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A TOPOLOGY OPTIMIZATION PROCEDURE FOR ADDITIVE MANUFACTURED COMPONENTS

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Abstract. *This paper proposes a topology optimization methodology oriented to orthotropic structures built in polylactic acid (PLA) and fabricated by fused deposition modeling (FDM). The proposed formulation aims to minimize the structural compliance while constrained by material volume. The problem is solved as a variation of the SIMP (Solid Isotropic Micro-structure with Penalization) method, where the penalty function is replaced by a model of the mechanical properties as a function of the infill density, which is a printing parameter of the FDM process. The infill densities are then treated as design variables, being assigned one value for each element of a mesh that defines the domain of the problem. The proposed optimization methodology consists in two stages. At first, Optimality Criteria is employed to solve the topology optimization problem resulting in an infill density continuously varying over the domain of the problem. Then, as conventional 3D printers cannot manufacture these components, a second optimization problem is designed to translate the continuous solution into a discrete one, where five possible infill density values are allowed. Numerical examples are developed comparing the results from the proposed methodology to those obtained using SIMP. The examples show that using the proposed methodology can achieve lower compliance values than the classic SIMP approach.*

Keywords: *topology optimization, SIMP, fused deposition modeling, infill optimization*

1. INTRODUCTION

Topology optimization is one of several methodologies developed for structural optimization. As defined by Sigmund and Maute (2013), topology optimization consists in a process to determine the material distribution inside a defined region in order to obtain the best structural performance. Although conceived initially for mechanical projects, topology optimization nowadays finds a wide range of applications from fluid mechanics to electromagnetism.

A classic topology optimization approach is the SIMP (Solid Isotropic Micro-structure with Penalization) method. In this method, the structural problem is modeled as a mesh and to each element of this mesh a value between 0 and 1, named artificial density, is assigned. The artificial densities modify the mechanical properties of their elements as a power law penalty function, and the optimization solutions are found by treating those densities as design variables (Bendsoe and Sigmund, 2004).

As structural optimization developed, complex designs arose as most favorable solutions. However, traditional manufacturing technologies were not able to keep pace with those new design approaches. In order to work around this discrepancy, alternatives can be found on the recent development of additive manufacturing. Additive manufacturing consists of a fabrication methodology where solid components are built by additive processes from a digital model. An additive process means that the component is created by successive deposition of layers of material. This approach allows the manufacture of more complex structures, when compared to traditional manufacturing techniques. Thus, this new technology might be able to fill the gap between topology optimization and the manufacturing of its optimal designs (Zegard and Paulino, 2016).

Fused deposition modeling is one of the available processes for additive manufacturing. In FDM, a thermoplastic material is extruded through a nozzle as it follows the geometry of the component being fabricated, layer by layer over a printing table. Through the process, the nozzle maintains its temperature slightly above the glass transition point of the material. After extrusion, the deposited filament solidifies, bonding to the previous layer (Costato, 2016). The properties of the component built depends on a series of printing parameters specified at the time of the fabrication. One of those parameters is named infill density which describes the quantity of material deployed in a region. Infill density parameters are strongly linked to the stiffness of the print.

The goal of this work is to propose an optimization methodology capable of representing the distinct mechanical properties inherent to the structures fabricated by FDM. Establishing a parallel between the SIMP method artificial densities and the printing parameter infill density, now being the elements infill density associated with each mesh element the new design variables. The SIMP penalty function should be replaced by a model that dictates the stiffness of an element as a function of its infill density. That way trying to approximate the optimization model to the real behavior of this type of structure and to explore the capability of the FDM method in manufacturing components with variable density.

2. MECHANICAL PROPERTIES

Bertoldi (1998) shows that the orientation of the part in relation to the printing table has great influence over the mechanical properties of components fabricated by FDM. Perkowski (2016) also presents a series of experimental studies about the mechanical behavior with different printing orientations. Both studies results showed that those components could be modeled as orthotropic materials.

Figure 1 defines the investigated orientations of an FDM built part with local reference axis xyz, in relation to the printing table axis system 123. Perkowski (2016) showed that, considering a linear infill pattern for the FDM process, components present virtually equal elasticity moduli on directions 1 and 2. However, the elasticity modulus in direction 3 is about five times smaller

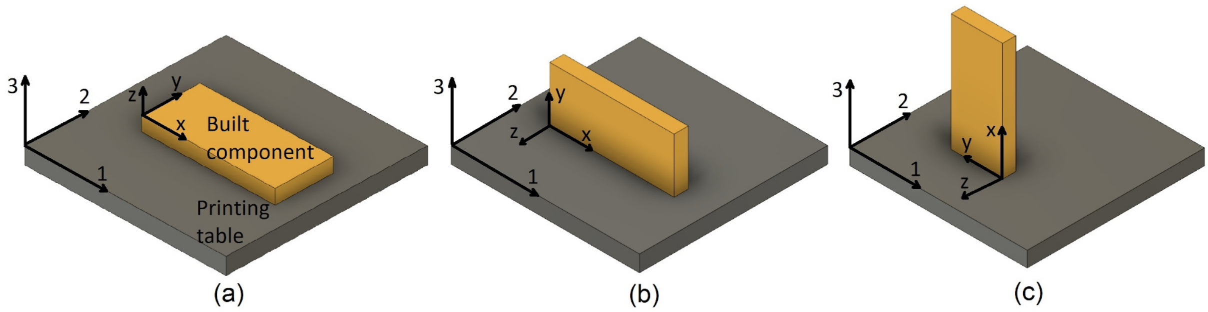

Figure 1. Reference axis used to define orientation of a part built by FDM

To approach the modeling of these properties three different bi-dimensional problems are defined based on the component orientation over the printing table and for simplicity those problems will be named A, B and C. Problem A corresponds to the bi-dimensional problem were the component is built with its xy plane parallel to the table (12 plane), as in Fig 1.a). For problem B, the components xz plane is parallel to the table, as in Fig 1.b). Finally, for problem C, the components yz plane is parallel to the table, as in Fig 1.c).

Even though the SIMP method was developed around isotropic materials, orthotropic materials can be admitted with a small modification on the model. As showed by Hoglund and Smith (2015) and Alamo and da Silva (2012), the constitutive matrix could be adapted to model orthotropic elasticity in which, for simplicity, plane stress state was considered. For the assumptions previously stated, the new constitutive matrix is given by Eq. (1).

$$D_0 = \frac{1}{1-\nu_{xy}\nu_{yx}} \begin{bmatrix} E_x & \nu_{yx}E_x & 0 \\ \nu_{yx}E_x & E_y & 0 \\ 0 & 0 & \frac{E_x(1-\nu_{xy}\nu_{yx})}{2(\nu_{xy})} \end{bmatrix} \quad (1)$$

Where E_x and E_y denote the Young modulus for the orthogonal directions x and y of the built component, while ν_{xy} and ν_{yx} are the respective Poisson ratios. The values assumed by these variables depends on the printing orientation considered. The experimental results obtained in Perkowski (2016) were used to build the constitutive matrices corresponding to each one of the printing orientations (problems A, B and C) evaluated. Based on the reference axis fixed to the printing table, the base values to the Young modulus used were E_1 = 3 GPa, E_2 = 3 GPa and E_3 = 0.6GPa.

Another important part of modeling FDM built structures consists of correlating the infill density parameter and the stiffness of the resulting structure. Lubombo and Huneault (2018) investigated the influence of different infill patterns and densities on the mechanical properties of PLA (Polylactic acid) parts. The experimental data obtained in the aforementioned article was then used to build a mathematical model correlating infill density (x_e) and the stiffness of PLA structures in the form of a power law $P(x_e)$ that multiplies the stiffness matrix of each element of the topology optimization domain. Equation (2) shows the obtained relation.

$$P(x_e) = x_e^{1.484} \quad (2)$$

The function obtained mimics the behaviour of the penalty function of the classic SIMP method, as both are expressed as power laws. However, the SIMP function describes an artificial material and is used to penalize and avoid intermediate densities on the solution. While the aim of Eq. (2) is to try a first approximation of the real behavior of the printed component, for different infill density levels, without a deep analisys on its microstructure. Usually, an exponent equal to 3 or higher is used for the SIMP power law in order to achieve results that lack intermediate densities (also known as 0-1 or black-white designs). Figure 2 shows how the proposed equation compares with the SIMP penalization function and with a linear relation of the resulting relative stiffeness as function of the density.

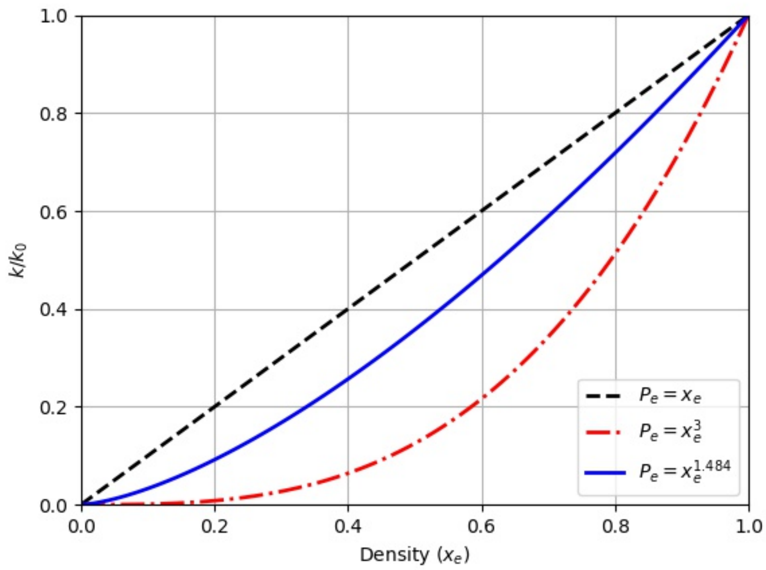

Figure 2. Comparing the power law obtained with the SIMP classic penalization

3. OPTIMIZATION PROBLEM FORMULATION

3.1 The topology optimization approach

The proposed problem consists in minimizing the structural compliance of a PLA component built by FDM while subject to a material volume constraint. The problem is modeled as a variation of the SIMP method, where now the design variables are the infill densities assigned to each element. The classic penalty function is substituted by the one that tries to approximate the mechanical properties of the elements as a function of those infill densities, as described in Eq. (2). Considering the stated assumptions, the compliance minimization problem is settled as in Eq. (3) to Eq. (6).

$$\text{min} : C(x_e) = \mathbf{U}^T\mathbf{K}\mathbf{U} = \sum_{e=1}^{N} P(x_e)\mathbf{u}_e^T\mathbf{k}_0\mathbf{u}_e \tag{3}$$

$$\text{subject to} : \frac{V(x_e)}{V_0} = f, \quad e = 1, ...N \tag{4}$$

$$\mathbf{K}\mathbf{U} = \mathbf{F} \tag{5}$$

$$0 \leq x_{min} \leq x_e \leq 1 \tag{6}$$

Where x_e are the design variables (infill densities), $\mathbf{U}$ and $\mathbf{F}$ are the global displacement and force vectors, $\mathbf{K}$ the global stiffness matrix, $\mathbf{u}_e$ and $\mathbf{k}_e$ are the displacement vector and stiffness matrix of each element, N is the number of elements of the mesh, x_{min} is a minimum value for the design variables in order to avoid singularities. As the infill density reflects directly the quantity of material used in printing the component, the function that defines the material volume used $V(x_e)$ is simply the sum of the design variables, V_0 is the maximum material volume given a domain and f represents the volume constraint. The method used to solve the optimization problem was the Optimality Criteria. As showed in Sigmund (2001), using the referred method the design variable can be updated by the heuristic scheme described in Eq. (7).

$$x_e^{new} = \begin{cases} max(0, x_e - m) \text{ if } x_e B_e^\eta \leq max(0, x_e - m) \\ min(1, x_e + m) \text{ if } x_e B_e^\eta \geq min(1, x_e - m) \\ x_e B_e \text{ otherwise} \end{cases} \tag{7}$$

Where m is named positive move limit and η is a damping coefficient. Both values control the variable update in each iteration and can be experimentally adjusted for better convergence efficiency. The value B_e is determined from the optimality condition as in Equation 8.

$$B_e = \frac{-\frac{\partial C}{\partial x_e}}{\lambda \frac{\partial V}{\partial x_e}} \tag{8}$$

Where λ is the Lagrange multiplier so that the volume constraint is satisfied. This value can be found using a bissection algorithm.

Associated with this type of density approach for topology optimization problems comes some numerical problems like the checkerboard patterns, the occurrence of local minima and mesh dependency. The checkerboard pattern problem consists in regions where the element densities alternate between only 0 and 1 values resembling a checkerboard. Such optimization solution should be avoided as it results from numerical instabilities and does not correspond to an optimal distribution of material (Díaz and Sigmund, 1995). The occurrence of local minima happens as variations of the initial parameters of the optimization can result in changes to the optimal solution. To mitigate the occurrence of local minima continuation methods can be applied, where the exponent of the penalty function is gradually raised until it reaches its desired value. The mesh dependency problem consists on obtaining different solutions for the optimization problem depending on the refinement level of the mesh used. This dependency denotes, in this case, non-uniqueness or nonexistence of solution as explained in Sigmund and Petersson (1998).

In order to avoid those problems on the topology optimization a filtering technique presented in Sigmund (2001) is implemented. This approach consists in modifying the design sensibilities at each iteration of the optimization process as shown in Eq. (9).

$$\frac{\partial C}{\partial x_e} = \frac{1}{x_e \sum_{f=1}^{N} H_f} \sum_{f=1}^{N} H_f x_f \frac{\partial C}{\partial x_f} \tag{9}$$

Where C is the objective function, x_e the design variable and H_f is the convolution operator defined as:

$$\begin{aligned} &H_f = r_{min} - dist(e,f) \\ &f \in N | dist(e,f) \leq r_{min}\}, e = 1, ..., N \end{aligned} \tag{10}$$

Where $dist(e,f)$ is defined as the distance between the centers of element e and f and r_{min} corresponds to a radius defining the area over wich the filter acts for each element. The value of r_{min} is a control parameter of the optimization and remains constant during the whole process. For $dist(e,f)$ greater than r_{min}, the convolution operator value is equal to zero.

3.2 Approximating the optimization results into discrete solutions

The optimization solutions obtained at this stage using the proposed methodology presents infill density continuously varying over the elements of the mesh, but conventional 3D printers cannot manufacture these components. Such behaviour happens as there is no longer a power law capable of fully penalizing intermediate densities, as in the classic SIMP approach. A second stage is necessary for the optimization problem where constant values of infill density are assigned to well defined regions, which is a possible design with conventional FDM fabrication. To work around this difficulty, the approach chosen was to approximate the continuous solution by a discrete one. For this, five possible infill densities were defined: $a_1 = 0$, $a_2 = 0.25$, $a_3 = 0.5$, $a_4 = 0.75$, $a_5 = 1.0$ and the attribution of values to each element is realized as an optimization problem as described in Eq. (11) to Eq. (13).

$$\text{min: } E(y_e) = \sum_{e=1}^{N} (x_e - \sum_{j=1}^{5} y_{ej} a_j)^2 \tag{11}$$

$$\text{subject to: } \sum_{j=1}^{5} y_{ej} = 1, \quad e = 1, ..., N \tag{12}$$

$$y_{ej} \in \{0, 1\} \tag{13}$$

The approximation of optimization results as proposed in Eq. (11) to Eq. (13) consists of minimizing the total quadratic difference between the original infill densities and the ones prescribed in the approximation. For each element, as iterating over the index e, five binary variables y_{ej} are assigned. The parameters a_j corresponds to the five possible infill densities as previously defined. Elements can only be assigned for one of the possible values, as dictated by the constraint in Eq. (12).

3.3 Algorithm implementation

Based on the methods described in the previous sections, an algorithm was implemented in Octave-4.4.1. The algorithm in this work was inspired by Sigmund (2001) and its basic structure is shown in Fig 3.

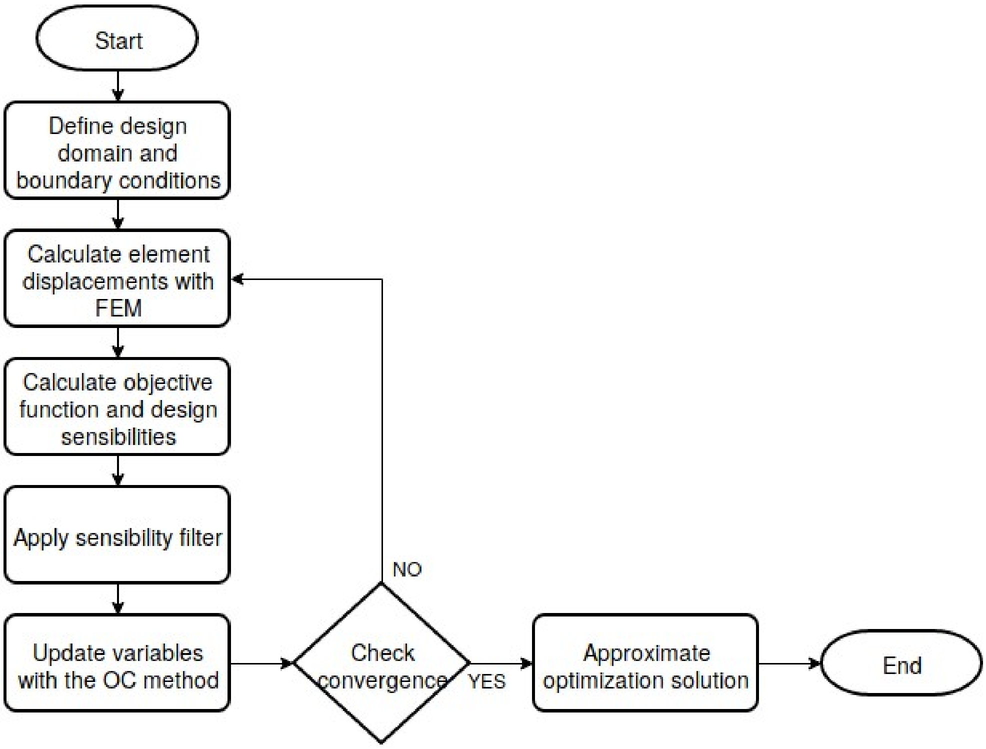

Figure 3. Flow chart describing the optimization algorithm as implemented

At an initialization step, the main information necessary to build the problem is settled. Including domain dimensions, loads and boundary conditions, the material volume constraint and filter radius (r_{min}). A function then builds the mesh over the problem domain assigning elements and node coordinates. The printing orientation of the component to be optimized should also be set, defining then the correct mechanical properties that should be used for the specific case. The initial values of the design variables are assigned and the iteration starts. The iteration procedure stops when the maximum change in the design variables is below 1%.

The first routine called inside the iterative process solves the structural problem using the finite element method (FEM). The stiffness matrix built for each element should be modified to represent the mechanical properties for the correspondent infill density assigned. Therefore, the basic matrix is multiplied by the value of Eq. (2) applying the elements respective current density. For the classical SIMP topology optimization method, at this stage the elements stiffness matrix are modified by using the penalty function. Following the workflow of the FEM, the nodal displacements are then calculated. With the results obtained from the finite element method routine, the objective function and design sensibilities are then calculated. The filter described in Eq. (9) is then used to modify each calculated sensibility. Lastly on the iterative block of the algorithm, the Optimality Criteria scheme described in Eq. (7) is used to update the design variables. If the convergence criteria is not fullfiled, the finite element method routine is called again considering the new density values.

Fulfilling the convergence criteria, the resulted solution is approximated by solving the secondary optimization problem using Eq. (11) to Eq. (13). This second optimization consists in quadratic problem, with linear constraints and binary variables. For simplicity, this routine is implemented using the Gurobi solver (Gurobi Optimization, Inc. 2016). For a fair comparison of results, the structural compliance of the results is recalculated after the approximation of the density values.

4. RESULTS

In this section some example optimizations are developed to illustrate the functionality of the proposed methodology. The well-known half Messerschimitt-Bolkow-Blohm (MMB) beam problem definition is considered as defined in Fig 4, using a 90x30 mesh size. Solutions are found for all three possible printing orientations considered previously (Fig. 1), using both the classical SIMP method and the new proposed approach. For the results obtained, the computational infrastructure used to run the Octave code consisted of a computer with an Intel Core I7-4720HQ 2.60 GHz processor, 8.00 GB RAM available and 64 bits Windows 10 operating system.

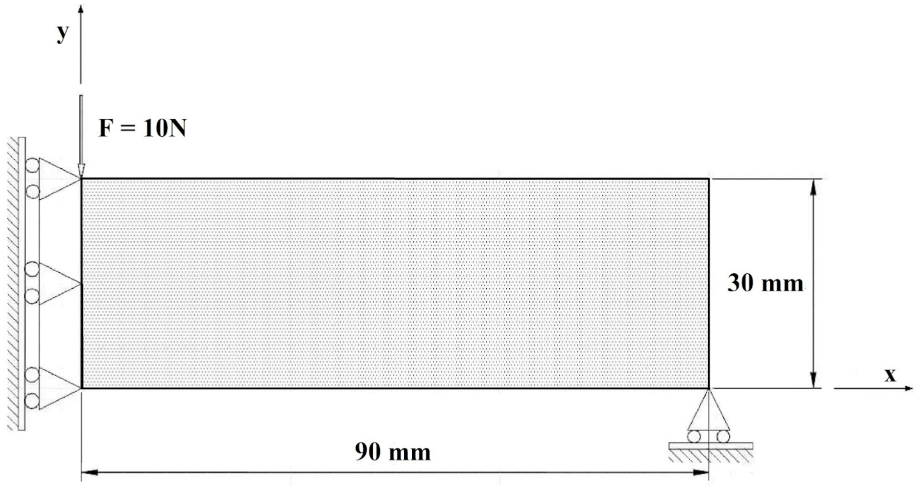

Figure 4. Half MBB beam problem definition

Figure 5 a), c) and e) shows the results obtained considering a classical SIMP penalty function, but including the anisotropy in the elastic behaviour of the components. For those three cases, a penalty function with exponent equal to 3 was used. The distinction is visible between the solutions due to the anisotropy present for printing orientations B and C. It si interesting to note that the SIMP solution for orientation C is substantially different from the other ones. This contrast exists probably due to elasticity modulus being five times smaller than for other orientations in the x direction, which is also the direction in which higher stresses are expected for the MBB problem.

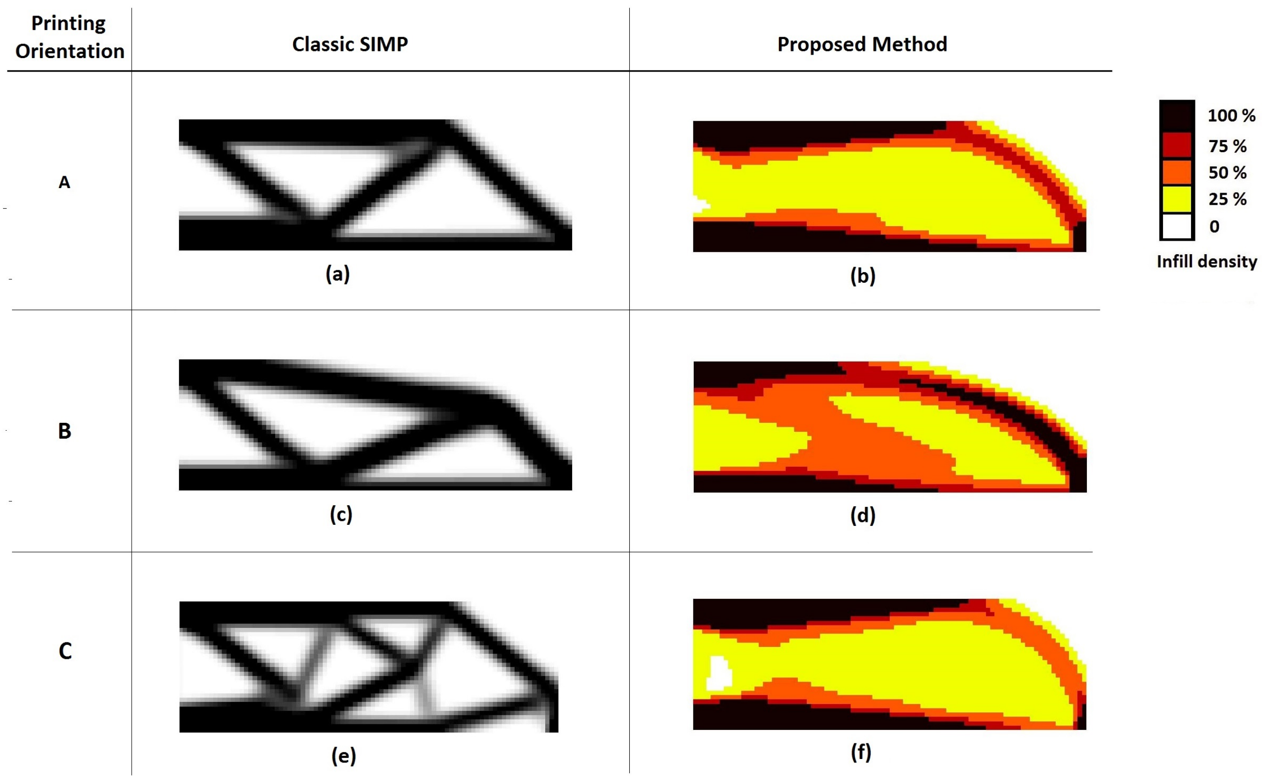

Figure 5. Optimization results obtained. a) Printing orientation A for a classic SIMP penalty function; b) Orientation A for the proposed method; c) Orientation B for a classic SIMP penalty; d) Orientation B for the proposed method; e) Orientation C for a classic SIMP penalty; f) Orientation C for the proposed method.

Figure 5 b), d) and f) shows the results obtained by applying the complete proposed methodology for the three printing orientations considered. In that case, those figures show the solutions after the topology optimization result is approximated in to a discrete solution.

Figure 5 b) shows the optimization solution obtained for the MBB problem considering it as a FDM built component with orientation A, where the component presents isotropic mechanical properties. As expected, higher infill densities are assigned at the top and bottom edges of the beam, as those are also the regions where the higher stresses originating from the bending moment should be present. As the intermediate densities are not fully penalized in this case, the effective solution results in a beam with its core filled with a region of 25% density, in contrast with the truss structures present when the classic SIMP penalization is used. To achieve this solution, 18 iterations were necessary for the topology optimization process, requiring a runtime of 137s.

Figure 5 d) shows the topology obtained for the half MBB beam considering orientation B. The higher infill densities are also assigned to the top and bottom edges of the beam. However, in this case, a distinct region of infill density equal to 0.5 appears in the middle area of the beam. The presence of this new feature might arise from the anisotropy shown by components printed with this orientation. As the elasticity modulus in the y direction is significantly lower (five times) than on the x direction. To achieve this solution, 24 iterations were necessary for the topology optimization process, requiring a runtime of 179s.

Figure 5 f) shows the result of the topology optimization of the half MBB beam considering orientation C. In this case the component also presents anisotropy, but opposing orientation B the elasticity modulus in the x direction is five times smaller than in the y direction. Again, as the elasticity modulus is lower in the direction of the highest stresses in this problem, it results in a compliance value way above the previous ones. In contrast to the SIMP solution, by the proposed method the solution for the orientation C has a density distribution closer to that of the solution with orientation A, presenting the 25% density core. To achieve this solution, 18 iterations were necessary for the topology optimization process, requiring a runtime of 133s.

Table 1 shows a comparison between the structural compliance values obtained using the proposed methodology and the classic SIMP method for the three orientations previously defined. To access the sensibility of the method to different initial values of the design variables, the optimization of the MBB beam for each case was performed several times varying those initial conditions. Each time, a new set of random values were assigned to the initial infill densities. Then the uncertainty of the minimum compliance values showed in Tab. 1 corresponds to the deviation identified over those several tests.

Table 1. Comparing the minimum structural compliance of optimization solutions using the proposed methodology and the classic SIMP method

Printing Orientation	Orientation A	Orientation B	Orientation C
Proposed method	6.721 ± 0.002	12.150 ± 0.016	32.343 ± 0.024
Classic SIMP method	7.052 ± 0.007	13.037 ± 0.004	34.986 ± 0.543
Average relative change [%]	4.7	6.8	7.6

For all three orientations considered, a lower value of compliance was obtained when using the proposed methodology. For orientation A a reduction of 4.7% in relation to the SIMP solution was achieved, while for orientation B 6.8% and for orientation C 7.6%. Very low values were found to the deviation between solutions by the proposed method, all under 0.15% of the minimum compliance values. However, topology optimization problems that use density penalization approaches do not ensure a unique global solution to be found. Under different initial values for the design variables distinct solutions may be found. Then, the low deviation found for the solutions with random initial densities suggests that local minima solutions might not have been found on the tests performed.

To further investigate the possibility of local minima solutions being found, it was analyzed how the infill densities from different solutions changed for a given problem. The local minima solutions are a problem inherent to the optimization described by Eq. (3) to Eq. (6). Therefore, the deviations between solutions were calculated for the values obtained before the approximation of the continuous density distributions to discrete ones. Those values were also found to be low, very close to the convergence criteria tolerance which set the optimization to stop at a maximum change of 1% for the design variables at the iteration step. Such findings also corroborate with the hypothesis that the small deviations of minimum compliance values might not correspond to local minima solutions being found. In fact, by repeating those experiments with a lower tolerance on the convergence criteria (0.1%), even lower deviations were found for the infill density distributions. Again, those deviation had values close to the new tolerance.

As the mechanical properties of PLA structures are difficult to define with precision, new optimizations were also performed in order to evaluate the sensitivity of the results to small deviations on the Young modulus. The proposed method was applied again to the MBB problem considering printing orientations A and C, that showed respectively the best and worst results in respect to the compliance minimization. For each orientation two scenarios were tested, a 10% increase of the elasticity modulus in the x direction (E_x) and a 10% decrease over the same value.

The results obtained for the 10% increase on the elasticity modulus (E_x) showed a reduction of 4% on the minimum compliance for the problem with printing orientation A and a reduction of 9% for the problem with printing orientation B. On the other hand, the 10% reduction on the elasticity modulus resulted in an increase of 8% on the minimum compliance for the problem A and 11% for problem B. To further investigate those differences, the density distributions obtained were also compared to the previous ones. The average deviation of the density values was found to be around 0.7% for problem A and 0.3% for problem B. As expected, a small change in the elasticity modulus apparently results in a change of minimum compliance about the same order of magnitude. However, the change on the infill density values obtained is of an order of magnitude lower. Which may indicate that small deviation of elasticity modulus does not result in drastic changes to the topology of the result.

5. CONCLUSION

In this work, a method for topology optimization of components built by FDM was proposed. The mechanical properties of FDM built structures were evaluated considering orthotropy depending on the printing orientation. Also, the elasticity modulus was modeled as a function of the printing parameter infill density in the shape of a power law. The power law obtained had the goal of replacing the SIMP penalty function in order to now try to approximate the real properties of structures with different infill densities. To build the models, experimental data available from other references were employed. To solve the proposed topology optimization problem, the Optimality Criteria method was implemented. To allow conventional 3D printers to manufacture these optimized components, a second optimization problem was designed to approximate the solutions, and it was able to translate the continuous solutions into discrete ones. The numerical solutions obtained with the proposed methodology demonstrated that the proposed methodology was able, under the proposed assumptions, to achieve better results: a lower compliance than the classic SIMP method. At the same time, it was verified that the method seemed to be able to maintain consistent results while submitted to different initial values of the design variables.

6. ACKNOWLEDGEMENTS

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