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Original Paper

Effect of infill pattern on bending and impact behaviour of 3D printed sandwich beams

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ABSTRACT

Poly lactic acid (PLA), used in green materials, is the most used polymer in scientific studies, especially in 3D printing production, with its low density and high strength value. PLA also finds a lot of application areas in sandwich beams where mass comes to the fore. The sandwich beams in this study were produced with 3D printing using different infill patterns. To investigate the effect of these patterns, bending and Charpy impact tests, which are most used in the characterization of sandwich beams, were performed. The obtained bending module, bending strength, bending displacement, Charpy impact energy and Charpy impact strength were examined in detail. The mass of the sandwich beams varied significantly with infill pattern, where cubic subdivision, concentric, and cross 3D patterns reduced the mass by approximately 10%, while the lightning pattern achieved a mass reduction of about 45% compared to conventional infill geometries. The concentric infill pattern provided the highest bending performance, showing approximately 28–30% higher bending stiffness and strength than most other patterns despite having about 10% lower mass, whereas the lines and lightning patterns exhibited the lowest stiffness due to limited structural connectivity. In Charpy impact testing, the concentric pattern exhibited the highest impact energy, followed by the lines pattern, which showed comparably high energy absorption, while highly discontinuous patterns such as lightning resulted in markedly lower impact resistance.

I. INTRODUCTION

Polymer materials have become increasingly important in modern engineering applications due to their low density, high specific strength, corrosion resistance, and processing flexibility compared to metallic materials [1,2]. These advantages have enabled polymers to be widely used in automotive, aerospace, biomedical, energy, and lightweight structural applications; however, their relatively low stiffness and impact resistance often restrict their use in load-bearing components [3]. To overcome these limitations, optimized structural concepts such as sandwich architectures have been developed, in which lightweight cores are combined with stiff face sheets to enhance bending stiffness and energy absorption efficiency [4,5]. In this context, additive manufacturing, particularly fused deposition modelling (FDM)-offers unique advantages by enabling the fabrication of complex internal core geometries with precise control over infill pattern, density, and load-path continuity [2,3,6]. Among FDM-compatible polymers, poly (lactic acid) (PLA) is one of the most extensively used materials due to its low density, biodegradability, dimensional stability, and relatively high stiffness, making it suitable for reproducible experimental investigations [7,8]. Previous studies have shown that infill topology strongly affects the flexural and impact behavior of FDM-printed polymer structures; however, systematic investigations focusing on PLA-based sandwich beams, where bending stiffness, deformation behavior, impact energy, and mass efficiency are evaluated together, remain limited in the literature [3–5]. In addition to mechanical performance studies, recent research has investigated surface quality improvement and tribological behavior of FDM-printed PLA, indicating significant

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effects of novel process controls on roughness and wear performance [9]. Beyond its widespread use in FDM, recent studies have demonstrated that secondary post-processing treatments can significantly enhance the mechanical and chemical performance of PLA parts, highlighting new optimization pathways beyond printing parameters alone [10].

Poly lactic acid (PLA) polymer is a nature-friendly, recyclable, biodegradable, and biocompatible material with low density and high strength values. Due to these properties, it is the subject of numerous studies in different fields. For instance, La Mantia & Morreale [7] reviewed green composites and emphasized the role of PLA as a sustainable polymer. Körber et al. [11]studied high-temperature resistant stereocomplex PLA for injection molding, while Yang et al. [12] analyzed molding methods and mechanical properties of jute/PLA composites. Lee et al. [13] investigated PLA foam [14]extrusion behavior, and Paramitha et al. [15] developed PLA nanocomposites reinforced with clay using extrusion. Eksi et al. [16] evaluated thermoforming behavior of 3D printed PLA sheets, while Inácio et al. [17], Rakesh et al. [18] and Reiser & Bruce [19] explored casting and lost-PLA applications. Previous studies have demonstrated that the impact behavior of FDM-manufactured PLA parts is highly sensitive to printing parameters such as infill configuration and internal structure, which directly affect energy absorption and failure mechanisms [20]. Further studies highlight the role of advanced adhesive strategies and hybrid bonding on mechanical integration of FDM parts, suggesting enhanced structural performance with optimized adhesives in composite configurations [21]. In particular, post-process modifications have been shown to alter the mechanical response and durability of FDM-printed PLA components, indicating that final part performance is strongly influenced by processing routes after printing [22].

3D printing has been the subject of increasing studies. Akderya [23] examined the effect of UV curing on the flexural and absorptive behavior of PLA, while Akderya [24] studied its impact behavior after post-curing. In biomedical fields, Ghilan et al. [25] reviewed opportunities and challenges of PLA in biomedicine; Melchels et al. [26] discussed additive manufacturing of tissues and organs; Levato et al. [27] presented biofabrication of cell-laden constructs; Nájera et al. [28] produced PLA/PCL/TiO2 composites for bone grafting; Niaza et al. [29] investigated PLA/HA scaffolds for bone reconstruction; Rogina et al. [30] combined porous PLA with chitosan-based hydrogels for tissue engineering. Recent work has also explored drop weight deformation and surface cleaning techniques to minimize roughness and improve mechanical response in FDM PLA, emphasizing emerging trends in surface engineering for additive manufacturing [10]. Recent contributions further emphasize the growing interest in combining FDM process optimization with post-processing strategies to improve functional performance and reliability of PLA-based components [31].

In bioprinting, Kosik-Kozioł et al. [32] reinforced alginate constructs with PLA fibers, while Pimentel et al. [33] fabricated thick constructs with perfused channels. In electronics, Hua et al. [34] developed photothermal actuators using PLA composites; Liu et al. [35] studied shape recovery in PLA/SiC composites; Postiglione et al. [36] printed conductive PLA/CNT microstructures; Tak et al. [37] produced lightweight antennas with 3D printed PLA; Vidakis et al. [8] analyzed dielectric behavior of pure PLA and PLA with graphene; Woo et al. [38] fabricated a femtosecond fiber laser using PLA/graphene absorbers. The combined influence of infill rate, testing conditions, and filament material on impact response has also been reported, indicating that mechanical performance cannot be evaluated based on a single parameter alone [14].

In energy applications, Foster et al. [39] created porous PLA anodes for lithium-ion batteries; Maurel et al. [40] produced PLA/graphite composite filaments for energy storage; Reyes et al. [41] 3D printed complete lithium-ion batteries using PLA filaments. In automotive and structural uses, Oksman et al. [1] reinforced PLA with natural fibers; Mei et al. [42] studied short fiber and SiC nanowire reinforced PLA composites; Wickramasinghe et al. [2] reviewed mechanical properties and defects of FDM-based PLA composites. In aviation, Bustillos et al. [43] developed graphene-reinforced PLA nanocomposites, while Micó-Vicent et al. [44] optimized optical appearance of PLA and ABS prints. Recent investigations have further confirmed that infill pattern and contour configuration significantly influence the mechanical response of 3D printed PLA components under different loading rates [45].

In emerging fields, Chen et al. [46] summarized progress of PLA in bone repair applications, Sun et al. [47] applied PLA in 4D-printed functionally graded structures, and Wang et al. [48] demonstrated biomimetic color-shape responsive PLA structures. In environmental applications, Kim et al. [49] designed a 3D printed PLA-based water filtration system for arsenic removal; Shi et al. [50] used PLA films coated with MOFs for dye removal; Zhou et al. [51] developed a PLA@graphene oxide/chitosan sponge for wastewater treatment. The bending behavior of 3D printed sandwich beams was shown to be strongly dependent on core topology, with different internal geometries leading to significant variations in stiffness and deformation characteristics [52].

Given this broad application spectrum, infill patterns in 3D printing play a critical role in mechanical properties, enabling lightweight yet durable structures. Several studies specifically focused on infill effects: Patil et al. [53] investigated surface roughness influenced by infill; Aloyaydi et al. [4] studied compression and impact behaviour; Chacón et al. [3] analyzed ductility, flexural and tensile strength; Rodríguez-Panes et al. [6] examined tensile strength under various print parameters; Mishra et al. [5] studied combined infill density and pattern effects on impact resistance. It has been reported that combined and complex infill patterns can significantly enhance mechanical properties by improving internal load-path continuity in FDM-produced parts [54].

The aim of this study is to investigate the bending and Charpy impact properties of PLA sandwich beams produced by 3D printing with different infill patterns. While previous studies generally focused on the effect of infill patterns on simple geometries such as standard tensile or compression specimens, the literature lacks a detailed analysis on sandwich beam structures, where the mass-to-strength ratio is of critical importance. Although the influence of infill density and pattern has been reported for flat or solid parts, the combined evaluation of bending stiffness, bending strength, displacement, and Charpy impact behaviour in lightweight sandwich beams has not been sufficiently addressed. Therefore, this study aims to fill this gap by producing thirteen different sandwich beam specimens with varying infill patterns, measuring their mechanical performance in detail, and discussing how the internal geometry can be optimized for both low mass and high mechanical efficiency. Although FDM-printed polymer sandwich structures and their bending behavior have been previously investigated, the originality of this study lies in the systematic comparison of thirteen different infill patterns within sandwich beam configurations and the combined evaluation of bending and unnotched Charpy impact responses from a mass–mechanical efficiency perspective. This approach enables mechanics-based insights into load-path continuity and provides application-oriented design guidance for lightweight FDM-manufactured structures.

II. MATERIALS AND METHODS

Within the scope of this study, the effects of the infill pattern in the slicing program on bending and non-notch Charpy impact loading of sandwich structures were examined. For this purpose, thirteen different infill patterns (Figure 1) defined in the Ultimaker Cura software [55] were employed, as the geometry of the internal structure directly determines the mechanical behaviour, mass efficiency, and energy absorption capacity of additively manufactured components. The grid pattern provides a balanced bidirectional reinforcement, distributing loads uniformly across two perpendicular axes. The lines pattern generates unidirectional paths, offering simplicity and reduced material usage but often at the expense of stiffness. The triangles pattern creates a rigid cellular network with strong angular connections, leading to high resistance against deformation. The cubic pattern constructs a three-dimensional lattice that enhances isotropy and load-bearing capability in multiple directions. The cubic subdivision is an optimized variation that subdivides cubic cells, maintaining strength while significantly reducing mass. The concentric pattern forms layered circular or prismatic contours, yielding high bending resistance through continuous and interconnected load paths. The cross and cross 3D patterns generate orthogonal or spatially intersecting lines, producing lightweight yet relatively stable structures. The gyroid pattern establishes a continuous, triply periodic minimal surface with high energy absorption and deformation capability due to its curved cellular morphology. The zigzag pattern, like lines but alternating direction layer by layer, balances print speed with moderate strength. The octet pattern introduces a tetrahedral and octahedral lattice geometry, mimicking high-strength truss structures. The quarter cubic pattern is a simplified cubic derivative, aiming for reduced weight while retaining acceptable stiffness. Finally, the lightning pattern selectively reinforces only critical stress regions, minimizing mass and material consumption but generally resulting in low structural strength. By incorporating such diverse infill geometries, this study enables a comprehensive evaluation of how internal pattern selection influences the mechanical response of PLA sandwich beams.

The shell thickness of these sandwich structures is 1 mm, the core thickness is 10 mm, their length is 127 mm, and their width is 12.7 mm. In sandwich structures, only the infill patterns of the core parts are different, but all other parameters (Table 1) are the same. After the sandwich structures were sliced, they were produced using an Ultimaker S5 brand 3D printer in the Additive Manufacturing Technologies laboratory of Manisa Celal Bayar University, Department of Mechanical Engineering. The PLA filaments used in this study were supplied by BASF, and all their properties are available online via the manufacturer's data sheet. Cura slicer, compatible with the Ultimaker S5, was used in this study. A layer height of 0.2 mm and an infill density of 25% were selected as representative FDM parameters to ensure reliable interlayer bonding and reproducibility while emphasizing the effect of infill geometry on the mechanical performance of lightweight PLA sandwich beams.

All tests were carried out using test devices in the Mechanics Laboratory of Manisa Celal Bayar University, Department of Mechanical Engineering. The mass difference between the printed parts was examined by weighing the samples produced for each parameter using an RADWAG PS 1000/C/2 brand precision scale. A 3-point bending test (Figure 2) was performed on each specimen at a crosshead speed of 1 mm/min according to ASTM D790, with five replicates conducted per sample using the Shimadzu Autograph universal testing machine, and the bending modulus, bending strength, and bending displacement values were obtained. Unnotched Charpy impact tests (Figure 3) were carried out on each specimen according to ASTM D6110 using the MTECH XJJ-50S

Digital Charpy impact testing machine (conducted using a 7.5 J striker), and the impact energy and strength values were obtained. Evaluations regarding the values obtained because of the tests are included in the next section.

Table 1. 3D printing parameters

Parameter	PLA
Layer Height	0.2 mm
Line Width	0.4 mm
Nozzle Diameter	0.4 mm
Wall Line Count	0
Z Seam Position	Shortest
Top Layers	5
Bottom Layers	5
Infill Density	%25
Print Temperature	195 °C
Build Plate Temperature	60 °C
Flow Rate	%100
Print Speed	60 mm/s
Travel Speed	100 mm/s

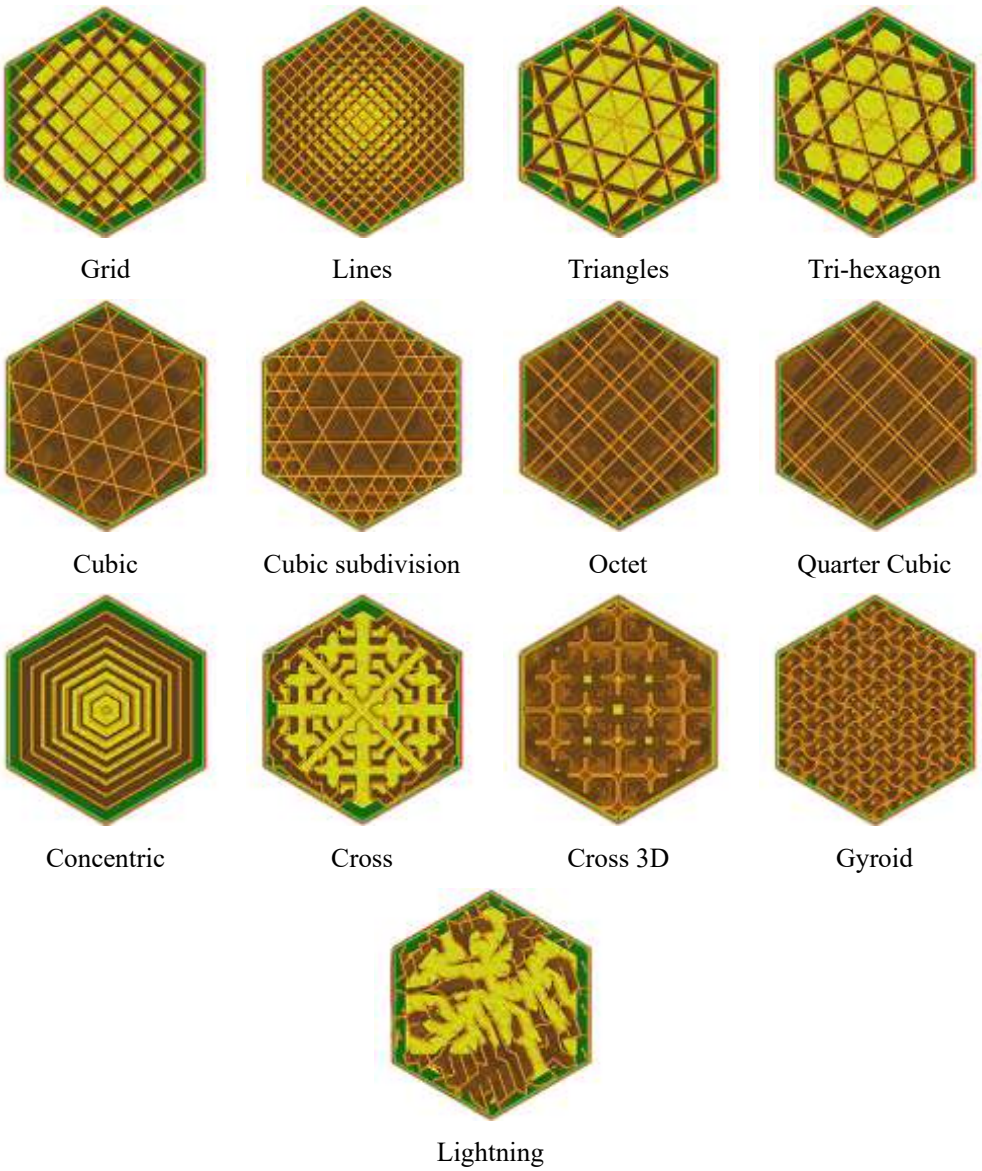


Figure 1. Infill patterns [55]



Figure 2. Bending test of sandwich beam



Figure 3. Charpy impact test of sandwich beam

III. RESULTS AND DISCUSSIONS

3.1 Mass change

The masses of the samples printed using the 3D printer, where only the infill patterns are different, are shown in Figure 4. The mass of the specimens varied considerably depending on the infill pattern, even though all other printing parameters remained constant. It was observed that cubic subdivision, concentric, and cross 3D patterns had approximately 10% lower mass compared to other geometries, while the lightning pattern reduced the mass by about 45%. The reduction stems from two main factors: (i) the total filament length required per unit volume, and (ii) the efficiency of the geometric topology in connecting structural regions. For example, the cubic subdivision pattern builds a three-dimensional lattice with subdivided cells that provide continuity with reduced material consumption, whereas the concentric pattern relies on continuous circular contours that minimize material usage while maintaining load paths. The lightning pattern, designed primarily to accelerate printing, selectively reinforces only stress-critical areas and leaves large hollow volumes, thus achieving a drastic mass reduction at the expense of structural continuity. Similar mass trends have been reported in the literature [5,6], where

lightweight lattice and gyroid infill were shown to reduce material use while still providing functional stiffness under low loads.

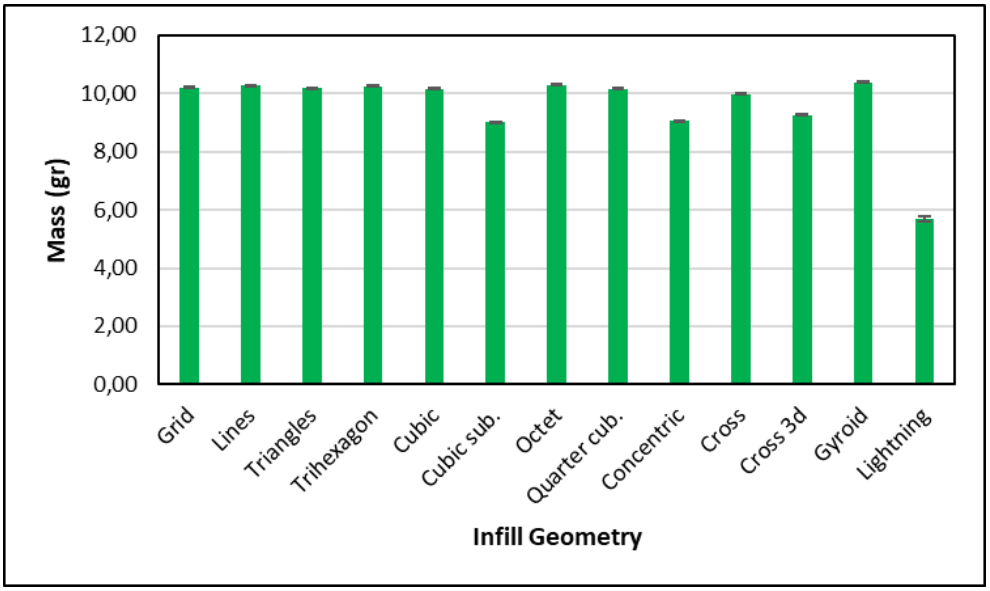


Figure 4. Mass change for infill patterns

3.2 Bending properties

The effect of infill patterns on bending properties is examined in this section. Figure 5 shows the bending stiffness, Figure 6 shows the bending strength, Figure 7 shows the bending displacement graphs and the effect of the infill pattern on these properties. The bending performance is governed by the sandwich mechanics of the beams: while the shells primarily resist tensile and compressive stresses under bending, the infill core maintains the distance between the shells, increases the second moment of inertia, and transfers shear stresses. Thus, the continuity and orientation of internal load paths created by the infill pattern become decisive.

The concentric pattern exhibited the best bending performance, with about 28–30% higher bending strength and stiffness than most other patterns, despite its 10% lower mass. This is attributed to the continuous circular contours that provide uninterrupted load paths across the section, effectively distributing stresses and delaying crack initiation. The lines pattern, by contrast, formed only unidirectional filaments with very few interconnections, which resulted in poor lateral support and shear transfer, making the structure highly flexible and leading to the lowest stiffness among all geometries. Cross and cross 3D patterns, despite their lower mass, showed approximately 17% reduction in stiffness because their connectivity was limited and lacked out-of-plane reinforcement. The gyroid pattern, based on a triply periodic minimal surface, displayed lower stiffness but significantly higher deformation capacity, since its curved cellular morphology enabled distributed strain and gradual collapse rather than sudden brittle failure. The lightning pattern, although drastically lighter, carried almost no bending load due to its sparse and discontinuous structure. These observations are consistent with previous studies: Chacón et al. [3] reported that geometries with poor connectivity led to reduced flexural properties. he flexural strength obtained in this study fall within the range reported for FDM-printed PLA specimens in previous studies, confirming that the selected printing parameters and testing methodology yield representative mechanical

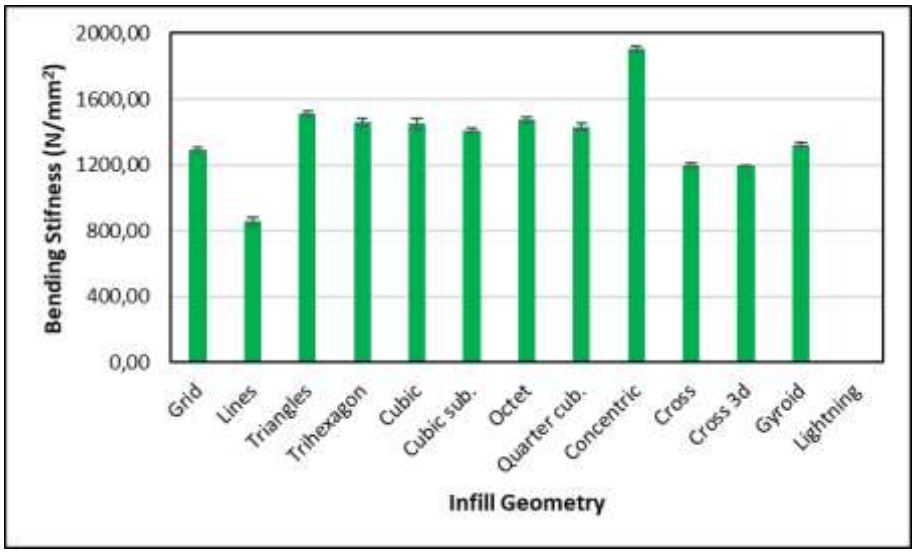


Figure 5. Bending stiffness for infill patterns

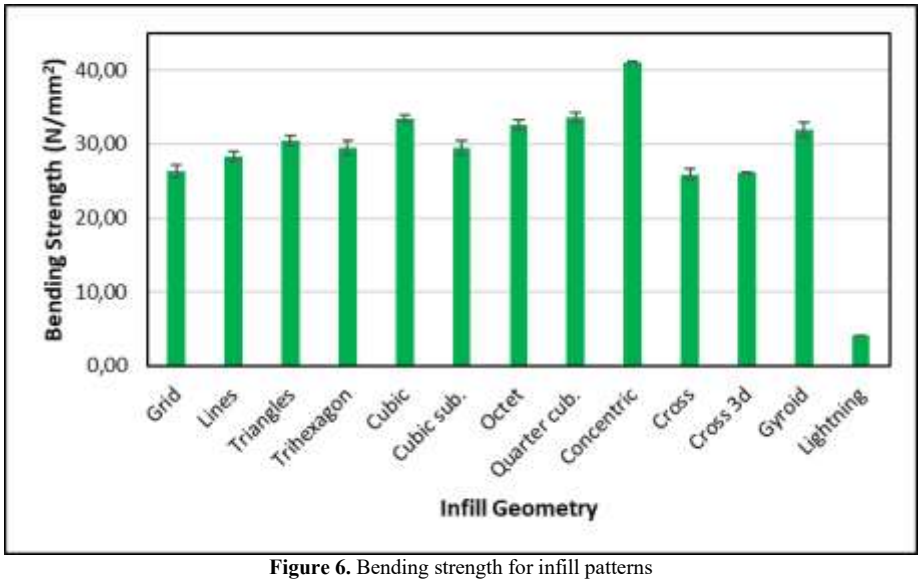


Figure 6. Bending strength for infill patterns

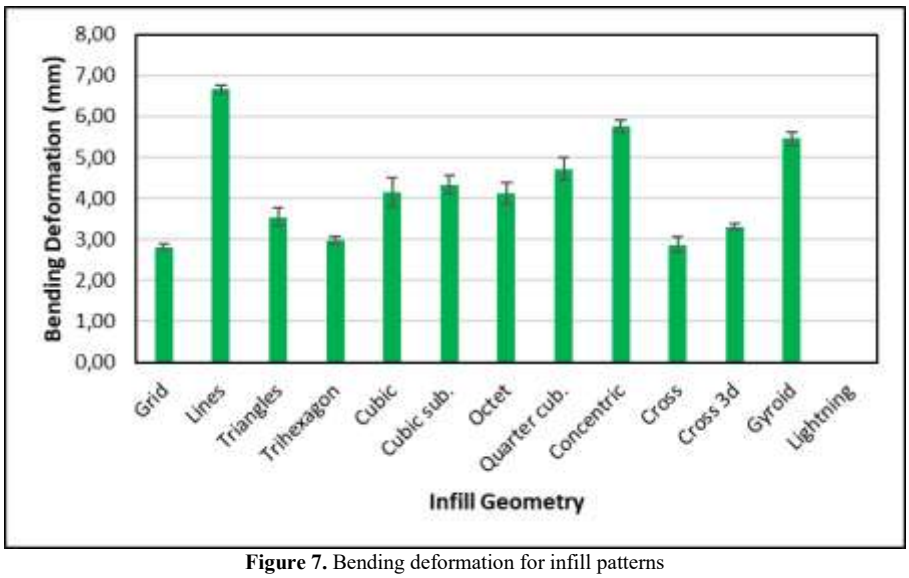


Figure 7. Bending deformation for infill patterns

behavior [56]. Consistent with earlier investigations, improved flexural strength is associated with enhanced interlayer bonding and internal load-path continuity, which explains the superior performance of concentric infill patterns observed in the present work [57]. Comparative studies on FDM-printed PLA further indicate that flexural strength is highly sensitive to internal geometry and processing parameters, supporting the pattern-dependent trends reported in this study [58].

3.3 Charpy impact properties

In this section, the effect of infill pattern on Charpy impact energy will be examined. While Figure 8 gives the Charpy impact energy value, Figure 9 indicates the impact energy per unit area. From a mechanics standpoint, bending stiffness and strength primarily depend on the continuity of load paths and the shear transfer capacity of the core, whereas impact energy absorption is more sensitive to the ability of the geometry to deform plastically and dissipate energy progressively. The concentric pattern excelled in both domains because of its closed-loop architecture, which simultaneously enhanced stiffness and allowed gradual energy dissipation. The gyroid also demonstrated superior impact behavior due to its periodic minimal surface topology. Conversely, patterns like lightning, which focus on reducing mass by minimizing interconnections, are unsuitable for load-bearing applications despite their advantages in material savings. These conclusions are consistent with broader findings [53] in additive manufacturing, where the interplay between infill density, geometry, and load case determines the overall mechanical efficiency. Similar trends in impact energy enhancement with improved internal connectivity of FDM-printed PLA structures have been reported in the literature, where infill configuration and load-path continuity were identified as dominant parameters governing energy absorption behavior [20]. Comparative studies on PLA-based FDM specimens also indicate that geometries promoting progressive deformation, rather than brittle fracture, exhibit higher impact resistance, which is consistent with the superior performance observed for concentric and gyroid infill patterns in the present work [59]. The impact energy levels obtained in this study are in good agreement with reported ranges for FDM-printed PLA under Charpy-type loading, further confirming the validity of the observed pattern-dependent impact response.

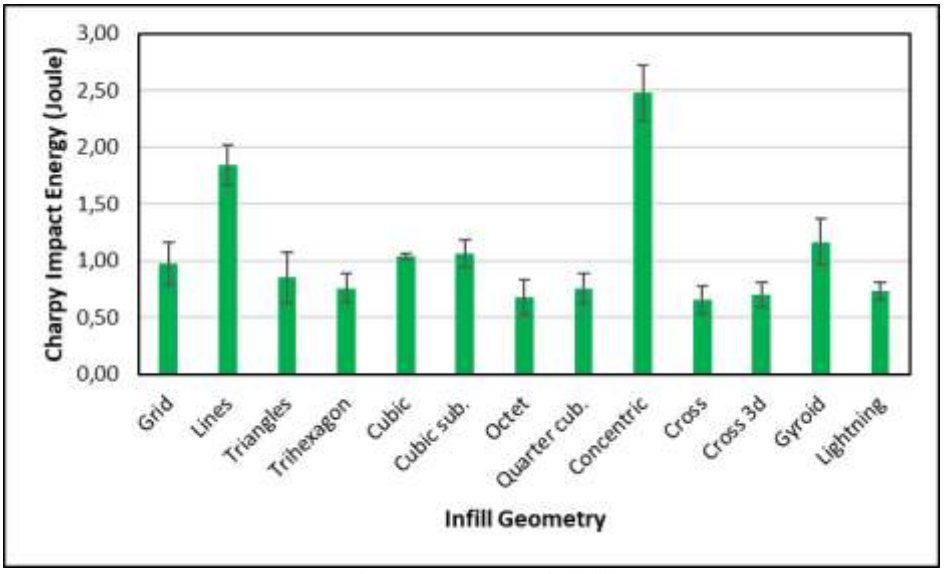


Figure 8. Charpy Impact Energy for infill patterns

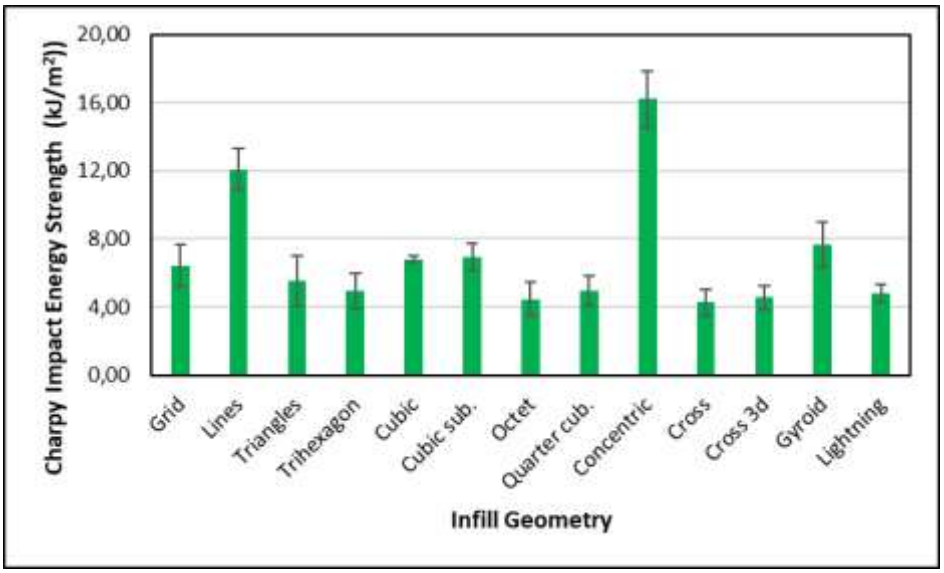


Figure 9. Charpy Impact Energy Strength for infill patterns

IV. CONCLUSIONS

This study demonstrated that infill geometry strongly governs the bending and impact behavior of 3D-printed PLA sandwich beams beyond simple mass reduction. Patterns such as cubic subdivision, concentric, and cross 3D achieved notable material savings, while lightning provided the lowest mass but almost no bending capacity, confirming that discontinuous topologies are unsuitable for structural applications.

Among all geometries, the concentric pattern offered the best overall performance, combining high bending stiffness with superior impact energy absorption due to its continuous load paths. The gyroid pattern also showed excellent impact resistance through gradual cell collapse, while the lines pattern absorbed significant energy but lacked stiffness. These results align with previous studies highlighting the critical role of infill connectivity in mechanical response.

In conclusion, concentric and gyroid patterns are recommended for lightweight yet mechanically efficient sandwich structures, whereas lightning should be limited to non-load-bearing prototypes. Future research should extend these findings by varying infill density, shell thickness, and print orientation to establish more comprehensive design guidelines.

From a practical and industrial perspective, the findings of this study provide direct design guidelines for lightweight and load-bearing components produced by FDM using PLA. The superior bending and impact performance of concentric and gyroid infill patterns, combined with their reduced mass, makes them particularly suitable for applications such as lightweight structural brackets, protective casings, energy-absorbing panels, and interior components in automotive and transportation industries. In aerospace and UAV structures, these infill designs offer opportunities for weight reduction in non-critical load-bearing parts while maintaining sufficient stiffness and impact resistance. Additionally, in packaging, tooling, and customized fixtures, optimized infill selection enables material savings, shorter production times, and improved mechanical reliability without changing the external geometry. Therefore, the results of this work can be directly implemented in industrial FDM design workflows to enhance mass efficiency and mechanical performance simultaneously.

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