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MECSOL 2022 – Application of Intelligent Filling Methodology in Additive Manufacturing by Fused Filament Fabrication (FFF) with Experimental Validation and Computational Simulation by Finite Elements

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Abstract: With the advent of additive manufacturing technologies, large companies in the world have delved into studies and research to find out how to adapt their processes to the use of this technology that has changed the way products are manufactured. One of the main concerns observed is the guarantee of the mechanical strength of the printed components once they have had their structure optimized, naturally seeking to reduce printing times and material consumption. The objective of this work was to develop and apply a methodology of structural optimization during the filling of parts in the FFF (Fused Filament Fabrication) additive manufacturing process, called Intelligent Filling. Therefore, the aim is to reduce the mass and printing time of specimens, while maintaining their mechanical strength by only changing the topology of the internal filling. A geometry that worked in normal bending and the PLA material were chosen for computational analysis performed in MSC Marc, Apex GD and Digimat RP software, the latter being specific for additive manufacturing, whereby the behavior of stresses was taken into account at the different simulation stages, as also the maximum deflections obtained, fusion between layers and internal filling involved in the process. From the computational results, some parts were printed applying the Intelligent Filling methodology and other parts were printed with conventional filling, allowing their comparison through experimental tests for each specimen. Both the impressions of the specimens and the tests were performed following the same boundary conditions used in the simulations. It was thus possible to prove the efficiency of the Intelligent Filling method proposed herein by comparative results that showed a reduction in the amount of material used by 26.3% and a 17.4% savings in manufacturing time, while maintaining the mechanical strength of the parts practically unchanged.

Keywords: Additive manufacturing, mechanical strength, computational simulation, intelligent filling, structural optimization.

INTRODUCTION

The fourth industrial revolution, also called Industry 4.0, combines large-scale production concepts with intelligent automation technology. In it, the additive manufacturing technology (AM) plays an important role in economic competitiveness.

The advent of additive manufacturing in modern society has been an increasingly recurrent topic of discussion, while the use of this manufacturing method has been a powerful ally to traditional industrial production methods, this technology has also been implemented for domestic uses in a proportion believed to have the potential to be highly disruptive to the current business model (Rayna & Striukova, 2015).

According to Dilberoglu et al. (2017), additive manufacturing can become a key technology for the manufacture of customized products due to its ability to create sophisticated objects with advanced attributes (new materials and geometries). Due to the growth in the quality of its products, AM is currently being used in several industries, such as: aerospace, biomedical and manufacturing. As a technology in development to create complex objects, with greater precision, more resistance, less weight, less cost and with greater speed of production, it will certainly offer a way to replace conventional manufacturing techniques in a very near future.

AM or 3D printing technology is truly innovative, opening new opportunities and providing hope for various possibilities for companies seeking to improve manufacturing efficiency. Conventional thermoplastics, ceramics, graphene-based materials and metals are the materials which can be printed by 3D printing technology. This technology has the potential to revolutionize industries and reshape the production line (Shahrubudin et al. 2019).

The different types of additive manufacturing are able to meet the different flexibility requirements of advanced manufacturing, with a high degree of customization and structural requirements (Porto, 2016). To improve the mechanical behavior of products, structural optimization aims to improve the mechanical behavior based on changes in the component structure (Sigmund & Bendsoe, 2003).

The materials available for AM, despite recent advances, are still scarce compared to the number of raw material options available in conventional processes. In addition, the technical data of the material is limited to those made available by the manufacturers, making it necessary to resort to direct contact with them or to mechanical tests following the standards of testing polymeric materials (Bueno, 2012). According to Zhai, Lados and Lagoy (2014), the evolution of additive manufacturing is the optimization of processes and materials, developing methodologies for the production of raw materials and products, in order to improve the mechanical properties of raw materials, as well as the mechanical behavior of the raw materials and products.

Due to its cost, AM was mostly used by large corporations at first, yet the progressive decrease in price has led to wider adoption. Today, most 3D printers in the $1,000 to $4,000 range are aimed at small and medium-sized businesses and entrepreneurs using rapid prototyping. The quality of prototyping has also improved, and current high-end printers, starting at $200,000, are capable of building fully functional multi-material prototypes in one go. (Rayna & Striukova, 2015).

The development of structural optimization techniques, such as topological optimization and the increasing use of commercial software, have also allowed great advances in additive manufacturing. Topological optimization is a field of engineering research that aims to design the optimal topology of structures according to a given set of design criteria, which can be the search for the lowest weight of the structure, or the restriction to a given stress limit value, displacement or natural frequency of the component (Almeida; Simonetti; Neves, 2014).

In this context, as observed, complex geometries can be easily created by intelligent filling of material only where it is most mechanically needed. Digital models are not only free-form, but can also be shared throughout the world, which makes instant local production possible on a global scale. In addition, AM technology does not require molds, fixtures, or tools, which effectively shortens the long period of product development caused by the slow manufacturing and design process of molds and/or tools.

The present work aims to develop and to apply a method to improve the mechanical behavior of components printed by FFF technology (Manufacture with Fused Filament) by the structural optimization of its internal filling, seeking to improve the mechanical resistance of the optimized component in relation to that printed in a conventional way, maintaining or even decreasing its mass and manufacturing time. A comparison between the experimental and simulated results of the optimized and non-optimized parts is discussed.

MATERIALS AND METHODS

Intelligent filling optimization consists in redistributing the material in a pre-defined domain by the optimized topology of the structure, seeking to maximize the final mechanical properties of the part according to the work requests. The procedure to achieve the desired geometry requires a series of intermediate steps that use a set of additive manufacturing and topology optimization software. The parts discussed herein were printed using the Inventor 3D printer, from Flashforge, and PLA filaments, provided by 3DProcer (Fig. 1).

Figure 1 - Flashforge Inventor Printer

It is firstly necessary to define a series of steps, as follows:

- Defining suitable materials for analyzing the mechanical behavior of 3D printed polymeric parts;
- Standardization the properties of the materials selected by mechanical tests according to norms indicated in the literature;
- Defining the geometries of the structural components to be analyzed in pure bending;

- Performing the topological optimization of the component, using software, to mobilize the filling intelligently, and to guarantee the improvement of the mechanical behavior, maintaining or decreasing its mass;
- Carrying out a new structural simulation of the components, under conventional and optimized conditions, for comparative verification of mechanical behavior;
- Conducting experimental tests in order to validate the results from the simulation;
- Preparing comparative tests comparing the results from parts printed by conventional methods with the optimized method.

Fig. 2 shows the flowchart of the entire process.

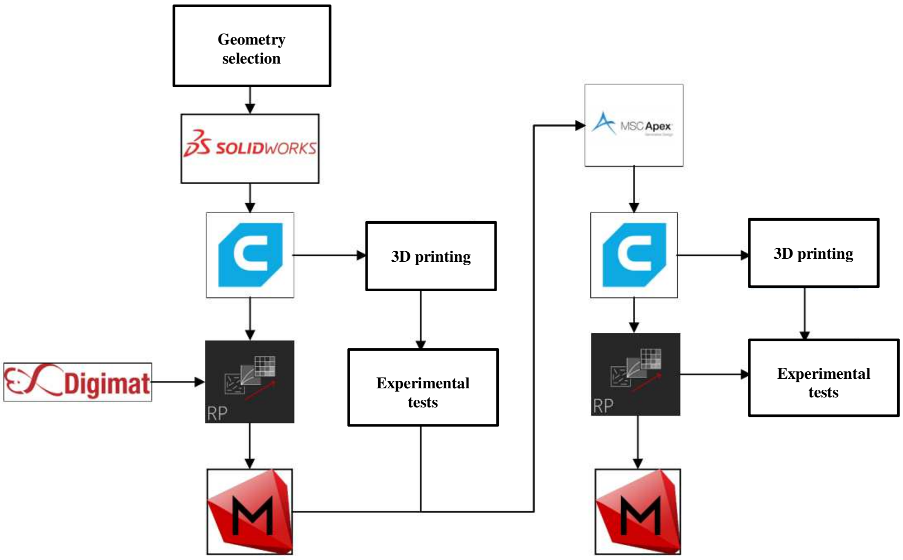

Figure 2 – Flowchart of the simulation and experimentation process

The geometry was selected for pure bending analysis, aiming to collect the values of vertical displacement (deflection) and external surface stress, with the aid of a Mitutoyo milesimal dial gauge and Excel unidirectional strain gauges. In this type of analysis, the part is clamped at one end and a downward vertical load is applied to the other. The geometry and its dimensions can be seen in Fig. 3.

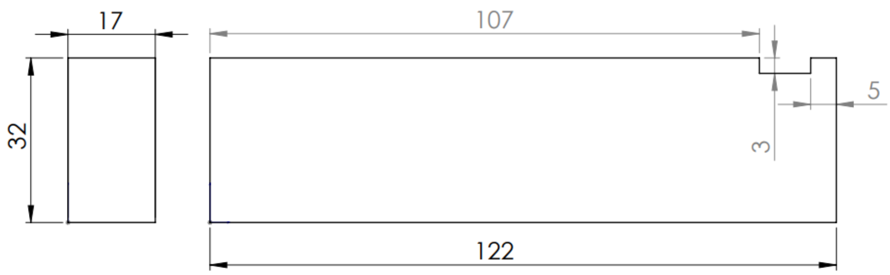

Figure 3 – Dimensions of selected geometry, in mm

Then, after defining the geometry and modeling in SolidWorks software, the file is exported in "STL" format and inserted into the Cura3D slicer software to prepare it for printing and simulation in MSC Digimat RP software. The strategy adopted meant to define a filling of 50% of the part, which represents the percentage of the region where there will be printed material, and to create a shell for aesthetic effect, as well as to facilitate the application of the load. The geometry with these parameters can be seen in Fig. 4, taken from the Cura3D software itself.

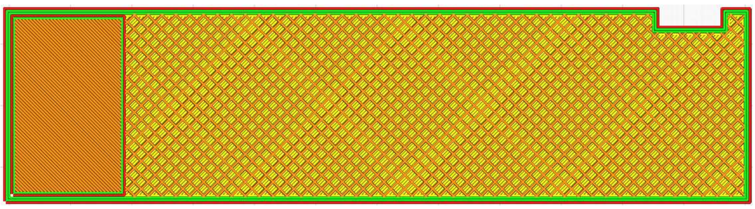

Figure 4 – Non-optimized geometry (conventional filling) in slicer software

At the end of this procedure, a file should be generated with the extension "GCODE", which is a set of coordinates that the printer extruder must go through while printing.

To improve the reliability of the results, we decided to carry out tensile tests in laboratory to validate the results and properties of the PLA filament used. A total of eight specimens were printed, complying with the appropriate standards for testing polymers determined by standard D638-98 of the American Society for Testing and Materials (ASTM). The tests performed provided the curves illustrated in Fig. 5 and their masses and volumes were also collected to determine the density of the material.

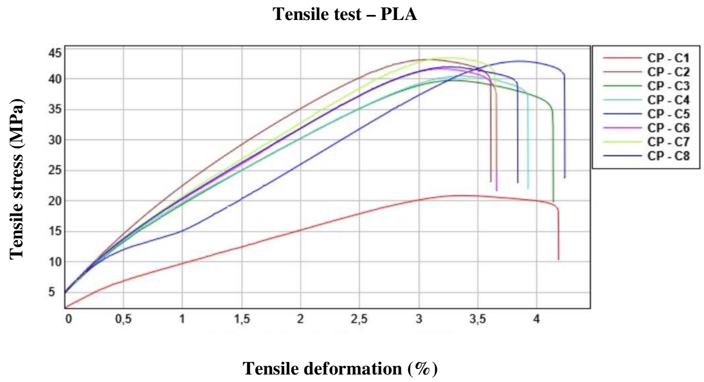

Figure 5 - Tensile curve of specimens

From the results presented, there is a deviation of properties in specimens C1 and C5, which were therefore discarded. The average properties obtained in the tests of specimens (SP) are shown below.

- Young's Modulus: $E_{sp} = 1900\ MPa$
- PLA density: $\rho_{sp} = 1{,}19.10^3 kg/m^3$

Simulation and practical tests

Proceeding to the simulation steps, the first software to be used is the RP ("Reinforced Plastics") module of the MSC Digimat software. In it, four types of file are required for analysis: the first is the structural model that depends on the geometry, efforts and supports of the selected part; the second contains exactly the properties of the material – in this file, both the properties obtained by the specimens and those obtained via the filament manufacturer's datasheet are used; finally, the last two imported files are the massive geometry of the part in the ".STL" format, obtained in the SolidWorks software, and the ".GCODE" obtained in the Cura3D slicer software. With all these files, the software performs a mapping of the massive geometry from the "GCODE", generating a mapped structural model and concentrating material only where it is previously determined.

The simulation performed in the MSC Digimat software, consisted in applying a load in increments of 50 N until reaching a total of 250 N. With the help of the MSC Marc software, for each of these increments, stress and strain values of the structure are obtained, as well as the values of the transverse displacement (deflection). These results are compared with the optimized geometry and experiments performed.

The next step, after the simulations, is the experiments. The printed part is clamped on the grip, shown in Fig. 6, and the load is applied to the opposite end. Strain gauges were glued to the upper surface of the part to measure the deformation and a dial gauge was used to measure the deflection.

Figure 6 - Apparatus for experimental measurements

From the results from of the simulations in the MSC Marc software and the experiments carried out, two loads were selected for generating the optimized part by the Apex GD software ("Generative Design"). Unlike other topological optimization software that use the material stiffness as a criterion, Apex GD performs topological optimization simulations using the material maximum strength criterion. After applying the boundary conditions (loads and support) to the structure, the software algorithm uses intelligent filling and concentrates the mass only in the necessary regions, seeking to maximize the mechanical properties of the part.

The optimized geometries are printed, repeating the entire simulation and experiment procedure performed for the non-optimized part.

RESULTS AND DISCUSSION

With the load being applied at intervals of 50 N at 50 N, the stress and deflection values of each of the geometries were collected until reaching a total of 250 N. The deflection was measured with a dial indicator positioned 34 mm from the free end of the part, while the strain gauges were positioned at 43 mm from the clamped end of the part, where the highest surface stresses occur, as observed in Fig. 7. These regions of higher surface stress were predicted by the simulation performed in the MSC Marc software, as shown in Fig. 8. The impressions of the non-optimized parts had an average duration of 6 hours and 15 minutes, with a total mass of 57 grams.

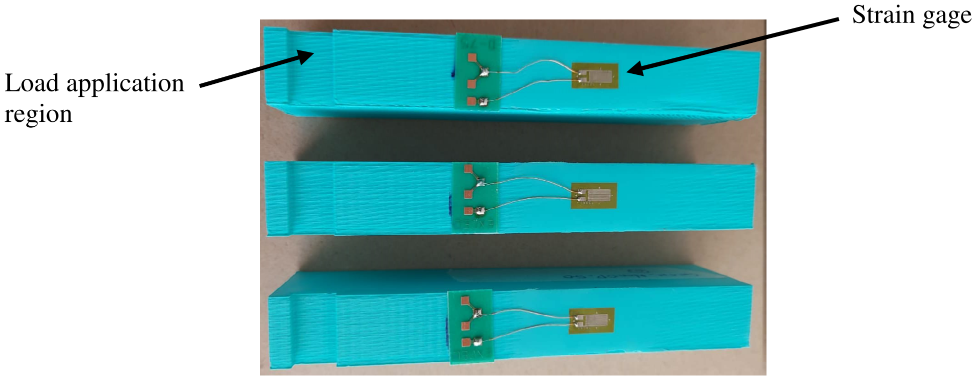

Figure 7 – Strain gauges positioning on parts

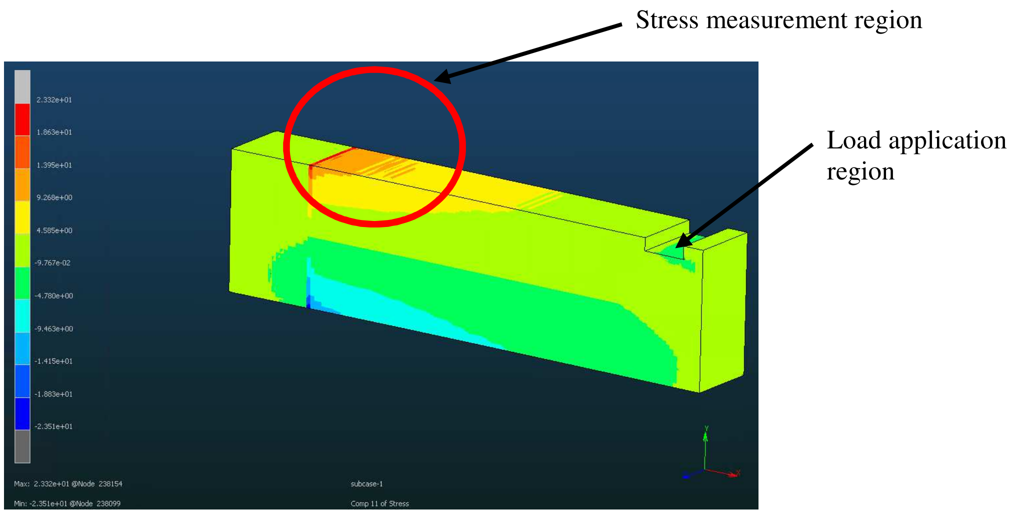

Figure 8 – Distribution of surface stresses of non-optimized geometry

The first results refer to the non-optimized geometry with 50% infill. Table 1 and Table 2 show the comparative results of stresses and deflections from the computational simulation and experimental measurements of specimens. Three measurements were performed for each case and the mean values are presented below.

Table 1 - Comparison of stresses (σ) of non-optimized geometry

Load [N]	$\sigma_{simulation}$ [MPa]	$\sigma_{experimental}$ [MPa]	$Deviation$ (%)
50	2.073	1.980	4.49
100	4.043	3.870	4.28
150	6.217	5.902	5.07
200	8.294	8.068	2.72
250	10.373	10.180	1.86

Table 2 - Comparison of deflections (y) of non-optimized geometry

Load [N]	$y_{simulation}$ [mm]	$y_{experimental}$ [mm]	$Deviation$ (%)
50	0.190	0.20	5.26
100	0.380	0.36	5.26
150	0.570	0.55	3.51
200	0.760	0.78	2.63
250	0.990	1.02	3.03

It is observed that the percentage deviation comparing the results from the simulations with the results obtained experimentally were less than 5.5% in all the measurements performed. The percentage deviation for the load of 200 N where the deflection y_{exp}= 0.78 mm and y_{sim} = 0.76 mm were obtained, for example, was only 2.63%. As the results for the 200 N and 250 N loads were the most accurate, these two loads were selected for the topological optimization analysis performed by Apex GD. The geometries optimized for the two loads can be seen in figures 9, 10 and 11.

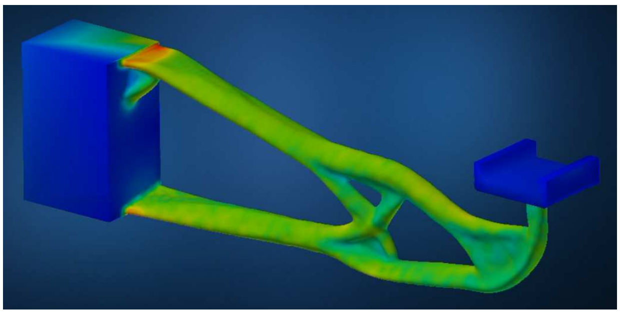

Figure 9 – Geometry optimized for the 200 N load

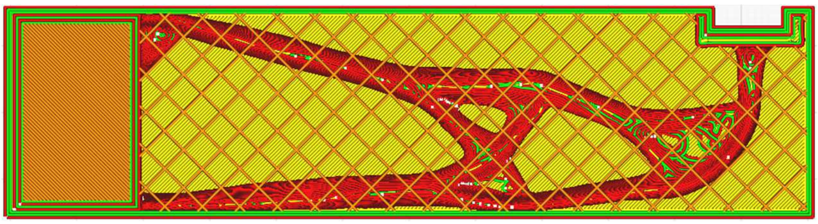

Figure 10 – Geometry optimized for 200 N load in slicer software

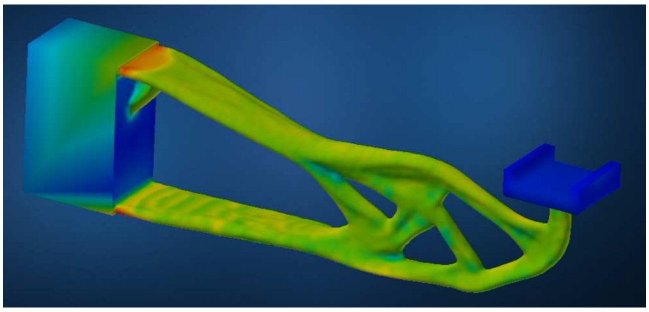

Figure 11 – Geometry optimized for 250 N load

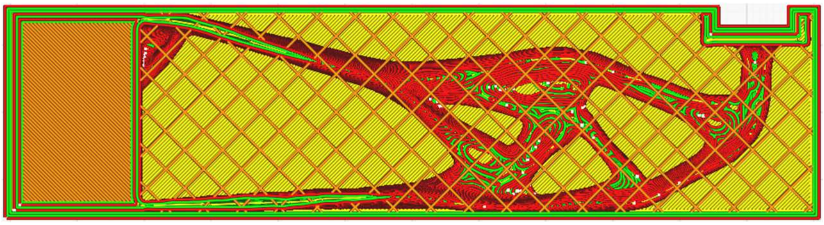

Figure 12 – Geometry optimized for 200 N load in slicer software

Fig. 13 presents the result of printing the part optimized for the load of 200 N. An external filling of 20% and an internal filling of 50% were used. The print duration for the two optimized pieces had its time reduced to 5 hours and 08 minutes, on average, with a mass of 42 grams, thus obtaining a reduction of 17.4% in printing time and a reduction of 15 grams or 26.3% in material consumption.

Figure 13 – Part optimized for 200 N printed on PLA

The two geometries printed under optimization and intelligent printing conditions were subjected to experimental analysis and computational simulation, and their stresses and deflections results are presented in Table 3 and Table 4.

Table 3 - Comparison of stresses (σ) of optimized geometries

Load [N]	$\sigma_{simulation}$ [MPa]	$\sigma_{experimental}$ [MPa]	$Deviation$ (%)
200	8.285	8.610	3.92
250	10.427	10.670	2.33

Table 4 - Comparison of deflections (y) of optimized geometries

Load [N]	$y_{simulation}$ [mm]	$y_{experimental}$ [mm]	$Deviation$ (%)
200	0.897	0.92	2.56
250	1.05	1.12	6.67

Similarly, to what was observed for the non-optimized part, the stresses and deflections obtained experimentally were very close to the values obtained via computational simulation. For the load of 200 N, the stresses obtained experimentally for the non-optimized geometry and for the optimized geometry were, respectively, 8.068 MPa and 8.61 MPa, obtaining a difference of 6.72%. For the load of 250 N, the tensions were 10.180 MPa and 10.670 MPa, obtaining a difference of 4.81%. These results prove the efficiency of the optimization method by the mechanical strength limit used in the simulations, whose objective was to reduce material consumption and the printing time of the parts, keeping the level of maximum active stresses close to the models without intelligent filling.

CONCLUSIONS

From the results, the use of the mechanical strength limit method used in the topology optimization software proved to be coherent, since the stresses obtained between the two types of geometry remained very close. However, it was not possible to ensure the same values for the deflections of the optimized and non-optimized geometry. When removing mass from the part, its moment of inertia decreased, resulting in a greater vertical displacement, a fact that was also predicted in the computer simulations.

It was also verified how important it is to carry out the tests of specimens to obtain the mechanical properties of the printing material, as well as the comparison with the properties taken from the filament datasheet provided by the 3DProcer manufacturer. The experimental results were closer to the simulated results for the properties obtained from the specimens, since these specimens and the tested geometries were printed using the same print settings, the same filament and the same printer.

The experimentation yielded very positive results by reducing the duration of impressions and the mass of the optimized pieces, resulting in very relevant financial gains, since there was a 26.3% decrease in material used and a 17.4% savings in manufacturing time.

In general, the methodology used in this work was successful in proving the positive effects of topological optimization by reducing fabrication time and reducing the geometry mass, concentrating it only on the most requested regions, using intelligent filling and the criterion of maximum tension, besides keeping the external geometry unchanged.

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