



RESEARCH ARTICLE

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MECHANICAL CHARACTERIZATION OF 3D PRINTED PLA/ GLASS FIBER COMPOSITE FOR CRASH BOX APPLICATION

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ABSTRACT

Rapid advancements in additive manufacturing, especially Fused Deposition Modeling (FDM), have made it possible to fabricate intricate and personalized parts for engineering and biomedical applications. Polylactic Acid (PLA) reinforced with glass fibers has drawn interest among the different materials used in FDM due to its exceptional mechanical strength, sustainability, and biocompatibility. This project focuses on analyzing the mechanical characteristics of PLA-glass fiber composites that are 3D printed for two important applications: automobile crash boxes and cranial implants. The mechanical characteristics of 3D printed PLA-glass fiber composites are the main focus of this study, which is intended for usage in crash boxes and cranial implants. Finding the best parameter combinations to optimize load-bearing capacity and energy absorption efficiency is the goal of the results. It is anticipated that the results will direct the creation of lightweight, impact-resistant automobile parts and patient-specific biomedical implants, showcasing the usefulness of PLA-glass fiber composites in crucial, performance-driven applications.



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I. INTRODUCTION

Owing to the thrust in green manufacturing processes, 3D printing has gained much importance in digital manufacturing of composite materials. Fused Deposition Modelling (FDM) is widely used for manufacturing fiber-reinforced thermoplastic composites due to its cost-effectiveness and design flexibility. The incorporation of short, long, and continuous fibers significantly enhances mechanical properties, but challenges such as fiber distribution, orientation, and interfacial adhesion affect the final performance [1]. The mechanical properties are strongly influenced by filament orientation. Specimens with infill aligned along their length exhibited superior mechanical characteristics, including higher Young's modulus, maximum strength, and toughness [2]. Even after much advances in printing of materials, challenges persist, including issues with fiber dispersion, interfacial bonding, and process parameter optimization, which can affect the structural integrity of the composites [3]. The printing parameters, particularly layer height and raster orientation, significantly influence void density and mechanical performance [4].

Studies indicate that incorporating various fillers, including carbonaceous and inorganic materials, can significantly improve tensile strength, stiffness, and impact resistance of 3D-printed composites [5]. Higher infill densities generally lead to increased strength and stiffness due to the greater material content and enhanced internal support structures. For instance, research indicates that increasing infill density from 60% to 100% can result in a substantial improvement in tensile strength, with some studies reporting increases of up to 50%. However, the relationship between infill density and mechanical strength is not strictly linear; the rate of strength improvement may diminish at higher densities [6], [7]. Additionally, the choice of infill pattern significantly affects mechanical performance; concentric patterns combined with 80% infill density and 100 µm layer thickness have been shown to enhancement of impact strength [7]. Printing PLA at lower nozzle temperatures can result in reduced material flow, leading to air gaps between layers and decreased mechanical performance. Conversely, higher nozzle temperatures enhance layer adhesion and reduce porosity, thereby improving mechanical properties.

However, excessively high temperatures may cause material overflow without substantial additional benefits. Optimal mechanical performance, including tensile, flexural, and compressive strengths, has been observed in the nozzle temperature range of 220–240 °C [8]. PLA composite samples that are FDM-printed in on-edge orientation with +45°/–45° raster angles have the highest mechanical strength in most cases. The angle of bonding between the layer is directly proportional to the mechanical behavior [9]. Hybrid reinforcement of PLA with glass fibers presents a promising approach for orthopedic applications. The combination of mechanical strength, bioactivity, and controlled degradation makes these composites suitable for biomedical implants. In additive manufacturing processes aimed at creating patient-specific implants. Furthermore, the inclusion of PLA-based composites in impact studies presents a promising opportunity for the development of sustainable crash box solutions [10], [11]. However, challenges such as material brittleness and structural integrity under impact conditions remain, necessitating further research into material selection and structural design to optimize performance [12]. 3D printed PLA implants are used in cranioplasty procedures. This approach offers a cost-effective and precise alternative to traditional materials and methods used in cranial defect reconstruction [13]. The present work studies the mechanical performances of 3D printed PLA/Glass composites with pure PLA and also suggest an optimal combination of printing parameters to achieve enhanced strength.

II. MATERIALS AND METHODS

II.1 MECHANICAL TESTING

This study employs Glass Fiber reinforced Poly-Lactic Acid (GF/PLA) composite as the primary material. Glass Fiber is selected as the reinforcement phase due to its exceptional mechanical and thermal performance. The PLA-GF composite filament used in this study is obtained in the form of 1.75 mm diameter filament, optimized for Fused Deposition Modeling (FDM) based additive manufacturing. The design of test specimens was carried out using Computer-Aided Design (CAD) tools to ensure precise geometry and adherence to relevant testing standards. The standard and dimensions are given in Table-1.

Table 1: Details of the specimen designed.

Material	Test	Standard	Dimension (mm)
PLA – GF	Flexural	ASTM D790	125 x 12.7 x 3.2
	Compression	ASTM D695	25.4 x 12.7 x 12.7
	Impact	ASTM D256	63.5 x 12.7 x 5

Source: Authors, (2026).

The additively manufactured PLA–Glass Fiber composite specimens were subjected to a series of mechanical tests to evaluate their strength and structural integrity. The primary objective of this testing phase was to assess the mechanical behavior of the composite material under different types of loading conditions. The tests conducted include Flexural, Impact, and Compression tests, each serving to reveal distinct mechanical characteristics. Each type of test was carried out for three repetitions. These repetitions helped reduce variability and improve the statistical confidence of the results. The average values were taken for discussions.



Figure 1: Flexural, Impact and Compression testing setup

Source: Authors, (2026).

II.2 DESIGN OF EXPERIMENTS

In this study, four key process parameters were strategically varied to analyze their influence on the mechanical performance of 3D-printed PLA-Glass Fiber (PLA-GF) composite specimens and are presented in Table 2. These parameters were selected based on their known impact on the internal structure, strength, and thermal behavior of Fused Deposition Modeling (FDM) printed parts. Each parameter was varied across three levels to enable a systematic evaluation of their effects (except wall thickness). The combination of these parameters was used to print the test specimens, with the objective of identifying the most suitable settings for maximizing the mechanical performance of the PLA-GF composite material.

Table 2: Parameter selection.

Control factors	Levels		
Infill density	50%	75%	100%
Infill pattern	Honeycomb	Gyroid	Archimedean chords
Nozzle temperature	190°C	210°C	230°C
Wall thickness	1mm	2 mm	--

Source: Authors, (2026).

To reduce the experimental load while retaining meaningful statistical analysis, a Taguchi L18 orthogonal array was adopted. This approach reduced the number of unique combinations to 18, presented in Table 3.

Table 3: L18 orthogonal array.

S.No.	Wall thickness (mm)	Infill Pattern	Nozzle temperature (°C)	Infill density (%)
S1	1	Honeycomb	190	50
S2	1	Honeycomb	210	75
S3	1	Honeycomb	230	100
S4	1	Gyroid	190	50
S5	1	Gyroid	210	75
S6	1	Gyroid	230	100
S7	1	A.Chords	190	75
S8	1	A.Chords	210	100
S9	1	A.Chords	230	50
S10	2	Honeycomb	190	100
S11	2	Honeycomb	210	50
S12	2	Honeycomb	230	75
S13	2	Gyroid	190	75
S14	2	Gyroid	210	100
S15	2	Gyroid	230	50
S16	2	A.Chords	190	100
S17	2	A.Chords	210	50
S18	2	A.Chords	230	75

Source: Authors, (2026).

3D printer Settings used in the Project is as given below.

- Material: PLA–Glass Fiber Composite
- Bed Temperature: 50°C
- Layer Height: 0.2 mm
- Print Speed: 50 mm/s
- Raster Angle: +45°/-45°

II. 3 OPTIMIZATION

To identify the most influential parameter and their optimum levels, the experimental data obtained from mechanical tests was statistically analyzed using the Taguchi method. This approach is particularly effective in identifying optimal process conditions while minimizing variability due to uncontrollable factors. A key feature of the Taguchi method is the use of the Signal-to-Noise (S/N) ratio, which serves as a measure to evaluate the quality and stability of output responses across varying conditions. In this context, the S/N ratio helps to pinpoint settings that not only deliver high performance but also maintain consistency across repeated trials. The various S/N ratio formulations available are, “smaller-the-better,” “larger-the-better,” and “nominal-the-best”. This study adopts the larger-the-better criterion, given in equation (1). This is because the mechanical properties under observation is desired to be as high as possible. The corresponding S/N ratio is mathematically expressed as:

$$\frac{S}{N} = -10 \log \frac{1}{n} \sum_{i=1}^n \frac{1}{y_i^2} \quad (1)$$

Where y denotes the response value for each trial, and n is the number of repetitions. A higher S/N ratio indicates better robustness, meaning the system performs well despite the presence of potential noise or disturbances

III. RESULTS AND DISCUSSIONS

III.1 MECHANICAL STRENGTHS

The experimental results are presented in Table 3 and graphically represented in Figure 2.

Table 3: Results of mechanical testing.

S.No.	Wall thickness (mm)	Infill Pattern	Nozzle temperature (°C)	Infill density (%)	Compression Strength (MPa)	Flexural Strength (MPa)	Impact Strength (kJ/m ²)
S1	1	Honeycomb	190	50	6.86	69.49	21.33
S2	1	Honeycomb	210	75	31.88	70.88	22.00
S3	1	Honeycomb	230	100	40.51	69.20	22.67
S4	1	Gyroid	190	50	9.29	35.75	21.33
S5	1	Gyroid	210	75	24.03	70.52	24.67
S6	1	Gyroid	230	100	37.24	72.49	22.00

S7	1	ACHords	190	75	14.00	71.13	20.00
S8	1	ACHords	210	100	35.49	80.72	23.33
S9	1	ACHords	230	50	19.11	69.42	19.33
S10	2	Honeycomb	190	100	37.70	71.76	22.67
S11	2	Honeycomb	210	50	3.75	69.32	22.00
S12	2	Honeycomb	230	75	42.63	71.54	21.33
S13	2	Gyroid	190	75	33.35	71.71	25.33
S14	2	Gyroid	210	100	47.55	68.72	26.00
S15	2	Gyroid	230	50	19.26	68.10	20.67
S16	2	ACHords	190	100	14.95	71.43	22.67
S17	2	ACHords	210	50	17.69	33.53	24.67
S18	2	ACHords	230	75	24.28	70.15	25.33

Source: Authors, (2026).

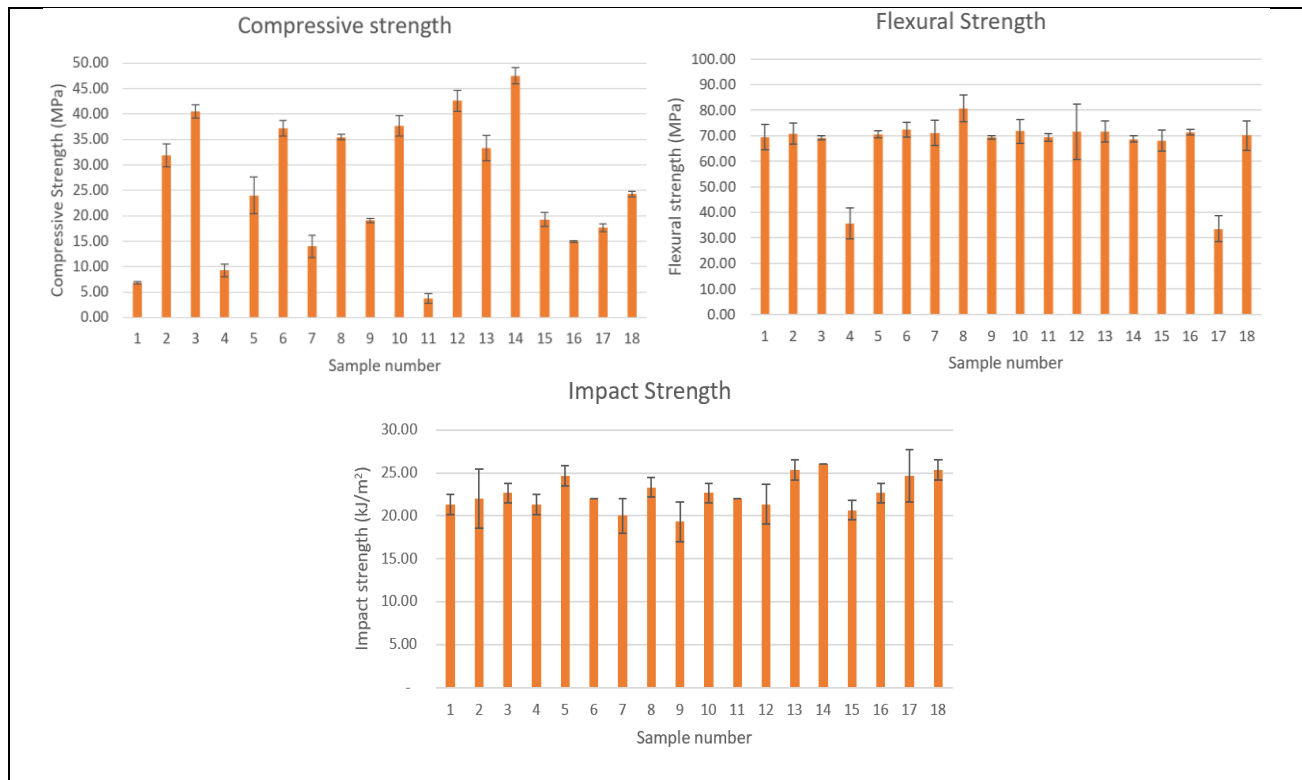


Figure 2: Mechanical strengths with standard deviation chart.

Source: Authors, (2026).

Compression strength determines the material's ability to withstand loads that reduce its size without breaking. It increases significantly as infill density increases from 50% to 100%. Low temperature (190°C) results in weak layer bonding, lowering strength, while 210°C – 230°C improves layer fusion and adhesion, increasing compressive strength. Increasing wall thickness (from 1mm to 2mm) enhances compressive strength due to more material supporting the load. Sample 14 of Gyroid pattern show the highest compressive strength (47.55 MPa) due to their efficient load distribution. Flexural strength determines the material's ability to resist deformation under bending. Higher infill density improves flexural strength as it increases material continuity and resistance to bending. Higher nozzle temperature (210°C–230°C) results in stronger interlayer bonding, increasing flexural strength, but does not always increase proportionally. For Archimedean chords, 100% Infill, Wall = 1mm, peak strength is observed at 210°C rather than 230°C.

Possible reason might be over-melting which may lead to fiber matrix detachment, weakening the material. Unlike compression strength, increasing wall thickness does not significantly impact flexural strength. Sample 8 of Archimedean chords exhibits the highest flexural strength due to its unique internal structure, which resists bending stress. Impact strength determines the material's ability to absorb energy before breaking. Impact strength does not always increase with infill density. For example, in a Gyroid infill pattern with 1mm wall thickness, 75% infill density has more impact strength compared to 100% infill density. Higher infill density makes the material stiffer, and overly stiff material becomes brittle under impact, leading to sudden failure instead of absorbing energy. With increase in nozzle temperature, there is only minimal increase in impact strength. Thicker walls (2mm) significantly improve impact resistance by adding structural integrity.

III.2 ANALYSIS OF S/N RATIO FOR PARAMETER OPTIMIZATION

Taguchi's Signal-to-Noise (S/N) ratio technique was used to identify the best 3D printing parameters for improving the mechanical performance of PLA-glass fiber composites. The calculated values are presented in Table 4.

Table 4: S/N ratio table.

Level	Wall Thickness	Infill Pattern	Nozzle temperature	Infill density
1	27.43	27.76	26.22	23.72
2	27.68	28.66	27.33	29.12
3	-	26.25	29.12	29.83
Delta	0.25	2.42	2.89	6.11
Rank	4	3	2	1

Source: Authors, (2026).

The objective was to determine the parameter settings that consistently produce the strongest features in order to reduce variability and increase robustness. With a focus on the "larger-the-better" criterion, which is appropriate for optimizing mechanical strengths, the S/N ratio was computed for every experimental trial using the observed mechanical test results. The best performing parameter values were then determined by tabulating and ranking the computed S/N ratios. The delta value represents the difference between highest and lowest average response characteristic value for the levels of a particular factor. Factor with the highest delta value has the most influence on the response characteristic. The findings showed that certain levels of variables including wall thickness, infill pattern, nozzle temperature and infill density had a major impact on the printed specimens' mechanical response, shown in figure 3.

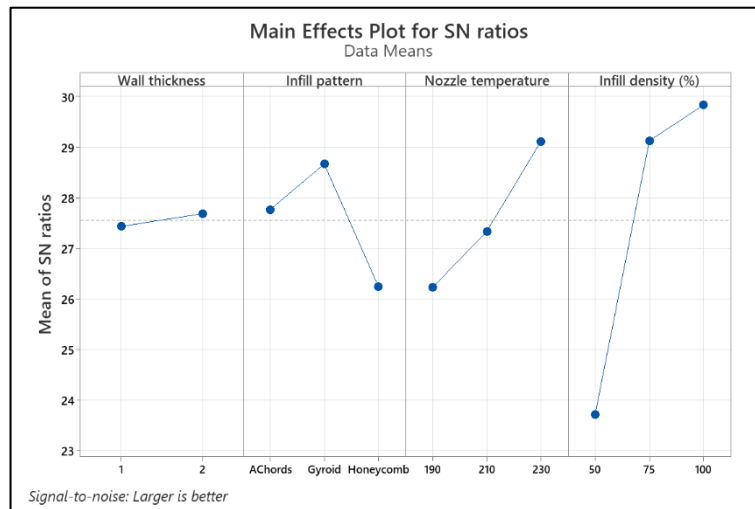


Figure 3: Main effects plot for S/N ratio for printing parameters.

Source: Authors, (2026).

Based on the combined Signal-to-Noise (S/N) ratio derived from compression, flexural, and impact strength results, the optimal combination of printing parameters for achieving multi-objective mechanical strength is wall thickness of 2 mm, gyroid infill pattern, nozzle temperature of 230 °C, and 100% infill density, following the 'larger-the-better' criterion.

IV. CONCLUSIONS

1. The study effectively examined PLA-glass fiber composites mechanical characteristics, with an emphasis on determining the best 3D printing parameters for crash box applications.
2. The experimental results demonstrate how well parameter optimization works to increase mechanical strength which is crucial for load-bearing as well as energy-absorbing structures like crash boxes.
3. Based on the analysis and S/N ratio, multi-objective mechanical strength can be achieved with wall thickness of 2 mm, gyroid infill pattern, nozzle temperature of 230 °C, and 100% infill density.

V. AUTHOR'S CONTRIBUTION

Conceptualization: Sridharan V, Nikhil Kumar A, Mathumitha K and Jeyabalaji SN.

Methodology: Sridharan V, Nikhil Kumar A, Mathumitha K and Jeyabalaji SN.

Investigation: Sridharan V, Nikhil Kumar A, Mathumitha K and Jeyabalaji SN.

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Writing – Review and Editing: Sridharan V, Nikhil Kumar A, Mathumitha K and Jeyabalaji SN.

Resources: Sridharan V, Nikhil Kumar A, Mathumitha K and Jeyabalaji SN.

Supervision: Sridharan V, Nikhil Kumar A, Mathumitha K and Jeyabalaji SN.

Approval of the final text: Sridharan V, Nikhil Kumar A, Mathumitha K and Jeyabalaji SN.

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