD modeling software. The original design is then structurally analyzed with the given loading conditions to see the stress and displacement distribution. Based on the stress and displacement distribution, the topology optimization removes material from areas that does not significantly contribute to carry the applied loads. Based on the topology optimization result the part is remodeled in a CAD software. The new CAD model is then verified with FEA to carry the loads and to satisfy the design requirements. If the model satisfies the verification physical model verification is done using any of physical prototyping methods. If not the remodeling is done again until verification is done. The final design is then prepared for the final additive manufacturing. The process is employed in the next section, case study, to redesign a jet engine bracket to show the potential of topology optimized design for additive manufacturing.

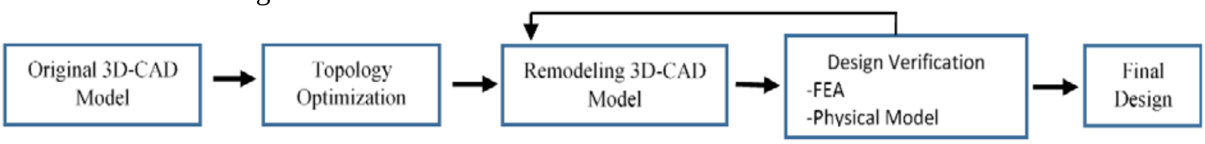

Figure 3. Topology optimized design process

4. Case study

In this study, a jet engine bracket shown in Figure 4 [27] is considered as a case study to show the potential of topology optimized design approach in reducing the weight of a product if coupled with additive manufacturing. The original bracket is based on General Electric (GE) design. The bracket is designed to sustain different loading conditions shown in Figure 5.

4.1. Analysis of the original bracket

Structural finite element analysis is carried out on the original bracket to see the stress distribution in the part. The contour plots shown in Figure 6 show the von Misses stress distribution for all the load cases in the part. The large areas of the part that are shown in blue color in the contour plot indicate inefficient use of material. It is very likely that these areas of the part need material removal as they have negligible effect on the performance of the part.

4.2. Design optimization

In this study, the bracket is redesigned using topology optimization design approach considering four loading conditions. The objective of the study is to reduce the weight of the bracket while satisfying all the design requirements. Altair Hypemesh 14 Optistruct commercial software is employed for the topology optimization. The design requirements for the engine bracket are listed below [27].

- The optimized geometry must fit within the original part envelope.
- The material was Ti-6Al-4V with an assumed yield strength of 904 MPa at the service temperature (23ºC).
- Minimum material feature size (wall thickness): 1.13 mm
- Interface 1: 19 mm diameter pin. The pin was to be considered infinitely stiff for analysis purposes.
- Interfaces 2–5: 9.5-24 AS3239-26 machine bolt. Nut face 10.287 mm max ID and 14.173 mm min OD. The bolts were to be considered infinitely stiff.

The topology optimization is formulated as in equation (2):

Minimize the weighted compliance i.e. to maximize the stiffness

Subject to

Mass fraction < 30 %

Minimum feature size >1.13 mm

(2)

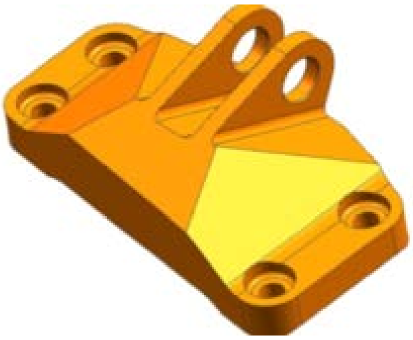

Figure 4. Original jet engine bracket.

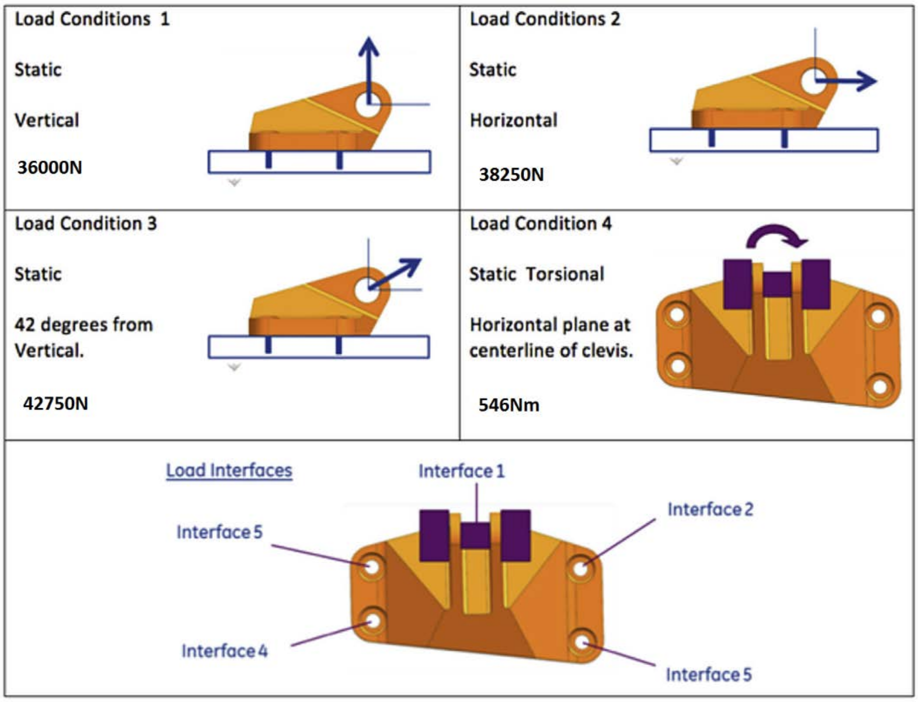

Figure 5. Loading conditions and function description of the engine bracket [27].

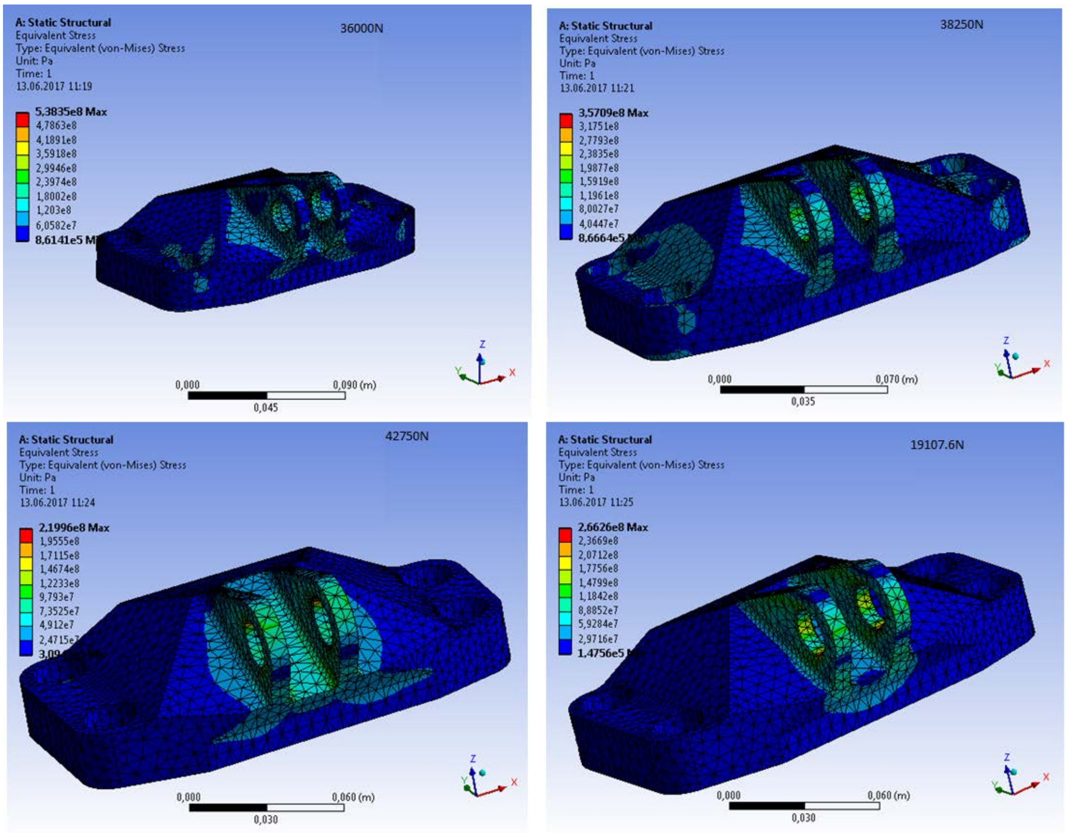

Figure 6. FEA of original engine bracket.

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The initial stage of the topology optimization is to divide the part into design (green) and non-design (yellow) spaces as shown in Figure 7. This is to separate the part into two parts; design space, a space on which the topology optimization is carried out and non-design space, a space that has nothing to do with the topology optimization and is unchanged. Furthermore, the non-design space is the part of the object through which, it is connected to others parts. Both spaces are then meshed using the same tool, Altair Hypemesh 14 Optistruct commercial software as shown in Figure 8. The mesh is done very fine with element size of 0.25 mm to obtain an even and acceptable materials distribution throughout the part.

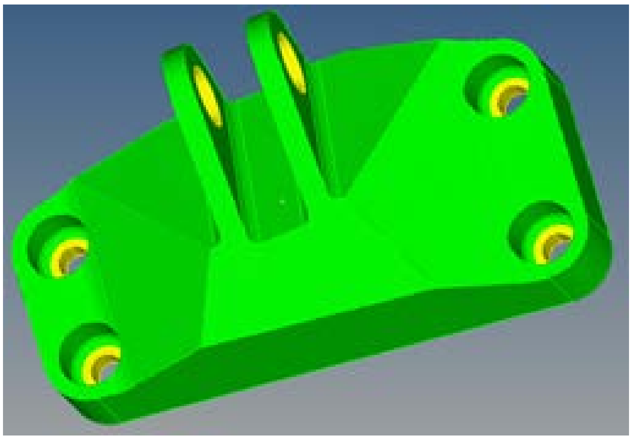

Figure 7. Design (green) and non-design (yellow) spaces

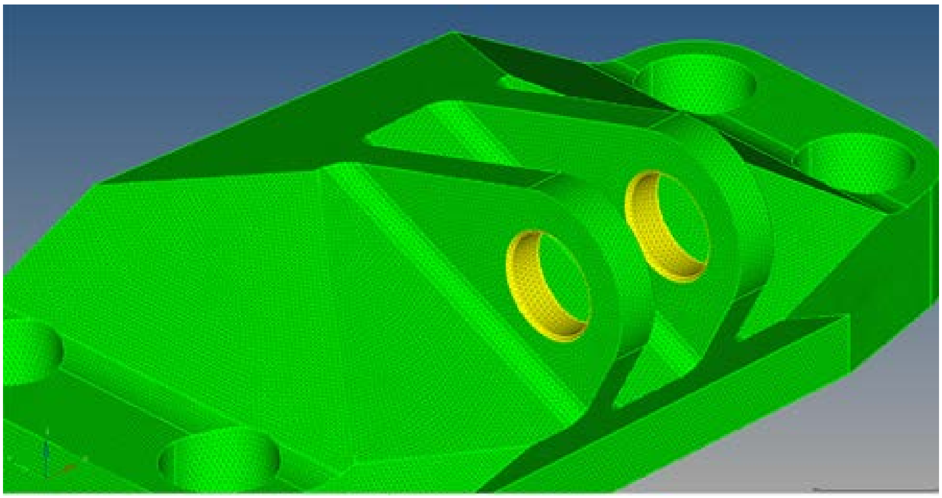

Figure 8. Meshing of the engine bracket.

All the loading conditions and the constraints are then applied on the part through the non-design spaces. The loads are applied separately on the part through the two horizontal hole surfaces defined as non-design spaces as shown on Figure 9 to make the part ready for optimization. The torque is applied as two equivalent force couples in different directions as there was a problem in the software to apply a torque.

The topology optimization tool computes the stress and displacement distribution on the part for all the loads separately. Based on the stress and displacement distribution, parts that are supporting less load or not significantly contributing to support the load are removed resulting in a very natural geometry shown in Figure 10 (left). As optimized the geometry is a very natural rough geometry showing the optimized material layout throughout the part. Since the initial optimized geometry from the tool is

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rough and does not look good aesthetically, remodelling of the part is important. The final design is then prepared on Autodesk Inventor Professional following the topology optimization as closely as possible as shown in Figure 10 (right).

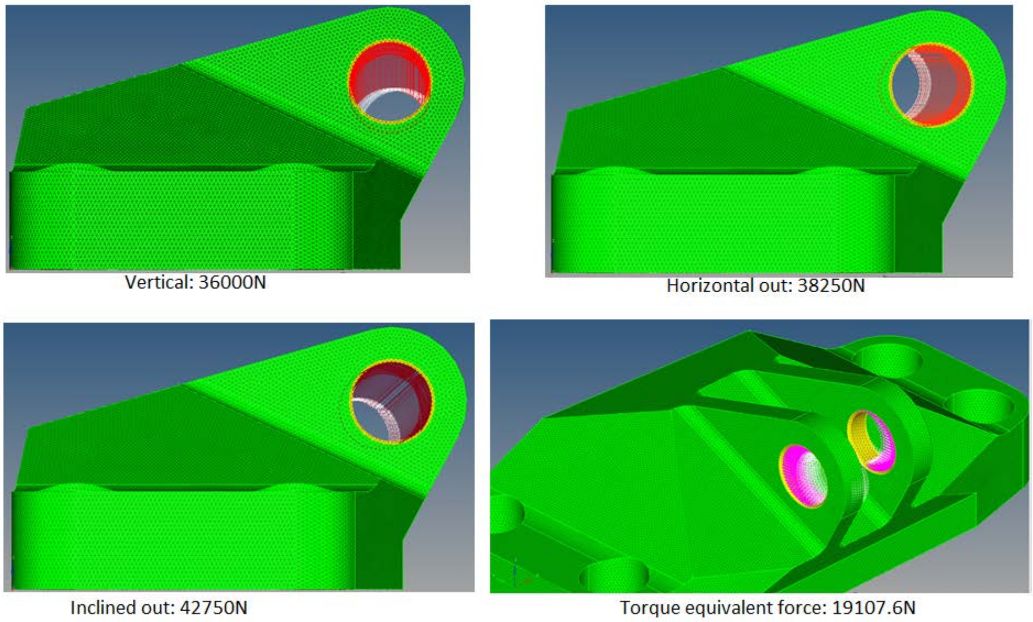

Figure 9. Loads applied on the engine bracket.

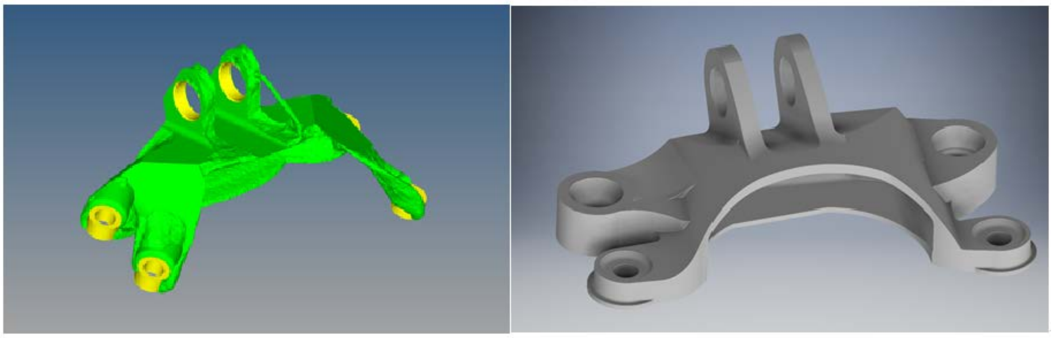

Figure 10. Topology optimized geometry: as optimized (left) and remodelled final part (right).

The newly designed part will have to sustain the same mechanical load while fulfilling the same design requirements. The final design has to be verified with the given design criteria that is the yield strength. The von Misses stress values for all the load cases should not exceed the yield strength. The structural verification analysis is done on ANSYS R17 Academic Educational tool. As shown in Figure 11 the von Misses stresses for all the cases are below the yield strength of the material. The final design satisfies the yielding condition with safety factor from 1.11 to 2.17. The final design is additive manufactured using fused deposition modelling (FDM) Fortus 450 from Stratasys for the physical design verification as shown in Figure 12. The final design resulted in 65% weight reduction, which is from 2.067 kg original part to 0.72 kg final one.

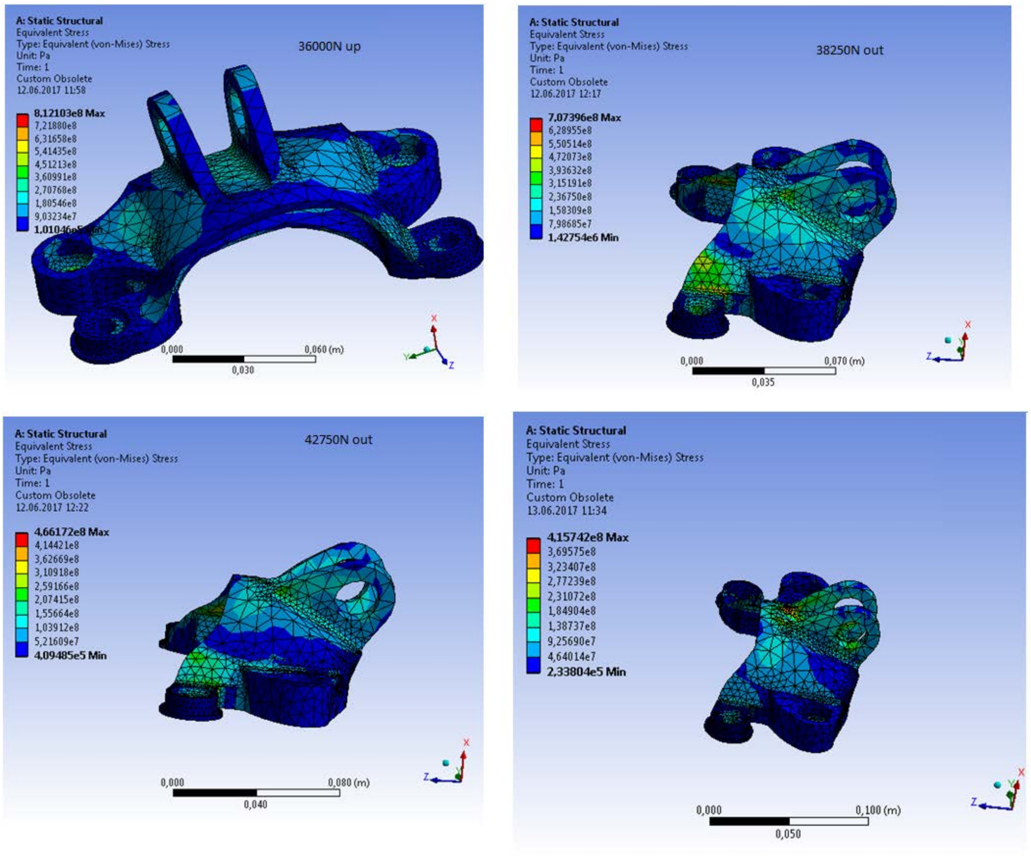

Figure 11. Final engine bracket design stress verification contour plots.

Figure 12. Additive manufactured final engine bracket design.

5. Conclusion

From the case study, it can be concluded that, topology optimization is a powerful design concept to reduce the weight of structural products. The reduction of weight saves huge amount of material and processing energy thus huge amount of money. It also shows that the capability of topology optimization can be fully utilized with additive manufacturing techniques, as the manufacturing constraints in the conventional methods are no longer available. From the case study result, which is 65% weight reduction, it can also be concluded that topology optimized design for additive manufacturing can reduce huge portion of the mass thus result in lightweight design.

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