Computational Methodology for Optimal Design of Additive Layer Manufactured Turbine Bracket

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Abstract

The design of critical components for aircrafts, cars or any other kind of machinery today is typically subject to two conflicting objectives, namely the maximisation of strength and the minimisation of weight. The conflicting nature of these two objectives makes it impossible to obtain a design that is optimal for both. The most common approach aiming for a single objective optimisation problem in aerospace is to maintain the weight minimisation as the objective, whilst setting strength requirements as constraints to be satisfied. However, manufacturing methods incorporate additional restrictions for an optimal design to be considered feasible, even when satisfying all constraints in the formulation of the optimisation problem. In this context, Additive Layer Manufacturing adds remarkably higher flexibility to the manufacturability of shape designs when compared with traditional processes. It is fair to note, however, that there are still some restrictions such as the infeasibility of building unsupported layers forming angles smaller than 45 degrees with respect to the underlying one.

Nowadays, it is common practice to use a set of software tools to deal with these kinds of problems, namely Computer Aided Design (CAD), Finite Element Analysis (FEA), and optimisation packages. The adequate use of these tools results in an increase in efficiency and quality of the final product. In this paper, a case study was undertaken consisting of a turbine bracket from a General Electric challenge (Figure 5). A computational methodology is used, which consists of a topology optimisation considering an isotropic material at first instance, followed by the manual refinement of the resulting shape taking into account the manufacturability requirements. To this end, we used SolidWorks®2013 for the CAD, Ansys Workbench®14.0 for the FEA, and HyperWorks®11 for the topology optimisation. A future methodology will incorporate the automation of the shape optimisation stage, and perhaps the inclusion of the manufacturability restriction within the optimisation formulation.

1. Introduction

Today, in industry and in an academic environment, stress analysis using Finite Element Method (FEM), Structural Optimisation, Additive Manufacturing (AM) and Hot Isostatic Pressing (HIP) post-treatment are used in order to improve existing designs or design new parts for several fields such as automotive or aerospace. In order to manage so many areas of expertise, a multidisciplinary team is needed. Although, a multidisciplinary team can relatively simply meet, the demands of this type of challenge, the team needs to work logistically in order to amalgamate the knowledge of the team members. Developing a working methodology we ensure that the goals are achieved in a more effective way.

AM [3] is a process for making a three-dimensional solid object from a digital model. AM is achieved using an additive process where successive layers of material are laid down in different shapes. AM is also considered distinct from traditional machining techniques (subtractive), which mostly rely on the removal of material by methods such as cutting, drilling or laser.

AM consists of both building an object “from scratch” or from a semi-finished part acting as substrate. Nowadays, these processes are used for rapid manufacturing purposes [7] and [8].

This new technology has produced a breakthrough in manufacturing technology followed by a breakthrough in design that at the moment is in process.

Renishaw’ s laser melting process is an emerging manufacturing technology with a presence in the medical (orthopaedics) industry as well as the aerospace and high technology engineering and electronics sectors. Laser melting (LMe) is a digitally driven additive manufacturing process that uses focused laser energy to fuse metallic powders in to 3D objects.

In this paper general ALMa (Additive Laser Manufacturing) concepts and ALMe (Additive Laser Melting) technology are presented through the solution for the General Electric (GE) Challenge presented a few months ago on GrabCAD platform online.

Renishaw’ s laser melting is an additive manufacturing technology that uses a high powered ytterbium fibre laser to fuse fine metallic powders together to form functional 3-dimensional parts.

The process is digitally driven, direct from sliced 3D CAD data, in layer thicknesses ranging from 20 to 100 microns that form a 2D cross section. The process then builds the part by distributing an even layer of metallic powder using a recoater, then fusing each layer in turn under a tightly controlled inert atmosphere. Once complete, the part is removed from the powder bed and undergoes heat treatment and finishing depending on the application.

For the case study presented in this paper, the characteristics of the present technology available in the College of Engineering at Swansea University were accounted for.

2. Jet Engine Bracket Challenge for General Electric. GrabCAD Platform Online.

GrabCAD is a community online where it is possible to share CAD files and put forward design challenges. General Electric has used this platform to launch its challenge called “Jet Engine Bracket Challenge”. Details about it can be found in https://grabcad.com/challenges/ge-jet-engine-bracket-challenge. The case study presented in this paper is the result of our participation (ASTUTE Team, College of Engineering, Swansea University) in the challenge mentioned above.

2.1. The Bracket

Loading brackets on jet engines play a very critical role. They must support the weight of the engine during handling without breaking or warping. The brackets

may be used only periodically, but they stay on the engine at all times, including during flight. New technologies like ALMe can contribute to reduced costs and improve the structural characteristic of components such as this.
The requirements needed to be fulfilled during the design process for the GE challenge are listed in the next section.

2.2. Requirements Established in the Challenge

The GE challenge consisted of an aim to reduce the weight of a turbine bracket, starting from an initial design. The case loads and the initial shape of the bracket are shown in Figure 1.

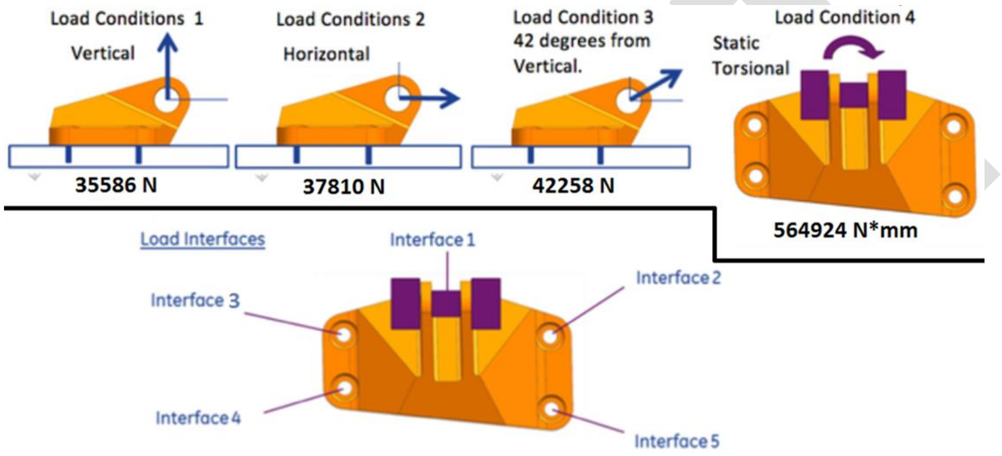
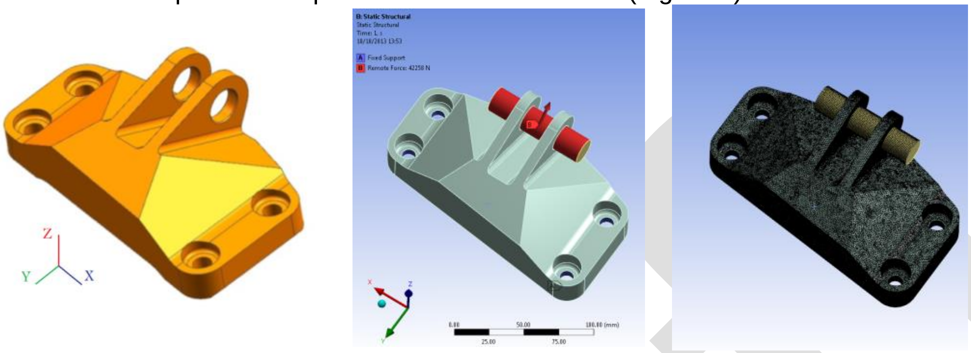


Figure 1 – Load cases and interfaces

The requirements for developing the optimisation are listed below:

- Static and linear elastic analysis is considered.
- The optimised geometry must fit within the original part envelope (Figure 2, left).
- The material properties are isotropic and elastic titanium Ti-6Al-4V.
- Optimisation is considering using the solid material with the mechanical properties: density, ρ = 4.43 g/cm3; Young's Modulus, E = 113.8 GPa; Poisson's Ratio, $\nu = 0.342$; Tensile Yield Stress (TYS) = 903 MPa.
- The service temperature is 24°C.
- The minimum material feature size (wall thickness) is 1.27 mm.
- Interfaces (Figure 1): Interface 1 – Rigid pin 19.05 mm diameter (19.1135 mm hole diameter); Interfaces 2-5: diameters between 10.3124 mm and 10.668 mm.
- All bolts are considered rigid.
- There are four loads conditions: Maximum Static Linear Load of 35,586 N Vertically Up; Maximum Static Linear Load of 37,810 N Horizontally Out; Maximum Static Linear Load of 42,258 N and 42 degrees from vertical;

Maximum Static Torsional Load of 564,924 N·mm horizontal at intersection of centerline of pin and midpoint between clevis arms (Figure 1).



Element Size 1 mm (733,908 tetrahedral elements), Smoothing: Medium, Transition: Slow

Figure 2 – Envelope, Scheme and FE mesh used for simulations

2.3. Material Properties

Using laboratory appropriate infrastructures, it is possible to obtain the mechanical properties of a material produced by means of ALM technologies [5]. Usually, because the way that this technology produces the different parts, each piece produced has an anisotropic mechanical property. Since the process produces parts with relative high porosity, HIP treatment can be used in order to reduce the mentioned porosity increasing the density of the material to achieve an optimum value.

2.4. Optimisation Process of the Part

Structural optimisation is an iterative process made in several steps. Usually, a preliminary design is available and a FEA on this is needed in order to assure the stresses and deformations are under the elastic limits (TYS and UTS). In this work the FEA mentioned above was made by means of Ansys Workbench [1], Figure 4. The first step after the initial FEA is the topology optimisation that in this case was made using Hyperworks 11 (OptiStruct). After the topology is defined the iteration process starts until the final optimised design is reached. The iterative process followed for this work is resumed in the next simple algorithm shown on Figure 3:

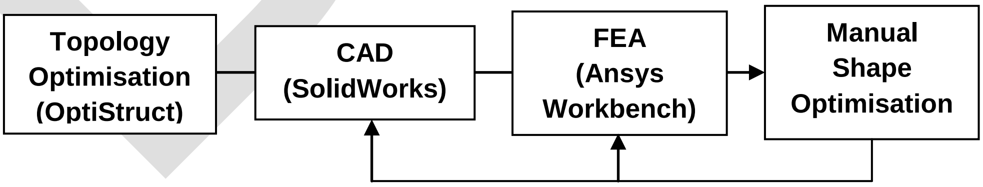


Figure 3 - Optimisation Flow Chart

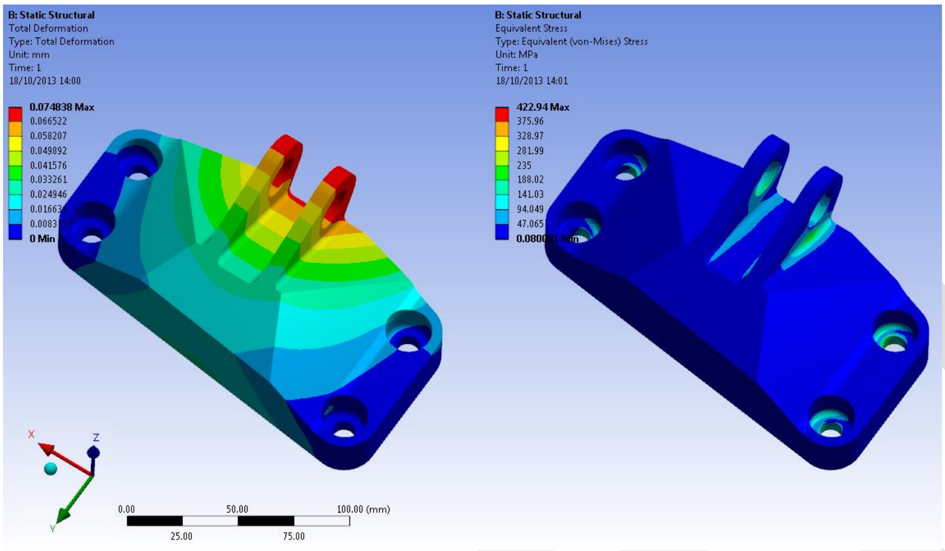


Figure 4 – Total deformation and Von-Mises stresses for oblique load

3. ALM in the Structural Optimisation Process.

A traditional manufacturing process has more restrictions than AM technology in general. There are several AM machines currently available in the world. To identify the specific manufacturing capabilities as well as the manufacturing constraints, training and experience are needed with the specific equipment used.

One important thing when applying a new technology is to understand the technology and its limitations. There is a general idea that it is possible to manufacture any shape using AM technologies without any limit. It is true, that AM permits the creation of amazing shapes and mechanisms but there are restrictions. It is true for example that complex parts, such as turbine blade shapes, can be made easily using AM technologies in comparison with milling or turning, but again with limitations. In general we can say that AM technology is more flexible and cheaper than traditional manufacturing routes. AM technology produces cheaper and more flexible shapes but they have more porosity and they are anisotropic. In our experience with 316L Stainless Steel, it was observed that the steel produced from the powder is more ductile than the solid material and it needs some posterior HIP process to improve its properties.

The purpose of this section is to show the complexity added regarding the material properties when AM technologies are used in general and with ALMe in particular.

In the particular case of the examples presented here, the Renishaw AM250 machine was used, together with the software MTT Autofab.

During the optimisation and design it is essential to keep in mind the printing of the part in the AM machine. The software MTT Autofab allows checks to be made of alternative methods of construction, to allow the user to make a decision which is the best strategy regarding support, cost and time.

ALM technology produces a piece of metal manufactured from superposed layers. The square base where the process is made is shown in the Figure 5. When a part is printed, each layer is bonded to the previous one by means of the laser melting the powder onto the lower layer. There is a limitation with regard to the angle that is feasible with respect of the x-y plane. Angles of less than 45 degrees in respect of the horizontal plane need support. Support is additional material needed to be able to construct the part. Example of support for construction of the bracket is shown in Figure 5. Obviously, this is not the best orientation choice, to manufacture the component, but it clearly shows the idea of the required support.

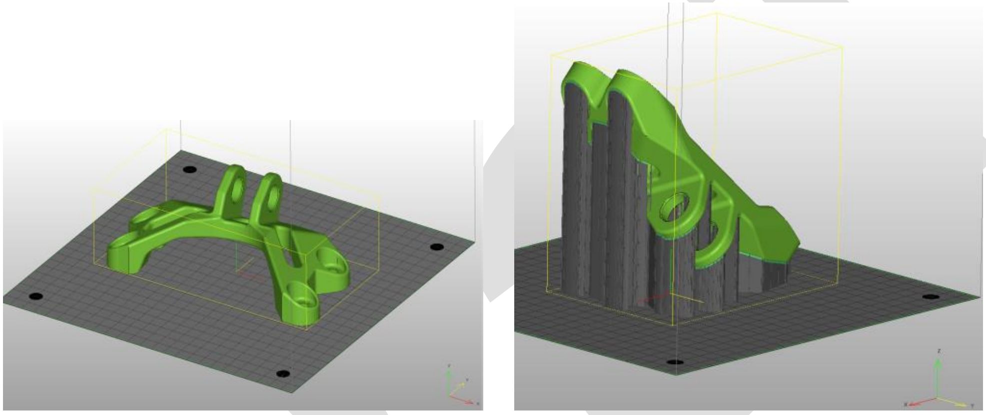

(a) (b)

Figure 5 – (a) MTT Autofab software; (b) Support needed to construct the part in this position

3.1. Stress analysis of the original design

In the process to optimise a design, we start with some initial domain. In this particular case, the initial domain is shown in Figure 2, left. This was the original design and the envelope inside which every alternative design had to be contained. The first step that had to be done was the FE analysis of the original design mentioned above. In Figure 2, right, the FE mesh used for the analysis is shown (element size 1 mm, smoothing medium, transition slow). The simulations were run by fixing the four holes and applying the loads on the rigid pin showed in Figure 2, middle. The 4 rigid pins fix the bracket to the turbine. The contacts between the bolts and the bracket were considered to be bonded.

Figure 4 shows the stress analysis for the oblique load case, carried out to check that stresses and deformations were under the elastic limits of the material (TYS and UTS). The FEA showed that, the oblique force load case was the worst case, so, this was taken as the reference case.

3.2. Topology optimisation from the original design

Topology optimisation was made using the initial design envelope. OptiStruct used the Solid Isotropic Material with Penalisation (SIMP) method and so the design variable used was element density [2]. The objective function to be minimised was the mass. The four load cases were added to the OptiStruct problem considering restrictions in Von Mises Stresses (<TYS). The zone around the four holes and the holes for the main pin, where the load is applied, were considered non-designable regions (red in Figure 6). The analysis incorporated all four load cases. The optimisation converged after 23 iterations to the solution shown in Figure 6. Only the element densities of 0.3 and above are shown.

3.2.1. General structural optimisation process

Topology optimisation [9] is a mathematical approach that optimises material layout within a given design space, for a given set of loads and boundary conditions such that the resulting layout meets a prescribed set of performance targets. Using topology optimisation, engineers can find the best concept design that meets the design requirements. Topology optimisation is used at the concept level of the design process to arrive at a conceptual design proposal that is then fine-tuned for performance and manufacturability. This replaces time consuming and costly design iterations and hence reduces design development time and overall cost while improving design performance. Engineer's designs should satisfy practical manufacturing requirements. In some cases AM technologies are used to manufacture complex optimised shapes that would otherwise need manufacturing constraints. Topology optimisation is distinct from shape optimisation since typically shape optimisation methods work in a subset of allowable shapes which have fixed topological properties, such as having a fixed number of holes in them. Therefore topology optimisation is used to generate concepts and shape optimisation is used to fine-tune a chosen design topology.

Structural optimisation is an optimisation where the objective function or constraints can be the compliance, frequency, mass, volume, moments of inertia, centre of gravity, displacements, velocities, accelerations, buckling factor, stresses, strains, composite failure, forces, synthetic responses, etc..

3.2.2. Topology optimisation with OptiStruct, Hyperworks 11®

RADIOSS and OptiStruct are two of the principal solvers provided with Hyperworks [4]. RADIOSS is a finite element solver for linear and non-linear simulations. It can be used to simulate structures and others problems. In this particular case, the bracket is in essence a structure.

Altair OptiStruct is an award winning CAE technology for conceptual design synthesis and structural optimisation. OptiStruct uses the analysis capabilities of RADIOSS to compute responses for optimisation.

Topology Optimisation generates an optimised material distribution for a set of loads and constraints within a given design space. The design space can be defined using shell or solid elements, or both. Both the classical topology optimisation set up solving the minimum compliance problem, and the dual formulation with multiple constraints are available. Constraints on von Mises stress and buckling factor are available with limitations. Manufacturing constraints can be imposed using a minimum member size constraint, draw direction constraints, extrusion constraints, symmetry planes, pattern grouping, and pattern repetition. A conceptual design can be imported into a CAD system [6] using an iso-surface generated with OSSmooth, which is part of the OptiStruct package.

The overall cost of design development can be reduced substantially by avoiding concept changes introduced in the testing phase of the design. This is the major benefit of modifying the design process by introducing topology and topography optimisation.

In the real world, the design process is not as straightforward as described above. The design is not just driven by one performance measure -- it has to be viewed as a multidisciplinary task. Today, the different disciplines work more or less independently. Analysis and optimisation is performed for single phenomena such as linear static behavior or noise, vibration and harshness. Still, the idea persists that if one performance measure improves, the whole performance improves. A simple example shows that this is not quite true. Take the design of a car high stiffness is necessary for good driving and handling characteristics, and high deformability is important for the crashworthiness of the design. This shows that improving one measure may result in degrading another. Therefore, compromises must go into the formulation of the optimisation problem. The definition of the design problem and of the design target is most important. The solution can be found through computational route. Multidisciplinary considerations, especially in the conceptual design, are, in many ways, still active research topics and are being covered by future developments of topology optimisation. However, the inclusion of manufacturing constraints into topology and topography optimisation is already implemented in OptiStruct.

OptiStruct can be used to solve and optimise a wide variety of design problems in which the structural and system behaviour can be simulated using finite element and multi-body dynamics analysis.

3.2.2.1. Bracket Topology Optimisation

In structural optimisation the simplest case is when there is only one part to be optimised. There are other cases where optimisation of mechanisms are needed.

Although, in those cases each component is a simple part, we have to analyse not only each part but the interactions between them.

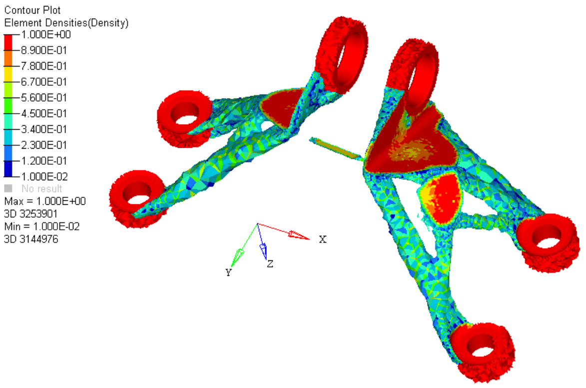


Figure 6 – Topology optimisation of the turbine bracket

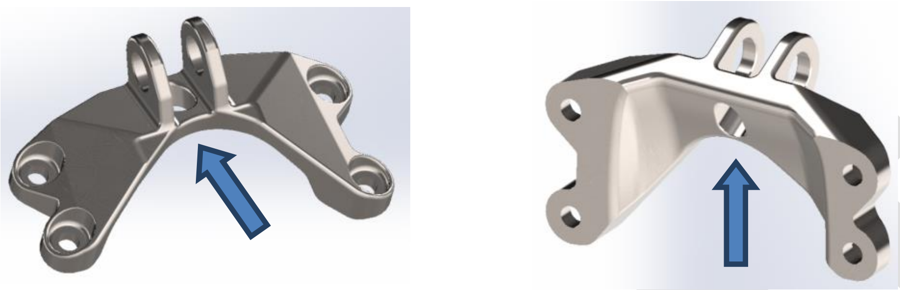
Figure 6 shows the result of the topology optimisation conducted with HyperWorks – OptiStruct 11. The red zones around the holes are non-design material and topology optimisation was made on the rest of the original envelop. The result appears logical and suggests a kind of design based on triangulation of the structure in order to transmit the load on the main pin to the four holes where the bracket is fixed to the turbine.

3.2.3. Concept Design

From the topology study the concept design shown in Figure 6 was obtained. From this concept design several iterations were made and at each stage that the four load cases were checked by running FE simulations with Ansys Workbench. In other words, the shape optimisation process was made by hand.
The topology optimisation suggests a triangulated structure formed by 4 legs connecting the main pin with the four holes and reinforcing the space between the legs with some material in the middle. This preferred reinforcement was to use triangulating material in order to generate a sort of truss.

3.2.4. Stress Analysis of the 4 Final Design Alternatives

Figures 7-10 and Table 1-4, show a summary of the FEA for the four designs presented in the challenge. The first one, called strongest, is the design with highest values of safety factor. The three next designs are only variations of the first one including holes. The second one has two holes that reduce the mass of the bracket but increases the values of the stresses.



Arrows indicate the construction direction by means of ALMe

Figure 7 – General Electric Challenge - Strongest Version (v55f)

Table 1 – Design Strongest: 763 grams (63% mass reduction)

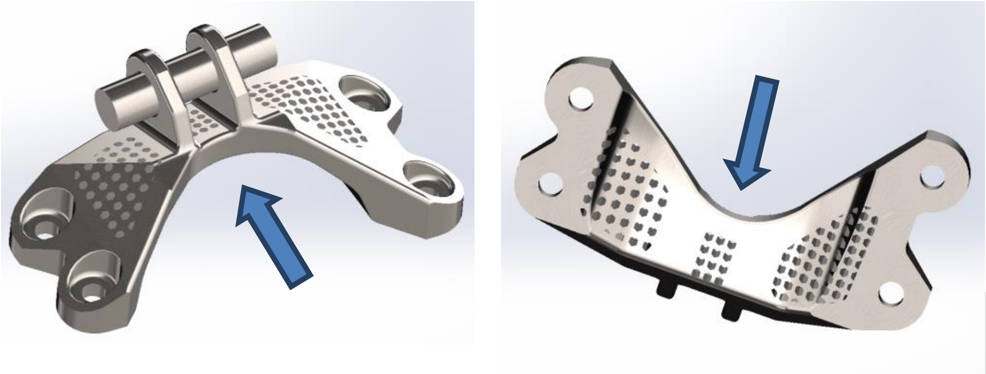
Yield limit 903 MPa	**Total Deformation** [mm]	**Maximum Von-Mises Stress** (MPa)	**Safety factor**
Vertical Load	0.39	760	1.19
Horizontal Load	0.36	582	1.55
Oblique Load	0.16	648	1.39
Torsion Load	0.13	503	1.79

Arrows indicate the construction direction by means of ALMe

Figure 8 - General Electric Challenge - Lightest Version (v58)

Table 2 – Design Lightest: 650 grams (68% mass reduction)

Yield limit 903 MPa	**Total Deformation** [mm]	**Maximum Von Mises Stress** (MPa)	**Safety factor**
Vertical Load	0.52	891	1.01
Horizontal Load	0.49	695	1.30
Oblique Load	0.21	690	1.31
Torsion Load	0.16	509	1.77

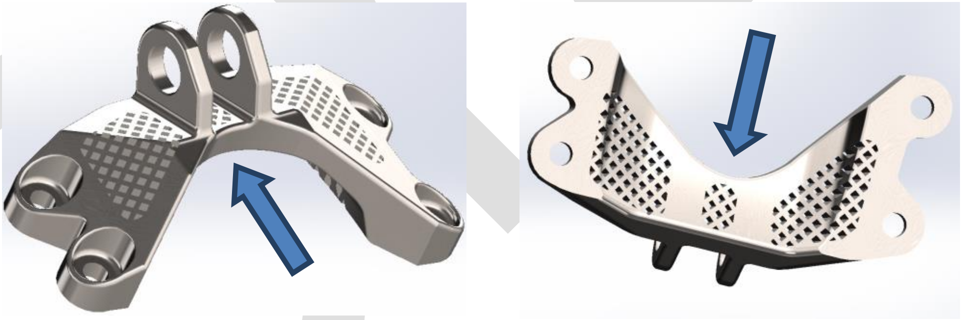


Arrows indicate the construction direction by means of ALMe

Figure 9 - General Electric Challenge - Intermediate Weight Version (v63f)

Table 3 – Design Intermediate Weight 1: 695 grams (66% weight reduction)

Yield limit 903 MPa	**Total Deformation** [mm]	**Maximum Von Mises Stress** (MPa)	**Safety factor**
Vertical Load	0.49	853	1.06
Horizontal Load	0.43	643	1.40
Oblique Load	0.19	622	1.45
Torsion Load	0.13	496	1.82



Arrows indicate the construction direction by means of ALMe

Figure 10 - General Electric Challenge - Intermediate Weight Version (v64f)

Table 4 – Design Intermediate Weight 2: 688 grams (66% weight reduction)

Yield limit 903 MPa	**Total Deformation** [mm]	**Maximum Von Mises Stress** (MPa)	**Safety factor**
Vertical Load	0.48	697	1.30
Horizontal Load	0.43	668	1.35
Oblique Load	0.19	764	1.18
Torsion Load	0.12	464	1.95

The third and fourth cases include some quasi-lattice to reduce the mass taking advantage of the ALM construction possibilities.

4. Conclusions

A case study is presented as a methodology linked with the theory on which the optimisation software is based.

A well establish methodology is used in order to optimise parts for any device under load.

The importance of taking into account anisotropy in loads, geometry and properties is remarked upon and explained as well as a working methodology being proposed.

The paper combines several concepts and technologies in order to improve the use of the tools and expertise regarding Structural Optimisation, AM technologies and Stress Analysis taking into account anisotropic properties.

5. Acknowledgements

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