Compressive Strength of 3D Fabricated Parts: Experimental and Numerical Studies

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Abstract **– Additively manufactured (AM) parts have mechanical properties that differ from the ones of the traditionally manufactured parts. The difference in the mechanical properties is due to the AM's specific working manner of adding the material in layers. By consulting the available literature on this matter, it is concluded that most of the research papers are concerning the tensile strength of the parts leaving only a small number of papers dealing with the compressive strength of the parts. The aim of the paper is to make contribution in this particular research area. As an AM process we are using the fused filament fabrication (FFF) process and polylactic acid (PLA) material. The study also explores the influence of the infill pattern on the compressive stress of the parts. Samples are designed and tested according to the ISO 604 standard. Three samples size 25x25x25 mm were tested on SHIMADZU AG-X 250 kN for the experimental study and in LS-Dyna and HypeMesh for the numerical study. Results showed correlation between the results in the experimental and numerical study. Lowest values for the compressive strength were achieved by the concentric infill samples. This is one addition in the studies correlating the process parameters to the mechanical properties.**

These types of studies are valuable input in the design process and material selection process for a particular application.

Keywords **– Fused filament fabrication (FFF), compressive strength, infill pattern, experimental analysis and numerical analysis.**

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1. Introduction

Main advantage of the additive manufacturing (AM) technologies is that the parts are fabricated directly from the CAD (Computer Aided Design) model without the need of any additional tools or process planning [1].

Additional advantage is that parts are built by adding the material in layers which allows fabrication of complex shapes. This working process is identical for all the processes that fall under the AM. In this paper we are focusing on the material extrusion process or Fused Filament Fabrication (FFF) process. Parts with FFF are built by extrusion of molten thermoplastic though a nozzle [1]. This is one of the widely used AM processes, mainly due to the affordable open-source machines. A comparison of a professional FDM (Fused Depition Modeling) machine and an open-source machine was conducted in study [2]. Their results suggest that professional FDM offers significantly better quality, but it is important to stress that their study is based on a fairly complex part [2]. In reality open-source machines have gotten better over the time and now they can be used in demanding applications. Parts fabricated with FFF are mainly used for functional parts or prototypes, where the mechanical properties are of high importance rather than for appearance prototypes. The process itself as well as the process parameters heavily influence the mechanical properties of the parts. Papers published over the last decade are analyzing the tensile and flexural properties of the part. Not many papers concerning the compression strength of the parts are published. Variation in the used materials is also influencing the mechanical properties and therefore is element that researchers are exploring.

Djokikj *et al.* [3] compared three different polymers (PC - polycarbonate, PETG – polyethylene terephthalate glycol, PLA – polylactic acid) in their studies. According to their results, PC specimens have the highest values for the UTS (ultimate tensile stress), right before PLA and PETG specimens. Regarding the maximum flexural stress, the highest values are achieved by the PLA specimens. The mechanical properties of different PLA manufacturers are compared whose results show that even samples with same material (PLA) can have variable mechanical properties regarding the manufacturer [14], [4]. This is important input in the material selection process for a specific application.

In [5] ABS parts are examined regarding the compressive strength. They were interested in the influence of the part orientation during fabrication, and the conclusion is that parts fabricated in horizontal orientation provide higher compressive strength. Hernandez *et al*. confirmed these findings [6]. Liu *et al*. [7] study the compressive strength of a carbon fiber-reinforced nylon material by varying the infill parameters. The conclusion is that parts with triangle infill have the highest compressive strength. Chin *et al.* [8] analyzes the connection between the material and the compression properties of parts fabricated with FFF. According to their study, the parts fabricated with PCL (Polycaprolactone) have the highest compressive strength. In [9] they investigate the part positioning on the compressive strength. The result of the study suggests that depositing layers perpendicular to the build plate is the optimal position for achieving high compressive strength. Lee *et al.* [10] also examined the part positioning and came to the same conclusion as [9]. [11] analyzed the connection between the compressive strength of ABS fabricated parts and the process parameters. According to their study, best results can be achieved with lower layer thickness and higher air gap. Mishra and colleagues [12] investigated also the impact of process parameters on compression strength of the fabricated parts. In [13] different processing parameters are studied for ULTEM 9085 parts. Their study shows that parts positioned horizontally on the build plate achieve higher values for the compressive strength. Jami *et al.* [14] compared compressive strength on ABS and PC parts and established that PC parts have better results. In their study they confirmed that process parameter as well as the infill percentage has significant influence. Dave *et al.* [15] analyzed the compressive strength of PLA parts by varying the infill percentage, layer thickness, and print speed showing that the compressive strength is influenced by the infill density. Parnet *et al.* [16] analyzed the effect of the infill pattern and percentage on the compressive strength.

They analyzed fourteen different infill patterns and concluded that 2D patterns with higher infill percentage presented better results [16].

2. Experimental Analysis

With this paper we wanted to examine the influence of the infill pattern on the compressive strength of FFF fabricated parts. We analyzed four different infill patterns (grid, concentric, triangles, and trihexagon). We are aware that for best results of the mechanical properties the parts should be solid but we wanted to analyze the parts as they are usually build with 20% infill. Also the influence of the pattern cannot be analyzed with infill of 100%.

2.1. Material

Polylactic acid (PLA) is used for the fabrication of the samples. This material is most common when working on an open-source machine. Also it has better printing quality that the acrylonitrile butadiene styrene (ABS) since the ABS has higher melting temperature.

Table 1. Process parameters during fabrication

Parameter	Value
Nozzle	0.4 mm
Layer thickness	0.2 mm
Orientation	x-y
Infill percentage	20
Infill pattern	grid, concentric, triangles, trihexagon

2.2. Sample Design

Samples were designed according to the ISO 604 with dimensions 25x25x25 mm [18]. Samples were designed in SolidWorks as simple solid cubes, and then in the slicer the appropriate infill was chosen.

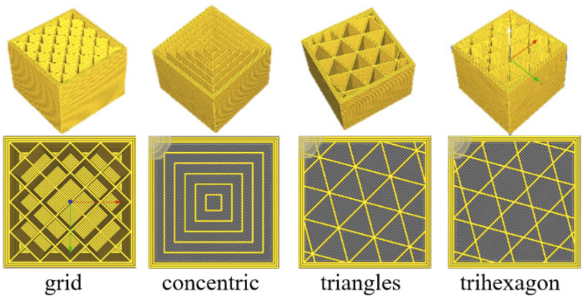

Figure 1. Infill patterns used in the study

2.3. Fabrication

For fabrication, samples were prepared in the Ultimaker Cura slicer according to the process parameters presented in Table 1. All the process parameters are same for the samples, only the infill pattern is changing (Fig. 1).

According to the ISO 604 standard three samples are fabricated from each infill pattern. During the fabrication all the samples are positioned in the centre of the build plate with x-y orientation, offering optimal quality of the fabricated parts. For the fabrication we used Crealty Ender 3 machine.

2.4. Experiment

For the experimental analysis SHIMADZU AG-X machine was used. The machine has a testing capacity of up to 250kN and travel speed from 0.0005 to 500mm/min. It is controlled through a special program, TRAPEZIUM X, where the machine is set up and the necessary information is filled in for the sample that will be tested. Through the TRAPEZIUM X program, the force-elongation diagram is obtained, which provides an overview of the relationship between the force and the elongations caused by it. All samples were tested with the same speed of movement of the plate, which is 5mm/min.

3. Numerical Analysis

Along with the experimental study we conducted a numerical study in order to compare the results. Numerical analysis for AM fabricated parts is challenge since the parts are not solid but rather porous with anisotropy.

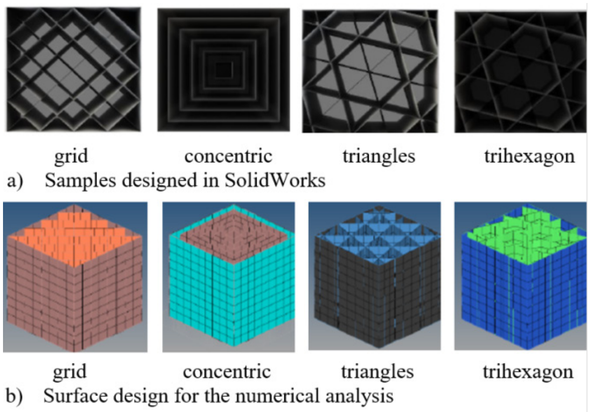

Figure 2. Samples used in the study

For the numerical analysis samples were designed in SolidWorks as surface models taken into consideration the infill pattern with dimensions 25x25x25mm (Fig. 2a). The numerical analysis is conducted in HyperMesh. Models designed in SolidWorks as surface were modified by adding thickness to the walls same as the one in the fabrication parameters (top and bottom 0.6 mm, shell 1.2 mm and infill 0.4 mm). LS-Dyna program was used for the simulation. Once the simulation is complete the results can be loaded into the HyperView program.

For the analysis mesh with rectangular elements is chosen. The size of the elements differs in different samples: 2.5 in the samples with grid and triangle infill, 1.5 in the sample with concentric infill and 2.6 in the sample with trihexagon infill.

During the analysis, the material MAT_24 from the library of materials in LS-DYNA was used, named *MAT_PIECEWISE_LINEAR_PLASTICITY for the samples and the material MAT_20 as *MAT_RIGID was selected for the plate that presses the cubes. Material characteristics are shown below in Figure 3. The MAT_24 material has an elastic-plastic characteristics with an uninformed stress versus strain curve and a uniform strain rate. Figure 3 shows selected materials in LS-DYNA for the PLA plastic in the HyperMesh program. Choosing the right material for the numerical analysis is crucial in order to get reliable results from it.

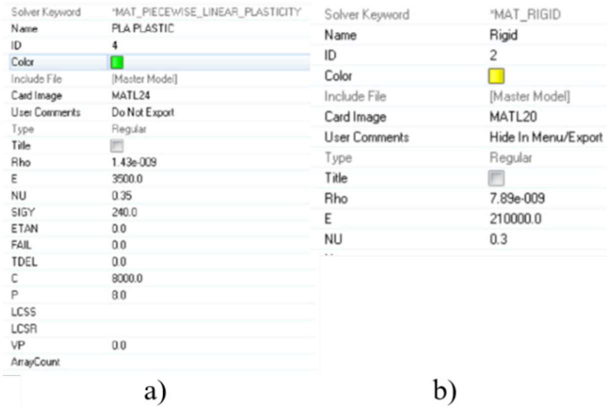

Figure 3. Definition of the material in LS-DYNA

All models have the same contacts. One of the contacts is between the base and the bottom of the cube, and the other contact is between the cube and the plate acting on it (Fig. 4).

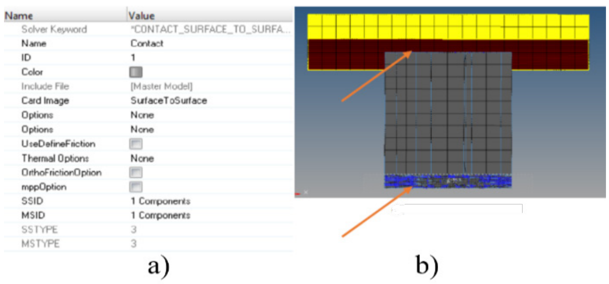

Figure 4. Defining the contacts for the numerical analysis

4. Results

Results from the experimental and numerical analysis are presented below. In the experimental study, force-displacement and stress-displacement diagrams of all the samples are presented and discussed. In the numerical study comparison of the achieved force and stress values is presented.

4.1. Experimental Study

As stated before for the experiment ISO 604 standard was consulted. The results on the cubes from the experiments are presented in Fig. 5 and graphical representation of the force-displacement and stress-displacement diagrams are presented in Fig. 6 and 7. From the Figure 5 it can be seen that grid, triangle and thixehagon have significant plastic deformation. The concentric infill presented best results.

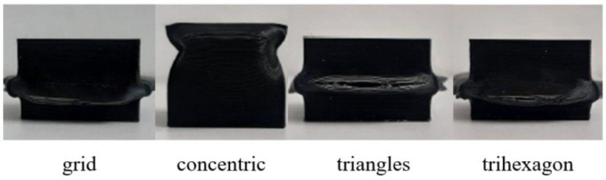

Figure 5. Tested samples

Maximum force for the samples with concentric infill is 6. 11 kN (Fig. 6), at a displacement of 2.58 mm. The maximum stress achieved is 9.8 N/mm^2 (Fig. 7). For the samples with grid infill, maximum force is 10.77 kN (Fig. 6), at a displacement of 2.17 mm, and the maximum stress is 17.3 N/mm^2 (Fig. 7).

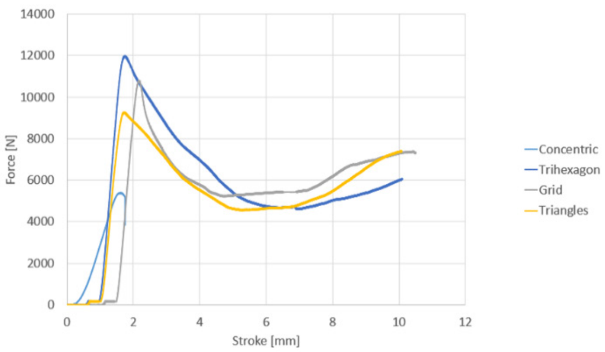

Figure 6. Force – displacement diagram for the tested samples

For the samples with triangle infill maximum force is 9.25 kN (Fig. 6), at a displacement of 1.73 mm, and the maximum stress is 14.4 N/mm2 (Fig. 7). In the case of trihexagon infill samples, maximum force is 11.85 KN (Fig. 6), at a displacement of 1.64 mm, and the maximum stress is 18.9 N/mm2 (Fig. 7).

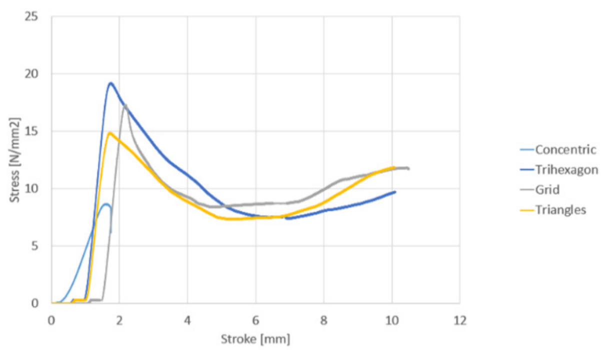

Figure 7. Stress – displacement diagram for the tested samples

We conducted also a comparison between the results of the each three samples for all the infill options (Fig. 8). Samples show low variations, which is caused by the lack of repeatability of the open-source FFF machines. According to the results, it can be concluded that the 3D printed samples have the greatest durability when using trihexagonal infill while samples with concentric infill are the weakest.

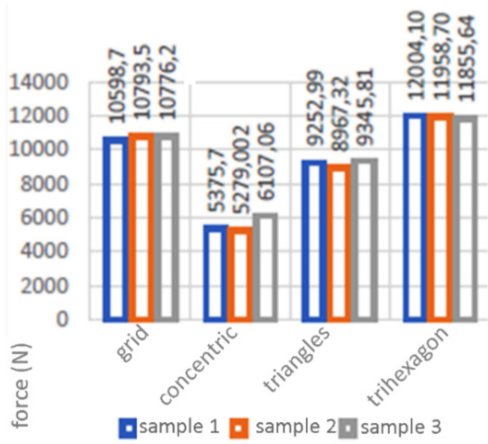

Figure 8. Comparison of the achieved force values for the tested samples

Having the values of the maximum stress of all the samples compared, it is evident that samples with trihexagon infill proved to be the strongest, i.e. have the greatest durability (Fig. 9). Whereas the samples with concentric infill show lowest durability.

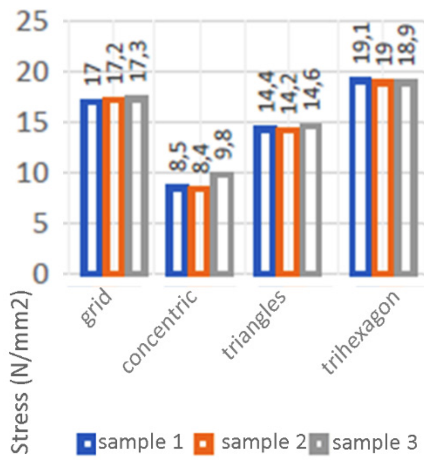

Figure 9. Comparison of the achieved stress values for the tested samples

4.2. Numerical Study

From the conducted numerical study, it can be concluded that samples with grid, triangular, and trihexagonal infill have approximately the same strength of about 1000 N (Fig. 10). The sample with concentric infill has significantly lower values, which can be caused by the difference in the design of the 3D model and the fabricated part.

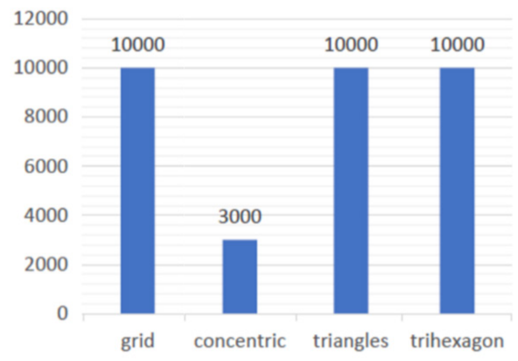

Figure 10. Results for the force achieved for every samples

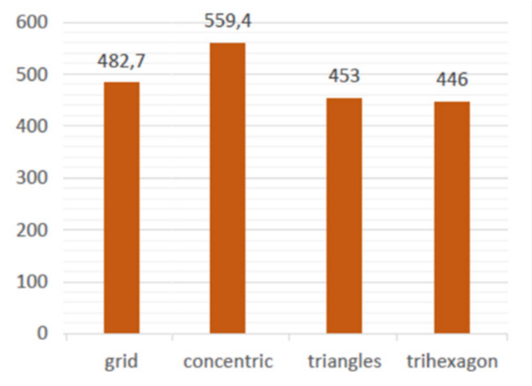

Figure 11. Comparison for the stress achieved for every sample

On the other hand the results for the maximum obtained stress show that highest values are achieved in the samples with concentric infill. Among all the other samples, results are pretty close.

5. Discussion

Having the results from the experimental and numerical study compared, difference in the stress values is noticeable especially in the samples with concentric infill. This is caused by the anisotropy and porosity of the fabricated parts. Also a discrepancy in the results is expected due to the fact that the print layers are not homogeny as the 3D model.

Table 2. Comparison of the results for maximum force

Infill pattern	Experimental analysis			Numerical
	Sample 1	Sample 2	Sample 3	FEA sample
concentric	5.4 kN	5.28 kN	6.1 kN	3 kN
grid	10.6 kN	10.8 kN	10.7 kN	10 kN
triangles	9.2 kN	8.9 kN	9.3 kN	10 kN
trihexagon	12 kN	11.9kN	11.8 kN	10 kN

However in the values for achieved force the results are better (Tab. 2).

Here it can be noted that trihexagon, triangle, and grid are pretty similar in the results among the fabricated samples but also compared to the FEA sample. However, there is difference among the fabricated samples with concentric infill and the FEA sample. That can be due to the fact that during the modelling of the infill complete similarity could not be achieved. The samples with concentric infill have maximum force lower for 6 kN than the samples with trihexagon infill.

6. Conclusion

The study in this paper represents the comparison between different infill patterns on the compressive strength of samples fabricated with PLA through process of FFF. During the analysis only the infill pattern differs, and all the other process parameters (material type, infill density, layer thickness) are kept constant. The infill pattern is analyzed through its compressive strength according to the standard examination procedure directed by ISO 604. With the experimental tests of four types of pattern, it was concluded that the trihexagonal pattern gives the highest compression resistance compared to the others. It can be also said that the compression strength of the trihexagonal, grid, and trigonal samples is significantly higher that the samples with concentric infill. The low values for the concentric infill are caused due to the absence of the connections between the adjacent walls. All other patterns have interconnected walls, ensuring stiffer structure.

Additionally, numerical study was conducted whose results differ from the experimental study, as it was expected due to the specific working manner of FFF. However, except in the case of the concentric infill, the results were on the same trajectory. We can say that with further adjustments, numerical study can be recommended for future research.

This study is conducted in order to determine the most appropriate infill for different applications. According to the results, the thihexagon infill is recommended for parts that need to withstand higher pressure and forces although grid and triangle infill do not fall behind. In the case of concentric infill, it is recommended to be used for flexible parts.

For further research, it is planned to test different machines and materials. Therefore, we can compare the results from this study in order to provide more general conclusions.

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