

Additive Manufacturing of Bio-inspired Design Elements for Lightweighting

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Abstract

This study explores the feasibility of applying metal additive manufacturing (AM) to realize complex, function-driven structures inspired by biological systems, with a focus on lightweighting. The paper presents a structured approach for manufacturing bio-inspired lattice structures by developing a bio-inspired design methodology that focuses on a repository of design attributes or elements informed by biological data. Drawing from biological models, the approach systematically translates natural strategies into analogous design elements tailored to material and AM constraints. These elements act as functional building blocks within the lattice design space, enabling the creation of application-specific, lightweight architectures. To evaluate the methodology, a series of proof-of-concept structures were fabricated via metal AM and tested for manufacturability and performance. The results demonstrate the potential of this bio-inspired design framework to inform and advance the development of next-generation lightweight structures across engineering domains.

Introduction

Biological systems have evolved over billions of years to survive within strict environmental constraints, using adaptive strategies across length scales and habitats to achieve unique functionalities [1]. As a result, biology offers a vast and rich repository of robust architectures and design strategies for creating multifunctional, resilient engineered products [1, 2]. Bio-inspired design (BID) is an interdisciplinary research area at the intersection of engineering design, computing, and biology. It seeks to systematically mine biological knowledge to address existing design problems, presenting a tested yet unstructured approach for both design innovation and engineering. Several approaches have been investigated to translate the biological design knowledge into an engineering design solution and can be found in published literature and references therein [1, 3-10]. Some of the key methodologies within include design-by-analogy, application of biology-driven and problem-driven approaches, as well as the use of biological information databases. On the other hand, publications concerning engineering implementations of bio-inspired strategies are often driven by curiosity of “aha moments” and the singular function of a species, such as the superhydrophobicity of a lotus leaf, applied for self-cleaning applications.

As such, several critical challenges remain for the implementation of bio-inspired approaches for real-world applications. The first challenge is to apply a bio-inspired approach toward solving real-world problems that can be translated into viable market-ready products [11]. The second is the development of a unified theory of biologically inspired design that transcends individual biological examples and can be generalized across functions and species [11]. The third is the advancement of materials and manufacturing capabilities that make biologically inspired design scalable, repeatable, and accessible.

This paper addresses these three challenges through the lens of biologicalisation, which is the use and integration of biological and bio-inspired principles, materials, functions, structures, and resources into intelligent and sustainable manufacturing technologies and systems to achieve their full potential [12]. The proposed methodology addresses the challenges by systematically extracting functional biological strategies as design attributes and mapping them to manufacturable design elements. To address the third challenge, a validation protocol is introduced, employing metal additive manufacturing (AM) to fabricate and test proof-of-concept structures. While design for AM typically prioritizes manufacturability over function, and BID methodology prioritizes function often without regard to manufacturability, this approach merges both by using manufacturing as a vector to realize biologically derived functions. In this framework, function remains the end goal, and AM serves as the enabling pathway to achieve it.

This work furthers the field by distilling the design process down to the functional level, where specific functions are decomposed from the bio-inspiration library for their translation toward engineering design. For this study, the function of lightweighting is selected as the focal point for design translation, chosen from a broader suite of other biological functions of interest, such as adhesion, superhydrophobicity, energy transformation, optical surfaces, antibiofouling, drag reduction, and energy absorption [1, 2, 13]. By focusing on a clearly defined function, the process of applying bio-inspired principles enables the development of a robust and structured pathway from biology to engineering application. This paper highlights the design and engineering potential of bio-inspired, high-performance, lightweight lattice structures manufactured using AM. It demonstrates that biological data can be translated into digestible biological information and then organized using an operational diagram to isolate the key features and structural principles that support desired functions, such as stiffness in lightweighting. These insights can be further translated into material and manufacturing constraints, enabling the design of cuttlefish-inspired lattice structures that are validated through AM-based fabrication as discussed below.

Overview of lightweighting

In biology, the essence of lightweighting is to achieve maximum efficiency with minimal consumption of available resources. The goal of lightweighting as a function is to minimize the structural weight under certain boundary conditions while meeting certain life and reliability

requirements [14]. At its core, lightweighting entails the strategic reduction of weight in products without compromising structural integrity, performance, or functionality. Lightweight structures, characterized by a high strength-to-weight ratio, often exhibit additional functionalities such as stiffness, energy absorption and dissipation, impact resistance, as well as torsional and bending resistance [15, 16].

Lightweighting in engineering applications can be achieved through four primary avenues. The first involves the use of lightweight materials that provide superior mechanical performance at lower densities. Second, lightweight manufacturing focuses on tailoring process parameters to suit such materials, with AM playing a critical role due to its ability to produce complex geometries. Third, lightweight structures are developed through methods such as structural topology optimization, shape and size optimization, topography optimization, freeform design, and structural bionics. Finally, lightweight designs integrate these materials, manufacturing, and structural strategies into cohesive, high-performance engineered systems.

Lightweight structures or design strategies can be classified by their configurations into categories such as multi-cell tubes, frusta, sandwich panels, composite structures, and cellular architectures like honeycombs, foams, and lattices [15]. Cellular materials with high mechanical efficiency are crucial for aerospace applications, lightweight vehicles, and systems that require energy absorption. Bio-inspired lattice structures are of particular interest due to their superior lightweighting and energy absorption capabilities, often attributed to local buckling characteristics. These structures, inspired by various biological organisms, demonstrate significant advantages over conventional lightweight configurations [17]. For instance, the skeletons of deep-sea glass sponges (*Hexactinellida*), such as *Euplectella aspergillum*, provide a blueprint for square lattice geometries optimized to prevent global buckling, enabling efficient material use in modern infrastructure [17–19]. Dual-scale microlattices observed in the biomineralized skeleton of the knobby starfish (*Protoreaster nodosus*) combine atomic-scale calcite with micro-scale diamond triply periodic minimal surfaces. This architecture enhances damage tolerance under compression, achieving excellent stiffness and toughness while maintaining a minimal weight [20]. The osteoderms of *Glyptotherium arizonae* (from the family of modern armadillos) demonstrate how dense outer layers and porous lattice cores can provide an optimal balance of strength and energy absorption [21]. Plant cell walls, composed of cellulose unit cells stacked with offset alignments, offer additional inspiration by transferring loads across beams to enhance stiffness and control buckling behavior [22]. Dual bio-inspired lattice structures, such as turtle shell-inspired honeycomb geometries that exhibit high mechanical efficiency and lightweight characteristics [23], have been manufactured with AM. However, the research connecting design, manufacturing, and functionality is limited.

One example of biological lightweight architectures is the cuttlebone, the internal endoskeleton of the common cuttlefish (*Sepia officinalis*), which has been studied extensively [24-

28] and will be the focus of this work. This naturally engineered cellular structure (Figure 1) is optimized for extreme environments, such as deep-sea hydrostatic pressures (100–400 m). With porosity exceeding 90% and an ultra-low density ($\sim 0.2 \text{ g/cm}^3$), the cuttlebone achieves exceptional strength-to-weight and energy absorption performance, outperforming conventional octet-truss lattices and polymer/metal foams by factors of 1.5 to 25. Its structure consists of lamellar septa separated by asymmetric, S-shaped curved walls—300–500 μm in height and only 8–10 μm thick. These form sinusoidal channels that enable efficient load distribution and internal fluid control. The architecture of the endoskeleton integrates hierarchical organization, directional fracture resistance, and a zero Poisson's ratio, allowing localized densification without lateral expansion, thereby resisting buckling. The material exhibits a long, stable stress plateau ($\sim 15\text{--}70\%$ strain), characterized by controlled, layer-by-layer energy dissipation and failure, a behavior uncommon in inorganic materials that helps prevent catastrophic collapse. Reinforced with aragonite nanoparticles and organic components, the cuttlebone also demonstrates remarkable stiffness and damage tolerance. These properties make the cuttlebone an ideal medium for inspiration for bio-inspired stiff lattice designs where lightweighting and multifunctionality are critical, such as aerospace and biomedical applications.

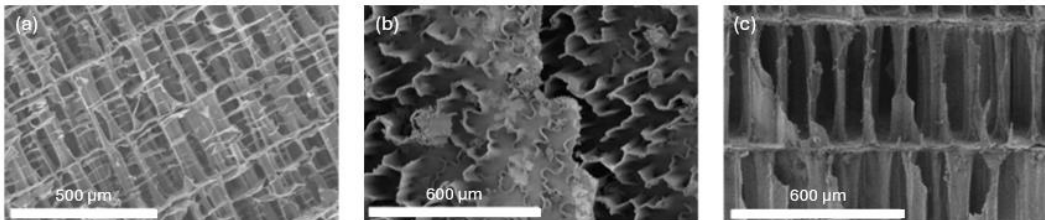


Fig 1: SEM image of cuttlebone (a) Detail of lamellar matrix transverse cross-section (b) channels formed by convoluted pillar (c) transverse cross-section displaying interconnected channeled structure. Images reproduced with permission from Ref. [29].

Design Approach

Cellular solids such as lattices are prevalent in both natural and engineered systems due to their exceptional mechanical efficiency. They offer high stiffness, strength, energy absorption, and dissipation, all while maintaining reduced weight, and can be tailored to meet specific application requirements. The distinction among lattices, foams, and honeycombs has been previously reported [30, 31], with findings indicating that lattices exhibit superior mechanical properties, particularly in their ability to suppress buckling [32–34]. A key advantage of lattice structures lies in their tunability, where each unit cell and strut can be treated as a decomposed design variable, allowing for integration and customization to meet specific functional requirements of interest. This provides significantly more flexibility in tailoring mechanical properties than is possible with foams or honeycombs, resulting in enhanced performance [35–37].

For the scope of this paper, the definition of lattice structures adopted is from [37], which includes both uniform and non-uniform lattices: “a porous three-dimensional spatial structure formed and tessellated by unit cells with different topological geometries and belongs to cellular structures.” Although lattices can be broken down into discrete unit cells of defined geometry, topology, and size, translating this modular definition into manufacturable designs, particularly for complex, functionally graded structures, is a challenge. Many natural materials, such as bamboo, balsa wood, and cancellous bone, demonstrate the complexity of cellular architectures with distributed unit cells while delivering exceptional mechanical performance while remaining lightweight [16, 38]. Additionally, when implemented in AM, further challenges arise in managing the spatial arrangement of these unit cells and meeting associated process requirements for multi-layered or non-uniform lattice designs.

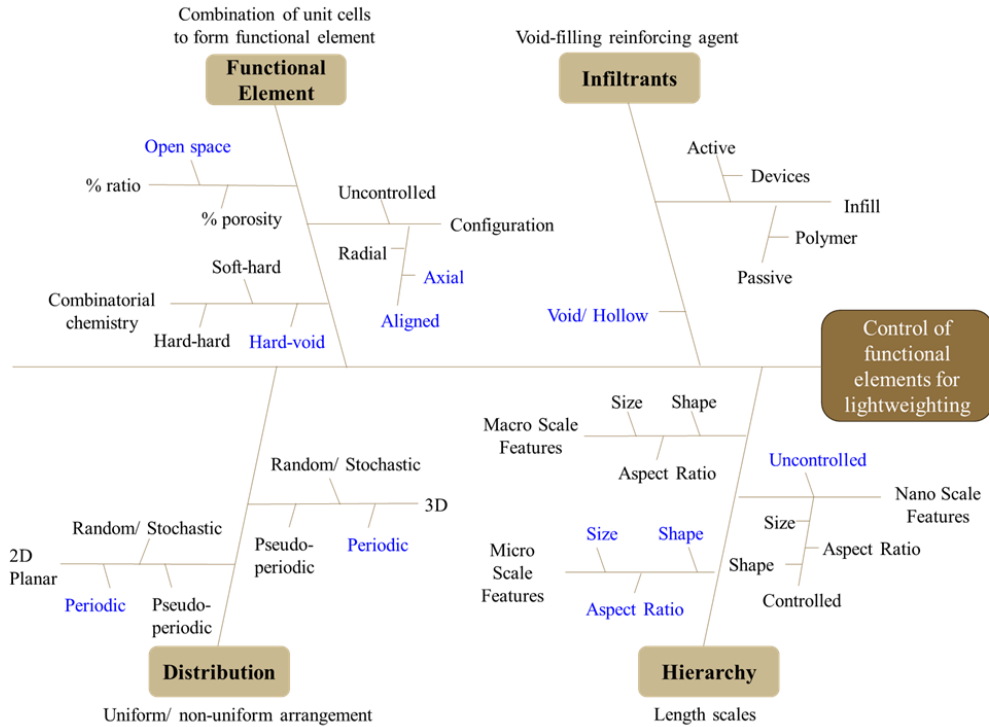


Figure 2: Bio-informed operational framework tailored for the cuttlebone-inspired structure to achieve stiffness and buckling resistance by functional lightweighting. Functional design elements of interest chosen for this study are highlighted in blue.

To address this, the present study extracts key features of lightweight lattice architectures and organizes them into simplified design variables termed *functional elements*. These functional elements are defined as combinations of varying unit cell geometries arranged in a specific configurational direction and composed of a controlled material composition (or "combinatorial

chemistry"). This expands the scope of lattice design beyond traditional definitions, allowing for greater adaptability in selecting and organizing design elements according to material and manufacturing constraints unique to the engineering problem.

This approach provides engineers with the flexibility to choose, combine, and repeat elements to achieve targeted properties during the translation of biological structures into engineered systems. To facilitate this selection process, an operational diagram (Figure 2) consisting of various ‘tunable’ design elements has been developed based on a repository of studied traits of lightweight structures in nature. Each decomposed design element can be thought of as a ‘knob’ or a ‘lever’ that could be tuned based upon the application-specific functional requirement [39], as reported in the previous work by co-authors. This diagram enables engineers to identify which elements contribute to specific design attributes, considering desired functionalities and boundary conditions. This method supports the systematic translation of biological design elements into lightweight engineering solutions, formalized into a bio-informed operational framework. The bio-informed operational diagram, as presented in this paper, has been tailored to the cuttlefish case study to demonstrate its application in guiding the development of additively manufactured, bio-inspired lightweight structures.

The proposed operational framework can be tailored to target a specific function associated with lightweighting by leveraging biological data through a series of systematic steps. First, biological data must be gathered and analyzed from one or multiple organisms, depending on the degree of bio-inspiration required. The next step involves identifying and classifying key structural features at the unit cell level that contribute to the desired function. This consists of the formulation of the Biological Design Toolbox (BDT), which is a modular toolset that captures and organizes the primary design attributes of biological systems [16]. These features are then translated into functional elements inspired by biological forms but defined within the constraints of available materials and manufacturing processes. Once the functional aspects are established, their spatial distribution and arrangement across hierarchical length scales must be defined to reflect how they will operate in the final structure. Where applicable, the potential for infiltrants or secondary materials should also be considered to enhance the performance or multifunctionality of the structure. Through these steps, an optimized design space is generated, forming a foundation that can be further refined using conventional design principles or computational design tools. For this feasibility study, cuttlefish is used as a source of inspiration to extract decomposed design elements, which are then translated into an engineering design that can be manufactured using a laser powder bed fusion (L-PBF) process. The following section outlines the experimental methodology for designing, manufacturing, and testing bio-inspired lattice designs for lightweighting.

Experimental Approach

To validate the approach discussed in the previous section, a cuttlebone-inspired structure was designed and tested for its mechanical response. The selection of unit cells and their corresponding functional elements, as defined by the bio-informed operational framework (highlighted by blue text in Figure 2) and informed by SEM observations [24, 29], is illustrated in Figure 3. In the biological model, the unit cell is defined by the space between two lamellar septa (pillar-like structures) and the intervening void chamber. This unit cell is configured axially, with hard-void chemistry and open spaces to form a functional element. The functional element, in this context, refers to the corresponding horizontal layer in the two-dimensional plane comprising multiple lamellar septa and void chambers arranged periodically. These elements can then be arranged or stacked as multiple layers in three-dimensional space with a slight stagger between adjacent layers, similar to the cuttlebone structure, which contributes to improved energy dissipation and arresting crack propagation. In the hierarchical length scales, these functional elements are controlled in the micro scale, while submicron scale features are essentially manifestations of the AM process itself, without direct design intervention. No infiltrates are required within the lattice structure.

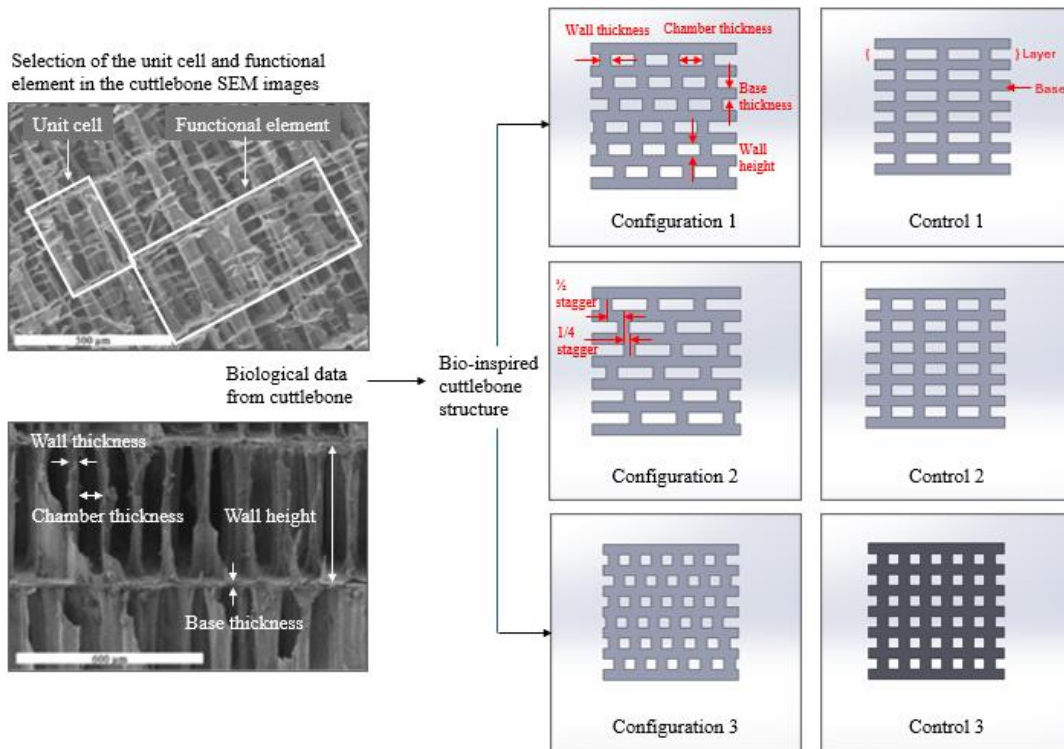


Figure 3: Selection of the unit cell and functional element based on cuttlebone morphology [29], with CAD models of the six bio-inspired lattice designs showing the translation of biological data into engineered structures. Images reproduced with permission from Ref. [29].

All necessary dimensions for defining the experimental test structure are provided in Figure 3 – chamber thickness (distance between two adjacent pillars), wall thickness (pillar thickness), base thickness (thickness of flat base on which pillars exist), wall height (pillar height), and the number of layers. These dimensional parameters enable the precise definition and fabrication of bio-inspired lattice architectures using L-PBF, while ensuring consistency with both biological inspiration and manufacturing feasibility.

To simplify the design space for a comprehensive study, two key parameters were selected for variation – the stagger ratio (offset between two pillars of adjacent layers) and the chamber thickness-to-wall thickness ratio (considered as the lightweighting ratio for the scope of the paper). The dimensional details of each structure are provided in Table 1. Structures were modeled using SolidWorks CAD software, shown in Figure 3. Three lattice configurations were designed, each with overall dimensions of 1 in. × 1 in. × 1 in., with variations in chamber thickness-to-wall thickness ratios as well as randomly generated quarter- and half-staggered arrangements (selected to narrow the scope of the design space as visually observed in the SEM images of cuttlebone) between layers. To serve as a baseline for comparison, three additional control samples with identical overall dimensions without any stagger were designed. These controls enable direct comparison of buckling behavior and failure mechanisms between staggered and non-staggered structures. To minimize the risk of print defects and ensure reproducibility, all dimensional decisions were made within the constraints of L-PBF processing and 18Ni maraging steel material properties, including margins for avoiding any irregularities. In particular, the wall thickness was maintained at 2 mm to ensure that any observed performance differences could be attributed solely to structural variations, rather than manufacturing-induced anomalies or distortions. These structures were designed to observe the layer-by-layer fracture behavior and the presence of an energy plateau during compression, in comparison to control samples of identical dimensions but without stagger taken as the focal point of inspiration from biology. The objective was to engineer anisotropic mechanical behavior, enabling the prediction of predictable failure modes and enhanced buckling resistance. This directional control represents a significant departure from the natural porous structures found in bone.

Table 1: Dimensions of all structures as designed.

Structure	Chamber thickness (μm)	Wall thickness (μm)	Chamber thickness to wall thickness ratio	Wall height (μm)	Base thickness (μm)	Stagger ratio
Configuration 1	6000	2000	3	1900	2000	¼ and ½
Configuration 2	4000	2000	2	1900	2000	¼ and ½
Configuration 3	2000	2000	1	1900	2000	¼ and ½
Control 1	6000	2000	3	1900	2000	NA
Control 2	4000	2000	2	1900	2000	NA
Control 3	2000	2000	1	1900	2000	NA

The lattice structures were fabricated using L-PBF on a Matsuura Lumex Avance-25 system. Process parameters were selected based on the previous know-how to ensure the fabrication of high-quality lattice structures with minimal defects and are detailed in Table 2. L-PBF was chosen for its ability to fabricate lattice geometries with high precision, making it well-suited for this feasibility study. It also lays the groundwork for potential future exploration of hybrid AM techniques (e.g., sintering + micromachining) for manufacturing lattice structures. The selected material was 18Ni maraging steel, a high-strength metal alloy chosen for its excellent mechanical performance and compatibility with L-PBF. The powder particle size distribution ranged from 20 to 45 μm , with D10, D50, and D90 values of 22, 33, and 44, respectively.

Table 2: L-PBF process parameters

Power (W)	Scan speed (mm/s)	Spot diameter (μm)	Hatch spacing (μm)	Layer thickness (μm)	Linear energy density (J/mm)	Volumetric energy density (J/mm^3)
320	700	200	120	50	0.46	76.19

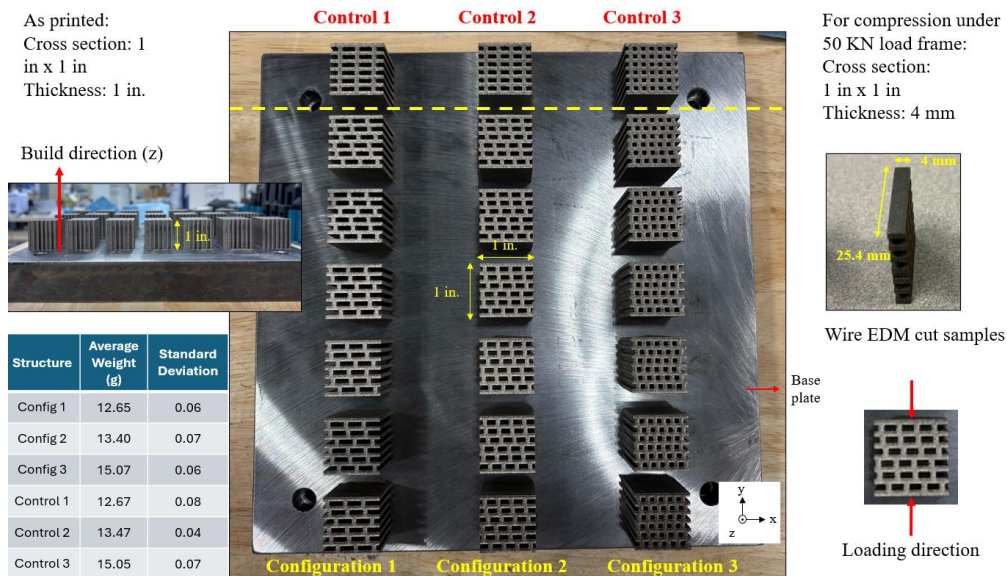


Figure 4: Printed lattice structures on the build plate.

The structure's print orientation, shown in Figure 4, was selected to minimize print defects associated with unsupported overhangs. To prepare samples for testing, the original 1-inch-thick printed structures were sectioned to a thickness of 4 mm using wire Electrical Discharge Machining (EDM). A total of five samples were selected from the central part (to minimize edge or build plate effects) of two build structures to ensure repeatability of test results. Compression testing was performed along the lattice pillars (in the Y-direction) using a single-axis Instron

34TM-50 testing machine equipped with a 50 kN load cell, at a strain rate of 1 mm/min. Loading direction was chosen to study layer by layer failure as hypothesized along the direction of the pillars. The results of six lattice configurations were compared under uniaxial compression, as discussed in the next section.

Results and Discussion

Figure 5 shows test results for various lattice configurations under compression tests. Two key trends were noted from the resulting force-displacement curves. First, the non-staggered control samples exhibited higher initial stiffness and greater yield strength than the bio-inspired staggered configurations. However, the control samples underwent sudden buckling and catastrophic failure immediately after yielding. In contrast, the bio-inspired staggered structures demonstrated a prolonged strain-hardening plateau, during which the applied force propagated in a controlled, layer-by-layer manner before crack initiation. These results were highly repeatable, with consistent behavior observed across five samples of each configuration, as shown in Figure 5, with most samples failing consistently at the exact pillar location. Due to constraints in the load cell capacity, configuration 3 and control sample 3 could not be tested to the point of failure which can be seen in the graph. The distinct difference in post-yield behavior between control and bio-inspired structures highlights the potential of staggered lattice designs to enable controlled energy dissipation and predictable failure modes.

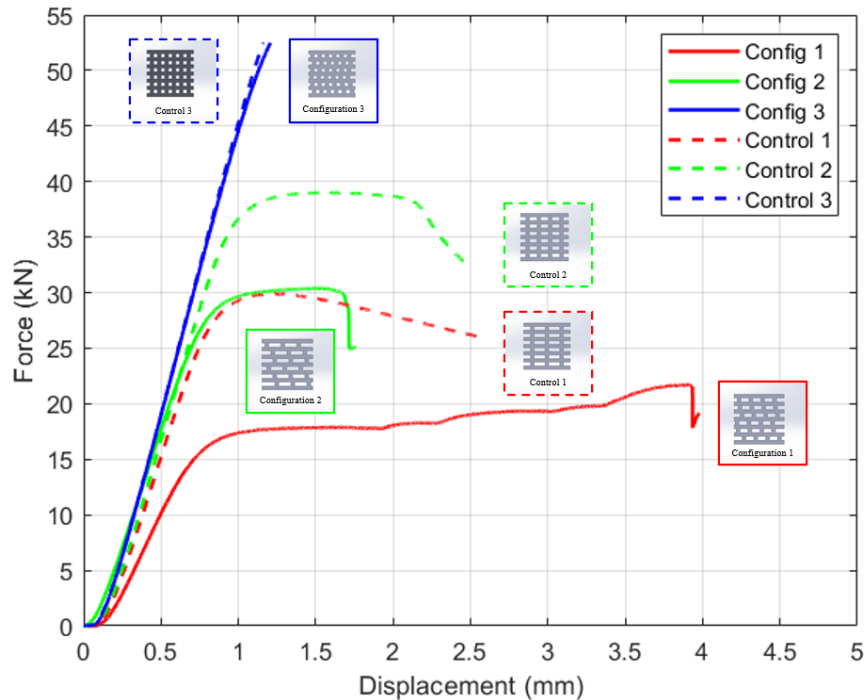


Figure 5: Force-displacement curve for the lattice structures.

The non-staggered control samples exhibited S- and C-shaped buckling failures (Figure 6 (a-b)), despite the cross-section being optimized to prevent such behavior. This may be attributed to the linear transmission of compressive force directly through the aligned pillars, from both the top and bottom of the structure towards the center. As the compressive force converges centrally and the material lacks lateral space to redistribute stress, localized instability leads to buckling. Consequently, catastrophic ductile failure typically occurred in the central layers of the pillars, or the test was terminated prematurely due to specimen slippage between the platens. In contrast, the staggered samples yielded earlier than the control group but demonstrated extended plastic deformation, sustaining deformation over a wider force range (Figure 6 (c-d)). This distributed or “rippled” brittle failure mode, which occurred through the staggered pillar network, effectively delayed catastrophic buckling. The progressive redistribution of force across the staggered architecture contributed to more stable and predictable mechanical performance under compression. This controllable failure mechanism is particularly valuable in the context of bio-inspired design and lightweighting. Biological systems often exhibit damage-tolerant, hierarchical structures that fail gradually rather than catastrophically. Emulating this, the staggered architecture introduces a failure path that can be anticipated and tuned, offering both structural resilience and design optimization potential. From a manufacturability standpoint, even within the resolution limits of AM, achieving such predictable failure provides a promising framework for functionally graded or energy-absorbing structures. This aligns with the core objective of this research: developing systematic, bio-inspired design methodologies for lightweight structures that are not only strong but also fail safely and reliably.

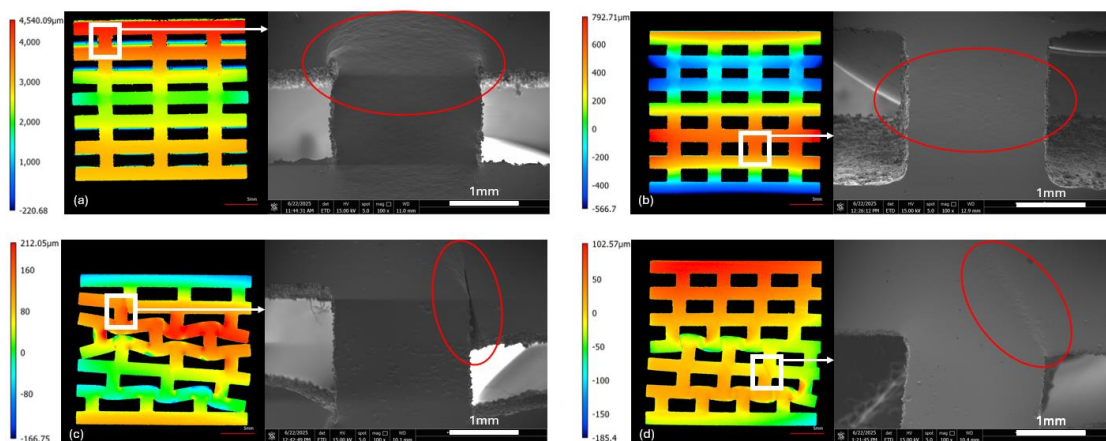


Figure 6: SEM and optical profilometry images reveal distinct failure mechanisms by highlighting differences in crack morphology and surface deformation across the samples (a) control 1, (b) control 2, (c) configuration 1, (d) configuration 2.

Although the design has significant areas of improvement in terms of stiffness and strength, it showed promising results in the feasibility study to avoid buckling (without altering overall cross-sectional dimensions or height) and demonstrates potential for a controlled failure mechanism through lightweight lattices.

Conclusion

This study demonstrated the successful translation of biological skeletal organization patterns into engineered lattice structures with enhanced buckling resistance and predictable failure behavior under uniaxial compression. By leveraging the bio-informed operational framework, functional elements were extracted, structured, and fabricated using L-PBF with 18Ni maraging steel, validating that biologically informed design can effectively guide anisotropic material behavior while maintaining manufacturability. The resulting staggered lattice configurations not only mimicked the layered failure mechanisms and energy dissipation observed in nature but also allowed for precise control over unit cell-level parameters, offering a repeatable pathway for designing directionally optimized, high-performance structures tailored for load-bearing applications.

Traditional strategies for avoiding buckling, such as increasing structural width or reducing height, often result in increased weight, compromising the lightweighting goal. This work presents an alternative: introducing tailored failure paths that more effectively distribute load across the structure. The staggered architectures exhibited strain hardening and delayed catastrophic failure, enabling controlled, progressive deformation and improved post-yield performance. This predictability in failure behavior creates valuable opportunities for design optimization in bio-inspired structural systems, particularly where mechanical efficiency, reliability, and manufacturability are critical. By integrating biological principles with engineering tools, this work advances a systematic and scalable methodology for bio-inspired design, offering practical, manufacturable solutions for resilient lightweight structures. The future experiments will target a systematic study of experimental design variables, the effect of printing orientations on the mechanical behavior of lattice structures.

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