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Natural cellular structures in engineering designs built via additive manufacturing

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ABSTRACT

Natural cellular structures inspire numerous engineering applications due to their lightweight and good load-bearing capabilities. Variations in their structural configurations result in diverse mechanical properties, rendering them ideal for bioinspired designs. This review explores the occurrence, properties, and applications of cellular structures in nature and their engineering counterparts built via additive manufacturing (AM). Additive manufacturing technologies enable replication of natural cellular structures with enhanced geometrical complexity. However, they face challenges associated with scale-based geometrical constraints and minimum printable size of various features. Current constraints and techniques for overcoming these challenges, including advancements in nanotechnology, multiscale modelling, novel biomimetic designs, and improved mechanical testing methods are discussed in this paper. It is noted in the paper that it becomes increasingly possible with these advancements to optimise bioinspired engineering parts for complicated applications.

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Cellular structures; bioinspired designs; additive manufacturing; hierarchical structures; biological tissues; mechanical properties

Introduction

Cellular structures have garnered significant interest in engineering and manufacturing fields because of their unique capability of combining lightweight designs while maintaining good load-bearing capacity [1]. This property renders cellular structures useful for a wide range of engineering applications in the aerospace, automotive and biomedical industries [1,2]. Cellular structures present in numerous examples of biological materials such as bone, wood, and glass sponge skeleton are hierarchically structured, which means they have configurations or arrangements at multiple scales, including macro, micro, and nano [3]. This hierarchical arrangement results in their good mechanical properties, lightweight designs, and overall effectiveness in their applications [3–5]. The strength, stiffness, and fracture toughness of cellular structures are the result of built networks of solid struts that form ribs, and cell walls [1,3,5]. These cells may occur in open, closed, or polygon cell-based designs, which have a significant effect on the structure's overall mechanical behaviour [3]. The latest research [6–9] is still unclear on which natural cellular designs can provide a set of significant advantages at once regarding their mechanical characteristics after being mimicked with synthetic materials. Additionally, specific engineering areas of application where such designs predominantly thrive or fall short have not been thoroughly examined in the literature.

Designing the geometries of cellular structures is very complicated due to their hierarchical nature and multiple scaling levels [10]. Mimicking such geometric configurations in nature-inspired designs with traditional manufacturing techniques such as casting, forging, machining, and moulding has been proven in some studies [10,11] to be highly challenging regarding their manufacturability. As an alternative, a great deal of scientific and technological advancements in this area of research has been made possibly by the emergence of additive manufacturing (AM) technologies such as binder jetting, digital light processing (DLP), selective laser sintering (SLS), direct metal laser sintering (DMLS) or selective laser melting (SLM), fused deposition modelling (FDM), and stereolithography (SLA) [10–13]. Such technologies have assisted in fabricating intricately geometrised, nature-inspired cellular designs to some extent [10,12,13]. Even so, there are gaps in knowledge related to the use of AM technologies for fabricating highly detailed nature-inspired cellular designs. These challenges are often associated with the variations and characteristics of material, multi-material printing, structural feature resolution and accuracy, intricate design scalability, functional gradients and structures with hierarchy, dynamic and responsive characteristics, process reliability and consistency, simulation and predictive modelling, post-processing challenges,

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surface roughness and porosity, biocompatibility, and sustainability and environmental impact [10–13].

The work reported in this paper provides an extensive review of the different cellular structures seen in nature, revealing their mechanical properties and structural configurations. By synthesising the latest research, it adds to a more thorough comprehension of the behaviour of biological materials designed with cellular structures. The result of this review work supports the choice of optimal designs based on particular requirements and limitations by conducting an in-depth examination of their efficacy for various engineering applications. It informs engineering design choices by determining areas where natural cellular structures provide significant advantages. The topic of this review article also highlights the challenges and advancements specific to additive manufacturing (AM) technologies as they pertain to the replication and application of nature-inspired cellular structures, suggesting areas for innovation and improvement. Previous literature [2–6,8–13] has extensively reviewed natural cellular structures and their broad applications in engineering. However, this paper differentiates itself by providing a detailed examination of how additive manufacturing (AM) technologies specifically facilitate the fabrication of these complex structures, which remain challenging to produce using traditional manufacturing methods. This review emphasises recent, state-of-the-art advancements in AM, such as multi-material integration, functional gradient fabrication, dynamic responsiveness, and scalable hierarchical design critical capabilities for precisely replicating the cellular architectures observed in nature within engineered systems. It also reviews how to overcome scale-based geometrical challenges and improve the quality of printed parts using advances in materials and methods. Additionally, this paper contributes fresh insights into the usefulness of multiscale modelling, optimisation, and simulation techniques for AM-fabricated structures, which are critical for improving predictability and structural performance. It specifically examines less-explored aspects of AM, including constraints in accuracy and resolution, manufacturing reliability, sustainability challenges, and the biocompatibility of nature-inspired designs. These insights are intended to accelerate design and optimisation processes, foster the development of advanced nature-inspired designs through the integration of computational tools and effectively managing uncertainties associated with modelling and experiments of such complex systems. This work synthesises these aspects to evaluate the role of additive manufacturing (AM) in biomimetic engineering while also proposing actionable strategies to address existing limitations in the field. This review establishes a focused link between natural cellular architectures and AM technologies, equipping researchers and engineers in this field with insights to make informed design decisions that capitalise on the structural and functional benefits inherent in biological systems. It also addresses the significance of stringent testing processes for validating design concepts and guaranteeing product quality and safety. Figure 1 depicts a graphic illustration of a research bridge connecting biological cellular structures with AM nature-inspired engineering cellular designs through mechanical and physical properties and applications.

In its entirety, this review advances bioinspired engineering by synthesising existing knowledge, addressing existing challenges, and suggesting areas for innovation and improvement. The primary objective of this work is to inspire the generation of improved designs for bioinspired engineering parts that draw on the principles of natural cellular structures through interdisciplinary collaboration and technological advancement.

Types and occurrence of natural cellular structures

Types of cellular structures in nature

There are three types of cellular structures often observed in the design of organic materials, namely open, closed, and polygonal cellular structures. Figure 2 shows a schematic that classifies the three types of cellular parts typically observed in biological tissues.

Open cellular structures are built using solid edges with voids in between, whereas closed cellular structures have solid faces that enclose the cells. The third type of cellular structure comprises polygon cells that are arranged in both two- and three-dimensional geometric designs to fill a design space. Cellular structures in nature are characterised by coherent pathways of hollow-like or enclosed cell structures with perforated pores and anisotropic cell walls. Figure 3 shows a few biological tissues with the aforementioned types of cellular structures [4,14,15].

Though there are recent advances in research [16–22] conducted on structural characterisation of open, closed, and polygon-based cellular structures, there is still a limited comprehension of how their particular topologies affect mechanical properties. By conducting a comparative analysis of open, closed and polygon-based cellular parts under different loading conditions, it is suggested that this work, the establishment of ranking in terms of their mechanical properties. This could include the use of new effective strategies in experimental testing, finite element analysis (FEA), and computational modelling to determine how the geometries of lattice designs influence mechanical properties such as stiffness, strength, and energy absorption. Furthermore, the available research [1–5,14,15,23] does not provide an

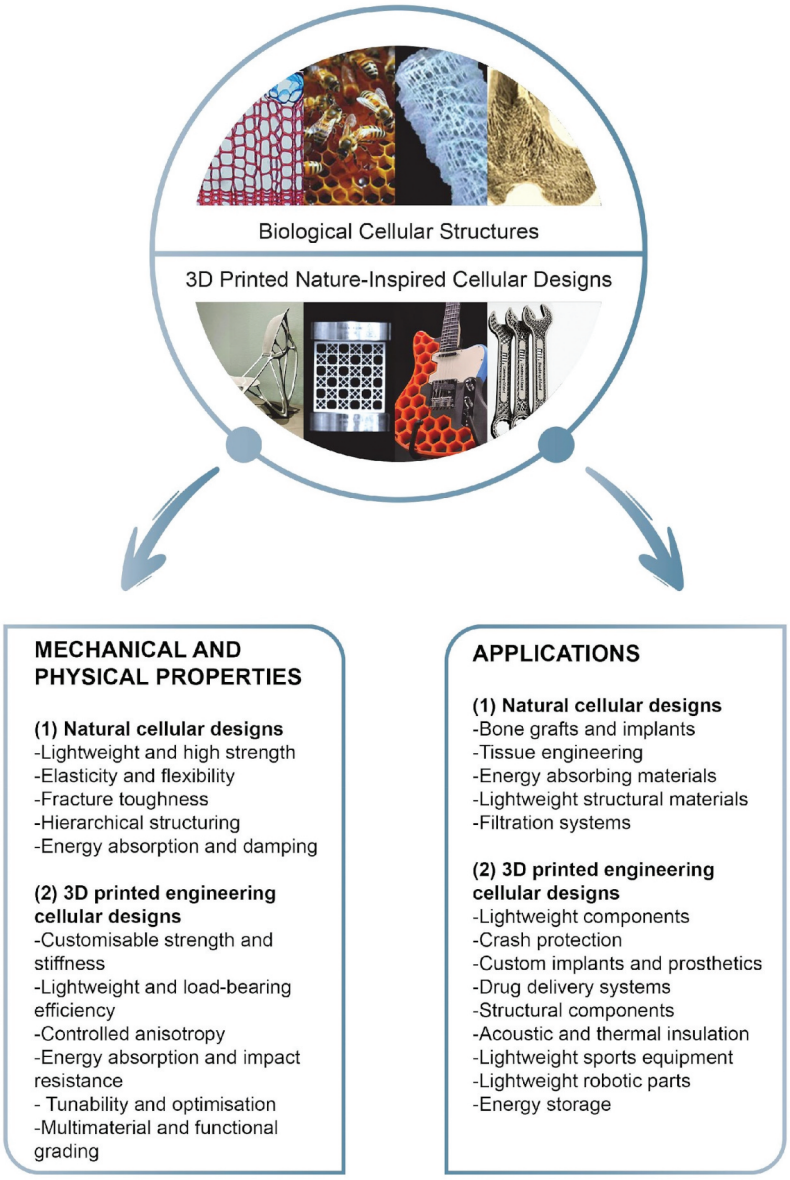

Figure 1. A graphic representation of a research bridge connecting natural cellular structures to 3D printed nature-inspired cellular designs in engineering.

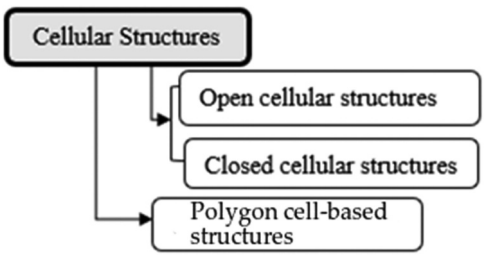

Figure 2. Different types of cellular designs in nature.

exhaustive understanding of the natural cellular architecture, particularly the presence of coherent channels, embedded pores, and anisotropic cell walls. Performing contemporary experimental studies and microscopy tests to characterise cellular configurations inherently built in organic structures is proposed here as well. The case is made for evaluating morphological characteristics and analysing their corresponding mechanical properties at smaller scales. This entails applying contemporary imaging techniques such as scanning electron microscopy and confocal microscopy, as well as incorporating computerised image processing algorithms in such analysis.

Occurrence of cellular structures in nature

In nature, the geometries of cellular structures are hierarchically structured. The hierarchical arrangement of biological tissues such as the glass sponge skeleton, bone, and wood are structured at the macro, micro, and nano scales [3,14]. The hierarchically structured tissues have superior mechanical properties as a result of the organism's subsequent structural optimisation [15]. This is a growth strategy that ensures that the structure has responsive load-bearing capacities to changing stimuli, which in turn allows biological tissues to adapt [16].

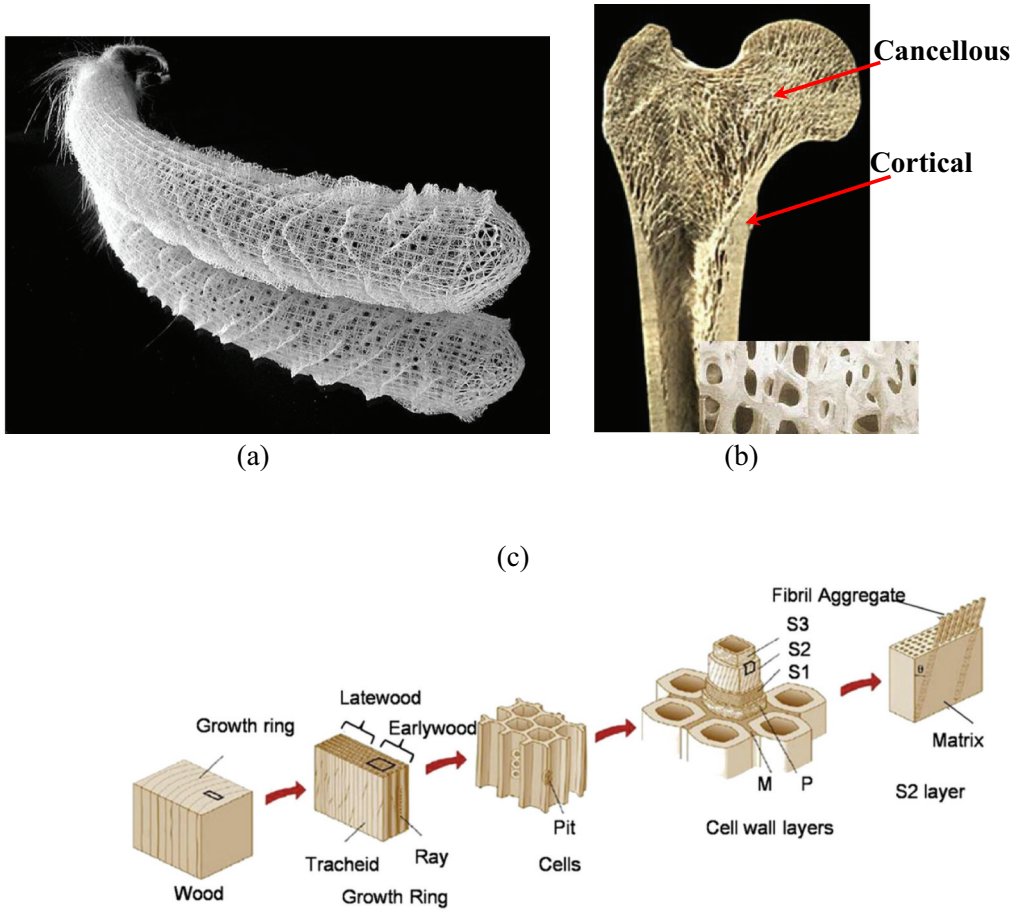

Figure 3. Types of cellular designs, namely, (a) an open cellular structure used to build a glass sponge skeleton, (b) a closed cellular structure used to build a tibia bone, and (c) a polygon cell-based structure used to build honeycomb (HC) cell walls in wood [4,14,15].

Glass sponge skeleton tissues have seven hierarchical levels that range in size from nanometres to centimetres, namely (a) laminated spicules (micrometres to centimetres), (b) axial filaments (nanometres-to-micrometres), and (c) silica particles and protein interlayers (nanometres to micrometres) [3,14,24]. The various levels of hierarchy all contribute to the structure of skeletal composites in nature. Figure 4 shows the skeletal composite of spicules in siliceous sponges, as comprised of cylindrical lattice cage-like structures with lateral openings [14].

The cylindrical lattice-like cage structure is supported by grids built from vertically, horizontally, and diagonally ordered struts, which function as bonded spicules, as represented in Figure 4 [14]. Figure 4b shows a red arrow indicating the intersecting grid for vertically and horizontally structured struts. The yellow arrow indicates the direction for a diagonally structured strut.

Bone tissues are typically grouped together into three categories: plate-like bones (such as the skull), short bones (such as the vertebra) and long bones (such as the femur) [14,23]. The tissue in question adopts different morphologies depending on the application, as seen in the final forms presented in Figure 5 [3].

Bone tissues are hierarchically structured at the macro, micro, and nano scales. Additionally, two subscales at the micro and nano levels can be present as well depending on the application [3]. Figure 6 shows the relationship drawn between the connected component phases of hierarchically configured bone structures at different scales [23].

Wood tissues have four hierarchical levels that range from the greatest to the smallest scale. This comprises the macroscopic structure, cellular structure, fibrillary structure and molecular structure, as depicted in Figure 7 [14].

The occurrence of cellular structures highlights the concept of function-driven design, in which the structure and arrangement of material corresponds to its application. Different biological tissues and materials have a variety of cellular architectures that are optimised for specific functions, including load-bearing, flexibility, or filtration. Additionally, biological materials can adapt to changes in external stimuli as a result of the dynamic process of evolution and hierarchical structuring of cellular structures. This adaptability is crucial for the longevity and growth of various organisms. In a comparable manner to engineering, having the ability to produce materials that can adapt to

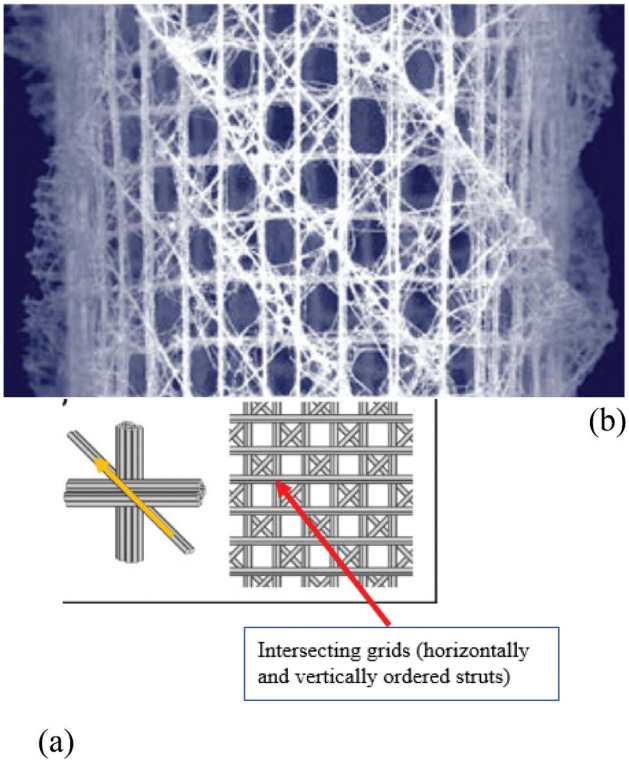

Figure 4. A skeletal composite of spicules in siliceous sponges built using cylindrical lattice cage-like structures, represented as (a) an organic and non-periodic form, and (b) a systematically modelled and periodic form [14].

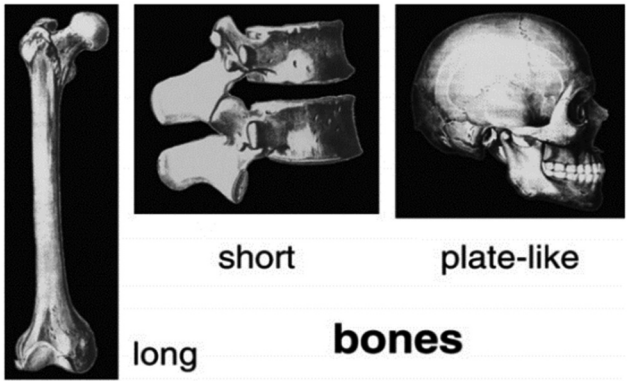

Figure 5. Numerous morphologies of bone tissue depending on their particular application [3].

changing conditions can be advantageous in numerous types of applications.

There are, however, gaps in knowledge that are highlighted in this work, related to existing studies [16–18,20,22] that are focused on the design and development of intricate adaptive materials and structures, capable of responding to changing external stimuli. Conducting studies on the design and manufacture of adaptable materials and structures inspired by biological systems is currently a hot topic with numerous challenges [16–18,22], and the reason why advances are recommended in this work. This investigation addresses work related to the design and manufacture of responsive materials, such as hydrogels, and shape memory alloys, in addition to smart structures, such as morphing structures, and self-healing materials that are adaptive to changing conditions. In addition, a full comprehension of the integration of sensing and actuation processes that could potentially allow real-time feedback and control of the adaptive lattice parts if considered is yet to be achieved. Comparative studies of hierarchical structures in engineered materials and biological materials are limited in the available literature as well, particularly when it relates to adaptability and function-driven design [17,18,21,22]. Han et al. [25] designed for additive manufacturing of locally reinforced open-cell nitinol stents for intracranial vascular aneurysm. The locally strengthened cerebral vascular stent was designed to enhance the radial load and wall apposition performance. Based on their findings in finite element modelling and

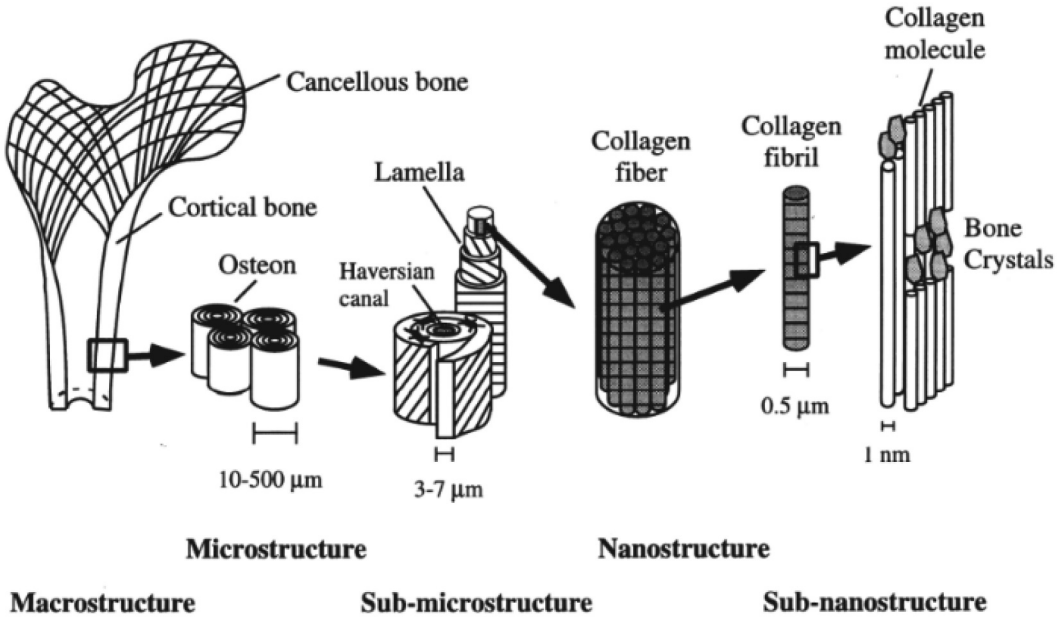

Figure 6. Different hierarchical orders of structuring material for numerous scales of a bone structure [23].

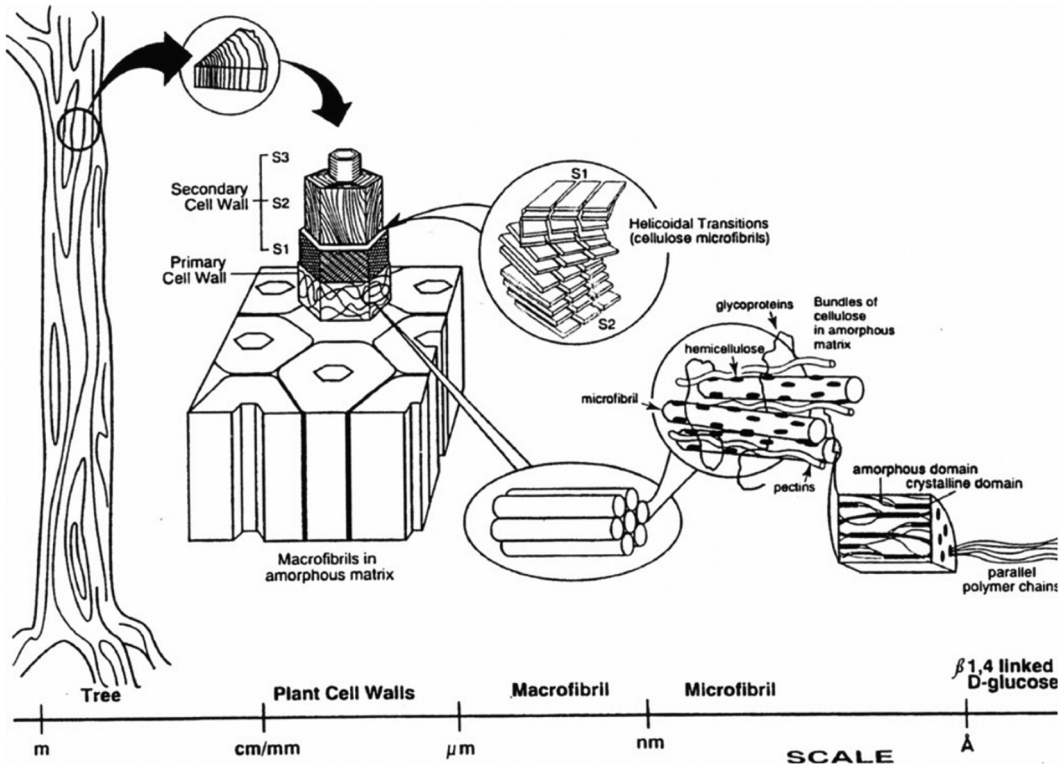

Figure 7. Numerous hierarchical levels of structuring material for a variety of scales of a wood structure [14].

extensive measurements, the local radial load was enhanced by 38.9%, as was the coil embolism's stability. The in-vitro releasing experiment indicated that the stent could attach to the arterial wall without causing gator backing. Their investigation showed that using a locally reinforced nitinol stent for intracranial aneurysm therapy could lower the possibility of vascular embolism and haemorrhagic apoplexy after placement. Hierarchical structuring, which typically occurs in cellular structures in nature, could prove useful for constructing bioinspired locally reinforced stents. This is expected to enhance the effectiveness and quality of stents used to treat cerebral vascular aneurysms. Advances in mechanical characteristics, biocompatibility, and drug delivery potential render this a promising area for further research and development. However, the complexity of additive manufacturing and the requirement for accurate control over the structure must be carefully controlled to fully reap these advantages.

Based on comparative analyses to evaluate the structural similarities and differences between engineered and biological materials to determine common design principles as well as methods for improving adaptability in engineered materials, it is recommended that biologists, material scientists, and engineers collaborate collectively on this research topic.

Application of cellular structures in nature

Cellular structures in biological tissues provide crucial functions which contribute significantly to the good health and functionality of living organisms. Significant applications of cellular structures in biological tissues are now discussed.

Cellular structures in bones, cartilage, nacre, and plant tissues offer mechanical support and allow these tissues to withstand loads without compromising structural integrity. The hierarchical arrangement of biological cells influences their mechanical properties such as stiffness, strength, and toughness [26–28]. In animal and plant tissues, cellular structures have gap junctions and membranes that allow connectivity between cells and transmission. These structures allow ions, chemicals, and electrical impulses to exchange between neighbouring cells, coordinating tissue behaviour [3,14,26]. Tissue regeneration and wound healing rely on cellular structures in tissues such as skin, blood vessels, and the intestinal tract [14]. After an injury, the ordered arrangement of cell aids in tissue repair and the restoration of normal functionality [26]. Cellular structures in the air passageways of the lungs allow for effective gas exchange during respiration. These thin-walled structures optimise the amount of surface area available for the circulation of oxygen and carbon dioxide between the air and blood [4,26,27]. Cellular structures also serve an important part in fluid filtration and secretion in organs such as the kidney and the salivary glands [26]. Furthermore, specialised cellular structures in biological tissues allow for the targeted movement of specific substances. Cellular structures, such as focal adhesions in tissues that are connected, allow cells to be fixed and interact with their environment by facilitating cell attachment to the extracellular matrix [3,4,26,28]. During the early stages of development for biological materials, the hierarchical structuring of cellular structures is crucial for cell differentiation and the formation of tissues and organs [3,29]. Numerous studies [6–10] have comprehensively addressed the process-structure-biological functional response in nature-inspired cellular designs fabricated using AM techniques, offering valuable and promising insights which were most predominant in progressing medical science and technology.

It is deduced from the foregoing material that the relationship between a cellular structure and its functionality in living organisms is complex. This is evident in numerous and diverse cellular structures found in biological tissues. Understanding these designs is crucial for the advancement of medical studies, including tissue engineering and regenerative medicine, as well as determining the causes of numerous diseases and disorders.

Mechanical properties of cellular structures

Glass sponge skeletons, nacre, keratin, bone, and wood have all been carefully studied in order to mimic their remarkable mechanical properties in nature [15]. Numerous studies have focused on the most important factors of loading structures, including loading direction, loading rate, degree of mineralisation, porosity, and hierarchical structuring for macro, micro, and nanoscales. To some extent, researchers have attained novelty and advances in fabricating at most energy absorption structures [15,30–33].

A bionic lattice structure mimicking the double slope-like reinforced structuring of a deep-sea sponge skeleton was suggested by Zhang *et al.* [34]. A bionic lattice built using a wall thickness value of $t = 1.2$ mm was observed to have better energy absorption capabilities as compared to one with a value of $t = 0.45$ mm. Their specific absorption energies *SEA*, absorption energy absorption *EA* and crushing mean force *Pm* increased by 216.5%, 745.0%, and 744.3%, respectively, with this decrease in wall thickness. It is worth noting that the skeletons of glass sponges have hierarchical configurations that span various length scales, from nanometres to centimetres. Although the double-diagonal reinforced configuration is macroscopically replicated by the bionic lattice structure, as observed in references [33,34], the authors of this review recommend the addition of hierarchical features at even smaller scales to further enhance the performance of the lattice design. To achieve this, prospective research must focus on the use of biomimicry and advanced manufacturing procedures such as AM to design and manufacture multiscale hierarchical structures mimicking the skeleton of a deep-sea sponge. Yao *et al.* [35] constructed a hierarchical foamy multiple-cellular square structure, modelled after the gradient distribution of various sizes of unit cells in organic structures, including the bamboo and bone tissue. Their findings showed that the 3rd-order biologically inspired hierarchical multiple cellular tube structure absorbs 173.7% more energy than the conventional square tube cellular structure. The hierarchical foamy multiple cellular square structure improves energy absorption, as determined by the findings of their research [35], and as reviewed by [33]. However, the specific mechanisms underlying this enhancement are not fully comprehended from these studies. Therefore, further studies are required in terms of physical experiments and numerical modelling, to

particularly develop full comprehension of the deformation behaviour, stress distribution and energy dissipation mechanisms within the hierarchical structure, none of which have been discussed in their work. Wang *et al.* [36] developed a novel thin-walled multiple cellular tubed structure comprising customised face-centred cubic (MFCS) cross sections, which were mimicked based on the physical properties of deep-sea sponge's skeleton. Through finite element simulation and physical experiments, the compression response and the capacity to absorb energies of the suggested structure were compared with those of the conventional multiple celled tube structure. Their findings regarding the energy absorption characteristics of the suggested multiple celled tube structure outperformed those of the strut-lattices and plate-lattices that were used for comparison. The suggested MFCS multiple celled tube design exhibited a specific energy absorption that is 37.13% greater when compared to the 3rd order bioinspired hierarchical multiple cellular tube structure. This indicates that their suggested MFCS multiple cellular tube design enhances the prospects for energy absorption of multiple cellular tube structures, as it was also reviewed in [24]. The parts were fabricated via AM technology, which allows for the direct integration of functional features and parts into the overall structure during the printing process. Further research work should focus on incorporating sensors, actuators or various functional parts into the MFCS multiple cellular tube structure to allow adaptive or controllable behaviour in response to the changing external stimulus.

Natural cellular structures are hierarchically structured with solid struts and unit cells building larger units. These units merge to produce even larger structures [33,37]. The hierarchical design results in repetition of unit cells, which in turn provide multiple load paths. These multiple load paths ensure efficient distribution of stress in biological tissues, improving their overall mechanical strength. The unit cells of these structures are built using solid struts and walls, which in turn add to their load-bearing capacity [3,37–41]. The material properties of these struts, such as their strength and stiffness, are crucial factors in determining the corresponding mechanical strength of the cellular material [40]. Moreover, the connectivity of the cells also assists in how the load is distributed effectively across the structure [37,40]. When subjected to external loads, the load is distributed among multiple cells and struts, minimising the stress concentration and increasing the overall structural strength of the tissue [42]. Cellular structures in biological materials can adapt and grow in response to mechanical loads. This dynamic growth mechanism allows tissues to change their cellular arrangement to optimise mechanical strength according to specific requirements for functionality [1,3,14,16]. Mechanical stiffness of cellular structures is influenced by their geometric configuration. The geometric configuration has factors such as cell shape, size, and cell connectivity that affect the stiffness of these structures [43]. Structures with larger cells or struts, for example, may have a higher stiffness [1,3,14]. Furthermore, the choice of material used for cellular structures has a significant effect on their mechanical stiffness as well [37]. In most studies [1,3,14,23,31,32,37], the stiffness of biological tissues is normally determined based on the modulus of elasticity of the solid struts and walls, but other material properties could be used as well. The interconnected cellular network of cellular structures ensures effective distribution of load, and also causes the structure to become rigid and stiff. This load-bearing capability is crucial for tissue structural integrity [1].

Higher values of mechanical strength have been reported [33,44–46] in biological nacres and seashells, which are typically plastic, with intrinsic deformation occurring at the nanoscale and extrinsic behaviour of deformation occurring at the micrometre level. By mimicking the robust and durable nacre designs, materials that are bioinspired, comprising hard micro scaled layers of mica, as well as soft polyimide have been built to achieve more effective mechanical strength for prospective aerospace materials, particularly those used in the lower Earth orbit [33,47]. For this lattice design, the nano scaled mica functions like a brick that substantially improves mechanical properties to achieve values as high as tensile strength of 125 MPa, surface hardness of 0.37 GPa and elastic modulus of 2.2 GPa for nanocomposites, as well as the enhanced temperature and ultraviolet resistance as reported by Soucek [47] and later reviewed by [33]. Though the work found improved mechanical characteristics in bioinspired materials that mimic nacre structures, there are gaps in it in comprehending the specific mechanisms that support the reported strength and durability. Prospective research must therefore concentrate on addressing nanoscale and microscale deformation mechanisms within materials, particularly the function of interfaces, defects, and stress distribution. The gradient-like feature that characterises organic plants highlighted in [33,48] has been adopted and mimicked in the design of bioinspired materials experiencing gradient microstructures, resulting in good mechanical properties or responsive behaviour. Frey *et al.* [49] generated smart response materials by incorporating biologically inspired chemical, structural, and mechanical gradients into delignified wood, mimicking the gradient-like structure and mechanical strength of natural wood. The value of stiffness for the delignified wood that these authors attained was 35 GPa and a high value of 270MPa for the strength compared to typical values of wood falling within the range 7–24 GPa and 7.2–48

MPa, respectively, as a result of the close connection between the hydrogen bonding and the mechanically interlocked fibres for good transfer of loads. Their work was centred around the enhancement of smart responding materials with bioinspired gradients, though there are possibilities to improve mechanical effectiveness and adaptability by optimising design and manufacturing parameters. New studies should include comprehensive studies into the influence of different gradient profiles, transitions, and interfaces on mechanical properties such as stiffness, strength, and other relevant parameters.

Audibert et al. [50] generated the size, shape, and configurations of porosities from either avian or terrestrial mammal bone structures and used them for topological optimisation and bioinspired structural design. A 3D metal printing process was used for fabricating steel structures with a density of approximately 65%, which were inspired by organic bone designs. The terrestrial mammalian-inspired beam improved the failure load and stiffness to reduce flexure by 7.5% and 17%, respectively, as compared to the topologically optimised beam-like design, due to reduced pore size and stress field homogenisation. Their study suggests that biological inspiration is relevant as well as applicable not just for material advancements, but additionally for 3D printing, and it opens up new avenues for developing tough and strong mechanical lightweight structures. Given that the work employed 3D metal printing for building bone-inspired steel structures, scaling up production and manufacturing procedures for engineering applications could also pose challenges in consistency and quality control of parts, as well as requiring extensive use of post processing and finishing. Extension of this work ought to look into scalable manufacturing procedures, process optimisation, and cost-effective production methods to enable large-scale deployment of bioinspired structures across engineering fields.

In its entirety, it is deduced that the mechanical strength and stiffness of organic cellular structures are influenced by their hierarchical configuration, solid struts, material properties, and adaptability. These properties assist organic tissues to withstand external loads, maintain structural integrity, and efficiently undertake their particular applications. The comprehension and mimicking of these physical characteristics hold significant promise for developing new materials and structures with improved mechanical characteristics, as well as improving flexibility in design. Researchers can pave new routes for novel strategies aimed at improving strength, durability, and functionality across a wide range of engineering and medical uses by drawing on concepts from biological tissues.

According to Gibson and Ashby [1], cellular structures have greater load-bearing capacity when they are loaded in the longitudinal direction as compared to transverse directional loading. Cellular structures fail with ease in the transverse direction due to shearing and bending loads that are critical. This is because the highest mineralisation rate of material in cellular structures is observed in the longitudinal direction [14,16,26]. Gibson & Ashby [1] observed that the axial direction has the highest yield stress as compared to the radial and tangential directions for a wood tissue. Figure 8 shows longitudinal and transverse stress vs. strain curves of loaded structures [51].

The mechanical behaviour of cellular structures is also influenced by the rate at which loads are applied [1,26,51]. Cellular structures may withstand rapidly applied loads far better than slowly applied loads. In this way, at increasing strain rates, cellular structures stiffen and strengthen, as seen in Figure 9 [51]. The increasing strain rate is represented by the red arrow.

Adharapurapu *et al.* [52] presented evidence that the strain rate is dependent on the cortical bone because it has the densest material or lowest porosity compared to other bone parts and, as a result, has the greatest load-bearing capability. It was established in this work that cortical bone possesses structural material that enhances stiffness by 150 MPa compared to the trabecular bone with a stiffness of 8 GPa, but with lower strains (2%) to failure. When compared to cortical bone, the trabecular bone structure is deflected from its original position without fracturing. The latter type of bone was shown to withstand lower loads (50 MPa) and lower strains (50% lower than the strains in the cortical bone) to failure. Simkin and Robin [53] studied the mechanical behaviour of all forms of bones under bending loads. It was found in this study that increasing bone formation improves load-bearing capacity. Ascenzi and Bonucci [54] studied the compressive behaviour of single osteons in a human femur and observed that the mechanical properties of bones are stronger and stiffer in compression than in tension. It was further noted that the

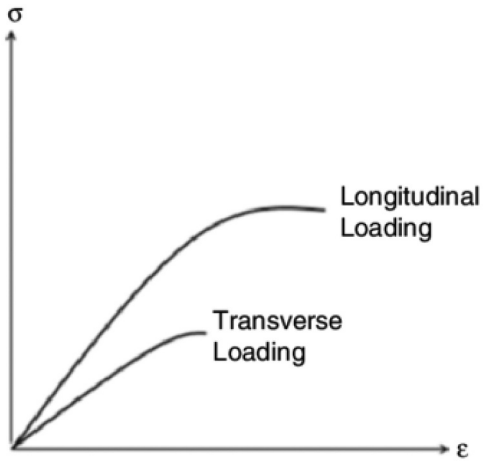

Figure 8. Curve plot showing stress-strain dependence on the direction of loading [51].

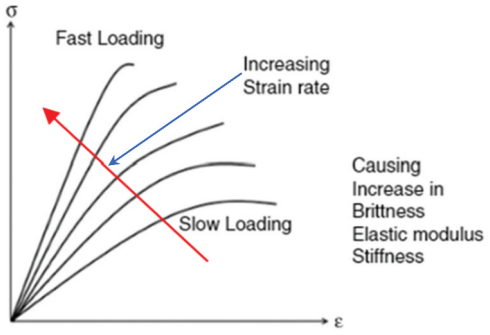

Figure 9. Curve plot showing stress-strain dependence on loading rate [51].

more mineralised the osteons in the bone became, the more rigid, and more brittle they became. The cell walls were observed to contract and contact those of neighbouring cells, thus reducing the pore gaps, and increasing the bone's compressive resistance. Tensile-loaded bone structures, to the contrary, were observed to exhibit lower values of stiffness than compression-loaded bone structures. The strained cell walls are separated at maximum tensile strains and, therefore, allowing cracks to form thus, leading to bone-fracture. However, for the stresses prevailing at the initial stages of plastic deformation, the bone develops some tensile toughness [14]. This property allows organic structures such as the bone, keratin, and nacre to withstand numerous types of loads without immediately cracking and in turn, aids in supporting and protecting tissues of the body [1,3,14,23,26]. Jeronimidis [55] proposed that the fibre pull-out process is primarily responsible for the good fracture toughness, as a result of the energy absorbed in the process for both bone and wood.

Niebel *et al.* [56] used Al_2O_3 and polymethyl methacrylate (PMMA) parts that mimic brick-and-mortar lamellar structures observed in nacre, which were effectively improved to generate a synthetic ceramic composite by freeze casting. The toughness of the manufactured parts reached 300 times that of its conventional structures, indicating the effectiveness of the toughening mechanisms found in naturally occurring biological composites. As a result of such studies [33,56], there has been a significant rise in interest in using natural cellular structure's toughening mechanisms in manufactured parts that are resistant to damage. The combined use of Al_2O_3 and polymethyl methacrylate in freeze casting to mimic the nacre structure could, however, be constrained by compatibility and processing of the materials. The next generation of work to be conducted in this area must therefore look into alternative materials or processing techniques that provide better compatibility, homogeneity, and control over microstructure, resulting in better mechanical properties and performance. Libonati *et al.* [57] experimented with a structure inspired by organic bone in composites with fibre-reinforcements to improve toughness level in reducing fracture while maintaining a balance of stiffness and strength. Carbon fibres, an epoxy matrix and glass fibres were used to replicate the lamellar, osteons, interstitial tissues and cement sheaths occurring in the osteonal, which is located in the secondary bone structure. Compared to the laminated composites and the additional structural materials, the design that is inspired by organic bone demonstrated substantially improved mechanical characteristics with reference to tensile strength, modulus of elasticity, fracture toughness, and stiffness, with tensile strength and fracture toughness improving by 26% and 86%, respectively, when contrasted against a previous structural design and other selected conventional laminated composites. The distinctive mechanical characteristics observed in organic bone structures have spurred the generation of polymer and polypeptide-based biomaterials [33]. Fibre-reinforced composites can pose challenges in terms of design complexity, manufacturing, and microstructure control when attempting to mimic the complex hierarchical structure of bone, including cement sheaths, interstitial tissues, lamellars, and osteons. To optimise the biomimetic design and comprehend the effect of various structural characteristics on mechanical properties, further work must include advanced computational modelling and simulation strategies.

Cracks begin and spread longitudinally as a result of shear stresses, contributing to the pulling apart of each cell wall without them experiencing transverse loads through fracture. Crack propagation along the grains of cells is much easier compared to propagation perpendicular to the grains, and thus higher resilience in the latter case. This is particularly so because cracks in the perpendicular direction are slowed by weak interfaces. The anisotropic toughening property of wood is similar to that of organic bone structures and has similarities to that of nacre [4,14]. This contributes to the cellular structures' high load-bearing capacity [1,4,14]. Amini *et al.* [58] developed a strong glass with enhanced mechanical characteristics based on mimicking the organic nacre structure. The glass comprised SiO_2 and modified polymethyl methacrylate with identical refractive indexes. The bioinspired design of the glass allowed for progressive fracture rather than catastrophic failure, increasing the work done to fracture and the toughness level in reducing fracture by 30% and 55%, respectively. Particularly, the toughness level in reducing fracture of biologically inspired glass was observed to be twice that predicted by SiO_2 tablet alignment. During the

fracture phase, deformation and delamination followed the toughening mechanism observed for extrinsic deformation, in which the polymer material binds and bridges the tablets until full debonding or the development of microscopic voids [33,58]. There are, however, limitations in the current understanding of the exact toughening mechanisms in effects associated with nacre-inspired glass, despite the fact that the study showed a considerable improvement in fracture toughness and work done on fracture as compared with conventional glass. To clarify the contributions of delamination, deformation, and polymer bridging to overall toughness, future studies should entail comprehensive characterisation using cutting-edge imaging and analytical methods.

The foregoing material describes nature's remarkable ability in building efficient and functional cellular structures. Understanding the concepts behind these natural designs could provide valuable insights to engineers and material scientists to develop novel structures and materials with improved mechanical properties.

Comparative evaluation of cellular structure designs

A brief comparative examination of different cellular structure designs, including HC, bone, wood and glass sponge skeleton, is carried out in this section, taking into account key aspects such as mechanical properties, adaptability in design, manufacturing possible outcomes, and application-specific requirements. This analysis contrasts their numerous cellular shapes based on mechanical performance and examines the trade-offs between structural integrity and adaptability within each design approach.

The honeycomb structure design

Mechanical properties

Strength and stiffness: Honeycombs (HCs) experience a high in-plane strength and stiffness associated with their geometric effectiveness in distributing loads across cell walls [1,2]. Even so, the out-of-plane effectiveness is low, limiting its use in applications requiring multi-directional strength.

Absorption of energy: HCs exhibit good energy absorption capabilities in the cell plane, which results in their suitability for crash applications such as crash absorbers and packaging [2].

Manufacturing possibility

Effectiveness in fabrication: HCs are easy to manufacture with traditional techniques (for instance, extrusion, and moulding) and the latest AM for customised shapes [2,13].

Cost of manufacturing: The basic geometries and scalability render HCs economical, even though large scaling complex, hierarchical HCs can become costly.

Adaptability or flexibility in design

Given that HCs have set or fixed geometric constraints, they lack extensive flexibility in design, therefore being better suited for conditions that require robust stiffness over adaptability [1].

Specific applications

On account of the HCs high in-plane strength and energy absorption characteristics, it is extensively used in aerospace, automotive crash structures, and lightweight structural panels [2].

The wood-like cellular structure design

Mechanical properties

Strength and stiffness: Wood is intrinsically anisotropic, exhibiting directional strength as well as adaptability in design because of its cellular architecture and fibre alignment, which are good for bending and torsional loads [14].

Fatigue toughness: Wood-like cellular designs exhibit high fatigue resistance, particularly along the direction of the grain formation, which increases its longevity under cyclic loading scenarios [4,14].

Manufacturing possibility

Effectiveness in fabrication: Conventional wood structures are restricted to natural materials, however biomimetic designs inspired by wood could be replicated using techniques for AM [4].

Cost of manufacturing: Wood is relatively less costly in its natural state; however, synthetic mimicry tends to be more expensive depending on the materials used [4].

Adaptability or flexibility in design

Dynamic response: Wood's hierarchical structure allows it to cope with changes in the environment, including temperature and humidity fluctuations, which leads to moderate adaptability in its geometrical design [4,14].

Shape customisation: AM-produced materials are capable of being tailored for stiffness and structural flexibility by mimicking the hierarchical structure of wood [4].

Specific applications

The wood is good for biomimetic designs for ecologically friendly architecture, bio-inspired prosthetics, and structures that require inherent elasticity and fatigue resistance [4,14].

The bone-like cellular structure design

Mechanical properties

Strength-to-weight ratio: By virtue of its porous, hierarchical structure, the bone structure has good mechanical performance and a high strength-to-weight ratio, particularly trabecular (spongy) bone [2,3,5,6,14].

Energy dissipation: Trabecular bone structure effectively absorbs energy and adapts to physiological changes, leading to improved impact resistance [2,14].

Manufacturing possibility

Effectiveness in fabrication: AM technologies, such as selective laser melting (SLM) and electron beam melting (EBM) that can accommodate complicated geometries, make it possible to replicate bone structures in synthetic materials [2,6].

Bioactivity: When printed using biocompatible materials, bone-inspired structures can be integrated with natural tissues, which is crucial for medical applications [6].

Adaptability or flexibility in design

Dynamic response: Bones reconstruct or change in dimensions over time in response to stress loads, which can be mimicked using shape memory alloys and AM materials. This adaptability renders bone-inspired designs good for use in dynamic responsive implants to physiological changes in the human anatomy. The research area is new and of great interest to the research community given the fact that the currently available commercial medical implants are primarily based on static designs.

Personalisation: Bone-like structures offer patient-specific tailoring, particularly in medical implants [2,6].

Specific applications

It is extensively used in medical implants such as bone grafts and scaffolds because of its bioactivity, load-bearing capacity, and its effectiveness in integrating with biological tissue [5,19].

The glass sponge skeleton structure design

Mechanical properties

Strength: Glass sponge skeletons, such as those seen in *Euplectella aspergillum*, feature a high level of mechanical toughness due to their distinctive lattice-like silica structure, which combines strength and low density [14].

Fracture toughness: This structure resists cracking and has a progressive failure mechanism, adding toughness under compressive loads [4,14].

Manufacturing feasibility

Effectiveness in fabrication: Replicating glass sponge structures is challenging because of their complicated geometries, although modern AM techniques such as multiphoton lithography have shown promise [4,12].

Cost: High production costs due to complex manufacturing and limited scalability for commercial applications [4,14].

Adaptability or flexibility in design

Structural stability: Glass sponge designs tend to be rigid, with limited elasticity, yet they are highly resistant to external damage [14].

Dynamic adaptability to external stimuli: The low adaptability to physiological changes limits its use for scenarios with variable loads, even though it excels in steady, load-bearing applications.

Specific applications

Application possibilities include lightweight aircraft structures, undersea structures and bioinspired designs that require high fracture resistance and load stability [4,14].

Subjective comments on the trade-offs between structural integrity and flexibility in cellular shape design

Honeycomb structure

Honeycomb architecture is characterised by high strength-to-weight ratios, providing substantial structural integrity. However, their adaptability is limited due to their inherent rigidity, which often restricts flexibility in dynamic loading conditions.

Wood-inspired architecture

Wood-like cellular structures exhibit a balance between strength and moderate adaptability. Their anisotropic mechanical properties make them highly effective for applications subject to directional or varying loads, as they can adjust structural responses along different axes.

Bone-mimetic geometries

Bone-inspired structures offer an optimal compromise between strength and adaptability, which is particularly beneficial in biomedical implants. These geometries promote biological integration and respond to load variations, supporting long-term implant performance within dynamic biological environments.

Table 1. A concise comparative analysis of the evaluated cellular structure designs.

Type of Cellular Structure Design	Mechanical Properties	Manufacturing Feasibility	Adaptability or Flexibility in Design	Applications
Honeycomb	High in-plane stiffness	High	Low	Aerospace, packaging, crash absorbers
Wood	Moderate strength, fatigue-resistant	Moderate	Moderate	Biomimetic designs, architecture
Bone	High strength-to-weight ratio, bioactivity	Moderate-to-High	High	Medical implants, prosthetics
Glass Sponge	High fracture resistance	Low	Low	Aerospace, underwater structures

Glass sponge-inspired architecture

Structures inspired by glass sponge morphology are optimised for high fracture resistance, making them ideal for applications prioritising stability over flexibility in design. However, this enhanced resistance to fracture typically comes at the cost of limited adaptability in design under dynamic conditions.

Table 1 presents a summarised comparative analysis of the examined cellular structure designs.

The evaluation carried out in this section reveals that while the HC and glass sponge structures exhibit superior mechanical integrity, bone and wood structures provide a more advantageous balance of adaptability in design and strength. This balance renders them well suited for applications requiring dynamic response and bio-integration. The selection between these structural designs is contingent on application-specific requirements, manufacturing limitations, and the optimal balance between mechanical strength and adaptability or flexibility in design.

Incorporating natural cellular designs in engineering applications

Incorporating biological cellular designs in engineering applications is an innovative and interesting method that has been inspired by the complexities as well as the efficiency of biological structures [2,5]. Nature has evolved over billions of years, resulting in intricate cellular structures that optimise a variety of behaviour, including stiffness, strength, toughness, and flexibility, as well as self-repair and adaptability [1,18,26]. Engineers are able to create more sustainable, efficient, and adaptive structures by mimicking cellular designs in nature [29,30].

Additive manufacturing of bioinspired cellular structures

Conventional manufacturing methods, including casting, forging and milling, are challenging to use in complex designs for bioinspired cellular structures. This is due to the fact that the intricacies of the internal structures and geometrical arrangements exhibited in bioinspired designs are difficult to mimic using these manufacturing methods [59–61]. This is so except for a special group of alloy materials known as 'gasars', particularly lotos-like gasars [62]. Gasars exhibit distinctive characteristics that allow for more accurate replication of intricate structures, potentially overcoming some of the limits imposed by current manufacturing techniques in developing bioinspired designs. High precision casting, low viscosity, thermal stability, fine grain structure, customisable characteristics, compatibility with additives, and corrosion resistance include some of its distinguishing characteristics [63]. Alternative manufacturing technologies that are more suited to bioinspired cellular parts have been investigated in order to solve these limitations. Among these advanced procedures is as follows: Additive manufacturing (AM), often known as 3D printing, which is advantageous for its ability in building complex designs of bioinspired cellular structures with high precision and customisation [37,40,59–61]. This method builds structures layer by layer wise, and in doing so aids in fabricating complicated designs which mimic natural cellular structures [59]. The combination of AM and bioinspired designs has enormous potential in industries such as automotive, aerospace, and biomedical [37].

With optimal control over design parameters, highly customised structures are attainable via AM. Functional cellular parts in specific applications are obtained by mimicking complex cellular geometries observed in nature, such as vascular networks, honeycombs, and trabecular bone structures [2,37]. These bioinspired cellular architectures often have a good strength-to-weight ratio, resulting in them being ideal for building robust yet lightweight parts [2]. With the implementation of AM, lightweight materials with complex internal structures could be built, thus improving their mechanical properties [37]. Typical hierarchical structuring and multiple-scale repetitive structures observed in natural cellular structures can be replicated through AM. In turn, this improves the effectiveness and usefulness of engineered cellular materials [2,5,37,59]. Additive manufacturing enables rapid manufacture of prototypes of cellular parts. This ensures that mechanical tests can be carried out for multiple bioinspired designs before finalising the product. This enables the acceleration of the development process and improvement of the overall efficiency of design iterations [37,40,64,65].

Mishra et al. [66] recently explored the use of supervised machine learning strategies to predict the ultimate tensile strength (UTS) of polylactic acid (PLA) samples manufactured via fused deposition modelling (FDM) technology. The accuracy and effectiveness of four algorithms classified under supervision strategies, including Decision Tree, Gradient Boosting classification, K-Nearest Neighbour (KNN) and Logistic classification, were evaluated by forecasting the UTS of the samples. Their findings showed that, although the Decision Tree and KNN algorithms achieved an F1 ranking of 0.71, the KNN-based approach outscored the other algorithms with an area under the curve (AUC) of 0.79. Their findings warrant further investigation into 3D-printed bioinspired cellular architectures. Significant insights into the possible use of such machine learning strategies for enhancing both the accuracy and performance of prediction models to be used in 3D printing of such complicated designs can be achieved for such investigation. Gong et al. [67] reviewed the latest advances in laser cladding (LC) technologies for high-entropy alloys (HEAs), including fundamentals, metallurgical phase, and microstructure, particular characteristics for advanced coating uses, and the function of ceramic particle reinforcement in HEA coating LC precipitation. They highlighted that over the past few years, new characteristics of HEAs, including high levels of specific and mechanical strength at elevated temperatures as well as good ductility and fracture toughness at cryogenic temperatures, have been observed and are associated with the effects of elevated entropy, significant lattice distortion, gradual diffusion, and the cocktail influence. In the light of interesting findings and recent progress in automation, machine learning, and artificial intelligence, they suggested that LC can develop new HEA coatings with enhanced characteristics for cutting-edge protective technologies. Given their valuable insights, it is now advised in the current review to include natural cellular architecture design strategies in HEAs fabricated using LC technology. This recommendation is given on the basis that cellular architectures with greater ease and accuracy could mimic the significant lattice distortion required for enhancing characteristics in HEAs coatings.

Application of bioinspired cellular structures in aerospace industries

Bioinspired cellular parts, including honeycombs and foams, have high strength-to-weight ratios [2]. In the aerospace sector, these structures are used for building lightweight structural parts including wing panels, fuselage parts, and fairings. Their reduced weight improves the fuel efficiency and the overall performance of aircraft and spacecraft [68]. Natural cellular designs are useful for parts with high absorption of strain energies in order to maintain passenger and crew safety during emergencies [1,2,5,26]. Aerospace engineers and scientists are also improving crashworthiness and impact resistance by incorporating bioinspired cellular materials in critical regions such as landing gear and cabin parts [69,70]. Natural cellular structures, including those observed in plant leaves, are capable of altering shape or responding to external stimuli [14]. Implementing similar principles to aircraft wings or other surfaces could result in adaptive and morphing structures that improve aerodynamics and control under different flying conditions [71]. In the case of spacecraft and re-entry vehicles, bioinspired cellular structures capable of resisting high temperatures are expected to be used as thermal protection materials, ensuring the safe entry of spacecraft into the Earth's atmosphere [37,72]. Inspired by the principles used by natural flyers such as insects and birds, engineers are looking into bioinspired propulsion systems. For some aeronautical applications, biomimetic propellers and flapping wing designs could result in improved efficiency and manoeuverability [73].

Application of bioinspired cellular structures in automotive industries

Automobile manufacturers lower the overall weight of vehicles by integrating lightweight materials into automobile parts such as body panels, chassis, and interior parts, this in turn, improve fuel efficiency and lower emissions [73]. Natural cellular architectures tend to be preferable with regard to energy absorption applications [2]. Vehicles are engineered to better withstand the energies generated by impacts during crashes by incorporating bioinspired materials in critical regions such as bumpers and crumple zones [69,70]. Moreover, bioinspired cellular architectures with optimised thermal conductivity are used to improve overall thermal management and vehicle performance in automotive cooling systems, battery packs, and engine components [74]. Researchers are investigating bioinspired tire tread designs inspired by natural surface patterns. These designs seek to improve traction, reduce rolling resistance, and improve overall tire performance, all of which contribute to an improved fuel efficiency [2,74]. The ability to mimic the flow patterns inherent in nature, such as fish scales or bird feathers, results in a more aerodynamically efficient vehicle designs [62]. Shapes that are more streamlined reduce drag while improving fuel efficiency [75,76]. Bioinspired self-healing cellular materials are being researched for automotive applications. These materials are capable of self-repairing small cracks or damage, thus extending the life of automotive parts, and lowering maintenance costs [75].

Application of bioinspired cellular structures in biomedical industries

Bioinspired cellular parts such as scaffolds can be used as structural support during tissue regeneration of damaged or wounded biological organs. These scaffolds mimic the natural extracellular matrix of biological materials, allowing cells to proliferate and differentiate into functional tissues [77]. Additionally, bioinspired structures could be used for vascularisation, which allows nutrients and oxygen to reach developing tissue [37,40]. Such structures are also used as carriers for targeted drug delivery. They are capable of encapsulating drugs while controlling their release, replicating the behaviour of cells within the body that carries and releases chemical substances as required [37]. Bioinspired materials, which mimic the cellular architecture found in biological tissues, can be used for building biocompatible implants. These implants have the capability to integrate seamlessly with the tissues that surround them, thus lowering the possibility of rejection while improving patients' prospects for recovery [2,5,31]. Misra & Misra [6] reviewed some of the fundamental synergies between biological sciences and cellular designs established with AM technologies to shed some insight into the merits of cellular configured implants for lowering stress-shielding and complying with the bio-mechanical property standards for modulus of elasticity, impact protection, and fatigue toughness when coupled with biological applications. They underlined that medical devices using cellular designs constructed via AM feature an interesting and feasible way of mimicking the complicated, interlinked porous design that is basic in attaining physical features comparable to the structure of bones (including variables such as low density) and mechanical properties (for instance, as good strength, resistance to fatigue, and energy absorption). Combined with improved biocompatibility, these advantageous properties are easily attained through carefully designing unit cells, optimising the relative density, and effectively controlling the volume of pore fractions within the cellular architecture. This linked porosity, design biological supports, and crucial cellular processes including adhesion, proliferation, differentiation, and mineralisation.

Li *et al.* [78] processed commercially pure titanium (Grade 1 ELI CP Ti) dental root-analogue implant (RAI) with oval cross-section abutment via selective laser melting (SLM) technology. Their research highlighted that CP Ti and SLM are suitable for the manufacturing of RAI. They additionally reported that the RAI manufactured resulted in improved osseointegration due to the transfer of stresses from the lowered elastic modulus of CP Ti. However, they failed to clarify to what level and how the implant better integrates with the tissue. Given the solid nature of their RAI design, the current study recommends that adding functionally graded cellular designs in areas of the RAI that come into direct contact with tissues could significantly increase the chances of seamless osseointegration. This is physically achievable given that it enhances the surface area for bone ingrowth and the porosity for vascularisation. Shanmugam et al. [79] also reported on recent advances in the design of artificial organs through regenerative medicine and 3D tissue manufacturing. They highlighted that biomaterials for medical use such as bio grafting and organ on a chip with tissue engineering are being developed through upgraded manufacturing and biomimetic design of structures and materials such as cellular architectures. Additionally, medical devices with biomimetic architecture and bionic material systems have been developed using advanced AM technology.

Research efforts [80,81] on the use of AM technology to fabricate nature-inspired cellular designs to improve the compression deformation and compression fatigue behaviour of bone implants have been made as well. Zhao *et al.* [80] investigated the impact of metallic lattice cell morphological designs on the compression–compression fatigue behaviour of Ti6Al4V manufactured by electron beam melting (EBM). These cellular shapes mimicked the structure used in bone implants and were studied using numerical and physical experimental tests. Their findings revealed that the fatigue mechanism for each of the types of lattice geometries examined (cubic, G7, and rhombic dodecahedron) included cyclic ratcheting and fatigue crack formation on the struts. They additionally reported that increasing buckling deformation on the struts in cellular shape designs reduced the topologies' cyclic ratcheting rate during cyclic deformation, resulting in higher compressive fatigue strength. Cellular solids of Ti-6Al-4 V that have good fatigue strength and low modulus similar to the structure of bones can be constructed using the EBM technology through optimising buckling and bending deformation using cell shape design. Wang et al. [81] examined the compression deformation to compression fatigue behaviour of functionally graded Ti6Al4V mesh-like lattice designs built using EBM technology to mimic the structure of bones. During cyclic deformation, they reported that the locally distributed stress within struts was not uniform owing to the constituents' inconsistent mechanical characteristics. They highlighted that the cracks caused by fatigue originated in the lowest strength constituent and subsequently propagated to the point where structural failure occurred. Even so, no apparent damage was observed in the other parts during their compression analysis. Compared to the iso-strain state, their work clearly showed that the rate of fatigue for graded

cellular designs is primarily determined by the part in the structural frame with the lowest strength.

There are further numerous research efforts [82–84] that investigated the functional response of 3D printed lattice designs for scaffold structures. Nune *et al.* [82] assessed the functional response of osteoblasts to functionally gradient titanium alloy lattice topologies constructed via AM. They found that the gradient lattice structure had a significant impact on cell adhesion and proliferation, which caused a high concentration of cells on the struts of the gradient lattice structure. Additionally, osteoblasts in lattice struts formed a confluent layer that linked the holes with many cytoplasmic extensions. They also gained insight into cellular activity and osteoblast functions through the examination of EBM gradient lattice structures.

Figure 10 shows some current instances where bioinspired cellular designs are used in numerous engineering industries [2,85,86].

Incorporating bioinspired cellular structures into engineering applications covers numerous industries, driving innovation, efficiency, and sustainability in a number of fields. This multidisciplinary strategy uses nature's design concepts to tackle complicated technological problems as well as develop advanced and advantageous technologies.

Multi-materials and their functional applications in cellular structure designs

Integrating multiple materials into cellular structure designs enhances performance by leveraging the unique properties of each material. This design approach is particularly beneficial for addressing complex engineering challenges requiring tailored mechanical, thermal, acoustic or electrical properties. Advanced manufacturing techniques, such as direct metal laser sintering (DMLS), and composite

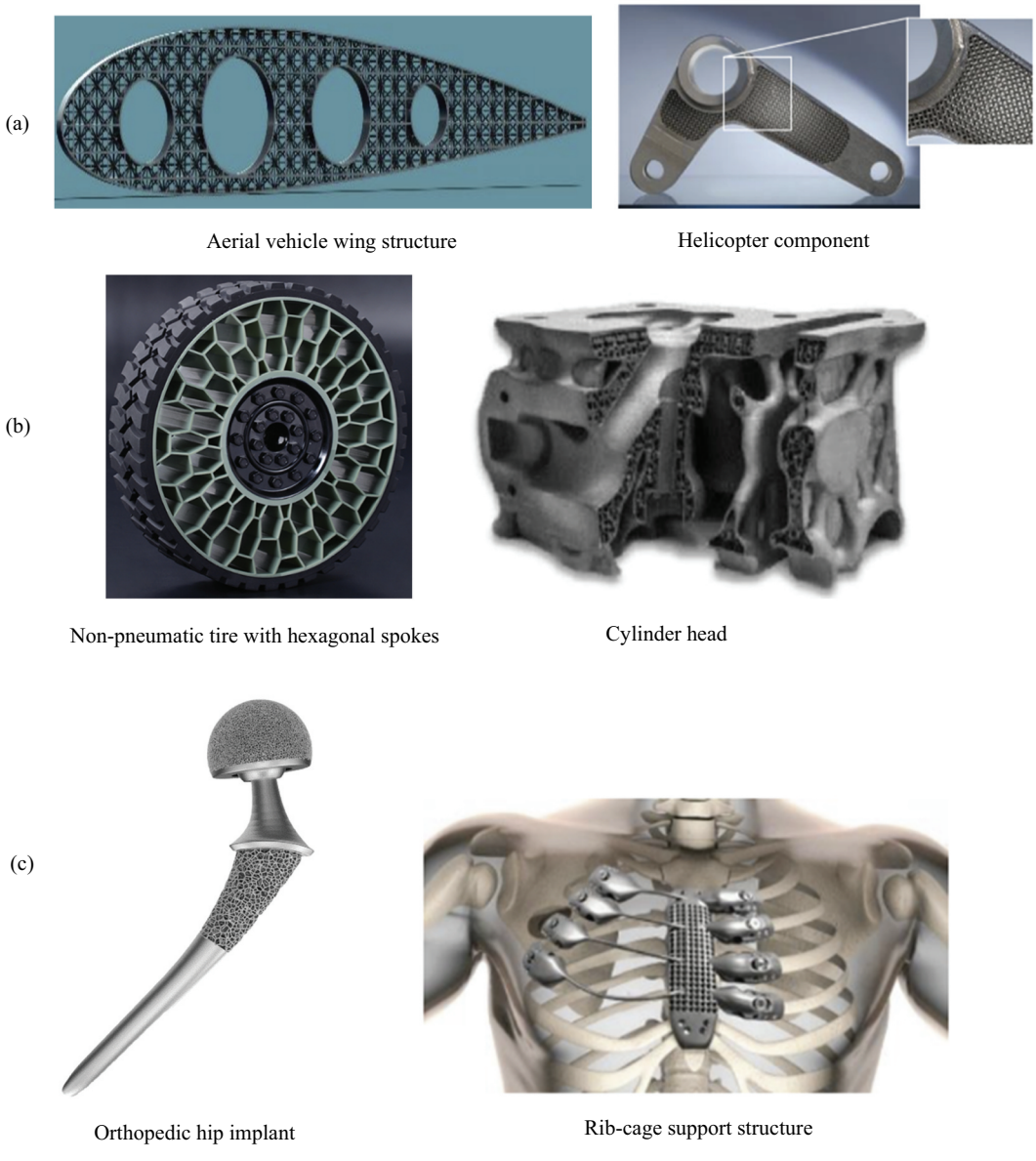

Figure 10. Current applications of bioinspired cellular designs in the (a) aerospace [85,86], (b) automotive [2,86], and (c) biomedical industries [2,86].

manufacturing enable the creation of intricate multi-material designs that were previously unattainable [87–89].

Mechanical characteristics

Multi-material cellular structure designs exhibit superior mechanical performance through strategically combining materials. As a result of combining specific materials, the strength, toughness, and fatigue resistance of structures can be optimised. For instance, combining stiff materials such as ceramics with tough polymers enhances the load-bearing capacity and impact resistance of a structure. Such hybrid designs support a variety of loads while simultaneously dissipating energy under impact loads, rendering them ideal for crashworthiness applications. Additionally, material property gradients across the structure reduce stress concentrations and delay crack propagation, extending service life and improving damage tolerance. Hierarchical designs that integrate materials at different scales, from micro to meso-levels, allow for specialised mechanical responses, including auxetic behaviour and optimisation of anisotropic strength [87–92].

Thermal properties. Enhanced thermal management is another advantage of multi-material cellular structures. By combining high-conductivity metals with low-conductivity polymers or ceramics, these structures can either direct heat flow or act as thermal insulators, depending on the application. Such properties are valuable in heat exchangers and thermal insulation systems. Furthermore, using materials with different coefficients of thermal expansion minimises thermal stresses, ensuring stability in environments with fluctuating temperatures, such as aerospace or electronics applications. Integration of phase-change materials (PCMs) into these systems adds functionality for energy storage and thermal regulation, making them indispensable in energy storage systems and temperature-sensitive environments [93–97]. Chen et al. [98] explored methods to enhance thermal dissipation in high-performance systems, such as LEDs, by developing a high thermal conductivity substrate inspired by leaf vein structures. Using topology optimisation and vat photopolymerisation 3D printing, they created a biohybrid composite by combining this structure with epoxy. The composite exhibited a significant improvement in thermal conductivity ($\lambda = 14.65\ Wm^{-1}\ K^{-1}$ at 40 vol % solid fraction), surpassing that of pure epoxy by 5585% and an Al_2O_3 /epoxy composite by 269%. This design also improved cooling efficiency of LEDs, by reducing the operating temperature by 8.9°C compared to conventional composites. Their study suggested that this biohybrid structure offers a scalable solution for cooling electronic components.

Acoustic properties

In acoustic engineering, multi-material cellular structures are highly effective in the absorption of sound, insulation, and damping of vibrations [99–102]. Porous configurations of soft, viscoelastic materials within rigid frameworks dissipate acoustic energy efficiently over a wide frequency range, making them suitable for the control of noise pollution [103–105]. The acoustic impedance mismatch between different materials in multi-material enhances the performance of sound barrier, making these structures ideal for use in buildings, vehicles, and industrial enclosures. Furthermore, combining viscoelastic and stiff materials allows for exceptional damping of vibrations, while maintaining mechanical integrity, a critical requirement in aerospace and machinery applications [105–107].

Electrical properties

Multi-material cellular structures also provide groundbreaking advancements in electrical functionality. By combining conductive materials like metals with insulating polymers, these systems achieve customisable electrical conductivity for lightweight conductive frameworks and electromagnetic shielding [90]. Hybrid designs that embed conductive materials and electrolytes can serve as structural energy storage systems, such as supercapacitors or batteries, integrating energy storage into load-bearing components. Additionally, materials with specific dielectric or magnetic properties allow for the design of antennas, waveguides, and electromagnetic interference (EMI) shielding. When piezoelectric or magneto-strictive materials are incorporated into cellular structures, it avails multi-functional devices capable of environmental sensing or generation of electricity under mechanical stresses [108–112]. Su et al. [113] developed SiOC ceramic materials for terahertz (THz) electromagnetic interference (EMI) shielding and absorption, thus addressing THz pollution and noise. Bulk SiOC ceramics absorb over 93% of THz waves within the 1.2–1.6 THz range, thus minimising reflective secondary pollution. Inspired by moth wings, the authors designed a lightweight honeycomb-structured SiOC using vat photopolymerisation 3D printing and pyrolysis, achieving superior EMI shielding effectiveness (SE) up to 64.1 dB with <1.4% transmissivity in the 0.2–1.6 THz range and 97–99.8% absorption between the 0.8–1.6 THz range. The material demonstrated excellent mechanical properties (compressive strength: 1.2 MPa; flexural strength: 16.5 MPa) and thermal stability up to 1100°C in inert conditions. Their study underscored the potential of nature-inspired SiOC ceramics as lightweight, high-performance solutions for THz EMI shielding in

electronics, aerospace, and telecommunications, leveraging advanced 3D printing and pyrolysis techniques.

Adaptability and functionality of design through smart materials

The integration of smart materials, such as shape-memory alloys (SMAs), piezoelectric materials, and magneto-responsive materials, into multi-material cellular structures enhances adaptability and functionality by enabling responsiveness to environmental stimuli like temperature, pressure, and magnetic fields. These materials can undergo changes in shape, stiffness, or other properties in reaction to external conditions, offering improved performance across diverse applications. Shape-memory alloys are often employed in multi-material structures to provide dynamic shape-changing capabilities. In medical implants, for instance, SMAs can alter the implant's shape in response to temperature variations, ensuring a better fit and facilitating integration with surrounding tissues. In aerospace, SMAs can enable structures to change shape with the fluctuations of temperature, thus optimising aerodynamic performance. Piezoelectric and magneto-strictive materials can be incorporated into cellular structures to serve functions such as sensing, actuation, or energy-harvesting. For example, piezoelectric materials in aerospace or automotive applications can be used for damping of vibrations, converting mechanical energy into electrical energy for power sensors or other systems [114–118].

In summary, the use of multi-materials in cellular structures not only extends their traditional advantages but also opens new avenues for multifunctionality, enabling innovative applications across diverse fields such as aerospace, electronics, energy-storage, and acoustics. This synergy between material science and structural engineering underscores the transformative potential of these systems in modern technology.

Modelling and optimisation techniques for cellular structure design

Modelling and optimisation of natural cellular structure designs has gained traction in engineering, driven by their good mechanical properties, low density, and nature-inspired adaptability to physiological changes. Capturing and leveraging these characteristics requires advanced analytical and numerical modelling, and optimisation strategies that accurately represent the intricate geometries and complex mechanical behaviour of cellular structure designs, including HC lattices, trabecular bone, wood, and glass sponge skeletons. This section reviews the current state-of-the-art modelling and optimisation techniques used in cellular structure designs.

Contributions of modelling techniques to cellular structure design

To accurately model natural cellular structure designs based on devised analytical models, which in most cases are algebraic equations and partial differential equations (PDEs), advanced computational methods are required to capture their intricate internal geometries and nonlinear mechanical behaviour under different loading scenarios [119]. Key computational techniques used in this field include:

Generalised finite element analysis (FEA)

FEA is frequently used for modelling the mechanical characteristics of cellular structure designs, generating data regarding their stress and thermal levels, distribution of stress and thermal loads, strain response, deformation and failure modes [19,120]. Finite element analysis models are particularly useful for complicated cellular designs because they allow comprehensive local and global assessments of stress patterns within the structure. The incorporation of nonlinear FEA models is one aspect that has also gained traction over cellular structure designs because of its ability to accurately analyse their deformation, particularly cellular structure designs that undergo large deformations under applied loads. Nonlinear FEA tools assist in the modelling of such deformations by capturing both geometric and material non-linearity, allowing for the precise prediction of material responses under high strain scenarios. This approach is critical in understanding complex behaviour within cellular structure designs, where deformation largely influences structural integrity and performance [121–123]. Furthermore, there are studies [19,121–125] that have demonstrated that the adoption of adaptive meshing has assisted in attaining well-refined mesh in areas with high-stress gradients while keeping coarser meshes in regions of less interest [124,125]. This strategy significantly reduces not only the computational cost but also improves accuracy in predicting the behaviour, particularly of irregular and hierarchical cellular structure designs.

Multiscale modelling

Cellular structure designs experience mechanical behaviour that is different across scales, from microstructural configurations to macro-level responses. Multiscale modelling integrates numerical approaches at different scales to predict the overall mechanical effectiveness of structures. This technique is crucial for material configurations such as the trabecular bone, where microstructural properties largely influence the macroscopic characteristics. The hierarchical multi-scale structuring approach is one that uses

numerical models that progress from the microstructure up to the macrostructure, often through FEA. At each scale, unique properties are computed, such as the stiffness and density, which are likely to influence the same model at the next scale [126–128]. The accuracy of this modelling approach relies on effectively capturing interactions at each scale, rendering it suitable for lattice and foam-like geometries. The concurrent modelling approach integrates the multiple scales into a unified numerical framework, providing a simultaneous analysis across these scales. The approach is particularly useful for structures such as cellular designs, which experience large deformation, as the strategy has the capacity to capture real-time responses, and inter-scale interactions [126–130]. Even though it is computationally demanding, concurrent modelling provides valuable insights into the possible occurring deformation mechanisms and failure modes across various scales, improving the accuracy of structural behaviour predictions. In cellular structure designs subject to multiple interacting fields (e.g. thermal, mechanical, and electromagnetic), coupled multi-physics modelling is often incorporated into the multi-scale frameworks to capture complex, cross-field interactions. This approach is particularly critical in applications that involve the development of biomedical implantable devices, where interactions between mechanical and biological systems across different scales largely influence the implantable device's performance and durability.

Homogenisation modelling

These methods simplify cellular structures by averaging their properties at the macro level, creating effective continuum models that retain essential characteristics without the complexity of fine details. This approach is especially valuable for large-scale applications, as it reduces computational costs while providing accurate performance predictions. Asymptotic homogenisation (AH) is one of the homogenisation modelling techniques, traditionally applied to periodic cellular structures. Its function is to separate a problem into micro- and macro-scale structures, and thereafter evaluating the local unit cell problem to generate effective physical and mechanical properties. The technique is useful for accurately capturing the behaviour of periodic, small-scale structures, but it tends to be numerically intensive for large-scale and complex geometries [131]. Finite element homogenisation (FEH) technique has a wider adoption because of its adaptability [132]. Its versatility comes from its capacity to adapt FEA in analysing problems wherein the representative are volume elements (RVEs) [133]. The technique generates accurate, tailors' effective properties of structures but requires careful meshing and periodic boundary conditions, rendering it numerically demanding for high-fidelity modelling of cellular structure designs [132]. The variational asymptotic method (VAM) reduces the model under numerical examination into a weak formulation with reference to the displacement field. This implies that the structural part is analysed for displacement fields separately as in-plane and out-of-plane components to derive effective stiffness parameters. The VAM technique is largely applied in composite cellular materials. It attains a balance between computational efficiency and accuracy; however, it is based on the assumptions of linear elasticity and material isotropy, which are challenging to achieve for large-scale, complex structures [134]. Two-scale asymptotic expansion (TSAE) is a semi-analytical approach that models unit cell deformations separately from the bulk structure. The approach is effective and ideal for high-contrast materials with unique microstructural length scales but has limited application for non-periodic or irregular structures. The empirical/analytical homogenisation modelling technique has been predominantly used because of its simplified analytical models [135]. For example, the well-established Gibson-Ashby model provides closed-form equations to predict mechanical characteristics, such as the modulus of elasticity and strength, based on parameters like relative density and cell geometry. These models allow for fast and generalised predictions; however, they lack accuracy for intricate designs and non-standard cellular shapes [1].

Discrete element modelling (DEM)

For cellular structure designs with granular or particle-based characteristics, DEM is typically adopted to capture contact interactions and dynamic behaviours. This technique is particularly relevant for biological materials such as wood, which exhibit anisotropic responses and variable density distributions [136]. Given that DEM largely models materials as sets of discrete particles, this approach provides a way for capturing complex mechanical interactions within cellular structure designs that conventional continuum methods tend to fail to accurately represent. In DEM, cellular structure models are represented as discrete particles or elements that correspond to the nodes or unit cells within a lattice framework [136–138]. The interactions between these particles, governed by contact models such as Hertz-Mindlin or Johnson-Kendall-Roberts (JKR) contact laws, are crucial for accurately modelling material behaviour under different loading scenarios. This approach effectively captures localised deformation and failure mechanisms, including cell wall buckling, crushing, and fracture, which are critical considerations in the design and performance analysis of cellular structure designs [139]. The DEM technique is also highly adaptable for multi-scale modelling, wherein the microstructural details of cellular materials can be integrated into macro-scale modelling. This adaptability is

particularly advantageous for cellular structure designs exhibiting hierarchical structuring. Models of DEM allow the parametric analysis of key aspects, including the unit cell geometry, relative density, and material distribution. In this manner, the DEM supports the optimisation of mechanical characteristics such as stiffness, strength, and energy absorption [136–138].

Contributions of optimisation techniques to cellular structure design

Topology optimisation

Topology optimisation is a frequently used technique for attaining the optimal distribution of material within a designated design space, often subject to constraints such as minimising weight and maximising stiffness. In cellular structure designs, topology optimisation improves structural performance by strategically removing material from low-stress regions. In this manner, the technique assists in attaining weight efficiency [22]. Commonly used algorithms, such as Solid Isotropic Material with Penalisation (SIMP) [140] and Evolutionary Structural Optimisation (ESO) [141], are applied to produce lightweight, structurally efficient designs. For cellular architectures, topology optimisation can replicate the graded material distribution observed in natural structures like bone, resulting in robust designs capable of effectively resisting external loads. Recent advancements in engineering integrate lattice and porous structure shapes into topology-optimised designs, significantly improving strength-to-weight ratios crucial for dynamic, bio-integrative applications [140]. By integrating cellular architectures within topologically optimised frameworks, these designs achieve adaptability at both the macro and micro scales, making them highly suitable for applications in biomedical implants and lightweight aerospace components [22,140,141].

Shape optimisation

Shape optimisation is a complementary tool often used in conjunction with topology optimisation. The technique focuses on refining the external and internal geometries of cellular structure designs to improve their mechanical properties, while meeting specific design constraints. In cellular designs inspired by their natural forms. Shape optimisation aids in attaining the best form that maximises strength and adaptability in design without the excessive use of material [142]. Techniques such as the B-spline parameterisation and level-set methods allow for high-precision changes in the shape of the geometry, which can be particularly beneficial for nature-inspired cellular structures, where geometry plays a crucial role in function. Shape optimisation also assists with the tuning of unit cell shapes within a lattice, allowing for control over properties such as anisotropy and flexibility in design. This customisation is a valuable tool in generating cellular structure designs that mimic the adaptable mechanical behaviour observed in biological materials such as bone and wood, in return, optimised responses to varying load conditions are attainable [142–145].

Multi-objective optimisation (MOO)

This area of multiple-criteria decision-making effectively addresses the challenge of balancing conflicting design criteria, such as achieving both high strength and flexibility in design or optimising stiffness while minimising weight [146]. Techniques like the Non-dominated Sorting Genetic Algorithm (NSGA-II) and Pareto front optimisation is often applied in this area, as they generate a suite of optimised solutions that illustrate various trade-offs between objectives [147]. In the context of natural cellular structure designs, MOO proves particularly useful for designing materials that must perform optimally across a wider range of applications. In medical engineering, for example, cellular structure implants require both high adaptability in design to fit complex biological geometries and have good mechanical strength to bear the physiological loads [148]. Through MOO, a range of solutions can be explored, emphasising different performance characteristics. This assists with the selection of the most suitable design based on specific application requirements.

Uncertainties in modelling, optimisation, and experiments for cellular structure design

The study of natural cellular structures has advanced significantly due to breakthroughs in modelling, optimisation algorithms, and experimental approaches. However, inherent uncertainties in these processes still pose challenges in accurately predicting the performance, reliability, and effectiveness of cellular structure designs in engineering applications. This section delves into the state-of-the-art uncertainties in modelling, optimisation, and experiments specific to cellular structure designs.

Uncertainties in modelling of cellular structures

Material characteristic variability. Natural cellular materials exhibit heterogeneous compositions and anisotropic properties. This inherent material property variability can lead to inconsistencies when modelling with traditional homogenisation methods, which often rely on assumptions of uniform material characteristics. While advanced multiscale modelling approaches attempt to account for this variability, they continue to face difficulties in accurately capturing the complex spatial heterogeneity characteristic of natural

cellular materials [126]. Trabecular bone, for instance, consists of an intricate network of interconnected struts and plates that differ substantively in terms of their shape, density, and material characteristics across different longitudinal locations. This implies that their mechanical behaviour depends on both the local structure and anisotropy induced by the directional alignment of its microstructure. Espousing homogenisation modelling techniques is often tied to the application of uniform material characteristics across the volume of interest. When applied to trabecular bone, these methods oversimplify the variability in its microstructure, leading to inaccurate prediction models of its macroscopic characteristics. The modulus of elasticity of the trabecular bone is one of the mechanical properties frequently studied by researchers. Variability in material properties of a trabecular bone can cause the elastic modulus to vary by orders of magnitude in different regions, such as the femoral head versus the vertebrae. Multiscale approaches attempt to bridge this gap by integrating microstructural properties into macroscale models. However, capturing the stochastic nature of trabecular bone's spatial heterogeneity where the microarchitecture changes even within a small region remains challenging [149]. For instance, computational models based on μCT (micro-computed tomography) scans require high-resolution input data and computationally intensive models. Even then, the models often fail to generalise well because of the variability in biological samples. This example underscores the need for innovative modelling frameworks, such as machine learning-enhanced predictive models, to better account for natural cellular material uncertainties.

Geometric complexity. The intricate geometries of natural cellular structures present substantial challenges for accurate modelling. Techniques such as FEA typically require geometric simplifications, which can introduce significant errors in modelling results. These uncertainties are further compounded by the limited resolution of scanning technologies used to capture the detailed geometries of natural cellular structures, often resulting in estimations that affect the accuracy of the models. For example, high-resolution imaging techniques, such as micro-CT or MRI, are used to capture trabecular structures. However, due to computer hardware limitations or scanning constraints (e.g. scan time, patient exposure to radiation), the resolution may be insufficient to resolve fine trabecular details [149,150]. This leads to missed micro-features or over-smoothing of the geometry, introducing uncertainty into the FEA models and resulting in inaccuracies in predicting mechanical behaviour.

Boundary condition assumptions. Accurate modelling requires reasonable boundary conditions that replicate real-world engineering scenarios. However, determining adequate boundary conditions for cellular structure designs given the variability in loading conditions, constraints, and interactions with surrounding tissues or materials (such as biomechanical applications) remains challenging. Assumptions made during modelling, regarding these aspects (loading conditions, constraints and interactions with surrounding tissues or materials) introduce further uncertainties, impacting the predictive accuracy of the models under real-world scenarios [151,152]. An illustrative example of the uncertainty in defining appropriate boundary conditions for cellular structure designs is the modelling of a lattice-based ribcage implant for paediatric patients. These implants must dynamically adapt to the physiological changes in the thoracic anatomy and differing biomechanical forces, such as those from breathing, coughing, and body movement. Interactions with adjacent tissues, organs (e.g. lungs and heart) and skeletal structures create complex loading and constraint scenarios. Simplified boundary assumptions, such as fixed constraints at implant ends or uniform loading, can result in inaccurate predictions of stress distribution and deformation behaviour. This can lead to designs that are either overbuilt, reducing effectiveness due to bulkiness or underbuilt, risking premature failure.

Multiscale modelling uncertainties. Cellular structures exhibit unique properties across multiple scales, ranging from the microscale to the macroscale. Multiscale modelling aims to bridge these scales to provide a comprehensive understanding of material behaviour; however, it introduces inherent uncertainties. Accurately capturing the complex interactions between structural scales presents significant challenges, often due to the non-linear and scale-dependent nature of these interactions. Predicting how microscale material defects influence the macroscale mechanical performance requires detailed multiscale models [126,153]. Errors in bridging these scales, e.g. oversimplified assumptions in homogenisation, cause discrepancies in the predicted deformation behaviour models. The deformation of cellular structures often involves complex, non-linear phenomena like buckling or localised yielding, which are challenging to capture accurately across scales. Furthermore, in applications like ribcage implants, growth-related dynamic changes add time-dependency to the uncertainty, complicating multiscale analysis even further in modelling.

Uncertainties in optimisation of cellular structures

Algorithmic constraints. Optimisation algorithms can encounter challenges by attaining convergence or may be solved only for local rather than global optima, particularly within the complex design spaces of cellular structures. This limitation can result in

substandard designs that fail to use the material advantages effectively [154]. For example, during the optimisation of a hierarchical honeycomb lattice in Ti6Al4V, the algorithm might identify a design that achieves a lower weight but has suboptimal stiffness because the algorithm settles into a local minimum. This suboptimal design does not fully exploit the anisotropic stiffness characteristics of the honeycomb or misses opportunities for enhanced crashworthiness due to underutilised hierarchical features. As a result, the material advantages are not used effectively, leading to a substandard honeycomb structure.

Objective function and constraint definition. Defining adequate objective functions and constraints is crucial in generating accurate, feasible optimised designs [100]. Even so, choosing one of these aspects often proves subjective and centred on the distinctive application, introducing uncertainty in optimisation outcomes. Moreover, balancing trade-offs between mechanical characteristics such as strength, flexibility in design and manufacturability complicates the optimisation process. When defining objective functions, it might not be clear how to weight each criterion [100,101,125,140]. Should the focus be on *maximising mechanical performance*, or *minimising material usage* for cost-efficiency? Constraints like *elastic modulus within a specific range* or *buckling resistance under load* can conflict with manufacturability or biocompatibility constraints.

For example:

- A highly stiff design (favourable for strength) might hinder adaptability, causing discomfort or failure in dynamic applications.
- Using hierarchical lattice structures optimised for lightweighting may lead to challenges in reliably manufacturing intricate geometries with desired tolerances.

Sensitivity to design variables. Cellular structures exhibit high sensitivity to design parameters such as cell size, wall thickness, and hierarchical configuration. Minor changes in these variables can lead to significant variations in performance, particularly in highly optimised designs. Robust optimisation techniques that account for these sensitivities are vital, though they typically increase computational demands and complexity [155,156]. Consider a titanium alloy lattice implant designed using AM for the reconstruction of a paediatric ribcage. The implant relies on cellular structures with hierarchical configurations to achieve high strength-to-weight ratios and adaptability in design. A slight deviation (e.g. 0.25 mm) in wall thickness or a minor variation (e.g. ±0.5 mm) in cell size during manufacturing can significantly affect the implant's mechanical characteristics, such as stiffness, strength, and fatigue life. This is particularly critical in applications where the implant must maintain consistent biomechanical behaviour to adapt to a patient's anatomy.

Manufacturing constraints and uncertainties. Manufacturing processes for bio-inspired cellular structures, particularly in AM, introduce uncertainties in aspects such as material deposition, dimensional accuracy, and residual stress [19]. These aspects can significantly impact the mechanical properties of the final structure, often requiring further optimisation steps to minimise their effects. When fabricating these nature-inspired cellular structures, uncertainties in material deposition may lead to incomplete or uneven layers due to variations in powder flow or laser energy density [157]. This can result in dimensional inaccuracies in the intricate lattice, affecting the intended geometry and thereby altering mechanical characteristics such as stiffness, strength, and fatigue resistance. Additionally, residual stresses induced during the rapid heating and cooling cycles of the AM process can cause warping or microcracking, further deviating the structure from its designed performance [19]. Such residual stresses also impact fatigue life, a critical aspect for nature-inspired structures intended for load-bearing applications.

Uncertainties in experiments of cellular structures

Variability in sample preparation and testing conditions. In experimental characterisation of natural cellular materials, significant uncertainty arises from variability in sample preparation, testing environments, and measurement precision. These materials often exhibit variations in composition, moisture content, and other intrinsic properties that influence mechanical performance, potentially resulting in inconsistent experimental findings [158]. For example, investigating the compression behaviour of balsa wood (a widely used lightweight cellular material), variations in moisture content and growth density can cause significant discrepancies in measured compressive strength and elastic modulus. Even specimens prepared from adjacent regions of the same log can show differences due to the material's anisotropy and natural variability. To address these uncertainties, researchers often use statistical analyses, such as analysis of variance (ANOVA) [159], to account for variability, or conduct experiments in highly controlled conditions. However, such uncertainties remain a challenge when attempting to generalise findings to broader applications.

Measurement precision and accuracy. High-fidelity characterisation techniques, such as micro-computed tomography (μCT) and mechanical testing, frequently encounter challenges in accurately capturing the intricate geometry and material properties of cellular structure designs. Measurement uncertainties may be introduced by equipment limitations, resolution

constraints, and the effects of specimen imperfections or surface roughness [160,161]. When using μCT to evaluate the internal geometry of a hierarchical lattice structure, the μCT scanner's voxel resolution might not be sufficient to capture the fine details of struts, particularly in regions with very thin walls or complex junctions. This can lead to missing or distorted geometric data, rendering it challenging to examine the as-manufactured structure accurately. Mechanical testing might yield inconsistent data due to microstructural variations introduced during AM, such as residual stresses, porosity, or non-uniform material distribution. The inherent surface roughness of the additively manufactured components can skew μCT imaging and the findings of mechanical testing. Surface imperfections scatter X-rays during scanning, generating artefacts in the 3D reconstruction, and causing stress concentrations during mechanical testing, thus reducing the measured performance below the theoretical predictions.

Scaling effects. Experimental studies on cellular structures are commonly conducted on reduced-scale models or simplified versions that may not accurately replicate the behaviour of larger or more complex natural structures. This introduces scaling-related uncertainties when extrapolating laboratory findings to real-world applications, particularly in biological and bio-integrative settings [162]. For instance, a nature-inspired scaffold designed for a small segment of bone may perform well in vitro but fail to provide the same mechanical support or promote adequate biological integration when deployed in a larger segment of a load-bearing bone in vivo. This scaling uncertainty poses challenges in translating laboratory findings to real-world biomedical applications.

Contributions of artificial intelligence-, machine learning-, and deep learning-driven approaches in managing uncertainties of cellular structure designs

The growing complexity of natural cellular structures has driven researchers to adopt advanced Artificial Intelligence (AI), Machine Learning (ML), and Deep Learning (DL) techniques to address uncertainties in modelling, optimisation, and experimentation. These approaches are essential for managing variability in material properties, geometric intricacies, loading conditions, and unpredictable environmental factors. As a result, AI- and ML-based methods have become integral to enhancing the predictability, adaptability in design, and robustness of designs inspired by natural cellular structures, such as bone, wood, HCs, and glass sponges.

Managing modelling uncertainties

Physics-Informed Neural Networks (PINNs). These integrate physical laws into neural networks to model complex structures with high-fidelity while managing uncertainties from limited data. By embedding conservation laws or other known physical principles within the network, these models can reduce reliance on extensive training data, rendering them highly efficient for modelling cellular structures with variable morphology [163–165]. Samaniego et al. [119] explored the potential of deep neural networks (DNNs) as an effective alternative to traditional numerical methods for solving PDEs in mechanics. By leveraging an energy-based approach, they demonstrated enhanced accuracy and relevance for engineering applications. Partial differential equations are fundamental to modelling natural and engineered systems, but their complexity in real-world scenarios often necessitates numerical methods, as analytical solutions are typically infeasible.

Uncertainty Quantification (UQ). The UQ framework, powered by AI and ML, is used to estimate the reliability of modelling for cellular structures under different conditions. These frameworks enable a systematic approach to understanding the impact of assumptions made in models and limitations of data on the accuracy of prediction [166–168]. This is particularly beneficial in applications like biomechanical implants, where unexpected responses can have serious implications. The UQ framework uses ML models to account for uncertainties in material properties such as fatigue resistance of shape memory alloys, anatomical variations, and the dynamic response to movements like breathing and coughing. AI-driven methods could model the implant's behaviour across a wide range of patient-specific scenarios, identifying critical modes of failure and validating the predictions arising from simulation. The framework can also be used to quantify the impact of data-limitations, such as incomplete patient-specific anatomical data or variability in the conditions of loading, allowing engineers to refine assumptions made in the design and improve the reliability of implants, and ultimately minimising failure of implants in service [168].

Optimisation under uncertainty

Reinforcement Learning (RL) for adaptive optimisation. The RL algorithms are used to optimise cellular structures adaptively, updating designs in real-time as new data become available. This adaptive approach can minimise uncertainty in design, enabling structures to better respond to real-world conditions [169,170]. The RL algorithms can be used to optimise cellular structures for adaptive scaffolds in bone tissue engineering. These scaffolds, composed of lattices, can adapt to external loads, growth factors, or mechanical stress feedback. Embedded sensors, such as strain gauges or pressure sensors, provide real-time performance data under varying physiological conditions.

The RL agent processes these data and iteratively adjusts design parameters, including cell size, shape, and distribution, to enhance mechanical performance and biological integration. Over time, the scaffold dynamically adapts to factors like bone growth rates and external forces such as body movement or loads borne, thus reducing design uncertainties and ensuring optimal functionality as tissue evolves.

Robust Design Optimisation (RDO). The RDO technique is applied on designs that remain optimal even with variations of parameters such as geometrical dimensions, material properties, structural configurations, manufacturing tolerances, loading and boundary conditions, leveraging AI to explore vast design spaces efficiently. By incorporating probabilistic measures of robustness, these algorithms allow engineers to arrive at cellular structures that maintain high performance despite inherent variability [171]. An application of RDO with AI in engineering could involve developing lightweight, hierarchical lattice structures for dynamic implants. The objective is to achieve optimal mechanical performance such as strength and flexibility, while accounting for variability in material properties, patient-specific anatomy, and environmental conditions. AI techniques, such as genetic algorithms or surrogate models, can efficiently explore a vast design space of lattice configurations. These models integrate probabilistic measures of robustness to evaluate performance across varying parameters, such as stiffness of materials, growth patterns bones, and distribution of loads. Incorporating methods of quantifying uncertainty, like Monte Carlo modelling, enables the identification of lattice topologies that maintain consistent high performance under all scenarios [172]. This approach enhances reliability of implants, reduces the risk of failure due to changes of parameters such as elastic modulus, yield strength, fatigue strength, density, corrosion resistance, porosity, hierarchical configuration, strut thickness and orientation, unit cell size and shape, and minimises the need for repeated surgeries, ensuring long-term functionality and comfort for growing patients.

Multi-Objective Optimisation (MOO) with evolutionary algorithms. AI-driven multi-objective evolutionary algorithms, such as Genetic Algorithms (GA) and Particle Swarm Optimisation (PSO), are well suited for cellular structures due to their ability to handle complex, non-linear relationships between multiple design objectives. By embedding UQ techniques within these algorithms, uncertainties are minimised, resulting in designs that exhibit predictable responses under dynamic loading conditions [173,174]. For example, optimising a lattice structure for a ribcage implant, multi-objective evolutionary algorithms, such as Genetic Algorithms (GA), are utilised to enhance the stiffness-to-weight ratio while minimising stress concentrations under physiological loading. Particle Swarm Optimisation (PSO) complements this by refining the dynamic adaptability of the lattice, optimising the distribution of shape memory alloys to accommodate growth. The UQ techniques, including stochastic sampling [166,167], are integrated into these algorithms to address variations in the properties of materials and unpredictable dynamic loads. This approach ensures that the lattice design maintains structural integrity and consistent deformation-patterns throughout the patient's growth, even under varying physiological conditions. The result is a robust, dynamically adaptive implant with minimised risk of failure and reduced need for surgical revisions.

Generative Adversarial Networks (GANs). The GANs have been used for the generative design of cellular structures, helping to explore diverse architectural configurations that balance adaptability and strength. The GAN-based designs can account for uncertainty in the behaviour of materials and variances in manufacturing by training on a broad dataset, thereby creating resilient structures [175–177]. The GANs have been applied to design complex lattice structures for absorption of energy and distribution of load in impact scenarios. By training the GAN on a dataset of existing lattice architectures with varying strut thicknesses and cell geometries, the network typically generates novel configurations, which are optimised for both strength and adaptability in design [177]. The outputs of GANs can also include structures that account for manufacturing tolerances, such as over-curing in stereolithography, and variability in materials, such as localised fluctuations of density, mostly in metal alloys.

Managing experimental uncertainties

Data-driven experimental design. Approaches for experimental planning that are powered by AI such as active learning, optimise the experimental setups by prioritising tests that yield the most informative data. This reduces the total number of experiments required, while AI-guided adaptive sampling refines the quality of data by focusing on regions of high variability or uncertainty in the material's response [178,179]. In developing lattice metamaterials, active learning can assist in optimising mechanical testing by prioritising load configurations and strain rates that provide the most insightful data on elastic and plastic behaviour [179]. For instance, an AI model trained on initial test data can predict areas of high variability in stress-strain responses under specific loading conditions. The active learning algorithm then focuses subsequent tests on these regions, minimising the total number of experiments while deepening insights into modes of failure and mechanisms of deformation. Furthermore, adaptive sampling enhances the

resolution of data around critical stress thresholds, refining measurements in areas of high uncertainty, such as transition points between elastic and plastic regimes.

ML-enhanced imaging and analysis techniques. The ML algorithms improve imaging resolution and accuracy in characterising complex cellular morphologies [180,181]. Techniques such as convolutional neural networks (CNNs) [182] and recurrent neural networks (RNNs) [183] are applied to enhance the extraction of data from imaging methods like CT scans, which can reveal subtle differences in structural properties and detect inconsistencies. An effective application of this approach involves using CNNs to improve the resolution and accuracy of micro-CT scans for studying hierarchical bone structures. By training CNNs on high-resolution scan datasets, the model learns to interpolate fine structural details from low-resolution images, enabling the reconstruction of microstructural features such as trabecular thickness and porosity. Additionally, RNNs can process sequential image slices to detect patterns indicative of structural anomalies, such as microcracks or density gradients, which are essential for predicting mechanical performance and failure mechanisms in biomimetic materials.

Uncertainty-aware data fusion and sensor integration. Models from ML have been employed to fuse data from multiple sensor sources, including strain gauges and load cells, to obtain a comprehensive and uncertainty-aware representation of the structure's response under different loading scenarios [184]. This approach is valuable for experimental validation, where multiple data sources may present different values of reliability. An example of this approach is the structural testing of a dynamic hip implant prototype. Strain gauges embedded in the implant's lattice and load cells placed at external loading points collect real-time data during cyclic loading tests. Machine learning models, such as Gaussian Process Regression (GPR) [184], integrate these data streams to create a comprehensive stress and deformation map under different loads. The model also quantifies measurement uncertainty, identifying sensor data affected by noise or calibration errors. This fused dataset enables more accurate experimental validation and supports iterative design enhancements.

Challenges, and future perspectives of incorporating natural cellular structure designs in engineering applications

Although adopting natural cellular structure designs into engineering applications has numerous advantages, there are certain limitations and challenges to consider, as now outlined. These limitations and challenges are paired with their corresponding future concepts and possible strategies for designing nature-inspired engineering structures that attempt to overcome current limitations, while maximising the numerous advantages of using natural cellular architecture.

Manufacturing complex geometries

Challenge. Natural cellular structures have intricate geometries that are difficult to mimic with traditional manufacturing methods, posing a challenge for creating seamless mimicry components [37].

Future perspectives. The integration of advanced manufacturing methods, such as AM, alongside adaptive, surrogate model-driven and metaheuristic algorithms, offers a promising approach to overcoming constraints in design. These technologies enable accurate control over the distribution of material and the formation of structures, allowing for the production of bioinspired cellular architectures. However, the computational models used still rely on simplified geometries, and further research is needed to develop advanced algorithms capable of replicating complex, bioinspired structures more effectively [30,185–188].

Biological relevance of synthetic materials

Challenge. Natural cellular structures are composed of biological materials that may not always be suitable or compatible with engineering applications. Directly replicating biological tissues, such as bone's hierarchical collagen and hydroxyapatite structure, is often unfeasible for synthetic materials [37].

Future perspectives. To address this, new strategies are required to incorporate biological materials into engineering applications, while maintaining the desired performance. These could include developing novel manufacturing techniques, modifying material compositions and optimising structural designs to achieve the required mechanical characteristics, while drawing inspiration from biological tissues.

High manufacturing costs and scalability

Challenge. The manufacture of nature-inspired structures often requires specialised tools and materials, such as high-grade titanium alloys, thus raising costs. Additionally, scaling up production while maintaining consistency and quality in larger quantities remains a significant challenge [40,41].

Future perspectives. Cost-effective scaling solutions can be critical for meeting industrial demands. Investigating the feasibility of using more accessible materials and exploring innovative manufacturing methods, like AM, could help address concerns of cost. Furthermore, ensuring homogeneity in cellular structures and mechanical properties could be essential for maintaining quality during mass production.

Balance between nature's design and innovation

Challenge. Focusing too heavily on replicating nature's designs may limit innovation in engineering. For example, biomimicry of natural structures like HCs may restrict the exploration of designs based on new topologies and materials with enhanced performance [37].

Future perspectives. While learning from nature is invaluable, future research should aim to strike a balance between mimicking natural designs and exploring innovative engineering solutions. This could lead to the development of novel materials and structures with improved performance characteristics beyond what nature offers.

Development of novel nature-inspired materials

Challenge. Bioinspired materials must not only mimic the structure of natural materials but also demonstrate properties like self-healing, high strength-to-weight ratios and enhanced thermal conductivity [40,41].

Future perspectives. Researchers should explore advanced manufacturing techniques such as integrating self-healing agents into polymers or designing hierarchical structures to optimise strength-to-weight ratios. Furthermore, the development of bioinspired materials with multifunctional properties, including self-healing capabilities and improved thermal properties, could open up new possibilities in fields like aerospace and automotive engineering.

Accuracy in manufacturing with nanotechnologies

Challenge. Replicating the complex, hierarchical structures found in nature requires high accuracy, which traditional manufacturing methods often cannot achieve at scale [14].

Future perspectives. Nanotechnologies and advanced manufacturing methods like 3D printing and nanofabrication hold significant promise for accurately replicating natural cellular structures at various scales. These technologies could enable high-precision fabrication of complex, nature-inspired materials, including medical implants tailored to the specific needs of patient, thus enhancing biocompatibility and functionality.

Multi-scale modelling and simulation

Challenge. Understanding the behaviour of bioinspired structures at multiple length scales is crucial for optimisation of design, but current modelling tools may not fully account for complex interactions at the nanoscale, microscale, and macroscale levels.

Future perspectives. Multi-scale modelling and simulation tools should be prioritised to predict the performance of nature-inspired structures across different scales. These tools could optimise strength, stiffness and durability while minimising weight. Modelling-driven design could also help predict failure modes and improve structural integrity for applications in aerospace, automotive, and biomedical engineering.

Designing for specific engineering applications

Challenge. Developing bioinspired designs for specific engineering applications requires deep insight into existing natural solutions to similar challenges.

Future perspectives. Bioinspired design concepts derived from the study of natural materials such as bones, plants, or spider webs could be used to create lightweight, durable structures for specific applications in industries like aerospace and construction. These concepts could help engineers optimise the distribution of material, load-bearing capabilities, and energy absorption, ultimately leading to innovative, high-performance engineering solutions.

Smart materials and adaptive structures

Challenge. Incorporating adaptive, smart materials into bioinspired structures is complex and requires real-time feedback for optimal performance in dynamic scenarios.

Future perspectives. Future bioinspired designs could incorporate smart materials like shape-memory alloys (SMAs) and embedded sensors to enable the production of adaptive structures. For example, UAV wings could change shape in response to aerodynamic forces, while bioinspired prosthetic limbs could adjust stiffness and damping to improve user experience. Integrating smart materials and sensors into these structures will enhance their functionality and responsiveness in real-time.

In addressing the foregoing challenges, bioinspired engineering is expected to contribute sustainable, efficient, and innovative technology in a variety of engineering industries.

Conclusions

Present-day cellular structures in nature are sorted into three types: open-based, closed-based, and polygon-based. These organic structures have an inherent multiscale hierarchical arrangement that has been strategically optimised through time as biological tissues evolve. The numerous morphologies of cellular structures allow them to be used for many different applications in nature. Furthermore, the mechanical properties of different cellular structures are impacted by their material and geometrical properties. Natural cellular designs are being

replicated for application in the automotive, aerospace, and medical industries. Fabricated bioinspired structures are limited by their capacity to mimic the cellular structures observed in nature. This is due to the highly complicated geometry of natural cellular structures at multiple scales. The research presented here provides crucial information on the incorporation of cellular designs into engineering applications and suggests possible areas for researchers to focus on in order to bridge the existing research gaps and for future growth of this area of study. It is expected that improved designs of bioinspired engineering parts will be easily achievable through the advancement of novel materials using nanotechnologies, the development of novel manufacturing processes, the use of multiscale modelling and simulation tools, the advancement of new biomimetic design concepts, and upgraded mechanical testing and validation methods.

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