

A review of the types and tessellation of lattice structures, their effectiveness and limitations in mimicking natural cellular structures

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Abstract. Lattice structures are useful in the automotive, biomedical, and aerospace engineering fields because of their good mechanical properties. The efficacy with which their geometries are designed influences their load-bearing capacity. The methods of generating different types of lattice structures have not been clearly outlined in literature. Furthermore, their applicability and shortcomings in trying to mimic biological cellular structures remain to be well investigated. In this paper, numerous types of lattice structures prevalent in literature are highlighted and their tessellation described. The paper also explores the application of lattice structures in terms of their capabilities and limitations, in mimicking cellular structures in nature.

1 Introduction

Lattice structures have attracted a lot of attention in the fields of engineering due to their advantageous traits, of high strength-to-weight ratios, efficient usage of material, and capacity to meet certain mechanical, optical, and electrical properties [1-2]. Lattice structures are presently being investigated for use in numerous automotive, aerospace, and biomedical applications. Lightweight structures are currently being investigated for their advantages in lowering fuel consumption and emissions, as well as for use as impact-absorbing materials in the aerospace and automotive industries. They are additionally being investigated for use as implantable medical devices in the biomedical industry [3-11].

Lattice structures are generated via tessellation. Based on how efficiently their material is arranged over a design space, these structures can have a high load-bearing capability [12]. The mechanical properties of such structures are determined by relating their configuration to the connecting edges and vertices of the unit cells. Lattice structures generated from different types of configurations do not have the same mechanical properties [13]. The lattice structures currently available in the literature include polygon-based, strut-based, skeletal and sheet triply periodic minimal surface (TPMS) based structures [14]. Advanced manufacturing

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technologies such as additive manufacturing (AM) are coupled with tessellation to fabricate lattice structures with good mechanical properties, and low usage of material [15]. Presently, the different types of lattice structures with good load-bearing capacities, have not been ranked clearly, in terms of area/volume-coverage and material usage [2, 14]. Volume coverage in this paper refers to the total volume within which polygons are fitted, whereas material usage refers to the actual material of the polygon struts in the fitted space. Therefore, it is necessary to undertake studies to relate the mechanical properties of lattice structures, to their greater area/volume-coverage, and usage of material.

Lattice structures are bioinspired, as they are designed by mimicking cellular structures found in nature [16]. Unfortunately, due to constraints in capturing the exact intricacies of the natural structural design, lattice structures are incapable of entirely reproducing the complexities of naturally growing cellular structures [17]. Furthermore, modern manufacturing tools like AM have limitations in terms of the minimum printable size of parts and part resolution that AM machines can effectively produce [18]. Further research is required to establish the effectiveness and limitations of lattice structures in mimicking natural cellular architecture. The aim of this paper is to evaluate the different types of lattice structures in use today and examine their tessellation, area/volume coverage and usage of material. Furthermore, the efficacy and limits of application of lattice structures in mimicking organic cellular structures are also investigated.

1.1 Types of lattice structures

Figure 1 depicts four types of lattice structures that are typically studied in engineering fields: polygon-based, strut-based, skeleton-based, and sheet TPMS-based [14, 19].

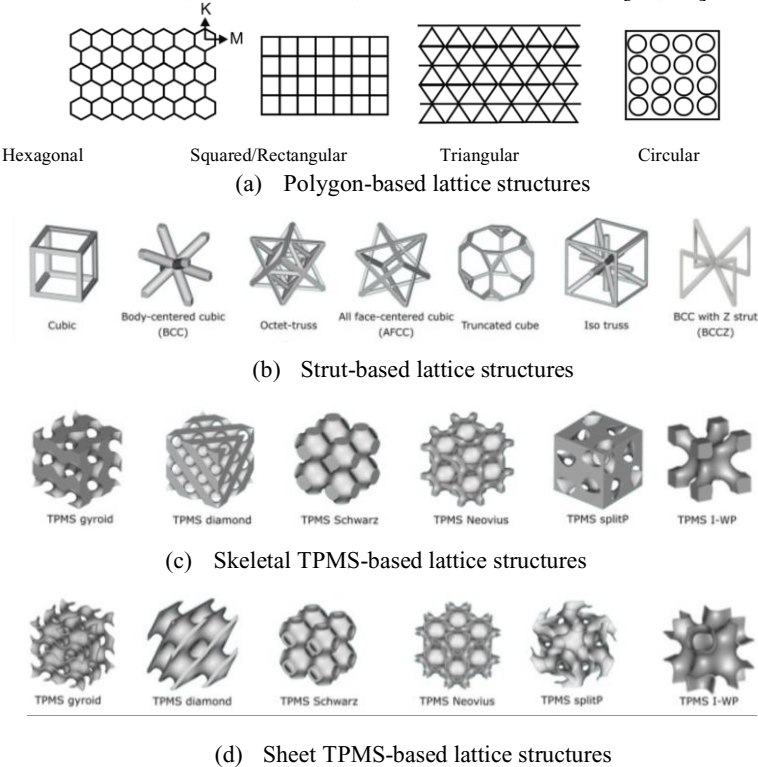


Fig. 1. Four types of lattice structures in engineering applications[14, 19].

Polygon-based lattice structures are generated by arranging unit polygons cells in a design space. Polygon cells are the basic building blocks of this type of lattice structures. These polygons can be triangles, squares, hexagons, or any other regular polygon shape [19]. Strut-based lattice structures are built using struts to generate three-dimensional (3D) structures [14]. Strut-based lattice structures include the body-centred cubic, rhombic dodecahedron and truncated cuboctahedron [14, 20]. Skeletal TPMS-based lattice structures are another particular type of lattice structure that are built via the geometry of triply periodic minimal surfaces. Triply periodic minimal surfaces are 3D minimal surfaces that have translational symmetry, which means their pattern can be repeated in all three directions indefinitely. These minimal surfaces have physical properties of minimal area or curvature [14, 20, 21]. These lattice structures are composed of a network of joined surfaces that adhere to mathematical descriptions of geometries of triply periodic minimal surfaces. The surfaces connect with one another at nodes or joints to create a design that is repeated throughout the structure [22]. The TPMS-gyroid, diamond, Schwarz primitive, and neovious models are some of the commonly used lightweight skeletal TPMS-based lattice structures in design. The same procedure for building skeletal TPMS-based lattice structures is used for sheet TPMS-based lattice structures, with the sole difference that sheets or panels are used instead of surfaces with similarities to struts or beams [23].

1.2 Tessellation of lattice structures

Lattice structures are designed and created primarily using tessellation techniques. The design process for lattice structures begins with determining the best unit cell and method for tessellation [24-25]. Lattice structures used in numerous engineering applications, which have larger area/volume coverage adopt different geometries than those of smaller area/volume coverage, to generate parts with particular mechanical and lightweight properties [2, 10, 14, 24-25]. The lattice structures are generated by repeating a unit cell in a specific geometric pattern. The design of lattice structures, therefore, includes both the design of unit cells and configurations [25].

1.2.1 Methods for designing unit cells

The smallest part which builds up and describes the entire lattice structure is referred to as a unit cell [25]. Currently, there are three established methods for designing unit cells, including (1) a planar-based approach, where a unit cell is built up as a two-dimensional (2D) polygon shape by reducing the third dimension to almost zero [19]; (2) a primitive-based approach, where the unit cell is made up of particular geometric primitives [26]; and (3) an implicit surface-based approach, where the surface of the unit cell is defined by mathematical equations [24-25]. When combined with the method of latticing or topology optimisation (TO), these methods for designing unit cells are advantageous in terms of the efficiency of designing structures built using unit cells [12]. The terms tessellation, repeating unit cell, and configuration are used interchangeably to refer to the process of joining small, regular unit cell shapes together without gaps or overlaps to entirely fill the design space.

A planar based technique is an easy one that uses a planar geometry (2D Euclidean geometry) to determine the internal and external geometry of a polygonal unit cell. As shown in Figure 2, for the case of a hexagon, the unit hexagonal cell is created by identifying the straight lines that connect the corners of a hexagon in a 2D space [19].

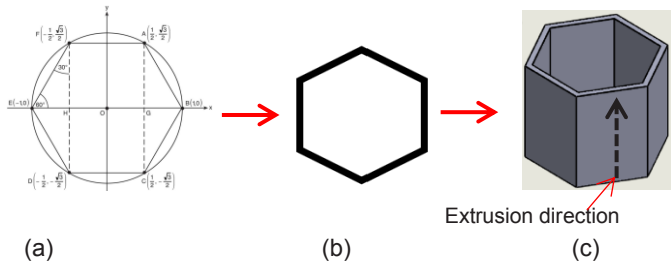


Fig 2. Schematics of a planar-based method for creating hexagonal polygon unit cells [19]

First, the procedure in Figure 2(a) is done for both the outer and inner hexagons to produce the planar unit hexagonal cell in Figure 2(b). In order to achieve the solid geometry shown in Figure 2(c), the planar unit hexagonal cell is then extruded in the third dimension. This approach is most preferable for generating polygon-based unit cells [16, 19, 25].

The primitive-based method works on Boolean operations of basic shapes, as shown in Figure 3 [25].

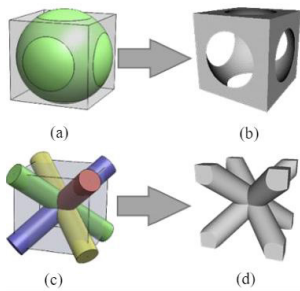


Fig 3. Designing unit cells using a primitive-based method [25]

The unit cubic cell in Figure 3(b) is generated by the procedure of Boolean subtraction shown in Figure 3(a). This method makes use of a cube as the base geometry and a concentric sphere as the subtractor. The unit truss-like cell shown in Figure 3(d), is generated by first performing a Boolean union of four diagonally structured cylinders before performing a Boolean intersection with a cube, as shown in Figure 3(c). This method is most preferred for generating strut-based unit cells [25].

In the design of unit cells, the implicit surface-based method is also a successful strategy. This technique represents the surface of a unit cell in three dimensions using implicit equations. Equations in the form $F(x, y, z) = 0$ are used to define an array of points that are positioned on the surface as a function of three coordinates with an origin at the point zero. For instance, Figure 4 shows a unit cell geometry and the equation which works with it. This approach is most useful for generating skeletal or sheet TPMS-based unit cells [24-26].

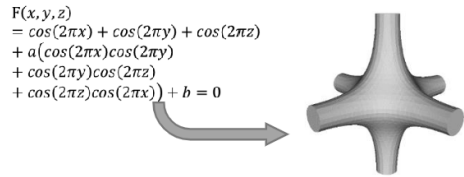


Fig 4. A skeletal TPMS-based unit cell type created by an implicit surface-based method [25]

Elsewhere, algorithms based of mathematical equations are used in TO for determining the most efficient distribution of material. This approach often uses lattice unit cells to introduce pores into a solid for determination of the best usage of material. Methods of TO are currently considered the most efficient for restructuring material on already generated unit cell structures. This is because the approach takes account of the load paths, thus ensuring that the unit cell has good mechanical properties [8, 12-13].

1.2.2 Design configuration (tessellation) methods

The procedure of repeating unit cells in two or three dimensions is known as design configuring or tessellation. Numerous reviews [25-27], have so far highlighted the following methods for tessellating lattice structure from a design and structural perspective: (1) regular or direct tessellation, in which the unit cells are translated repeatedly [27], and (2) conformal tessellation, in which the cell units are repeatedly packed in a way conforming to a specific surface geometry [25]. The configuration of designs is often complemented by structural optimisations in order to optimise the distribution of material. Latticing and TO are two methods that are used to optimise not only the material distribution within a unit cell but also the materials within in a spatial replication of the unit cell across the entire design space [28]. These methods have been used extensively in the fields of engineering for building lightweight parts with good mechanical properties [12, 24].

In most studies [3, 6, 16, 19, 29, 30], unit cells are built as rectangular/square and cubic geometric models for ease of use. Then, by periodically repeating the unit cells in two or three dimensions (along the x, y, and z-axis), lattice structures can be created directly. In Figure 5, lattice structures made of 2 x 2 (2D), and 2 x 2 x 2 (3D) unit cells [25], are depicted using this approach by translating the unit cell twice along each of the coordinate axes.

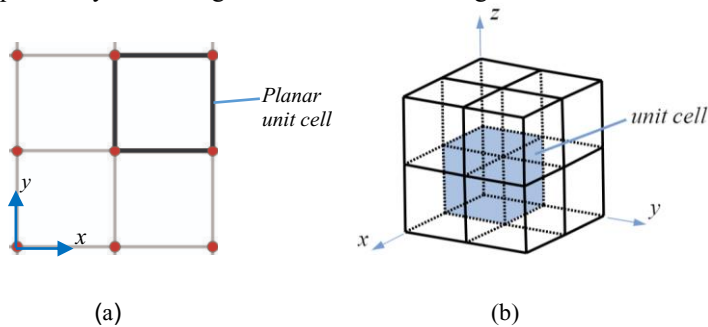


Fig 5. Diagrams for direct patterning in both (a) two, and (b) three dimensions [25]

Conformal structuring directs the total number of unit cells to conform to the shape of a design space such as the dome-like lattice structure shown in Figure 6 [31].

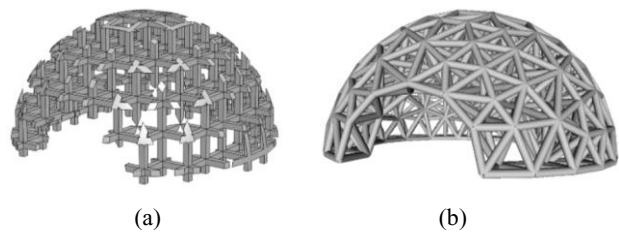


Fig 6. The (a) direct structuring method as opposed to the (b) conforming structuring method [31]

Direct structuring uses extra Boolean operations, as opposed to conformal structuring, which preserves the structural integrity of the unit cell, and is considered a better approach to stiffening or strengthening of structures [24-25]. This is because it allows for the distribution of loads uniformly throughout the entire structure. Nguyen et al. [31] developed a two-step procedure for creating a conformal lattice structure from a given surface of a part. In this procedure, a 3D conformal hexahedral mesh must first be computed to fit the unit cell. In the second step, the unit cells are populated to fill the hexahedral space occupied by the mesh elements from the previous step.

Latticing and topology optimisation are two independent methodologies used in engineering and design to optimise the structure of a component for specified performance. Latticing involves creating a lattice structure from an existing solid geometry for the purpose of reducing weight, whereas topology optimisation begins with an empty design space and redistributes material to optimise a component's performance depending on specific constraints. Latticing and TO methods can be applied to the already designed configurations of unit cells for best efficiency in the use of material, as has been done by a number of researchers [1, 25, 32-33]. A lattice structure was developed in Alzahrani et al. [33], using information on the density derived from TO performed using ABAQUS FEA software, as shown in Figure 7.

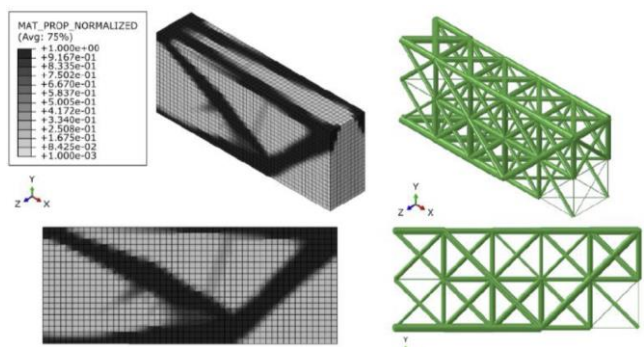


Fig 7. A strut-based lattice structure generated from density data [33]

The configurations arrived at through direct structuring are most preferred for the tessellation of lattice structures as the approach preserves the structural stability of parts made of unit cells. Additionally, methods of combined latticing and TO offer the advantage of determining how to distribute the material in a design space in the most efficient way. This is because the latter tool, TO, is capable of determining the load path of a structure before assigning an objective to reduce strain energies and response to where material should be lowered. A combination of these methods should, therefore, be considered when designing lattice

structures in order to improve the building procedure and achieve better mechanical properties.

Generative design approaches such as TO are advantageous, particularly when it appertains to lattice structures. These tools are capable of improving the manufacturability of such lightweight structures, whilst accounting for the manufacturing constraints imposed by the complexities of lattice structure designed shapes. They also help generate material-efficient designs that can be tailored according to particular performance-driven requirements [12, 32]. When integrated with advanced manufacturing approaches, generative designs are driving innovation in numerous types of industries, from aerospace and automotive to architecture and biomedical [12]. In addition, the use of generative design with TO can significantly reduce the time and costs that are typically related to conventional experimentation design methods [12, 32].

1.2.3 Design considerations for lattice structures

The mechanical properties of lattice structures generated via tessellation are affected by the design that arranges how the material is distributed, the degree of porosity inherent in the structures and the material used. In order to create parts with good mechanical properties that are unique to the chosen engineering application, careful consideration of these factors is necessary.

Existing literature [13-14,19, 24-26, 33-39, 42-47] shows that, only explanations regarding the mechanical behaviour of specific types of lattice structures have been given separately, based on their edges and connectivity of their vertices, and the chosen unit cell. It is recommended that customisation of the size, shape, and connectivity of the polygons be done to tailor the mechanical properties of their related lattice structure to different applications.

Tessellation allows for the creation of numerous cell topologies of structures. However, differences in the area covered and how much material is used within a specific design space influence the mechanical properties of such structures with different cell topologies. Figure 8 shows the area covered by four different polygon-based lattice structures, including the triangular, squared, hexagonal, and circular within the same design space [48].

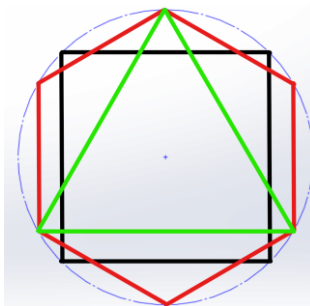


Fig 8. The relationship between four different cell polygons within the same design space [48]

The mechanical properties of the structures built with the polygons shown in this figure can be determined via tessellation in reference to the deduced relationships between the connecting edges and vertices of cells, similar to what was done in references [13, 39, 40, 61]. As a result, structures built from different types of polygonal arrangements will have different mechanical properties. Figure 9 shows how different planar polygons tessellated on the same

design space create different numbers of polygons, area coverage, and use of materials for a given wall thickness [48].

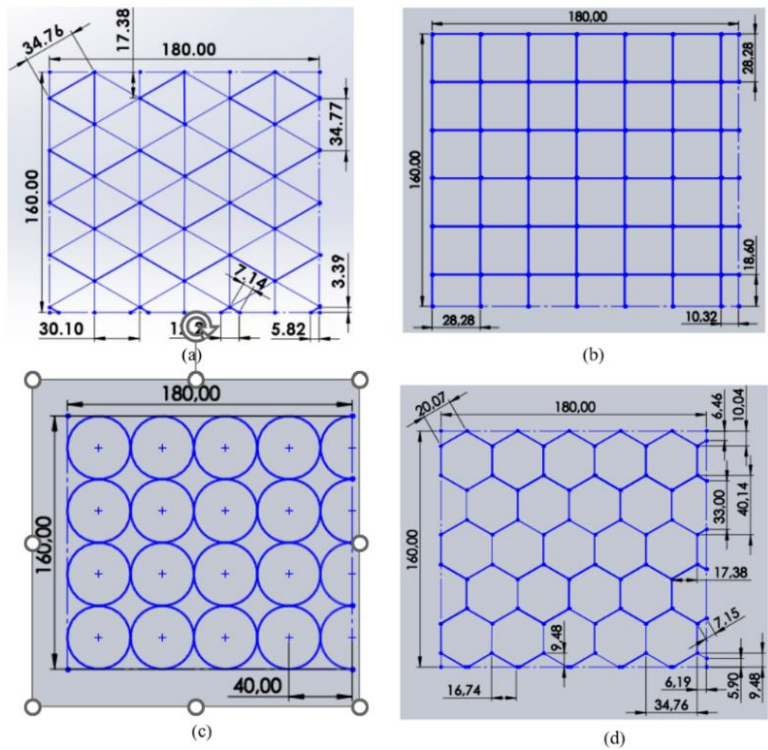


Fig 9. Planar tessellated structures with (a) triangular, (b) squared, (c) circular, and (d) hexagonal cells [48]

From Figure 9, it is deduced that the squares, triangular, hexagonal, and circular polygons have area coverages of 100%, 99.78%, 93.93%, and 78.54%, respectively, ignoring the very small incomplete polygon forms in Figures (9a and 9d). The incomplete polygons in Figures (9b and 9c), on the contrary, are taken into account because they cover a significantly observable fraction of the design space. As noted earlier in this paper, area coverage here refers to the area within which polygons are fitted. The percentage figures for the amount of material used relative to the area of the whole design space for the same polygons, in the same order, are 15.28%, 20.81%, 10.32%, and 7.85%, respectively. The amount of material used for each polygon type was calculated using a wall thickness of the polygon structures of 1 mm.

It is clear from the foregoing figures that, the square polygon is undoubtedly the preferred shape in terms of area coverage when tessellated in a design space. This is because, structures with greater area coverage tend to have better mechanical properties compared to those with smaller area coverage [2]. This demands care when designing structures with porosity so that they cover large enough areas to ensure good mechanical responses. Due to its minimal material requirements, the circular polygon will likely be the one with the lowest production costs. However, the hexagonal polygon is the most preferable when compared to the other polygons since it has a material requirement that is substantially lower than the square polygon while covering a slightly smaller area than it.

When the results obtained from determining the area covered and how much material is used are combined, they facilitate ranking of different types of lattice structures in terms of mechanical properties and manufacturing costs. In order to determine the efficient design of lattice structures with the lowest production costs, the following recommendation is made. That in addition to the methodology for ranking the four types of lattice structures based on their different sizes, shape, and connectivity of the polygons, the effect of area coverage and usage of material on the mechanical properties and production costs of lattice structures be taken into consideration.

Though auxetic type of lattice structures are outside the envisaged scope of this paper, it is noted that their design principles are particularly important to comprehend because these structures exhibit a unique and counterintuitive mechanical property known as a negative Poisson's ratio. The design concepts for auxetic lattice structures involve altering the arrangement of unit cells to attain negative Poisson's ratios [49-51]. Therefore, the design of auxetic lattice structures requires a thorough review of unit cell shape, stretching mechanisms, orientation, scaling, material properties, boundary conditions, manufacturing methods, and validation procedures [51]. The negative Poisson's ratio of auxetic lattice structures distinguishes them from other structures, resulting in them being useful in a number of engineering applications as outlined in references [50, 52].

2 Application of lattice structures in engineering

Recent developments in the design and fabrication of lattice structures have had a significant impact on the aerospace, automotive, and biomedical engineering sectors [1]. The good properties of lattice structures fill a gap in the manufacturing industry, providing new opportunities for structures with improved manufacturing efficiency [1-4, 7, 9, 13, 16, 17, 24, 25, 44]. The mechanical properties of lattice structures determine their wide range of applications [2].

2.1 Application in aerospace industries

In the field of aerospace, lattice structures are used in the design and production of aircraft parts such as wing structures, fuselages, and interior panels [2, 9, 11, 13, 16, 20, 24, 25, 34, 37, 44]. The lightweight design of lattice structures reduces the total weight of the aircraft, thus, improving fuel efficiency, and increasing the amount of cargo that can be carried. Aircraft engine components such as turbine blades, compressor vanes, and combustion chambers are also built as lattice structures. This is due to the reduced thermal conductivity and favorable strength-to-weight ratio of lattice structures that make them ideal for the high operating temperatures and high loads of aircraft engines [19, 24, 47, 53]. In thermal management systems used in aerospace applications, lattice structures are also used. They work well as heat exchangers, cooling panels, and thermal protection systems such as heat shields for re-entry vehicles because of their open-cell design, which enables effective heat transfer and dissipation [19, 54-56]. Figure 10 shows a few of the current uses of lattice structures in the aerospace sector [25, 54-55].

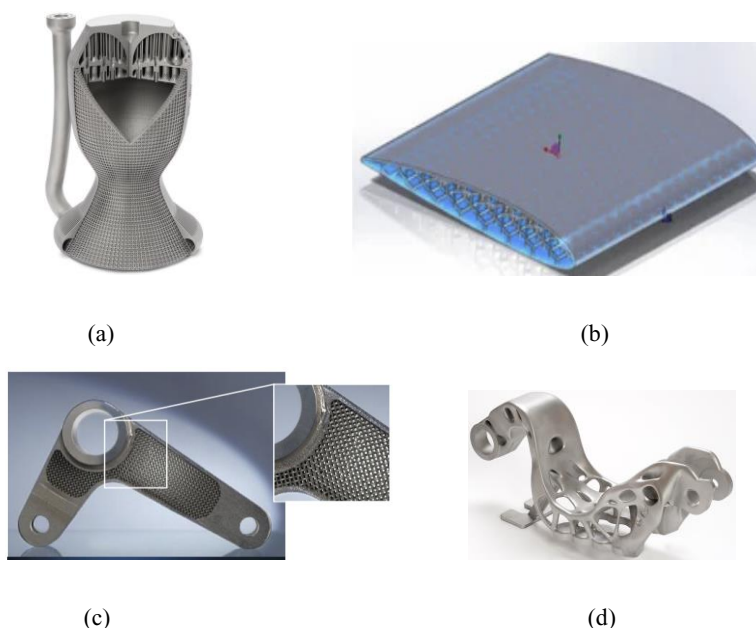


Fig 10. Present-day applications of lattice structures in the aerospace sector (a) rocket propulsion engine [55], (b) wing structure of an aerial vehicle [54], (c) helicopter component [25], and (d) Gooseneck kueger flap actuator bracket [55]

2.2 Application in automotive industries

In the field of automotive engineering [1, 3, 4, 11, 16, 19, 24-26, 39, 46, 53], lattice structures are used for building lightweight vehicle structures such as chassis, frames, and body panels. Automobile manufacturers can reduce the total weight of vehicles by using lattice structures, resulting in reduced fuel consumption and emissions, greater maneuverability, and increased load-carrying capacity [3, 19, 24-26]. Lattice structures are useful in automotive safety systems given that they are good at absorbing and dissipating impact energy. To improve the safety of passengers during accidents, they are used in the design of crashworthy parts, such as impact-absorbing bumpers, safety cages, and reinforced structures. In automotive suspension systems, lattice structures offer strength, stability, and weight reduction [19, 24]. They are used in the design of lightweight suspension parts such as control arms and knuckles, which improve vehicle control, stability, and comfort while driving. Figure 11 shows a few of the present-day applications of lattice structures in the automotive sector [19, 25-26, 55].

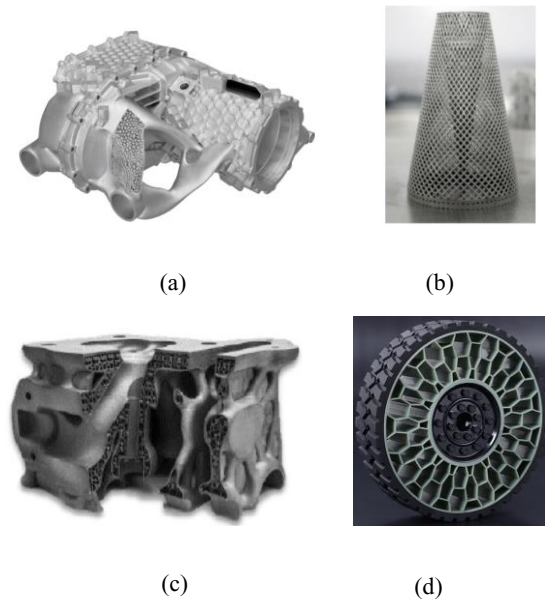


Fig 11. Present-day applications of lattice structures in the automotive sector (a) an electrical drive housing [55], (b) a filter [25], (c) a cylinder head [26], and (d) a non-pneumatic tire with hexagonal spokes [19]

2.3 Application in biomedical industries

In the fields of tissue engineering and regenerative medicine, lattice structures are used to build scaffolds that mimic the natural extracellular matrix [2, 5-8, 10, 11, 17, 19, 24-26, 37, 39-40, 43]. These scaffolds provide a three-dimensional structure that supports cell growth and arrangement, allowing the regeneration of tissues [5-8, 56-57]. In addition to facilitating tissue integration and lowering the risk of implant failure, the permeability of lattice structures allows for transport of nutrients and oxygen. In order to provide mechanical stability and encourage ingrowth and long-term integration of tissue, lattice structures are used in orthopedic implants such as bone plates, screws, and hip replacements. Lattice structures are used to create lightweight, high-strength surgical instruments and tools, as they allow for weight reduction, while maintaining mechanical strength and rigidity. Surgical instruments with lattice structures, such as forceps, retractors, and surgical trays, are designed to improve design and reduce fatigue during surgical procedures [19]. Lattice structures are also crucial in three-dimension (3D) bio-printing, a technology used to create complex tissue structures. Biological inks that consist of living cells suspended in a hydrogel matrix are used in bio-printers, and lattice structures are often integrated into the design of the bio-ink. In such applications, the lattice structures provide mechanical support and guidance for the printed cells, allowing for the formation of intricate tissue structures [56-57]. Figure 12 shows current typical uses of lattice structures in the biomedical sector [19, 25, 58-59].

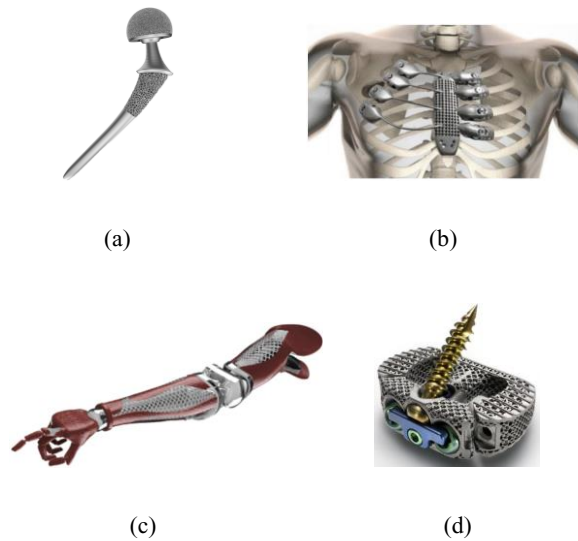


Fig 12. Present-day biomedical applications of lattice structures (a) orthopedic hip implant [19], (b) rib-cage support [25], (c) prosthetic hand [58], and (d) spinal implants [59]

3 The efficacy and limitation of lattice structures in mimicking natural cellular structures

Cellular structures typically occur in nature. These biological structures are created by an interconnected network of organic solid struts that form ribs and cell walls. Different examples of cellular structures in nature, include bone, wood, glass sponge skeletons and honeycomb, which have been extensively studied [19, 24, 37-38, 61-62]. A recent review article [57] on the use of cellular designs in engineering structures, focused on the biomimetic design of cellular materials. Figure 13 shows micro-computed tomography (micro-CT) scans of some naturally occurring cellular materials [62].

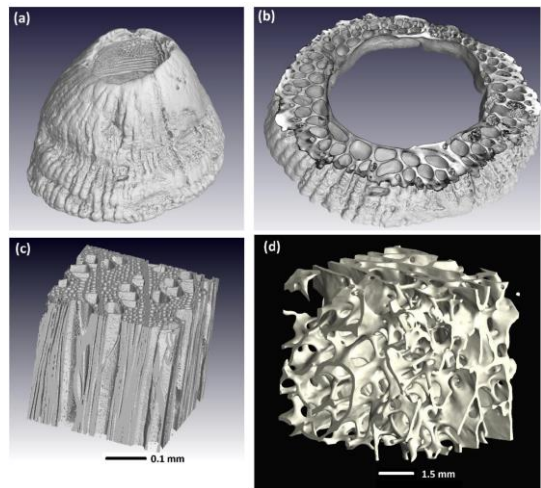


Fig 13. Cellular structures in nature (a-b) barnacle, (c) microstructure of wood material, and (d) structure of the human trabecular bone [62]

Cellular structures in nature have generated considerable interest, and this interest has worked a path into functional mechanical engineering via the latest developments in AM technologies [24]. This is because the design flexibility of AM technologies allows one to construct lattice structures by mimicking the complex cellular designs in nature. Biological cellular materials have been targeted for bioinspiration and biomimetic studies particularly because of their superior mechanical properties, including high stiffness, strength, and fracture toughness. Researchers rely on this knowledge to develop structures that mimic the hierarchical configuration of biological tissues. In turn, designs of lattice structures that have specific geometry and mechanical properties can be attained via this process [2].

Several benefits of mimicking cellular structures in nature have been highlighted in reference [39]. Biological tissues typically show hierarchical structuring, with structures arranged at multiple length scales [60]. Lattice structures are designed to mimic natural cellular structures by hierarchically arranging unit cells of various degrees of complexity and size. In return, this mimics the structural configuration observed in structures of nature [24]. This approach is useful for improving the mechanical properties and functionality of lattice structures. In biology, cellular structures are well known for having superior mechanical characteristics such as lightweight, high strength-to-weight ratios, and energy absorption [19, 60]. By optimising the geometry, unit cell shape, and material composition of lattice structures, mechanical characteristics comparable to requirements in various engineering applications are attained [2, 24-26]. This allows for the development of lightweight materials with increased strength and impact resistance, which can be used in a variety of applications ranging from biomedical, automotive, aerospace to safety equipment.

The porosity and permeability of cellular structures allow for the efficient transport of fluids, nutrients, and waste products [60]. Lattice structures with controlled porosity are designed to mimic the transport properties of biological structures. This is particularly advantageous in tissue engineering, where the interrelated scaffolds with porosity allow for the exchange of nutrients and growth of cells simultaneously [24]. Lattice structures can also be customized to mimic tailored biochemical and biological functions that occur in natural cellular structures. Functional molecules or bioactive agents, for instance, can be integrated into the lattice design to promote adhesion, proliferation, and differentiation of cells, thus making them useful for applications in tissue engineering and regenerative medicine [63]. The capacity for self-assembly and reproduction in some biological cellular structures permits growth and adaptation. Although artificial lattice structures lack the same degree of complexity, researchers have looked into self-assembly methods to develop dynamic lattice structures that are capable of altering their configuration in response to outside stimuli [25]. This mimics the evolution and growth of biological structures. However, even though lattice structures offer new possibilities for mimicking cellular structures in nature, there are a number of challenges and limitations to consider that are a result of the unique properties of biological tissues [19, 24, 37, 61].

Choosing the right materials for lattice structures is crucial in attaining the desired properties. However, it is often difficult to determine materials that mimic the mechanical and biochemical properties of biological tissues. Although progress has been made in developing biomimetic materials [19, 24, 37, 61], matching the full range of properties found in nature is still difficult [37, 60]. Wang et al. [64] generated four Ti6Al4V scaffolds based on honeycomb designs to repair human bone defects. The elastic modulus, strength, and permeability of the four scaffold designs were evaluated in comparison to human bones. Their findings showed the elastic modulus of the four scaffolds was in the 1.6-3 GPa range. This is comparable to the range of human trabecular bone (0.1-4.5 GPa). The yield strength in the range, 88-146

MPa, was, however, significantly higher than that of the femoral neck (0.56-3.71 MPa). Except for the conventional uniform scaffold's excess permeability, the permeability of the other three scaffold designs (1.5×10^{-8} - 4.8×10^{-8} m²) were all within the range of cancellous bone permeability (0.5×10^{-8} - 5.0×10^{-8} m²). The same trend was observed in reference [65]. The authors found no relevant information in literature that provides a direct quantitative comparison of natural cellular structures and their biomimetic architectures in terms of coefficients of diffusivity and thermal conductivity. This is ongoing work by the researchers that is primarily focused on improving fluid transportation and heat management systems in industrial applications.

Numerous dynamic behaviour, including shape changes, growth, and responses to stimuli, are often observed in biological cellular structures [39, 62]. It is however difficult to mimic this dynamic behaviour in lattice structures. Despite the development of some self-assembling and reconfigurable lattice structures [24], these structures typically lack the complexity and adaptability observed in biological structures.

The ability to integrate with biological structures is of the utmost importance when mimicking cellular structures for biomedical applications. Lattice structures must not only mimic the physical properties of biological tissues, but they should also interact with surrounding tissues, such as allowing adhesion, migration of cells, and regeneration of tissue [2, 5-8]. It continues to be difficult to attain seamless integration of lattice structures with biological structures [8, 19].

Fabrication of lattice structures is complicated and difficult via conventional methods. Traditional manufacturing techniques, such as subtractive machining or casting, are often inadequate for lattice structures because they require intricate internal geometries that are challenging to attain [2, 7]. Even though AM (3D printing) has emerged as a promising technique for fabricating lattice structures, it continues to face challenges when it comes to the selection materials, speed of manufacturing, and scaling of parts [9-11, 15].

The materials used to construct lattice structures have a bearing on their manufacturability. For optimum performance, some lattice geometries require materials with specific mechanical properties, such as high strength or stiffness [15]. However, not all materials are appropriate for all manufacturing methods [25]. Certain lattice structures designed for AM, for instance, could require materials with specific thermal properties to ensure efficient printing without deformation or delamination. Choosing materials for lattice structures is often difficult due to a lack of material options that are compatible with specific manufacturing processes [10-11].

Support structures are often required when building lattice structures, to prevent them from failing or deforming during construction. The removal of support structures after manufacturing, however, is often time-consuming and could result in surface imperfections or call for extra post-processing steps to achieve the desired finish on the surfaces. The manufacturing process thus becomes more complex and costly as a result of this and their structural design. In the worst cases, lattice structures have permanent internal supports, which means they cannot be removed [7, 9-11, 15]. Research has recommended the use of improved designs for the lattice structure, to ensure no support is needed inside the lattice regions [24].

The fabrication of lattice structure, particularly through AM, can be time-consuming. Building intricate lattice geometries layer by layer can take a long time, especially for large

structures. When there is a demand for rapid manufacturing or mass production, this extended production time becomes a drawback [11, 39]. Furthermore, because there are often large volumes of left-over powder in areas where the laser does not strike during printing, specific manufacturing equipment, and post-processing requirements, the cost of manufacturing lattice structures could be higher than that of solid structures [11, 15, 24].

The build size of 3D printers can limit the largest dimensions for lattice structures. This can be a limitation when attempting to create large-scale lattice components. Secondly, certain lattice geometries could prove challenging to produce accurately because of the limitations of resolution of respective AM machines, or the behaviour of materials during the process of printing [11, 15, 46]. Rahmati [66], highlighted that the minimum resolution for a DMLS machine ranges between 10-45 μm . Dropping below the minimum resolution will, therefore, result in fewer details of the designed structures being obtained [11, 66]. Furthermore, structures with thinner walls of less than 1mm thickness could fail readily due to residual stresses generated by rapid cooling during manufacturing [15, 66]. To achieve the desired results, printing process parameters ought to be carefully tailored and considered.

Lattice structures typically have complex geometries with interconnected beams or struts, causing them to be highly prone to manufacturing defects. Manufacturing flaws such as cracks, voids, or inconsistencies in the lattice members result in stress concentration points. Stress concentrations occur in localized areas of high-stresses, thus reducing the overall strength and load-bearing capacity of structures. The presence of defects causes cracks to form or propagate, resulting in premature failure under applied loads. Manufacturing defects also reduce the stiffness of lattice structures. Irregularities or variations in the size, shape, or thickness of lattice members cause irregular deformation and deflection under load. This results in reduced stiffness, which is undesirable in applications where rigidity and minimal deformation are required. Defects in lattice structures further act as stress raisers, speeding up the initiation and propagation of fatigue cracks. Cyclic loading, when combined with the presence of manufacturing defects, results in the formation and growth of cracks, thus reducing the fatigue life of structures [11, 15, 18]. This shortcoming is particularly crucial in applications where lattice structures are subjected to repeated loading or dynamic loads [23]. Furthermore, manufacturing defects have a bearing on the deformation properties of lattice structures. In AM procedures, for instance, voids or improper fusion occur in areas of reduced material density and irregular powder depths, respectively, thus resulting in differences of mechanical properties such as strength, stiffness, and toughness [24-26]. Such discrepancies could give rise to unpredictable behaviour and compromise the lattice structure's overall performance and reliability. Lattice structures with intricate internal designs are often challenging to inspect and control during the manufacturing process. Conventional non-destructive testing methods such as visual testing, penetrant testing, magnetic testing, ultrasonic testing, radiographic testing and eddy current testing often prove ineffective for detecting defects within the internal parts and surfaces of the members of lattice structures [11, 15]. Therefore, determining and correcting manufacturing defects during sampling becomes difficult and increases the risk of creating defective or substandard lattice structures. To overcome these constraints, manufacturers must employ stringent measures of quality control, as well as inspection techniques tailored to lattice structures. Internal defects and the quality of lattice structures can be detected using advanced imaging technologies such as X-ray computed tomography and ultrasound [24]. In addition, optimizing manufacturing processes, refining fabrication techniques, and implementing process monitoring can help reduce defects and improve the overall quality and reliability of lattice structures [18, 24].

The powder is also prone to get stuck in intricate regions such as between sharp changing edges and vertices of lattice designs. This results in reduced density of lattice structures and is potentially hazardous in cases of medical implants. Figure 14 shows a micro-CT image of a printed bracket with powder stuck inside certain parts of the lattice [24].

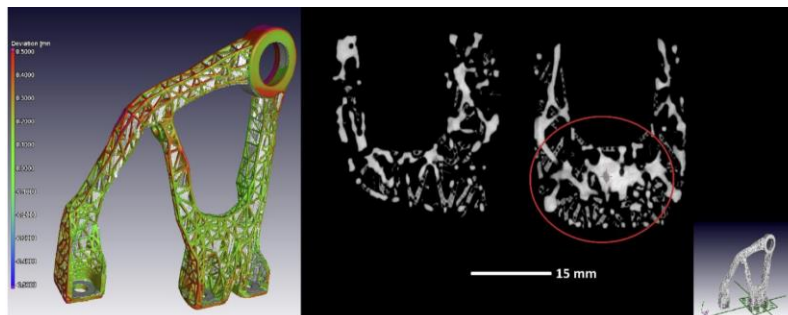


Fig 14. Micro-CT scan white contours depicting powder that is stuck inside certain parts of an additively manufactured lattice bracket using a [24]

After AM of parts, the removal of support structures and powder stuck to them is a then carried out. Powder and support removal methods and their efficacy differ based on the AM process and materials used [15]. The preferred methods and efficacy for powder and support removal include the following seven methods. (1) manual removal, which involves manually breaking or cutting off support structures as well as removing surplus powder, typically using basic hand tools such as pliers, wire cutters, and brushes. Manual removal is efficient for parts with basic geometry and easily accessible support structures. However, complex, or intricate designs could prove time-consuming and labor-intensive [18]. (2) Blowing with compressed air is a rapid and efficient approach to removing powder but is not efficient in removing all of the support structures, particularly in difficult-to-reach regions. As a result, the approach is often followed by manual removal of any residual support structures [15, 18]. (3) Parts are mechanically agitated in a tumbler or vibratory finishing machine using abrasive media such as plastic beads to remove stuck powder and support structures. This method works efficiently for parts with complicated geometries and difficult-to-reach areas. It additionally makes the surface smoother [11]. (4) High-pressure water jets are also highly efficient in removing excess powder and support structures, particularly when working with water-soluble supports and complex parts. However, the strategy might not be completely suitable for all materials [18, 25]. (5) Soaking in a solvent bath such as acetone for some plastics dissolves support material. Ultrasonic agitation is typically used to speed up the process. Solvent baths are efficient in removing support structures and could result in high-quality outcomes. They might, however, require post-processing to remove any leftover solvent from parts. (6) The procedure of heat treatment also referred to as thermal de-binding, involves exposing the part to high temperatures in order to burn off or evaporate support structures. Heat treatment is useful for removing support structures; however, it may require specially designed equipment and careful control of the temperature to prevent part deformation [2]. (7) Numerous AM technologies include built-in support removal features. To remove supports, these technologies employ automated processes such as cutting and milling. Automated processes, particularly for industrial-scale production, are typically highly efficient and accurate. They are, however, not available for all AM technologies [7, 15, 18, 25].

4 Future work and trends in the design of lattice structures for AM

This section summarizes significant issues for researchers and industry professionals to focus on, in the development of lattice structures.

These include the development of novel optimisation methods specifically tailored for lattice structures. These algorithms should take account of numerous design parameters, such as the shape, size, density, and topology of a lattice unit cell, in order to maximize mechanical performance, weight-reduction, and functional integration of lattice parts. Multi-objective optimisation methodologies should be used to balance competing design goals, such as stiffness and weight reduction.

Researchers should continue to look into new materials suited for lattice structures, including metals and metal alloys, polymers, ceramics, and composites. Emphasis should be placed on understanding the mechanical behaviour of these materials at the microscale and changing their properties to improve the functionality of lattice structures. This entails material testing, characterisation, and the development of accurate constitutive models for use in simulation of properties and optimisation of design.

Understanding the mechanical properties of lattice structures demands the development of accurate as well as effective multiscale modeling and simulation tools. In the future, researchers should combine microscale material models with macroscale structural analyses to accurately predict the performance of lattice structures under different loading conditions. Researchers should be able to improve the design and performance of lattice structures at different length scales as a result of this.

Lattice structures allow for functional integration by integrating additional features such as fluid conduits, electrical circuits, or heat transfer systems within them. Future research should be focused on determining design processes and AM techniques that allow these features to be seamlessly integrated into lattice structures. This is expected to allow for the development of lightweight, multipurpose components with improved performance.

Scalability and process optimization will be the main areas of future research as AM technologies develop. To these ends, the methods of manufacturing lattice structures should be optimised. This should focus on raising the quality of the surfaces of printed structures, simplifying building processes, and cutting down the time and cost of production. In order to produce larger and more complex lattice structures for a variety of applications, including in the aerospace, automotive, and biomedical sectors, efforts should also be made to scale up AM technologies.

Further understanding of the nature-inspired theories of design, such as biomimicry should also be pursued by researchers and scientists, as this is expected to provide crucial insights for the development of lightweight and high-performance lattice structures. Improvement of the mechanical properties and optimisation of the performance of lattice structures can be achieved by further understanding of and mimicking the design of biological materials, such as bone and plant structures.

For non-linear geometries of strut-based, skeletal-based, and sheet-based TPMS types of lattice structures, a ranking of mechanical properties and production costs ought to be conducted as well.

Overall, the future of lattice structural design and AM offers huge potential for improving lightweight, high-performance, and customized structures in a variety of industries. Continued research and collaboration among material scientists, engineers, and designers will be critical in achieving the full potential of lattice structures and pushing the frontiers of AM technology.

5 Conclusions

- Present-day lattice structures are sorted into four basic categories viz. polygon-based, strut-based, skeletal, and sheet triply periodic minimal surface (TPMS)-based structures.
- The efficient generation of lattice structures depends on both the design and arrangement of unit cells.
- Latticing and TO methods are the most efficient for designing lattice structures as the latter takes account of load paths in the structures, which ensures good load distribution and, as a result, the attainment of better mechanical properties in structures.
- The different mechanical properties of different lattice structures facilitate varied design tailored to different engineering applications.
- The mechanical properties of lattice structures are influenced by a number of parameters such as shape, size, and topologies of unit cells, as well as cell-configuration.
- Determining the area/volume coverage of different polygons used to make lattice structures and the amount of material used in each case facilitates ranking according to which of the arising lattice structures can offer better mechanical properties and/or lower costs of production.
- Lattice structures mimic natural cellular structures to some extent, but are restricted by geometrical complexities, as well as the minimum resolution of printable parts in AM technologies.
- Given the disparity between the materials of making up biological structures and their equivalent biomimetic structures, the latter still struggle to match the entire range of properties observed in biological structures.
- There is still an absence of quantitative comparisons in literature with regard to the efficiency and challenges of biomimetic structures in replicating the diffusion coefficients and heat conductivity of natural cellular structures.
- The seamless integration of lattice structures with biological structures remains a challenge.
- Methods for removing stuck powder and support structures in complex lattice parts still lack capacity to entirely remove the stuck powder and support structures.

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