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LATTICE TOPOLOGY OPTIMIZATION AND ADDITIVE MANUFACTURING OF A 316L CONTROL ARM

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Abstract. This paper presents a methodology to design optimum lattice-like engineering components that can be easily created using additive manufacturing. The optimal performance of the design is assured through a topology optimization, whereas the manufacturability is ensured thanks to the lattice nature of the designs. The paper discusses some advantages of lattice topology optimization compared to a traditional topology optimization approach, both in terms of performance and manufacturability of the final designs. The methodology combines different commercial software tools in order to effectively create such designs, that can be used in a wide range of sectors such as automotive, aerospace or medical.

1 INTRODUCTION

Topology optimization (TO) and Additive manufacturing (AM) techniques are nowadays mature enough disciplines to be used in industry [1]. The combination of both opens the door to produce novel and disruptive designs, such as the ones presented in [2, 3], that are not possible to create with traditional manufacturing processes. However, there are still some practical limitations for combining TO and AM effectively, mostly related to the fact that the TO results generally require a post-processing step in order to fine-tune the design and make it apt for AM. This fine-tuning process is usually done by a CAD engineer and includes, among others, avoiding overhanging structural members or limiting massive members that may lead to stress concentrations in the material (caused by overheating). As a consequence, several interactions between the design and manufacturing experts are required, and different alternatives might come up for the same optimal results. Figure 1 shows an example of the TO results of baffle supports in a satellite (left), several design interpretations of the results (middle) and the final design created using AM (right). This iterative design process also involves that the final design that is manufactured usually deviates from the optimum in terms of mass and stiffness.

In order to overcome some of these difficulties, novel optimization strategies, such as Lattice Topology Optimization (LTO) are increasingly being used. Lattice structures consist of a pattern repetition of small cell shapes or types, trying to simulate the internal micro-structure of the material. As a consequence of being built-up by small ”bars” that are connected to each other,

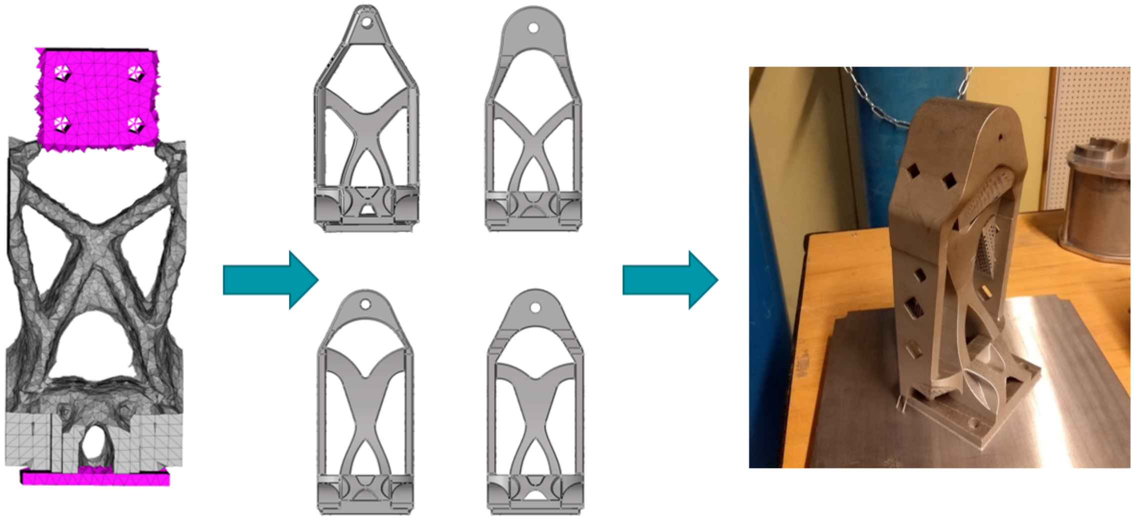

Figure 1: TO results of baffle supports in a satellite, several design interpretations and final design using AM

most of the AM problems described in the above paragraph do not apply to them. In particular, overhanging is avoided since the dense network of small bars is self-supporting (when talking about printability) and the small size of the bars avoids any stress concentration problem due to material overheating.

As stated in [4], the development of AM technology has relaxed the limitations when fabricating lattice structures (although there still exist some manufacturing constraints, they are way less than in a design coming from a traditional TO). In other words, LTO enables a faster process from design towards manufacturing, mainly because the LTO output relates directly to the shape to be manufactured, meaning that it does not require (or very limited) design interpretation of the optimum results.

Another advantage of lattice structures is that they possess some desirable characteristics from a design perspective, such as lower weight, better performance and stability (due to the large network of structural members), good energy absorption and high thermal and acoustic insulation compared to its solid counterpart [5]. This increased performance of LTO designs over traditional TO designs supports the choice of LTO for this study.

2 METHODOLOGY

This paper proposes a methodology that covers all the steps in the design of a new lattice optimized component that is intended to be produced using additive manufacturing (Figure 2). It starts with a LTO that is performed in Altair Optistruct [6], and afterwards the results are converted into ”lattice printable information” (generally a geometry file such as .STL) using the dedicated software 3matic-STL from Materialise [7]. The final step is to prepare the geometry files so they can be properly processed by the 3D printer in order to achieve the best manufacturing quality (i.e. create supports, check printability, etc.). This is done using the dedicated software 3DXpert [8]. In order to perform a LTO in Altair Optistruct, the optimization problem is spit into two phases:

- PHASE I: consists of a conventional topology optimization applied to the design space, followed by a lattice generation (replacing solid elements with intermediate densities by lattices) that depends on the parameters defined by the user.

- PHASE II: consists of a sizing optimization of the lattice structure obtained in PHASE I, where the design variables are the cross-section of the small bars. The size optimization phase is aimed at incorporating some anisotropy to the lattice structure, thereby making the structure more efficient.

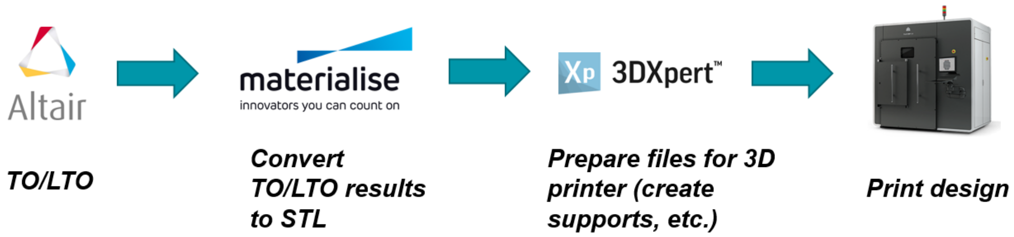

Figure 2: Flowchart of steps for the design and additive manufacture of a lattice metal component

In PHASE I, the optimization problem is defined, including the lattice settings such as the ”Lattice type” (internal structure or cell shape of the lattice), ”Porosity” (similar to the penalization factor in a traditional TO using the SIMP approach, which leads to a lower or higher number of elements with intermediate densities, that correspond to a lower or higher percentage of lattice structures), and ”Lattice fill” (defines the upper and lower bound of the element densities in order to replace solid elements by lattices). From the designer perspective, one of the hardest decisions in this phase is the selection of the lattice cell type, which must be done up-front without knowing the potential effects that it will have in the structural behaviour of the optimal design. Probably it will not have a major effect due to the optimization process afterwards, but it is possible that the stiffness properties of the lattice cell have their influence on the final structure. In general, there are a few parameters that the designer needs to tune in this phase in order to perform the LTO.

In PHASE II, the definition of the optimization problem stays the same, however the user needs to perform two operations: define the upper bounds (UB) and lower bounds (LB) of the new design variables (cross-section of lattice beams), and ensure that all the solid elements in the model (i.e. in the non-design space) are tetrahedrons, since this is necessary to export the geometry in an .STL format. Altair Optistruct provides an option to convert all the solid non-tetrahedral elements into tetrahedrons within the software.

3 APPLICATION EXAMPLE

The methodology described in Section 2 is tested with a case example of an automotive control arm (see Figure 3), taken from the Altair Optistruct documentation [6].

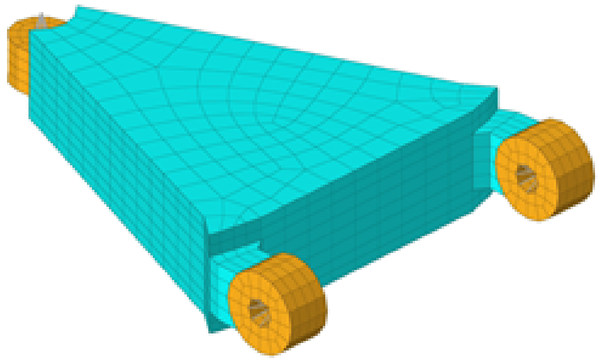

Figure 3: Automotive control arm

The dimensions have been modified (102x133x21 mm) in order to make it fit in the printing area (maximum of 275x275x420 mm). The material is defined as 316L stainless steel, with mechanical properties of $E = 210000$ MPa and $\rho = 7.85e-9$ T/mm^3. The goal of the optimization is to reduce the mass of the control arm, while fulfilling a number of displacement constraints in three different load cases.

$$\min_{\mathbf{x}} Mass \tag{1}$$

subject to:

$$disp(\text{LC1}) = 0.05 \text{ mm} \tag{2}$$

$$disp(\text{LC2}) = 0.02 \text{ mm} \tag{3}$$

$$disp(\text{LC3}) = 0.04 \text{ mm} \tag{4}$$

Several optimization have been performed in order to evaluate the influence of the UB and LB of the parameter ”Lattice fill” in the performance of the designs. In this study, the rest of parameters were not modified since the focus of this study was to obtain a simple-cell lattice structure that could be easy to manufacture. In that sense, the ”Lattice type” is always a tetrahedron, and the ”Porosity” is set as ”HIGH” (generating a structure with a higher number of lattice elements, which is beneficial for buckling considerations). The optimal designs obtained from the LTO have been compared against traditional TO with and without manufacturing constraints (see Figure 4), in terms of mass and stiffness. An artificial metric ”Performance” has been defined in order to compare in an easy way all the designs (y-axis of Figure 4). The x-axis of the figure shows the different cases that are studied (i.e. ”LTO 001-06” states that the case is a LTO design where the bounds of the ”Lattice fill” parameter are LB = 0.01 and UB = 0.6).

$$Performance = 1/(Mass * Compliance) \tag{5}$$

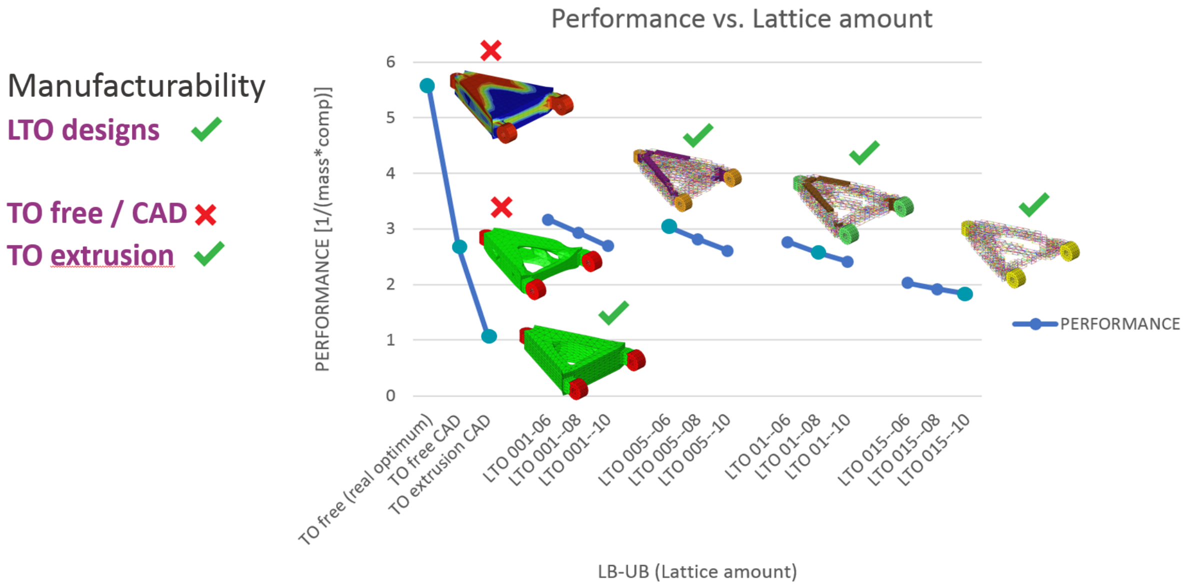

Figure 4: Summary results of TO and LTO

The results prove that the performance of all the LTO designs is higher than the TO designs when manufacturing constraints are considered. On the other hand, the performance of the LTO can be worse if it is compared to a free TO where manufacturing constraints are not taken into account. However, in this scenario the LTO designs offer the extra advantage of being always manufacturable, as explained in Section 1.

The results show that, if the LB of the ”Lattice fill” parameter is constant, an increase of the UB implies a decrease in the performance of the design (this is expected since more intermediate elements that were solid are replaced with lattices, which are less stiff). A similar conclusion can be drawn from the LB of the ”Lattice fill”: if such parameter increases and UB stays constant, the performance tends to decrease, since lattice elements are replaced by void elements. The mass improvement in the model if such elements are removed is not enough to compensate the loss of stiffness. Table 1 shows a more detailed view of some of the results of Figure 4.

Table 1: Comparison of TO designs (with and without manufacturing constraints) vs. LTO

Case (LB-UB)	TO (free)	TO (extrusion)	LTO (0.05-0.6)	LTO (0.1-0.8)	LTO (0.15-1.0)
Mass [kg]	0.68	0.97	0.638	0.767	1.127
Comp [mm/N]	55	97	51.44	51.9	48.58
Performance	2.67	1.06	3.04	2.51	1.82

After the LTO study, one of the LTO designs (LB = 0.05, UB = 0.6) has been transformed to an .STL file in order to be sent to the metal 3D printer. Figure 5 shows the FE model of the design (left) and the .STL geometry generated in 3DXpert (right). The selection of the design among all the ones studied is arbitrary, the only requirements are that it should be a mixed solid-lattice design with a high enough number of lattices, in order to see if the 3D printer runs into problems. The 3D printer is a ProX DMP 320 from 3D Systems, which allows to print components up to 275x275420 mm, in different metal and ceramic options. The printing layer thickness is set to 5μm, although other thicknesses are also possible. The intention is to finalize this research by 3D printing the prototype shown in Figure 5, verify its manufacturability and perform a test in order to validate its stiffness.

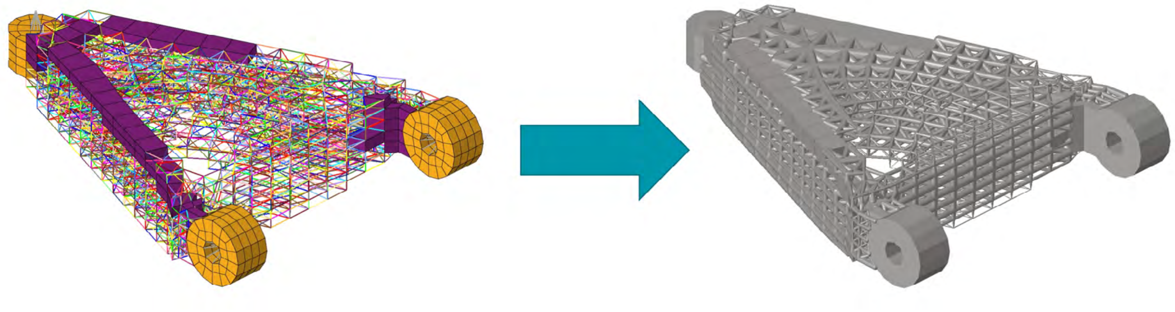

Figure 5: Example of lattice design (left) and STL file for sending to the 3D printer (right)

4 CONCLUSIONS

This study proposes a general methodology to design lattice topology optimized engineering components, that can be fabricated through additive manufacturing (AM) techniques. Topology optimization (TO) is a discipline that is heavily related to AM, however the manufacturability of TO designs is not trivial or straightforward. It always requires the explicit definition of manufacturing constraints in the optimization problem, and usually even extra iterations between the design and manufacturing experts. Lattice topology optimization (LTO) is introduced in this paper as an alternative to traditional TO in order to ease the manufacturability of designs, avoiding the classical problems of TO. The results show that the performance of LTO designs is consistently higher than in TO designs where manufacturing constraints are set. Moreover, LTO assures the manufacturability of the designs even if manufacturing constraints are not explicitly defined in the optimization. On the other hand, the main drawback of LTO is that it requires an extensive knowledge from the designer, in order to tune some specific key parameters of the LTO such as the lattice type, the porosity or the upper and lower bounds of the lattice fill.

REFERENCES

[1] Gebisa, A.W. and Lemu, H.G. A case study on topology optimized design for additive manufacturing. *IOP Conf. Series: Materials Science and Engineering* (2017) **276**:012026.

[2] Orme, M., Madera, I., Gschweitl, M. and Ferrari, M. Topology Optimization for Additive Manufacturing as an Enabler for Light Weight Flight Hardware. *Designs* (2018) **2(4)**:51.

[3] Zegard, T. and Paulino, G.H. Bridging topology optimization and additive manufacturing. *Structural and Multidisciplinaray Optimization* (2016) **53**:175-192.

[4] Tang, Y., Dong, G., Zhou, Q., and Zhao, Y.F., Lattice Structure Design and Optimization With Additive Manufacturing Constraints. *IEEE Transactions on Automation Science and Engineering* (2018) **15(4)**:1546-1562

[5] Liu J., Gaynor A.T., Chen, S., Kang, Z., Suresh, K., Takezawa, A., Li, L., Kato, J., Tang, J., Wang, C.C.L., Cheng, L., Liang, X., To, A.C., Current and future trends in topology optimization for additive manufacturing. *Structural and Multidisciplinaray Optimization* (2018) **57**:2457-2483

[6] Altair Hyperworks. Altair Optistruct 2017.1 documentation (2018)

[7] Materialise. 3matic-STL documentation (2018)

[8] 3D Systems. 3DXpert documentation (2018)