

New Lightweight Optimization Method Applied in Parts Made by Selective Laser Sintering and Polyjet Technologies

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The continuous evolution of materials and technologies of Additive Manufacturing (AM) has led to a competitive production process even for functional parts. The capabilities of these technologies for manufacturing complex geometries allow the definition of new designs that cannot be obtained with any other manufacturing processes. An application where this capability can be exploited is the lightening of parts using internal structures. This allows to obtain more efficient parts and, at the same time, reduce the costs of material and manufacturing time. A new lightweight optimization method to optimize the design of these structures and minimize weight while keeping the minimal mechanical properties is presented in this paper. This method is based on genetic algorithms (GAs), metamodels and finite element analysis (FEA). This combination reduces the number of FEA simulations required during the optimization process, thereby reducing the design time. This methodology is experimentally applied to a reference geometry oriented both for Selective Laser Sintering (SLS) and Polyjet technologies. In both cases an optimized and a non-optimized design are manufactured and tested in order to experimentally compare the stiffness results between them. The optimum design achieved a specific stiffness 72.82% higher than the non-optimized design in the SLS case study, and 3.14 times higher in the Polyjet case study.

Keywords: Additive Manufacturing, Lightweight Optimization, Genetic Algorithms, Finite Element Analysis

1. Introduction

Improvements in materials as well as the reliability and repeatability of Additive Manufacturing (AM) technologies (Kruth *et al.* 1998) have led to a steady increase in their use over the past decade (Gibson *et al.* 2009). Nowadays, the evolution of AM technologies allows their use even for manufacturing of functional parts, which has become the most important application of these techniques (Wong and Hernandez 2012).

The capabilities of these processes have changed the design rules employed for conventional manufacturing processes. In Additive Manufacturing, the almost inexistent restrictions associated with the manufacturing process involve an enormous design freedom (freeform manufacturing) (Hopkinson *et al.* 2006). This freedom allows the production of complex parts impossible to achieve with conventional production processes. In this sense, one of the most interesting applications of these capabilities is the lightweight optimization of AM parts using internal cellular structures. This concept has been used in many cases related to tissue engineering (Yang *et al.* 2001, Sachlos and Czernuszka 2003, Yeong *et al.* 2004, Yoo 2011, Almeida and Bártolo 2013), but can also be applied in many other sectors such as automotive or aeronautic. This lightweight optimization can lead to a more efficient design due to weight reduction, which is a key factor in some applications. Moreover, the mass reduction enables cost savings related to material used and manufacturing time, which means that with the application of lightweight optimization, more competitive products can be produced and with faster time to market. However, the lightweight optimization requires an initial design effort as well as the time required for the optimization process.

For this reason, in order to reduce the time and cost of design, a new optimization program based on GAs and surrogate model is proposed, taking advantage of the commercial software of 3D design and FEA to evaluate the quality of different designs. In order to facilitate the application of this methodology for any AM user, this program is integrated into the 3D design and FEA software through the Application Programming Interface, which provides a friendly and simple user interface.

2. New lightweight optimization method

Despite some authors have proposed very interesting methodologies for lightweight optimization with truss structures applied in AM, these methodologies are complex and

require interaction between different software. Additionally, main innovations in these references are related to the geometry modelling to define the truss structure (Wang and Rosen 2001, Wang *et al.* 2005, Rosen 2007, Chu *et al.* 2008, Chu *et al.* 2010, Chang and Rosen 2013). However, in this paper the objective is to optimize the variables of the internal structure according to the parameterized geometry proposed by the user in commercial 3D CAD software, which means that the most important issue is the optimization method. On the other hand, there are many topology-based commercial optimization software that remove the low-stressed zones to reduce the weight. However, these methods lead to rough designs or even unfeasible designs that cannot be manufactured even by AM. Although these limitations are being reduced more and more with the new AM-oriented commercial tools (such as 3-maticSTL, Materialise), the external surface can suffer modifications with this type of topology optimization. Nevertheless, the methodology presented in this paper is focused on parametric optimization in order to keep invariable the external surface and also to achieve the final optimum without any subsequent step.

As commented in section 1, FEA are used to evaluate the quality of proposed designs. Hence, modifying the parameters defined by the user in the CAD/FEA software, it is possible to change the design of the geometry and calculate the mechanical performance. Taking advantage of these tools, it is aimed to carry out an automatic optimization process (Dai *et al.* 2005, Marjanovic *et al.* 2009), reducing the optimization time as much as possible. Some authors (Roman Gatzi 2000) have applied genetic algorithms to optimize their designs. In this case, FEA is used to evaluate the fitness function of each individual proposed during the genetic algorithm evolution. However, this implies hundreds of FEA, which leads to an excessive consumption of processing time. To avoid this, some other authors (Jin *et al.* 2001, Zhu *et al.* 2009, Lee

et al. 2010) have proposed the use of metamodels to reduce the number of computationally expensive FEA simulations and thereby reduce the optimization time. For this reason, the optimization methodology proposed in this paper combines the potential of GAs, surrogate models and FEA to reduce optimization time.

2.1. Proposed methodology

The proposed methodology is divided into 3 different phases:

- (1) Initial design of experiments (DOE). In this phase some designs are calculated by FEA in order to obtain data to create the metamodel. This DOE is subdivided into 3 stages. In the first one, the points with all variables at their lowest value, mean value and maximum value are evaluated. This means that 3 points are simulated. The next stage of the DOE consists of applying GA with binary coding to add 'n' new points (n=number of design variables). A 0 means a variable at its lowest value, and 1 at its maximum value. This GA maximizes the difference of each variable compared with previous sampling points, which means that new points are added at the corners of the domain as far away as possible from the previous sampling points. Finally, 'n' new points are added in the last part of the DOE. In this case, a GA with ternary coding is applied to maximize the difference of each variable compared with previous sampling points. But now '-1' is related to the minimum value of the variable, '0' to the mean value and '1' to the maximum value. Furthermore, the GA penalizes designs with no gene at its mean value in order to add sampling points at different levels.
- (2) Feasible/unfeasible border approximation by GAs. After the initial DOE, a new phase is accomplished. This consists of creating a Kriging metamodel with a

linear regression model and an exponential correlation model, using all available data from the DOE. This metamodel is used to evaluate the fitness function during the evolution of a GA. This GA minimizes mass and penalizes individuals if any constraint is not satisfied. Additionally, in the first iteration of this phase, individuals close to the best design evaluated at earlier stages are penalized in order to explore new regions of the search space. Finally, the optimum achieved is simulated and the result is used to update the Kriging. This GA is repeated many times, but penalizing proximity to points added in this phase (a similar concept to niche sharing) (Della Cioppa *et al.* 2004) in order to explore new regions of the feasible/unfeasible border (Rubén *et al.* 2013). Once 'n' points have been added at this stage, the GA is applied again but without proximity penalty until achieving an optimum in which the mean absolute percentage error of the results estimated by Kriging, are less than 5% compared to the simulation results.

- (3) Final optimization by GAs. The last stage of the program consists of a GA similar to the previous phase (without proximity penalty). The Kriging metamodel is employed again to evaluate the fitness function of the GA individuals. The optimum achieved is simulated. This design will be the optimum if it is better than the best design of the previous stages of the optimization program. Otherwise, this GA is repeated until the best design of previous stages is improved. However, if more than '5+n' points have been simulated in this phase without enhancing the best design, and at least one of them was a feasible design, then this best design will be the final optimum.

The GAs applied in these 3 phases were based on a population of 100 individuals and maximum number of generations of 100. The selection was carried out with a

tournament selection of 2 individuals. The cross and mutation probabilities were 50% and 60% respectively. Elitism was also applied.

In the case of the GAs of the last 2 phases of the optimization program, arithmetic crossover was used and the mutation amplitude was 50%. However, in the GAs of the DOE, partition and recombination crossover was employed because of the binary and ternary encoding. Moreover, the mutation consists of changing the gen value in the binary encoding, and randomly modifying the gen to the other 2 possible values (50% probability) in the ternary encoding.

This optimization strategy was integrated into the CAD/FEA software via the Application Programming Interface. This application enables programming to automate the CAD/FEA software through multiple functions available that can be called from different programming languages such as Visual Basic. Additionally, the Matlab Window application is automatically employed in real time during the optimization problem to carry out the Kriging metamodel (Lophaven *et al.* 2002, S N Lophaven 2002). The user defines the geometry, parameters and numerical analysis following certain conventions to correctly apply the optimization program. Once the geometry, parameterization and FEA are defined, the user executes the optimization problem and also introduces certain data needed to start the optimization, such as the number of variables and their lower and upper limits, the number of constraints with their limit values and feasible zones, and the maximum length of the finite element for the mesh generation.

2.2.Comparison with other optimization methods

The proposed methodology was compared with 2 optimization methods available in commercial software of CAD/FEM (SolidWorks): the “high quality” method, based on

DOE of Box-Behnken and estimation of the optimum by response surfaces, and the “fast result” method, based on DOE of Rechtschaffner and optimum search by response surface estimation.

These 3 methods were tested in 7 different examples with complex geometries (Figure 1) and with different number of variables, from 3 to 20. In all the case studies the proposed method achieved a solution to the optimization problem while the other methods were limited depending on the number of variables, which means that the presented methodology is more versatile than these 2 commercial methods. Moreover, the optimum achieved by this method was always better than the optimum of the “high quality” method, improving it up to 3.41% and reducing the sampling required from 88% to 3.8 times. Likewise, the new method obtained a better solution (up to 6%) than the “fast result” method, reducing also the sampling up to 76% in some cases. Although these commercial methodologies are widely used when a low sampling intensity is required, the developed method improved the results both in terms of quality of the optimum and sampling intensity.

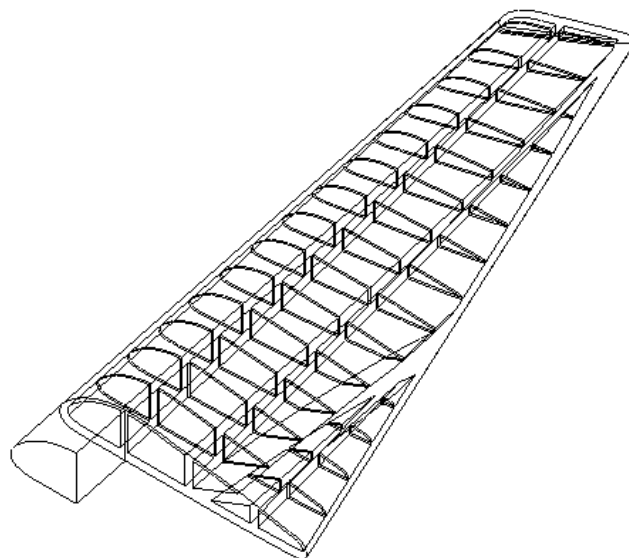


Figure 1. Example of complex geometry used to compare the 3 optimization methods.

3. Case study geometry

The geometry selected for this case study was a squared prism of $40 \times 40 \times 170 \text{mm}^3$. This geometry is supported by 2 plaques with a distance of 160mm between contact zones. Additionally, a punch is employed to apply a force on the upper face of the geometry (Figure 2). This punch is located in the middle of the geometry to apply the force in the midsection. For the FEA, a vertical force of 500N is applied on this punch. Material employed for the 2 plaques and punch was Al EN-AW 5083.

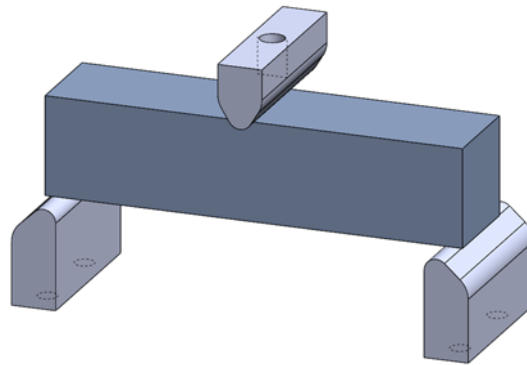


Figure 2. Case study geometry with supports and punch.

The objective is to minimize the weight of the part but keeping the maximum deflection lower than 0.5mm.

Two technologies were studied with this case study, the first by SLS and the second by Polyjet. In both cases, the design of the internal structure is symmetrical to the middle cross section and to the middle longitudinal section. Therefore, symmetry conditions were applied in the FEA to simplify the model. In addition, the same zones and hollows for removing support material were defined in both cases (SLS and Polyjet) (Figure 3). The type of mesh selected was the curvature-based mesher. This mesher automatically refines the mesh in zones with high curvature. The main parameters of this mesher are the maximum and minimum element size. However, in this case the minimum element size was defined as one fifth of the maximum element size. Therefore, the key parameter is the maximum element size. Different values of this parameter were proved

until selecting a value of 5mm. This element size achieved results with a deviation lower than 2% compared with the results of the smallest element size proved (1mm), but reducing the calculation time more than 20 times.

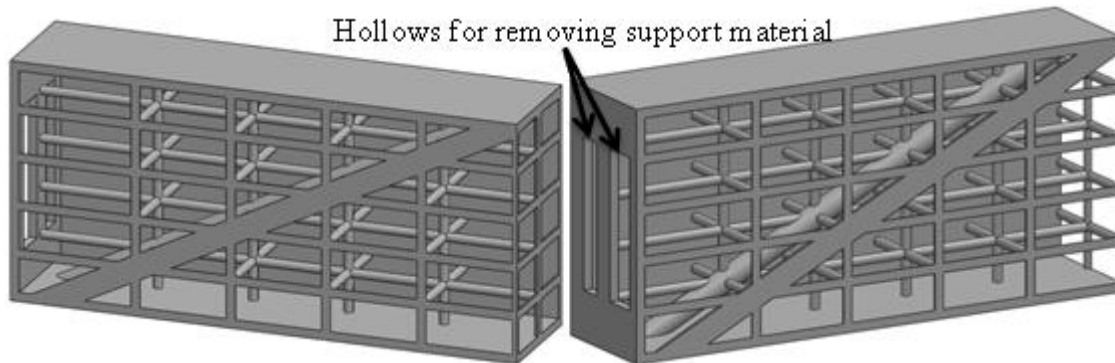


Figure 3. Case study geometry with symmetrical simplification and hollows for removing support material.

4. SLS case study

The geometry described in section 3 was lightened with an internal parameterized structure to be optimized. Three replicas of the optimum design were manufactured. Additionally, a non-optimal design evaluated during the optimization process was also manufactured (3 replicas). These parts were tested under flexural load.

4.1. Geometry

The lightweight design of the internal structure is shown in Figure 4. This design has a total of 23 variables associated to the wall thickness of the external faces (variables from 1 to 10) and the diameter of the bars in different groups (variables from 11 to 23).

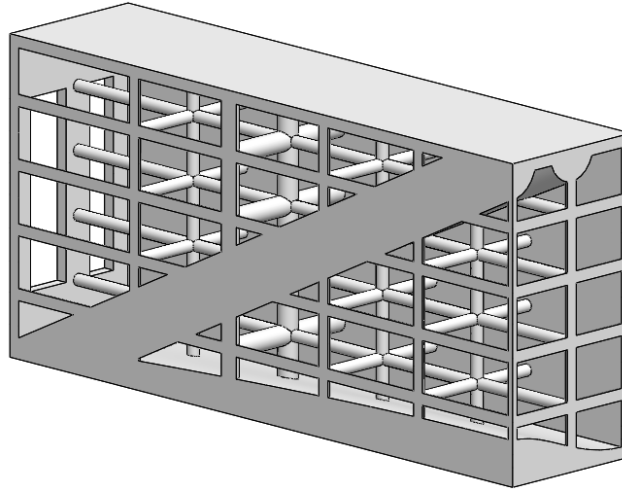


Figure 4. SLS case study geometry.

According to the symmetry conditions, this geometry was modelled by fixing the lower face of the support, constraining the displacement in the normal direction of all faces in the planes of symmetry, and applying a force of 125N (double symmetry) on the upper face of the force plaque (Figure 5). A non-penetration type of contact was defined between the different parts. The material was polyamide PA3200GF, with a modulus of elasticity for the FEA of 1990MPa (experimental evidence provided by the manufacturer), and a Poisson's ratio of 0.34, typically employed in PA (Muraru *et al.* 2010). The density was 1.22g/cm³.

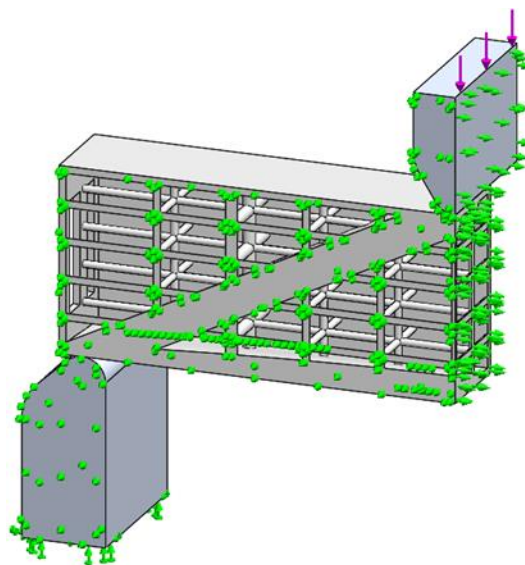


Figure 5. Boundary conditions for the FEA.

4.2. Optimization

The geometry defined in section 4.1 was optimized with 5 runs of the program described in section 2. The most representative optimum in terms of mass among the 5 optima achieved was selected to be manufactured. In this case, it was reached in execution number 1, with a mass of 23.040g (0.49mm deflection), while the average value of the 5 optima was 23.052g, and was reached after 90 sampling points (the highest among the 5 executions), with a total optimization time of 88.3min (Figure 6). Figure 7 shows the value of the design variables of the 5 optima. Here it can be observed how most of variables change considerably among optima.

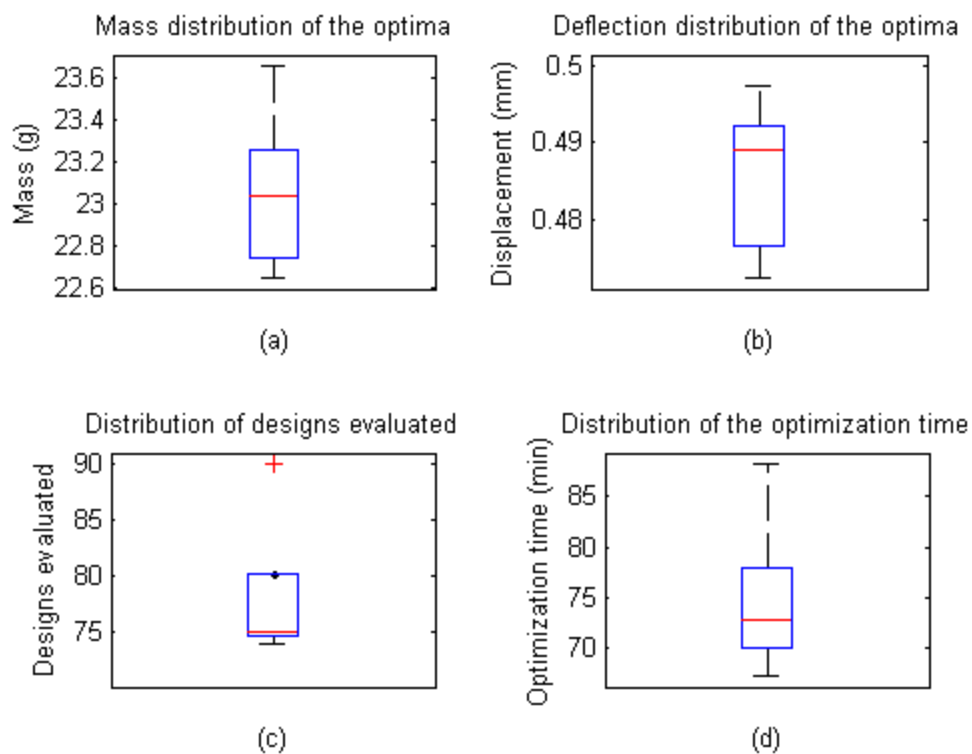


Figure 6. Distribution of mass of the optima (a), distribution of deflection of the optima (b), distribution of number of designs evaluated (c) and distribution of the optimization time (d) for the SLS case study.

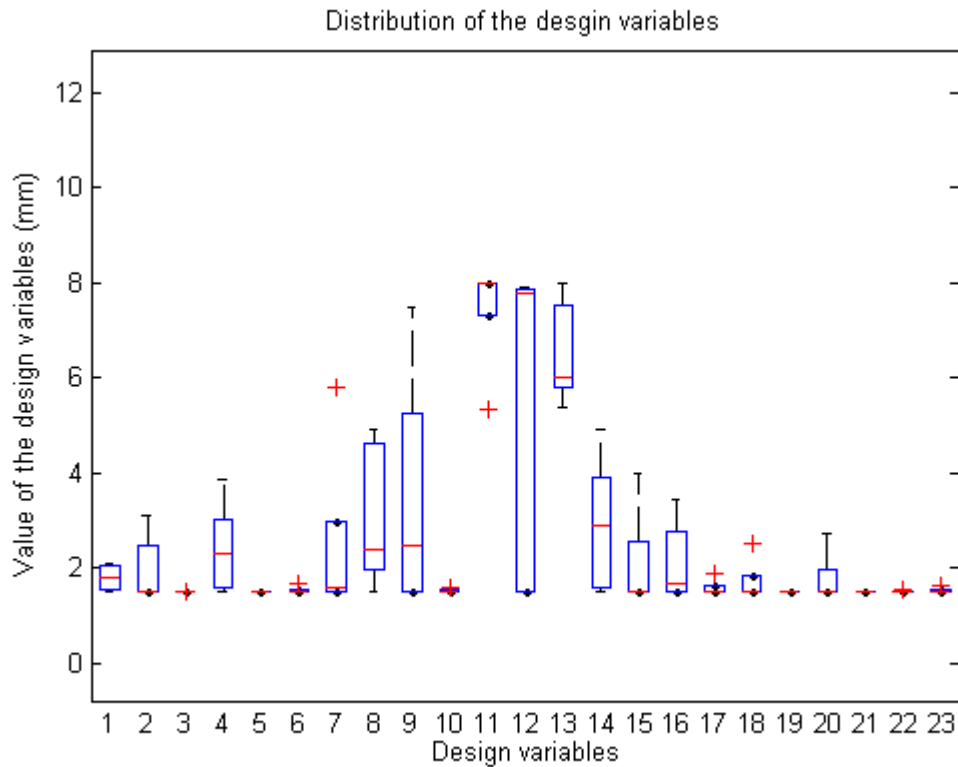


Figure 7. Distribution of the design variables of the 5 optima (SLS case study).

Apart from the optimum selected, a non-optimal design evaluated during execution 1 was also selected to be manufactured. The design selected was the number 12 for having the lowest specific stiffness among the designs evaluated. This design has a mass of 32.412g and a deflection of 0.52mm.

Applying symmetry with respect to the two planes of symmetry, the optimum and non-optimum designs were defined. In Figure 8 and Figure 9 can be observed the optimum and non-optimum, respectively, with some transparent faces to show the internal structures.

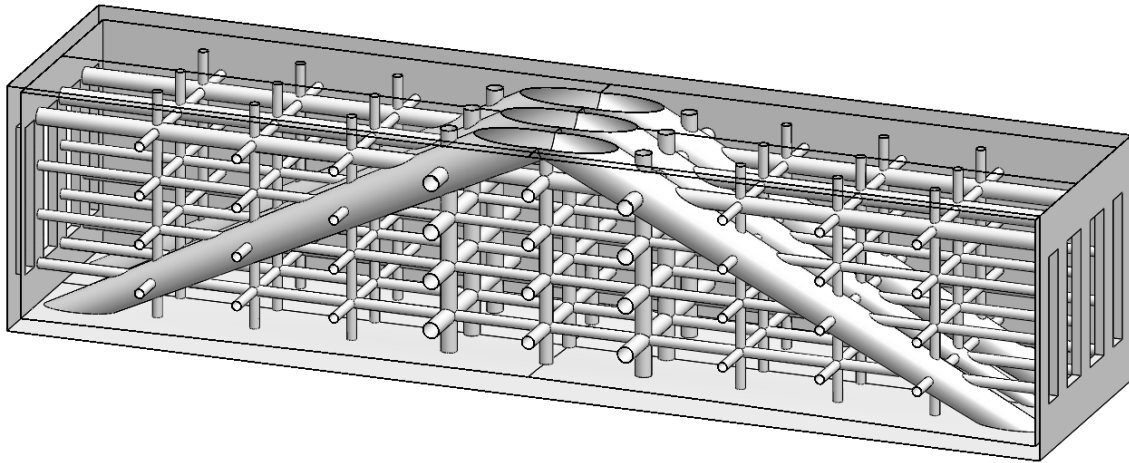


Figure 8. Optimum design selected (SLS case study).

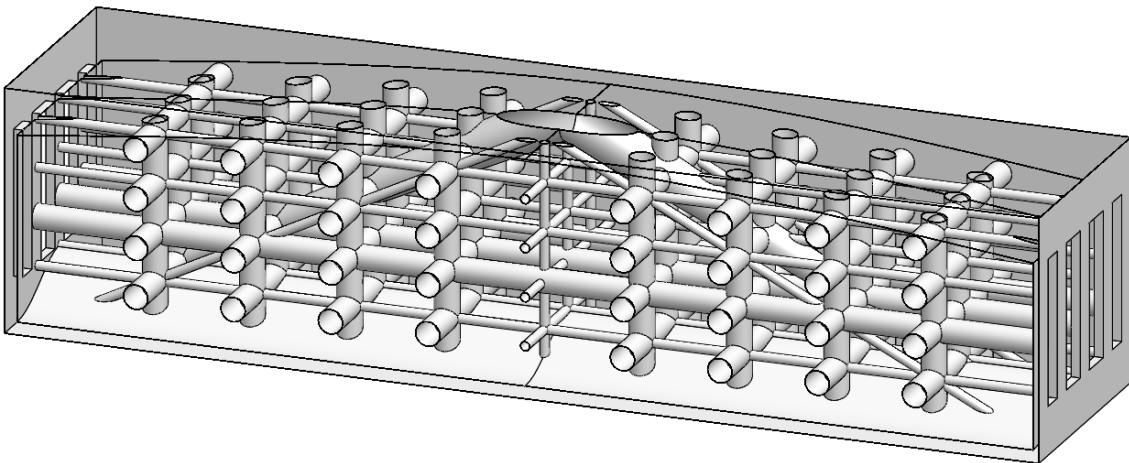


Figure 9. Non-optimum design selected (SLS case study).

4.3. Parts manufacturing and flexural test

Three replicas of both designs were manufactured in a SLS EOSint P380 machine, with a laser power of 13.225W, 0.15mm layer thickness and 50% of recycled material (PA3200GF). The optimal parts were codified with an “O” and non-optimal parts with an “N”, while number 1 to 3 differentiate the 3 replicas (Figure 10).

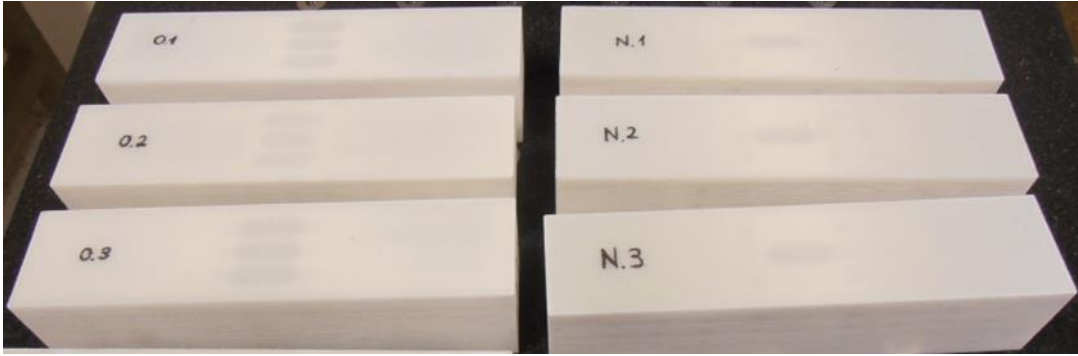


Figure 10. SLS parts manufactured.

Flexural tests were carried out according to the boundary conditions explained in section 3, with a distance between supports of 160mm. The load was applied with a speed of 2mm/min and measured with a calibrated load cell (PCE-FG1K).

Non-linear behaviour in the initial phase of the flexural test was observed. This is due to a geometry distortion that causes the positioning error as well as a non-perfect contact with the punch and the supports. However, in the final zone of the curves the behaviour was more linear. For this reason, linear regression was performed on that final zone in order to obtain the slope of the fitting line, which represents the stiffness of the part (K). Table 1 and Table 2 show the weight, stiffness and specific stiffness ($K_s=K/\text{weight}$) of each part, as well as the mean value and sample standard deviation (σ), both for non-optimal and optimal replicas, respectively.

Table 1. Results obtained for the non-optimal replicas (SLS).

Part	Weight (g)	K (N/mm)	K_s (N/mm/g)
N.1	134.516	642.77	4.78
N.2	137.486	693.18	5.04
N.3	136.245	587.10	4.31
Mean value	136.082	641.02	4.71
Sample standard deviation	1.492	53.06	0.37

Table 2. Results obtained for the optimal replicas (SLS).

Part	Weight (g)	K (N/mm)	K_s (N/mm/g)
O.1	94.954	808.44	8.51
O.2	86.99	663.75	7.63
O.3	101.621	840.77	8.27
Mean value	94.522	770.99	8.14
Sample standard deviation	7.325	94.27	0.46

It can be seen that the sample standard deviation of the optimal replicas is greater than that of the non-optimal replicas. Laser dispersion of the SLS machine can lead to manufacture parts not-well sintered, which means a lower density and inferior mechanical properties (Gibson and Shi 1997). This explains why the part ‘O.2’ has a lower mass and also a lower stiffness and specific stiffness than the other replicas (‘O.1’ and ‘O.3’).

The average stiffness of the non-optimal and optimal geometries are 641.02 and 770.99N/mm, respectively. This means that the optimal geometry is 20.28% stiffer than the non-optimal geometry. In terms of specific stiffness, the average value of the non-optimal geometry is 4.71 N/(mm·g), while the average value of the optimal geometry is 8.14 N/(mm·g), 72.82% higher. These values do not match exactly the FEA results because there are many factors associated with the manufacturing process and the experimental test that can have an important influence on the results. However, both the experimental and FEA results show a significant improvement in the specific stiffness of the optimal geometry.

5. Polyjet case study

The geometry of section 3 was also lightened with an internal parameterized structure

with 2 different materials, taking advantage of the multimaterial capability of Polyjet technology. Three replicas of the optimal geometry and three replicas of a non-optimal geometry were manufactured and tested.

5.1. Geometry

In this case 2 different materials (VeroBlackPlus and FullCure720) were employed in order to show the potential of multimaterial AM technologies. The flexural modulus of both materials was obtained from some flexural samples according to standard ISO 178. The mean value obtained for the VeroBlackPlus and FullCure720 was 1490.74 MPa and 2123.92MPa respectively. These values were used for the FEA, with a Poisson's ratio of 0.3 (Colburn *et al.* 2001, Vesenjok *et al.* 2009, Gibson *et al.* 2010) and a density of 1.18g/cm³ and 1.19g/cm³ respectively. Since FullCure720 is stiffer than VeroBlackPlus, FullCure720 must be located in the most stressed zones in order to do a more optimal design (Bruggi and Taliercio 2013). According to an initial FEA of the solid part, the most stressed areas are in the zone of the force application, the contact zone with the support and the lower zone of the middle cross section (Figure 11). Hence, FullCure720 must be placed in those zones, as reinforcement.

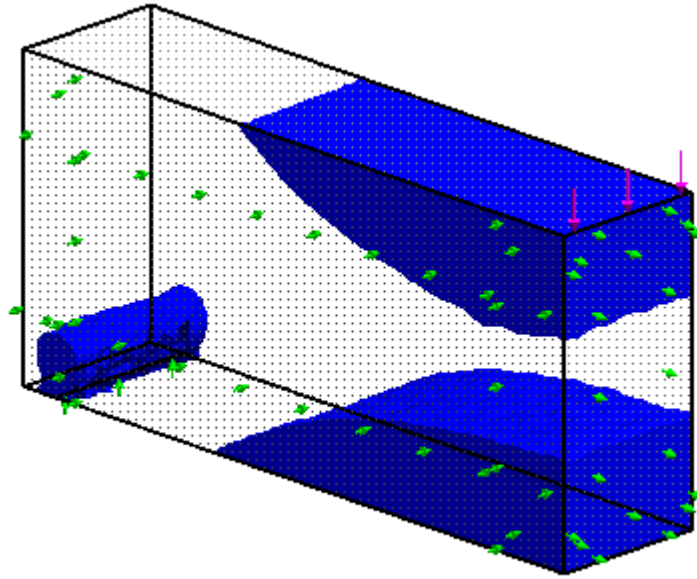


Figure 11. The most stressed areas of the geometry.

With this in mind, the design of the internal structure was carried out (Figure 12), again applying double symmetry. A total of 17 design variables were defined, associated with the length and height of the FullCure720 reinforced zones (variables from 1 to 6), thickness of the external faces (variables from 7 to 10) and the diameter of the bars in different groups (variables from 11 to 17).

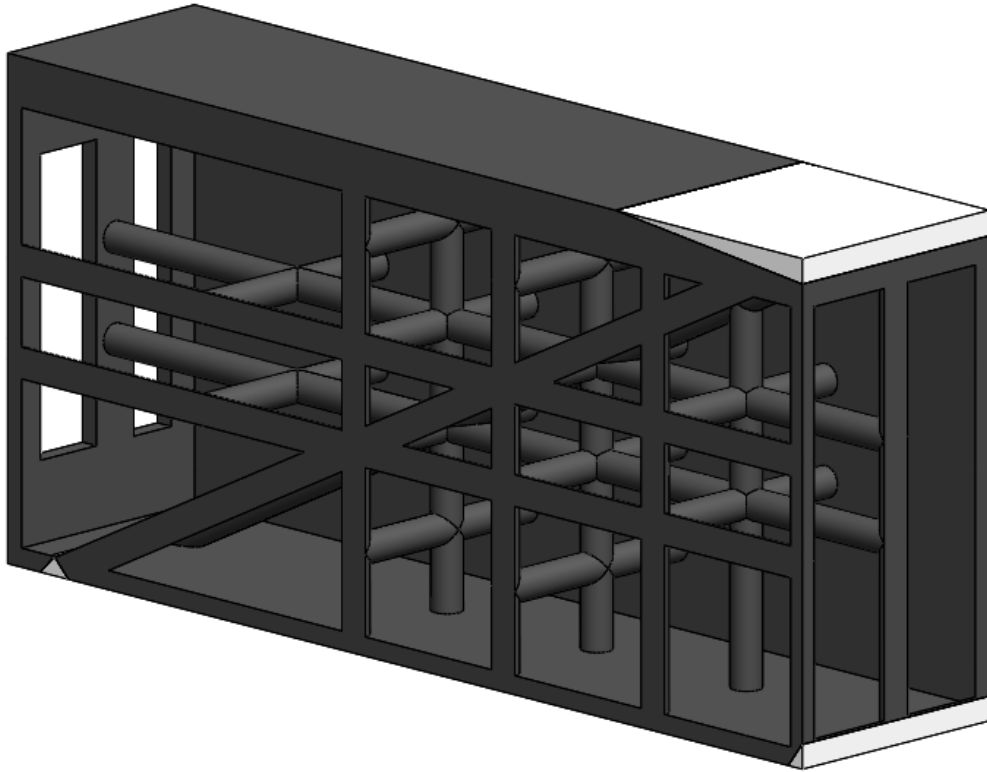


Figure 12. Polyjet case study geometry.

5.2. Optimization

The geometry defined in section 5.1 was optimized with 5 executions of the program described in section 2. The most representative optimum in terms of mass among the 5 optima achieved was selected to be fabricated. In this case, it was reached in execution number 2, with a mass of 26.573g (0.49mm deflection), while the average value of the 5 optima was 26.632g. A total of 60 designs were evaluated in this execution (the highest among the 5 executions), with a total optimization time of 68.0min (Figure 13). Figure 14 shows the variability of the design variables of the 5 optima.

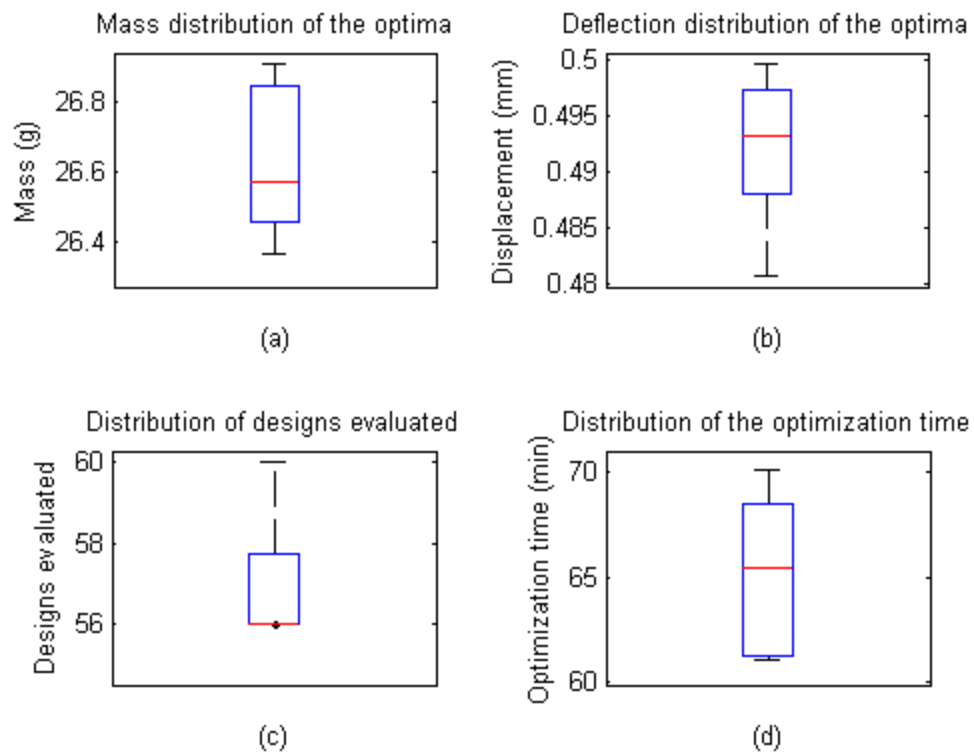


Figure 13. Distribution of mass of the optima (a), distribution of deflection of the optima (b), distribution of number of designs evaluated (c) and distribution of the optimization time (d) for the Polyjet case study.

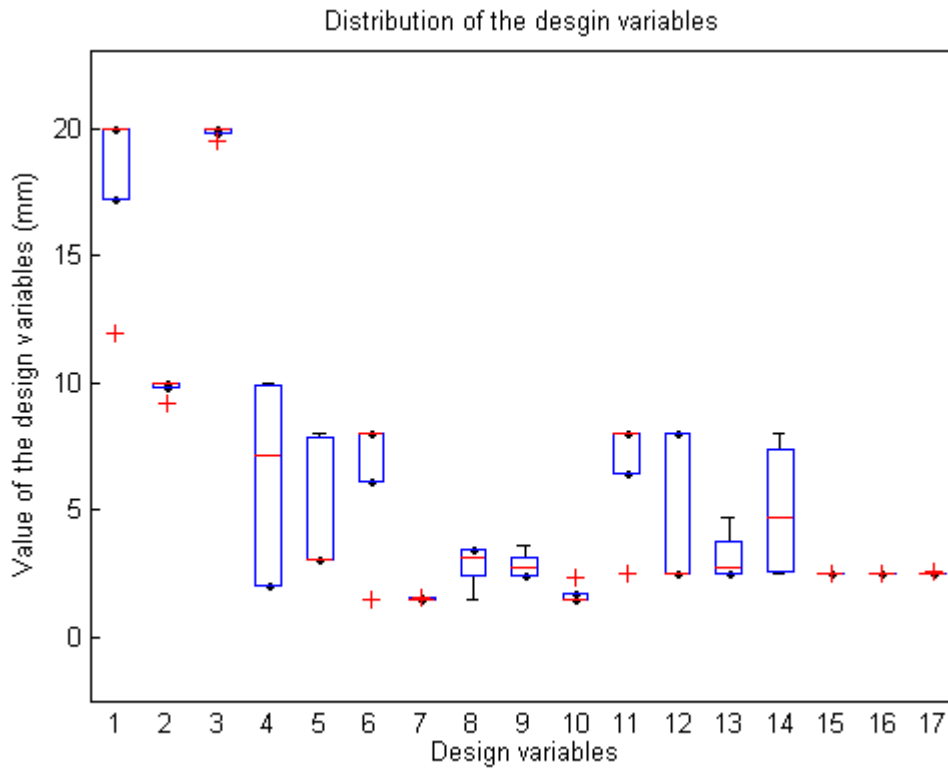


Figure 14. Distribution of the design variables of the 5 optima (Polyjet case study).

Apart from the optimum selected, a non-optimal design evaluated during execution 2 was also selected to be fabricated. The design selected was the number 9 for having the lowest specific stiffness among the designs evaluated. This design has a mass of 30.049g and 0.75mm of deflection.

Applying symmetry with respect to the two planes of symmetry, the design of the optimum (Figure 15) and non-optimum (Figure 16) were obtained.

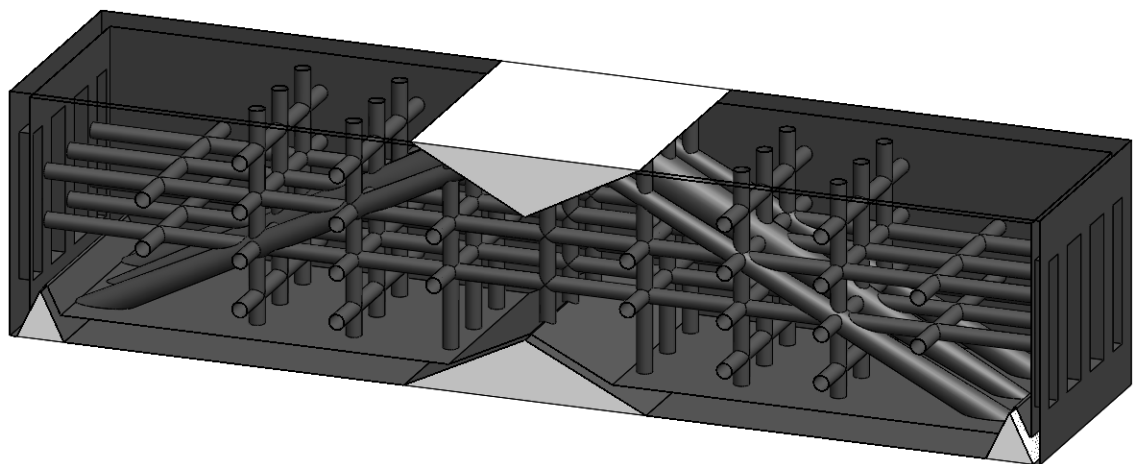


Figure 15. Optimum design selected (Polyjet case study).

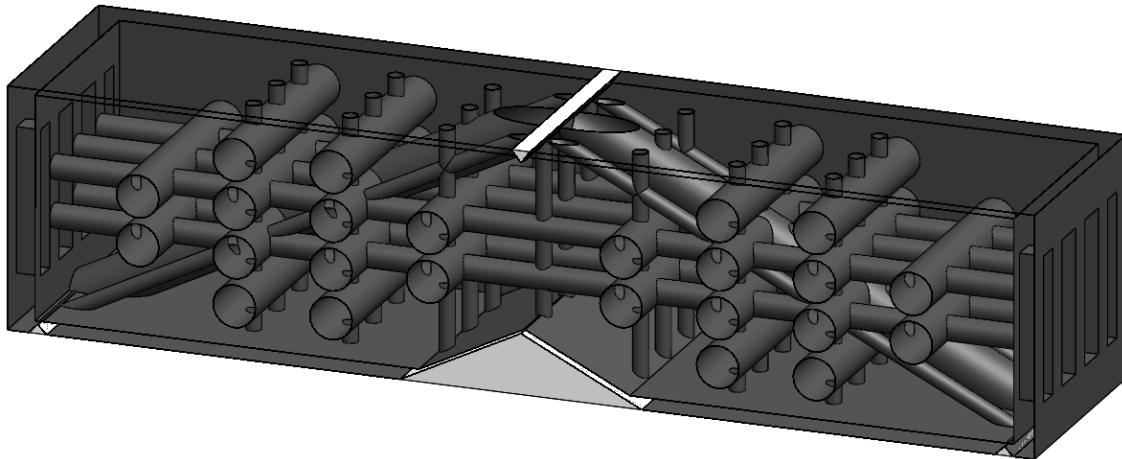


Figure 16. Non-optimum design selected (Polyjet case study).

5.3. Parts manufacturing and flexural test

A 3D Objet Eden 330 machine with 16 μm resolution was employed to manufacture the 3 replicas of the optimum and non-optimum designs. In this case a post-processing was needed to remove the support material. This task was carried out using pressurized water and caustic 7% NaOH dissolution to dissolve the support material (Cazón *et al.* 2014). This cleaning phase required an important effort, especially in the non-optimal parts, where the internal structure was denser and the support material extraction was more complex and laborious. This is a clear disadvantage of the Polyjet technology compared to other AM technologies where the base material serves as support material, as in SLS technology. In SLS powder that is not sintered can be easily removed from the final part. Moreover, this material is recyclable, while in the Polyjet technology is not.

Finally, the flexural tests explained in section 4.3 were applied in these parts. Table 3 and Table 4 summarize the results obtained for non-optimal and optimal parts respectively. In this case the weight deviation of both optimal and non-optimal geometries is lower than in the case of SLS, where an important deviation was observed

specially in the optimal replicas. This same conclusion can be obtained from the flexural results. The stiffness and specific stiffness values between replicas of the same geometry are far closer than in the case of SLS.

Table 3. Results obtained for the non-optimal replicas (Polyjet).

Part	Weight (g)	K (N/mm)	K_s (N/mm/g)
N.1	126.026	297.14	2.36
N.2	125.68	288.88	2.30
N.3	126.051	286.32	2.27
Mean value	125.919	290.78	2.31
Sample standard deviation	0.207	5.65	0.04

Table 4. Results obtained for the optimal replicas (Polyjet).

Part	Weight (g)	K (N/mm)	K_s (N/mm/g)
O.1	106.623	795.03	7.46
O.2	107.605	795.09	7.39
O.3	109.834	756.51	6.89
Mean value	108.021	782.21	7.24
Sample standard deviation	1.645	22.26	0.31

Moreover, experimental results were again quite different from FEA results. However, it is observed that the optimal design is stiffer and lighter than non-optimal design. The average value of stiffness of the optimal geometry (782.21 N/mm) is 2.69 times the average value of the non-optimal (290.78 N/mm). In terms of specific stiffness, the average value of the optimal geometry (7.25 N/mm/g) is 3.14 times the average value of the non-optimized (2.31 N/mm/g). In Figure 17 all the flexural test curves are shown

together. It can be observed how the optimal geometries, despite being lighter, have a higher stiffness compared to non-optimal replicas.

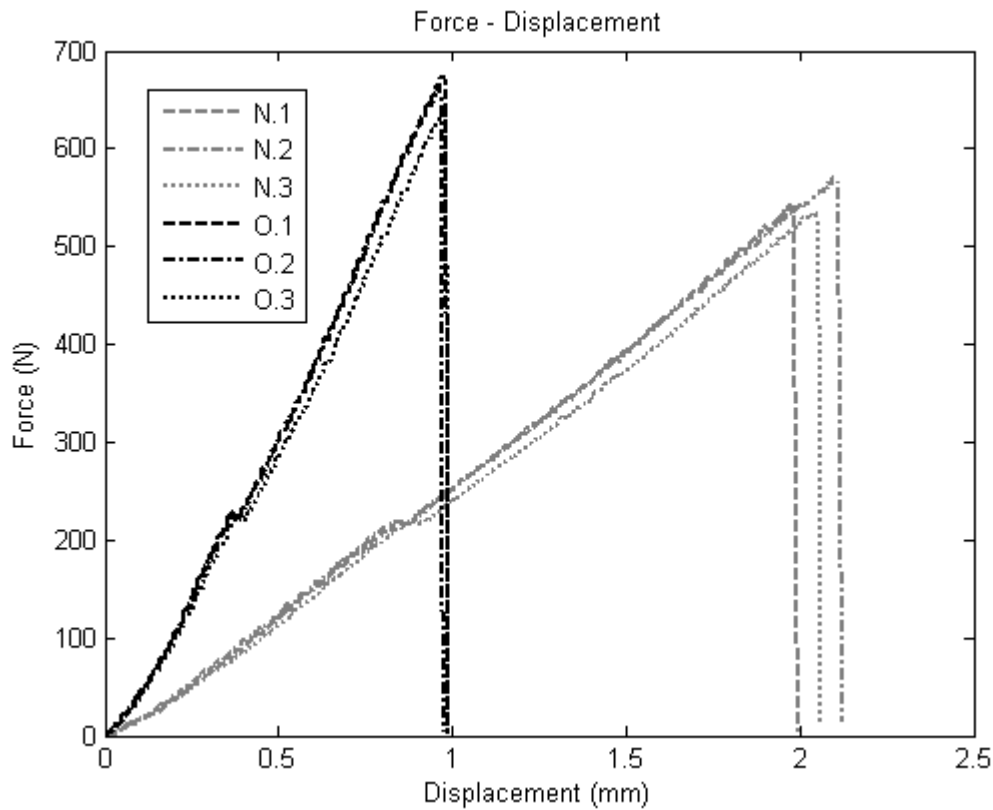


Figure 17. Force-displacements curves of the 3 replicas of non-optimal and optimal geometries (Polyjet case study).

6. Conclusions

A new optimization methodology based on GAs, Kriging metamodel and FEA has been proposed to lightweight optimization of AM parts. This method has been implemented in the Application Programming Interface of a commercial 3D CAD design and FEA software, and has been applied in a case study with two different internal designs adapted to SLS and multimaterial Polyjet respectively. In both cases, three replicas of the optimal and non-optimal designs were manufactured. For the Polyjet technology, the support material removal was a very laborious task, which means that this lightweight

optimization methodology is more appropriated for AM technologies where the base material can be used as support material, or even for AM technologies where support material is not necessary.

According to the experimental results of the flexural tests, for the same design and among replicas, parts made with SLS technology present more variance than those made with Polyjet technology due to the laser dispersion in the work platform.

Comparing the results of the optimal and non-optimal geometries, both SLS and Polyjet optimal geometries have a better behaviour in terms of stiffness and specific stiffness than non-optimal parts, which means that the proposed methodology works correctly.

Although the new method proposed achieves good results, some ideas will be developed in the future work to improve the methodology. First of all, different test will be accomplished to evaluate the influence of the regression model used in the Kriging metamodel. The idea is to use the linear model when the number of data is low, and once the number of data is enough, to use the quadratic model to improve the quality of the estimations. On the other hand, this method works only with continuous variables. Therefore, the objective is to adjust the code to be able to operate with continuous and discrete variables together, allowing the parameterization of CAD features defined by discrete variables.

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