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STUDY OF SELECTED MECHANICAL PARAMETERS OF STRUCTURES PRINTED USING FDM TECHNOLOGY

FDM (Fused Deposition Modeling) technology, initially used to create prototype models, has gained importance in the serial production of structural elements in various fields of engineering. In this paper, the influence of the internal structure and infill density on the strength properties of samples printed using FDM technology was analyzed. Static tensile tests were performed on samples made of ABS (acrylonitrile butadiene styrene) and PA6+CF15 (polyamide reinforced with 15% carbon fibre) materials, with different filling levels: 25%, 50%, 75% and 100%, using two internal structures – linear and honeycomb. The experimental results were verified by numerical analysis. The obtained results allow for a better understanding of the relationships between printing parameters and the mechanical characteristics of printed elements, maximum strength and material consumption efficiency.

Keywords: FDM technology; 3D printing; ABS filament; strength tests; numerical analysis

1. Introduction

3D printing technology is widely used in the process of producing prototype elements. An example of such use can be the alternative method of stiffening cold-formed profiles made using 3D printing technology, developed by the authors of this article [1]. However, their use in engineering structures requires knowledge of the mechanical parameters of the materials from which these elements are made. It is optimal to use materials with high mechanical strength, but this is associated with a higher cost of both the material itself and the printing process.

Commonly used filaments in FDM (Fused Deposition Modeling) technology, such as ABS (acrylonitrile butadiene styrene), are characterized by ease of printing and low cost. On the other hand, filaments based on nylon reinforced with cut carbon fiber PA6+CF15 (polyamide reinforced with carbon fiber in the amount of 15% of the filament weight) are characterized by increased mechanical strength. However, compared to standard filaments such as ABS, carbon fiber-reinforced materials are more expensive and the printing process itself is more demanding. Printing with filament reinforced with cut carbon fiber also requires the use of 3D printers equipped with heads adapted to processing abrasive materials and resistance to higher temperatures.

The article presents the results of tests on mechanical parameters of samples manufactured using FDM technology from ABS and PA6+CF15 filaments. The research included static tensile tests performed on samples with a defined internal structure and different filling densities. Two filling structures were used in the tests: linear and honeycomb, at four filling density levels: 25%, 50%, 75% and 100%. Analysis of different structures and filling levels allowed for the assessment of their influence on strength properties and material efficiency.

A numerical analysis of the static tensile test was also performed. It takes into account the nonlinear state, which allows for a more accurate representation of the actual working conditions of materials and verification with experimental tests. The analysis used material parameters obtained from experimental tests, which were converted into real curves. The use of numerical methods combined with physical tests enables the assessment of the mechanical properties of printed elements and the optimization of the printing process in terms of its efficiency.

2. Static tensile test of ABS and PLA CF filament

The materials used for the tests were ABS (acrylonitrile butadiene styrene) and PA6+CF15 (polyamide with carbon

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fiber admixture). ABS is a material obtained in the process of polymerization of 1,3-butadiene and copolymerization of acrylonitrile with styrene with simultaneous grafting of the resulting copolymer onto polybutadiene [2,3]. It is characterized by high impact strength, hardness and scratch resistance. It also shows satisfactory resistance to alkalis, diluted acids, aliphatic hydrocarbons, oils and fats. However, it is not very resistant to acids, esters and ketones. PA6+CF is a modified polyamide enriched with carbon fiber, which improves its stiffness, tensile strength and resistance to deformation. Its disadvantage is greater brittleness and more difficult processing compared to ABS [4,5].

The samples were printed using FDM technology on an OMNI 200 CF printer using "Spectrum Premium Filament for 3D Printing" filaments with a diameter of 1.75 mm. The density of the ABS filament was 1.04 g/cm^3, while that of PA6+CF15 was 1.25 g/cm^3. The basic printer settings were: head temperature of 236°C for ABS and 280°C for PA6+CF15, bed temperature of 70°C for ABS and 100°C for PA6+CF15 and printing speed of 60 mm/s.

All shapes were modeled in AutoCAD and saved as an STL file to create machine code supported by the Slicer program. The main task of 3D printing is to transform the model prepared in the Slicer program into a physical object [6]. The test samples were made of 0.2 mm thick layers. The outer part forms a closed shell composed of a lower and upper part and walls in which the supporting structure is filled. In the case of printing the research shapes, the lower and upper parts consisted of 3 layers of 0.6 mm thickness, while the walls were built of 2 outlines of 0.4 mm thickness. The structure of the internal part was selected from the Slicer library. A linear and honeycomb pattern was used to construct the test samples (Fig. 1).

Models with 100% fill or completely empty are rarely printed. The fill densities of the samples tested were 25, 50, 75 and 100%.Wherein 100% infill corresponds to the structure of linear printing. Line fill is one of the basic patterns created by a grid of lines printed in one direction on one layer, and the lines of the next layer are rotated by 90° (Fig. 1a). This type of infill allows for quick printing and lower filament consumption compared to honeycomb. The honeycomb-based filling structure consists of octagons (Fig. 1b). Printing with this infill takes longer and causes greater filament consumption.

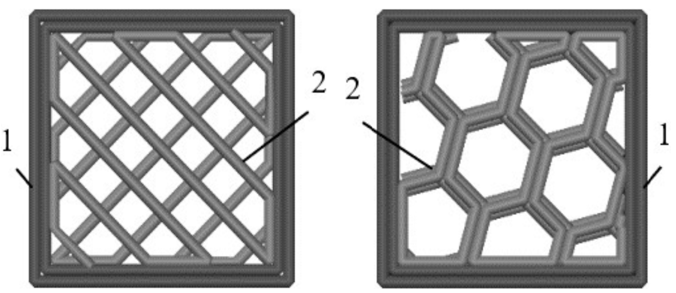

Fig. 1. View of the walls and filling with a density of 25% on the example of cubes intended for compression tests (1 – line creating the outline of the wall, 2 – line creating the structure: a) linear structure, b) honeycomb structure

The static tensile test was performed on a single-column SHIMADZU testing machine model EZ-LX with a maximum load of 5 kN (Fig. 2).

Fig. 2. SHIMADZU testing machine with recording equipment used for tensile testing

The static tensile test was performed using the standard PN-EN ISO 527 Plastics – Determination of mechanical properties by static tension – Part 2: Test conditions for plastics intended for various moulding techniques [7]. The tests were performed on three samples for each adopted structure and filling degree. The sample dimensions are shown in Fig. 3. The samples were clamped in the machine and stretched at a speed of 2 mm/min. During the test, the tensile force and displacement were recorded.

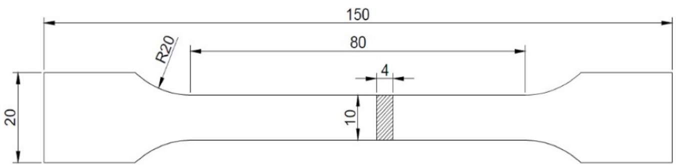

Fig. 3. Sample for static tensile strength tests (dimensions in millimetres) according to PN-EN ISO 527 [7]

3. Analysis and research results

Figs. 4-7 show the tensile force as a function of displacement depending on the filling degree (25%, 50%, 75% and 100%) and the internal structure – honeycomb and linear. The graphs with continuous lines represent samples made of PA6+CF15 filament, while the dashed line corresponds to samples made of ABS filament. The tests were performed on three samples for each adopted structure and filling degree, which are described in the graphs as test 1, test 2 and test 3. The honeycomb structure samples (Figs. 4a, 5a, 6a) show lower stiffness in the initial loading phase compared to the linear structure samples (Figs. 4b, 5b, 6b, 7b). A higher slope of the graphs for linear filling indicates greater resistance to deformation, resulting in higher stiffness. The PA6+CF15 filament is characterized by higher tensile strength than ABS, but its breakage occurs without a clear deformation boundary, in a more sudden manner. ABS samples, unlike PA6+CF15 samples, show greater ductility, which means that after reaching the maximum tensile force, the displacement increases without an increase in force. Increasing the degree of filling leads to increased stiffness and maximum force value.

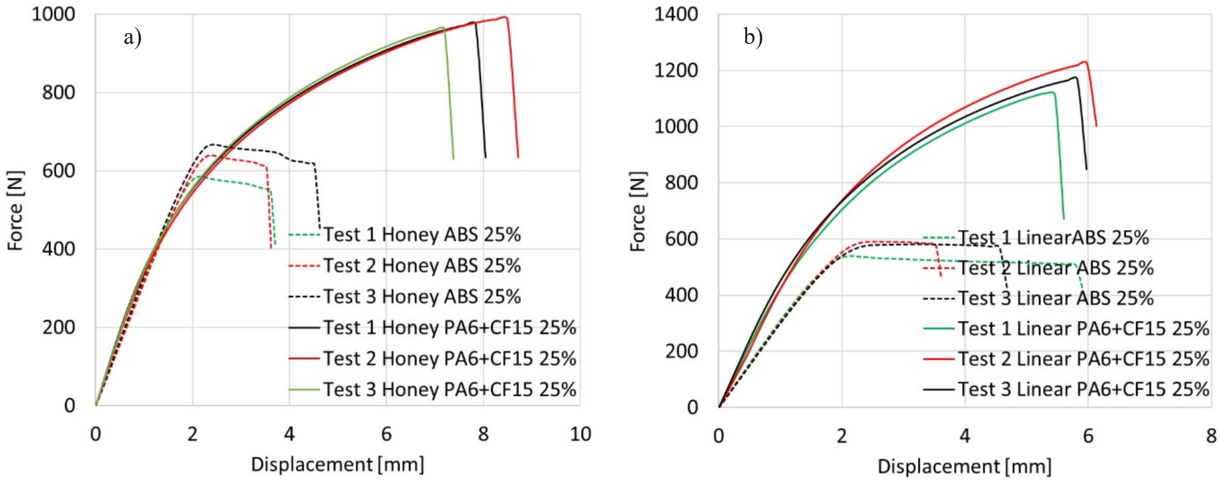

Fig. 4. Force-displacement graphs of samples made of ABS and PA6+CF15 filament with an infill density of 25% and the infill structure: a) honeycomb, b) linear

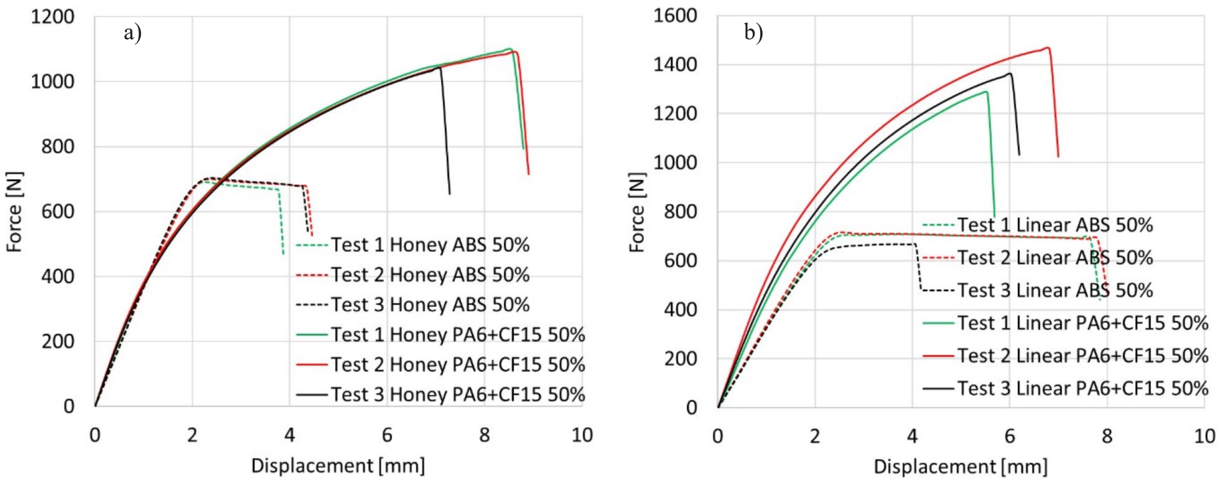

Fig. 5. Force-displacement graph of samples made of ABS and PA6+CF15 filament with 50% fill density and the following fill structure: a) honeycomb, b) linear

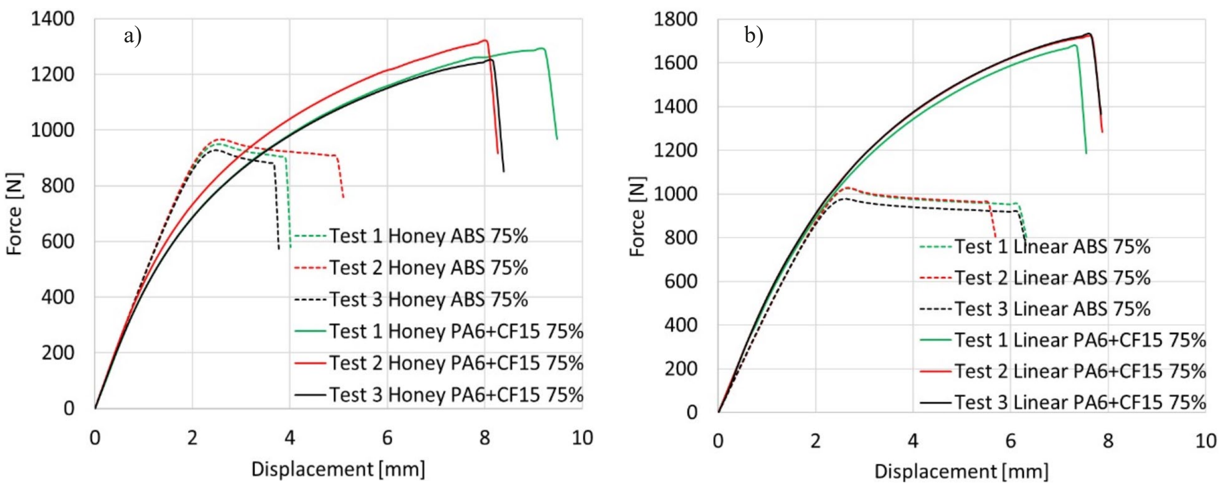

Fig. 6. Force-displacement graph of samples made of ABS and PA6+CF15 filament with an infill density of 75% and the infill structure: a) honeycomb, b) linear

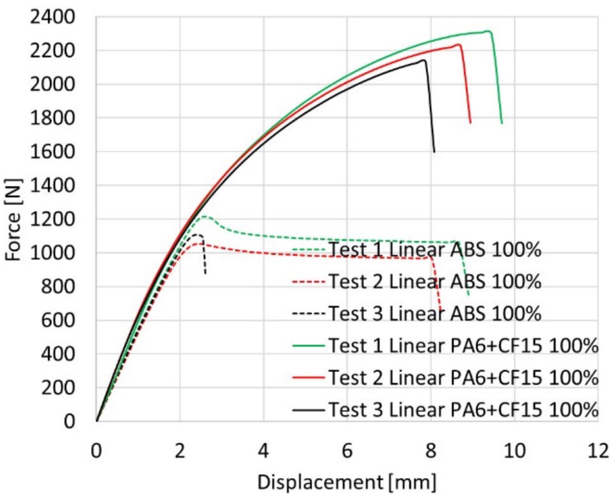

Fig. 7. Force-displacement graph of samples made of ABS and PA6+CF15 filament with 100% fill density and fill structure honeycomb and linear

TABLES 2 and 3 present the tensile strength (Rm) for samples with different filling levels and structures. The highest tensile strength is achieved by samples made of PA6+CF15 filament with linear filling and 100% density, whose average maximum force is 2219.95 N. In the case of ABS, the maximum strength was also achieved when fully filled, reaching a value of 1126.23 N. For the same PA6+CF15 filling, CF shows more than twice the strength of ABS. The lowest tensile strength was demonstrated by samples with honeycomb filling and 25% density – this value is 975.31 N for PA6+CF15 and 630.96 N for ABS. Comparing the analyzed filling structures, it can be seen that for lower densities (25% and 50%) the strength of the linear structure is higher than that of the honeycomb, however, for densities of 75% and 100% the differences between them decrease. When analyzing the standard deviations, the greatest dispersion of results concerns samples with full linear filling (PLA CF: 86.42 N, ABS: 82.98 N). In turn, the smallest standard deviation (6.66 N) was obtained for ABS with honeycomb filling and 50% density, which indicates a greater homogeneity of the results in this category.

4. Validation of research results using numerical analysis

In order to validate the experimental results, numerical analysis was performed in Ansys Workbench 21R [8,9]. The simulations were performed in the nonlinear range, and the material data used in the calculations came directly from the laboratory tests. Based on the obtained results, real curves were developed for numerical analysis, which were used to represent the actual behaviour of materials subjected to tension [10,11]. Comparison of experimental and simulation results showed good agreement of the force versus displacement curve (Figs. 8-10). The best convergence of results was obtained for samples with a honeycomb structure (Fig. 8). In the linear structure, larger deviations are visible, especially in the final loading phase (Figs. 9 and 10), which may be due to the influence of local structural irregularities and non-linear phenomena, which were more difficult to accurately represent in the numerical model. Due to excessively long calculation times and numerical difficulties, the analysis for a filling density of 75% was not performed.

TABLE 1

Tensile strength of linearly filled samples

Filament type and fill rate [%]	Test 1 Rm_1 [N]	Test 2 Rm_2 [N]	Test 3 Rm_3 [N]	Average Rm [N]	Standard deviation Rm [N]
ABS [25%]	539.77	591.28	581.88	570.98	27.43
PA6+CF15 [25%]	1119.83	1227.40	1170.13	1172.45	53.82
ABS [50%]	707.91	716.59	667.63	697.38	26.13
PA6+CF15 [50%]	1285.77	1460.98	1358.43	1368.39	88.03
ABS [75%]	1026.75	1029.08	977.56	1011.13	29.10
PA6+CF15 [75%]	1671.14	1717.14	1724.42	1704.23	28.89
ABS 100 [100%]	1216.866	1053.997	1107.822	1126.23	82.98
PA6+CF15 [100%]	2304.35	2223.86	2131.64	2219.95	86.42

TABLE 2

Tensile strength of honeycomb filled samples

Filament type and fill rate [%]	Test 1 Rm_1 [N]	Test 2 Rm_2 [N]	Test 3 Rm_3 [N]	Average Rm [N]	Standard deviation Rm [N]
ABS [25%]	585.78	639.26	667.85	630.96	41.66
PA6+CF15 [25%]	975.13	987.93	962.86	975.31	12.54
ABS [50%]	690.60	699.25	703.70	697.85	6.66
PA6+CF15 [50%]	1094.36	1086.37	1039.16	1073.30	29.83
ABS [75%]	949.28	967.46	929.05	948.60	19.22
PA6+CF15 [75%]	1285.05	1315.80	1246.28	1282.38	34.84

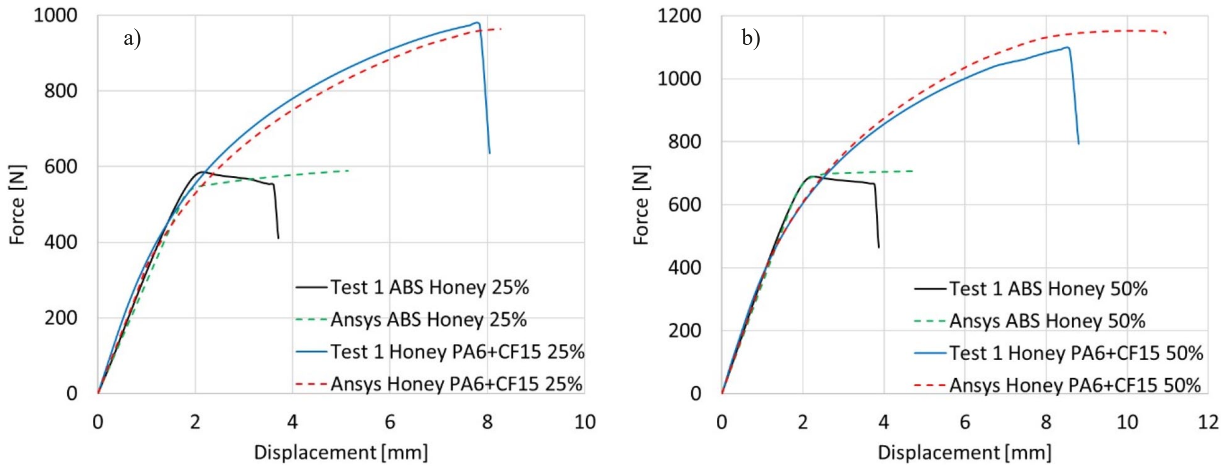

Fig. 8. Comparison of the force-displacement curves of the experimental samples with the numerical model: a) honeycomb structure 25%, b) honeycomb structure 50%

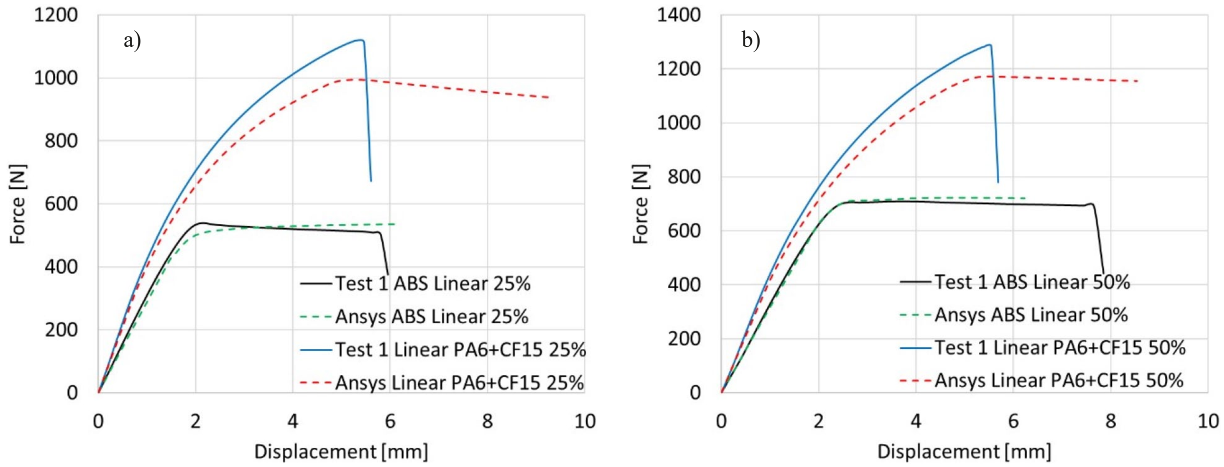

Fig. 9. Comparison of the force-displacement curves of the experimental samples with the numerical model: a) 25% linear structure, b) 50% linear structure

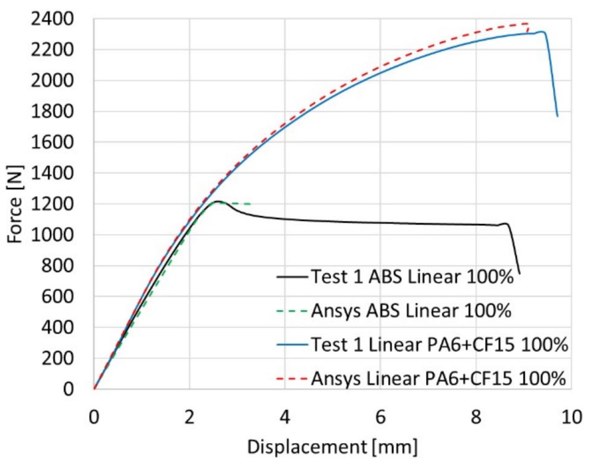

Fig. 10. Comparison of the force-displacement curves of the experimental samples with the numerical model – 100% linear structure

5. Summary and conclusions

3D printing technology offers a wide range of possibilities for producing non-series and prototype elements, but requires conscious selection of printing parameters and materials, which directly affect the durability of the finished model. The results of the conducted research on the static tensile test of samples made of ABS and PA6+CF15 filaments provide information for designers and engineers involved in the optimization of mechanical properties of 3D prints.

The conducted experiments show that the tensile strength of samples with a low degree of filling (25% and 50%) is relatively low, being about 15% of the value obtained for full filling. In the case of higher density (75% and 100%) the strength increases almost twice as much as in samples with a less dense internal structure. Analysis of the results showed that the carbon fiber content in the PA6+CF15 filament increases the stiffness and tensile strength compared to the ABS filament samples. The internal structure has a significant influence on the mechanical properties of the samples. The linear filling is characterized by better strength parameters compared to the honeycomb.

Additionally, the numerical analysis performed in Ansys Workbench 21R confirmed the general relationships obtained in experimental studies. The largest differences between experiment and simulation were observed for low fillings (25% and 50%)

and in the final stages of deformation, which may be due to difficulties in modeling nonlinear effects. The numerical analysis well reproduced the mechanical behavior of the samples, which confirms its usefulness in the design process.

In summary, for models with low strength requirements, an infill of 25-50% is optimal, which reduces printing time and costs. In the case of elements that must be characterized by high strength, it is necessary to use an infill of 75-100%. When selecting printing parameters, the designer should take into account the nature of the model's operation, expected loads and economic aspects in order to achieve an optimal balance between the durability and efficiency of the printing process.

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