Original article

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Influence of fabrication parameters on the elastic modulus and characteristic stresses in 3D printed PLA samples produced via fused deposition modelling technique

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Abstract: Commonly used 3D printed samples are partially infilled to reduce time and cost of printing, with mechanical properties dependent on the infill. In this work, the influence of the percentage and pattern of infill in PLA printed samples on the elastic modulus and characteristic stresses was analyzed. The elastic modulus, E , and characteristic stresses ($\sigma_{0.2}$, σ_4 and the maximum tensile stress) were determined for each sample using impulse excitation technique, IET, and uniaxial tensile tests. An apparent density was calculated for each pattern and infill percentage, and the mechanical parameters were studied as a function of such density. The results of IET obtained in different modes of vibration were analyzed and an apparent value of E was calculated. FEM simulations were carried out and the results were compared with the experimental ones. The mechanical properties for different infill percentages and

infill patterns were studied by comparing the specific values of E and the stresses. Samples with higher infill percentages exhibit the best specific values of maximum stress and E , but the sample with 20% infill has the highest specific yield stress and a good value of the specific E from flexural vibrations.

Keywords: 3D printing; characteristic stresses; elastic modulus; impulse excitation technique; mechanical tests.

1 Introduction

The most common method of 3D printing is the fused deposition modelling technique, FDM, which allows to 3D print layers of materials using a continuous filament of a thermoplastic polymer. The expectations of this technique are enormous, due to the possibility of printing materials with specific functionalities, based on the design and combination of different materials.

The generally used commercial polymers available as 3D printable filament are ABS (acrylonitrile butadiene styrene) and PLA (polylactic acid). PLA is environmentally friendly due to its biodegradability properties, but it exhibits worse mechanical properties than ABS. However, the printing parameters strongly influence the properties of the final printed samples. This fact highlights the importance of studying the mechanical properties of samples printed with PLA filament and the influence of printing parameters in order to improve their mechanical behavior.

The optimal selection of printing parameters is critical, because it influences the quality of the mechanical properties of samples according to the infill pattern and print orientation [1–3]. Samples made by 3D printing are anisotropic and highly dependent on the infill pattern [3]. Recent studies have also demonstrated the different mechanical behavior of 3D printed samples in tension and compression [4]. Also, the layer height, bed temperature, print speed and printing direction affect the mechanical behavior of

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the samples [1, 5, 6]. Other recent studies have been conducted to analyze the effect of the printing parameters on tribological and friction behavior, and the hydrolytic degradation of printed samples [7, 8].

A challenge of 3D printing is to develop and establish techniques and procedures to study the mechanical properties of the samples manufactured in this way. Since printed parts have unique characteristics in terms of filling and homogeneity, the application of conventional techniques must be done with care. In general, studies on this type of samples are performed on completely filled specimens, although in practice it is common to carry out partially filled samples.

One of the main mechanical properties of interest is the elastic modulus E . E can be determined from mechanical tests, but non-destructive techniques have some advantages and have gained relevance.

In impulse excitation technique, IET, the frequency of free vibration is measured. In the case of the flexural mode of rectangular cross-section bars, the displacement of the vibration at each point of the bar, w , can be described by the following differential equation [9]:

$$\rho S \frac{\partial^2 w(x, t)}{\partial t^2} + \frac{\partial^2}{\partial x^2} \left(EI \frac{\partial^2 w(x, t)}{\partial x^2} \right) = 0 \quad (1)$$

where S is the cross-sectional area, ρ is the density and I is the second moment of the bar area in the direction w [9]. The bar is located along the direction x .

The frequency of vibration f_n can be calculated from [9]:

$$f_n = \frac{X_n^2}{2\pi L^2} \sqrt{\frac{EI}{\rho S}} \quad (2)$$

where L is the length of the bar and X_n are the eigenfrequencies, that in the case of free-free ends, follow the next equation [9]:

$$\cos X_n \cosh X_n - 1 = 0 \quad (3)$$

In the case of square cross section bars, E can be calculated from the fundamental frequency, f [10]:

$$E = 0.94642 \frac{mL^3 f^2}{bt^3} T \quad (4)$$

where m is the mass, b is the width and t is the thickness of the sample. T is a correction factor that can be estimated using Equation (5) [10]:

$$T = 1 + 6.585(1 + 0.0752\mu + 0.8109\mu^2) \left(\frac{t}{L}\right)^2 - 0.868 \left(\frac{t}{L}\right)^4 - \frac{8.340(1 + 0.2023\mu + 2.173\mu^2) \left(\frac{t}{L}\right)^4}{1 + 6.338(1 + 0.1408\mu + 1.536\mu^2) \left(\frac{t}{L}\right)^2} \quad (5)$$

where μ is the Poisson's ratio.

For longitudinal free vibration, the following equation allows E to be determined from f [10]:

$$E = \frac{4m \left(2\frac{L}{n}\right)^2 f^2}{K\pi D^2 L} \quad (6)$$

where n is the vibration mode, K is a correction factor [11] and D is the diameter of the cylindrical sample. For a bar of rectangular cross section, the following approximation of D can be used [10]:

$$D = \sqrt{\frac{2}{3}(b^2 + t^2)} \quad (7)$$

IET has been used in homogeneous materials at the macroscale: metals, alloys [11], polymers [12] or composites [13], and compared with other experimental techniques [14]. However, the literature related to applications of this technique to not completely filled samples, such as those manufactured by 3D printing, is scarce. It is important to note that E obtained from the resonance frequency in printed samples should be considered as an apparent modulus of the specimen (E_{Ap}), but not of the material (PLA in this work), which will be named E_{Mat} .

The aim of this work is to determine and analyze the mechanical properties of PLA samples. In particular, the focus was on E and stresses in the uniaxial test. The samples were made with partial infill to take into account the characteristics of those commonly used. By IET, the resonant frequencies were measured and the results were analyzed as a function of the infill percentage and infill pattern. The main novelty of the present work is based on a joint study between E obtained in different modes and the characteristic stresses for printed samples with different infill.

2 Materials and methods

Samples were manufactured using a 3D printer type Prusa 3, mounted in the laboratory. The filament used was PLA with a nominal diameter of 1.75 mm and black color. It was purchased at Print Factory, Buenos Aires, Argentina. The extruder nozzle was heated to melt the filament, and the molten material was deposited to print the sample layer by layer. The first layer was deposited on the bed which was also heated. The layer height, extruder temperature and bed temperature were specified in the G-code that controls the printer to make the sample. In this case the printing parameters were: layer height: 0.2 mm; extruder temperature: 217 °C; bed temperature: 60 °C; nozzle diameter: 0.5 mm.

The samples were printed flat and the surface of the plate was covered with hairspray to improve the adhesion of the polymer. They were made with different infill percentages between 20 and 100%, and the following infill patterns: grid, concentric, honeycomb and alternated (see Figure 1). The cover and base were made of 0.6 mm thick, while the side walls were made of 2 mm thick.

Figure 1: Infill patterns of filament deposition: grid, concentric, honeycomb and alternated. The different deposition layers are indicated for alternated and honeycomb patterns. For grid and concentric patterns all layers are the same.

The Cura Engine v3 [15] and Slic3D 1.2.9 software [16] were used to generate G-code files and control the process parameters, while the Repetier Host 1.5.2 software [17] was used to manage the printing.

The uniaxial tensile tests were carried out on a universal machine EMIC DL1000 at a constant deformation speed of 5 mm/min. The monotonic tensile tests were done at room temperature (around 293 K) in accordance with the ASTM D638-14 method. For tensile tests, Type I specimens with dog bone shape were modeled using the FreeCad 0.18 application [18] and exported as an STL file.

f of rectangular cross-section bars was determined by IET. The IET device was developed in the laboratory and has been used in different types of materials [11–13]. IET is a non-destructive technique and allows fast, simple and low cost measurements with high accuracy. In fact, the increase of E with the filler content in composites and the variation of E with the microstructural changes in copper-based alloys have been analyzed with IET [11, 13]. In this technique, the free flexural vibration frequency of a bar of length L , supported by two sharp edges at distances of $0.224 L$ from one end of the bar, is determined. The excitation is produced by a punctual impact in the center of the bar by the fall of a small ball of polymer. The frequencies out of resonance are naturally attenuated. The vibration was recorded with a battery-powered electret microphone whose electrical output signal was amplified and monitored by a Tektronix TBS1022 digital oscilloscope. The microphone was located in the center of the bar on the opposite side of the impact. The vibration signal was sent to a personal computer where it is recorded using the software provided by Tektronix.

Then, the frequency spectrum and f were determined by Fast Fourier Transform (see ref. [11–14] for more details). At least 10 measurements were made for each sample. In longitudinal mode, the bar is supported horizontally in the center, the punctual impact is produced at one end and the vibration is recorded at the other end.

Bars of rectangular cross-section were specifically printed to be measured by IET, with dimensions of $70 \times 11 \times 6 \text{ mm}^3$. E was determined by two modes of vibration, in mode A the vibration displacement was parallel to the direction of filament deposition, while in mode B the vibration was perpendicular to the direction of filament deposition, as is shown in Figure 2.

f of rectangular cross-sectional bars with grid infill pattern were calculated using the finite element method (FEM). For FEM simulations the free and open-source software CalculiX [19] was used under the FreeCad 0.18 interface [18]. From f , E of each specimen was determined using the same equations that were used for the experimental frequencies.

3 Results and discussion

3.1 Infill percentage

In order to analyze the influence of the infill percentage on the mechanical properties, bars for IET measurements with

Figure 2: (A) Representative sample with grid pattern, where the arrow indicates the direction of filament deposition. A cut of the sample was done for viewing. (B) Scheme of vibration in mode A and mode B, where the arrows indicate the vibration direction.

a 20, 40, 60, 80 and 99% grid infill pattern were 3D printed. The samples were testing in both vibration modes, A and B.

The density of the filament prior to extrusion was measured experimentally by weighing and measuring the dimensions of the filament, obtaining a value of 1.20 g cm^{-3} . This value is similar to that expected for PLA of 1.24 g cm^{-3} [20, 21]. The measured density of a wire after extruded and cooled to the air was 1.18 g cm^{-3} . On the other hand, the Archimedean method was used to estimate the density of the extruded wire on the hot bed, given a value of 1.07 g cm^{-3} . Some differences could be expected depending on the cooling process. An alternative way was used to estimate the density of the material, considering the amount of filament needed to make a sample, given by the printer software, and the mass of the finished sample. The density of the material calculated from this method varies with the infill percentage and infill pattern, given a value between 1.15 and 1.19 g cm^{-3} for the printed samples with a grid pattern and infill percentages between 20 and 99%. Therefore, slight differences in density would be expected between different parts of a specimen. In the present work, the density of the material obtained from this last method will be considered as an input for FEM simulations. On the other hand, an apparent density (ρ_{Ap}) was defined as the ratio between the mass and the external volume of the sample. ρ_{Ap} increases linearly with the infill percentage.

f was measured by IET. However, the IET equations cannot be used due to the particular nature of printed samples. Samples with infill percentages lower than 100% have an inhomogeneous linear density. The product ρS in Equation (1) is not constant throughout the sample, particularly at the ends, where the samples are filled to 100%. Then, the differential equation cannot be solved analytically.

However, in this work it will be assumed that the samples can be modeled as bars with an apparent homogeneous density and a constant cross-sectional area, equal to bt . Furthermore, it will be assumed that the second moment of sample area, I_{sample} , is also constant along the bar. Under these considerations, and in analogy with Equation (4), it is proposed that the product $E I_{\text{sample}}$ be proportional to:

$$E I_{\text{sample}} \propto m L^3 f^2 T' \quad (8)$$

where T' is a correction factor analogous to T . However, T' varies slightly with the ratio L/t and then the same value of T' will be assumed for all samples. Therefore, it is proposed that:

$$E I_{\text{sample}} \propto m L^3 f^2 \quad (9)$$

A 100% filled sample will be used as a completely solid sample, with an elastic modulus equal to those of the

material, E_{Mat} , and I of a square crossbar, which is well-known:

$$I = \frac{bt^3}{12} \quad (10)$$

Samples with infill percentages lower than 100% have unknown E and I_{sample} values. For this reason, an equal modulus E_{Mat} will be considered for all samples, i.e. the modulus of each filament is the same, regardless of filling. On the other hand, it is proposed that I_{sample} can be approximated by Equation (11) based on a completely filled bar of the same dimensions:

$$I_{\text{sample}} = k \frac{bt^3}{12} \quad (11)$$

where k is a constant, with the value of 1 for the case of a sample with 100% infill. Then, using I_{sample}/I values were determined. Using Equations (10) and (11) k was determined for each infill, and the values obtained are shown in Figure 3. k increases linearly with the infill percentage in both modes with a similar slope.

Using a reasoning similar to that mentioned above and f obtained from FEM simulations, the values of k were estimated for bars with 20, 40 and 80% infill. In this case, different E_{Mat} values were considered for the simulations and E_{Ap} was calculated for each value. A linear behavior was found between E_{Ap} and E_{Mat} for each infill percentage and the slope obtained was considered equal to k . The digital models of the specimens were made following a grid pattern. In addition to the value of the modulus, FEM simulations use the density and Poisson's ratio of the

Figure 3: Variation of k with the infill percentage for mode A and mode B calculated from Equations (9)–(11), and using FEM. The lines are linear fits.

material as input. The density of the material was determined as indicated above and a Poisson's ratio of 0.35 was used. The values of k calculated from simulations for different infill percentages are also presented in Figure 3 for mode A and mode B. k increases linearly as a function of the infill percentage in both modes, but the slope obtained from FEM simulations is lower than that obtained from the experimental results.

It is worth mentioning that for a fixed infill percentage, a FEM simulation of the vibration of a completely filled bar with an apparent density and an apparent modulus, the same frequency to that of the printed sample and using E_{Mat} was obtained, within an error of 3%.

The aim of this work is to study an approximate method to analyze the IET results in samples made with a 3D printer. From the calculation carried out previously, two approximations could be made: consider an I value of a solid bar and therefore an apparent modulus E_{Ap} , or consider the modulus of the material E_{Mat} and an apparent value of the second moment of area I_{sample} . Then, the $E_{\text{Mat}}/E_{\text{Ap}}$ ratio is practically equal to $I/I_{\text{sample}} = 1/k$. In this sense, E_{Ap} is a fictitious value but it can provide important information. This result can be very useful from the engineering point of view for the application of 3D printed samples in different working conditions, since knowing the dependence of k with the infill percentage and E_{Mat} , it is possible to predict E_{Ap} . This information is very useful to optimize the design of the parts, specifically with the aim of saving time and printing cost. On the other hand, if the material of the filament is changed, E_{Ap} could be estimated using the dependence of k found in this work and the properties of the material.

It is important to revise the assumption that E_{Mat} is independent of the infill percentage. This assumption can be analyzed considering, for example, the formation of voids between layers [22]. Parameters such as layer height or print speed can modify the void formation, but the influence of the infill percentage and infill pattern is unclear. Moreover, the crystallinity may be different if the cooling conditions of the deposited filament change, due to

modifications of the printing parameters. Different void density and crystallinity fractions can generate different E_{Mat} . In this section, only the infill percentage was varied, while the other parameters were kept constant.

In Figure 4A, the variation of the modulus E_{Ap} with filler content is presented for samples printed with different infill percentages and vibrations in mode A and mode B. In Figure 4B, E_{Ap} is presented as a function of ρ_{Ap} . E_{Ap} increases linearly with the infill percentage in both vibration modes.

The specific modulus for each specimen was also calculated as the ratio between E_{Ap} and ρ_{Ap} , and the results are presented in Figure 5. A decrease in $E_{\text{Ap}}/\rho_{\text{Ap}}$ is observed when the apparent density increases, until reaching a minimum in densities close to 1 g cm^{-3} , which corresponds to infill percentages between 60 and 80%. Then, the values increase and the value corresponding to 99% infill is similar to that of 20% infill in both modes.

The frequency of free vibration in longitudinal mode in printed samples was measured by IET, while E_{Ap} was calculated from Equation (6). The values obtained are presented in Figures 4(A, B) and 5, together with those of

Figure 4: Variation of E_{Ap} with the infill percentage (A) and ρ_{Ap} (B) for samples done with grid pattern. Results obtained using mode A, mode B and longitudinal mode are presented.

Figure 5: Variation of $E_{\text{Ap}}/\rho_{\text{Ap}}$ with ρ_{Ap} for mode A, mode B and longitudinal mode.

mode A and mode B. The values obtained in the longitudinal mode are systematically lower than those of flexural modes. It can be also seen that the samples printed with grid pattern shown anisotropic behavior, and the anisotropy decreases for higher infill percentages.

In order to analyze the influence of the grid pattern in a different orientation, a sample was made with 40% infill upright. E_{Ap} for this sample was obtained in flexural vibration mode, and the results are shown in Figure 4B as a function of the apparent density for comparison with the results presented above. There is no difference between mode A and mode B, and the values of this sample are higher than those of samples with similar densities made horizontally.

3.2 Tensile tests

Tensile tests were carried out on specimens with a grid pattern and different infill percentages. Three tensile samples were printed and tested for each infill percentage, but about 30% of the samples broke outside the gauge length. It should be noted that the methodology used for the performance of the tests and the design of the samples is ASTM D638, which is the standard test method for the tensile properties of plastics, and refers to completely filled samples with isotropic properties. However, in the literature, this methodology has been widely used to study the mechanical properties of 3D printed samples with 100% infill [2, 3, 5, 23–29]. Even in completely filled samples, some authors have reported complications with the geometry of the specimens, due to the concentration of stresses in the fillet area, which would cause them to fail prematurely [5, 24, 30, 31]. In the present study, maximum stress results were considered only for samples that broke within the gauge length.

Representative stress–strain (σ – ϵ) curves are shown in Figure 6A. Differences in the shape of the curves are observed for samples with different infill percentages. To study these differences, the characteristic stresses of each

curve were determined. The offset yield stress ($\sigma_{0.2}$), the stress for $\epsilon = 4\%$ (σ_4) and the maximum tensile stress ($\sigma_{\max}$) were calculated for each sample. The average values obtained for each infill percentage are presented in Figure 6B. It is important to note that these characteristic stresses are associated with each sample, but they are not material properties. All parameters increase until reaching a stable value at 80% infill. The relationship between the values obtained for the samples with 20% infill and 99% infill are: 0.7 for $\sigma_{0.2}$; 0.64 for σ_4 and 0.5 for $\sigma_{\max}$. Therefore, $\sigma_{\max}$ is the parameter that is most influenced by the infill percentage within the characteristic stresses studied here.

From the results shown in Figure 6B, it is observed that samples with 80–99% infill exhibit the highest $\sigma_{\max}$, around 35 MPa, while $\sigma_{0.2}$ is around 20 MPa. Therefore, samples with 80–99% infill would be suitable for uses where high strength is required, but it must be taken into account that the specimen begins to deform plastically from 20 MPa. For the case of samples with low infill percentages, $\sigma_{\max}$ values are closer to $\sigma_{0.2}$, with values of 14 and 18 MPa, respectively, for the sample with 20% infill. These results indicate that, although the sample has a low $\sigma_{\max}$, it begins to deform plastically at 14 MPa, which is not so different from the 20 MPa of the samples with 80–99% infill. The characteristic stresses of the samples with different infill percentages can be used as an input for the choice of the filling of a printed part submitted to an external stress. It is important to specify the requirements of the printed part. If the sample is required not to break, $\sigma_{\max}$ should be considered for the choice. However, if it is required that the sample does not flow and maintain its original dimensions, $\sigma_{0.2}$ must be considered for the choice.

Specific values $\sigma_{0.2}/\rho_{Ap}$, σ_4/ρ_{Ap} and $\sigma_{\max}/\rho_{Ap}$ were calculated, and are presented in Figure 7. $\sigma_{0.2}/\rho_{Ap}$ values slightly decreases while σ_4/ρ_{Ap} exhibits almost constant values as the infill percentage increases. $\sigma_{\max}/\rho_{Ap}$ presents a minimum for 40% infill and a maximum for 80% infill.

As was analyzed for the grid pattern, $\sigma_{\max}$ increases with the infill percentage of the printed samples. However, for specimens fabricated from 3D printers, which are

Figure 6: (A) Stress-strain curves of representative specimens printed with grid pattern and different infill percentages. (B) Characteristic stresses for different infill percentages.

Figure 7: Variation of $\sigma_{0.2}/\rho_{Ap}$, σ_4/ρ_{Ap} and σ_{max}/ρ_{Ap} with the infill percentage for a grid pattern.

generally not completely filled materials, it is of great importance to analyze the normalized stresses with the apparent density. These normalized stresses would give us an idea of the specific stresses of a specimen per unit mass for a given pattern. To carry out a comprehensive analysis of the results presented in Figure 7, it is convenient to analyze them in conjunction with the values of the specific E reported in Figure 5. Samples with 80–99% infill, have the highest σ_{max}/ρ_{Ap} (Figure 7) and the highest values of the specific E for all vibration modes (Figure 5). However, $\sigma_{0.2}/\rho_{Ap}$ in this range of infill is the lowest. On the other hand, for example, the sample with 20% infill has the highest $\sigma_{0.2}/\rho_{Ap}$, a good value of the specific E for modes A and B, but a low value of σ_{max}/ρ_{Ap} . The information presented in Figures 5 and 7, analyzed in conjunction, would allow a correct choice to be made in order to optimize the infill percentage of printed parts for a specific need, considering the specific E of the part in different vibration modes, $\sigma_{0.2}/\rho_{Ap}$ and σ_{max}/ρ_{Ap} . It is important to consider that a higher density of a sample implies a greater amount of material used, a higher weight and a greater time and cost of printing.

3.3 Infill pattern

Specimens with different infill patterns and 60% infill were fabricated. The patterns used were grid, concentric, alternated and honeycomb, and were chosen because they can be generated by the most widely used slicing software. Grid, concentric and alternated are relatively simple patterns and were compared to a more complex pattern such as honeycomb. The E_{Ap}/ρ_{Ap} results obtained from the IET measurements for both modes are shown in Table 1. It is observed that the smallest difference between both modes corresponds to the honeycomb pattern, although the highest value of the modulus is obtained for a concentric pattern in mode A.

Mechanical test specimens were printed with different infill patterns and 60% infill and submitted to uniaxial tensile tests. From the stress-strain curves, $\sigma_{0.2}$ and σ_4 were determined. In Table 1, $\sigma_{0.2}/\rho_{Ap}$ and σ_4/ρ_{Ap} are presented for different patterns. The highest values of the specific stresses are observed for the concentric pattern. For a 4% strain, the specific stresses of the samples with different patterns exhibit similar values, while the specific stress at 0.2% strain is slightly lower for honeycomb and alternated patterns.

It can be seen in Table 1, that the concentric pattern exhibits the highest $\sigma_{0.2}/\rho_{Ap}$ and the highest specific E , when the vibration displacement is parallel to the direction of filament deposition. However, due to the high anisotropy of this pattern, it exhibits a low specific modulus when the vibration displacement is perpendicular to the direction of filament deposition. For the case of the grid pattern, it has a high value of $\sigma_{0.2}/\rho_{Ap}$ and a high value of the specific modulus when the vibration displacement is perpendicular to the direction of the filament deposition. This pattern also has a high anisotropy and E determined in the other mode is the lowest. It is very important to take into account the anisotropic behavior of this type of pattern for the design stage of a part, because its mechanical behavior, specifically E , is highly dependent on the relationship

Table 1: E_{Ap}/ρ_{Ap} obtained from IET measurements for both modes, and characteristic stresses σ/ρ_{Ap} of samples printed with different infill patterns and 60% infill.

	E_{Ap}/ρ_{Ap} (GPa cm ³ g ⁻¹)		$\sigma_{0.2}/\rho_{Ap}$ (MPa cm ³ g ⁻¹)	σ_4/ρ_{Ap} (MPa cm ³ g ⁻¹)
	Mode A	Mode B		
Grid	2.58 ± 0.06	2.91 ± 0.06	20.2 ± 6.2	24.1 ± 4.0
Concentric	3.02 ± 0.06	2.69 ± 0.05	23.8 ± 2.6	27.4 ± 1.3
Honeycomb	2.90 ± 0.06	2.93 ± 0.06	17.2 ± 1.6	24.7 ± 1.9
Alternated	2.99 ± 0.06	2.77 ± 0.06	17.8 ± 3.0	24.3 ± 0.3

between the direction of vibration of the sample and the direction of filament deposition. On the other hand, the samples with a honeycomb pattern exhibit similar values of the specific E in both directions, which indicates that they have lower anisotropy than those printed with other patterns and 60% infill. However, honeycomb samples have the lowest $\sigma_{0.2}/\rho_{Ap}$. The values presented in Table 1 can be used for the choice of the most appropriate pattern of a printed part.

The results obtained in this work would provide the necessary information to be able to choose and optimize the design of a part with respect to the infill pattern and infill percentage. For a specific need, it is essential to have information on both, the range of elastic and plastic deformation of the part. It is also important to know the behavior of the part under stresses applied in different directions. A combined analysis of the behavior of E and characteristic stresses, as well as their specific values, makes it possible to better understand and decide the most suitable design parameters for a specific part subjected to different mechanical requirements.

In the present work, the effect of changes in the internal morphology of the printed pieces, in particular only the effect of the infill pattern and infill percentage, on their mechanical properties was studied and analyzed. For this study, it was used, as a first approximation, that E_{Mat} has a fixed value, independent of the filling. However, in a following work it will be analyzed if there is an influence of the filling on E_{Mat} , due to a different crystallization or density of voids. These characteristics may also depend on other printing parameters, such as layer height or deposition speed.

4 Conclusions

In this work, samples were made by 3D printing using different infill patterns and infill percentages. E was determined by IET, tensile curves were obtained and the characteristic stresses were determined. The use of bar vibration equations in printed samples was analyzed in the case of grid infill and an apparent E value was used to characterize the samples. The results were correlated with FEM simulations. In this way, it is possible, as an approximation, to assume that the bar is completely filled with an apparent density and an apparent modulus. The specific E_{Ap}/ρ_{Ap} values have a behavior with a minimum in an infill percentage between 60 and 80%. The specific characteristic stresses have different behaviors depending on the infill percentage. $\sigma_{0.2}/\rho_{Ap}$ values slightly decreases while σ_4/ρ_{Ap} exhibits almost constant values as the infill percentage increases. σ_{max}/ρ_{Ap} presents a minimum for 40%

infill and a maximum for 80% infill. This information, analyzed in conjunction, would allow a correct choice to be made in order to optimize the infill percentage of printed parts for a specific need. Samples with 80–99% infill, have the highest values of σ_{max}/ρ_{Ap} and the highest values of the specific E for all vibration modes. However, $\sigma_{0.2}/\rho_{Ap}$ in this range of infill is the lowest. On the other hand, for example, the sample with 20% infill has the highest $\sigma_{0.2}/\rho_{Ap}$, a good value of the specific E for modes A and B, but a low value of σ_{max}/ρ_{Ap} .

Specimens with different infill patterns were analyzed observing that honeycomb exhibits lower anisotropy than the other patterns with 60% infill but the lowest $\sigma_{0.2}/\rho_{Ap}$, and the concentric infill in mode A has the highest specific E .

The results obtained in this work provide information on the mechanical properties of partially filled samples, which allows us to choose the best design configuration by evaluating E , characteristic stresses, and cost and printing time.

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