A Study on the Evaluation of the Compression Behavior of PLA Lattice Structures Manufactured by FDM

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ABSTRACT

The paper brings forward the results of a study on the compression test of 28 lattice structures made of PLA by FDM, with the height of the deposited layer at a pass of Hs = 0.20 mm and 50% filling percentage Pu. The 28 samples were made on Anycubic 4 Max Pro 2.0 the 3D printer, considering 7 filling patterns: Grid, Tri-hexagon, Octet, Triangles, Cubic subdivision, Gyroid, and Cross 3D for each type of lattice structure. The dimensions of the specimens, before and after the compression test, were determined using the DeMeet 3D coordinate measuring machine. In this context, a minimum printing accuracy value of 98.98% and a maximum deformation value of 57.70% were recorded for the lattice structure corresponding to the Triangles fill pattern. For the same Triangles type lattice structure, the highest average maximum compressive force of 87.32 kN was obtained. The maximization of the ratio between the use value and the production cost, one of the fundamental technical-economic principles of value analysis, was obtained for the lattice structure corresponding to the Cubic subdivision filling model.

Keywords -FDM; PLA; lattice structure; infill pattern; slicer; compression; experimental tests; value analysis

I. INTRODUCTION

In the last 30 years, additive manufacturing technologies have continuously evolved and have been embraced by numerous industries [1-2]. The interest was sparked by the advantages they have in comparison to the conventional formative and subtractive technologies [13-17]. The main advantages of additive manufacturing technologies are: low manufacturing costs, short time for landmark making, control over the way the parts are made (adjustment of process parameters), making complex geometries without designing the base and fixing landmark, and the amount of technological waste is insignificant [4]. The optimization of printing parameters is an important criterion as they have a direct impact on the mechanical characteristics of the produced landmark.

Authors in [5] presented the results of the compression test of some Ti6Al4V lattice structures, manufactured by SLM additive technology. In [6], the influence of the filling pattern on the mechanical characteristics of the samples manufactured by DLP additive technology was studied, the best results being obtained for the Gyroid filling pattern. In [7], the influence of the variable parameters, Hs - the height of the layer deposited in one pass and Pu - the filling percentage, on the compression behavior of the samples manufactured by FDM additive technology, from PLA, ABS and thermally treated PLA, was studied. The authors' conclusion is that with a decrease in the height of the layer deposited at a pass (Hs), an increase in the compression stress is recorded.

In this context, the compression behavior of 21 lattice structures (specimens) manufactured of PLA by FDM will be evaluated, using the constant parameters from Table I, with 3 pieces for each of the 7 filling models: Grid, Tri-hexagon, Octet, Triangles, Cubic subdivision, Gyroid, Cross 3D. The accuracy of FDM printing and the maximum compressive strain value of the lattice structures, before and after the compression test, will be determined by measuring them in the Z plane. Using the experimental data and the fundamental principle of value analysis to maximize the ratio of utility value and the production cost [8-11] of all the analyzed filling patterns, we will establish the optimal option from a technical and economic point of view for the manufacture of compression-resistant lattice structures from PLA by FDM.

II. DESIGN, FABRICATION, MEASUREMENT, AND COMPRESSION TESTING OF LATTICE STRUCTURES

The 3D model of the specimen (lattice structure) was designed in SolidWorks 2023 [19] and has the dimensions shown in Figure 1. The 3D model of the sample was converted to *.STL format. In order to set the printing parameters presented in Table I the Cura slicer [18] was used.

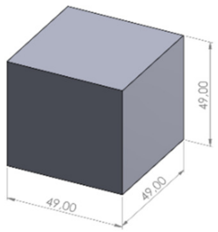


Fig. 1. 3D model of the specimen for the compression test.

TABLE I. FDM PRINTING OF PLA LATTICE STRUCTURES PARAMETERS

<table>
<tr><th>Constant parameters</th><th>Filling pattern</th><th>Printed parts</th><th>Mass of the piece</th></tr>
<tr><td rowspan="8">Piece orientation, X - Y

Extruder temperature, T_e = 200 °C

Table temperature, T_b = 60 °C

Print speed, V_p = 40 mm/s

Height of the deposited layer, H_s = 0.20 mm

Fill percentage, P_u = 50%

Wall thickness, W_t = 0.80 mm</td><td>-</td><td>(Items)</td><td>(Kg)</td></tr>
<tr><td>Grid</td><td rowspan="7">4</td><td>0.069</td></tr>
<tr><td>Tri-hexagon</td><td>0.038</td></tr>
<tr><td>Octet</td><td>0.069</td></tr>
<tr><td>Triangles</td><td>0.069</td></tr>
<tr><td>Cubic subdivision</td><td>0.069</td></tr>
<tr><td>Gyroid</td><td>0.069</td></tr>
<tr><td>Cross 3D</td><td>0.052</td></tr>
</table>

Figure 2 shows the filling models used for the FDM fabrication of the specimens (lattice shells) from PLA. The 3D printer - Anycubic 4 Max Pro 2.0 (Figure 3) was used to make the lattice structures. It has a printing volume of 270×210×190 mm and uses additive FDM technology. The semifinished product used for FDM manufacturing of lattice structures is PLA filament with 1.75 mm diameter (Filafill). With the 3D printer in Figure 3, using the constant parameters from Table I, we made 28 lattice structures, sets of 4 for each 7 filling patterns, as shown in Figure 2. The 28 lattice structures were measured in the Z plane using the DeMeet 3D machine (Figure 5(a)). The data are centralized in Table III.

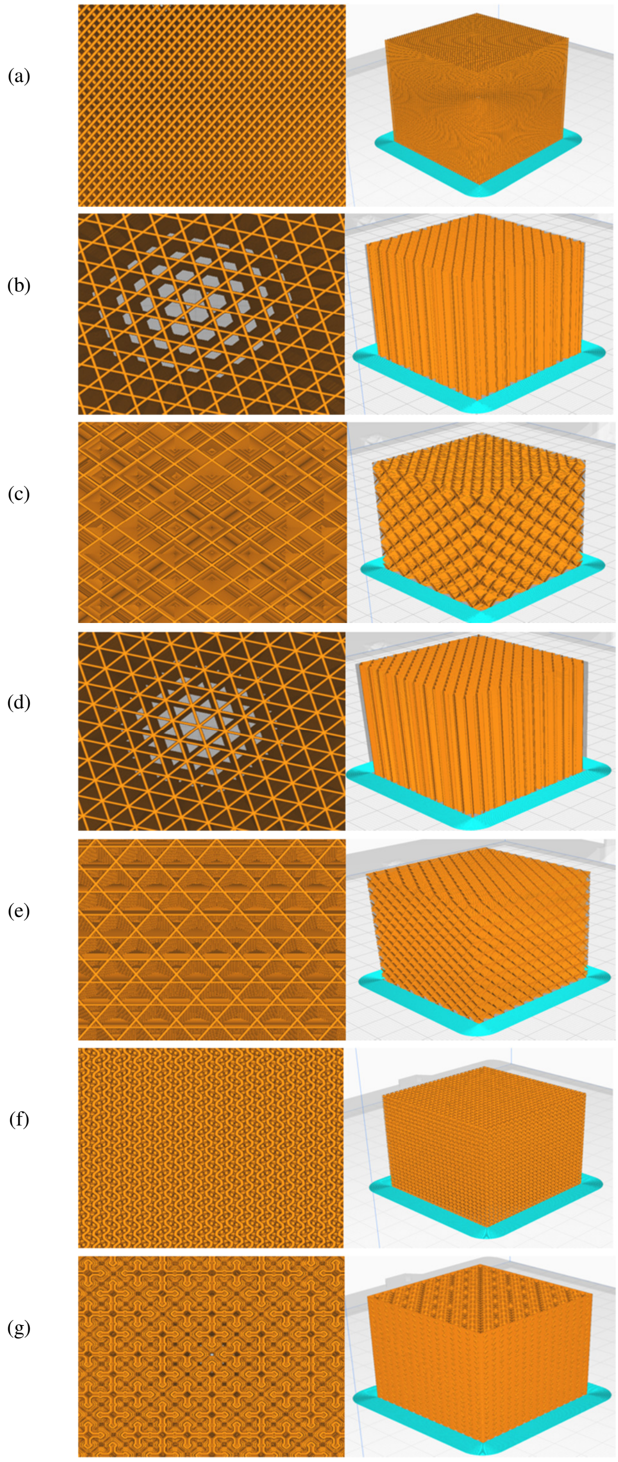


Fig. 2. Filling patterns used for the manufacture of lattice structures from PLA by FDM: (a) Grid, (b) Tri-hexagon, (c) Octet, (d) Triangles, (e) Cubic subdivision, (f) Gyroid, (g) Cross 3D.

We tested 21 of the constructed items for compression on a Microcomputer controlled electronic Universal Testing Machine (UTM) - TIME WDW-300M series 0306. The compression Tests (Figure 4) were performed according to the ISO 604:2002 standard, at a speed of 5 mm/min [20].

Fig. 3. The Anycubic 4 Max Pro 2.0 3D printer, used to manufacture the lattice structures from PLA through FDM.

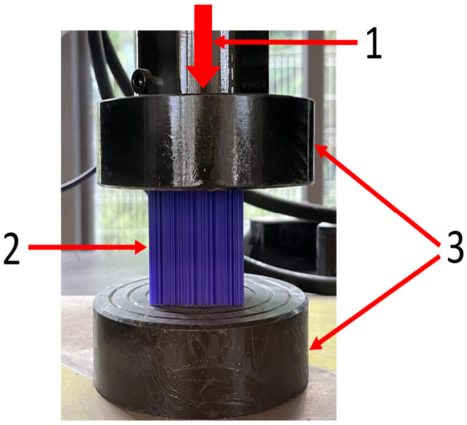
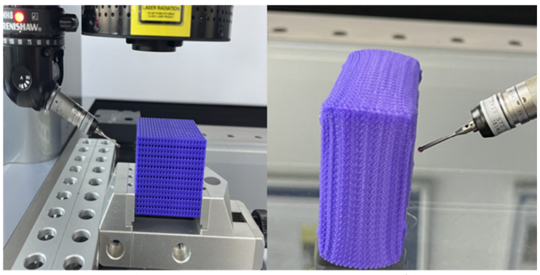


Fig. 4. Compression test of the lattice structure made of PLA by FDM. 1: loading direction, 2: sample, 3: the platens of the UTM.

After the compression test, the 21 lattice structures were measured in the Z plane using the DeMeet 3D machine (Figure 5(b)). The data are shown in Table III.



(a) (b)

Fig. 5. Determining the dimensions of the lattice structure made of PLA by FDM, with the coordinate measuring machine - DeMeet 3D: (a) before and (b) after the compression test.

III. RESULTS AND DISCUSSION

A. Compression Testing

The results of the compression test of the 21 lattice structures are shown in Table II and are graphically represented in Figures 6-12.

TABLE II. COMPRESSION TEST RESULTS OF THE LATTICE STRUCTURES MADE OF PLA BY FDM

Filling pattern	Maximum compressive force, Fmc, (kN) Sample			Average maximum compressive force, MFmc, (kN)
	1	2	3	
Grid	87.4	86.2	86.68	86.76
Tri-hexagon	19.33	19.06	19.32	19.24
Octet	53.31	53.48	52.60	53.13
Triangles	87.62	87.02	87.32	87.32
Cubic subdivision	54.83	53.21	55.98	54.67
Gyroid	64.79	63.63	64.99	64.47
Cross 3D	23.04	20.9	19.36	21.01

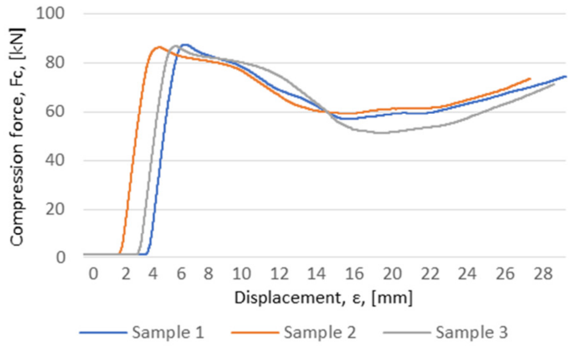


Fig. 6. Compression tests graphs of the lattice structures made of PLA by FDM, Grid filling pattern.

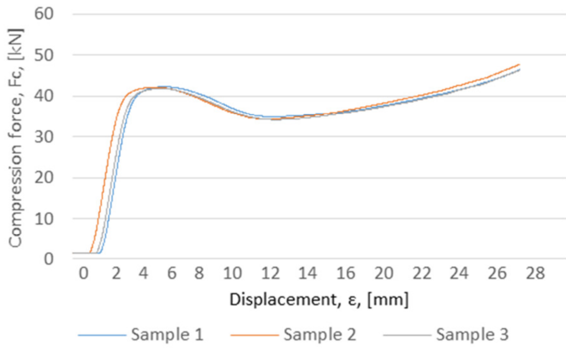


Fig. 7. Compression tests graphs of the lattice structures made of PLA by FDM, Tri-hexagon filling pattern.

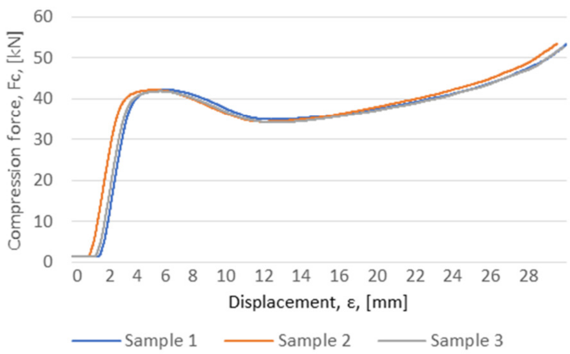


Fig. 8. Compression tests graphs of the lattice structures made of PLA by FDM, Octet filling pattern.

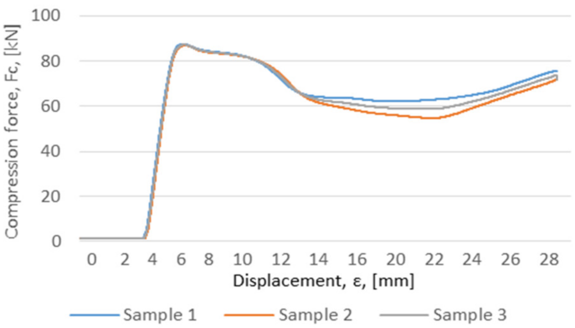


Fig. 9. Compression tests graphs of the lattice structures made of PLA by FDM, Triangles filling pattern.

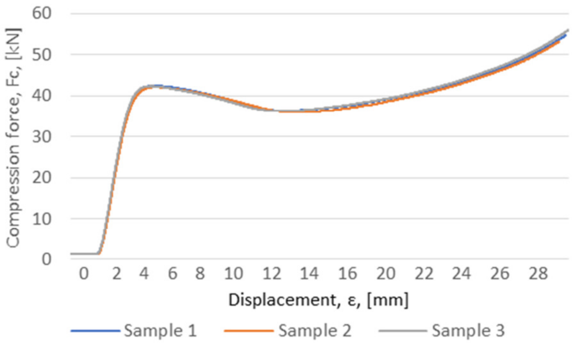


Fig. 10. Compression tests graphs of the lattice structures made of PLA by FDM, Cubic subdivision filling pattern.

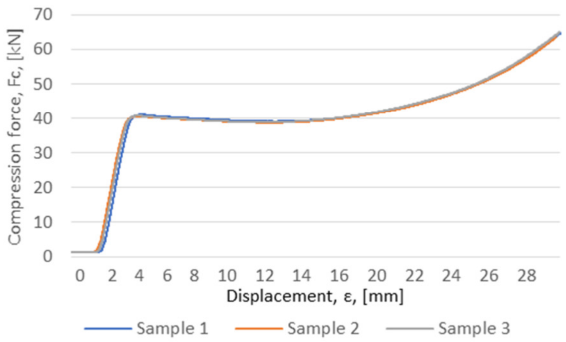


Fig. 11. Compression tests graphs of the lattice structures made of PLA by FDM, Gyroid filling pattern.

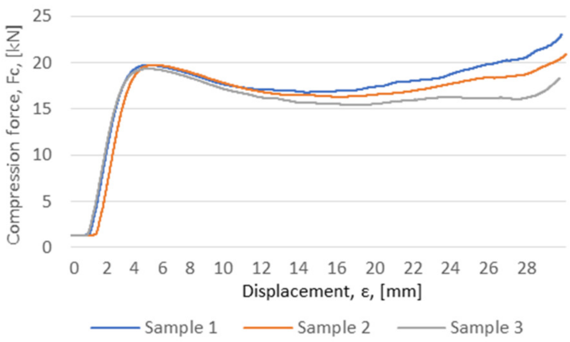


Fig. 12. Compression tests graphs of the lattice structures made of PLA by FDM, Cross 3D filling pattern.

Figure 13 shows the average values of the maximum compression forces (Table II) for the 7 filling patterns used for the fabrication of the lattice structures of PLA by FDM.

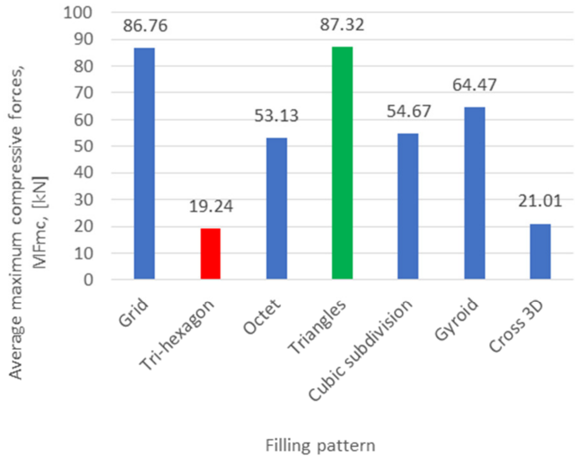


Fig. 13. Average maximum compressive forces for each filling pattern of lattice structures made of PLA by FDM.

It can be observed that the average values of the maximum compression forces for the 7 filling models fall range between 19.24 and 87.34 kN. The highest average value of the maximum compressive forces is 87.32 kN and was obtained for the Triangles lattice structure.

B. Determination of FDM 3D Printing Accuracy and Compressive Strain of the PLA Lattice Structures

All the 28 lattice structures made of PLA by FDM (Figure 2) on the Anycubic 4 Max Pro 2.0 3D printer (Figure 3) were measured in the Z plane using the DeMeet 3D machine (Figure 5(a)). Twenty one of the samples were measured in the same plane and with the same machine after being tested in compression (Figure 5(b)). The average values of the heights of the lattice structures made of PLA by FDM, calculated for each of the filling patterns of Figure 2, before and after their compression test, are shown in Table III.

TABLE III. ACCURACY OF FDM 3D PRINTING AND COMPRESSIVE DEFORMATION OF PLA LATTICE STRUCTURES

Filling pattern	**The average height of lattice structure, (mm)**		**Printing accuracy 3D, (%)**	**Compression strain, (%)**
	Before compression	**After compression**		
Grid	48.79	27.50	99.61	55.55
Tri-hexagon	48.50	27.98	99.57	56.36
Octet	48.76	27.14	99.78	54.04
Triangles	48.89	26.42	98.98	57.70
Cubic subdivision	48.83	27.14	99.41	56.76
Gyroid	48.81	27.11	99.51	55.67
Cross 3D	48.71	27.65	99.65	55.86

The values corresponding to the 3D printing accuracy for the 7 filling patterns range from 98.98 to 99.78 %, the maximum value of the accuracy being determined for the case of the Octet type filling pattern.

The values of compression range from 54.04 to 57.70 %, the maximum value of the deformation being determined for the case of the Triangles filling pattern.

At a variation between 0.11 and 1.02 % of the 3D printing accuracy, a variation of 3.66 % of the compression strain was obtained.

C. Setting the Optimal Option from a Technical and Economic Point of View for the Manufacture of Compression-resistant Lattice Structures of PLA by FDM

Using the fundamental principle of analyzing the maximization value of the ratio between the use value *Vi* and the production cost *Cp* [8-12] we identified the optimal filling pattern from the technical and economic point of view as to manufacture compression-resistant lattice structures of PLA by FDM:

$$\frac{V_i}{C_p} \rightarrow max. \quad (1)$$

In this study, the use value depends on the lattice structure density, which is calculated by:

$$\rho = \frac{m}{v}, \quad (2)$$

where m represents the mass of the lattice structure (sample) and v is its volume.

The volume of the lattice structure (sample) with L=49 mm (Figure 1) is:

$$V = L^3 = 118 \times 10^{-6} \text{m}^3. \quad (3)$$

To calculate the production cost, we used the relation:

$$C_p = C_{mat} \times P_m + T_e \times C_{en} \times P_{en}, \quad (4)$$

where C_p represents the production cost, C_{mat} is the material consumption, P_m is the material price (26 euro/kg), T_e is the execution time, C_{en} is the energy consumption (0.23 kWh), and P_{en} is the electricity price (0 .26 euros/kWh).

Table IV shows the results of the performed calculations using (1)-(4), for the 7 filling models used in the manufacture of lattice structures from PLA by FDM, to determine the values of the V_i/C_p ratio.

Figure 14 uses the values of the V_i/C_p ratios shown in Table IV and the 7 filling patterns used for the manufacture of the lattice structures of PLA by FDM (Figure 2).

TABLE IV. V_i/C_P RATIO DETERMINATION

Filling pattern	Density, $\rho = V_i$	Manufacturing time, T_e	Production cost, C_p	$\frac{V_i}{C_p}$
	kg/m^3	ore	euro	kg/(m^3 × euro)
Grid	584.75	5.40	2.12	276.22
Tri-hexagon	322.03	5.37	1.31	246.03
Octet	584.75	5.41	2.12	276.15
Triangles	584.75	5.50	2.12	275.45
Cubic subdivision	584.75	3.35	1.99	293.20
Gyroid	584.75	9.47	2.36	247.76
Cross 3D	440.68	7.33	1.79	246.12

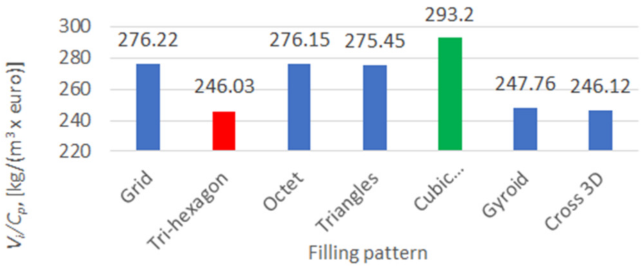


Fig. 14. Values of the V_i/C_p ratio for each filling pattern of lattice structures made of PLA by FDM.

In Figure 14, we notice that the maximum value of the V_i/C_p ratio is 293.20 kg/(m^3 × euro) and was obtained for the case of the Cubic subdivision filling pattern. This is the optimal option from the technical and economic point of view for PLA manufacturing by FDM of compression-resistant lattice structures.

IV. CONCLUSIONS

- The accuracy of FDM fabrication of PLA lattice structures on the Anycubic 4 Max Pro 2.03D printer, using the constant parameters shown in Table I for the 7 filling patterns shown in Figure 2 is very good (Table III), and ranges between 98.98 and 99.78 %, with the maximum value of the precision determined for the case of the Octet type filling pattern.
- The maximum value of compressive strain of 57.70 % was determined for the Triangles filling pattern. The values of the compression strains for the 7 filling patterns used in the FDM fabrication of the lattice structures range from 54.04 to 57.70 %.
- The maximum compression force values were obtained from the Triangles type (Figure 13). In this case, an average of the maximum compression forces of 87.32 kN was obtained (Table II). In [6], the Gyroid type was considered as the proper choice due to its good mechanical resistance. Taking in consideration the mechanical proprieties of pieces made by FDM from PLA, Gyroid it is a good solution, but we have better options like Triangles and Grid (see Table II).
- From the technical-economic point of view, the optimal solution to manufacture compression-resistant lattice structures from PLA by FDM is the Cubic subdivision type, for which the highest value of the ratio between the use value ($V_i = \rho$) and the production cost was obtained (C_p).

The results of the current study can be widely used in different contexts using other process parameters, other materials, and/or other types of mechanical tests.

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