

Mechanical Behaviour of a novel 3D-Printed Cubic Cellular Structures Under Bending Loads: An Experimental and Numerical Analysis

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Abstract. This research presents a novel 3D-printed cubic cellular structure fabricated using fused deposition modelling (FDM) with a no-infill technique. It reports on both experimental and numerical analyses of these cubic cellular structures, examining configurations with 1, 2, 3, and 4 cell layers subjected to 3-point loading. The experimental results suggest that there is a correlation between the number of cell layers and the structural response under bending. A distinct transition in mechanical behaviour is observed from the 2-cell to the 4-cell structures, characterised by a linear trend, with a notable reduction in the amount of deflection as the number of cell layers increases. Meanwhile, the 1-cell layer structure exhibits a bending-dominant deformation. The results of the finite element model clarify the influence of the strut diameter and the number of cell layers on the bending behaviour, aligning well with the experimental findings. Overall, the 1-cell layer structures demonstrate bending dominance, while the 3- and 4-cell layer structures exhibit linear dominance. The 2-cell configuration uniquely combines both bending and linear behaviours.

Keywords: cubic cellular structures, FDM, mechanical characterisation, truss structures, polymer

1. INTRODUCTION

Fused deposition modelling (FDM) is regarded as a pioneering and the most widely used technique in the field of additive manufacturing (AM) due to its printing accuracy, low manufacturing costs, ease of use, and ability to create complex geometries (Rahman et al., 2023; Ammar Ahmed et al., 2021; Reddy et al., 2020; Lalegani Dezaki et al., 2021). These advantages have led to the adoption of FDM technology in various industries, including aerospace, automotive, and biomedical applications (Rahman et al., 2023; Ammar Ahmed et al., 2021; Reddy et al., 2020). The final quality of printed products is significantly influenced by several parameters, such as layer thickness, temperature, print speed, infill, and pattern density, regardless of the material used (Rahman et al., 2023; Wang et al., 2020; Liu et al., 2020).

Various materials, including polymers, composites, and metals, can be utilised in the FDM process (Lalegani Dezaki et al., 2021). Among these, PLA (polylactic acid), primarily derived from starch and natural resources, stands out as the most widely used material in FDM technology (Rahman et al., 2023). Its popularity stems from its high efficiency in additive manufacturing, affordability, sustainability, biocompatibility, and adequate mechanical performance, making it suitable for a wide range of applications. Furthermore, PLA has gained traction in the fabrication of mechanical structures, particularly lattice structures, due to its versatility in both short- and long-term used in the mechanical industries (Rahman et al., 2023).

Lattice structures are periodic arrangements created by the regular repetition of a unit cell in three dimensions (Pereira et al., 2022). They can be designed and manufactured to achieve specific mechanical properties (Cao et al., 2023), provide thermal insulation (Pereira et al., 2022), support bone and skin regeneration (Liu et al., 2020; Herath et al., 2021), and enhance energy absorption (Gibson, 2003; Sankineni & Yennam, 2021). One of their key advantages is their low weight. Various lattice structures have been explored in the literature, commonly based on unit cells such as

pyramidal, diamond, octahedral, and rhombic configurations (Pereira et al., 2022; Gibson, 2003). However, despite their unique properties, the fabrication of these structures remains challenging (Cao et al., 2023; Myers et al., 2022).

The fabrication of lattice structures is primarily accomplished through additive manufacturing (AM), which offers operational efficiency and advantages over traditional methods. Among the various AM techniques, FDM is widely utilised for producing lattices layer by layer. However, this process inherently introduces anisotropy in the final structure (Pereira et al., 2022), as the layer-by-layer deposition affects the adhesion between layers, resulting in variations in mechanical performance. Research indicates that parameters such as layer thickness, infill density, and strut orientation significantly impact the structural integrity of the final product (Reddy et al., 2020; Jian et al., 2024).

A significant challenge in FDM-printed lattice structures is the detachment of layers and failure at joint connections, which arise from insufficient bonding between successive layers (Pereira et al., 2022). While higher infill densities generally improve mechanical properties, the deposition process can still lead to localised weaknesses. Additionally, reducing layer thickness changes failure modes, resulting in more compact and mechanically robust structures. However, in lattice structures, the thin layers or beam members do not permit infill density (Rahman et al., 2023). The compressive energy absorption capacity of these lattices is influenced by factors such as strain rate, cell orientation, and strut alignment, further emphasizing the challenges associated with layer-by-layer manufacturing (Sankineni & Yennam, 2021; Bates et al., 2016).

Recent studies have implemented strategies to address challenges associated with the manufacturing of complex designs, notably using adaptive slicing techniques, which adjust layer thickness based on the geometry of the model. This approach has demonstrated improvements in interlayer adhesion and a reduction in stress concentrations at the joints (Tamburrino et al., 2019). Additionally, incorporating graphene or carbon nanoparticles into the filament material has enhanced the interfacial bonding between layers, resulting in improved mechanical performance of lattice structures (Radhika Mandala et al., 2025). Furthermore, applying post-processing techniques, such as heat treatment or chemical smoothing, has effectively reduced surface roughness while enhancing layer adhesion, leading to increased compressive strength and energy absorption capacity (Sawant et al., 2023).

Currently, the impact of printing parameters, such as nozzle temperature, printing speed, and cooling rate, on the mechanical properties of lattice structures is being studied. The optimisation of nozzle temperature has significantly enhanced layer bonding, while both printing speed and cooling rate have drastically influenced residual stresses (Kothandaraman et al., 2024). Moreover, the adoption of hybrid manufacturing techniques, which combine Fused Deposition Modelling (FDM) with other additive manufacturing methods like selective laser sintering (SLS), has been proposed to mitigate the limitations of FDM technology in producing high-performance lattice structures with complex geometries (Li et al., 2024). These advancements underscore the ongoing efforts to address the inherent challenges of FDM-printed lattice structures and broaden their applications in fields such as aerospace, automotive, and biomedical engineering.

The dimensions of the struts play a crucial role in determining the mechanical behaviour of lattice structures and have been extensively studied. Increasing the strut diameter enhances compressive strength and energy absorption capacity, while reducing the strut diameter increases the flexibility of the lattice structures (Ali et al., 2023). Furthermore, the introduction of hierarchical lattice designs, which incorporate multiple levels of strut thicknesses, has been shown to improve the load-bearing capacity and energy dissipation characteristics of these structures (Di Frisco et al., 2024).

Lattice structures subjected to compression can be broadly classified into bending-dominated and stretching-dominated types (Karthic et al., 2023). Furthermore, uniaxial stretching of polymers aligns the polymer chains in a single direction, enhancing their mechanical properties (Li et al., 2019). However, achieving this chain alignment in FDM is challenging due to the layer-by-layer process, which typically results in polymer chains aligning perpendicularly to the nozzle. This alignment can be beneficial for unidirectional testing, leading to improved isotropy and mechanical properties when using struts. Recent studies have employed finite element methods (FEM) to estimate the mechanical properties of FDM-printed lattice structures, revealing correlations with the elastic modulus at the macro level, particularly for cell samples ranging from 3 to 5 mm (Rahman et al., 2023; Ji et al., 2023). Recent studies have integrated machine learning algorithms with finite element methods (FEM) to predict the mechanical properties of lattice structures more accurately and efficiently (Zhao et al., 2023). However, the FEA simulation has demonstrated a strong correlation with the experimental results in the linear regime, showing minimal influence from the infill pattern and the dimensions of the unit cell. In contrast, as displacement progresses, a divergence of the curves appears (Photiou, 2021; Mohammadi, 2024) when dealing with 3D unit cell configurations. On the other hand, the accuracy of FEA models in representing unit cell structures—especially in 2D configurations that include infill—has been clearly evident, particularly during the transition from the linear to the non-linear regime. This indicates that FEA closely replicates the mechanical response of additively manufactured components, even when considering the layer-by-layer deposition process (Najafi, 2022; Johnston, 2021; Musavi, 2025). Conversely, when FEA is applied under impact loading conditions, the correlation with experimental results becomes moderate. This is primarily due to the absence of full 3D modelling and the influence of the layer-by-layer manufacturing process. Nevertheless, the simulations remain predictive under low displacement scenarios, while the infill pattern plays an important role as displacement progresses (Papa, 2025). These models can account for complex interactions between material properties, geometric parameters, and loading conditions, enabling the design of lattice structures with tailored mechanical responses.

Despite significant advancements in additive manufacturing and the mechanical characterisation of FDM-printed PLA lattice structures, including tensile, compressive, and bending tests, most studies focus on common infill patterns, layer height, temperature, and print speed (Rahman et al., 2023; Reddy et al., 2020; Cao et al., 2023). There is a notable lack of research specifically addressing lattice structures composed exclusively of interconnected struts. For instance, Photiou (2021) explored 3D strut-based structures with dimensions of a 30 mm unit cell; however, the study relied on a 100% infill density and employed selective laser sintering (SLS), rather than investigating the complete removal of the layer-by-layer condition or alternative fabrication methods such as Fused Deposition Modelling (FDM). Furthermore, while several investigations have examined common lattice topologies, fewer studies have explored the effects of varying vertical scaffold height on mechanical behaviour under bending conditions. Additionally, there is a lack of comprehensive validation through experimental and finite element analysis (FEA) for these beam-based lattices under bending scenarios.

This research aims to address critical gaps in the current literature by presenting a novel scaffolded lattice beam composed entirely of interconnected strut members, arranged in unit cells measuring just $3 \times 3 \times 3 \text{ mm}^3$. In contrast to prior studies, which typically focus on larger-scale lattice structures—often 30 mm or more per unit cell—and utilise different additive manufacturing techniques, this study demonstrates the capability of fabricating fine, fully three-dimensional strut-based architectures using Fused Deposition Modelling (FDM) technology. The structures were manufactured without the application of any internal infill, diverging from typical lattice designs that combine solid infill with cellular geometries (Gharehbaghi, 2025), which are commonly fabricated in 2D honeycomb

formats considering layer-by-layer parameters. These approaches often lead to misleading results due to the orientation of the printed layers.

Conversely, the fabrication of true 3D unit cells remains a challenge in Fused Deposition Modelling (FDM) technology due to the small dimensions of the strut members. This issue is compounded when external loads are applied vertically, leading to complex mechanical interactions that are not yet fully understood—especially in geometries belonging to the auxetic domain, where strut elements typically range from 1.2 to 1.5 mm in diameter and are deposited layer by layer horizontally. However, the current study minimises the use of 3D printed struts with a layer-by-layer technique, achieving a thickness of just 0.3 mm. This allows for a clearer investigation of the mechanical response of the structure, reducing the influence of the layer-by-layer effect. Consequently, the study examines how varying the number of vertical cell layers (i.e., structure height) and the arrangement of thin strut members influences overall mechanical performance without the impact of layer-by-layer deposition.

Previous work conducted by Gharehbaghi et al. (2024) has examined energy absorption in lozenge-grid honeycomb structures under various loading angles; however, their analysis was limited to 2D configurations and did not address the manufacturing constraints or mechanical behaviour of fully 3D printed architectures. Similarly, bio-inspired designs that mimic natural structures, such as palm trees, have been explored (Avarzamani, 2024), yet these studies also largely omit the implementation of 3D unit cells. Thus, this study makes a novel contribution by enabling the fabrication and mechanical evaluation of small-scale, strut-based 3D lattice structures using FDM, overcoming many of the limitations present in the current literature.

The mechanical behaviour of the structures is experimentally characterised under three-point bending tests, providing insight into the flexural response of minimal-material lattice beams. These experimental results are further validated through finite element analysis (FEA), establishing a strong correlation between physical testing and numerical predictions. This combined experimental–numerical approach offers a deeper understanding of how geometry and material distribution affect stiffness in strut-based architectures.

2. MATERIAL AND METODOLOGY

2.1- Materials and manufacturing

The structures are printed using poly-lactic acid (PLA) filament with a diameter of 1.75 mm, sourced from 3DLAB in Brazil. A fused deposition modelling (FDM) system, specifically the Ender-3-S1 printer, equipped with a direct extrusion system, is utilised. The proposed geometry is a lattice cubic cellular structure with unit cell dimensions of $3 \times 3 \times 3 \text{ mm}^3$, featuring extruded diameters of 0.6 mm for the vertical members and 0.5 mm for the horizontal members, as illustrated in Figure 1c. The lattices are fabricated using the FullControl GCode Designer library for python (Gleadall, 2021). This approach is particularly beneficial because FDM technology is highly adaptable, enabling extrusion along the Z-axis and a variable extrusion amounts throughout the 3D printing process.

Figure 1 provides a detailed, step-by-step illustration of the extrusion process. The grey lines indicate the path followed by the laser, while the dark lines represent the printed filament. The first layer printed is the one resting on the bed (Figure 1a). This is followed by the extrusion of the vertical member in the Z direction (Figure 1b). Finally, the horizontal members are printed (Figure 1c). If the structure includes multiple scaffolds, the process continues by printing all the vertical members first, followed by the horizontal ones.

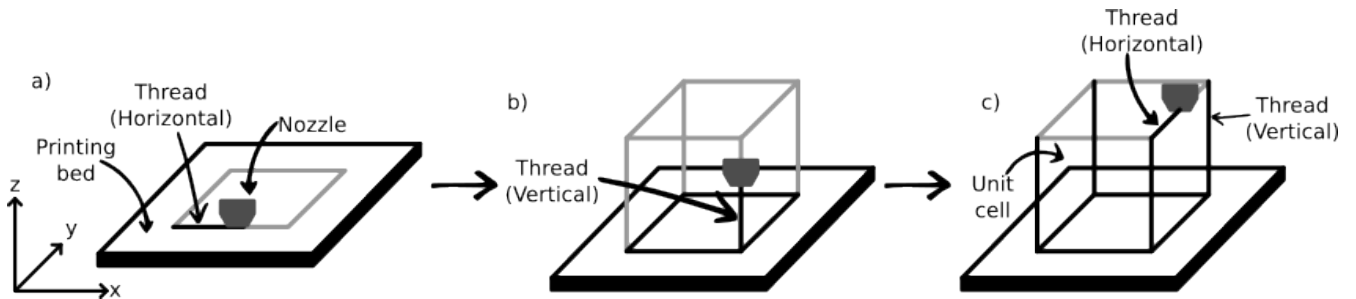


Figure 1. Stages of the 3D printed lattice structure: a) on the print bed, b) vertical member, and c) horizontal member of the unit cell.

Four structures, each comprising 1, 2, 3, and 4 scaffolds with 4 samples each, have been fabricated. The scaffold in contact with the print bed, referred to as scaffold 0, exhibits deformed horizontal struts due to its interaction with the bed. Consequently, it has been removed using a laser cutting process, as illustrated in Figure 2, to achieve more uniform samples.

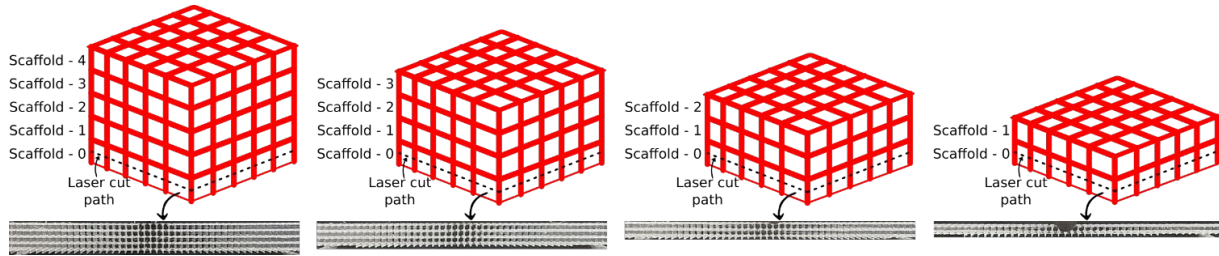


Figure 2. Illustration of the structures made with 1, 2, 3, and 4 scaffold and the location of the laser cutting.

2.2 Experimental and numerical analysis

The three-point bending test is adopted to characterise stiffness and strength of the cellular structures proposed in this work. All samples consist of 50-unit cells in length (150 mm), 4-unit cells in width (12 mm), and variable number of cells in the thickness based on the number of scaffolds 1-, 2-, 3-, and 4-unit cells corresponding to heights of 3, 6, 9, and 12 mm, respectively. An Instron machine equipped with a 1 kN load cell is used to test the samples at a rate of 1.5 mm/min, maintaining a constant span of 130 mm at room temperature ($\sim 22^\circ\text{C}$), in accordance with ASTM standards D790-17 and C393/C393M (2017).

The finite element analysis (FEA) of the lattice structures is performed using Ansys® 2024, employing a nonlinear static analysis with large deflection. The model utilises 1D beam elements (Beam188), with each beam divided into 5 elements for mesh refinement. The support rollers and indenter are treated as rigid constraints, while contact parameters are defined for the supports and the indenter. The analysis involves lowering the indenter, which also incorporates contact parameters, to simulate the mechanical interaction accurately. The PLA is modelled with a Young's modulus of 3.5 GPa and a Poisson's ratio of 0.3 (Baeza Campuzano et al., 2024). The material non-linearity is modelled using a yield stress of 12.5 MPa and a tangent modulus of 1600 MPa. The samples are modelled as $\frac{1}{2}$ using the symmetry about the y-axis. The beam elements are modelled using the axis of the vertical and horizontal struts illustrated in Figure 3.

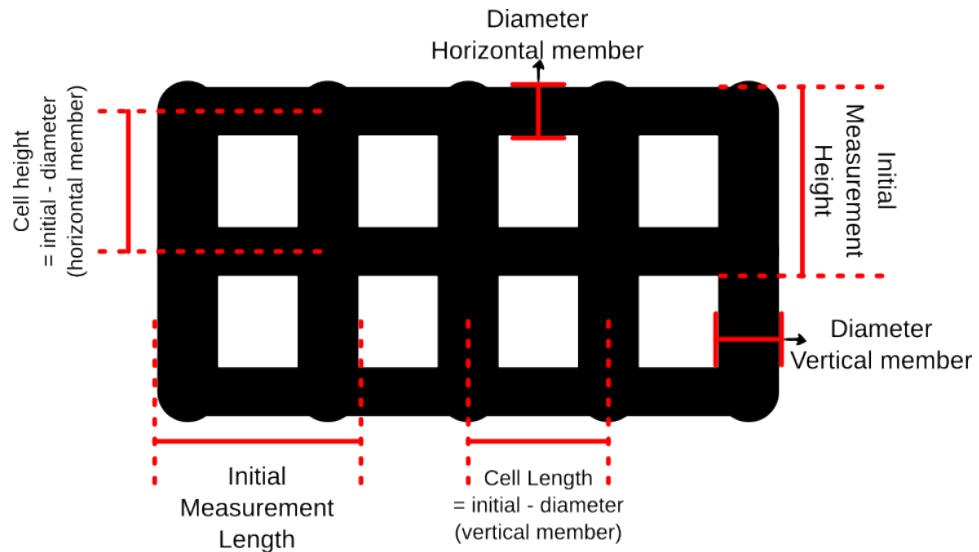


Figure 3. Cell dimensions considering the dimensions of the struts

The dimensions of the cells in the 3 directions are measured using a Python® code through digital image analysis of pictures of the truss structures. The selected cells and members are those in contact with the indenter, as illustrated in Figure 4. The sample featuring the centre member and cells is highlighted in red (Figure 4a), while measurements are taken along the vertical and horizontal members (Figure 4b). The results of these measurements will be discussed later.

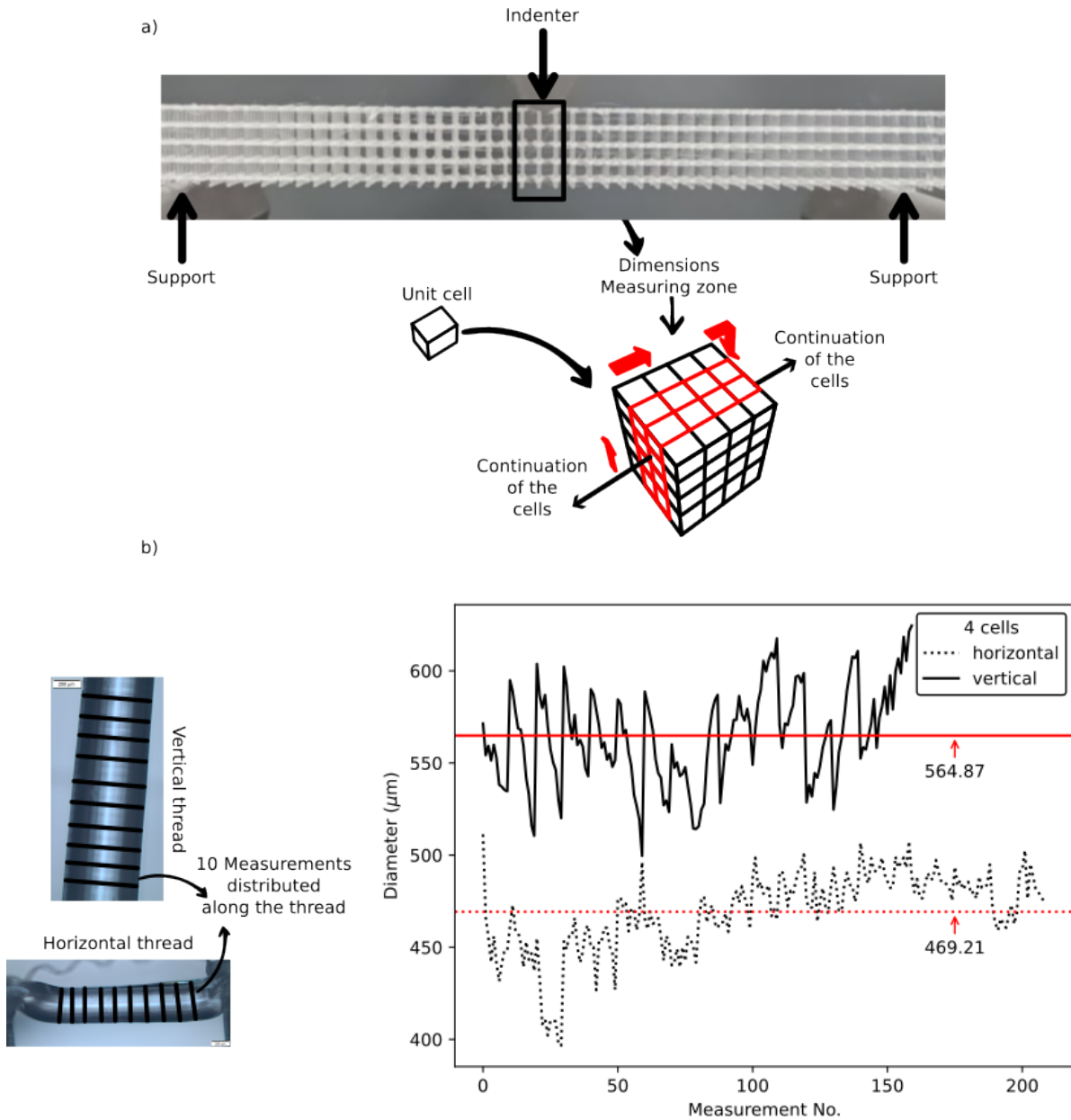


Figure 4. a) Cells members considered for dimension analysis, as highlighted in red, b) measurement performed on the vertical and horizontal members.

3. RESULTS AND DISCUSSION

The results from the three-point bending test indicate a direct correlation between structural height and maximum strength. The structure with a height of four cells achieves the highest mean force of 9.45 N, while the mean force gradually decreases with reduced height, reaching 1.454 N for the structure with a height of one cell. This trend is consistent with the principle that stiffness is proportional to the second moment of area. As height increases, so does the moment of inertia, which enhances stiffness and leads to a greater load-bearing capacity.

The flexural modulus is calculated in accordance with ASTM D790 to provide insight into the stiffness of cubic lattice structures with varying heights. The results indicate a progressive decrease in

flexural modulus as the height of the cubic structures increases. Specifically, the four-cell structure has the lowest mean elastic modulus, while the one-cell structure shows the highest value. However, despite this reduction in material stiffness, the overall structural stiffness increases with the number of cells due to geometric effects—taller structures experience less deflection under load and greater resistance to bending. This behaviour indicates that while the flexural modulus of the material is lower in taller structures, their increased second moment of area enhances their apparent stiffness, leading to reduced bending and deflection.

The modulus of toughness is defined as the area under the stress vs. strain curve, which illustrates the material's ability to absorb energy before failure. A distinct pattern emerges in the modulus of toughness, reflecting the material's capacity to withstand energy absorption prior to fracturing. The one-cell structure exhibits the highest mean toughness modulus, while the two-cell structure shows the lowest. Interestingly, both the four-cell and three-cell structures present identical mean toughness moduli, despite variations in flexural modulus, as depicted in Table 1. This suggests a transition in the structural behaviour from being stiffness-dominated to bending-dominated. The energy absorption capacity increases due to the greater deformation potential before failure in shorter structures. In contrast, taller structures tend to exhibit more localised failure mechanisms, which diminishes energy dissipation. Furthermore, total deflection increases as height decreases, as lattices with fewer cells demonstrate lower stiffness, resulting in greater bending displacement (see Figure 5a). Conversely, the four-cell structure, characterised by higher stiffness, experiences reduced displacement and minimises bending curvature. The displacement values for the two-cell and three-cell structures are nearly identical, indicating a shift from bending-dominant behaviour to a more linear response. These trends are further illustrated in Figure 5 and Table 1.

Figure 5 illustrates the FEA model, where the actual dimensions of the cellular structures and their components are derived using a previously described Python code. The graph presents force-displacement curves for each group of cell layer number (4, 3, 2, and 1 cell), with the 4 cell layer structure consisting of four repetitions. The curves corresponding to the samples with the highest and lowest recorded forces define the boundaries of a shaded region, representing the range of experimental variability. Consequently, the force-displacement results from the FEA model align with this region, as clearly demonstrated by Photiou (2021) and Mohammadi (2024), thereby validating the accuracy of the numerical analysis. Figure 5f illustrates the finite element model depicting the displacement within the structure, which correlates well with the physical model. It is evident that the red regions indicate localized deformation in a few cells near the indenter. As the distance from the indenter increases, the cells exhibit progressive elongation that eventually diminishes, resulting in more squared cell shapes. This behaviour is particularly noticeable in the 4-cell members, highlighting a strong influence of shear effects. In contrast, the 3-cell members display less pronounced cell deformation, leading to a more uniform square shape and suggesting a reduced dominance of shear effects. This trend becomes even more apparent in the 2-cell members. Conversely, the 1-cell structure demonstrates more bending-dominated behaviour at the centre. Although potential shear effects may be present farther from the indenter, they are not as clearly visible as in the 3- and 4-cell cases. Additionally, key regions of the curves, such as the linear elastic regime, plastic deformation, and fracture, are highlighted with rectangles to indicate common elastic and non-elastic regions (Figure 5). However, for the one-cell configuration, the behaviour of the curve

is clearly observed to increase between 14 and 16 mm, demonstrating bending behaviour as evidenced by the sample images. The structures consist of horizontal and vertical members, each contributing differently to stiffness and load-bearing capacity, making their precise representation essential for an accurate force-displacement response. Finally, it was clearly visible a fracture effect compared to crushing as obtained in previous work conducted by Gharehbaghi and Farrokhbabadi (2023).

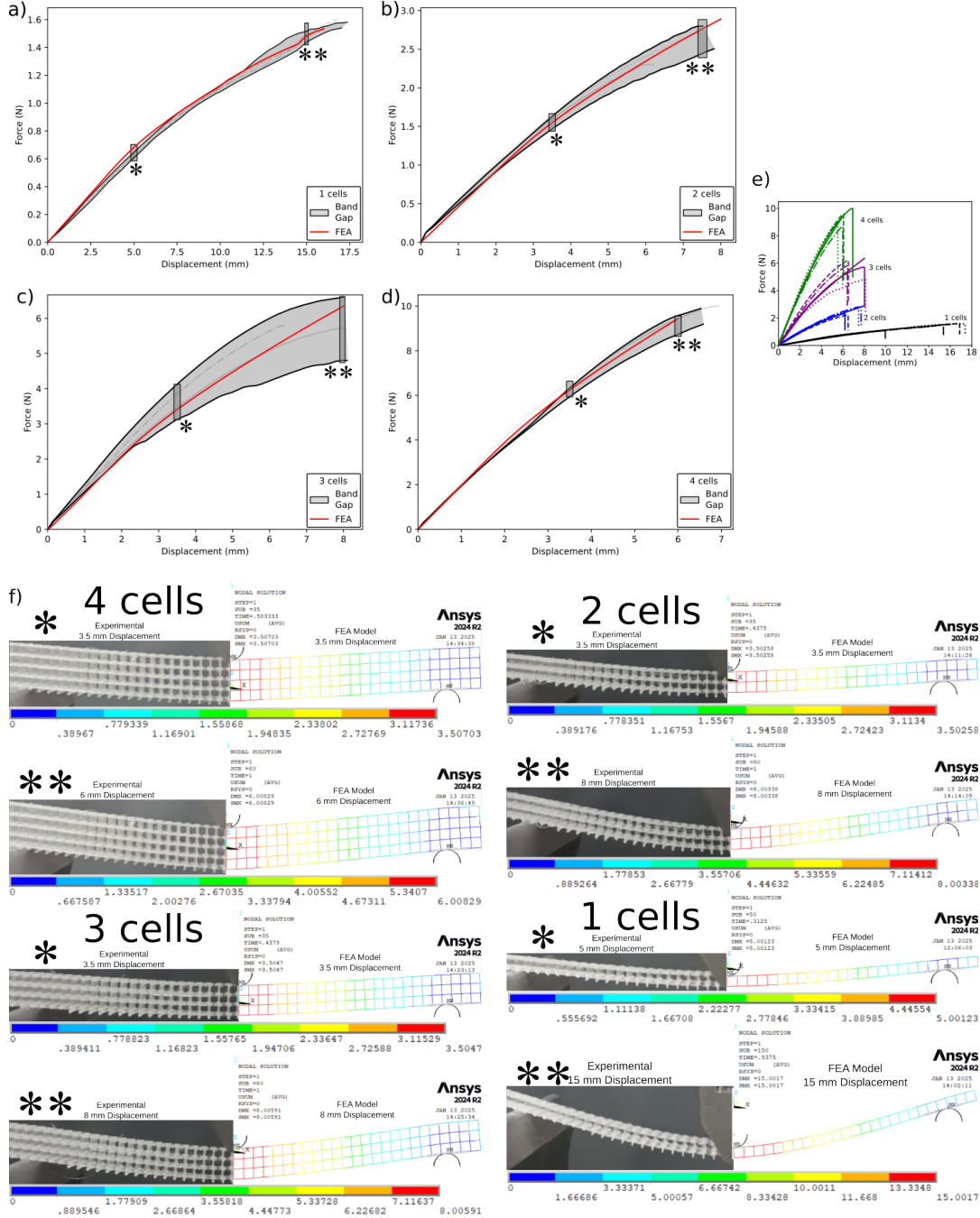


Figure 5. Force vs displacement curves for samples under three-point bending (a) 1-, (b) 2-, (c) 3- and (d) 4-cell height lattices, e) scale comparison, f) FEA model at different location (*, **).

Table 1. Mean maximum force, elastic modulus, and modulus of toughness for each condition, categorised by the number of cells.

No. Cells	Mean Maximum Force (N)	Std (N)	Mean Flexural Modulus (MPa)	Std (MPa)	Mean Modulus of Toughness (MJ/m ³)	Std (MJ/m ³)
1	1.45	0.25	216.91	14.02	0.0244	0.0093
2	2.60	0.29	96.23	11.72	0.0089	0.0032
3	5.73	0.72	70.23	6.72	0.0158	0.0019
4	9.45	0.64	50.43	2.71	0.0158	0.0027

The Young's modulus, yield stress, and tangent modulus used in the FEA to simulate the behaviour of the different cell layers are the same across all structures. The dimensions of the truss structures and unit cells, which are reported in Table 2, have been measured through a Python-based pixel analysis method. The FEA model uses the average values for the geometry of the cell structures, however, the diameter values for the three-cell, two-cell, and one-cell structures have been slightly modified within the range defined by the standard deviation as 29.91, 54.43, and 59.13 microns respectively, to match the experimental results and account for manufacturing variability. In contrast, the 4-cell structure did not require any adjustments to its diameter, as the experimental diameter values closely aligned with the FEA curve, resulting in strong agreement with the experimental three-point bending curve. The predictions from the simulations closely align with the experimental results, confirming the validity of the numerical model and its capacity to accurately capture the mechanical behaviour of the structures.

Table 2. Structures, member and cell dimensions with their respective standard deviation.

No. Cells	Mean Structure Dimensions						Mean Member Dimensions			
							Vertical		Horizontal	
	Height (mm)	Std (mm)	Width (mm)	Std (mm)	Length (mm)	Std (mm)	Diameter (mm)	Std (mm)	Diameter (mm)	Std (mm)
1	3.54	0.11	12.48	0.02	150.15	0.06	0.56	0.012	0.46	0.026
2	6.68	0.11	12.13	0.09	150.66	0.18	0.55	0.023	0.47	0.022
3	9.76	0.16	12.36	0.13	150.62	0.19	0.57	0.022	0.46	0.032
4	12.78	0.08	12.03	0.11	150.70	0.160	0.57	0.026	0.47	0.021
Mean Cell Dimensions										
	Height (mm)	Std (mm)	Width (mm)	Std (mm)	Length (mm)	Std (mm)				
1	3.079	0.114	3.008	0.057	3.178	0.044				
2	3.097	0.108	3.019	0.141	3.195	0.097				
3	3.107	0.157	3.008	0.191	3.177	0.132				
4	3.073	0.081	3.012	0.106	3.155	0.163				

Table 3 presents the statistical differences ($p < 0.05$) observed between all pairs of conditions. The adjusted p-values, ranging from approximately 0.0001 to 0.001, indicate a progressive increase in maximum force from the 1-cell structure (mean of 1.454) to the 4-cell structure (mean of 9.450). The mean differences between conditions are substantial, confirming a distinct separation between the

groups. Figure 6a illustrates the differences among conditions, revealing a slight increase in force from the 1-cell to the 2-cell structure; however, a significant increase occurs from the 2-cell to the 3-cell structures, which is nearly equal to the difference observed between the 3-cell and 4-cell structures.

Figure 6b reveals a clear box plot upward trend in median force output as the number of cells increases, with the 1-cell condition exhibiting the lowest median force of 1.55 and the 4-cell condition the highest of 9.45. The interquartile range (Height of each box) indicates the variability in the data, with the 1-cell condition displaying the low variability, while 4-cell condition shows a slightly larger moderate variability (IQR). The whiskers, demonstrate the range of typical force measurements for each condition. Two outliers are observed, one in the 1-cell condition and another in the 3-cell condition, represented as individual dots beyond the whiskers. These outliers may indicate experimental variability or unique responses in those specific replicates. Despite the presence of outliers, the lack of overlap in the IQRs between conditions supports the statistically significant differences in force output, as confirmed by the Tukey HSD test.

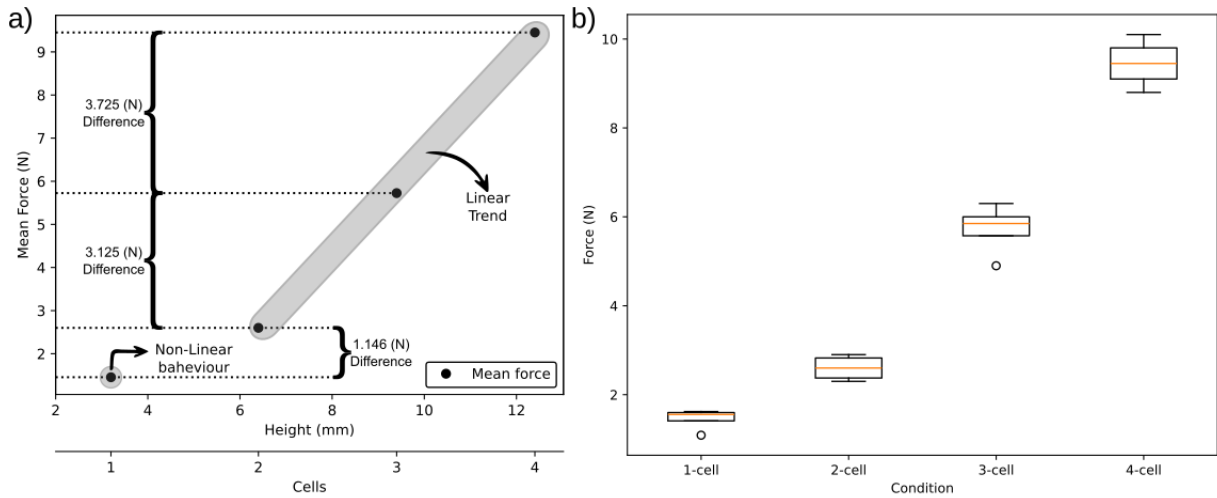


Figure 6. Mean maximum force for the different layer heights, presenting a linear, trend and nonlinear behaviour .

Table 3. Tukey test results for maximum force across unit heights of 1, 2, 3, and 4 cells..

Tukey Test						
Group 1	Group 2	Mean diff Max force	P- value (adj)	Lower	Upper	Reject
1-cell	2-cell	1.15	0.0173	0.19	2.09	TRUE
1-cell	3-cell	4.27	0	3.32	5.22	TRUE
1-cell	4-cell	7.99	0	7.05	8.95	TRUE
2-cell	3-cell	3.13	0	2.17	4.08	TRUE
2-cell	4-cell	6.85	0	5.89	7.80	TRUE
3-cell	4-cell	3.73	0	2.77	4.68	TRUE

Figure 6 illustrates both linear and nonlinear behaviours that correlate with the height of the sample. Notably, the 1-cell structure deviates from the linear trend observed in the other three heights. Instead, it aligns with the theoretical understanding that nonlinearity is associated with bending-

dominant behaviour, as previously explained. This phenomenon can be described by a power-law equation, derived similarly from prior scientific research (Ashby, 2006), as follows:

$$F = k \cdot h^n$$

Where k is a constant ratio for lattice geometries, n describes the scaling relationship, h is the height and F the force.

By applying the scaling law and power-law equation for cellular and lattice structures, the exponent n is determined to assess the bending or linear effects (see equation below). The 1-cell structure primarily experiences bending deformation, with struts bending under load while the effects of axial compression or tension remain minimal. Therefore, the calculation is as follows:

$$\begin{aligned}\frac{F_j}{F_i} &= \left(\frac{h_j}{h_i}\right)^n \\ \frac{F_1}{F_4} &= \left(\frac{h_1}{h_4}\right)^n \\ \frac{9.45}{1.45} &= \left(\frac{12.4}{3.2}\right)^n \\ 6.50 &= (3.88)^n \\ \ln(6.50) &= n \cdot \ln(3.88) \\ n &= \frac{\ln(6.50)}{\ln(3.875)} \approx 1.38\end{aligned}$$

The combined analysis of force and height for structures ranging from 1 to 4 cells yields a mean scaling exponent n of 1.55 ± 0.43 , with a minimum value of 1.38 and a maximum of 1.95. These values are obtained using the following configurations: F1/F2, F1/F3, F1/F4, F2/F3, F2/F4 and F3/F4. The cubic lattice structures exhibit a nonlinear increase in load resistance with increasing height, while the 1-cell structure follows this trend, demonstrating a clear bending-dominant response, as illustrated in Figure 6. Conversely, experimental results confirm the absence of bending dominance in the 4-cell and 3-cell structures, while the 2-cell structure presents a transition between bending and non-bending dominance. The 1-cell structure exhibits a pronounced bending effect, as previously mentioned, which is depicted in Figure 7a. This observation is further supported by finite element analysis (FEA), where the 1-cell structure displays bending-dominant behaviour, whereas the 2-cell, 3-cell, and 4-cell structures exhibit a more linear response. The strong agreement between the FEA predictions and experimental data is evident in the overlapping curves, with the red-coloured deformed structure representing the state just before failure. When the ratio between the diameters of the struts increases or decreases, the joint can no longer develop the yield moment or the plastic moment of the cross-section. As a result, the failure mode tends to approach a brittle behaviour, characterised by a lack of gross permanent or plastic deformation in the material at the moment of failure, these findings highly correlate with previous research (Kadkhodapour et al., 2015). This is consistent with the stress concentration at the joints, where the strut diameter ratio inhibits the

development of a yield moment. The brittle failure is further exacerbated by the reduced cross-sectional area in shorter structures, which limits the material's ability to redistribute stress and absorb energy before fracture.

Figure 7b illustrates the observed fracture locations in the 4-, 3-, 2-, and 1-cell structures. In all cases, failure consistently initiates at the bottom of the beam near the central loading point, corresponding to the region experiencing maximum tensile stress during three-point bending. This behaviour aligns with classical beam theory, where tensile stresses dominate at the bottom surface while compressive stresses develop at the top. Due to the localised geometry of the strut intersections, failure likely originates at stress concentrators formed at the lower joints, particularly where the struts converge.

The second moment of area, which is strongly influenced by the structure's height, governs the stress distribution across the cross-section. As the number of vertical unit cells increases, the bending stiffness also increases, resulting in reduced overall deflection but higher localised stress concentrations near critical joints. Structures with fewer cells (e.g., 1- or 2-cell heights) exhibit more pronounced global deformation prior to failure, often displaying progressive joint weakening and ductility-like behaviour despite the inherent brittleness of PLA. In contrast, taller structures (3- and 4-cell heights) demonstrate higher stiffness and more abrupt, brittle fracture patterns, often characterised by clean separation at the base joints.

Additionally, the unique strut-based architecture of these lattices introduces a combination of bending, axial, and shear forces within the individual struts. As bending progresses, the bottom struts undergo tensile elongation, while those closer to the neutral axis experience minimal deformation. This uneven stress distribution contributes to crack initiation at specific joints, where stress is amplified by geometric discontinuities or imperfect interlayer adhesion resulting from the FDM process.

The consistent failure location and fracture characteristics observed suggest a failure mechanism driven by tensile joint rupture, exacerbated by stress concentrations and weak interfacial bonding between printed struts. However, minimal deflection is observed in the horizontal members near the joints, which remain within the elastic region, as seen in the 4- and 3-cell structures (Figure 7b, before and after).

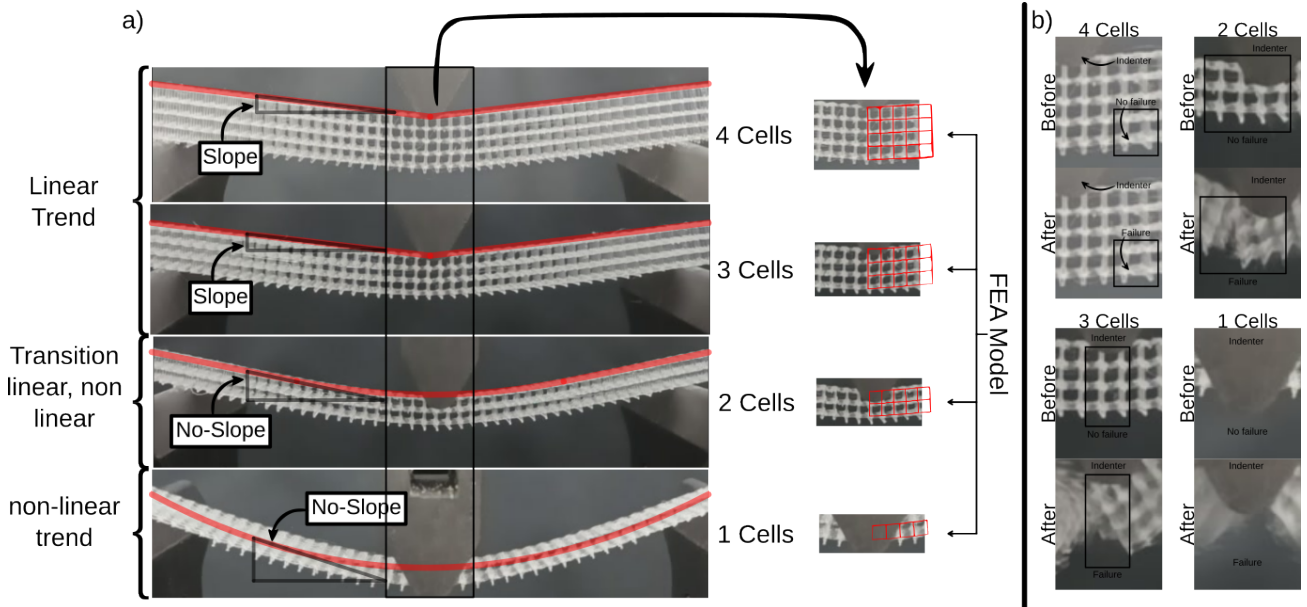


Figure 7. (a) Linear trends indicating non-bending dominance in 4-cell and 3-cell lattices, and nonlinear trends reflecting bending dominance in 1-cell lattice, (b) Brittle fracture for all structure heights, 4-, 3-, 2-, and 1-cell.

Loo Yong, (1973), investigated the failure mechanism of printed connection members with a rectangular cross-section, considering two cases. The first case examines the impact of a contact ratio equal to 1, where forces are transmitted through the faces of the horizontal member (Figure 8a). In contrast, when the ratio deviates from 1, forces are predominantly transmitted through the corners of the prismatic shape, as illustrated in the front and side views (Fig. 8b). For cylindrical members, forces are transmitted through the edges (Fig. 8c) or tangential connections (Fig. 8d) between the members, with the latter being particularly evident in the smaller connections. The side view shows that forces are transferred from the vertical member to the horizontal member through the centre of the member (Fig. 8c). The lattices examined in this study are characterized by a circular filament section with a dimension ratio of less than 1 (Fig. 8d), where forces are transmitted solely through the edge. To correlate this force distribution with the failure mechanism, Figure 9 illustrates the mechanical behaviour leading up to fracture.

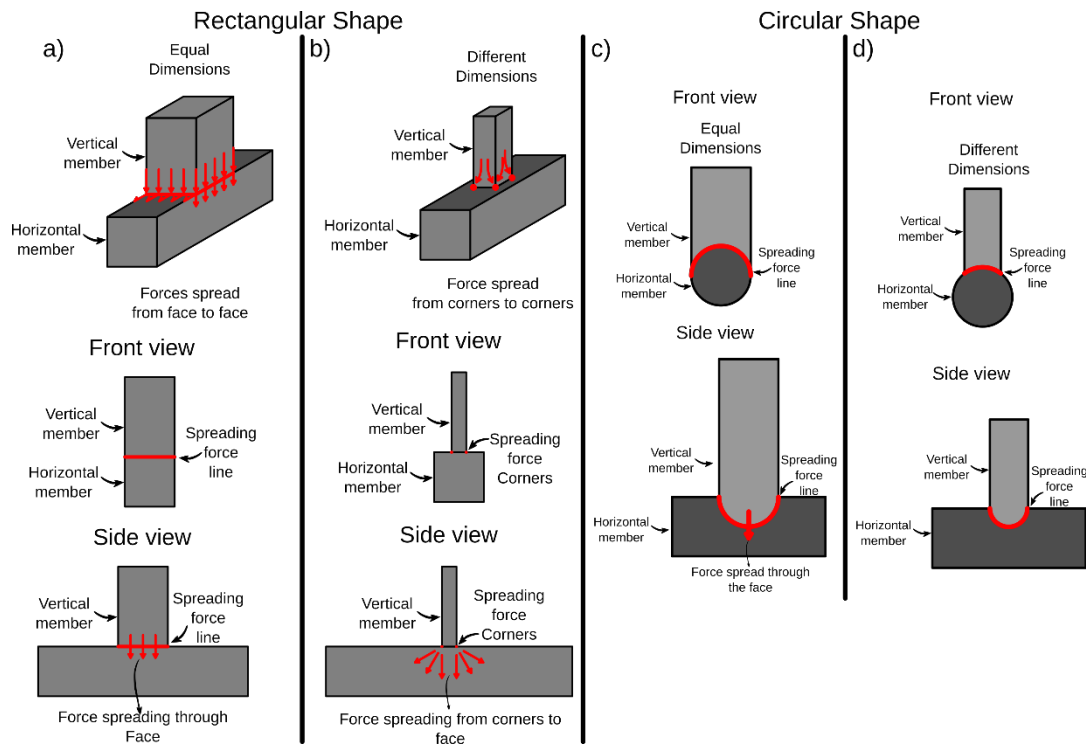


Figure 8. Member connections for rectangular shapes with (a) equal dimensions, (b) different dimensions and circular shapes with (c) equal dimensions, (d) different dimensions.

Figure 9 illustrates the typical bending behaviour curve, highlighting the associated failure mechanism. The effects of the bending forces applied to the structure can be categorised into four distinct stages. In the first stage (Stage 1), the structure remains fully connected, with no relative motion occurring between the members, indicating that the system is stable and intact. As the force increases, the structure enters the yield stage (Stage 2), where plastic deformation begins to manifest. This stage is characterised by tilted angles and the formation of rhomboid-shaped cells, signalling the onset of strain within the system. Progressing to the detachment stage (Stage 3), the force further weakens the system, leading to the partial detachment of one member from another. At this point, brittle failure is observed, predominantly occurring at the joints. Finally, in Stage 4, the vertical member becomes entirely detached from the horizontal member, highlighting the extent of structural damage. It becomes evident that the curvature at the end of the vertical member remains intact, allowing for a perfect fit with the horizontal member. These stages illustrate the progression of the failure mode, which is closely linked to Figure 8b.

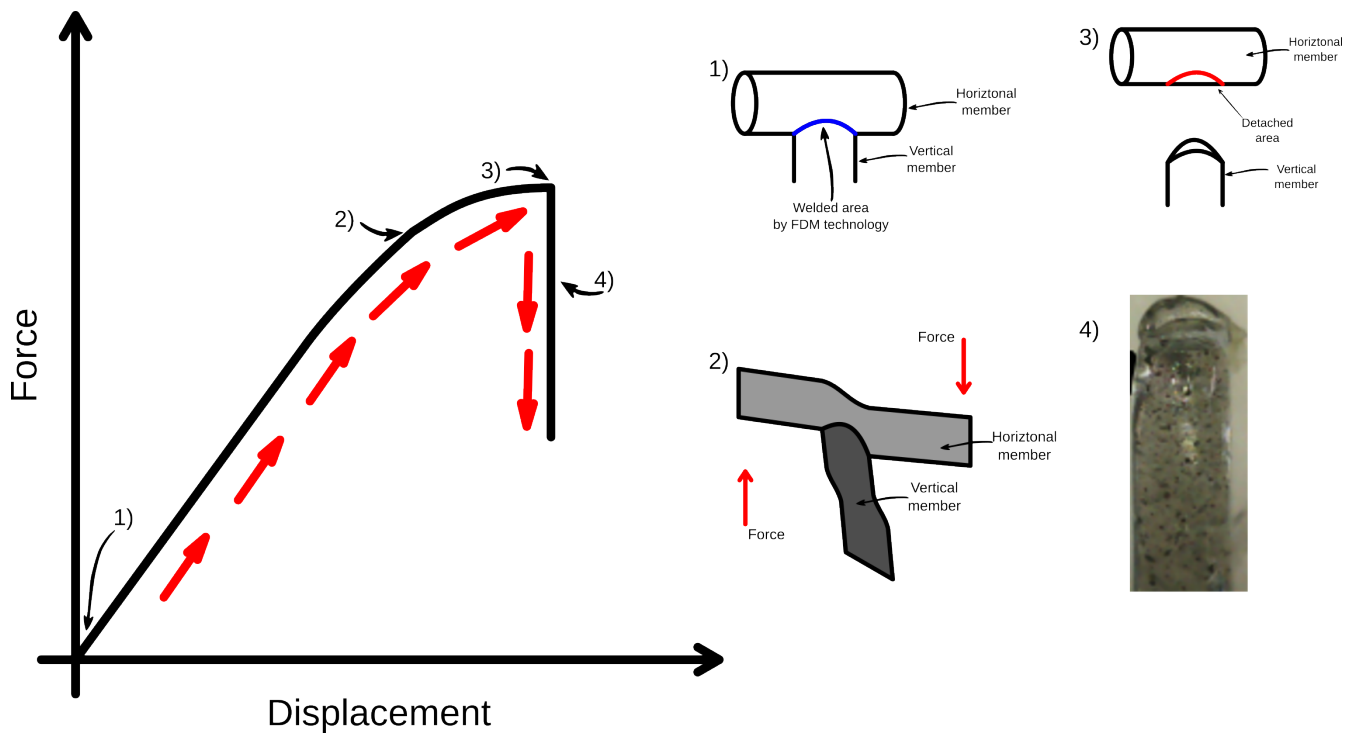


Figure 9. Progressive stages of structural deformation and failure under applied force: (1) Start-up stage, (2) Yield stage with heat effect, (3) Detachment of strut members, and (4) Final stage.

4. CONCLUSION

The influence of geometry on stiffness and load-bearing capacity is significant. The height of the structure greatly affects its stiffness; taller lattices can withstand larger loads with reduced deflection. This is attributed to an increase in the second moment of area, which enhances resistance to bending. However, when normalised to account for geometry, the flexural modulus decreases with height. This suggests that while taller structures appear stiffer, their material efficiency diminishes due to stress redistribution and increased joint participation.

The mechanism of deformation and transition differs from classical beam theory, which predicts bending-dominated behaviour across all configurations. Experimental results revealed a shift in load transfer mechanisms. The 2-cell structure exhibited characteristics of axial-dominated deformation, indicating that an increase in height leads to a reorientation of load paths along the strut axes. This transition arises from the hybrid bending-axial nature of strut networks, a behaviour further amplified by joint constraints.

Failures at the joints were identified as the primary failure mode, as all structures failed at the joints, with minimal deformation observed in the struts themselves. This suggests that stress concentrations occur at nodal intersections, where tensile stress leads to fracture. These joints likely act as local stiffness discontinuities due to geometric irregularities and weak filament bonding, making them the weakest points in the load path.

Validation through FEA and the implications of strut diameter were clearly observed in the FEA simulations, which closely matched the experimental results, particularly for taller structures. This reinforced the observed shift from global bending to localised axial deformation. Additionally, the numerical results highlighted the impact of strut diameter on stiffness and strength. Smaller diameters reduce bending stiffness while amplifying stress concentrations at nodes, revealing the delicate balance between lightweight design and structural reliability.

These findings provide valuable insights into the design of lightweight, high-strength 3D-printed lattice structures, with potential applications in aerospace, biomedical, and structural engineering. Future work should explore the use of diverse materials, alternative lattice cell geometries, and further optimisation of additive manufacturing processes.

5. LIMITATIONS AND FUTURE WORK

While this study introduces significant advancements in the fabrication and mechanical characterisation of fully 3D strut-based lattice structures using FDM, several limitations must be acknowledged.

Firstly, the manufacturing process is time-consuming, with each sample requiring approximately six hours to print. Increasing the print speed was not feasible due to issues such as stringing and material dragging, which compromise geometric accuracy and print quality — particularly in small-scale struts with high surface-area-to-volume ratios. Additionally, post-processing was necessary, as the first printed layer exhibited deformation due to excessive adhesion to the build plate. This required laser cutting to ensure sample uniformity and consistency.

Secondly, the mechanical testing setup posed constraints. The universal testing machine lacked a low-capacity load cell, which limited the precision of force measurements for lightweight structures. Furthermore, due to the rapid onset of failure, the available imaging equipment was insufficient to capture crack initiation and propagation in high detail, making it challenging to fully analyse the fracture process and deformation modes.

Future work should explore the optimisation of print parameters and printing path strategies to reduce manufacturing time while maintaining print fidelity. In terms of testing, high-speed imaging and digital image correlation could provide more detailed insights into deformation and failure mechanisms. Additionally, expanding the analysis to include dynamic loading and fatigue performance would offer a more comprehensive understanding of these structures.

Declaration of Competing Interest

The authors declare no conflict of interest.

Data Availability Statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Mechanical behaviour of a novel 3D-printed cubic cellular structures under bending loads: an experimental and numerical analysis

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