Effect of Relative Density in In-Plane Mechanical Properties of Common 3D-Printed Polylactic Acid Lattice Structures

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ABSTRACT: Lattice structures are employed as lightweight sandwich cores, supports, or infill patterns of additive manufacturing (AM) components. As infill structures, the mechanical properties of AM parts are influenced by the infill pattern. In this work, we present the mechanical characterization of three commonly used infill patterns in AM, triangular, square, and hexagonal, and compare them with analytical and numerical models. Fused filament fabrication of polylactic acid (PLA) thermoplastic is used as the printing material for the compressive and tensile tests. First, a parametric analysis is performed by changing the infill density to obtain numerically and analytically the mechanical properties of the studied samples. Next, we compare the experimental results with numerical and analytical models and propose numerical correlations for high-density honeycombs. The stiffest infill pattern was the square, and the explanation is provided in detail. Also, there is a nonlinear correlation between density and the mechanical properties; however, the strongest part was not possible to determine with a significant statistical value. Finally, we propose simplified models for predicting the compressive and tensile response of AM PLA structures by considering the infill regions as homogenized structures.

1. INTRODUCTION

Cellular structures, also known as lattice structures (LS), commonly appear in cores for lightweight composite structures, support structures for additive manufacturing (AM) parts, and natural structures like trabecular bone.1,2 LS possess qualities such as impact resistance, high toughness, and low weight,3 characterized by cell size, cell geometry, and topological connectivity of cells and the material. Currently, LS are used as infill patterns of AM parts in which a particular cell repeats periodically in a region, reducing the printing time and material used compared to the bulk solid, while maintaining relatively high stiffness and strength. The repeating unit in LS could be in the form of a slender beam or strut forming truss LS or in the form of a bidimensional shape such as honeycomb cores. Although LS can have multiple formats such as triply periodic minimal structures (TPMS) such as gyroids, diamonds, and Fisher–Koch, they minimize the volume of a given area, showing that LS are not constrained into a bidimensional pattern.

AM technologies are suitable for producing LS because they create a component from a 3D CAD model in a layer-wise manner, thus introducing significant advantages over traditional subtractive, corrugation, or bonding methods, and with higher geometrical complexity in the manufactured LS.4 One of the most used AM technologies for polymers is fused filament fabrication (FFF),5,6 which is a cost-effective alternative for manufacturing LS. Despite the complexity available for 3D printed lattices, simple 2D lattices are still widely employed in functional prototyping or composite parts, such as those of Markforged. Furthermore, the mechanical behavior of those simple structures is well documented; nevertheless, the implications of AM defects and the role of relative density in mechanical properties are not fully understood. Therefore, the motivation of this research is to close this knowledge gap.

The combinations of all possible LS given variations in materials, manufacturing methods, and geometrical dimensions prevent a complete experimental study in such arrangements. Nevertheless, studies have been performed in a wide range of LS, materials, and methods. Al-Saedi et al.7 produced by powder bed fusion selective laser sintering (SLS) three common metal TPMS LS, and Maharjan et al.8 evaluated the manufacturability and compressive behavior of the gyroid type 3D polymeric lattice with different unit cells and volume fractions. Abou-Ali9 compared different types of TPMS for SLS of the Nylon material. Also, in the study by Zhang et al.,10...
tripy periodic minimal surface structures were printed in ceramic materials, presenting pseudo-ductile failure. They obtained those tripy periodic minimal surfaces by changing the microstructure design and using a ceramic stereo-lithography (SLA) process. Truss structures are suitable for metal AM fabrication, showing a vast number of studies concerning primary body-centered cubic (BCC), BCC-Z, face-centered cubic (FCC), and FCC-Z truss LS. For polymers, Rezaei et al. used polyactic acid (PLA) body-centered cell (BCC-Z) LS to assess manufacturability, repeatability, and mechanical properties. Fadel et al. employed ABS to produce BCC truss LS and determine the effect of vertical strut reinforcement, while Abdulhadi and Mian produced BCC Truss LS with varying strut length and orientation. Gautam et al. produced and studied via FFF Kagome lattices. Honeycomb cores and bidimensional LS are usually unsuitable for metal AM due to the relative density, making them ineffective compared to TPMS or truss LS. Honeycomb LS are mainly studied in polymeric materials. Khosravani et al. used a 3D printer to study the behavior of the composite sandwich with a polymeric core of ABS and ASA thermoplastics, and Kumar et al. fabricated and compared different types of LS, closed cells, open SU cells, and honeycomb using FFF PLA. Infills and sandwich cores have remarkable compressive properties, particularly out-of-plane compressive strength. Ye et al. observed three post-failure mechanisms, including strain-hardening, stable deforming, and softening, depending on the slenderness of the strut. Moreover, Leonardi et al. evaluated bending stresses in heterogeneous lattices showing the possibility to tune an AM lattice spatially, that is, define density or geometrical shape as a position function. This tuning could be used to provide graded properties, increasing, even more, the space design of AM LS. Other LS are obtained from combined elements and hierarchical honeycombs. For instance, second-order structures are structures made of repeating structures or connected with smaller ones.

Given the high number of materials, parameters, and forms of LS, analytical models are of the utmost importance in describing mechanical behavior. Different analytical models are available to determine the mechanical properties of LS, notably those of Gibson–Ashby coefficients. Generally, the models are independent of the manufacturing process and size of the cells and are developed on some hypotheses such as the strut behaves like a beam for slender struts and low-density values. Vigliotti and Pasini developed a linear analysis method for predicting stiffness and strength of open and closed cell LS with varying topology, while Souza et al. employed a micromechanical analysis to obtain the effective properties. Analytical models are not always available; therefore, finite element analysis (FEA) can fill the void when LS is complex for an analytical solution. Cho and Lee investigated using FEA various LSs: simple cubic lattice, BCC lattice, and modified FCC lattice. The work showed an increasing uneven stress distribution for high-density values usually not accounted for in analytical formulations. Some works, such as that of Ye et al., investigated the compression properties of pyramidal 3D printed trusses, using an experimental approach and FEA, finding a good fit between both data. Maskery et al. produced polymeric TPMS lattices using AM. The lattices were evaluated using tensile-compressive tests, compared with the finite element model, showing good agreement for the stiffness and deformation mechanisms. FEM and analytical approaches can be used to analyze lattice performance.

Another proposed method is multiscale analysis. Gorguluar-slan performed a multiscale analysis of LS and then proposed a validation metric that evaluates their method with experimental data using ABS in a FFF machine, showing the importance of a validation methodology for multiscale models. Analytical expressions teach the independence of the pore size in the mechanical properties when the relative density is conserved. However, Alief et al. used a FFF machine to print LS in different pore configurations and different materials to evaluate the effect on the compressive mechanical properties, and this effect was also observed in metal LS. Despite the excellent tolerance capabilities of the AM process, the cell dimension presented a nearly 50% difference due to the small cell size (square-shaped). As expected, there was a variation of the compressive strength considering the pore dimension because the AM process introduces defects. Finally, the mechanical properties and failure behavior can depend on the material, the process, and the geometry of the infill structure. Mainly, relative density, a geometric feature, can play a crucial role in mechanical behavior.

Despite the great diversity of AM infill structures and possible mechanical behaviors that can be produced, they can be limited by the manufacturing capabilities of AM technologies, particularly defects that can affect the geometrical and mechanical characteristics. FFF introduces porosities in parts because of thermal contraction, void presence in the filament, and a nonuniform melt profile. Depending on the AM process, various types of defects can occur; interbead porosities are widely prevalent for all FFF, intrafilament porosities have a lower effect than interbead porosities, but they can also reduce the AM mechanical properties. The layer-wise construction creates stepped-like geometries, making the piece prone to surface and geometrical imperfections. Furthermore, the failure mechanisms of infill patterns and the interaction with defects and processing parameters from AM are unknown. Monkova et al. showed the importance of considering process-related issues through studies for the line fill and grid infill. Experimental results revealed considerable errors in stiffness (from 20 to 60%) due to the imperfect layer-to-layer interfaces and overall material anisotropy, thus showing the importance of considering process-related issues. Rezaei et al. showed that the stress–strain curve exhibits a nonlinear and asymmetrical behavior via experimental and numerical behavior in the stress–strain curve. Alkhader and Vural investigated numerically the role of topology and microstructure irregularity of the cellular solids in the compressive properties by AM. One other factor is connectivity, which plays a significant role in mechanical response by influencing bending or stretch-dominated deformation modes. Maharjan et al. showed that the compressive strength obtained is higher when the pore dimension is low and when the pore density is high. Karamooz Ravari et al. showed that AM can produce LS with controllable cell size and geometry. However, the diameter of the strut can vary along its length, and this research used FEA to account for the effect on mechanical properties of diameter variation along the strut.

Karamooz Ravari and Kadkhodaei presented a computationally efficient way of obtaining the stress–strain curve for LS using a finite element model. They used a single strut modeled with imperfections and defects, performed a virtual tension test with the same stress–strain curve as the solid material, and then deployed a second unit cell with no defects.
or imperfections, but with the same bulk material properties of the first, they modeled the lattice showing good accuracy. Park et al.\cite{41} used a two-step homogenization to determine the effective mechanical properties of extrusion AM LS, finding a good accuracy in the elastic estimation considering the AM characteristics such as air gaps, stair steps, and filament voids. Finally, Park and Rosen\cite{42} quantified the stair-step irregularities between layers and the air gaps deposited along the filament, performing a voxel generation for accounting for these geometric errors.

Analytical expressions, homogenization, FEA, and experimental methods are employed to retrieve the mechanical response of the infill and LS subjected to various loads. In this work, we perform the mechanical characterization for three AM bidimensional infill LS, namely, square, triangular, and honeycomb, via FEA, analytical methods, and comparing with experimental data. This work will address the validity of using such analytical models in considering AM processes and their relevant defects. Furthermore, we present numerical correlations to determine the stiffness in higher density infill structures. This knowledge allows for an optimal design in which, for instance, relative density is minimized, while maintaining a specific strength or stiffness. Section two introduces the analytical and numerical models for dealing with cell structure infills. Section three describes the materials and methods used to validate the models. Later, we discuss the FEA applicability in studying the failure mechanisms in tension and compression lattices. Finally, we introduce our significant conclusions.

2. ANALYTICAL AND NUMERICAL MODELS

In this section, to define the stiffness and the relative density, which is the ratio of the lattice density $\rho^*$ and the solid density $\rho_s$, in terms of the infill pattern geometry, the analytical models are adapted from previous works.\cite{1} Three common AM infill patterns are square, honeycomb, and triangular. The triangular lattice represents the stiffer structure for a given relative density value. Equation 1 gives the relative density as a function of the strut length $l$ and the thickness of the strut $t$, while eq 2 evaluates the stiffness $E$ as a function of the elastic modulus of the solid $E_c$.

\[
\frac{\rho^*}{\rho_s} = 2\sqrt{3}\left(1 - \frac{\sqrt{3} t}{2 l}\right) \quad \text{for } l > 3.5t  \tag{1}
\]

\[
E = 1.15E_c\left(\frac{t}{l}\right) \tag{2}
\]

Honeycomb patterns are relatively fast to produce via AM due to their low density for a given stiffness. In hexagonal honeycombs, all equal sides produce an isotropic lattice. Also, honeycombs have exceptionally out-of-plane properties, making them suitable for impact applications in which loads came in the out-of-plane direction.\cite{1} Equation 3 gives the relative density as a function of thickness and side length. Equations 4 and 5 provide the elastic modulus and in-plane shear modulus for a regular hexagonal honeycomb.

\[
\frac{\rho^*}{\rho_s} = 2\frac{t}{\sqrt{3}}\left(1 - \frac{1}{2\sqrt{3}}\frac{t}{l}\right) \tag{3}
\]

\[
E = 2.3E_c\left(\frac{t}{l}\right)^3 \tag{4}
\]

\[
G_{12} = 0.57E_c\left(\frac{t}{l}\right)^3 \tag{5}
\]

Square patterns are also easy to reproduce but with less stiffness than triangular patterns. They can be created from a set of parallel and perpendicular bead bands. Equations 6 and 7 provide the relative density and the elastic modulus of a square pattern.

\[
\frac{\rho^*}{\rho_s} = \frac{2l - t^2}{l^2} \quad \text{for } l > t \tag{6}
\]

\[
E = E_c\left(\frac{t}{l}\right) \tag{7}
\]

The LS strength can be estimated from the behavior of the constituent material. Elastomeric materials show an elastic buckling failure, while plastic and elastoplastic materials fail in a plastic yielding, called plastic collapse, characterized by the localization of yield in points known as plastic hinges.\cite{1} Finally, ceramics and brittle materials usually present brittle crushing fractures. The plastic collapse stress for a regular hexagon is given by eq 8, where $\sigma_{pl}^*$ denotes the plastic collapse stress, $t$ and $l$ are the thickness and length of the struts, and $\sigma_y$ is the yield stress of the material.\cite{1}

\[
\sigma_{pl}^* = \frac{2}{3}\left(\frac{t}{l}\right)^2\sigma_y \tag{8}
\]

Table 1. Relative Density Values (%) Used in the Three Infill Patterns

| lattice type            | tension A | tension B | compression |
|-------------------------|-----------|-----------|-------------|
| square                  | 36, 55, 75| 10, 36, 56, 90| 29, 42, 62 |
| honeycomb regular hexagonal | 22, 35   | 44, 52, 60 | 36, 44, 67 |
| triangular              | 49, 66    | 28, 37, 46, 55 | 24, 37, 45 |

3D manufactured samples were selected, considering that not all the densities values are possible to obtain\cite{39} due to restrictions in the minimum side length, minimum thickness, and incremental sensibility of these distances. Also, from a DOE perspective, one could choose several discrete values (levels) from a continuous range if there is no apparent restriction. Although in this methodology, levels among lattices are difficult to compare in an ANOVA analysis, it helps populate the graphs with different density values.

As shown before, analytical models assume the solid as a group of beam structures, which is valid when considering low-density values (typically, no greater than 18% according to Gibson–Ashby\cite{40}), that is, large slenderness values in the strut. For higher density percentages values, the LS could be considered as a solid with uniform porosities. Rodriguez et al.\cite{44} use this approach for characterizing an ABS solid with a good amount of porosities generated from the FFF process, and 9 show the elastic response, where $E_i$ are the elastic modulus in the directions $i = 1, 2, 3$ and $p_i$ is the porosity. While these
equations were obtained from asymptotical homogenization to diamond-shaped voids, they could be extended to other geometry pores, with density values high.

\[ E_1 = (1 - p_1)E_i \]  
\[ E_2 = (1 - \sqrt{p_1})E_i \]  
\[ E_3 = E_2 \]  

We perform a parametric FEA of the LS using the finite element software ANSYS along with the analytical formulations presented. The bulk material model used was an isotropic linear elastic, with values of elastic modulus \( E = 2850 \text{ MPa} \) and Poisson’s ratio \( \nu = 0.35 \). The geometry was parametrized to adjust the length and thickness according to the given relative density value. The model uses 3D solid elements, and the results were mesh-independent, as the convergence analysis of the maximum displacement for the model shows no more than a 2\% change. The LS are modeled considering zero vertical displacements at the bottom and fixed support in a bottom corner edge as boundary conditions. As a result, the structure is subjected to traction or compression stresses of 1 MPa at the top of the piece and zero displacements for the out-of-plane direction, as shown in Figure 1. Numerical results provide displacements, strains, and stresses in the domain and the average displacement in a longitudinal band, as indicated in Figure 2, which combined with the average stress can be used to determine the overall structure stiffness by dividing the applied pressure into the average strain of the transversal area.

### 3. RESULTS AND DISCUSSION

The average values and coefficient of variation (COV) for the elastic modulus and maximum stress for the different configurations of lattice patterns and densities are shown in Table 2. For the tensile test, the stiffness calculations consider the solid portion of the overall estimation. Thus, a compensated value of solely the lattice region is displayed. For type A, in all three sections (lattice regions and unclamped top and bottom solid PLA) is assumed the same stress, as springs in the series model configuration. On the contrary, we modeled the sample type B as a parallel springs model yielding eqs 12 and 13

\[ \frac{L_T}{E_{LL}} + \frac{L_s}{E_{ss}} = \frac{\delta}{\sigma} \]  
\[ E_L = \frac{\sigma \delta}{A_L L_T} - \frac{E_{ss} A_{ss}}{A_L} \]  

**Table 2. Average and COV for the Stiffness and Strength of PLA 3D Printed LS**

| type      | relative density (%) | elastic modulus [MPa] | COV [MPa] | max. stress [MPa] | COV (%) |
|-----------|----------------------|-----------------------|-----------|-------------------|---------|
| solid     | 100                  | 2849.87               | 6.7       | 45.46             | 2.0     |
| A square  | 36                   | 1003.16               | 10.5      | 6.34              | 12.8    |
| A square  | 55                   | 1821.11               | 3.1       | 9.91              | 26.1    |
| A square  | 75                   | 2517.70               | 5.1       | 8.37              | 21.0    |
| A triangular | 49               | 923.83                | 10.5      | 2.56              | 13.0    |
| A triangular | 66               | 1186.70               | 9.5       | 5.37              | 28.2    |
| A hexagonal | 22               | 192.17                | 5.3       | 1.96              | 19.8    |
| A hexagonal | 35               | 232.73                | 9.9       | 1.99              | 23.1    |
| B square  | 10                   | 95.77                 | 12.47     | 2.62              | 23.3    |
| B square  | 36                   | 656.97                | 0.40      | 10.15             | 11.1    |
| B square  | 56                   | 942.23                | 10.03     | 9.78              | 53.9    |
| B square  | 90                   | 2292.10               | 3.03      | 15.8              | 16.2    |
| B triangular | 28              | 347.30                | 4.44      | 6.96              | 9.3     |
| B triangular | 37              | 331.73                | 1.99      | 7.37              | 2.8     |
| B triangular | 46              | 303.20                | 2.50      | 13.44             | 9.9     |
| B triangular | 55              | 431.56                | 6.12      | 8.73              | 6.1     |
| B hexagonal | 44               | 121.78                | 2.97      | 15.92             | 2.7     |
| B hexagonal | 52               | 223.90                | 2.39      | 15.79             | 4.4     |
| B hexagonal | 60               | 247.88                | 2.97      | 15.92             | 2.7     |
| comp square | 29             | 268.17                | 8.6       | 3.03              | 13.7    |
| comp square | 42             | 486.98                | 2.0       | 9.40              | 6.4     |
| comp square | 62             | 870.19                | 2.2       | 23.83             | 17.0    |
| comp triangular | 24          | 159.35                | 1.1       | 2.66              | 6.7     |
| comp triangular | 37         | 287.47                | 4.6       | 7.47              | 3.4     |
| comp triangular | 45         | 290.79                | 13.2      | 7.25              | 6.9     |
| comp hexagonal | 36      | 47.93                 | 2.8       | 1.60              | 8.8     |
| comp hexagonal | 44      | 81.68                 | 4.8       | 3.14              | 4.6     |
| comp hexagonal | 67      | 360.24                | 6.1       | 8.92              | 1.8     |
where \( L_l \) is the lattice length (48 mm), \( L_s \) is the length of the solid section, which can be obtained by subtracting \( L_l \) from the total gauge length \( L_T \), and \( E_l \) and \( E_s \) represent the lattice modulus and the solid section modulus, which are assumed as the values reported for the solid material. Finally, \( \delta \) is the applied displacement, and \( \sigma \) is the calculated stress. In 13 \( A_s \) and \( A_l \) are the solid section and lattice section transverse areas, respectively. They differ in the number of layers in each region.

In Table 2, the highest elastic modulus of 2849.87 [MPa] corresponds to the solid material or \( E_s \) and the COV of the elastic modulus of all samples covers the range of 1.1–13.2%, showing low scattering between samples. On the other hand, the maximum stress presents a greater spreading of values with typical values from 2 to 28%. Thus, they expose the influence of the manufacturing process variations in the sample strength rather than the stiffness. Figures 3–5 show a graphical representation of the data provided in Table 2.

![Figure 3](image_url)  
Figure 3. Stiffness and strength results of type A LS for different density values.

![Figure 4](image_url)  
Figure 4. Stiffness and strength results of type B LS for different density values.

![Figure 5](image_url)  
Figure 5. Stiffness and strength results of type C LS for different density values.

![Figure 6](image_url)  
Figure 6 shows the stress–strain curves for the three infill patterns at different relative densities for the compressive test. In the figure, the first letter represents the infill type, for example, S for square, the two following numbers represent the relative density in percentage, and finally, the last letter is a convention for naming the replica number. As expected, for high densities, the stiffness and strength increase not proportionally, suggesting a nonlinear relation of relative density.

The tensile stress–strain curves present the same initial behavior as the compressive test, failing right after the peak stress is reached. However, in the compressive test, after the first peak, the structure experiences a continuum process in which saw-toothed (or ripple) profiles appear when a plastic band collapses; see Figure 7. This deformation is consistent with the compression behavior of bonded or corrugated honeycombs where three phases can be distinguished: (i) the elastic zone and the plastic yielding initiation, (ii) plateau stress area when the stress remains relatively constant even with increasing strain, and (iii) densification occurs when all the cells collapse together and the stress increases until fracture. AM LS display similar behavior.

Figures 8–10 compare the stiffness as a function of the relative density in the three infill patterns. The three models are shown in lines and the experimental results with points. Rule of mixtures (ROM) represents an upper bound in most cases. However, the analytical form using the Gibson–Ashby coefficients diverges largely from experimental results for higher relative density values. Thus, FEA is a better predictor of the mechanical properties of high-density LS.

Regarding the three models, the root mean square error is used to evaluate their accuracy, the ROM model has the higher error with 25.8%, the analytical model based on Gibson–
Ashby coefficients presents an error of 12.7%, and finally, the FEA has the lowest error with 6.4% (183.3 MPa) of the solid stiffness, respectively. From the FEA, in 14 we propose correlations similar to Gibson–Ashby coefficients, but with numerical model data, for the LS stiffness.

\[
\frac{E}{E_s} = A \left( \frac{\rho^*}{\rho} \right)^2 + B \left( \frac{\rho^*}{\rho} \right) + C
\]  

(14)

A, B, and C are the correlation factors, from a quadratic polynomial regression, for the square pattern with values of 0.7839, 0.1435, and 0.0327. For the triangular pattern, A, B, and C are 0.2897, 0.1499, and 0.0560, respectively. Finally, coefficients A, B, and C for the honeycomb pattern are 0.2897, 0.0180, and 0.0006.

Regarding the strength, it is harder to compare due to high dispersion, which could indicate some dependence on the type of test performed, the compression data being the better to fit or test the available numerical or analytical models for predicting strength. This better fit for the compressive test could be explained considering the large thickness compared with the other coupons, thus diminishing the role of bonding or layer imperfections. Available models for predicting strength as in eq 8 overestimate by a factor of 2, in mean, the strength of fused filament-fabricated honeycombs. Given a quantitative description of the stiffness and strength of additive manufactured LS, we can discuss the density-dependent features for failure behavior.
Tensile and compressive behavior under different relative densities for square, triangular, and honeycomb LS is studied in this paper. We perform the tensile tests on three types of coupons: type A has the advantage that the LS is visible; however, for determining the effective properties of the lattice, we should remove the effect of the solid end parts. As with type A, the stiffness of type B tensile tests needs to be corrected because of top and roof layer influence. In contrast, this correction is much simpler than for type A. Compression tests (type C) are most suitable for studying AM LSs. They present lower scattering in the results, probably due to the high number of layers compared to the tensile test.

Three models for characterizing three common LSs are compared: square, honeycomb, and triangular. The finite element model accurately describes the experimental results, with an error of 6.7% for the stiffness, compared to Gibson–Ashby 12.7% or ROM model 25.3%. However, when analyzing the behavior of more complex parts with infill lattice structures, it is possible to use the numerical expressions given in this work, provided that they can reduce the computational cost of modeling the complete lattice and maintaining good accuracy. The already known Gibson–Ashby formulation is a good fit with experimental data. However, care should be taken if it is applied to high relative density values. The ROM has the problem of being independent of the geometry of the specimen but can be helpful to provide upper bounds of the mechanical response.

The failure process of PLA is dependent on the nature of the applied force. For example, compressive samples fail mainly due to plastic yielding, which in grid infills were from buckling of plastic hinges located at the vertices of horizontal bands, honeycomb structures fail in diagonal bands, and triangular lattice cells tend to buckle if loaded in their stiffer direction. Also, it is known that triangular lattices are stronger than square lattices for the same relative density. However, here, we observe the contrary behavior, possibly due to the effect of stress concentrations in the struts union and the alignment of the extruder can have preferable directions in which defects can be lower, thus making square lattice stronger.

This work did not consider the effects of defects in manufacturing. However, we could observe interlayer issues, retracements due to the low feed rate, and geometrical imperfections in some specimens. Despite the manufacturing defects, the model presented here could be used with fair accuracy to predict stiffness, making the compressive tests most robust in this aspect.

## 5. EXPERIMENTAL SETUP

A suitable design is a factorial design with two factors: pattern relative density and pattern type. The factorial design uses different levels for the factors, three qualitative levels for the infill type, and quantitative levels for the relative density values. Finally, to decrease the error and the model deviation, a minimum of three valid samples were evaluated. Notice that it is not possible to generate a uniform density value among all types due to manufacturing constraints. These constraints refer to extruder sensibility, minimum possible feature size, time, and cost of printing samples.

The test coupons are fabricated in a Geetech A10 FFF 3D, with the software Cura Ultimaker for the G-code generation. The specimens are made of PLA thermoplastic provided by MADLAB manufacturer in white color, with a layer thickness of 0.2 mm, a maximum feed rate of 30 mm/s in the contour, and 60 mm/s in the infill. Tensile and compressive tests are performed in an MTS Bionix universal testing machine 370.02 based on the ASTM D638 standard. The dimensions of the specimens are presented in Figure 11. Three types of coupons were evaluated: type A, tensile coupon with the lattice in the narrow section of the specimen across the thickness and the gripping area cross section is solid, it has a thickness of 2 mm; type B, tensile coupon with top and bottom solid layer, filled with the LS in the core, and with the exact outer dimensions as type A except for a higher thickness of 3.2 mm; finally, type C is a compressive coupon of dimensions $S_{o}$ of 25 mm minimum and a height of 5 cells minimum and a thickness of $S_{t}$. The loading stagespeed was 1.2 mm/min; the in-place LVDT displacement sensor and a mechanical extensometer are used.
Figure 11. Geometry of the three test specimens: (a) type A tensile test, (b) type B tensile test, (c) compression lattice test honeycomb.

to perform the displacement measurement. Figure 12 shows the setup.

Figure 12. Experimental setup for (a) tensile and (b) compressive test.

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Notes
The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

The authors acknowledge the support given by project Convocatoria Interna VIE 2522 and PhD grant from Universidad Industrial de Santander. Authors acknowledge the support of Tecnoparque Nodo Bucaramanga for the help in fabricating the 3d samples and “Ensayos mecánicos” laboratory for the tensile and compressive tests.

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