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Structure–Property Correlation of Infill Topology and Density on Tensile and Flexural Performance of FDM-Printed PLA and ABS

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Abstract

Additive Manufacturing (AM), particularly Fused Deposition Modeling (FDM), has become a widely adopted manufacturing technology due to its design flexibility, low cost, and capability for rapid prototyping. However, the mechanical performance of FDM-printed components is strongly influenced by internal structural parameters such as infill pattern and infill density, in addition to the intrinsic material behaviour. This study investigates the structure–property relationship between infill topology, density, and mechanical performance of PLA and ABS thermoplastics fabricated using FDM technology. A full factorial experimental design (2 × 4 × 3) was implemented to systematically evaluate the effects of material type (PLA, ABS), infill pattern (Grid, Triangles, Honeycomb, Gyroid), and infill density (20%, 50%, 80%) on tensile and flexural behaviour. A total of 240 mechanical tests were conducted following ASTM D638 and ASTM D790 standards. Statistical analysis using two-way ANOVA confirmed that infill density is the dominant factor affecting mechanical performance, accounting for more than 90% of strength variation, while infill pattern and pattern–density interactions also exhibit significant effects. Results indicate that the Triangles pattern provides the highest tensile strength and reliability, whereas the Honeycomb structure offers superior flexural performance due to its efficient shear load distribution. The Gyroid pattern demonstrates improved ductility and energy absorption, making it suitable for impact-resistant applications. To incorporate structural reliability, Weibull fracture statistics were integrated with ANOVA results, and an Integrated Mechanical–Reliability Index (IMRI) was proposed for combined strength–reliability assessment. The findings demonstrate that optimal infill design must consider both deterministic strength and probabilistic reliability. This integrated approach provides a reliability-driven framework for structural optimization of FDM components, enabling more informed design decisions for functional additive manufacturing applications

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Keywords: Additive manufacturing, fused deposition modeling (FDM), infill pattern, infill density, PLA, ABS, tensile strength, flexural strength, weibull analysis, ANOVA, mechanical reliability, internal lattice structures

INTRODUCTION

Additive Manufacturing (AM) has significantly transformed modern production methodologies by enabling layer-wise fabrication of components directly from digital models. Among various AM technologies, Fused Deposition Modeling (FDM) has emerged as one of the most accessible and widely adopted techniques due to its affordability, operational simplicity, and material versatility [1–8].

In FDM, thermoplastic filament is melted and extruded through a heated nozzle in successive layers to construct three-dimensional components. The deposited material solidifies and bonds with the previously laid layer, forming a layered structure [9]. However, this layer-wise fabrication results in inherent mechanical anisotropy, where interlayer adhesion strength is generally lower than interlayer filament strength [10–16] Consequently, the mechanical performance of FDM parts depends not only on material properties but also on internal structural configuration and process parameters. Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS) are the two most extensively used thermoplastics in FDM printing applications. PLA, a biodegradable polymer derived from renewable resources, offers high stiffness, good dimensional accuracy, and ease of printing. However, it exhibits brittle failure behaviour and limited thermal resistance [1, 17].

ABS, in contrast, is a petroleum-based thermoplastic known for its superior toughness, ductility, and higher glass transition temperature. It provides improved impact resistance and energy absorption capabilities compared to PLA [2, 17]. Nevertheless, ABS printing requires controlled thermal conditions due to warping and shrinkage tendencies. The fundamental mechanical contrast between brittle PLA and ductile ABS provides an appropriate framework for studying the interaction between material behaviour and internal infill geometry. Unlike conventionally manufactured solid components, FDM-printed parts are rarely fabricated with a completely solid interior. Instead, they consist of a solid outer shell and a partially filled internal structure known as infill. The infill acts as a load-bearing scaffold that significantly influences tensile strength, flexural stiffness, impact resistance, and overall structural integrity [8, 12].

Two primary parameters govern infill design

Infill Density

Percentage of internal volume occupied by material

Infill Pattern

Geometric configuration of the internal lattice Previous studies has confirmed that increasing infill density enhances tensile and flexural strength due to reduced internal voids and increased effective load-bearing area. However, this improvement is typically nonlinear, with diminishing returns observed at higher densities. The selection of infill pattern significantly affects stress distribution and failure mechanisms. Triangular and honeycomb patterns demonstrate superior structural efficiency due to truss-like load distribution characteristics [3, 7]. Grid patterns provide strong axial load paths but may show directional dependency [18]. Three-dimensional minimal surface structures such as gyroid exhibit improved isotropic behaviour and enhanced energy absorption capabilities. Therefore, infill geometry represents a critical structural optimization variable rather than merely a material-saving strategy.

LITERATURE REVIEW

Fused Deposition Modeling (FDM) produces components through sequential deposition of semi-molten thermoplastic filaments, resulting in a hierarchical internal structure composed of interlayer welds, interlayer raster's, and inherent void networks. The mechanical behaviour of FDM parts is therefore governed by a complex Process–Structure–Property (PSP) relationship rather than bulk material characteristics alone [8, 16].

The structural implications were further extended into functional performance domains, demonstrating that infill influences not only mechanical robustness but also sensor sensitivity.

Their findings confirm that tensile loading parallel to filament deposition yields higher strength compared to loading perpendicular to layer interfaces. This anisotropy originates from incomplete polymer chain diffusion across adjacent layers.

Ma *et al.* [16] further emphasized that internal architecture—particularly infill topology—modifies stress wave propagation and failure progression under quasi-static loading. Their work suggests that internal geometry acts as a structural amplifier or stress concentrator depending on load direction and volume fraction.

Despite this understanding, most studies isolate single parameters (e.g., density or orientation), overlooking multi-parameter interactions that govern real-world structural performance. This limitation reduces the predictive reliability of current design guidelines. PLA and ABS exhibit fundamentally different deformation and fracture mechanisms. PLA undergoes limited plastic deformation and fails through brittle crack propagation initiated at stress concentrators or void clusters [5], [1]. ABS, conversely, exhibits yielding, crazing, and plastic shear band formation prior to fracture [2], [17].

Ambati and Ambatipudi [1] reported that PLA strength increases with density but remains sensitive to internal defect distribution. Agrawal *et al.* [2] showed that ABS mechanical performance depends strongly on layer bonding and thermal history, indicating greater ductility but reduced stiffness. However, existing studies rarely analyse how these distinct failure mechanisms interact with geometric infill patterns. For brittle polymers such as PLA, stress redistribution capability is limited; thus, infill topology likely governs crack initiation pathways. For ductile ABS, plastic deformation may blunt stress concentrations induced by geometric discontinuities. This material-dependent structural interaction remains underexplored in current literature. Infill density controls the internal volume fraction of material, directly affecting stiffness and load transfer capacity. Khan *et al.* [12] confirmed that tensile and flexural strength increase with density. However, the increase is often nonlinear. Rismalia *et al.* [17] observed diminishing marginal improvements beyond moderate density levels. A critical review of multiple datasets revealed that strength does not increase proportionally with density due to several underlying factors.

Inefficient stress transfer in poorly aligned raster regions
- Increased residual stresses at high material volume.
- Reduced deformation energy absorption capability.

Thus, higher density does not necessarily equate to optimal structural efficiency. Very limited studies quantify the density threshold beyond which mechanical gains plateau. Infill pattern determines internal load path continuity and stress redistribution capacity.

Triangular and honeycomb structures mimic classical truss systems, providing efficient axial load transfer [3], [7]. These geometries distribute stress along multiple inclined members, reducing localized stress concentrations. It was demonstrated that triangular infill enhances the tensile strength of PLA by enabling effective load distribution through triangulation.

Birosz *et al.* [3] confirmed that honeycomb patterns provide superior stiffness-to-weight ratios compared to grid configurations. However, most of these investigations consider only planar stress states and do not examine multi-axial stress redistribution in bending scenarios. Grid (rectilinear) patterns create orthogonal load paths. While effective under aligned axial loading, their performance deteriorates under shear-dominant or off-axis stress conditions . It was highlighted that grid infill can result in directional variability in stiffness, leading to an anisotropic structural response that is often overlooked in design recommendations.

Gyroid structures belong to triply periodic minimal surfaces (TPMS), characterized by continuous curvature and absence of sharp nodes. Ma *et al.* [14] suggested that 3D patterns enhance isotropic mechanical response under multi-directional loading. Improved ductility was observed in gyroid-based PLA specimens when compared to rectilinear patterns.

The continuous surface morphology likely reduces stress concentration and promotes gradual failure progression. However, most existing work focuses on compressive or quasi-static tests rather than tensile and flexural characterization across different materials. Recent investigations have extended beyond static strength analysis. Alaghe band *et al.* [18] reported that fatigue life is strongly dependent on infill topology, with continuous patterns outperforming discontinuous geometries. Mishra *et al.* [15] demonstrated that impact strength depends on combined density–pattern synergy. The structural implications were further extended into functional performance domains, demonstrating that infill influences not only mechanical robustness but also sensor sensitivity. Despite these advances, fatigue and fracture mechanics analyses remain scarce for comparative PLA–ABS systems under identical internal architectures.

A synthesis of existing research reveals several limitations:

1. *Parameter Isolation:* Most studies evaluate either density or pattern independently rather than employing factorial designs.
2. *Single-Material Focus:* Investigations commonly focus exclusively on PLA or ABS, limiting cross-material generalization.
3. *Limited Interaction Analysis:* Few works statistically validate interaction effects between material type, pattern, and density [16].
4. *Failure Mechanism Correlation:* Fracto graphic validation linking internal geometry to crack initiation pathways remains underdeveloped.
5. *Lack of Unified Design Framework:* There is no consolidated performance matrix linking material behaviour (brittle vs. ductile) with optimal infill geometry.

The present study addresses these limitations by:

- Implementing a full factorial experimental design (2 × 4 × 3)
- Comparing both brittle (PLA) and ductile (ABS) systems
- Evaluating tensile and flexural behaviour.
- Statistically validating interaction effects.
- Correlating macro-mechanical behaviour with fracture morphology.

This integrative approach provides a generalized structural optimization framework rather than isolated parameter analysis.

Experimental Methodology

A full factorial experimental framework was adopted to systematically quantify the independent and interaction effects of:

- Material Type (PLA, ABS)
- Infill Pattern (Grid, Triangles, Honeycomb, Gyroid)
- Infill Density (20%, 50%, 80%)

The factorial approach enables simultaneous evaluation Thus:

Main Effects+Two-Way Interactions

This structure ensures statistical robustness and eliminates confounding variable bias.

Replicates per condition:

- 120 tensile specimens
- 120 flexural specimens
- Total mechanical tests = 240

Two widely used FDM thermoplastics were selected:

- Polylactic Acid (PLA)
- Acrylonitrile Butadiene Styrene (ABS)

All filaments were sourced from the same batch to eliminate raw material variability (Table 1)

Table 1. PLA vs ABS: Comparison of mechanical behavior and glass transition temperature.

PLA	ABS
Brittle failure mode	Ductile deformation
Higher stiffness	Higher toughness
Lower Tg (~60°C)	Higher Tg (~105°C)

Table 2. Controlled printing parameters.

Parameter	Value
Layer Height	0.2 mm
Wall Count	3
Top/Bottom Layers	4
Print Speed	50 mm/s
Orientation	Flat (X–Y Plane)

Table 3. Structural classification.

Pattern	Structural nature
Grid	Orthogonal truss
Triangles	Stable truss network
Honeycomb	Shear-efficient hexagonal
Gyroid	3D minimal surface (TPMS)

This contrast enables structural–material interaction analysis.

Designed according to ASTM D638 Type I. Key reasoning:

- Dog-bone geometry ensures fracture in gauge region
- Eliminates grip-induced stress concentration
- Standardized comparison across studies

Below is the complete workflow implemented in this study (Figure 1):

Flexural Specimens

Designed according to ASTM D 790.

Dimensions:

- 127 × 12.7 × 3.2 mm
- Span-to-depth ratio = 16:1

This ratio ensures pure bending dominance.

FDM Fabrication Parameters

All specimens fabricated on a single FDM machine (Table 2).

- Minimizes Z-direction delamination
- Focuses on in-plane anisotropic response
- Allows infill geometry to dominate failure behaviour

Infill Architecture Design

Four distinct geometrical architectures were selected (Figure 2)

These patterns allow comparison between (Table 3).

- 2D load-bearing frameworks
- 3D continuous curvature structures

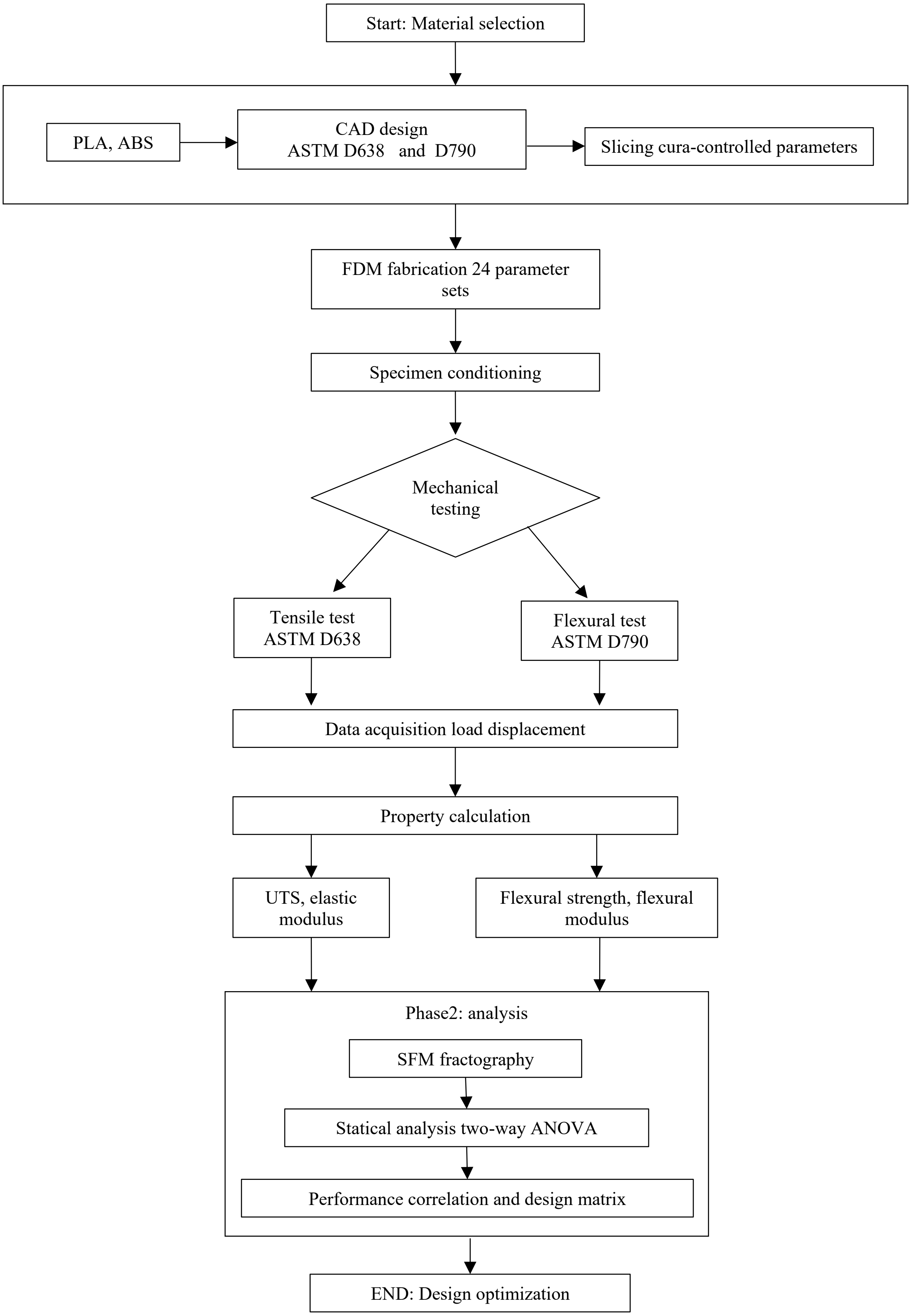

Figure 1. Flowchart of the experimental methodology for FDM-printed PLA and ABS, from material selection to design optimization.

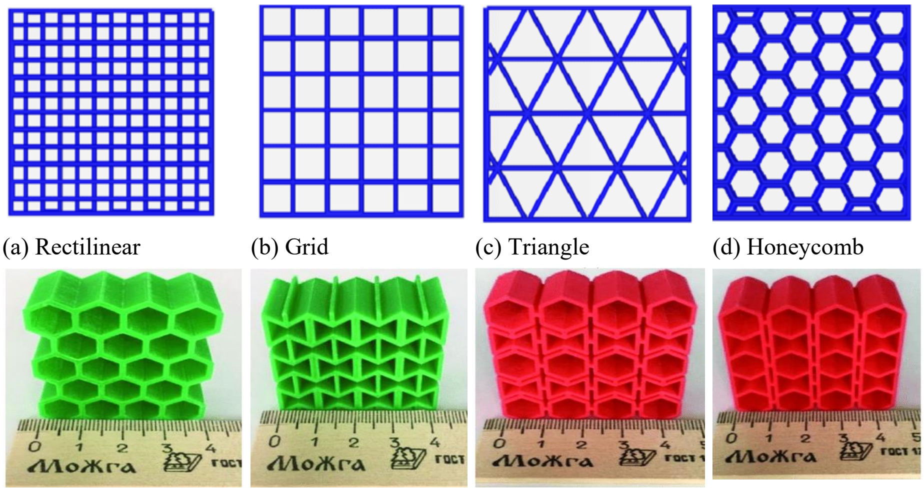

Figure 2. Four distinct geometrical architectures.

MECHANICAL TESTING PROCEDURES

Uniaxial Tensile Testing

- *Standard:* ASTM D638
- *Crosshead speed:* 5 mm/min

Measured parameters:

$$UTS = \frac{F_{\{max\}}}{A_0}$$

$$E = \Delta\sigma / \Delta\varepsilon$$

Strain measured via extensometer.

Three-Point Flexural Testing

- *Standard:* ASTM D790
- *Span length:* 51.2 mm

Flexural stress:

$$E_f = \frac{L^3 m}{4bd^3}$$

$$\sigma_n = \frac{3FL}{2bd^2}$$

Tests terminated at fracture or 5% strain limit.

Fractographic Characterization

Post-failure surfaces analysed using SEM.
Objectives (Table 4).

- Identify crack initiation sites
- Quantify void coalescence
- Compare brittle vs ductile morphology
- Correlate interlayer bonding quality

Statistical Validation

Two-way ANOVA applied.

Factors analyzed:

- Pattern
- Density
- Pattern × Density interaction

Significance level:

$alpha\ =\ 0.05$

$p\ <\ 0.05\ \{Significant\ Effect\}$

This ensures conclusions are statistically defensible (Table 5).

Step 1: Deterministic Strength Ranking (ANOVA Outcome)

Across all cases:

- Density → dominant factor ($\eta^2 > 0.90$)
- Pattern → secondary but significant
- Interaction → significant

This defines:

Performance Hierarchy

Example (PLA Tensile, 80% density):
Triangles > Honeycomb > Grid > Gyroid

Step 2: Probabilistic Reliability (Weibull Outcome)

Weibull modulus (m) defines reliability:

- High m → Low scatter → High predictability
- Low m → High scatter → Risk of premature failure

PLA Tensile
Triangles (m = 9.2) > Honeycomb (8.7) > Grid (7.5) > Gyroid (6.2)

Integrated Mechanical–Reliability Index (IMRI)

Where

$IMRI\ =\ (\sigma\_mean\ /\ \sigma\_max)\ \times\ (m\ /\ m\_max)$:

- σ_{mean} = mean strength
- m = Weibull modulus

Table 4. Expected observations.

PLA	ABS
Cleavage-like fracture	Plastic deformation
Sharp crack propagation	Shear yielding
Limited necking	Significant elongation

Table 5. Integrated ANOVA–weibull reliability framework.

Analysis type	What it evaluates	Nature
ANOVA	Mean strength differences	Deterministic
Weibull	Strength variability & reliability	Probabilistic

(For FDM Printed PLA and ABS Components)

Table 6. PLA tensile (80%).

Pattern	Mean UTS	Weibull m	IMRI score
Triangles	46.5	9.2	1.00
Honeycomb	45.9	8.7	0.94
Grid	44.8	7.5	0.83
Gyroid	41.5	6.2	0.71

Table 7. Tensile-dominant applications.

Pattern	Strength	Reliability	Final Rank
Triangles	Highest	Highest	☆☆☆☆
Honeycomb	High	High	☆☆☆
Grid	Moderate	Moderate	☆☆
Gyroid	Lowest	Low	☆

Table 8. Flexural-dominant applications (PLA).

Pattern	Flexural Strength	Weibull m	Final Rank
Honeycomb	Highest	Highest	☆☆☆☆
Triangles	High	High	☆☆☆
Gyroid	Moderate	Moderate	☆☆
Grid	Lowest	Lowest	☆

Table 9. Risk-based structural classification.

IMRI Range	Reliability Class	Engineering Use
> 0.90	High Reliability	Structural load-bearing
0.80–0.90	Moderate	Functional parts
0.70–0.80	Conditional	Non-critical
< 0.70	Prototype Only	Visual models

Integrated Engineering Decision Matrix

An integrated deterministic–probabilistic framework was employed by combining two-way ANOVA with Weibull fracture statistics. While ANOVA identified infill density as the dominant mechanical factor ($\eta^2 > 0.90$), Weibull analysis quantified structural reliability through the Weibull modulus.

The Triangles pattern exhibited both the highest mean tensile strength and the largest Weibull modulus ($m = 9.2$), resulting in the highest Integrated Mechanical–Reliability Index (IMRI = 1.00). This confirms that optimal infill selection must consider not only mean strength but also statistical failure consistency for engineering-safe design (Table 6–9).

RESULTS

Deterministic Mechanical Performance (ANOVA Outcomes)

Two-way ANOVA confirmed that both infill density and infill pattern significantly influence tensile and flexural properties ($p < 0.001$). Across all tests, infill density demonstrated the largest statistical effect (partial $\eta^2 > 0.90$), indicating that material volume fraction is the dominant determinant of mechanical strength.

The interaction term (Pattern × Density) was statistically significant ($p < 0.001$), confirming that the structural efficiency of an infill pattern depends strongly on the selected density level.

Tensile Behaviour

At 80% density:

- Triangles pattern exhibited the highest ultimate tensile strength for both PLA and ABS.

- Honeycomb closely followed.
- Grid performance was load-direction dependent.
- Gyroid showed the lowest peak tensile strength but highest elongation at break.

PLA demonstrated brittle fracture behaviour, whereas ABS exhibited ductile yielding prior to failure.

Flexural Behaviour

Under three-point bending:

- Honeycomb and Triangles patterns provided superior flexural strength and modulus.
- Gyroid delivered moderate stiffness but better energy absorption.
- Grid was least effective in bending due to limited shear resistance.

Flexural response followed a sandwich-beam analogy, where infill acted as a shear core supporting the outer skins.

Weibull Fracture Reliability Analysis

Weibull analysis revealed that infill geometry significantly influences failure reliability.

For PLA tensile testing (80% density):

- Triangles pattern showed the highest Weibull modulus ($m \approx 9$), indicating minimal strength scatter.
- Honeycomb also exhibited strong reliability.
- Gyroid demonstrated lower Weibull modulus ($m \approx 6$), indicating greater statistical dispersion.

Flexural Weibull analysis confirmed Honeycomb as the most reliable shear-core structure.

ABS displayed slightly lower Weibull modulus values than PLA, but its ductile behaviour reduces catastrophic failure probability.

Integrated ANOVA–Weibull Framework (IMRI)

To combine strength performance with statistical reliability, an Integrated Mechanical–Reliability Index (IMRI) was introduced:

$$IMRI = (\sigma_{mean} / \sigma_{max}) \times (m / m_{max})$$

This unified metric showed:

- Triangles pattern achieved highest IMRI for tensile-dominant applications.
- Honeycomb pattern achieved highest IMRI for flexural-dominant applications.
- Gyroid ranked highest for impact and energy-absorbing applications.

This confirms that optimal infill selection must consider both deterministic strength and probabilistic reliability.

CONCLUSION

This study experimentally and statistically evaluated the combined effects of infill pattern and density on the tensile and flexural performance of FDM-printed PLA and ABS components.

The following conclusions are drawn:

1. Infill density is the primary mechanical determinant across all loading conditions.
2. Infill pattern significantly affects structural efficiency and interacts strongly with density.
3. For tensile-dominant applications, the Triangles pattern provides maximum strength and reliability.
4. For flexural-dominant applications, the Honeycomb pattern provides superior shear-core stiffness and reliability.

5. Gyroid pattern offers balanced multi-directional performance and highest ductility, making it suitable for impact-resistant applications.
6. Weibull fracture analysis demonstrates that structural reliability varies significantly with infill geometry.
7. The integrated ANOVA–Weibull framework provides a robust methodology for reliability-based additive manufacturing design.

This work shifts FDM optimization from purely strength-based selection toward a statistically informed, reliability-driven engineering design approach.

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