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## TENSILE BEHAVIOUR OF PLA PARTS MANUFACTURED BY FDM: EFFECT OF INTERNAL DENSITY AND RASTER CONFIGURATION

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**Abstract:** This paper investigates the influence of infill percentage and pattern on the tensile behavior of PLA specimens manufactured using Fused Deposition Modelling (FDM). The main objective was to examine how internal structure design affects strength, stiffness, and deformation under applied load. Tensile experiments were conducted in accordance with ISO 527-1, employing an Artillery Genius-Pro 3D printer and a Zwick/Roell Z150 testing machine. The results demonstrate that increasing infill density leads to a substantial enhancement in tensile strength and stiffness, whereas grid and honeycomb arrangements demonstrated the most efficient internal geometries. The findings of this research provide valuable insight into the way infill strategy influences the structural behavior of FDM-printed PLA components, supporting further advancements in the design of lightweight and high-performance parts for engineering applications.

**Key words:** PLA specimens, FDM, infill density, infill pattern, tensile strength, additive manufacturing.

### 1. INTRODUCTION

In recent years, engineering production has increasingly shifted toward layer-based fabrication methods, where components are generated directly from digital files without conventional tooling. This approach enables highly complex geometries while reducing raw material consumption. Within additive techniques, FDM stands out due to its accessible equipment, relatively low operational costs, and compatibility with numerous thermoplastic polymers. [1], [2].

The mechanical behavior of components produced by FDM remains highly dependent on several printing parameters that control the material deposition process, including layer height, raster orientation, printing speed, and infill strategy [3].

Within these parameters, the infill percentage and pattern represent two of the most influential factors governing the stiffness, strength, and failure mode of printed parts [4]. The internal architecture of a printed component not only determines its load-bearing capability but also its overall weight and material efficiency. Previous investigations have analyzed the

impact of internal geometry modifications on the tensile and flexural behavior of thermoplastic materials, including PLA (polylactic acid) and ABS (acrylonitrile butadiene styrene), highlighting the compromise between structural performance and manufacturing efficiency. [5], [6].

Polylactic acid (PLA) remains one of the preferred materials for FDM, primarily because it prints reliably, maintains dimensional accuracy, and originates from renewable resources [7]. Despite these advantages, its mechanical reliability can be compromised by process-induced anisotropy and the presence of internal voids resulting from the chosen infill configuration [8]. Consequently, optimizing the infill architecture is essential to achieve predictable and improved mechanical performance in both structural and functional components manufactured via FDM.

This work focuses on experimentally quantifying how variations in material volume fraction and internal raster geometry affect the tensile response of PLA components manufactured by FDM. Tensile tests were carried out according to ISO 527-1 to evaluate yield strength, elastic modulus, and strain at

break. The experimental results aim to deepen the understanding of the relationship between internal structure and overall mechanical performance, thereby contributing to the optimization of design parameters for lightweight yet mechanically efficient polymer components in additive manufacturing.

## 2. MATERIALS AND EQUIPMENT

The test samples were produced using PLA filament, a biodegradable thermoplastic widely utilized in FDM applications because of its stable printing behavior, dimensional accuracy, and reduced environmental impact [5], [7]. The PLA filament used in the experiments (3DKordo, Romania) had a nominal diameter of 1.75 mm with a  $\pm 0.03$  mm tolerance and a density of 1.24 g/cm<sup>3</sup>. According to the manufacturer's recommendations, the optimal extrusion temperature lies between 190°C and 220°C, while the build-plate temperature should be maintained within 50–60°C to promote proper adhesion and reduce the risk of warping.

The specimens were printed using an Artillery Genius-Pro 3D printer (Figure 1), equipped with a 0.4 mm brass extrusion nozzle and operating on a Cartesian coordinate motion system. The system provides a working envelope of 220 × 220 × 250 mm and utilizes a direct-drive extrusion mechanism to ensure accurate filament deposition and layer consistency. The printing paths were generated using Simplify3D slicing software, which produced G-code instructions while maintaining consistent process parameters across all samples. The printing speed was fixed at 60 mm/s, with a layer height of 0.3 mm and a rectilinear outer contour applied for all configurations.

Mechanical characterization in tension was conducted using a Zwick/Roell Z150 testing frame equipped with calibrated instrumentation. All tests were performed at room temperature with a constant crosshead speed of 0.5 mm/min, and a mechanical extensometer was employed to record specimen elongation with high accuracy. The machine's integrated testXpert II software was used for both data acquisition and analysis of the stress–strain curves.



Fig. 1. Artillery Genius-Pro 3D printer

All specimens were printed and tested under identical environmental conditions to ensure data reproducibility and comparability between samples. Prior to mechanical testing, the samples were equilibrated for 24 hours at  $23 \pm 2^\circ\text{C}$  and  $50 \pm 5\%$  relative humidity, in accordance with standard recommendations for thermoplastic testing [8].

## 3. PRINTING PARAMETERS

The experimental investigation focused on evaluating the influence of infill percentage and infill pattern on the tensile behavior of PLA specimens produced through FDM printing. To ensure consistent and reliable results, all other printing parameters, apart from the infill configuration, were kept constant throughout the fabrication process.

The infill percentage varied across five levels: 10%, 30%, 50%, 70%, and 100%, while six distinct infill patterns were selected for comparison, namely: rectilinear, grid, triangular, zigzag, fast honeycomb, and full honeycomb. These configurations were chosen because of their frequent use in engineering applications and the contrasting internal geometries they

create, which directly affect stress distribution and inter-layer bonding between adjacent filaments [4], [5].

Each specimen was designed in compliance with the geometry specified in ISO 527-2:2012 for tensile testing of thermoplastic materials, as illustrated in Figure 2. All specimens were printed in a horizontal (flat) orientation on the build plate, minimizing anisotropy effects caused by layer deposition and material flow direction [3], [6].

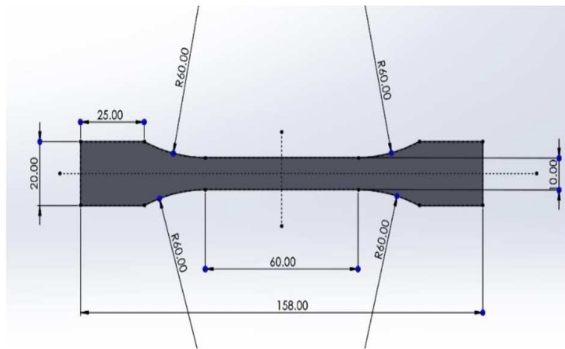


Fig. 2. The specimen geometry

Following fabrication, all printed specimens were carefully examined to verify dimensional accuracy and to ensure the absence of extrusion-related defects such as under-extrusion, delamination, or surface irregularities. The printed samples were properly labelled prior to mechanical testing. Representative specimens with different infill percentages and internal patterns are presented in Figures 3 and 4.



Fig. 3. PLA specimens with different infill percentages

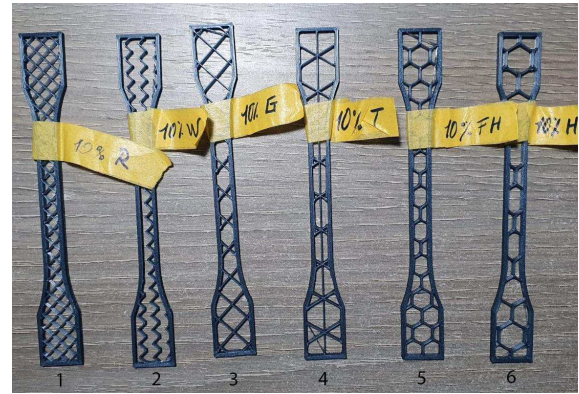


Fig. 4. PLA specimens with different infill patterns

The use of standardized geometries and controlled printing conditions ensured a high level of repeatability and reliability of the experimental data, thereby enabling an objective evaluation of how infill density and internal structural configuration influenced the mechanical behavior of PLA specimens.

#### 4. EXPERIMENTAL METHOD

The mechanical characterization of the printed specimens was carried out through uniaxial tensile testing, following the international standard ISO 527-1:2019. The aim of these tests was to evaluate the yield strength, elastic modulus, and strain at break of the PLA specimens manufactured with varying infill percentages and internal patterns.



Fig. 5. Tensile test specimen

All tensile measurements were conducted on a Zwick/Roell Z150 universal testing machine (Figure 5), equipped with a 150 kN load cell and a high-precision mechanical extensometer for accurate strain measurement. The crosshead speed was maintained at 0.5 mm/min, as recommended for rigid thermoplastics,

providing quasi-static loading conditions and reducing potential rate effects [8]. All tests were conducted under controlled laboratory conditions at ambient temperature.

For each configuration (infill percentage and pattern), five individual specimens were tested, and the average values were calculated and considered for subsequent analysis, thereby improving the statistical reliability of the results. The collected data were processed and compared to highlight differences in mechanical performance between the tested parameters. Representative stress–strain diagrams were generated to highlight the typical tensile behavior exhibited by the material.

## 5. RESULTS

### 5.1. Influence of infill density on tensile properties

Experimental data indicate that modifying the internal material fraction directly alters the tensile performance of the printed PLA specimens. Increasing the internal fill level from 10% up to full density resulted in a steady rise in both ultimate strength and stiffness, following an approximately linear trend. This trend reflects the increased material continuity and the reduction in void content within densely filled samples, which enhance load transfer between adjacent extruded filaments.

At an infill of 10%, the specimens exhibited relatively low tensile strength and pronounced ductile deformation prior to failure, attributed to the high proportion of air gaps within the internal structure. Increasing the infill to 50% resulted in a substantial improvement in stiffness and yield strength, as the internal walls began to distribute loads more evenly throughout the specimen. Fully solid specimens exhibited the maximum measured strength and elastic modulus among all configurations tested.

The improvement in stiffness with increasing infill percentage can be attributed to enhanced filament interconnection and a reduction in local stress concentrations within the solidified matrix. However, denser infill also led to lower ductility, suggesting a transition from a more ductile to a brittle fracture behavior. This trade-off should be considered when designing

lightweight structural components where both strength and flexibility are critical requirements.

A graphical representation of the obtained results is provided in Figures 6 and 7, illustrating the variation of tensile strength and elastic modulus as a function of infill density.

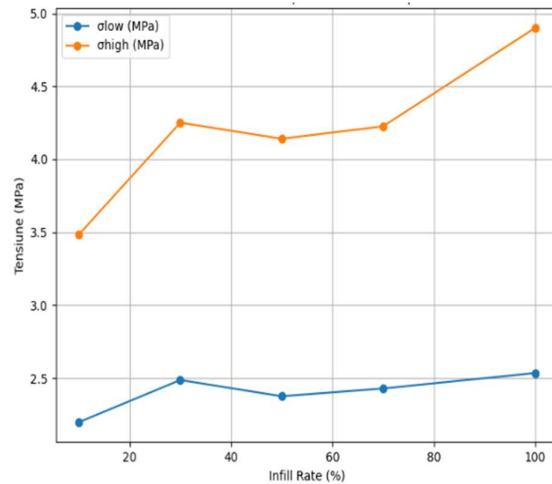


Fig. 6. Tensile strength as a function of infill percentage

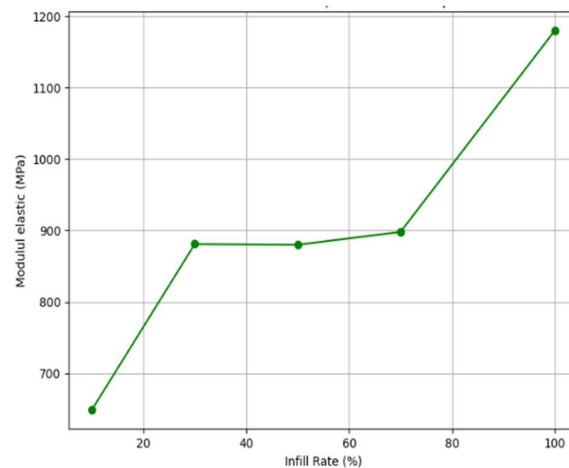


Fig. 7. Elastic modulus as a function of infill percentage

### 5.2. Influence of internal architecture on tensile properties

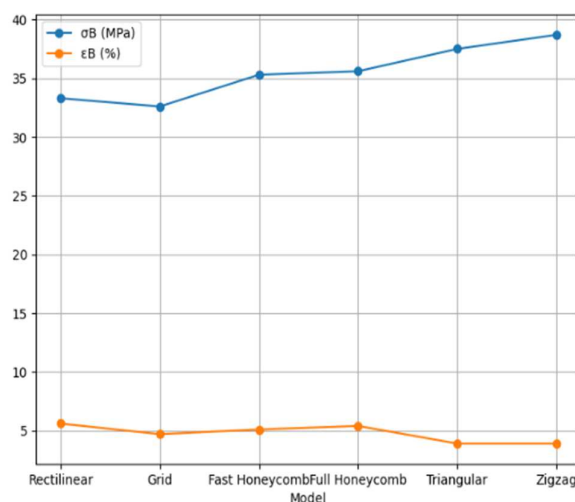
The effect of internal geometry was examined on specimens manufactured with a fixed infill density of 50%, while altering the internal configuration across six distinct patterns: rectilinear, grid, triangular, zigzag, fast honeycomb, and full honeycomb. The results revealed a strong dependence of mechanical

performance on the internal structure, even when the total material volume remained unchanged.

Among the tested geometries, the grid and full honeycomb patterns displayed superior mechanical behavior, reaching the highest tensile strength and stiffness values. These configurations promoted a more uniform stress distribution across the specimen cross-section and exhibited a progressive failure mode, enabling the material to absorb more energy before fracture. The fast honeycomb pattern also performed well overall, although it showed a slightly lower stiffness due to its larger cell size and thinner filament intersections.

In contrast, the rectilinear and triangular infill patterns produced lower tensile strength and higher strain at break, indicating premature failure along layer boundaries. These structures tend to concentrate stresses anisotropically, since the filament paths are mostly aligned along two orthogonal directions, reducing their ability to resist multi-axial loading.

Representative stress–strain curves for selected infill patterns are shown in Figure 8, highlighting the distinct mechanical responses and fracture behaviors observed among the different structures.



**Fig. 8.** Stress–strain curves for different infill patterns at 50% infill density

The experimental results confirm that both infill percentage and pattern play a crucial role in defining the overall mechanical behavior of FDM-printed PLA components. Increasing infill

density predominantly improves tensile strength and rigidity, while selecting an appropriate internal geometry enhances load distribution and energy dissipation.

The grid and full honeycomb configurations combine these advantages, resulting in parts that offer a balanced compromise between mechanical performance, stiffness, and weight efficiency. These patterns create continuous load paths throughout the component volume, effectively limiting the initiation of localized failures. Conversely, low-density or poorly interconnected architectures such as triangular or rectilinear patterns tend to exhibit stress concentrations and inter-layer delamination, which diminish their structural integrity.

## 6. CONCLUSIONS

The experimental program demonstrated that both internal material distribution and raster configuration significantly influence the tensile behavior of PLA components fabricated via FDM.

The study confirms that the distribution of material within the printed volume fundamentally governs the tensile performance of FDM-fabricated PLA parts. A progressive increase in internal density from sparse to fully solid structures led to higher tensile resistance and stiffness, primarily due to reduced void content and improved load transfer paths.

At the same time, higher infill densities led to a reduction in strain at break, suggesting that the material becomes less ductile and more prone to brittle fractures as more material is added. This finding emphasizes the importance of balancing stiffness and flexibility depending on the intended application.

The selected internal geometry significantly influenced stress distribution mechanisms within the printed structures. Among the patterns tested, grid and full honeycomb structures provided the highest strength and stiffness, allowing the components to bear greater loads and resist fracture longer. In contrast, rectilinear and triangular patterns showed weaker performance, mainly due to anisotropic stress concentrations and less effective bonding between filaments.

From a structural efficiency perspective, selecting an appropriate density level together with a load-distributing cellular geometry provides the most favorable compromise between weight reduction and mechanical integrity. These results confirm that careful design of internal architecture is crucial for enhancing the structural integrity and functional performance of polymer parts in additive manufacturing.

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## Comportamentul la tracțiune al epruvetelor din PLA fabricate prin tehnologia fdm: influența densității de umplere și a geometriei interne

**REZUMAT:** Această lucrare analizează influența diferitelor procente de umplere și a tipului de model de umplere asupra proprietăților mecanice ale epruvetelor din PLA fabricate prin tehnologia Fused Deposition Modeling (FDM). Obiectivul principal este de a determina modul în care structura internă afectează rezistența, rigiditatea și deformarea la solicitare. Testele de tracțiune au fost realizate conform standardului ISO 527-1, utilizând imprimanta Artillery Genius-Pro și mașina de testare Zwick/Roell Z150. Rezultatele arată că o densitate mai mare de umplere îmbunătățește semnificativ rezistența și rigiditatea, în timp ce modelele de tip rețea și fagure oferă cea mai eficientă geometrie internă. Acest studiu contribuie la o mai bună înțelegere a modului în care strategia de umplere influențează comportamentul structural al componentelor PLA obținute prin imprimare 3D FDM și sprijină dezvoltarea de piese ușoare și performante pentru aplicații inginerești.

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