Bio-inspired structures in AM industry

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Additive manufacturing (AM) involves production by building objects layer by layer, minimizing waste and enabling the creation of complex geometries. This thesis explores the integration of bio-inspired structures and designs into AM. Bio-inspiration draws inspiration from the structures and mechanisms observed in nature. These structures are studied for their material efficiency and superior mechanical properties such as high strength to weight ratio and lightweight characteristics. The thesis has been done as a literature review of bio-inspired designs, their application in current AM technologies and the challenges and opportunities they present. All sources were found using utuvolter, google scholar and scopus, which are academic search engines. Notably, the thesis investigates the differences of a select few bio-inspired structures, the advantages of AM in their production and their applications across aerospace, automotive, and maritime industries. Bio-inspired designs in AM enhance mechanical properties, enabling the cost-effective production of complex parts with superior strength-to-weight ratios, ideal for aerospace, automotive, and maritime industries. However, challenges such as complex geometric modelling of bio-inspired structures need to be further studied. Future research could focus on improving design and modelling softwares and exploring the limits of currently utilized methods of AM to overcome current limitations.

Contents

1 Introduction

Additive manufacturing (AM), known also as industrial 3D printing, includes multiple different manufacturing methods. The key part being that materials are added layer-by-layer to locations where they are needed, compared to subtractive manufacturing where material is removed. This process creates less waste and offers a way to create traditionally impossible designs.

1.1 Aim of the thesis, research problem and questions

Bio-inspired structures, derived from natural forms and processes, have garnered significant attention due to their remarkable properties such as being lightweight, having a high compressive or tensile strength, and material efficiency (Javaid et al., 2021). AM offers design freedom and customization options and the ability to incorporate bio-inspired designs for optimizing structural performance and material usage. However, despite the growing interest in this area, there remains a need to compile existing knowledge, identify gaps, and address problems to further advance the integration of bio-inspired structures into AM industry. This review seeks to address key research questions:

- What are the fundamentals of bio-inspired design and their relevance to additive manufacturing industry?
- What are the current state-of-the-art bio-inspired structures fabricated using AM techniques?
- What challenges and opportunities exist in the application of bio-inspired structures in additive manufacturing?

By addressing these questions, this study aims to provide information for industrial practitioners in utilizing the potential of bio-inspired structures in AM.

1.2 Research methods and framing

This thesis was written as a literature review using sources found with utuvolter, Google Scholar and scopus. These are academic search engines serving as tools to search through academic literature. In this thesis bio-inspired structures, their usage and impact in the additive manufacturing industry is studied.

2 Bio-inspired additive manufacturing

AM involves building components by adding material layer-by-layer, until a finished object is completed. The process starts by the creation of a 3D model of the desired object. This is achieved through 3d-mapping an already existing physical object or using computer-aided design (CAD) software. This model is then sliced. Slicing is the process of dividing a 3D model into thin horizontal layers or slices. Depending on the method of AM used, the layer thickness, object orientation and the objects positioning relative to the build platform must be considered in the slicing process. (Guo & Leu, 2013)

AM is practical at producing components with intricate geometries, at times surpassing the capabilities of subtractive manufacturing. AM reduces material wastage, manufacturing time and eliminates the need for most manual processes that rely on skill.(Gibson et al., 2021)

2.1 Basic methods of additive manufacturing

AM technologies are distinguished by their ability to produce complex geometries and wide customization capabilities. AM can be categorized into seven main methods, each characterized by distinct mechanisms of layer formation and material processing. Each of these seven contain multiple sub-categories. Table 1 explains these seven methods briefly. (Kanishka & Acherjee, 2023)

Table 1. The seven methods of additive manufacturing explained (Gibson et al., 2021)

AM method:	Description
Material extrusion	Material in a molten state is pushed through a nozzle under constant pressure and in a continuous stream onto a build platform. The material then solidifies and bonds to already existing material to create solid structures.
Powder bed fusion	Powder is layered on a build bed and is melded together by a heat source, such as a laser or electron beam, to create solid layers. Material can be metal or plastic.
Binder jetting	A liquid bonding agent is selectively deposited onto a bed of powdered material, bonding the particles together to form solid layers. This process is repeated layer by layer until the object is complete.
Directed energy deposition	A focused energy source, laser or electron beam is used to melt material which is simultaneously deposited by a nozzle. Material can be metal or ceramic. Used in repair of high-quality functional parts.
Vat polymerization	In a vat of liquid photopolymer resin that solidifies when exposed to radiation, typically ultraviolet (UV) light, each layer is selectively

	cured. A build platform then gradually lifts the solidified resin, creating layers of the desired object.
Sheet lamination	A sheet of material is placed onto a cutting bed and securely bonded in place over an existing layer. Following the instructions of the sliced model, the sheet is then cut accordingly, and a new layer is added atop the previous one. Alternatively, the sheets can be cut first, and then the individual cut layers can be positioned and bonded together to form the object.
Material jetting	Material is jetted onto a build platform using either a continuous or selective method. The jet is positioned above the platform, depositing droplets of material where needed. These droplets swiftly solidify to form the layers. After deposition, the layers cool and harden. Due to the material deposition in droplets, material options are limited.

Table 1 introduces an overview of the seven foundational AM technologies, highlighting their working principles, material compatibilities and the flexibility of AM as a manufacturing method. These methods encompass a broad range of materials and applications, from prototyping to functional part production across industries such as aerospace, automotive, healthcare, and consumer products.

2.2 Advantages and disadvantages of additive manufacturing

AM offers speed, a wide range of materials, freedom for geometrical complexity and is relatively easy to implement. Materials in AM can range from polymers, waxes, paper laminates, composites, metals and even ceramics. Although high-end CNC machining outpaces most AM methods in volume removed, compared to volume added through AM, AM is still comparatively fast since machining usually requires multiple stages. The more complexity a part has, the more time is saved using AM.(Gibson et al., 2021)

When creating a part as a single piece using CNC, certain geometric features may prove impossible to produce, for example in hollow structures, due to the limitations posed by the spindle carrying the machining tool. In contrast, AM is not subject to these limitations, allowing for the easy construction of undercuts and internal features without the need for detailed process planning. Complex parts that CNC can only manufacture by dividing them into smaller pieces and assembling them afterwards can be created in their entirety with AM. (Egan, 2023)

The flexibility of technology allows for the creation of geometries that are specifically tailored to meet the unique needs of individual applications. As industrial manufacturing is moving towards where customization is not just a luxury but a demand, the value placed on customer-specific solutions is increasingly on the rise.(Egan, 2023)

Also, the ability to produce parts on-demand close to the point of use are all factors that contribute to the growing adoption of AM. Lowering the transportation costs and advancing towards a more sustainable, efficient, and customer-focused manufacturing.(Gibson et al., 2021)

Despite the advantages of AM, there are disadvantages that need to be addressed. There is a high cost of entry associated with AM machinery and materials, which can be a barrier to wider adoption and scalability. AM also often requires post-processing, which can add to the overall time and expense of production. (Attaran, 2017)

2.3 Advantages and disadvantages of bio-Inspired structures in additive manufacturing

Bio-inspired structures in AM represent an intersection where biology meets advanced manufacturing. These structures are inspired by natural processes, organisms, and systems, embodying principles such as high strength-to-weight ratios, adaptability, and material efficiency. Combining nature's complexity with newer forms of manufacturing technologies offer innovative solutions to complex engineering problems, leading to the development of structures with superior properties and functionalities. (Greco et al., 2023; Podrouzek et al., 2019)

Bio-inspiration involves mimicking or taking inspiration from natural systems to solve human engineering and design challenges. By harnessing the principles of nature, bio-inspired structures in AM offer a promising pathway to revolutionize how we design and manufacture products, making them more efficient, sustainable, and adaptable.(Stano & Percoco, 2021)

Combined with AM the ability to manufacture and produce bio-inspired structures that are too complex for traditional methods of manufacturing is gained. AM technologies offer an economical way to produce engineering parts that are otherwise challenging to make through traditional manufacturing methods. AM is employed to construct components with unique structures applicable across many different industries. (Behera et al., 2021; Wang et al., 2022)

While AM enables the creation of intricate designs, the capabilities of traditional computer-aided design (CAD) software are often insufficient for managing their complexity. Traditional CAD systems employ a boundary-representation technique for modelling three-dimensional objects, where models are described as shells composed of surfaces with no thickness. These shells form from polygons. A model that fails to form a distinction between the inside and the outside of an object cannot reliably define its internal and external boundaries. This creates a risk of errors occurring in the model, where either there are gaps or intersections between the polygons of the model. These errors present themselves in the slicing process of the object. (Brennan-Craddock et al., 2012)

Although this modelling approach works well for standard products and components, it is not well-adapted for depicting bio-inspired lattice structures. A lattice structure, even with only a moderate level of complexity, involves thousands of struts, and can become overwhelmingly complex for a computer to model. (Letov et al., 2021)

2.4 Sustainability

AM has potential to improve sustainability across various industries, offering pathways towards more environmentally friendly manufacturing processes. AM, and by extension bio-inspired AM, can improve production efficiency, support repair and remanufacturing of metal products, and contribute to more sustainable production modes. (Colorado et al., 2020)

One of the most significant sustainability benefits of AM is material efficiency. Unlike traditional subtractive manufacturing processes, which often involve cutting away significant portions of raw material, AM builds objects layer by layer, using only the material that is needed. This approach reduces waste, making it a more resource-efficient manufacturing method. (Colorado et al., 2020)

The energy consumption of AM processes varies widely depending on the technology and material used. While some AM methods can be energy-intensive due to high temperatures and vacuum conditions required, ongoing technological advancements aim to improve energy efficiency. Moreover, the ability to produce parts closer to the point of use reduces transportation-related energy consumption and carbon emissions. (Khalid & Peng, 2021)

3 Bio-inspired structures

3.1 Bio-inspired infill and support structures

Supports in AM are temporary structures that support overhanging features during the manufacturing process. Without supporting structures, any part of the model that extends beyond a certain angle relative to the build plate would have nothing beneath it, causing these sections to droop or collapse. (Guo & Leu, 2013)

Infill refers to the internal structure of the object. Unlike supports, infill is a part of the final object. Traditionally infill patterns have been simple, and for the most part two dimensional. Non-traditional three-dimensional infill patterns such as Gyroid, Schwarz diamond and Schwarz primitive are investigated for their beneficial mechanical properties and emergence from numerical topology optimization, indicating a shift towards more complex, performance-oriented designs in AM. With proper design, the infill structures can also work as a combination of support and functionality. Figure 1 shows the infill patterns discussed. (Podrouzek et al., 2019)

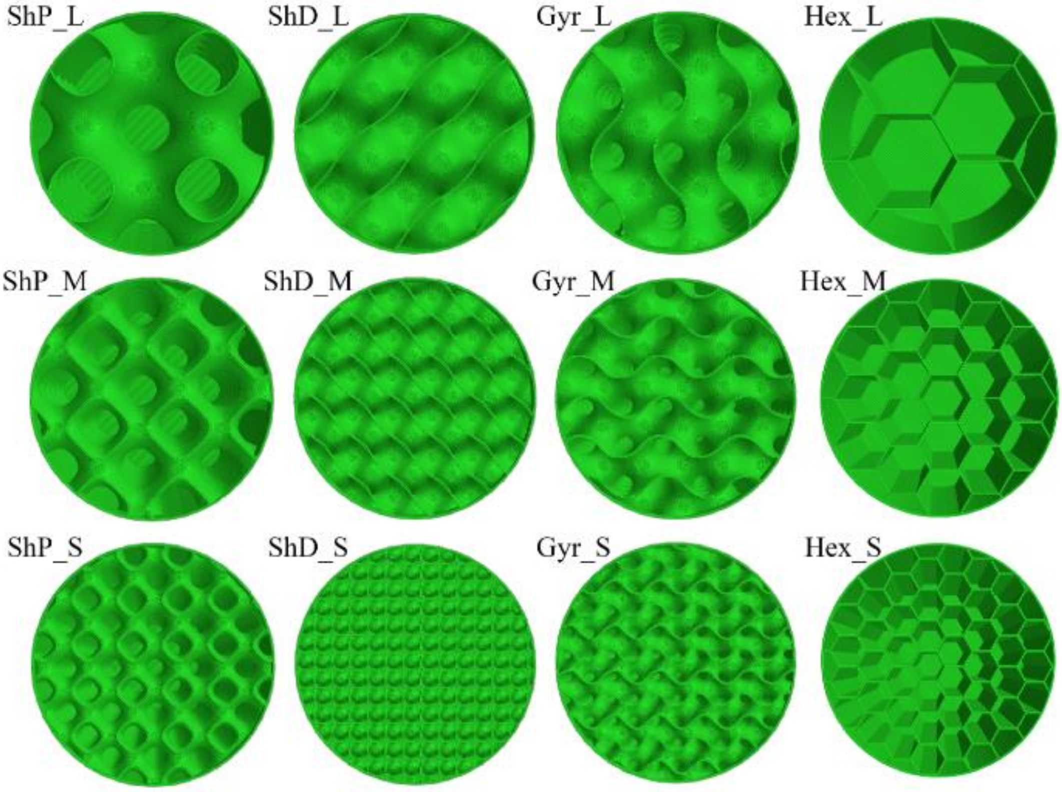

Figure 1. A top-down look at four different bio-inspired infill patterns, in different sizes. From left to right these are the Schwartz primitive, Schwartz diamond, Gyroid and Hexagonal honeycomb lattice. (Podrouzek et al., 2019)

As figure 1 shows, there are three nontraditional three-dimensional infill structures, and a traditional two-dimensional hexagonal infill structure. The 3D patterns are from a family of triply periodic minimal surfaces (TPMS). TPMS are a class of surfaces that naturally occur in various physical and biological systems. These surfaces are mathematically defined as being minimal, which means they locally minimize surface area under small deformations, and they are periodic in three independent directions, much like the repeating patterns seen in a crystal lattice. (Podrouzek et al., 2019) These types of structures can be implemented using software like NTopology for example in airless tyres. (Jafferson & Sharma, 2021)

3.2 Lattice structures

Bio-inspired lattice structures draw from natural patterns and forms to create lightweight and mechanically high-performance materials. These lattice structures emulate the cellular configuration of materials like bone, plant stems, and honeycombs, featuring a repetitive arrangement of nodes and struts that provide an excellent strength-to-weight ratio (Wang et al., 2022). The design of bio-inspired lattices allows for the creation of parts with tailored mechanical properties that can be optimized for specific applications for example aerospace and automotive components. Following examples about lattice structures are taken from different applications point of view and they are selected to introduce the versatile nature of lattice structures. (Greco et al., 2023)

3.2.1 Honeycomb lattice

The honeycomb lattice is a structure of repeating interlocking unit cells. Most commonly associated to the hexagonal honeycomb structure of a beehive, honeycomb cells can consist of any type of interlocking shape. Using traditional manufacturing methods, its usage has been limited, but with AM it is possible to create three-dimensional honeycomb lattices. (Mathiazhagan et al., 2024; Wang et al., 2022) Figure 2 shows three examples of simple honeycomb lattice structures.

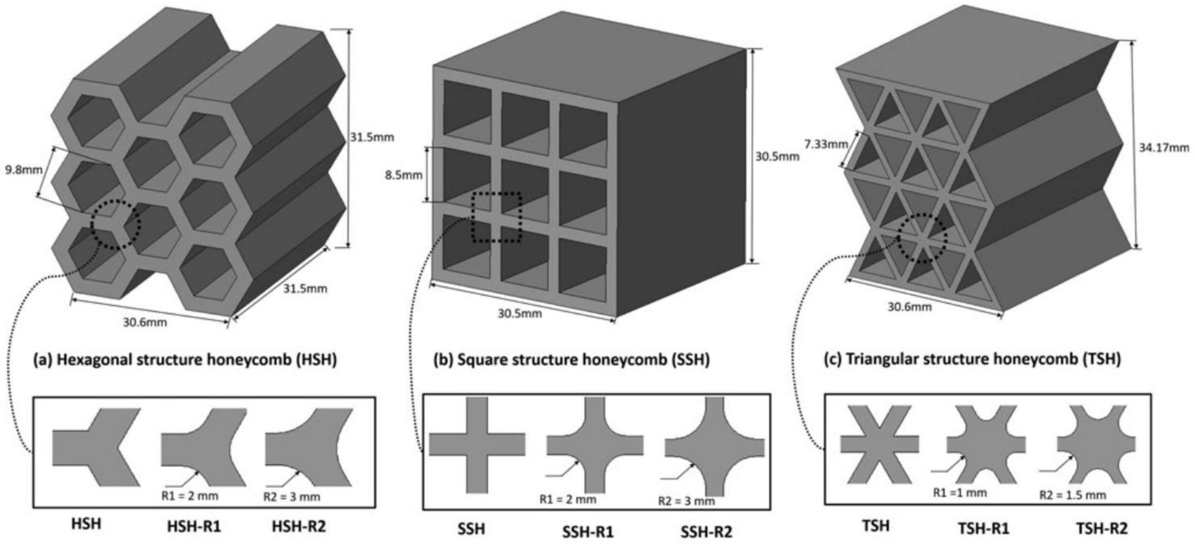

Figure 2. From left to right showing the a) hexagonal honeycomb, b) square honeycomb and c) triangular honeycomb (Nazir et al., 2022)

It can be seen from figure 2 that honeycomb lattice structures are not always hexagonal in shape, even though the hexagonal structure is most commonly associated with the term. From the three different honeycomb structures seen in figure 2, it was found that an increase of material at the nodes within honeycomb structures increases both stiffness and energy absorption efficiency, except when surpassing a certain threshold at the nodes leading to a decrease in stiffness. This is because the excessive concentration of material at the nodes compromises the strength in other areas of the structure. (Nazir et al., 2022)

3.2.2 Horsetail bio-honeycombs

The stem of a horsetail plant is an example of structural adaptation in the plant kingdom. The horsetail stem is hollow and reinforced by a series of ridges that run longitudinally, providing mechanical support. The hollow centre decreases the plant's weight while maintaining structural integrity. The stem also contains vascular bundles arranged in a ring around the central cavity, contributing to further structural support. This efficient design could be used in support structures and be utilised for it's energy absorption properties. Figure 3 shows the structure of different horsetail plants. (Niu et al., 2024)

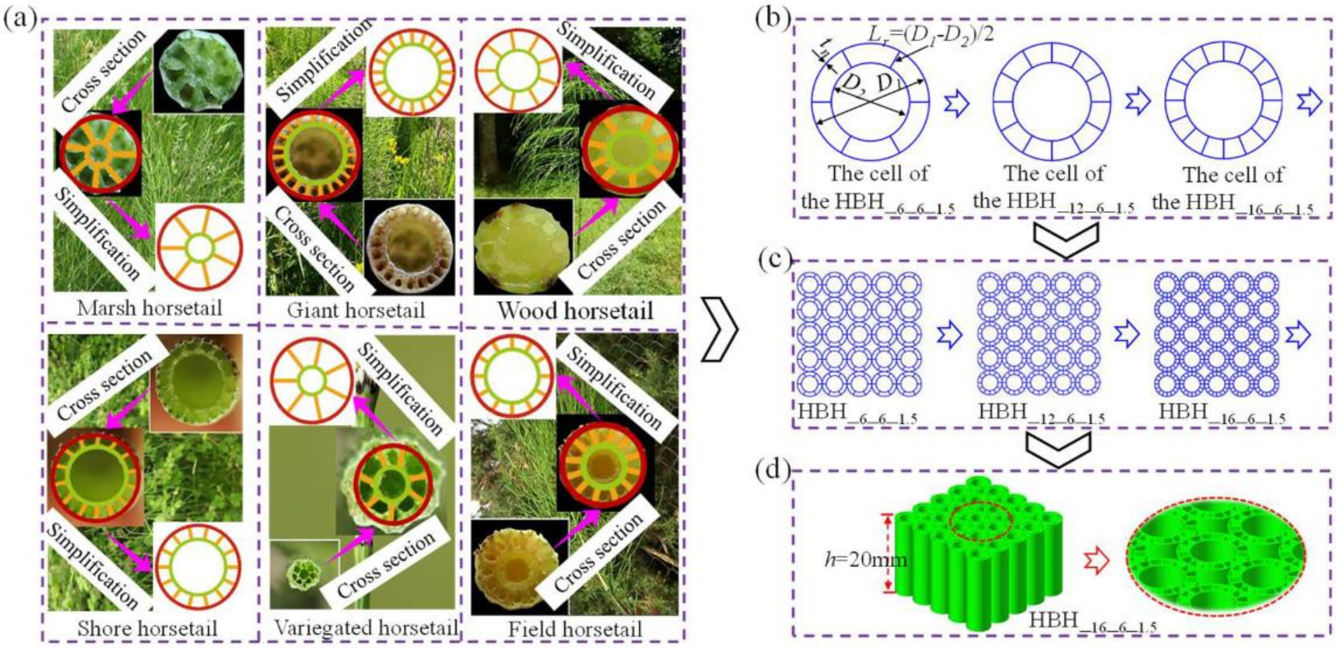

Figure 3. Cross sectional picture of a few species of horsetail stems and their simplified structures. (Niu et al., 2024)

As it can be seen in figure 3, the structures of different species of horsetail and their stems cross-sectionally differ slightly, but the main repeating cell has a clear pattern. Panel (d) shows a three-dimensional model of a horsetail stem structure, as an example of how the structural properties of the horsetail can be used in the field of biomimicry. (Niu et al., 2024)

3.3 Foamlike structures

Foams are characterized by their ability to combine low density with high specific mechanical properties, such as stiffness, strength, and energy absorption capacity. The mechanical behaviour of foam-like structures is largely determined by their relative density and the arrangement of their cells, which can be either open or closed. Closed-cell foams typically offer higher stiffness and strength due to the presence of air trapped within the cells, which provides additional resistance against deformation. Open-cell foams, with interconnected pores, exhibit higher energy absorption capabilities, making them ideal for impact resistance applications. (An & Fan, 2016; Karagiozova et al., 2016)

3.3.1 Luffa

The luffa sponge features a blend of structural and mechanical qualities, thanks to its connected porous structure. This type of cellular structure is known for its mechanical strength at reduced densities. The structure of the luffa sponge is made up of cellulose fibres set within a matrix of lignin and hemicellulose, which improves its strength and flexibility. Mechanical tests indicate that the fibres of the luffa sponge possess a modulus of elasticity and a level of strength that is comparable to wood. This makes them appropriate for multiple uses, such as in devices designed to resist crushing. Figure 4 illustrates the structure of a luffa sponge. (An & Fan, 2016)

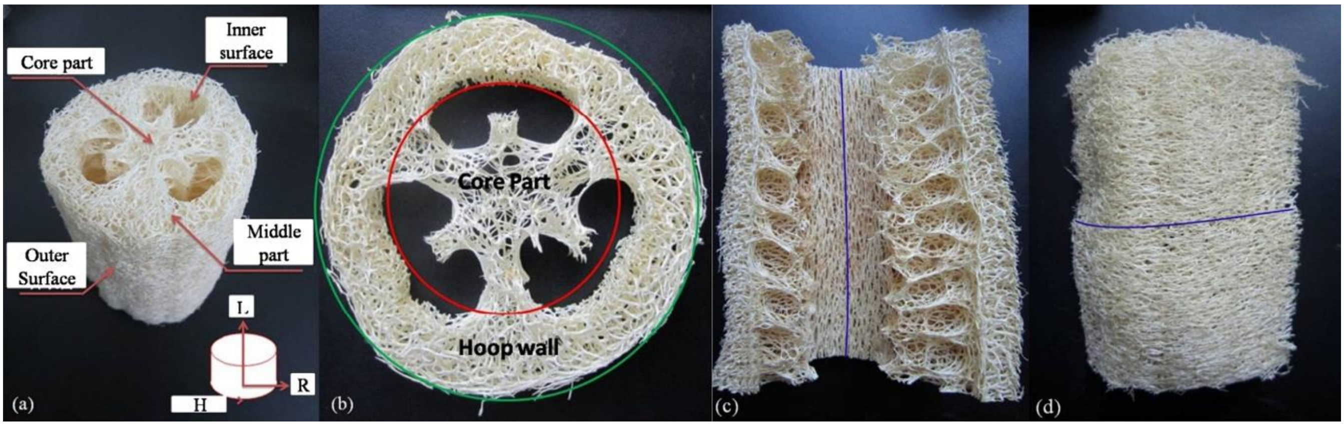

Figure 4. a) A definition for different parts of a luffa sponge. b) An up down look at the structure of a luffa, noting the difference in structure in the core and the outer wall of the plant structure. c) A side view of the structure of a luffa. d) The outer surface of the luffa plant structure. (Chen et al., 2014)

It can be seen from figure 4, that the the core and outer wall of the luffa plant differ in density. This causes the mechanical behaviour between the outer wall and core part to vary significantly, with the outer wall showing superior compressive and tensile properties. This is due to the more porous structure of the core. If made to a template, a structure made completely mimicking the structure of the outer wall shows promise in impact absorption. (Chen et al., 2014)

3.4 Plate structures

3.4.1 Fish scale

Fish possess flexible armour for protection that could be designed into bio-inspired protective devices where high penetration resistance and energy absorption is required. The overlapping scales on fish skin allow for flexibility, distributes the load from a penetration evenly, and minimizes localized stress, leading to higher resistance against punctures. Angling the edges of scales in overlapping or interlocked arrangements significantly increases puncture resistance. (Vernerey & Barthelat, 2010)

3.4.2 Turtle shell

In a study on the structural properties of box turtle shells, it was found that their shell consists of a multiphase composite material with a hierarchical structure, featuring a sandwich composite of denser exterior layers and an interior fibrous foam-like layer (Rhee et al., 2009). The study explores the turtle shell's deformation mechanism under compression, likening it to synthetic foams and highlighting its energy absorption capabilities. Finite element simulations provided an understanding of how turtle shells deform, showing results that closely matched experimental data, especially regarding the impact of voids and porosity on the material’s structure. Figure 5 show the structure of a box turtle shell. (Rhee et al., 2009)

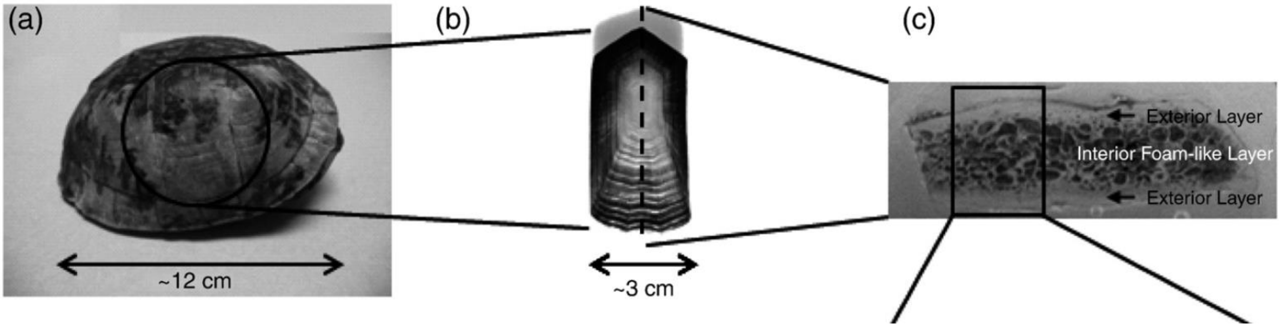

Figure 5. a) Image of whole turtle shell carapace. b) A scute of a turtle shell. c) A cross sectional view of the carapace.(Rhee et al., 2009)

As it can be seen from figure 5, that the carapace structure has denser exterior layers and an interior fibrous foam-like layer. This interior closed-cell foam layer plays a significant role on the overall deformation behaviour of the turtle shell. Future applications for this type of structure could possibly be in ships hulls, and warrants study. (Rhee et al., 2009)

4 Applications of bio-inspired additive manufacturing

4.1 Aerospace and automotive

Lightweight, strong structures are crucial for fuel efficiency and performance. Examples include lattice structures for aircraft components and bone-inspired lightweight chassis for vehicles.(Egan, 2023) For automotive industries one major factor in design is not only structural integrity, but also energy absorption in a crash situation. For these types of situations, the structure of horsetail bio-honeycombs (HBH) is being investigated, finding that HBH structures improve energy absorption compared to a more traditional circular honeycomb structure (Niu et al., 2024).

Similarly, bio-inspired hybrid interleaved composite structures, manufactured by interweaving composite laminates, have demonstrated enhanced energy dissipation under high-velocity impacts, suggesting potential for improved protection in aerospace and automotive industries (Kazemi et al., 2024).

4.2 Maritime industries

The integration of lattice structures through AM into shipbuilding could enhance the structural properties of ships. Lattice structures contribute lightweight design, energy efficiency, and improved material utilization, presenting significant advantages over traditional support elements used in ship construction.(Armanfar et al., 2024) Figure 6 shows where lattice structures could be implemented in the building of a ships hulls.

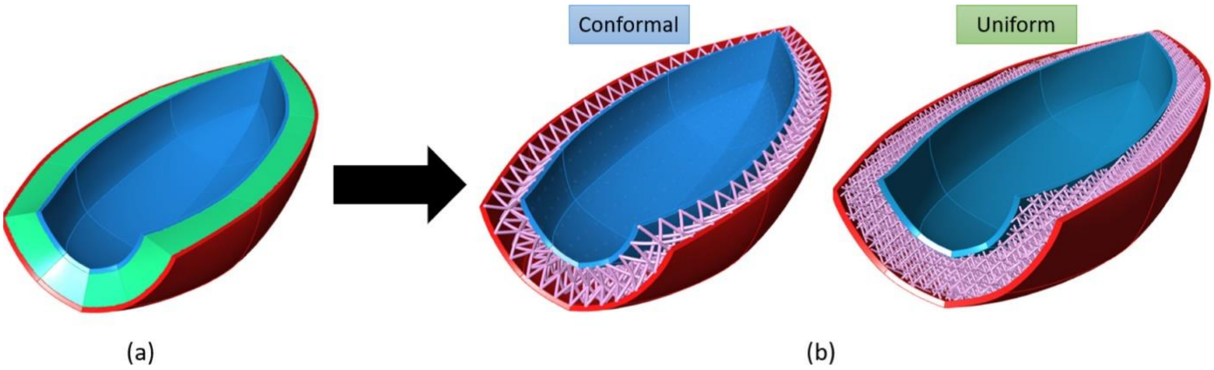

Figure 6. Ships hulls shown as three layers, outer layer as red, middle layer as green and the interior layer as blue. a) Usually, a ship’s hull consists of a solid middle layer. b) The middle layer is show as a conformal or uniform lattice structure.(Armanfar et al., 2024)

In figure 6, a method of incorporating lattice structures into shipbuilding is shown. The clear advantage being that weight is reduced, while the structural integrity remains. Challenges in utilizing AM in the construction of hulls are the size and cost of machinery necessary. While these structures show promise in models, more studies need to be conducted. (Armanfar et al., 2024)

Additive manufacturing is influencing the shipbuilding industry by offering design flexibility and new capabilities of manufacturing components. Wire arc additive manufacturing (WAAM) shows potential to be the future of ship part manufacturing. WAAM is a form of DED, where a metallic wire is used as feedstock and electric arc as the heat source. WAAM offers cost efficiency and deposition rates suitable for large components such as propellers and rudders. (Taşdemir & Nohut, 2021) Challenges of implementing WAAM include higher residual stresses, poor surface finish and limited material options compared to other additive manufacturing techniques. (Bandari et al., 2015) Figure 7 shows where WAAM could be utilized in the manufacturing bio-inspired structures inside of rudders. (Taşdemir & Nohut, 2021)

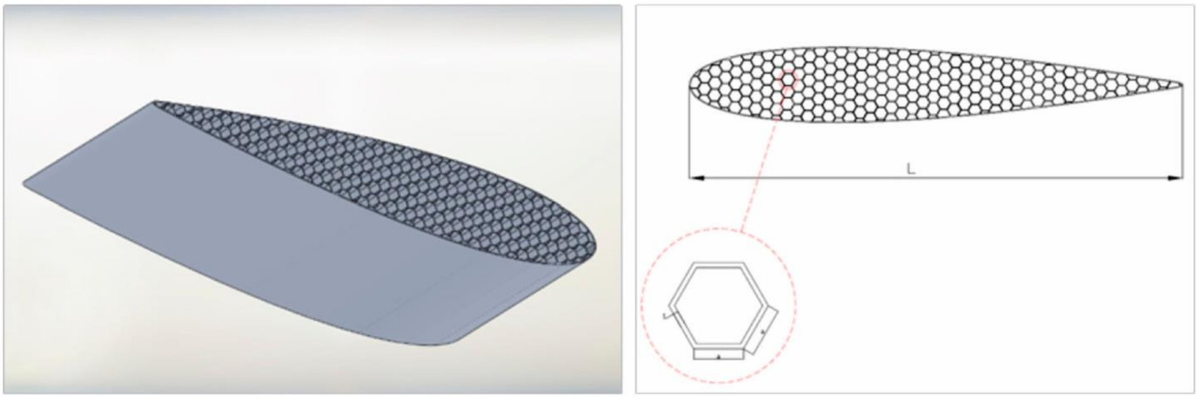

Figure 7. A cross section of a rudder profile with a hexagonal honeycomb infill. (Taşdemir & Nohut, 2021)

In figure 7 a hexagonal honeycomb structure is incorporated into the typical profile of a rudder. While promising, more studies need to be conducted to determine the effects of slicing methodologies and the structural integrity parts created using WAAM. (Taşdemir & Nohut, 2021)

5 Conclusions

Bio-inspired designs offer improvements in mechanical properties such as strength, flexibility, and lowered weight. These structures allow for part optimization that is not typically achievable with traditional manufacturing methods. By utilizing AM, bio-inspired structures can be produced offering a cost-effective manufacturing method for parts that would be challenging and expensive to produce using conventional methods.

Bio-inspired lattice structures, such as honeycomb lattice and horsetail bio-honeycombs, and foamlike structures like the internal structure of the luffa plant, demonstrate a high strength-to-weight ratio and are applicable across various industries including aerospace, automotive, and maritime. These structures are particularly valuable for their energy absorption and mechanical support.

Bio-inspired AM supports sustainability by improving material efficiency, thus reducing waste compared to subtractive manufacturing and potentially lowering energy consumption through optimized design and production processes.

The integration of lattice structures through AM into shipbuilding could improve the structural properties of ships. These structures provide a lightweight design, increase energy efficiency of manufacturing and improve material utilization, presenting advantages over traditional support elements used in ship construction, though the impact of implementation should be studied.

Bio-inspired AM does present challenges such as the complexity of geometric modelling and the size and cost of machinery required. Future directions include addressing these challenges and continuing studies in the design and application of bio-inspired structures to further leverage the unique capabilities of AM technologies.

Future studies should be conducted on scaling up the production of bio-inspired structures for industrial applications, addressing challenges related to the size and cost of AM machinery, as well as real-world application testing to review the performance, practical challenges and economic impacts of these implementations.

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