The Effect of Deposition Orientation and Thickness on the Flexural Strength of PLA Plate Produced by 3D Printing

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Abstract: In this study, the influence of deposition orientation and specimen thickness on the flexural strength of 3D-printed polylactic acid (PLA) plates was examined. The samples were fabricated using the Fused Deposition Modeling (FDM) method with five deposition orientations—0–0, 0–90, 45–45, 90–90, and honeycomb—and two thicknesses of 3.2 mm and 6.4 mm. Flexural testing followed the ASTM D790-03 standard procedure. The results indicate that deposition orientation plays a decisive role in determining the mechanical response. Specimens printed at 0–0, where filaments run parallel to the loading axis, achieved the highest flexural strength (103.10 ± 6.29 MPa at 3.2 mm thickness), while honeycomb structures exhibited the lowest values (around 17.5 MPa). A two-way ANOVA confirmed a highly significant effect of deposition orientation on flexural strength ($p< 0.001$). Although the main effect of thickness alone was not statistically significant ($p = 0.153$), the interaction between orientation and thickness was significant ($p< 0.001$), suggesting that the impact of thickness depends on the printing direction. Post-hoc tests further showed that only the 0–0 and 90–90 orientations displayed meaningful differences between thickness levels. Overall, the findings highlight that the mechanical anisotropy of FDM-printed PLA is largely controlled by filament alignment and interlayer bonding. By selecting appropriate deposition orientation and part thickness, the flexural strength of printed PLA components can be notably improved, providing practical guidance for engineers in designing reliable, load-bearing 3D-printed parts.

Keywords: 3D printing, FDM, PLA, deposition orientation, specimen thickness, flexural strength.

I. INTRODUCTION

3D Printing is ones of additive manufacturing (AM) technologies, and in particular material extrusion methods such as fused deposition modelling (FDM), have become increasingly prevalent in both prototyping and low-volume manufacturing [1, 2].FDM offer flexibility, relative cost-effectiveness, and rapid turnaround times [3]. FDM processes typically involve extruding a thermoplastic filament layer-by-layer to build a three-dimensional object. Among commercially available polymers, polylactic acid (PLA) has emerged as one of the most widely used [4]. PLA has lower extrusion temperature compared to engineering plastics and offering a reasonable balance of stiffness and printability. PLA is also ones of biodegradable polymers which widely used as biomaterials [5, 6].

Nevertheless, parts produced via FDM often exhibit significant anisotropy [7] and mechanical-property variability due to the layered nature of the build. The mechanical performance of FDM-printed PLA parts therefore cannot simply be assumed to match that of solid PLA [8]. The mechanical properties depend on the presence of inter-layer voids, weak bonding, deposition orientation, process parameters such as layer thickness, infill density or pattern, build orientation, and thermal history.

The effect of internal geometry variation on the mechanical behavior of specimens produced by commercial 3D printers has been investigated [9]. The study shows that the mechanical properties is affected by infill geometries such as line and honeycomb patterns generated by varying slicing parameters. However, that study did not account for the influence of specimen thickness and deposition orientation, which are also known to significantly affect the mechanical strength and failure characteristics of printed components [10].

Further research focusing on the combined effects of infill structure and specimen thickness on the mechanical performance of 3D-printed materials is required. This paper aims to analyze the effect of deposition orientation and thickness variation on the flexural strengthof PLA specimens produced by FDM-based 3D printing. The findings are expected to provide valuable reference

data for improving the design and fabrication of 3D components, especially when optimizing structural strength and reliability in additively manufactured parts.

II. METHOD

The flexural test specimens were designed based on ASTM D790-03 standards for testing the flexural properties of unreinforced and reinforced plastics. Two thickness variations were prepared, 3.2 mm and 6.4 mm, while maintaining the overall specimen dimensions at 127 mm × 12.7 mm. The 3D geometries were modeled using Autodesk Inventor and subsequently exported in STL (Stereolithography) format, which is compatible with the slicing software used for FDM printing.

The STL files were processed using the Cura Engine slicer integrated within Repetier-Host software. During slicing, printing parameters such as layer height, infill density, infill pattern, and raster orientation were defined. For specimens with specific orientations (i.e., 0°–0° and 90°–90°), the G-code was manually edited to ensure that the layer-by-layer deposition path matched the desired orientation precisely. This step was crucial to accurately evaluate the influence of deposition direction on the flexural properties. The deposition orientation is shown in Figure 1.
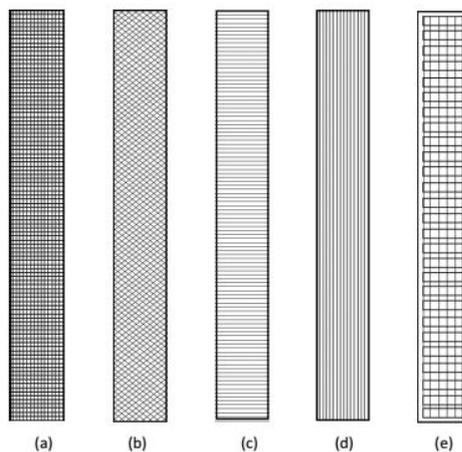

Figure 1: Deposition orientation. (a) 0-90, (b) 45-45, (c) 90-90, (d) 0-0, (e) honeycomb

All specimens were fabricated using a Fused Deposition Modelling (FDM) 3D printer operated via Repetier-Host. Commercial PLA filament (1.75 mm diameter) was used as the feedstock material. The nozzle temperature, bed temperature, printing speed, and extrusion flow rate were kept constant throughout all printing processes to minimize uncontrolled

variability. Each set of specimens was printed in triplicate to ensure statistical reliability and consistency of the results.

After printing, dimensional accuracy was verified using a digital caliper with ±0.01 mm resolution. The dimensions of each specimen were compared with the nominal values defined by ASTM D790-03. Only specimens with deviations less than 1% were considered acceptable for subsequent mechanical testing. This verification ensured that all samples met the standard requirements for flexural testing.

The three-point bending test was performed using a Universal Testing Machine (UTM) model GD-1100. Each specimen was placed on two supports, and a central loading nose applied the force at a constant crosshead speed appropriate to the specimen thickness as shown in Figure 2. The test setup was designed to determine the flexural strength of the printed PLA specimens. The span-to-depth ratio, loading rate, and environmental conditions were kept constant for all tests.

During testing, load–deflection data were automatically recorded by the UTM software. The maximum load and corresponding deflection values were used to calculate flexural strength and modulus using the standard ASTM equations. The results were statistically analyzed to evaluate the effect of deposition orientation and specimen thickness on the mechanical behavior of PLA. Additionally, the fracture surfaces of selected specimens were examined under optical magnification to qualitatively assess interlayer adhesion and failure mechanisms.
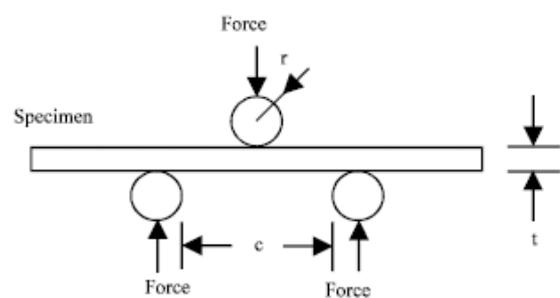

Figure 2: 3 Point bending test

III. RESULTS & DISCUSSION

The bending test results are shown in Table 1 and Figure 4. The results clearly indicate that deposition orientation has a significant effect on the flexural strength of 3D-printed PLA specimens. Specimens printed in the 0-0 orientation (where filament paths are parallel to the loading axis) exhibited the highest flexural strength for both thicknesses, reaching 103.10

MPa at 3.2 mm and 70.84 MPa at 6.4 mm. This orientation allows the applied bending load to act along the direction of continuous extruded filaments, thereby maximizing load transfer and minimizing inter-layer shear stress.

Table 1: Flexural Strength Test Results

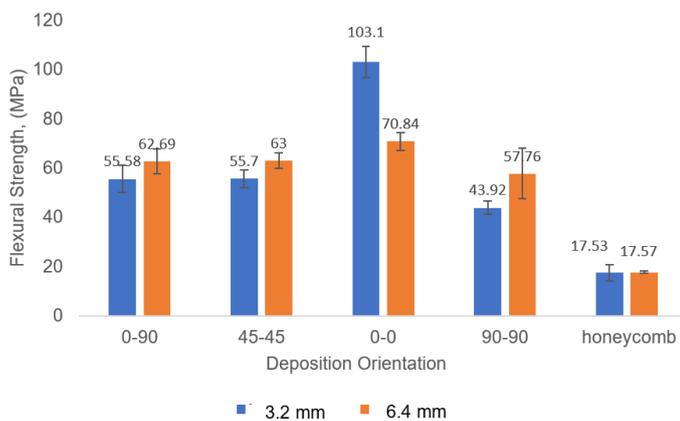| Deposition Orientation	Flexural Strength (MPa)	
	3.2 mm	6.4 mm
0-90	55.58 ± 5.49	55.58 ± 5.49
45-45	55.70 ± 3.58	63.00 ± 3.24
90-90	43.92 ± 2.73	57.76 ± 3.31
0-0	103.10 ± 6.29	70.84 ± 3.54
honeycomb	17.53 ± 3.31	17.57 ± 1.49

Figure 3: Flexural Strength Specimens

In contrast, the 90-90 orientation—where printed filaments are perpendicular to the loading axis—showed markedly lower strength, attributed to weak inter-layer adhesion and the dominance of tensile and shear stresses across layer interfaces during bending. The 45-45 orientation produced intermediate results, consistent with mixed stress distribution between filament directions and layer boundaries. These results are in agreement with previous research [11, 12, 13, 14] which reported that build orientation strongly influences mechanical anisotropy in 3D printed PLA. The mechanical anisotropy is caused by the varying inter-layer bonding efficiency and filament continuity relative to the loading direction. For most orientations, increasing specimen thickness from 3.2 mm to 6.4 mm led to an increase in flexural strength. This trend is particularly evident for the 45-45 and 90-90 orientations, which increased from 55.70 MPa to 63.00 MPa and from 43.92 MPa to 57.76 MPa, respectively. The improvement can be attributed to a greater number of load-bearing layers and increased bending stiffness in thicker samples.

However, an opposite trend was observed in the 0-0 orientation, where flexural strength decreased from 103.10 MPa to 70.84 MPa with increased thickness. This reduction may result from the accumulation of residual thermal stresses and imperfect bonding between adjacent layers in thicker prints, which can promote delamination or crack initiation under bending loads. The minimal difference between the 3.2 mm and 6.4 mm honeycomb infill specimens ($\approx$17.5 MPa) confirms that internal geometry and infill type dominate mechanical response when the structure is not fully solid, overshadowing the effect of overall thickness.

The flexural strength of the best-performing configuration (0-0, 3.2 mm) was approximately 5.9 times higher than that of the honeycomb structure and nearly 2.4 times higher than that of the 90-90 orientation. These results emphasize that the alignment of filament deposition with the principal loading direction is the most critical parameter governing flexural performance in FDM-printed PLA parts.

Statistical analyses were performed to determine the effects of deposition orientation and specimen thickness on the flexural strength of 3D-printed PLA plates. A two-way analysis of variance (ANOVA) was conducted using a fixed-factor design with two independent variables:

- Deposition orientation (five levels: 0–90, 45–45, 90–90, 0–0, honeycomb)
- Thickness (two levels: 3.2 mm and 6.4 mm)

Each combination contained three replicates (n = 3). When significant effects were detected, Tukey's Honestly Significant Difference (HSD) post-hoc test was applied for pairwise comparisons between deposition orientations. In addition, independent-sample t-tests were conducted to examine the influence of specimen thickness within each orientation group. The summary of Two Way ANOVA for deposition orientation and thickness is shown in Table 2.

Table 2: Two Way Anova Analysis

Source	df	F-value	p-value	Significance
Orientation	4	220.30	< 0.001	***
Thickness	1	2.20	0.153	ns
Orientation × Thickness	4	28.27	< 0.001	***
Residual	20	—	—	—

ns: not significant; ***:*p < 0.001*

The two-way ANOVA show that a highly significant effect of deposition orientation on flexural strength ($F(4, 20) = 220.30$, $p < 0.001$). However, the effect of specimen thickness was not statistically significant ($F(1, 20) = 2.20$, $p = 0.153$). Nevertheless, the interaction effect between orientation and thickness is significant ($F(4, 20) = 28.27$, $p < 0.001$). It's indicating that the impact of thickness depended strongly on deposition orientation.

Further analysis using Post-hoc Tukey tests confirmed that the 0–0 orientation was significantly stronger than all other orientations ($p < 0.001$) while the honeycomb structure was significantly weaker than all others. This is indicated by the value p, 0.001. Whereas among 0–90, 45–45, and 90–90 orientations showed smaller and not-significant differences ($p > 0.05$).

Independent t-tests comparing thickness levels within each orientation showed that thickness significantly influenced flexural strength only for the 0–0 and 90-90 orientation with p value is 0.0038 & 0.0056 respectively. In contrast, 0–90, 45–45, and honeycomb configurations did not exhibit statistically significant differences between 3.2 mm and 6.4 mm specimens. These results are in accordance that deposition orientation is the dominant parameter affecting flexural performance, while the influence of thickness is conditional on orientation [15, 16]

IV. CONCLUSION

This study investigated the influence of deposition orientation and specimen thickness on the flexural strength of PLA plates fabricated using the Fused Deposition Modeling (FDM) technique. The experimental results demonstrated that both parameters play a crucial role in determining the mechanical performance of 3D-printed components.

The 0–0 deposition orientation, where the filament paths align parallel to the loading direction, produced the highest flexural strength among all tested configurations, reaching 103.10 MPa for the 3.2 mm specimen and 70.84 MPa for the 6.4 mm specimen. This configuration effectively transferred bending loads along continuous filament paths and minimized inter-layer failure. Conversely, the 90–90 orientation exhibited substantially lower flexural strength due to weak inter-layer bonding and poor load transfer between adjacent filaments.

The effect of specimen thickness was found to be orientation-dependent. Increasing thickness generally improved flexural strength due to higher bending stiffness and increased load-bearing cross-section. However, in the 0–0 orientation, thicker specimens experienced a reduction in strength, likely caused by residual thermal stresses and imperfect bonding between stacked layers. The honeycomb infill structure, while reducing material usage and weight, displayed the lowest flexural strength (≈ 17.5 MPa) and is therefore unsuitable for high-load applications.

Overall, this study confirms that deposition orientation is the dominant factor governing the flexural performance of FDM-printed PLA. Optimizing print parameters—particularly filament alignment relative to the loading axis—can significantly enhance mechanical reliability without altering the material composition. These findings contribute valuable insight for engineers and designers seeking to tailor 3D printing parameters for structural or functional prototypes where flexural properties are critical.

The combination of optimal deposition orientation and controlled specimen thickness enables significant enhancement in mechanical performance without changing the base material. Hence, proper parameter selection can compensate for the inherent anisotropy of FDM structures, improving their reliability for functional and load-bearing applications.

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