IJEASED | INTERNATIONAL JOURNAL OF EASTERN ANATOLIA SCIENCE ENGINEERING AND DESIGN

Uluslararası Doğu Anadolu Fen Mühendislik ve Tasarım Dergisi
ISSN: 2667-8764 , 5(2), 198-214, 2023
https://dergipark.org.tr/tr/pub/ijeased

Araştırma Makalesi / *Research Article*
Doi: 10.47898/ijeased.1313827

Learning from Nature for Sustainable Solutions in Architecture: Biomimetic Lightweight Structure Designs

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Yazar Kimliği / *Author ID (ORCID Number)*	Makale Süreci / *Article Process*	
*Sorumlu Yazar / *Corresponding author*: gunesavinc@gmail.com https://orcid.org/0000-0003-1049-2689, G. Mutlu Avinç	**Geliş Tarihi / *Received Date*** :	13.06.2023
	Revizyon Tarihi / *Revision Date* :	17.07.2023
	Kabul Tarihi / *Accepted Date* :	20.09.2023
	Yayım Tarihi / *Published Date* :	15.12.2023

Alıntı / *Cite* : Mutlu Avinç, G. (2023). Learning from Nature for Sustainable Solutions in Architecture: Biomimetic Lightweight Structure Designs, International Journal of Eastern Anatolia Science Engineering and Design, 5(2), 198-214.

Abstract

Recent advances in technology have enabled nature's design principles to be understood and communicated more effectively than ever before. Using nature as a mentor, the biomimetic approach is the practice of generating solutions from nature's systems, processes and designs to solve human problems. However, although this approach is a new field in architecture, it has the potential to transform the sustainable approach in building design and construction. Hence, this article explores the potential of the biomimetic approach as a source of sustainable solutions for lightweight structures in architecture. In this research, the biomimetic approach, examples of lightweight structures in nature and how they can be applied to lightweight structures are discussed. In this context, "Shell Lace Structure, Trabeculae Pavilion, NonLin/Lin Pavilion, BUGA Fibre Pavilion, livMatS Pavilion, 3D-Printed Pavilion, Tower of Light" projects are examined as biomimetic lightweight building designs in architecture. The examples are analysed in terms of the natural model/system they refer to, the purpose for which they were built and the materials used. The analysed examples show that by learning from nature and applying the principles of nature to the built environment, aesthetic, functional, lightweight and high-strength structures can be designed. As a result, the biomimetic approach offers guiding ideas for architects to design environmentally friendly, sustainable and innovative lightweight structures that can respond to today's problems.

Keywords: Biomimetic approach, Lightweight structure, Sustainability, Architecture.

Mimaride Sürdürülebilir Çözümler için Doğadan Öğrenme: Biyomimetik Hafif Strüktür Tasarımları

Özet
Teknolojide yaşanan son gelişmeler, doğanın tasarım ilkelerinin daha önce hiç olmadığı kadar etkili bir şekilde anlaşılmasını ve aktarılmasını sağlamıştır. Doğayı bir rehber olarak kullanan biyomimetik yaklaşım, insan sorunlarını çözmek için doğanın sistemlerinden, süreçlerinden ve tasarımlarından çözüm üretme pratiğidir. Bununla birlikte bu yaklaşım, mimaride yeni bir alan olsa da bina tasarımı ve inşasında sürdürülebilir yaklaşımı dönüştürme potansiyeline sahiptir. Buradan hareketle bu makale, mimaride hafif yapılar için sürdürülebilir çözümlerin kaynağı olarak biyomimetik yaklaşımın potansiyelini araştırmaktadır. Araştırmada, biyomimetik yaklaşım, doğada hafif yapı örnekleri ve bunların hafif yapılara nasıl uygulanabileceği ele alınmıştır. Bu bağlamda mimaride biyomimetik hafif yapı tasarımları olarak "Shell Lace Structure, Trabeculae Pavillion, NonLin/Lin Pavillion, BUGA Fiber Pavilion, livMatS Pavilion, 3D-Printed Pavilion, Tower of Light" projeleri incelenmektedir. Ele alınan örnekler referans aldıkları doğal model/sistem, hangi amaçla gerçekleştirildiği ve hangi malzemeyi kullanıldığı analiz edilmektedir. Analiz edilen örnekler, doğadan öğrenerek ve doğanın ilkelerini yapılı çevreye uygulayarak, estetik, işlevsel, hafif ve dayanımı yüksek yapılar tasarlanabildiğini göstermektedir. Sonuç olarak biyomimetik yaklaşım, mimarlara günümüzde yer alan problemlere yanıt verebilecek çevre dostu, sürdürülebilir ve yenilikçi hafif yapılar tasarlamaları için yol gösterici fikirler sunmaktadır.

Anahtar Kelimeler: *Biyomimetik yaklaşım, Hafif strüktür, Sürdürülebilirlik, Mimarlık.*

1. Introduction

From ancient civilizations to modern times, architects have looked to the natural world for inspiration and solutions to design challenges. In recent years, however, the need for sustainable architecture has become increasingly important. With climate change, resource depletion, and population growth, architects are faced with the challenge of creating not only aesthetically beautiful and functional structures but also environmentally responsible and sustainable buildings. A promising approach to achieving this goal is the biomimetic approach, which involves studying and transferring design principles found in nature. The biomimetic approach is applied in a wide range of fields, from engineering and materials science to medicine and robotics. In architecture, biomimetics offers a promising approach to creating lightweight structures that are both efficient and sustainable.

Natural systems, models, and structures are efficient in terms of lightness, resilience, material utilization, and stability (Arslan-Selçuk, 2009:2). This is because nature contains many structures that have been optimized over time by developing properties and functions such as lightness, flexibility, high stiffness, etc. for natural stimuli and constraints. Learning from these optimized biological structures offers sustainable solutions to architectural and engineering problems (Al Khalil, Belkebir, Lebaal, Demoly & Roth, 2022). Today's construction industry is responsible for the efficient use of natural resources that minimize material consumption (Dixit & Stefańska, 2022). In this context, the biomimicry approach that produces solutions to this problem will help humanity to start the transition from the industrial age to the ecological age (Pawlyn, 2016:14). This approach, called biomimetic design, mimics structures and functions found in nature to solve design problems or create new products and technologies.

Developing lightweight and high-strength solutions is a problem waiting to be solved in many fields. For example, in a study conducted by Nebelsick et al. (2016), the shell formation process of land snails was investigated to produce self-supporting lightweight architectural shells. In another study, Klang et al. (2016) conducted research on the production of concrete-based building materials with reference to the multi-layered and fibrous system of coast redwood and the spiny structure of sea urchins. Liu et al. (2019) conducted lightweight fibreglass material research based on the cellular morphology and anatomy of radiolaria. These studies show that the advantages of biological models are taken as a guide for light weight and high strength performance in structures such as structures and materials.

Within the scope of the study, a systematic literature review was conducted to reveal the studies produced on “Biomimetic Lightweight Structure”. Because “Literature review is an essential feature of academic research” (Xiao & Watson, 2019). The aim of this literature review is to provide an overview of research in this field and to review existing studies. As a result of the searches on the Web of Science site with the keyword "Biomimetic Lightweight Structure", a total of 111 studies between 2000-2023 were identified. The studies were analysed in terms of years, fields and document types.

In this context, the year graph of 111 articles is presented in Figure 1. According to this graph, 2 publications were produced in 2003 and the number of studies produced on this subject has increased with each passing year.

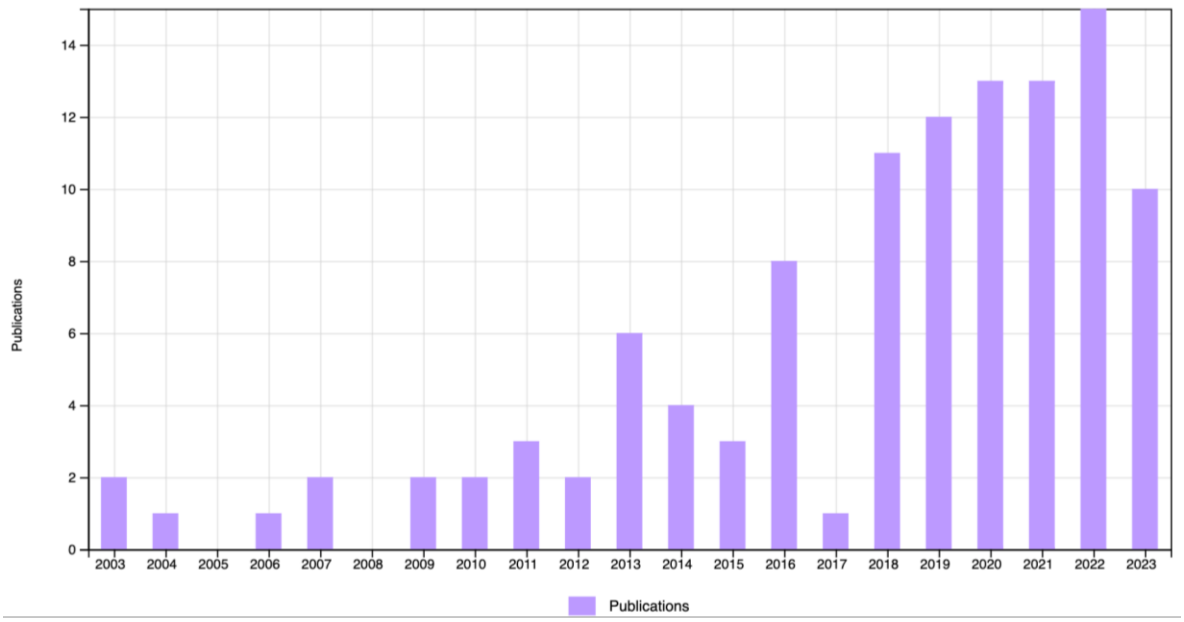


Figure 1. Published studies according to years

The fields for the studies obtained as a result of the search can be seen in Figure 2. In this context, it is seen that the fields where the most studies are produced are engineering multidisciplinary, materials science biomaterials and engineering mechanical.

Figure 2. "Biomimetic Lightweight Structure" studied areas

As a result of the analysis, 74 Articles, 29 Proceeding Papers, 8 Review Articles and 2 Book Chapters were found (Figure 3).

Figure 3. Document types of the studies

In this context this article explores the potential of the biomimetic approach as a source of sustainable solutions for lightweight structures in architecture. The paper first provides some background information on lightweight structures in nature, which are characterized by lightness and high strength. After reviewing past research on lightweight structures in architecture, the use of lightweight structures strategies of living things in nature in architectural design is analyzed through case studies. The analysed studies show that the structural load carrying capacity has been generally improved. Therefore, it is presented in order to guide future researchers in this field and to provide important references.

In conclusion, this paper shows that by learning from nature and applying its principles to the built environment, not only esthetic and functional but also sustainable and resilient structures can be created. In this context, it can be said that the biomimicry approach has the potential to transform the approach to building design and construction and help create a more sustainable future.

3. Materials and Method

This research aims to explore the potential of using nature-inspired designs for creating lightweight and high-strength buildings in architecture. In this context, the literature review provides an overview of biomimetic lightweight structures, biological references, objectives and materials in existing studies are examined and the findings are explained. Thus, it is seen that the biomimetic approach has a significant potential to develop solutions for lightweight structures and high strength.

From this point of view, firstly, examples of lightweight structures in nature and architecture are examined. Then, the use of lightweight building strategies found in nature is discussed through case studies in architectural design. The analyzed examples, including project name, year, referenced natural model, innovative materials used, and research objectives, are presented in a table. Additionally, the research process is illustrated in Figure 4.

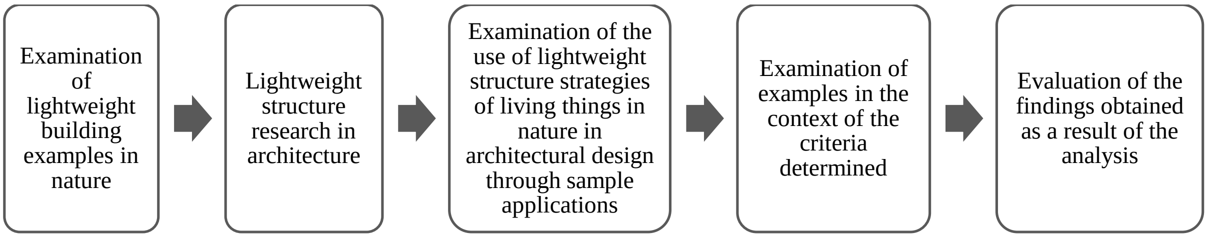


Figure 4. Flowchart of the research

For examples of lightweight building strategies/models/systems/structures in nature, a search was conducted with the keyword "lightweight" in Asknature (URL-1) website. Then, examples of "lightweight structure" examples in the literature with reference to nature were investigated. The examples analysed within the scope of the study were determined as a result of research on architectural websites such as Archdaily (URL-2), Archivibe (URL-3), Dezeen (URL-4), Inhabitat (URL-5), Arch2o (URL-6), Architizer (URL-7). Attention was paid to the fact that these examples were sustainable researches referring to nature carried out in order to obtain lightweight and high strength. The researches examined within the scope of the study were limited to the examples carried out between 2010-2023.

4. Examples of Lightweight Structures in Nature

Learning from lightweight structures in nature is very important for several reasons. First, nature has evolved over millions of years to optimize structures for their intended function using minimal materials and energy. By studying these structures, we can gain insight into design principles that have already been tested by nature and potentially apply them to man-made structures, resulting in more efficient and sustainable designs. Secondly, many of the materials and techniques used in nature's lightweight structures are biodegradable and environmentally friendly, making them a potential source of inspiration for sustainable design. By learning from these structures, architects and engineers can develop innovative solutions that are in harmony with the environment and minimize the impact of man-made structures on the planet. Therefore, mimicking nature's form and processes leads to maximizing resource efficiency and minimizing the negative impact on the environment (Srisuwan, 2019).

In this context, feathers, bones, beaks and claws of birds stand out as structural biological materials due to their low weight, which is balanced by structural support or robustness for activities such as survival, which in most birds is essential for flight. In addition, the Toucan (*Ramphastos toco*) and the wreathed hornbill (*Rhyticeros undulatus*) have distinctively long and thick beaks. The Toucan's bill is one-third of the bird's total length. Although the toucan bill is light, it accounts for one-thirtieth to one-fortieth of the bird's total mass (Seki, Bodde & Meyers, 2010). As another example, dragonfly wings offer highly efficient flight and lightweight characteristics thanks to an array of adaptable materials that form a very complex composite structure (Figure 5) (URL-8).

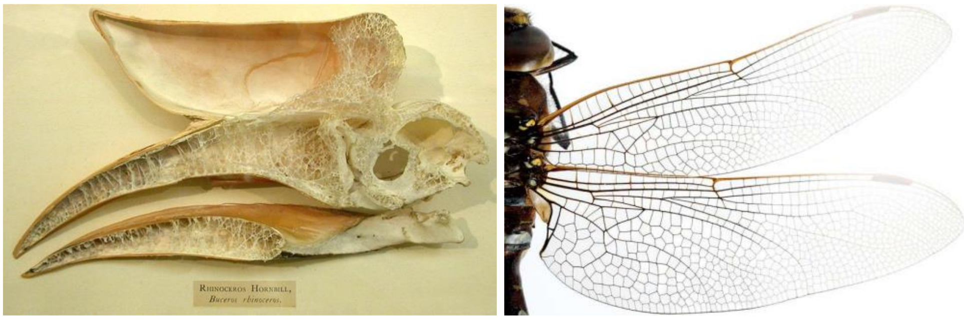


Figure 5. The internal structure of the Toucan beak (URL-9) and the Dragonfly wing (URL-10)

Similar to the Toucan’s beak the dried cactus skeleton of the prickly pear is lightweight and has high strength (Ortega et al., 2014). The texture of the straight side shoots of the prickly pear cactus is also web-like, arranged in layers and intertwined with bundles of interconnected wood fibers. As a result, the tissue of the prickly pear cactus is characterized by a particularly high load-bearing capacity (Figure 6) (URL-11).

Figure 6. Prickly Pear Cactus (Ortega et al, 2014)

As seen in the examples analyzed, lightness and high resilience are seen in many other phenomena in nature such as bamboo, bird wings, muscles, feathers, and bone structure. These biological phenomena have the potential to be transferred as information to architectural design with their lightness and high strength. The use of natural lightweight structure designs in architecture is discussed in the next section.

5. Examples of Lightweight Structure in Architecture

An example of a design inspired by lightweight structures in nature is the Crystal Palace structure designed by James Paxton, inspired by lotus leaves (Figure 7).

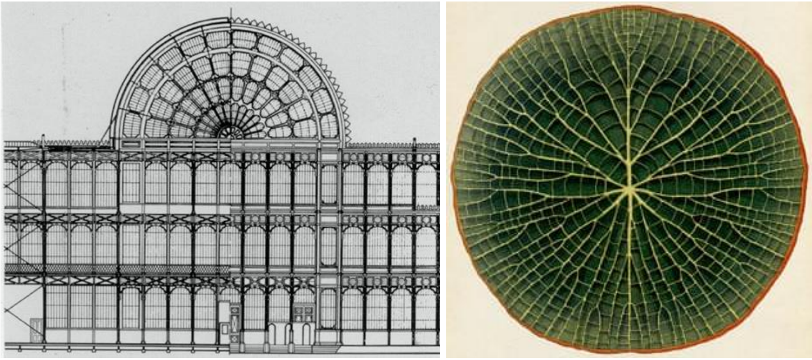


Figure 7. Crystal Palace (URL-12); Water Lily (URL-13)

Another researcher like James Paxton is contemporary shell designer Heinz Isler (Baghdadi, Heristchian & Kloft, 2019). Isler has conducted lightweight shell research (Figure 8), with an interest in natural shells such as mussels, eggshells, nuts, flower petals, and onion skins, and has a collection of seashells (Kotnik & Schwartz, 2011).

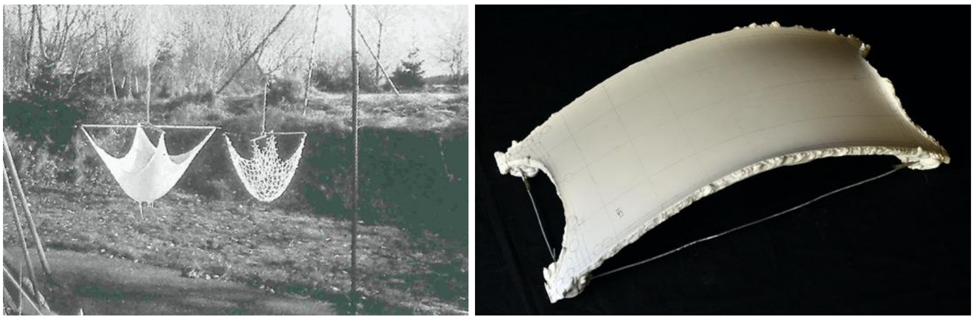


Figure 8. Experiments with hanging cloths, nets, and shells (URL-14)

Frei Otto (Meissner & Möller, 2015:7), who conducted research on lightweight structures in nature and founded the Institute for Lightweight Structures at the University of Stuttgart in 1964 (Meissner & Möller, 2015:7), used his knowledge of nature to research membranes, cable webs and retractable roofs, umbrellas, arches, grid shells, branching, and pneumatic structures. Otto developed innovative structures with lightweight and high strength by making the best use of new materials such as thin cables made of high-strength steel or thin membranes made of synthetic fabric (Figure 9) (Arslan-Selçuk, 2009:22).

Figure 9. Olympic Stadium from the Olympic Tower, Munich (URL-15); Spider sheet web (URL-16)

It is understood that the designs analysed so far are based on lightweight structures found in nature such as water lilies, seashells and spider webs. In this context, it is seen that the lightness and robustness of organisms in nature and structures made by organisms are used as a source of solution for architectural design. Similarly, it is important to reveal the researches on lightweight structures today and the references from which these researches are designed. From this point of view, the use of lightweight construction strategies of living things in nature in architectural design is analysed through sample applications.

6. Investigation of the Use of Lightweight Constructions Strategies of Living Things in Nature in Architectural Design through Case Studies

Lightweight structures are recognized as a material-efficient, energy-saving, and cost-effective design. In this case, the effective use of materials prevents the waste of resources (Srisuwan, 2019). In this context, research is carried out in the light of information learned from nature with the biomimetic approach.

An example of this research is the 'Shell Lace' structure developed by London-based architectural practice Tonkin Liu with the support of Arup engineers (Figure 10). Modern construction methods using advanced digital modeling, analysis, and fabrication combined with tailoring principles create the 'Shell Lace' innovation. By mimicking natural forms such as seashells, lightweight and high-strength designs are being explored that feature optimized curvilinear geometries as a structural typology. In the first phase, 'Shell Lace' is digitally modeled as a surface. Lightness and transparency are achieved by punching flat sheets in the laser cutting stage. This creates efficient and responsive structures with minimal weight and waste (Dudley, 2022). To design this new structural technique, Tonkin Liu studied the structures of mollusk shells. It was found that the studied shells showed high resistance to the surrounding environment while consisting of minimum thicknesses (Rawn, 2014).

Figure 10. ‘Shell Lace’ structure design, 2014 (Rawn, 2014)

In another study, a research team from the architecture school of Politecnico di Milano (URL-17) designed and built a 3D-printed pavilion based on the microstructure of bones using a biomimetic approach. Together with the ACTLAB research team (URL-18) in Milan and their industrial partner FILOALFA®(URL-19), they transferred the principles behind biological models into the pavilion design. The Trabeculae Pavilion is a lightweight prototype produced with an innovative and sustainable construction technique that minimizes the use of materials. In this research, the internal microstructure of the bone was analyzed with a biomimetic approach, and algorithms were used to create three-dimensional cellular structures with the knowledge obtained from biology. As a full-scale prototype, the pavilion was 3D fabricated using biopolymer (Figure 11) (Naboni, Breseghello, & Kunic, 2019).

Figure 11. *Trabeculae* Pavillion, 2017 (Grozdanic, 2017)

Another work examined within the scope of the study is the NonLin/Lin Pavilion (Figure 12), designed by Marc Fornes - TheVeryMany (URL-20) office and made of perforated aluminium material resembling a giant piece of coral. Composed of 27 components and four meters high, it can be disassembled and reassembled in different locations. Surfaces containing more than 155,000 star-shaped holes of different sizes form a pattern on the surface of the pavilion (Fearson, 2011). The aim of this study was to create a coral-like structure that is lightweight and has high strength (URL-20).

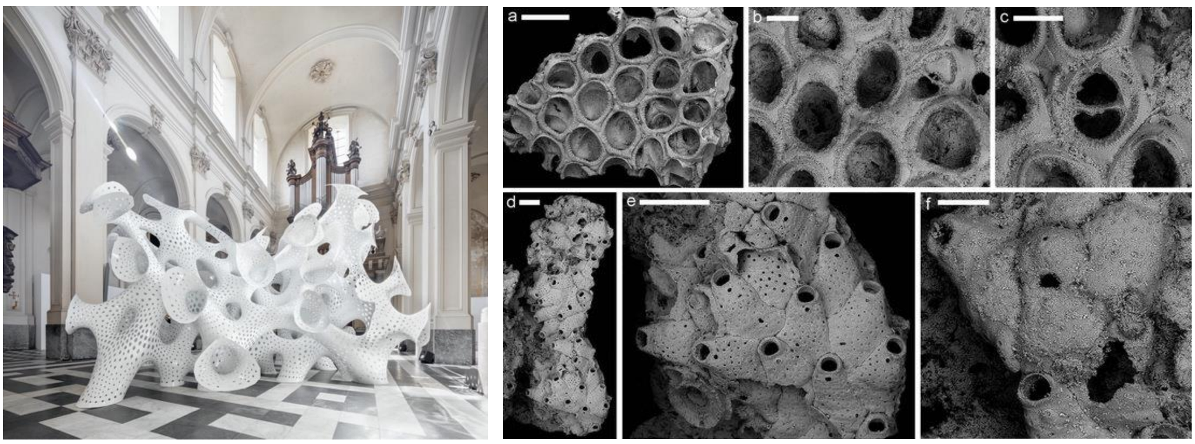


Figure 12. NonLin/Lin Pavillion, 2018 (URL-20) ; Microscopic images of corals (Rosso et al, 2017)

Similarly, the BUGA Fibre Pavilion project (Figure 13) is the result of research on lightweight and high-strength structures. This study is based on biomimetic research conducted at the Institute for Computational Design and Construction (ICD) (URL-21) and the Institute for Building Structures and Structural Design (ITKE) (URL-21). It is produced by transferring principles from the fibrous structures of the exoskeleton of arthropods and the forewing shells of flying insects, referred to as elytra (Dambrosio et al., 2019). It demonstrates how the interdisciplinary exploration of biological principles combined with the latest computational technologies can lead to a truly new and real digital fiber composite building system. The pavilion is enclosed by a transparent and mechanically pre-stretched ETFE membrane. This lightweight structure design is stated to be approximately five times lighter than a conventional steel structure of the same dimensions (URL-22).

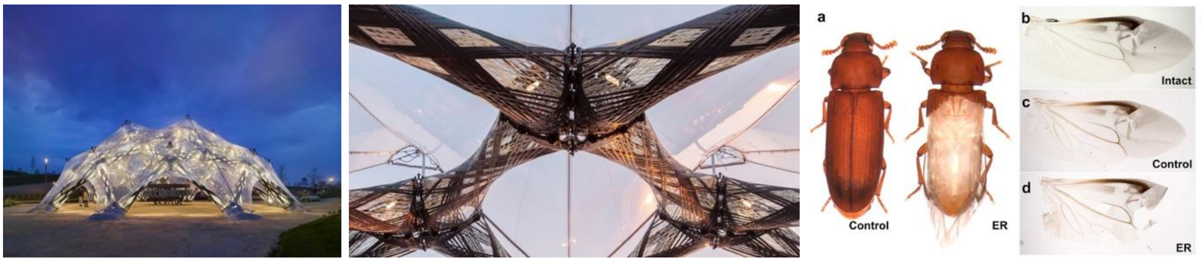


Figure 13. BUGA Fiber Pavilion, 2019, The elytra of insects (URL-22: Linz et al., 2016)

The livMatS pavilion, produced by ICD/ITKE Stuttgart University (URL-21) and located in the Botanical Garden of the University of Freiburg (URL-23), offers a sustainable, resource-efficient alternative to traditional construction methods (Figure 14). livMatS pavilion is inspired by the Saguaro cactus (Carnegia gigantea) and prickly pear cactus (Opuntia), characterized by their special wood structure (URL-4). It is made entirely of robotically wrapped flax fiber with a naturally renewable, biodegradable, and locally available material (URL-12). Fiber composites provide an excellent basis for the development of innovative and material-efficient lightweight structures (URL-4).

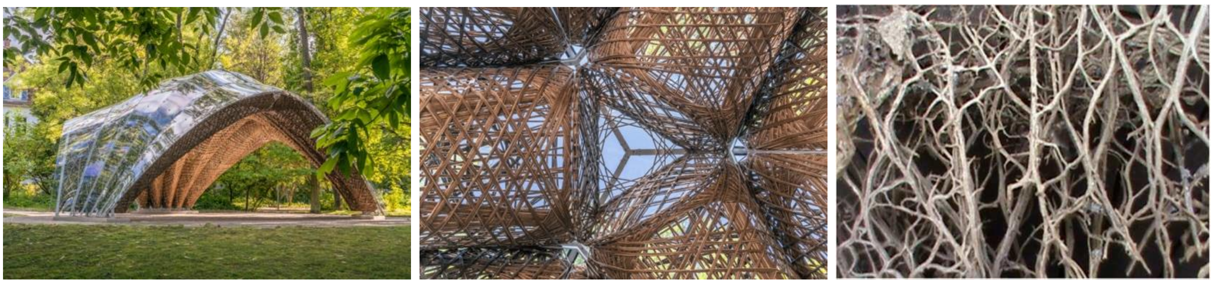


Figure 14. livMatS Pavilion 2020-21, *Prickly Pear Cactus* (URL-11; Ortega et al, 2014)

In another example, architecture students at the University of Tennessee (URL-24) built the 3D-Printed Pavilion in the fall semester of 2022 with the help of industrial partner Loci Robotics (URL-25) (Figure 15). For the pavilion design, inspired by the double curved surfaces and radial geometries of 60 and 120 degrees found in the native plant (*Trillium Tennesseense*), the pavilion was designed as a three-lobed 3D-printed structural dome. In addition, one of the innovations of this research is the design of the thinnest possible structural shell with a thickness of approximately 147.32 mm. The thin-shell structure is reinforced with carbon fiber, which is recycled and can be recycled into new prints (URL-26).

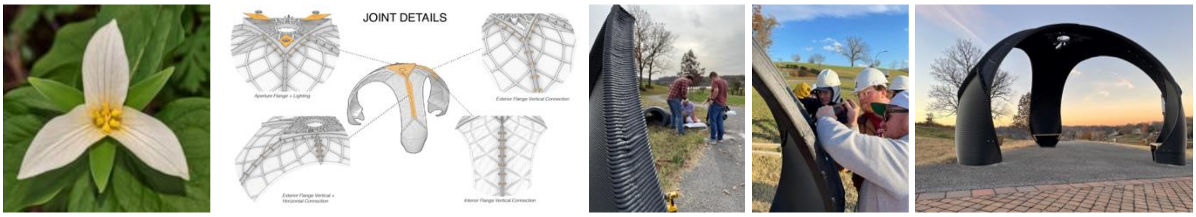


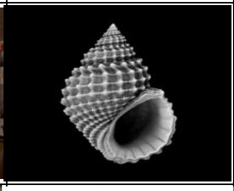
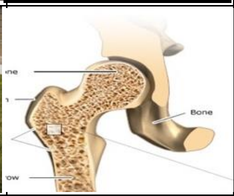
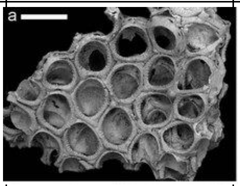
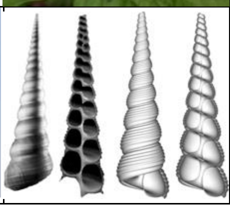
Figure 15. 3D-Printed Pavilion, University of Tennessee, 2022 (URL-26)

Another structure developed by Tonkin Liu is the 40-meter-high Tower of Light in Manchester, which supports and surrounds the chimneys of the low-carbon energy hub (Figure 12). The tower is constructed from 6 and 8-millimeter-thick flat steel sheets, specially adapted, laser-cut and then welded together to form a curved, rigid, and strong surface (Figure 16) (URL-27).

Figure 16. Tower of Light, 2022, geometric structure of seashells (URL-27; Selcuk, Fisher & Williams, 2005)

To summarize, all the examples discussed so far are the results of biomimetic research carried out to produce lightweight and high-strength structures using minimal materials. The findings of the examples examined within the scope of the study are presented in Table 1.

Table 1. Findings of the analyzed samples

Project name and year	Image	Natural Model	Objective of the research	Material
Shell Lace Structure, 2014			Lightweight and high strength designs	Sheet metal material
Trabeculae Pavillion, 2017			Production using minimal materials, lightweight, innovative, and sustainable construction techniques.	Biopolymer usage
NonLin/Lin Pavillion, 2018			Lightness and high strength	Perforated aluminum material
BUGA Fiber Pavilion, 2019			Lightweight steel structure design	ETFE membran
livMatS Pavilion 2020-21			Innovative and material-efficient lightweight construction research	Renewable, biodegradable and regional linen fiber material
3D-Printed Pavilion, 2022			Thin structural shell design	Carbon fiber that is recycled and can be recycled into new products
Tower of Light, 2022			Lightweight and high strength, solid surface formation	Flat steel plate

In the examined examples, it is seen that lightweight building systems inspired by nature result in diversity in designs, different geometric and structural forms. In the analysed researches, they are designed based on lightweight models in nature such as plants, shells, corals, bones and wings. However, in these designs, it is understood that the researchers carried out innovative structural research by utilising the macro, meso and micro scales of biological models.

7. Conclusions and Recommendations

Over millions of years, nature has evolved to create lightweight structures with high strength that best adapt to their environment. Architects, engineers, and designers are turning to nature for innovative and sustainable design solutions because nature has optimized structures for strength and efficiency. Concepts developed with reference to nature, such as resilience, high strength, and lightness, stand out as innovative developments. Therefore, in this study, the lightweight structure applications of the biomimetic approach in the field of architecture are examined and its importance as a sustainable design approach is emphasised. As it can be understood from the examples examined in the study and the systematic literature review, it is seen that architects, engineers and researchers refer to the knowledge of nature for minimum waste, resource efficiency, high strength and lightweight building designs.

However, it has been determined that the number of researches on biomimetic lightweight structures is increasing day by day. As a result, this research provides an overview of the use of lightweight systems/structures in nature as a resource for creating innovative concepts in architectural design. The examples examined in this study emphasize that the structural and morphological properties of natural structures, such as bones, wings, and shells, have significant potential. In addition, the analysed researches show that the biomimetic approach requires interdisciplinary cooperation.

As a result, the adoption of biomimetic approach in architecture is one of the innovative approaches towards the transition to sustainable practices in this field. In this context, lightweight structure researches with biomimetic approach contribute to the understanding of future architecture by reducing the use of materials, encouraging the use of recyclable materials and proposing a cyclical process.

In this context, researchers who want to work in this field will be able to gain the necessary knowledge to produce lightweight and high-strength designs by analysing structures such as webs, bones, wings, corals and shells in nature.

Research and Publication Ethics

The study complied with research and publication ethics.

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