Bionic Design Architectural Innovations Inspired by Nature with a Focus on Concrete Shell Structures

Thesis · September 2020

DOI: 10.13140/RG.2.2.25490.48329

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Bionic Design

Architectural Innovations Inspired by Nature

with a Focus on Concrete Shell Structures

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Bachelor Thesis

Bachelor of Science in Civil Engineering

Technical University of Munich

Bionic design

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Thesis for the degree of Bachelor of Science

Acknowledgments

Al Hamdulillah.

First of all, I thank God for being able to do what I do and being given the chance to accomplish my furthest dreams. In spite of all obstacles and problems I had to face throughout my journey as an international student, my constant faith and strong belief in God helped me overcome every moment of weakness and kept me focused on my goals.

I would like to thank Prof. Oliver Fischer and my direct supervisor Mr. Daniel Auer for believing in me and giving me the opportunity to work with them and contribute to the scientific research of our institution, which is an honor I will always cherish and keep in mind as I move on to further challenges.

I would also like to express my gratitude towards Prof. Christoph Gehlen, Prof. Gerhard Müller, Mrs. Eva Bodemer, Mrs. Johanna Ziegltrum, Mrs. Veronika Singer, Mr. Pierre Wiesmath, Ms. Marlise Schneider and Ms. Madison Montgomery for all the different kinds of support they have provided me with. They have been of great assistance throughout my academic development leading to this thesis and I owe them a huge thank you.

Another tremendous thank you goes to all my friends at the TUM that have been there for me in hard and happy times: Fatma, Emna, Julian, Nick, Sana, Aylin, Adriana, Pinar, Melissa, Hedi, Elyes, Otman, and Mulook El-Mishwar. They had my back when I needed them and cheered me up in more situations than I can remember.

A special thank you is dedicated to my brothers from other mothers Youssef, Yassine, Aziz, Khalil, and Salah who did not allow distance to have any major impact on me by sharing every moment of joy and struggle with me since the very beginning.

To my family, my grandfather M'hamed, my grandmothers Ommi Fayza and Ommi Naima, my big brother Ma7mou7, my sister As2ous, my brother Ayoub, my sister Khaoula, my beloved family members watching from heaven Baba Jalloul, Uncle Imed, and my dear aunt Tta Hbiba: I love you all and I am profoundly grateful to you.

Keeping the best for last, I dedicate my life along with this thesis to my dear parents, to whom I owe everything. They are and have always been my biggest supporters, my strongest motivation, and my deepest love. They sacrificed a lot for me and my future, their happiness has always depended on mine and I do not take that for granted. I love you both beyond measure and I hope I will keep making you prouder and prouder.

With love to all readers.

Ismail Hmidet

Abstract

In order to achieve greater stability and structural efficiency, engineers use nature as an inspiration for their design. Considering the level of sustainability in biological systems, they analyze their structural behavior, browse for compatible analogies with technical systems, abstract the observed physical and mechanical principles, and implement these principles into the final product. This process defines the bionic design approach. The term “bionics” refers to the scientific discipline that addresses the transfer of properties from biology to technology. This thesis aims to study the theoretical fundamentals of this concept, explain its methodologies, and demonstrate its applicability in architecture. Through the assessment of bionically built shell structures, the different steps of the design process are illustrated, and the elements of each analogy are evaluated on both biological and technological ends. The chosen examples in this thesis incorporate concrete, masonry, steel, and timber structures. Multidisciplinary literature is reviewed to deliver a thorough explanation for each design project. Based on this research, the structural benefits that characterize certain biological systems can be transferred into architectural design, and improve the load bearing capacity of shell structures in particular, using the bionic approach.

Abstrakt

Um eine größere Stabilität und strukturelle Effizienz in der Gestaltung zu erreichen lassen sich Ingenieure von der Natur inspirieren. Angesichts der Nachhaltigkeit von biologischen Systemen analysieren sie ihr strukturelles Verhalten, suchen nach kompatiblen Analogien mit technischen Systemen, abstrahieren die beobachteten physikalischen und mechanischen Prinzipien und implementieren diese in das Endprodukt. Dieser Prozess definiert den bionischen Designansatz. Der Begriff „Bionik“ bezieht sich auf die wissenschaftliche Disziplin, die sich mit dem Transfer von Eigenschaften von der Biologie zur Technologie befasst. Diese Arbeit zielt darauf ab, die theoretischen Grundlagen dieses Konzepts zu untersuchen, seine Methoden zu erklären und seine Anwendbarkeit in der Architektur zu demonstrieren. Durch die Bewertung von bionisch gebauten Flächentragwerken werden die verschiedenen Schritte des Designprozesses veranschaulicht und die Elemente jeder Analogie sowohl auf biologischer als auch auf technologischer Ebene beurteilt. Die ausgewählten Beispiele in dieser Arbeit umfassen Beton-, Mauerwerks-, Stahl- und Holzkonstruktionen. Multidisziplinäre Literatur wird verwendet, um eine gründliche Erklärung für jedes Designprojekt zu liefern. Auf Basis dieser Forschung können strukturelle Vorteile, die bestimmte biologische Systeme charakterisieren, in die architektonische Gestaltung übertragen werden und insbesondere die Tragfähigkeit von Schalenkonstruktionen mithilfe des bionischen Ansatzes verbessern.

Contents

1. Introduction

Nature has always been a source of inspiration for designers from different disciplines. The innate tendency to follow the model of nature [1] has majorly affected the urban landscape and the evolving image of our surroundings, especially in terms of architectural development. Zaha Hadid, for instance, known for the seamlessness and fluidity in the design of her structures, found inspiration in “the complexity of form in nature, Arabic calligraphy, and the natural seamless flow of the landscapes in Sumerian village, Iraq that happens between reeds, water, and sand” [2]. However, this type of inspiration usually seems to reflect only on the aesthetics and the appearance rather than the functioning of the product, whether it is a building, a machine, or any other object.

Alternatively, the bionic design approach suggests a way to exploit nature in a deeper manner that involves the implementation of technical solutions given by biological systems and natural models, from macroscopic organisms like animals and plants to nanostructures and conglomerates on the atomic level. This concept of “biologically inspired” innovation focuses more on the abstraction of functionally beneficial features found in nature that can help develop a more efficient design of a certain structure.

Bionics, the science that addresses the transfer of the abstracted principles from biology to technology, is a relatively new discipline. Therefore, most of the related academic publications and research papers on this topic are recent and adhere to contemporary developments and challenges in technology. Reference books of Werner Nachtigall, Julian Vincent, Janine Benyus and several other researchers who helped popularize the concept of bionics across the world date mostly from the early 21st century, establishing a newly founded knowledge base for multidisciplinary applications of bionic projects with up-to-date concerns.

A particular concern of civil engineers and architects for which the bionic design approach can potentially present valuable solutions to, is the stability and the structural efficiency of buildings in terms of load bearing capacity. In this context, this thesis aims to answer the following question: How can the inspiration from nature affect the design of buildings in a way that improves their structural behavior? In other words, to what extent does bionics revolutionize architecture, and what are the lessons learned from the past biologically inspired architectural projects?

The research consists of two main chapters. The first chapter introduces the concept of bionics and its development into a scientific discipline throughout history, defines and explains its main principles and methodologies, and clarifies some common misconceptions, such as considering buildings that are shaped similar to a certain biological system as an application of bionic design. Then, the applicability of bionics in architecture is assessed by displaying analogies in form between nature and architecture, and by studying shell structures, which are chosen to be the focus of this thesis, in terms of mathematical description, mechanical properties, and comparability in shape and function to biological organisms. The next chapter then provides a catalog of bionic projects that exemplify the transfer of structural principles from biology to architecture. The first section of it highlights the potential of thin concrete shells in bionic design, while the remaining sections illustrate biologically inspired buildings of other materials.

2. Bionics

2.1 Before "bionics"

As modern as the term "bionics" is, imitating biological systems and using nature as a source of inspiration to develop technological inventions and engineering solutions is a process that has been seen often throughout history. In this first section, historic bionic innovations - that took place before the term was first introduced - are presented, and the duality of "technical biology" and "bionics" present in most of them is assessed.

2.1.1 Mathew Baker's galleons

Inspired by saltwater fish

In 1576 and following John Hawkins' plans, English shipwright Matthew Baker started designing a new class of galleons characterized by their reduced water resistance, greater speed, better maneuverability, and better course stability. In order to optimize the underwater hulls, he studied the adaptation of saltwater fish to water flow, then developed new underwater cross-sectional distributions for the boat's shape based on these studies [1]. The first stage, where the biological system is analyzed and studied using technology, is called "technical biology". The second stage, where physical characteristics are abstracted and utilized as a basis for the design process, corresponds to "bionics".

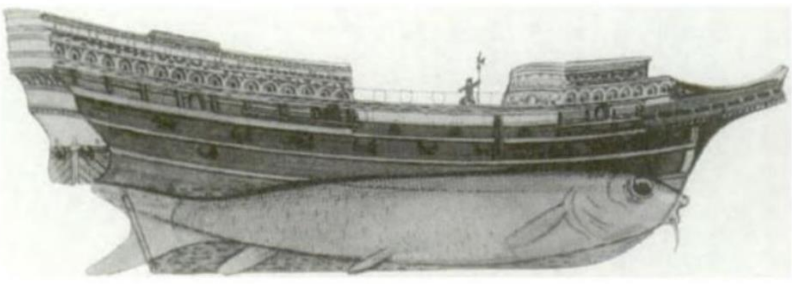


Figure 1: Baker's galleons with the fish body drawn in

2.1.2 Cornelius Lie's pilot fish

Inspired by cods

Another classic example that emphasizes the direct transfer of information from biology to technology is Cornelius Lie's "pilot fish": a ship piloting device that he developed in 1905 in the form of a mechanical fish [3]. The caudal fin responsible for generating propulsion had an outline similar to that of a cod. The device also had dorsal, pelvic, and pectoral fins in the same spots as a fish, which were used accordingly for side and depth control [4].

However, this one was called out by Werner Nachtigall on being a form of unnecessary copying from nature and neglecting the "function-concept". He claims that according to the Reynolds numbers of this wire dragging device, other shapes would have been more appropriate and that a simple pivot propeller would have made the drive more maneuverable than a tail fin-drive. "Only the position of the lateral- and depth-control behind, respectively in front of the mass center should be chosen in such a meaningful manner, as realized by a fish", he says [5].

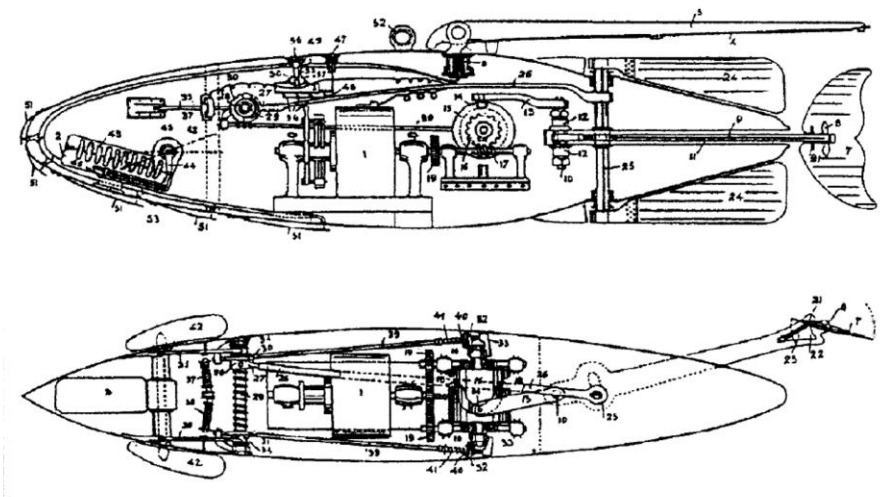


Figure 2: Cornelius Lie's pilot fish

2.1.3 Technical biology & bionics

"To practice 'technical biology' means to research and describe nature from the point of view, and with the methodical procedure, of technical physics and related fields", states Nachtigall [6].

He defines technical biology as the process of research, description and understanding of constructions of the living world through the introduction of physical and technical knowledge, while bionics is rather about learning from nature for technology [3].

He also considers them "antipodes" that "complement each other like images and mirror images", saying that bionics, on the one hand, cannot be practiced without prior investigation of natural conditions and basic research in the biological field, and that the results of technical biology, on the other hand, risk withering away if they were not picked up by bionics, processed, and offered to the technology for implementation [7].

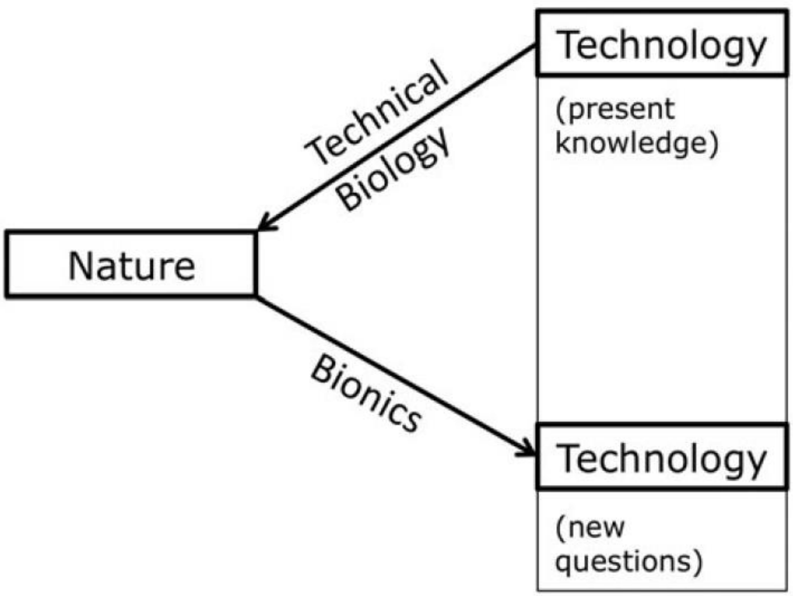


Figure 3: Diagram explaining the relationship between bionics and technical biology

2.1.4 Leonardo da Vinci’s wings

Inspired by birds

This duality was manifested in the early 16th century by Leonardo da Vinci – “founding father” of both these modern perspectives as referred to by Nachtigall [1] – when he studied the “swing wing” phenomenon (*Sul volo degli uccelli*, Florence 1505). He described how the wings of a large bird fold together under the effect of air pressure on tee, but spread apart on serve, which is a technical biology observation. Based on that, he tried to build flapping wings consisting of wicker branches and linen-soaked flaps (Fig.4). In other words, he transferred the biological model into flight technology, which represents a bionic approach [1].

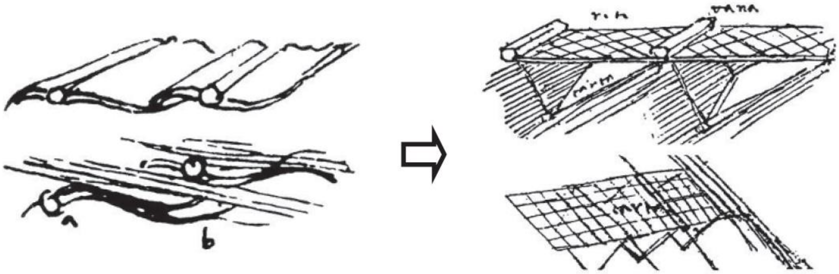


Figure 4: Leonardo da Vinci's wings

2.1.5 Castanet, Gasc & Renous’s adhesive film

Inspired by snakeskin

French researchers Castanet, Gasc, and Renous from the Musée d'Histoire Naturelle in Paris found that South American *Leimadophis* snakes have a special kind of abdominal scale structure that allows them to crawl on slippery ground because it provides little resistance when sliding forward, but simultaneously prevents sliding backwards. The result of the biological-technical investigation is that the abdominal scales act as direction-dependent friction generators [6].

Following this finding, an adhesive film analogous to the snakeskin was developed. Glued to cross-country skis, it drastically reduced the annoying backwards slipping, while not having any noticeable effect on the forward sliding [6].

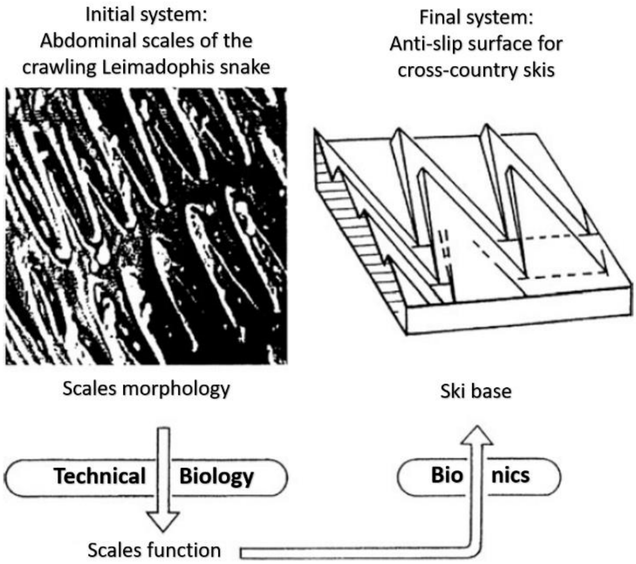


Figure 5: Functional morphology of the snakeskin and conception of a slip-preventive adhesive film for cross-country skis

2.1.6 Joseph Monier's reinforced concrete

Inspired by Opuntia

In the late 19th century (1867 according to [4], 1880 to [8]), French gardener Joseph Monier was so concerned about the price and fragility of stone and clay plant pots that he developed his own bionic solution to the problem. From the observation that cross-linked branching sclerenchyma structures of *Opuntia* (Fig.6) give rigidity to the leaf masses, he developed the idea of multi-component structured plant pots [4].

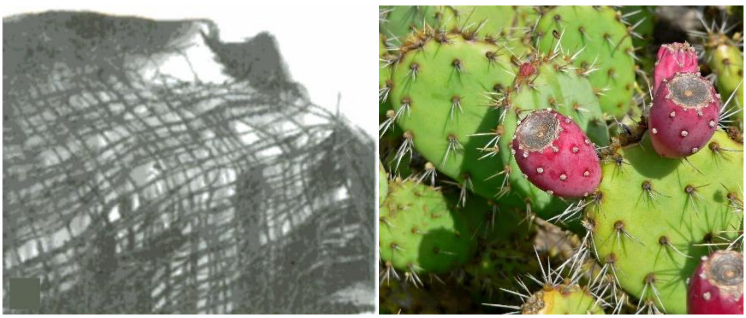


Figure 6: Sclerenchyma structure of Opuntia, known as the prickly pear

The parenchymal mass made of closely spaced, turgor-stabilized cells is pressure-resistant but relatively sensitive to traction. On the other hand, the structure of the sclerenchyma, with its often woody, elongated bundle-forming cells, is not stable against lateral pressure but is extremely tensile. The combination of materials ideally combines compressive with tensile strength. The pressure-resistant parenchymal mass keeps the tensile sclerenchyma network at a distance, behaving similarly to a poured hardening cement mesh and a wire skeleton, which in the case of a planter is the wire basket, and in that of a railway sleeper the correspondingly shaped wire winding (Fig.7). Thus, thresholds or buckets made of cement with wire matrix inserts show resistance against both compressive and tensile forces, which is the most important characteristic of reinforced concrete. [4]

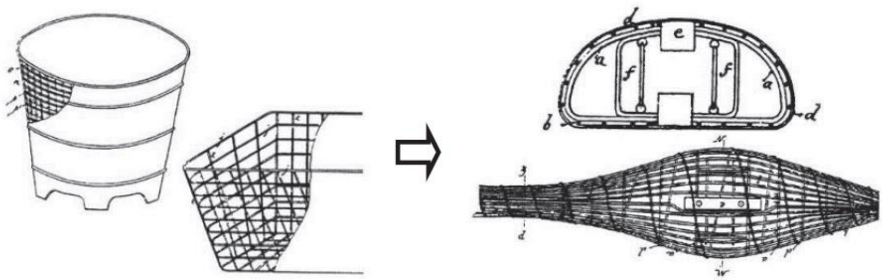


Figure 7: The wire skeleton of the wire basket and the railway sleeper

This example presents a very typical bionic transfer from biology to technology: a principle of nature is abstracted and used in developing a technical solution without slavish copying of forms [8].

- The natural principle:

  mechanical synergy of a tensile-resistant cylindrical network of sclerenchyma with a pressure-resistant parenchyma matrix.

- The technical principle:

  mechanical synergy of a sclerenchyma-analogous steel reinforcement with a parenchyma-analogous cement medium. [8]

The development of Monier's process known in germane countries (1880-1890) as Monierbau, was the basis of Matthias Koenen's theory of reinforced concrete. At the beginning of the 20th century, French engineers took this invention into account and proposed the first reinforced concrete code in 1906. [9]

2.2 History of the term "bionics"

The term "bionics" was coined in August 1958 by psychiatrist and Major (later Col.) of the U.S. Air Force's Aerospace Division Jack E. Steele, and was meant to be promoted as a new science. A research program, which was to receive the name "bionics" in the spring of 1959, was inaugurated at the Wright-Patterson Center of the U.S. Air Force. Bionics was under discussion for the first time at the 12th Annual Aeronautical Electronics Conference held in May 1960. Four papers on bionics were presented in that meeting, including one by Major Steele, and were later published in August 1960. However, the official launch of the new science took place in September 1960 at a congress in Dayton, Ohio, where 700 engineers, physicists, mathematicians, psychologists, psychiatrists, biologists, and biophysicists were invited; 30 of these participants spoke about bionics. [10]

Werner Nachtigall talked about the congress and Steele's speech and how the term "bionics" had been brought to life, saying that it was definitely not a result of combining the German words "Biologie" and "Technik" together and that it does not even apply in the English language [7], although "the view that 'BIONICS' is an artificial word, combined from 'biology' and 'technics' is unavoidable" [8].

Basically, it is the suffix "ic" - meaning "having the nature of" - added to the Greek word for life [10], which means "things related to living systems", as Nachtigall formulated [7].

According to him and to the conference's transcript, Steele talked about the dawn of a new era of scientific and technological development, as designed devices and systems started to look to the naive observer as if they were alive, and certain processes and techniques were bringing in functions that previously only existed in living systems [7]. This new concept and the methods used in developing such systems needed to be named. "We have given the name 'bionics' to the recognition and practice of these methods", Steele said [7]. He ended his speech on an optimistic note regarding the future of bionics, saying: "The manner in which bionics will mark its greatest contribution to technology is not through the solution of specific problems or the design of particular devices. Rather it is through the revolutionary impact of a whole new set of concepts, a fresh point of view" [7].

2.3 Definitions of bionics

Based on the origins of the term, “bionics” has been defined in many different ways throughout the years. One of its most general definitions is “the technical implementation of principles of nature” [11]. As plain as this definition seems to be, Nachtigall thinks it summarizes the methodical procedure of bionics, which he explains in the following sequence of three major steps [11]:

> A) Exploration of the living world: Recognition of structure-function relationships in certain types of animals and plants.
>
> B) Abstraction of general principles from the biological “original data” that resulted from A.
>
> C) Adequate, technically appropriate implementation of general principles according to B until implementation by the design engineer.

The importance of step B and the fact that bionics is not about copying nature as much as it is about transferring abstracted natural principles, will be emphasized in a following section of this chapter.

In the early seventies, Nachtigall defined bionics as “learning from nature for independent engineering design” [1]. He explains it saying “nature does not provide blueprints for technology”, which underlines that nature gives suggestions of all kinds that can be “incorporated into technical design”, while simply copying them would never lead to the goal [1].

In 1993, at a conference on “Analysis and Evaluation of Future Technologies” in Düsseldorf with the motto “Technology analysis bionics”, the Association of German Engineers (VDI) agreed on the following definition: “Bionics as a scientific discipline deals with the technical implementation and application of construction, process and development principles of biological systems” [1]. Bionics is therefore an application discipline, the subjects of which can be summarized in three basic disciplines: construction bionics, process bionics and development bionics (Fig.8). The “suchness” of biological systems presents the basis in the knowledge gaining process and for every transfer aspect [1].

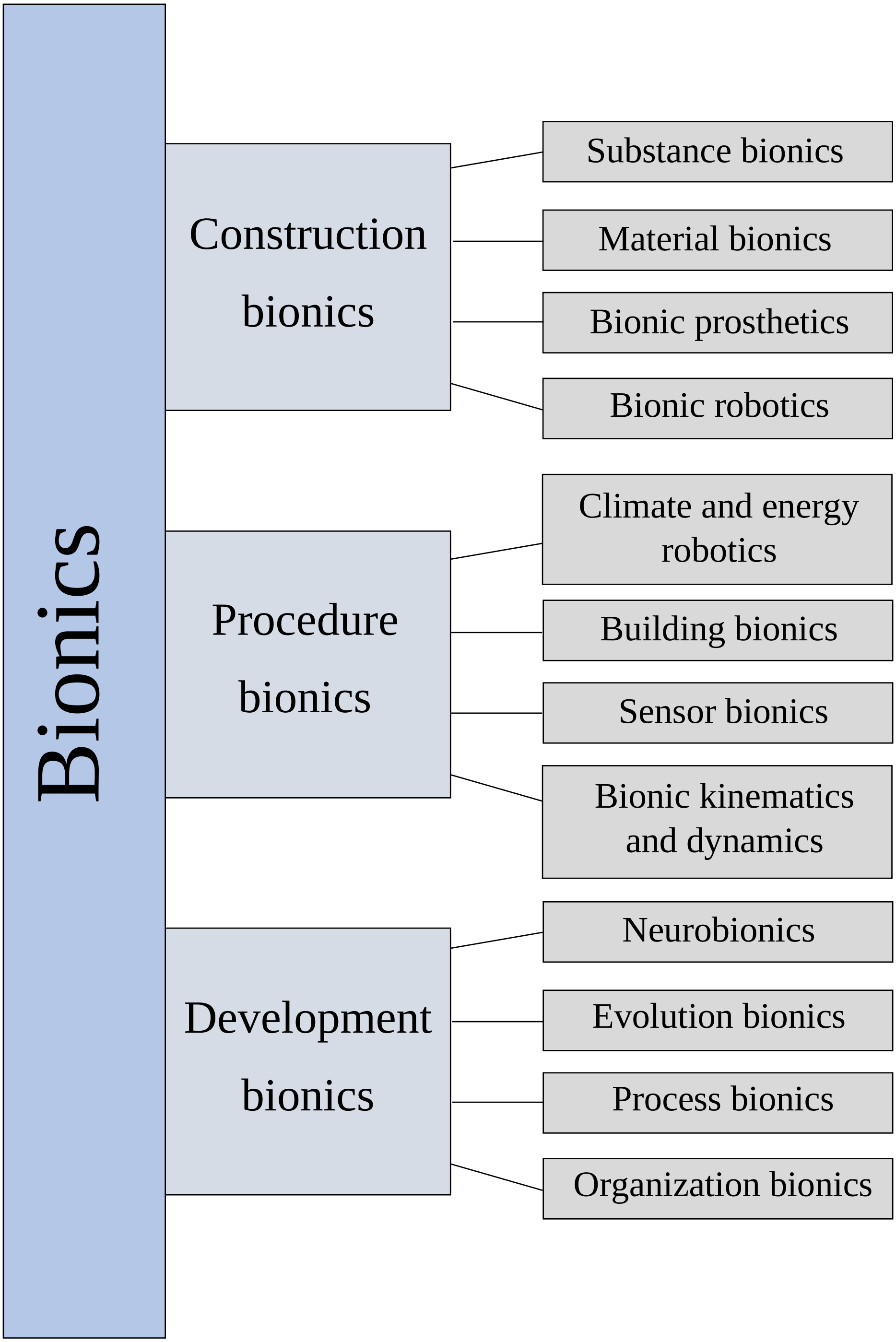


Figure 8: Aspects of bionics according to VDI's definition

- Construction bionics

Construction elements and mechanisms from the biological and technical world are analyzed and compared, and their interaction to form functioning structures is studied. Similarities can be found, for example, in insect saliva pumps, in vertebrate hearts, and in technical pumps. Nonetheless, the natural world has led to integrative constructions more than technology has, in which every single element often has to fulfill a multitude of tasks. Unconventional material peculiarities, such as locally different elasticities, also play a role here. The aspect of better integrative coordination of individual components for multipurpose tasks is particularly important with regard to technical constructions. [1]

Examples: The lotus effect (Fig.9), Mercedes-Benz "bionic car" (Fig.10)

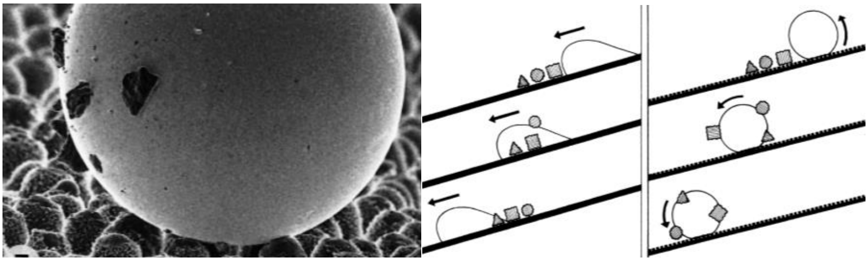


Figure 9: The Lotus effect

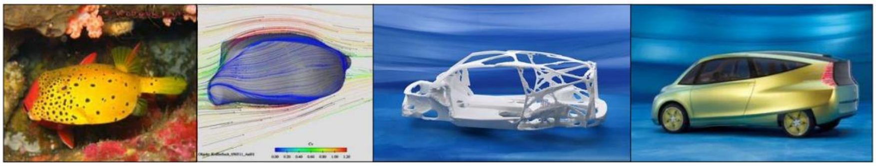


Figure 10: The Mercedes-Benz bionic car

- Procedure bionics

Not only natural constructions can be checked for their technical usability, but also methods that nature uses to control certain procedures. Photosynthesis, for instance, is one of the main models for future hydrogen technology and photovoltaics. Furthermore, aspects of ecological sales research and physiological-organismic regulation can be examined with great profit with regard to the management of complex industrial and economic enterprises. It is ultimately important to consider the natural methods of total recycling in every detail as models in packaging and waste management. [1]

Examples: Artificial photosynthesis, bionics in management.

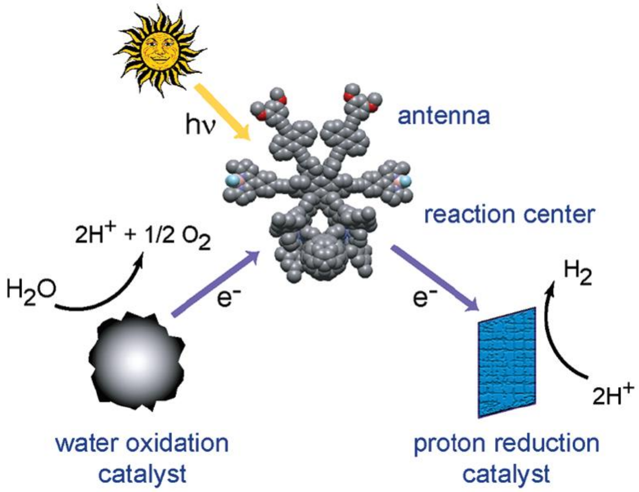


Figure 11: The artificial photosynthesis

- Development bionics

A central scheme for development bionics is the evolution strategy introduced by Ingo Rechenberg and his fellow researchers. The evolution strategy aims to make the methods of natural evolution usable for technology. In particular, if the mathematical formulation of complex systems or processes has not yet progressed so far that computational simulation would be possible, the experimental trial and error development remains an interesting alternative. [1]

Example: Optimization of a two-phase supersonic nozzle.

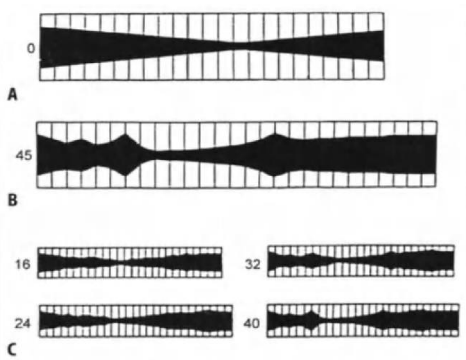


Figure 12: Evolution strategy considerations leading to the optimization of a two-phase supersonic nozzle (from the classic Venturi nozzle to the optimized final shape)

In 2002, as the latter definition seemed to be too restrictive and in order to make it future-adaptive, Nachtigall added: “This also includes aspects of interaction between animate and inanimate parts and systems, as well as economic-technical application of biological organizational criteria” [7]. He then restructured it into a shorter and broader definition of bionics: “Doing bionics means learning from the construction, process and development principles of nature for a more positive networking of people, the environment and technology” [7].

Another definition that allows bionics to take a broader sense and describes it more as an extensive discipline, is that of Jörn Hansen in 1999, where he says: “Bionics means decoding ‘inventions of living nature’ and their technical implementation” [11].

Hansen, who – based on Nachtigall’s bionics textbook – set the course for the Biomimetics Network of Excellence e.V. (BIOKON) founded in 2004 [12], belongs to those who believe that bionics is already practiced once “models” from nature are being examined with the intention of later implementation, while Nachtigall only uses the term bionics referring to the application of research and technical implementation of biological principles, as in step C mentioned above [11]. The first point of view makes “technical biology” part of bionics; the second one excludes it [11].

2.4 Other terminology

When it comes to imitating nature for the benefit of technology, bionics is not the only term used in academia and media. This section gives an overview of the other common terms that refer to a similar meaning as bionics, and in some cases are considered synonyms. All of them are used in multiple contexts throughout this thesis based on their common use in the literature corresponding to each passage.

2.4.1 Biomimetics

In 1957, Otto H. Schmitt, who attempted to develop a physical device that mimics the electrical action of a nerve as part of his doctoral research, perceived what he later labeled “biomimetics” as a “disregarded – but highly significant – converse of the standard view of biophysics” [13]. He first put the term biomimetics into practice in the title of a paper he published in 1969 [13]. According to Bar-Cohen, the term was derived from “bios” and "mimesis", meaning "life" and "to imitate" respectively [14], and according to Bhushan, it was derived from the Greek word "biomimesis" [15]. Biomimetics first appeared in Webster's Dictionary in 1974, with the following definition: "The study of the formation, structure, or function of biologically produced substances and materials (as enzymes or silk) and biological mechanisms and processes (as protein synthesis or photosynthesis) especially for the purpose of synthesizing similar products by artificial mechanisms which mimic natural ones" [13]. Pohl and Nachtigall define biomimetics as "the understanding of biological structures and procedures and their comparable technological applications, methods, or procedures" [8]. They also chose to use it as a term because it was more recent than bionics [8].

2.4.2 Biomimicry

Biomimicry, defined by Michael Pawlyn as the design inspired by the way functional challenges have been solved in biology [16], was introduced in 1962 as a generic term that involves cybernetics and bionics, and refers to "all sorts of imitation of one form of life by another" [17]. The term was commonly used by materials scientists, as seen in Connie Lange Merrill's dissertation in 1982 [18], before getting popularized among others by Julian Vincent, who defines it as "the implementation of good design based on nature", and Janine Benyus, who describes it as "the conscious emulation of nature's genius" [16]. Benyus was also known for writing "Biomimicry: Innovation inspired by nature" in 1997, co-founding the world's first bio-inspired consultancy called "Biomimicry 3.8" in 1998, co-founding the Biomimicry Institute in Montana, USA in 2006, and starring in a documentary film about biomimicry by Leonardo DiCaprio in 2015. She defines biomimicry as "a new science that studies nature's models and then imitates or takes inspiration from these designs and processes to solve human problems" [19].

According to Maibritt Pedersen Zari, biomimicry can be applied on three different levels with five possible dimensions, as summarized in a framework she proposed, in which she exemplifies the analogies on each level and dimension by the mimicry hypothesis of termites in building design (Fig.13) [20].

Level of Biomimicry		Example - A building that mimics termites:
Organism level (Mimicry of a specific organism)	*form*	The building looks like a termite.
	material	The building is made from the same material as a termite; a material that mimics termite exoskeleton / skin for example.
	construction	The building is made in the same way as a termite; it goes through various growth cycles for example.
	process	The building works in the same way as an individual termite; it produces hydrogen efficiently through meta-genomics for example.
	function	The building functions like a termite in a larger context; it recycles cellulose waste and creates soil for example.
Behaviour level (Mimicry of how an organism behaves or relates to its larger context)	*form*	The building looks like it was made by a termite; a replica of a termite mound for example.
	material	The building is made from the same materials that a termite builds with; using digested fine soil as the primary material for example.
	construction	The building is made in the same way that a termite would build in; piling earth in certain places at certain times for example.
	process	The building works in the same way as a termite mound would; by careful orientation, shape, materials selection and natural ventilation for example, or it mimics how termites work together.
	function	The building functions in the same way that it would if made by termites; internal conditions are regulated to be optimal and thermally stable for example (fig. 6). It may also function in the same way that a termite mound does in a larger context.
Ecosystem level (Mimicry of an ecosystem)	*form*	The building looks like an ecosystem (a termite would live in).
	material	The building is made from the same kind of materials that (a termite) ecosystem is made of; it uses naturally occurring common compounds, and water as the primary chemical medium for example.
	construction	The building is assembled in the same way as a (termite) ecosystem; principles of succession and increasing complexity over time are used for example.
	process	The building works in the same way as a (termite) ecosystem; it captures and converts energy from the sun, and stores water for example.
	function	The building is able to function in the same way that a (termite) ecosystem would and forms part of a complex system by utilising the relationships between processes; it is able to participate in the hydrological, carbon, nitrogen cycles etc in a similar way to an ecosystem for example.

Figure 13: The three levels of biomimicry according to Zari

Although biomimicry seems to have the same meaning as bionics and biomimetics, some nuances between these terms are highlighted in literature. Pawlyn, for instance, despite using both words as synonyms, mentioned the presence of a single significant difference between biomimetics and biomimicry, stating that “many users of the latter intend it to be specifically focused on developing sustainable solutions, whereas the former is often applied to fields of endeavor such as military technology” [16]. Wahl also tends to link biomimicry to “ecologically informed design for sustainability” while describing bionics as more technologically oriented [21].

2.4.3 Bio-inspired

Farzaneh and Lindemann define biologically inspired, or bio-inspired, design as “the application of knowledge of biological systems in research and development for technical inventions and innovations” [22]. Helms et al. state that it “uses analogies to biological systems to develop solutions for engineering problems" [22]. It is commonly considered a synonym as well, however, according to Pawlyn, it may be overly broad as a term. He believes that "both biomimicry and biomimetics imply copying, whereas 'bio-inspired' is intended to include the potential for developing something beyond what exists in biology" [16]. As an architect, Pawlyn prefers adopting the term biomimicry because "bio-inspired architecture suggests a very broad definition – including everything from superficial mimicking of form all the way through to a scientific understanding of function and how that can inspire innovation", especially after the emersion of the term "Biodesign" in the medical and robotics world [16]. As explanatory as the term is, it is necessary to consider the context in which it is used to determine whether the inspiration corresponds to a bionic design process that includes the abstraction of biological principles and their technical implementation, or if it falls into the category of biomorphic architecture as explained later in section 2.6.

2.5 Principles and methodologies of bionics

Like any other scientific discipline, bionics went through a development process where biologists, engineers and researchers contributed in finding ways to protect its purpose and define its boundaries from many different angles and standpoints (i.e. structural, energetic, environmental, purely technological, etc.), in order to facilitate its practice in the future. This was accomplished either by suggesting a hand full of principles and requirements, by explaining specific aspects covered by bionics, or by discovering new practical methods and procedures that can help deliver a biologically inspired product. This section displays some of the most popular approaches and methodologies relied on by practitioners of bionics, as well as certain principles and aspects discussed in literature, that sometimes relate more to the environmental impact of bionics than the technological side of it.

2.5.1 Analogy research

As superficial as they might be, it is essential to consider every similarity or resemblance between biological and potential technical systems in order to find adequate analogies and transferable laws and mechanisms that can provide solutions to a technical problem. This "analogy research" is in fact a process that biologist Johann G. Helmcke termed in 1972 and is still purposefully used until today [3] as a way of seeking inspiration in bionic design and developing ideas that may or may not be valuable in a certain project.

The example of the wheat stem and the television tower has often been used in literature to emphasize the unexpected benefits of such comparisons, as it exhibits many structural-functional cross relationships, both in longitudinal (Fig.14) and cross-sections (Fig.15). From a structural point of view, the formation, structural support, and embedding of stiffening tension elements on the edge of the straw are particularly interesting. Three types of reinforcement are present in one system as shown in the cross section [7].

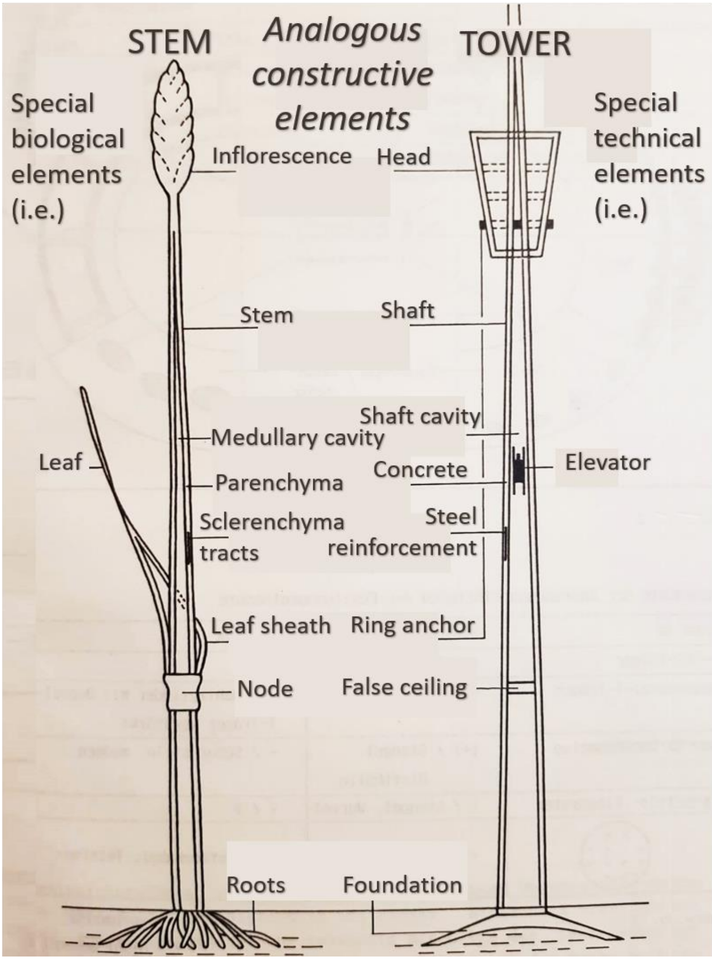


Figure 14: The analogy of the wheat stem and the television tower (longitudinal section)

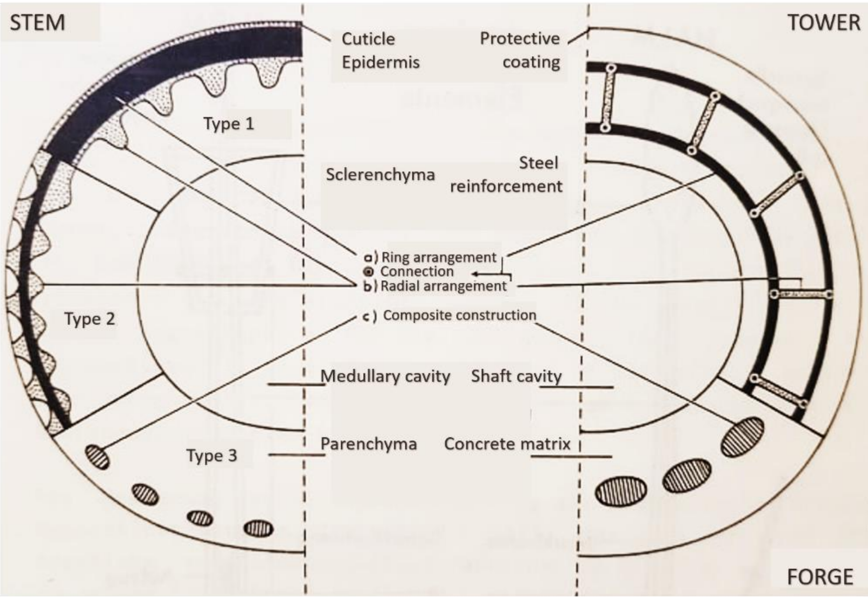


Figure 15: The analogy of the wheat stem and the television tower (cross-section)

Before going through a "catalog of requirements" developing into a new product, a technical system starts with a certain current state. A biological system evidently has a current state as well, recognized and described at the time of investigation. Nachtigall says: "Analogy research consists of the comparison of these two current states, that of the technical and that of the biological comparative example" [1].

A comparison can take place on two levels [11]:

- Comparing forms, where the biological and technical systems are screened for similarities and differences in shape [11], which for bionic work, in a narrower sense, could be secondary [1]
- Comparing functions, which mostly concerns the requirements catalog for the product's development on the technical side, and the description catalog of the system's current state on the biological side

These comparisons and the resulting cross relationships lead to a bionically shaped or inspired "technical" product. According to Nachtigall, there is no such thing as a "bionic product" [11].

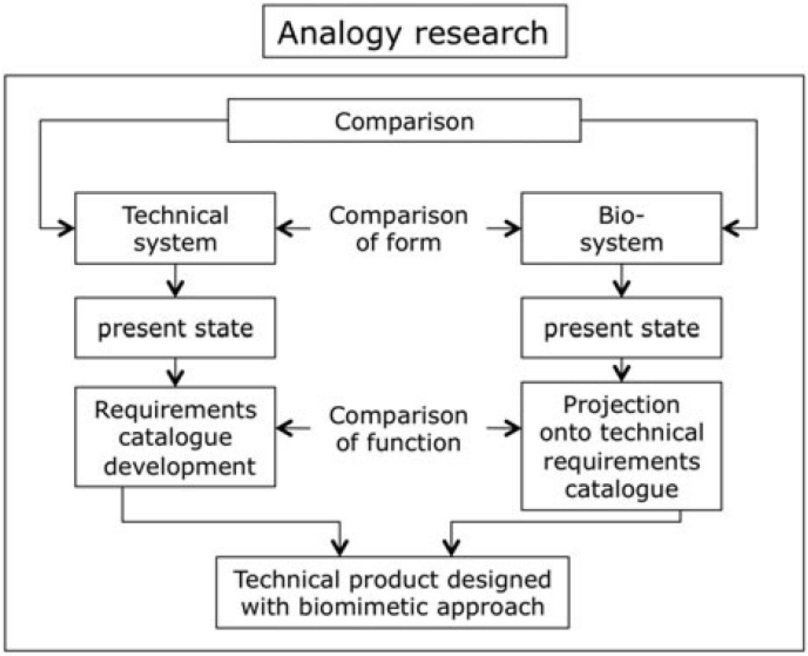


Figure 16: The concept of analogy research according to Nachtigall

2.5.2 VDI's perspective of bionics

The challenging part in bionics lays in its interdisciplinarity and the need for organized collaboration between biologists, engineers, and scientists from different industries. Several approaches have been made in this matter to abstract and define a certain range of steps and procedures, including a number of principles, that are exemplified in literature through diagrams in different formats and put bionics in different positions based on their individual perceptions. The following scheme (Fig.17) presents the VDI association's understanding of bionics throughout the whole product development process, based on the concepts they proposed at the 1993 conference mentioned in 2.3. Bionics is conceived as the link between biology and technology, while all three of these disciplines are stimulated by classical sciences, especially physics, chemistry, and engineering. It also simplifies the entire technical procedure into four steps: analysis, evaluation, implementation, and application. At the interface between evaluation and implementation comes the introduction of "suggestions from nature" via "the medium of bionics". [11]

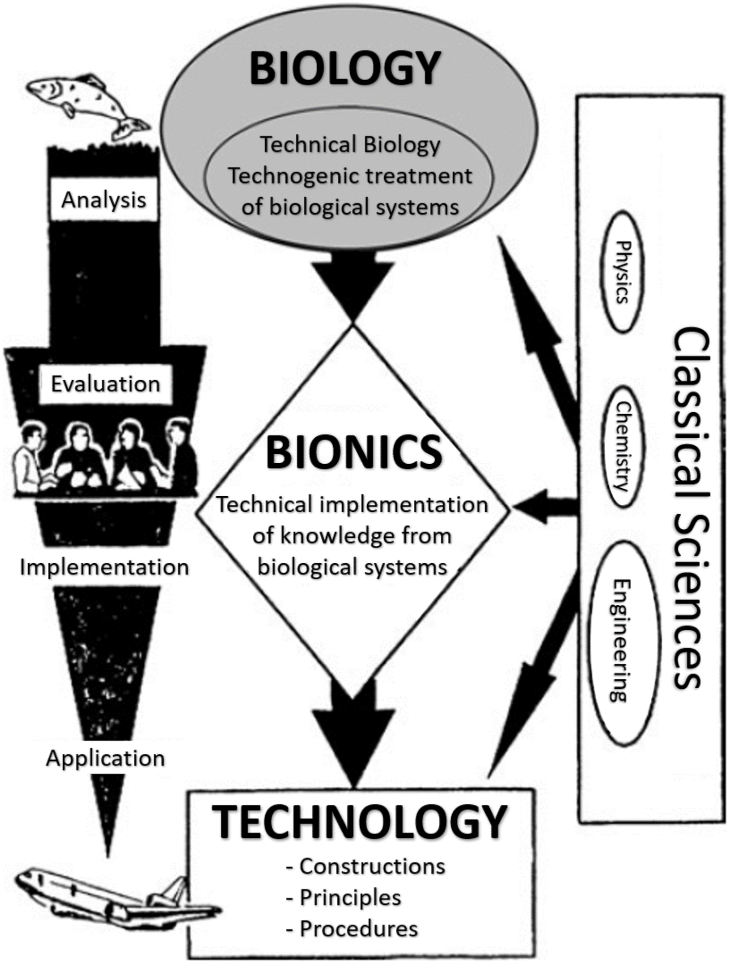


Figure 17: Integration of bionics between biology and technology according to the perspective of VDI

2.5.3 Three-step-way

Nachtigall described this role played by bionics as "basically a mediating method", when explaining the main steps previously mentioned in 2.3 and summarized as follows [1]:

- Analysis of natural systems
- Abstraction of discovered fundamental principles
- Transfer of these principles in a technically appropriate way

He refers to it as the “three-step-way” [5]. Each of these steps is defined and illustrated below with the example of an adhesive tape, designed to stick on irregularly curved watery or oily surfaces without compromising the possibility to apply substances on them, like pharmaceuticals [1].

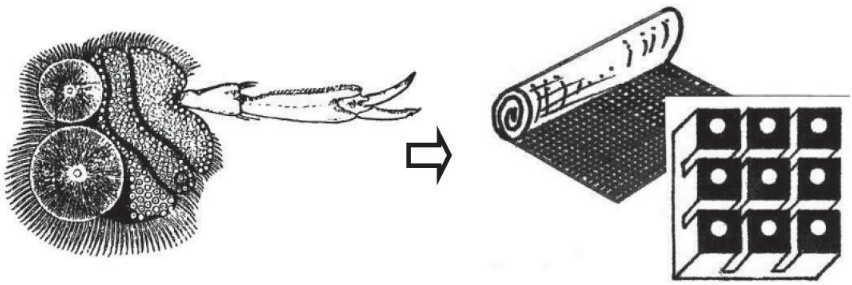


Figure 18: Adhesion tape from the front-tarsi of water bugs

- Analysis:

Exploring nature and recognizing structure-function relationships in certain types of animals and plants or their organs [1].

A detailed literature review on existing adhesive biological components and systems led to the observation that adhesive surfaces of the diving beetles’ front legs (Fig.19) consist of a multitude of elements that stand in series and work according to the suction cup principle in one genus, more to the wet adhesion principle in another, and leave gaps between each other, which qualifies them to be particularly transferable and adequate to the engineer’s needs.

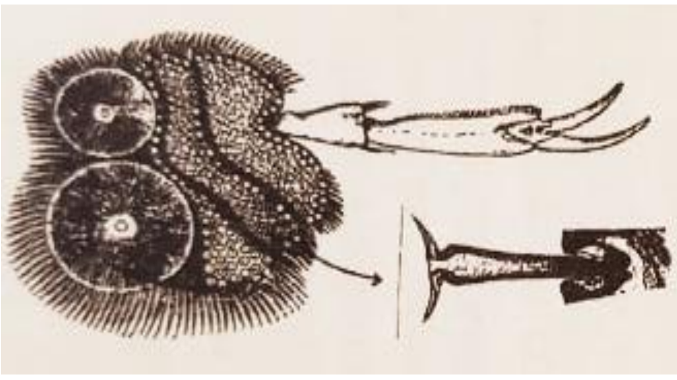


Figure 19: The diving beetles’ front legs

- Abstraction:

Abstracting general principles from the original biological data that resulted from the first step [1].

The following principles were derived from the water bugs example:

- The principle of digitization: adhesive surfaces are composed of single elements that operate individually.
- The principle of serial arrangement: the elements stand in rows.
- The principle of multifunctionality: the elements leave space between each other so that mucus or putty substances can be stored, which occurs parallel to their main function of adhesion.
- The principle of statistical adhesion: only a certain number of elements cling, which is enough for the leg's adhesion, but it cannot be predicted exactly which elements are clinging.

Thus, the resulting reduction of these principles:

"Dissolution of an adhesive surface in digitized, serially arranged, multifunctional, and statistically adhering elements".

- Transfer:

Implementation of the general principles according to the second step by the design engineer in an adequate and technically appropriate way [1].

The development engineer's task at this stage is to apply the abstracted principles to design an adequate product on both technical and economic levels. For this example, the analogous elements could be stamped into a plastic band, brought out by cross cuts, drawn deep, and superficially modified by heat treatment so their shape and the cracks between them can fulfil the intended function (Fig.20).

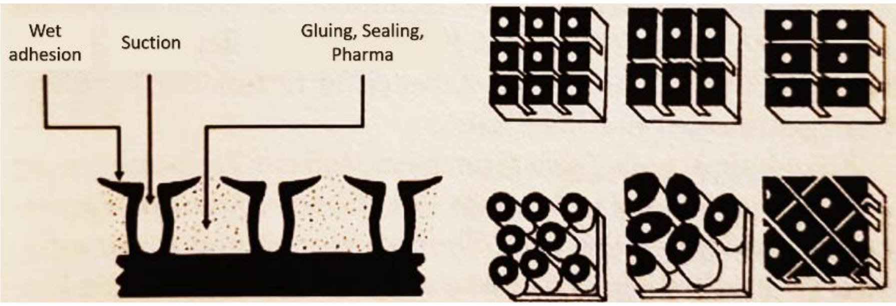


Figure 20: Suggestions for the technical implementation of the abstracted principle

2.5.4 Catalog method

Another approach that allows bionics to be more of a demand from technology on biology than an offer from biology to technology is B. Hill's catalog method. He developed a strategy model for target determination and solution finding that is represented in Fig.21 as a process chain with multiple levels. This approach relies on "orientation models" that serve the systematization of biological structures and are manifested in "catalog sheets" as shown in Fig.22. Material, energy, and information are this method's three reference levels for the biological basic functions, on which the catalog sheets are classified [1]. Hill states: "With these catalogs, users from all technical fields have a rich arsenal of analogous solutions for constructive problems. They are a strategic and solution-generating aid for the designer" [1].

1. Goal determination **Steps / methodological aids**	**2. Finding a solution** **Steps / methodological aids**
1.1 Investigation of the market and demand situation (determine special observation area) / W-question method 1.2 Carrying out a system analysis / functional analysis, structural analysis 1.3 Recording the state of the art / development status table 1.4 Carrying out a generation analysis / generation table 1.5 Determination of the evolution status / evolution status table 1.6 Determination of effectiveness factors / effectiveness equation 1.7 Establishment of the requirement matrix and selection of relevant contradictions 1.8 Description of the paradoxical requirement	2.1 Determination of the basic functions / orientation model of biological basic functions on which the contradicting requirements are based 2.2 Detection of relevant biological structures with the same or similar functional characteristics / catalog sheets 2.3 Compilation of relevant structures in a table and derivation of first solutions (principle solutions) / table of biological structure representations 2.4 Transfer of the determined solution approaches into a technical solution according to the requirements, conditions (economic, technical-technological, ecological, social...) 2.4.1 Varying and / or combining relevant characteristics / variation and / or combination method 2.4.2 Evaluation of solution elements or technical variants / evaluation methods 2.5 Elaboration of the technical solution
Development task **with an inventive goal**	**Technical Solution**

Figure 21: Hill's strategy model for biologically oriented development processes

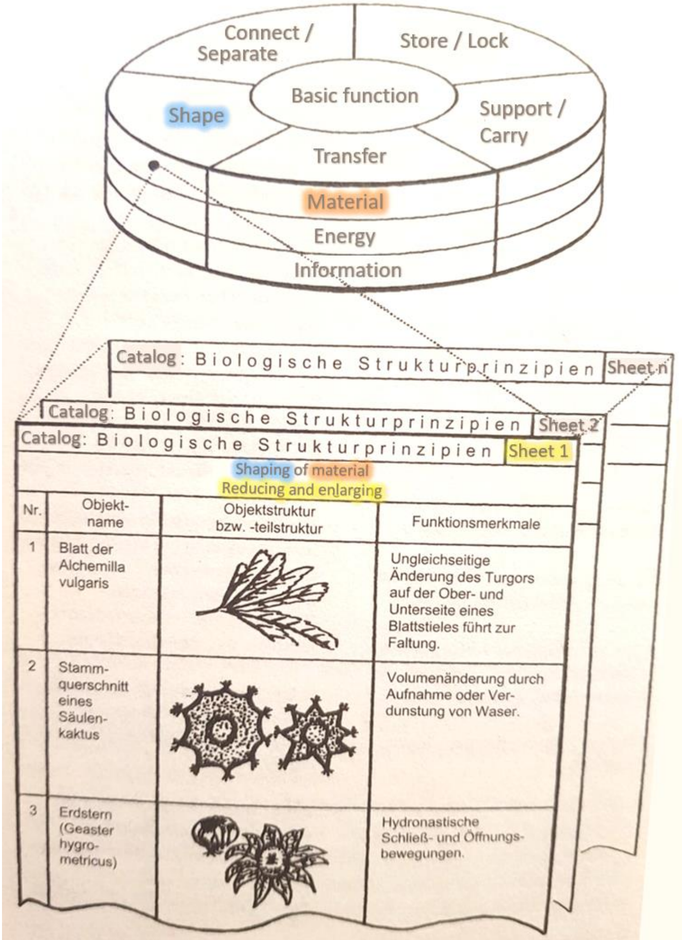


Figure 22: Orientation model with catalog sheets of basic biological functions

2.5.5 Technology pull – Biology push

The question that motivated Hill's approach, whether a bionic project is based on a technical need or a biological offer, is in fact one of the most classic starting points when it comes to developing bio-inspired design methods. Two distinct and frequently referenced types of approaches that respond to this question and classify a wide range of design methods are known as the inverse "technology pull" – also called top-down or problem driven – and "biology push" – also called bottom-up or solution driven – procedures [22].

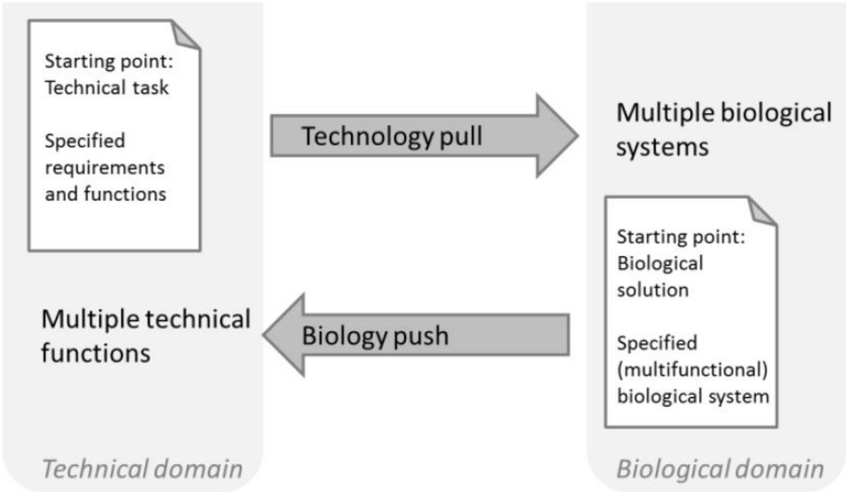


Figure 23: Technology pull - Biology push

Technology pull approaches necessitate a specific technical task to start with and lead to a biological inspiration (Fig.23). Throughout this type of procedure, the original technical problem sets boundary conditions for designers and forces them to consider a predefined set of requirements and functions. In turn, they are free to look into different biological systems and have the possibility to transfer multiple analogies that help develop the product. To visualize this, a five-stage technology pull procedure proposed by Lenau et al. is demonstrated in Fig.24. The analogous stages of three other similar approaches are provided in the overview in Fig.25. [22]

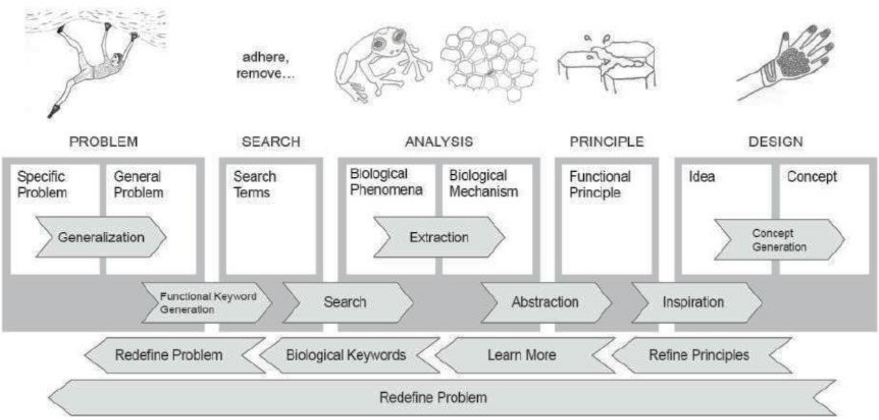


Figure 24: Technology pull procedure by Lenau et al.

Technology pull procedure (Lenau et al. 2010)	**SQUAT (Rummel 2014)**	**Design Spiral (The Biomimicry 3.8 Institute 2016)**	**Problem-driven process (Helms et al. 2009)**
Problem definition phase	Problem identification	Identify function	Problem identification
	Problem restructuring	Define context	Reframe the problem
Search phase	Scanning nature	Biologize challenge	Biological solution search
Analysis phase	Principle analysis	Discover natural models	Define the biological solution
Principle phase	Principle transfer	Abstract design principles	Principle extraction
Design phase	Modelling of technical solution	Emulate nature's strategies	Principle application
		Evaluate against life's principles	

Figure 25: Overview of technology pull approaches

Biology push approaches, on the other hand, originate from a biological phenomenon that presents a potential solution to several technical problems. The system is analyzed in detail by the designers in order to be applied later to a technical product (Fig.23). This method may restrict the analysis to one system in particular, but it often results in more than one technical application, especially with multifunctional biological systems, which can lead to multifunctional technical systems. Helms et al. intended to describe the observed working processes in bio-inspired design in general, yet their interpretation of these can still be viewed as a guideline for planning a biology push procedure according to Farzaneh and Lindemann (Fig.26). A tabled overview is also provided to compare it with other researchers' approaches, such as Nachtigall's "three-stage procedure" and the Biomimicry 3.8 Institute's "design spiral" (Fig.27). [22]

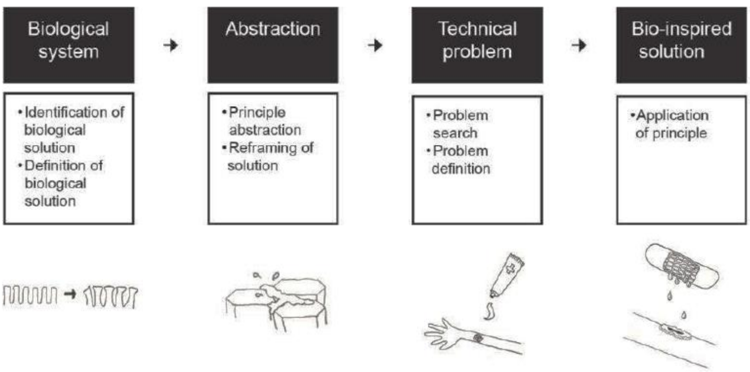


Figure 26: Biology push procedure by Helms et al.

General phases of biology push procedures	Solution-Driven Procedure (Helms et al. 2009)	Design Spiral (The Biomimicry 3.8 Institute 2016)	Three-Stages Procedure (Nachtigall 2010)
Biological system analysis	Solution identification	Discover natural models	Biological basis: research, describe, evaluate
	Define biological solution		
Abstraction	Principle extraction	Abstract design principles	Abstraction of biological findings: formulation of general principles
	Reframe solution		
Technical system analysis	Problem search	Brainstorm potential applications	-
	Problem definition		
Bio-inspired solution development	Principle application	Emulate nature's strategies	Technical application: conceptual strategy, comparison of principles, procedure
		Evaluate against life's principles	

Figure 27: Overview of biology push approaches

Based on material from a Biologically Inspired Design (BID) course offered at Georgia Institute of Technology to engineering, biology, and biomedical engineering majors, Yoseph Bar-Cohen presents a scheme that summarizes both problem driven and solution driven procedures or processes. He explains their respective abstracted steps, exemplifies them with two different case studies, and adds a note to each step of the procedure to highlight the important details about them throughout the different stages. The first case study was the design process of a lightweight bulletproof vest, where a multitude of biological inspirations contributed to the solution. The second one was the development of an underwater spy-bot based on the observation of how an aquatic microcrustacean approaches a pray stealthily and with minimal water disturbance, due to a specific kind of leg motion [23]. The steps used in these "pseudo-algorithms" correspond to the procedures proposed by Helms et al. in [24] and found above in the overview tables, knowing that Michael Helms is a Co-Director at the Center for Biologically Inspired Design (CBID) at Georgia Institute of Technology where the course was offered [25].

Problem Driven BID Process

Problem definition	Define a human problem in terms of required function(s) and constraints.	"Design a light-weight, bullet proofvest"	Don't be too vague, or overly specific.
Reframe problem	"Biologize" the problem by reframing the human problem in biological terms	How do animals withstand high impact forces in nature?"	Abstract over the human problem, don't just repeat it.
Biological solution search	Apply search strategies in the biological world to find sources that solve the "biologized" problem.	Abalone Shell, Ram Horns Rhino Horns, Lobster Shell, etc...	Make certain the source is actually solving the problem you want addressed; look at MANY sources.
Solution understanding	Understand how the biological source solves the "biologized" problem.	Abalone shell uses elastic protein/calcium interleaving to reduce crack propagation.	Focus on the behaviors and functions of the structure; pay attention to constraints.
Principle abstraction	Identify solution-neutral behaviors and principles used by the biological source.	Interleaving of rigid and elastic substances.	Try to eliminate specific structural reference altogether. Does this remove constraints?
Trial design	Apply the behaviors and principles to solve the original human problem.	"Sliding plate" vest.	Don't forget your original constraints.

Solution Driven BID Process

Solution identification	Identify a biological source that has solved a challenging problem.	"WOW. look at how that cop ep od sneaks up on its prey!"	Pick a specific function of the organism.
Solution understanding	Understand how the biological source solves the "biologized" problem.	The cop ep od uses a very specific kind of leg motion that doesn't create wake.	Focus on behaviors, look for behaviors that accomplish more than one function. Define constraints.
Principle abstraction	Identify solution-neutral behaviors and principles used by the biological source.	Synchronized motion to reduce disturbing the surroundings.	Try to eliminate specific structural reference altogether. Does this remove constraints?
Reframe solution	"Humanize" the solution in terms relevant to meeting human goals.	"How do humans move through their environment without disturbing it?"	Abstract the solution into a high-level question.
Problem search & definition	Find salient human problems that match the "Humanized" solution, select one, and define constraints.	Scientific observers want to observe without interfering with natural processes.	Look at more than one candidate problem.
Trial design	Apply the principles to solve the "humanized" problem.	Underwater spy-bot.	Don't forget your original constraints.

Figure 28: Problem-driven and solution-driven bioinspired design processes

2.5.6 Nachtigall's ten commandments

Doing bionics comes with a certain consciousness and deep enough understanding of its main purpose, which is applying nature's principles to technology for technological advances. In order to accomplish that, one has to acknowledge the findings about nature that distinguish it from other sources of inspiration, and in some cases, even contradict common rules in technical design.

Nachtigall compiled a list of ten commandments, or principles in nature, that he considers essential to recognize so the outcome of an analogy research would fit in the process and meet the prerequisites of a bionic project. He states that these principles form the basis of a catalog of requirements for bionic design, which aims to use the advantages of evolving nature [26]. Translated to English by D.C. Wahl [21], they are all listed below; a selected four that are most relevant to this research are subsequently assessed.

1. Integrated instead of additive construction
2. Optimization of the whole, rather than maximization of individual elements
3. Multifunctionality instead of monofunctionality
4. Fine-tuning adapted to particular environments
5. Energy saving instead of energy squandering
6. Direct and indirect use of solar energy
7. Temporal limitation instead of unnecessary durability
8. Total recycling instead of waste accumulation
9. Networks instead of linearity
10. Development through the process of trial and error

Nachtigall believes, as he explains the first principle, that while technology assembles constructions from individual elements and optimizes them for themselves, nature works almost entirely with integrated constructions. This means while systems consist of individual elements, these are often neither morphologically nor functionally distinguishable from their neighboring elements [11]. The bug's saliva pump shown in Fig.29 is a perfect example to clarify this detail. Although it is only 2/10 mm in size, just like a classic technical pump, it contains certain construction elements namely cylinders, pistons, seals, valves, and a drive. As shown in the figure, all of these elements exist, but are completely integrated, or interconnected. It is impossible to see where the piston passes into the seal or the seal into the cylinder, but they all contribute as a unit to the main function of the pump with their respective functions [6].

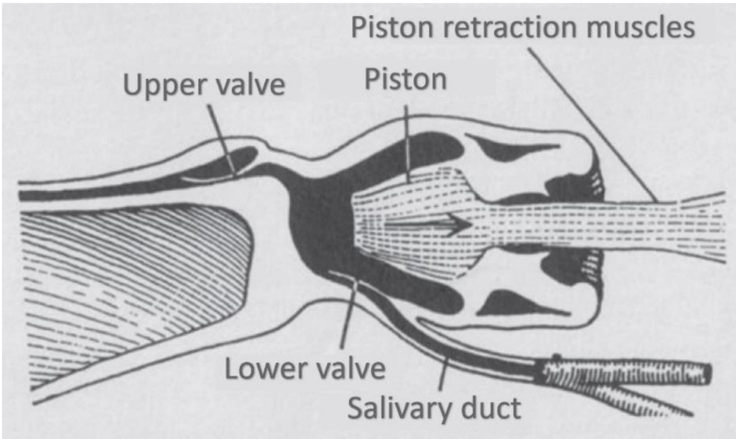


Figure 29: Saliva pump of a bark bug

The third principle highlights the multifunctionality aspect present in the pump's elements, as well as in the example of the adhesive tape inspired by beetles previously mentioned in 2.5.3. In technology, elements are often developed to fulfil individual tasks, while in nature, there is almost never a single-task element. Natural systems are usually designed to perform a multitude of functions and adapt to very different, sometimes physically opposite, requirements [11].

Nature also tends to optimize systems as a whole instead of maximizing individual elements avoiding complicated possibly disruptive inter-element relationships, which represents the second principle [11]. This relates indirectly to the ninth principle, where Nachtigall claims that nature's enormous potential of self-organization and "statistical" mode of operation make everything meshed and networked together, leading to relatively stable systems [26].

Some common inquiries about bionics, however, include whether nature really "optimizes" structures of biological systems, and further, whether "copying nature" is appropriate as a term and a process when it comes to biologically inspired solutions to engineering problems, an issue that is particularly common in architecture and bionic design of buildings.

2.6 Copying nature

"Copying is the wrong term. Obviously, the bionic method cannot lead to copies of natural systems, neither in form nor function, but it helps understand nature's way of construction and development, and adopt certain parts as the basis for similar models in the course of technical design development", states Nachtigall [7].

He also thinks that architectural bionics risks getting lost in similarities in shape as in "biomorphic buildings", while it is mainly the function that counts. According to him, natural forms are always functional, but only with reference to their respective tasks. American architect Friedrich Kiesler, for example, designed a theater in the 1960's that had a stage construction formed like a human intestine and an auditorium like a stomach. Since none of the intestine's functions such as transport or absorption are manifested or analogized in this building, it is by no means considered bionic design. In other words, unless the form is functionally embossed, architecture designed after organic matter does not have anything to do with bionics. As a matter of fact, real bionic transfers are often inconspicuous. [4]

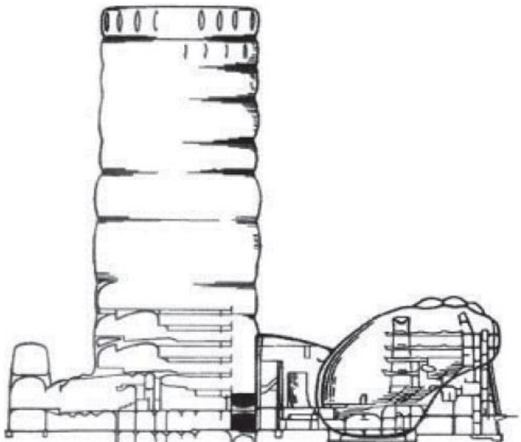


Figure 30: Theater designed by Friedrich Kiesler

Nachtigall clarifies the meaning of this statement through two simple contrasting examples. The first one is the Sony Dog developed in the shape of a real dog (Fig.31). It imitates its movement and behavior, but does not demonstrate any abstraction of principles or technical implementations based on biological knowledge, thus, it is not bionic. In fact, a walking machine that mimics the static, dynamic, and cybernetic properties of a dog running, even without the appearance of a dog, would be more eligible to be considered a bionic construction. The second example of Frei Otto's branched support columns in the former Stuttgart Institute for light shell structures emphasizes just that (Fig.31). Their ability to absorb large surface loads despite their thin structure is due to the implementation of principles abstracted from the model of trees, including the branching angles, the succession of "branch generations", and the laws according to which the branches are thinning. It is the biologically inspired, abstracted, and technically applied principles that solved the technical problem of finding the lowest possible mass to the columns for the given boundary conditions, which is practically the definition of a bionic approach. [1]

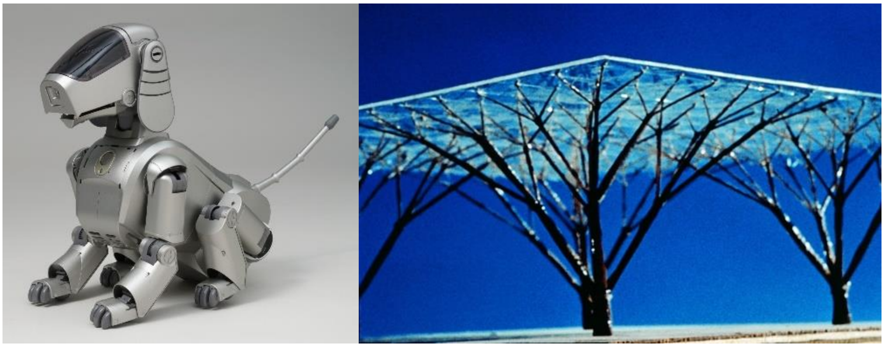


Figure 31: The Sony Dog and a model of Frei Otto's tree structures in an exhibition at Yale University, USA, 1960

With that being said, it is now clear why Nachtigall, when referring to Matthew Baker's galleons (2.1.1), said it would have been pointless to construct the underwater hull exactly according to the coordinates of a cod [1]. It is rather about the abstraction of fish adaptations as phenomena. He believes that "direct nature copying would only be misleading" [1].

2.7 Optimization

"A biological form always represents an optimized compromise response to different functional requirements" [27]. At first sight, this statement and many similar phrases that mention optimization in biology may project a certain deviation from the original meaning. But as Blüchel and Malik explain further, it turns out that the key word in that sentence was "compromise". The principle is certainly finding the best and most suitable solution for a functional system. However, biological systems, as emphasized in 2.5.6, tend to prioritize the optimization of the whole over the maximization of individual elements. This means that nature only offers a "functionally-optimized" [27] solution that still obeys certain biological restrictions, which may not exist in technical systems.

German architect and structural engineer Frei Otto – who designed the roof of Munich's Olympic Stadium in 1972 inspired by spider webs and diatoms – thinks it is only fair not to call natural systems totally "optimal" considering nature's limitation to only a few processes, like cell division, and materials, despite their abundance and variety [28]. For instance, there are no high-strength metals or extremely solid carbon fibers in living nature. Although technical constructions have been much more primitive than biological ones so far, they are not restricted to a few materials such as proteins, cellulose, lignin, lime, and silica. Technology uses effective components like wheels, screws, and internal combustion engines that are not featured in biology. All building materials, self-developed or those of living and non-living nature, can be employed [28]. Therefore, as Frei Otto elucidates, "only with caution and restraint can we say that living objects are structurally 'optimal'. They are undoubtedly highly developed in general, but with inherently insurmountable limitations. Nevertheless, depending on their origin, they can be described as 'relatively' optimal" [28].

Nachtigall also expressed his dissatisfaction with the "uncritical" use of the term "optimization" [1]. He justified his position by comparing the technical and biological meanings of optimization through numerous case studies [7]. He started by explaining the process as it occurs in the business and technological fields. Usually there is a problem that has to be translated into a mathematical formula, in order to define a specific parameter that determines whether the observed system, for a certain set of boundary conditions, is optimized. In the most common case of linear optimization, this can be represented by a function Z, the variables of which are x_i, the quantities to optimize, weighted by constant factors c_i that are determined according to the optimization criteria. The problem is considered solved and the optimal value is reached when the so-called objective function Z yields a maximum or a minimum, depending on the needed results [7].

$$Z = c_1x_1 + c_2x_2 + \cdots c_nx_n = \sum c_ix_i$$

In the numerical modeling of the bar structure displayed in Fig.32, for example, the input variables to the objective function correspond to the values of thickness, length, and angles of the different bars. These are changed until the criterion of lowest possible dead weight of the entire structure is met. The resulting optimized final shape to this example is given by Kai-Uwe Bletzinger in Fig.32. [7]

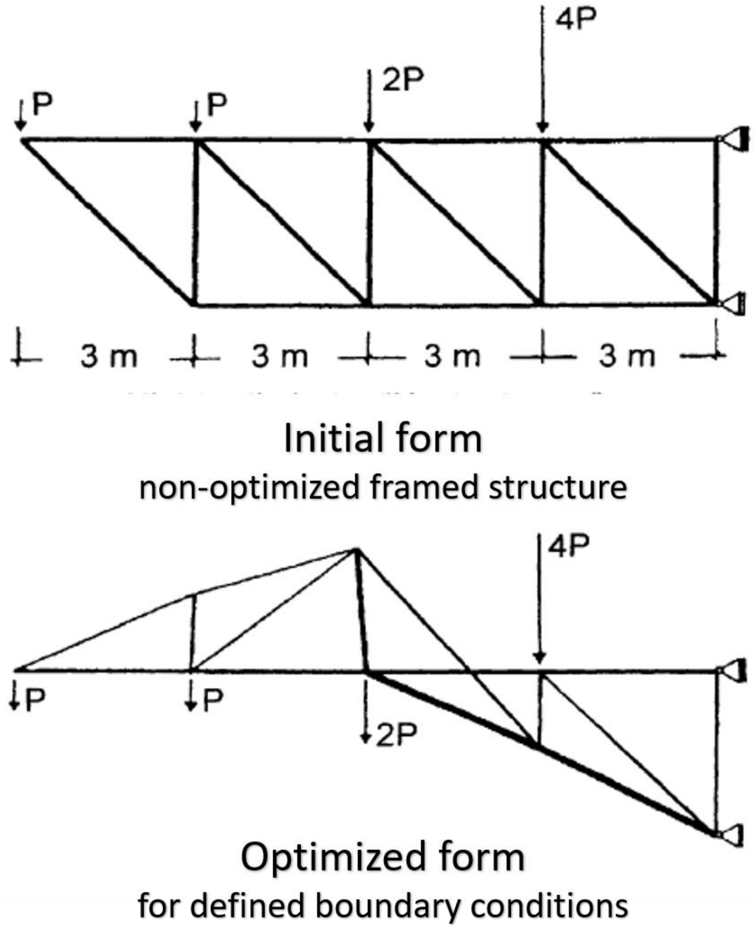


Figure 32: Optimization of a framed structure

In a similar context but in a more complex example using a Finite-Element-Method software, Fig.33 shows the major difference between the original 3D cantilever beam model and its optimized version after 32 numerical iterations, when the objective function finally reached its minimum value [29].

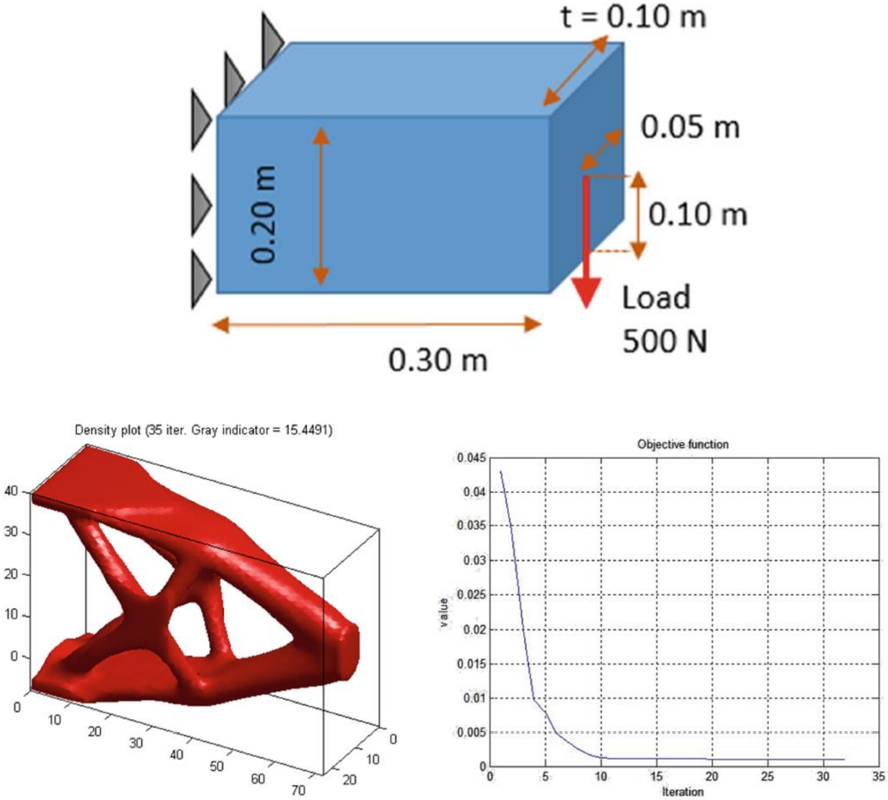


Figure 33: Optimization of a 3D cantilever model

When Bletzinger studied the shape optimization of rotationally symmetrical shells, he exhibited the final results for each load case in a 3D model (Fig.34). The first two illustrations show the difference of the optimized structure after changing the type of support from simple/movable (A) to pinned/hinged supports (B). The other two correspond to the linear dead weight load (C) and the constant snow load (D). [30]

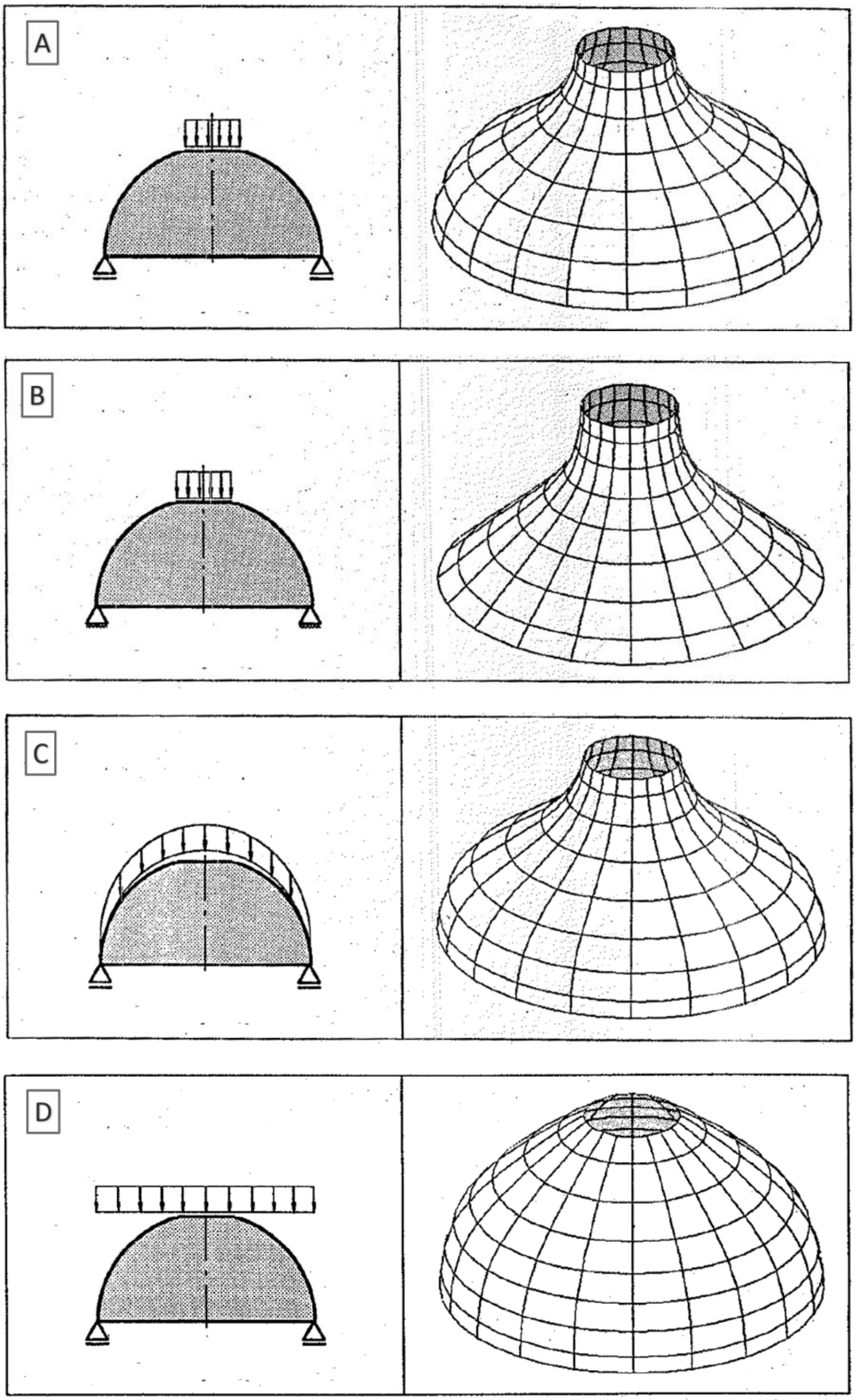


Figure 34: Optimization of rotationally symmetrical shells for different load cases

Observing such examples in technology emphasizes how important it is to know all the input characteristics of a system, so that a legitimate judgement about its optimization can be made. However, grasping these boundary conditions and criteria in nature, and defining the parameters required to formulate a unique objective function, is almost impossible due to the complexity of biology. For that reason, Nachtigall thinks that using the concept of optimization in a biological context is always problematic unless it is used as a heuristic principle [1]. "One cannot say with certainty to what extent a model system is optimized, but technical strategies can be used to trace the way nature comes by its systems" [7].

Despite technically not providing optimized structures, nature remains an enormous source of inspiration to designers and architects, as exemplified by the "tension fork" [31]. When the two upper parts of a fork-like structure – or branches in the case of a tree – bend away from each other, the inside of the fork undergoes tension due to the bending moments that occur (Fig.35).

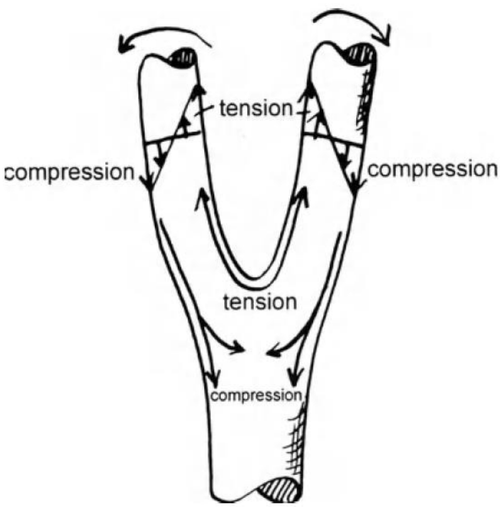


Figure 35: The tension fork

If an engineered semicircular notch is considered, extremely high tensile peaks appear at the edges, referred to as notch stresses. On the other hand, slight restructuring in the notch area to imitate the parabolic [5] form found in trees resulted in a body of the same tension after only a few iterations (Fig.36). Due to this transformation, the bottom of the notch, previously at a great risk of fracture, becomes just as stable as the two sub-trunks above the bifurcation spot (Fig.37) [7, 31]. According to Claus Mattheck, the tree "follows the axiom of uniform stress and lays down material in the region of the notch stresses by adaptive growth, thus immediately reducing these stresses" [31]. "This natural phenomenon is a stroke of constructional genius, a master design: a notch without notch stresses", he adds [31].

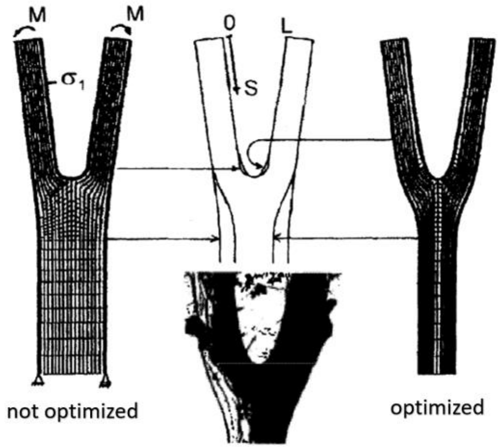


Figure 36: Change in shape of an initially assumed semicircular, not optimized tree fork

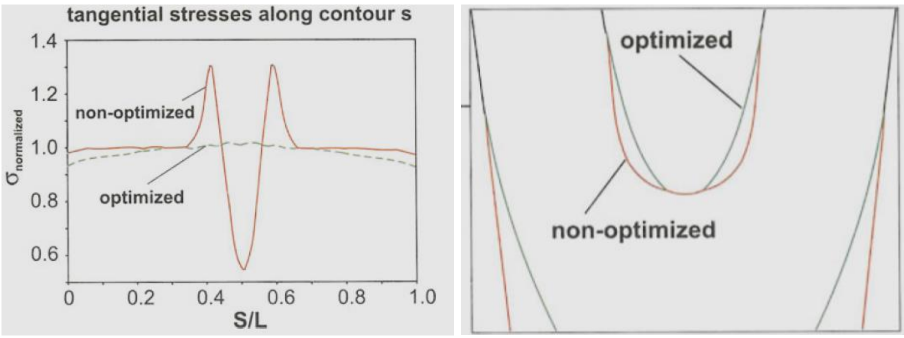


Figure 37: The effect of shape optimization on stress distribution in the tree fork

In fact, many architects share Mattheck's admiration for the model of trees and found inspiration in them to design renowned constructions, such as Antonio Gaudi's Sagrada Familia in Barcelona (Fig.38), as well as Stuttgart Airport, where the principle of Frei Otto's branched columns mentioned in 2.6 was applied on a larger scale (Fig.39). Bletzinger shows that Otto's tree support structure, in fact, demonstrates a minimal weight compared to the non-optimized structure (Fig.40) [30].

Figure 38: The Basílica de la Sagrada Família, Barcelona

Figure 39: Stuttgart Airport

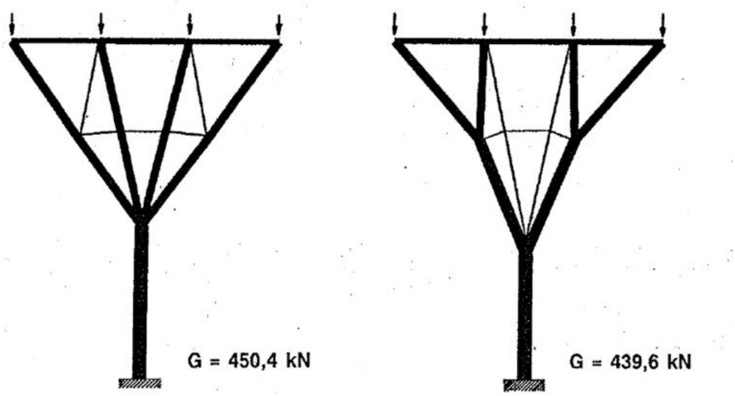


Figure 40: Optimization of the tree structure

2.8 Bionics in architecture and building design

"Architects are always expected to deliver creative solutions" [32] and seeking inspiration in nature has been of great assistance to meet these expectations. The comparison between animate nature and built environment keeps creating new insights [33] and providing problem-solving ideas that, during the last few decades, have been turning into revolutionary constructions and increasingly popularizing the concept of biomimetic design. The next chapter gives a catalog of examples from the building industry that are recognized as manifestations of bionic design. Shell structures in particular are the focus of this research, hence the choice of the assessed constructions. Therefore, this section presents a number of inspiring forms found in natural organisms, compares them with analogous architectural forms, and then explains the concept of shell structures on the technical level.

2.8.1 Forms in natural organisms

When it comes to nature's forms and structures, there is certainly a wide range of differences between them and the industrially designed constructions. Gruber emphasized these differences in a comparative table based on Stephen Vogel's work (Fig.41) [33].

natural construction	technical construction
round form	right angle
few parts, varied properties	many parts, homogenous
diffusion, surface tension, laminar flow	gravity, thermal conductivity, turbulent flow
strength	stiffness
toughness	brittleness
bending, twisting	sliding
flexible	streamlined
non metallic	metallic
tension	compression
-	wheel, rolling
submarines	surface boats
big "product" compared to factory	small products
continuous rebuilding	minimal maintenance
wet	dry

Figure 41: Comparison between natural and technical constructions according to Vogel

However, the fundamental principles in both structural sciences and biology are comparable throughout [8]. This can be observed when forms of building structures in nature and their technical analogs are juxtaposed to one another. Pohl and Nachtigall, for instance, displayed a multitude of analogies, including dome-forming node-and-rod structures exclusively composed of pressure and tension rods, and jointing nodes. These work optimally with a minimal number of members, "which ideally form a triangular mesh network and regulate the flow of forces so that the individual members are relieved of bending stress and bear only pressure and tension stresses" [8]. In this type of dome, five or six members are connected to one node. Each node is surrounded by equilateral triangles and they all lie on an imaginary spherical shell. While technical, rigidly arranged, spherical meshes are symmetric and cannot be modified once they are built, irregular meshes with a larger number of members surrounding the nodes are found in biological systems. The structure of the Radiolaria (Fig.42), for example, actively morphs and adjusts itself, and the center of gravity around which it rotates is often not quite centered, causing a slight deviation from the spherical form leading to instability. [8]

Figure 42: Dome-forming node-and-rod structures in nature and in architecture - Silicate skeleton of a radiolarian and first planetarium of Zeiss, Jena

Another comparison Pohl and Nachtigall highlighted was between the orthogonal lattice structures present in the walls of tube-like glass sponges, as living and actively growing fauna (Fig.43), and in buildings, in the form of load-bearing floor systems. In contrast with Frei Otto's design of purposefully oriented rods connected by rigid nodes that keep the structure stable and compact (Fig.43), a biological system like the glass sponge is flexible and shapes itself according to the forces applied to it. The star-shaped spikes suspended in the membranes bear arms in the six directions of spatial axes. These arms grow to meet the neighboring arms, fuse together, and form the orthogonal lattice shown in Fig.43, but due to the active tensing and slackening movements of the membrane, the spikes shift from the original orientation, creating a new displaced grid network. Once the network is organized and the members are all connected, the nodal points undergo bending stress, stimulating a natural self-strengthening process, and additional spines are formed to stabilize the system. The difference between technical design and nature is that the former relies on pre-calculated, measured, and stably prefabricated structural elements, while the latter works with slight instabilities leading to accidental variations, yet reaches stability by growing additional elements or changing the structure in response to the loads affecting it. In the case of bionics, those preset principles are learned from natural organisms, like glass sponges. [8]

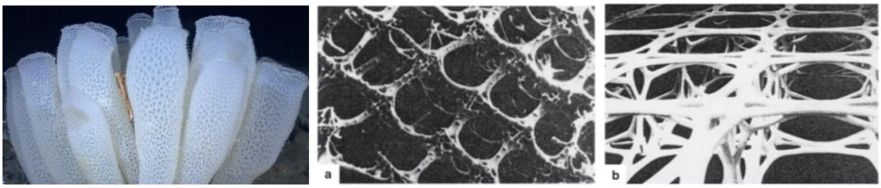


Figure 43: Orthogonal lattice structures in nature and architecture - The glass sponge and an experimental node-and-rod structure by Frei Otto

The 1984 discovery of correlations between network forming node-and-rod structures and panel structures by Danish engineer T. Wester led to the reformulation of the computer programs meant for geodesic domes to enable the assessment of panel structures. These are stable structures characterized by the meeting of no more than three panels at one vertex, and their edges in a "Y" formation, flexibly joined to one another, which favors the presence of shear forces. An equilibrium of the entire structure is obtained when the sum of all occurring torques is equal to zero. An example of this type of constructions from the building industry is Wester and Hansen's project of a museum designed in 1988 (Fig.44). Similarities in shape and function are observed in the Australian sea urchins *Phyllacanthus imperialis* (Fig.44), although these could be, according to Pohl and Nachtigall, behaving simultaneously like a panel and a shell structure, being subject to shear and bending-induced forces, respectively. "As panel structures, the sea urchins could use the anticipated shear forces on the interlocking edges of the panels expected in such a structural form for the accumulation of calcite crystals, as a stable shell structure it could use the deformations elicited by the shifting panels for its construction". They believe the ability of the biological shells to grow both longitudinally and latitudinally in such a construction process could provide a solution to delicate technical problems like volume variation, which is "always linked with tension points in one direction or another along the surface". [8]

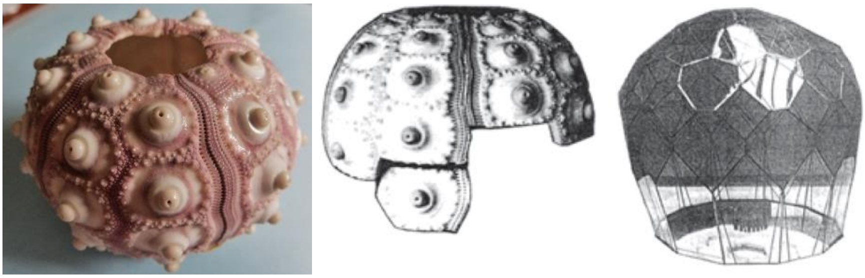


Figure 44: Panel structures in nature and architecture – The Australian sea urchin and a project for a museum building by T. Wester and K. Hansen

When four panels intersect at one vertex, the structure becomes foldable. X-shaped vertices are formed instead of the Y-shaped ones observed above. These are a basic requirement in fold structures, along with the mirrored arrangement of the surfaces around the vertex and the stress solely in the planes of the surfaces [8]. This type of structure is found in lightweight architecture on the one hand, and in light biological systems, such as flower petals, deciduous tree leaves, and insect wings, on the other hand. Palm leaves, for example, are laid out folded and their radial zigzag ribbing ensures stability, especially against fluctuating wind loads [34]. As in panel structures, only tangential shear forces occur at the fold edges. One advantage of fold structures is that for isotropic and thin-gauge materials, a surface cannot be warped along the fold due to their inelastic deformation behavior, which can be tested easily with paper origami. Although this can offer a wide range of creative design solutions, one major downside is the geometric complexity that usually causes difficulties in production. [8]

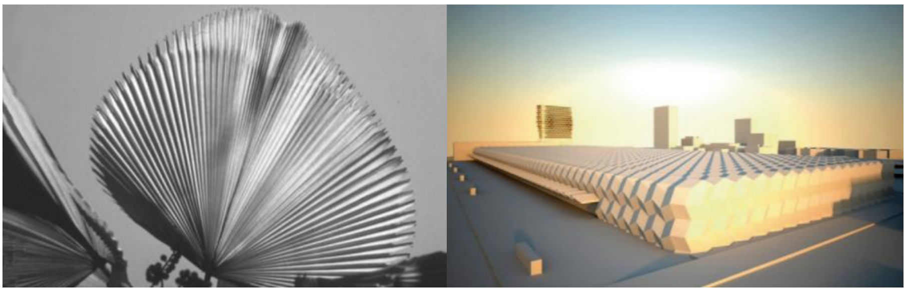


Figure 45: Fold structures in nature and architecture - The palm tree leaf and the design model of the convention center Luxembourg

Complex geometry in lightweight architecture might present certain limitations in terms of manufacturing, but when architects are innovative, which is usually the case in bionic design in particular, the final design could be revolutionary. Swiss architects Herzog and De Meuron demonstrated that when they designed Beijing's National Stadium, commonly referred to as the "Bird's Nest" (Fig.46). In order to cantilever the roof structure of the stadium, prefabricated segments of multiple intertwined hollow structural sections (HSS) were connected on site using 128 welding joints (Fig.47). The HSS components are characterized by their strength in torsion, which was needed to compensate eccentric loading at the rounded intersection of the roof and the wall. The architects used steel for the facade surrounding the inner bowl of concrete seating, similar to the way birds use straw to build nests, considering the high strength-to-weight ratio in both dimensions. Another aspect of this analogy highlighted by Rogers et al. is the in-filling of the facade with translucent ETFE panels for protection from outer elements and acoustic insulation, the same way "a nest is insulated by stuffing small pieces of material between the twigs that make up the structure". [35]

Figure 46: Beijing's National Stadium known as the Bird's Nest

Figure 47: Welding of truss columns and HSS elements of the Bird's Nest

Nonetheless, this building might not be in total accordance with the principles of structural bionics outlined in this thesis due to the dominant aesthetic motif behind its design. For instance, some of the infill members, namely those colored in red in Fig.48, were only installed to balance the appearance of the facade [35]. The example aims, however, to emphasize the prevalence of lightweight yet stable structures in nature, inspiring designers to, in Nachtigall's words, mimic "the always strictly functionally organized biological constructions" [34] in order to achieve greater stability with less material.

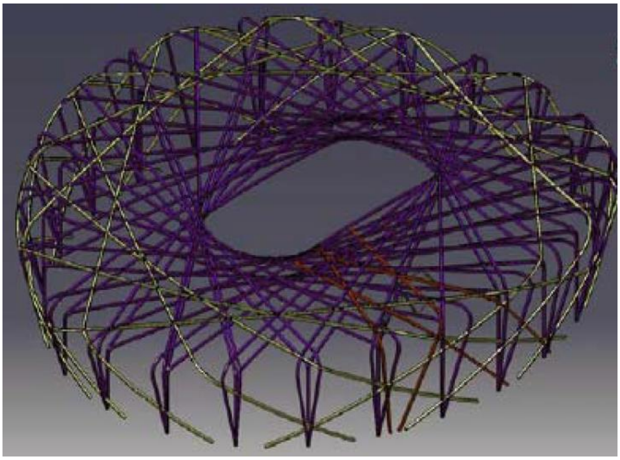


Figure 48: CAD model of the stadium

In fact, creating a high strength-to-weight ratio was mentioned by Neal Panchuk as one of six fundamentals of natural form that ensure the structural efficiency and mobility of biological systems, while keeping the required input of material as minimal as possible [36]. He also summarized the forms of natural organisms in six categories and attributed possible analogous technical structures to each of them as follows [36]:

- Curved shells: skulls, eggs, exoskeletons (domed roofs)
- Columns: tree trunks, long bones, endoskeletons (posts)
- Stones embedded in matrices: worm tubes (concrete)
- Corrugated structures: scallop shells, cactus plants, stiffness without mass (doors, packing boxes, aircraft floors, roofs)
- Spirals: sunflowers, shells, horns of wild sheep, claws of the canary bird (domed roofs)
- Parabolic forms: tardigrade (pneumatic structures)

Nachtigall categorized biological systems in a much more specific way in what he called a collection of construction-morphological elements and systems from the living world based on their functions and forms, such as connections and anchorages, joints and lever devices, and nets and catch constructions. When it comes to technical-functional details from the animal and plant sectors in particular, he suggested a classification into five sections: materials and building, structures and mechanisms, posture and movement, food intake and reproduction, and weir and weapons [34].

The classification of biological systems used in bionic analogies differs from one researcher to another, especially because bionics is a relatively new scientific discipline with high potential for development and limitless discoveries. Therefore, this section is not about putting labels on each category of forms, as much as it is about displaying the most common analogies and buildings inspired from them. Many other natural forms and systems that marked the biomimetic design, besides the ones mentioned above, like honeycombs, bones, and seashells will be assessed within their respective examples in the next chapter.

2.8.2 Shell structures

When it comes to plane structures, meaning structures that are large in two dimensions and small in the third one [28], a few terms appear in different reference books and academic publications. The most common generic term referring to this type of structures is “plate and shell structures”. Their dimensional behavior is explained through Fig.49, where h represents the relatively small third dimension, perpendicular to the reference surface at every point. These structures are characterized by three types of stress resultants, namely the membrane forces n, the shear forces v, and the bending and twisting moments m. They are governed by the equations below, with x, y, and z the cartesian coordinates tangential or perpendicular to the reference surface, and are represented at the side faces of a structural element with length 1 in the x and y directions. σ_x, σ_y, $\tau_{xy} = \tau_{yx}$ are the normal and shear stresses in the plane of the element, τ_{zx}, τ_{zy} are the shear stresses perpendicular to the plane of the element. [37]

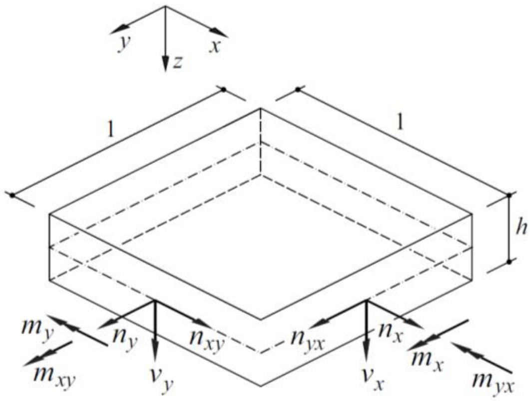


Figure 49: Stress resultants in plate and shell structures

$$n_x = \int_{-h/2}^{h/2} \sigma_x dz \quad , \quad n_y = \int_{-h/2}^{h/2} \sigma_y dz \quad , \quad n_{xy} = n_{yx} = \int_{-h/2}^{h/2} \tau_{xy} dz$$

$$v_x = \int_{-h/2}^{h/2} \tau_{zx} dz \quad , \quad v_y = \int_{-h/2}^{h/2} \tau_{zy} dz$$

$$m_x = \int_{-h/2}^{h/2} \sigma_x z dz \quad , \quad m_y = \int_{-h/2}^{h/2} \sigma_y z dz \quad , \quad m_{xy} = m_{yx} = \int_{-h/2}^{h/2} \tau_{xy} z dz$$

According to Peter Marti, there are four distinguishable types of plane structures: plates, slabs, folded plates, and shells. He defines plates as a form of plane structures that carry "in-plane loads only, where a coplanar stress state constant over h is assumed ($\tau_{zx} = \tau_{zy} = 0$)", which results in membrane forces only ($n_x, n_y, n_{xy} = n_{yx}$). A slab, in turn, "is a form of plane structures that carries loads perpendicular to its plane and is primarily or exclusively subjected to bending and twisting moments m_x, m_y, $m_{xy} = m_{yx}$ plus shear forces v_x, v_y". Folded plates, according to Marti, are three dimensional structures "made up of plates structurally connected along their longitudinal sides and further braced by the inclusion of end plates". Their global or local structural behavior is accordingly dominated by membrane or bending effects. Lastly, "a shell is a form of structure in single or double curvature which as a rule is subjected to general loads (perpendicular to and parallel with the middle surface) and stress resultants (membrane and shear forces plus bending and twisting moments)". Marti believes "an idealization as a membrane shell or membrane with dominant membrane forces and negligible shear forces as well as bending and twisting moments is often justified". Further, he claims that shells can always be approximated using suitable folded plates. [37]

Shells are characterized by their Gaussian curvature, also referred to as total curvature K, of which the expression is given below, where r_1 and r_2 are the principal radii of curvature as shown in Fig.50 [37].

$$K = \frac{1}{r_1 r_2}$$

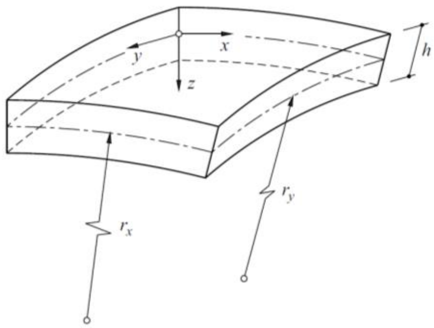


Figure 50: Shell element with principal radii of curvature

"Elliptical surfaces with $K > 0$ (e.g. dome-type shells) are very stiff when supported in a manner compatible with membranes. Hyperbolic surfaces with $K < 0$ (saddle forms) are less stiff and require some form of stiffening at the edges for stability. Parabolic surfaces in single curvature with $K = 0$ (cylindrical and conical forms) are developable and require frames or end plates to maintain their form". [37]

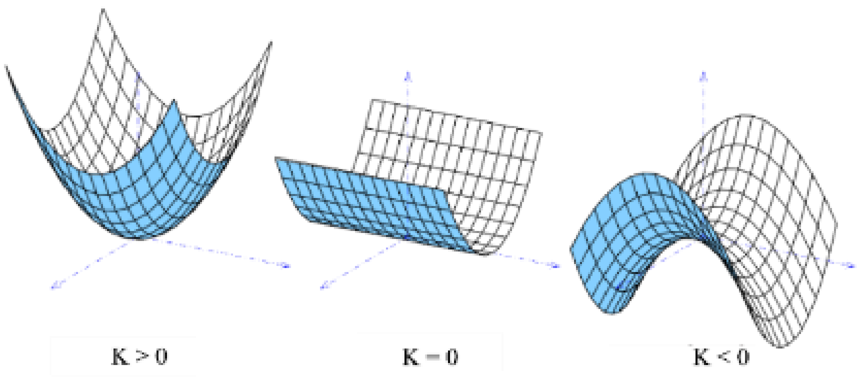


Figure 51: Elliptical, parabolic, and hyperbolic surfaces

British engineer Christopher Reuben Calladine considers continuity and curvature “the essential ingredients in a shell structure” [38]. Shells, according to him, are required to be “structurally continuous in the sense that they can transmit forces in a number of different directions in the surface of the shell”, which is a different mode of action from that of skeletal structures that are “only capable of transmitting forces along their discrete structural members” [38].

He also highlights the difference between closed and open shells in terms of rigidity. He clarifies it, among other examples, with the figure of a closed chocolate box that cannot be twisted until the lid is open, or a tin can initially rigid that becomes easy to squash once one end has been removed. Since building completely closed shell structures to provide structural continuity is often not feasible, compromise solutions are adopted, such as reinforcing the edges of the openings to a degree that depends on their size. In the case of large openings, which is very common in shell constructions, “the provision of adequate edge ribs, together with suitable supports, is of crucial importance”. A judgement about the quantification of openings in shell structures is usually hard to make, yet could have serious consequences on the structure’s stability, which explains the number of textbooks that assess this matter in detail. [38]

An additional factor to the rigidity of shell structures is convexity. Cauchy’s theorem states that “a convex polyhedron is rigid”. Calladine argues that, although some non-convex polyhedra are rigid, special cases of non-convex polyhedra are possible to be proven not rigid and capable of undergoing at least infinitesimal distortions. He then concludes that “convexity guarantees rigidity” in this context, while “non-convexity may produce deformability”. [38]

Another aspect in shell structures that Calladine calls attention to, is the eventuality of catastrophic failure. He believes that “one of the main difficulties in the design of thin-walled structures, which are to be loaded in compression, is that such structures are prone to buckling of a particularly unstable kind”. He exemplifies this phenomenon with the crumpling of thin-walled tubes under load, which leads to irretrievable loss of initial geometry. Hence, an important characteristic to consider when building shell structures is their poor post-buckled rigidity. [38]

Jin Guang Teng claims that research on thin shell buckling will remain active for a long time due to several unsolved practical problems, of which he names “buckling of shells under local or non-uniform loads, the effect of real imperfections, and the direct application of numerical buckling analysis in design" [39].

The stimulation of interest in using thin shells for roofing purposes, according to Calladine, is related to the development of reinforced concrete and the need for more spacious buildings, which was made possible in the Middle Ages after the development of masonry domes and vaults [38]. However, thin reinforced-concrete shell constructions are now used in more than just roofs. Their impact on technology encompasses the development of large economical natural-draught water-cooling towers for thermal power stations (Fig.52) and arch dams, as typical examples. Thin steel shells can as well be observed in various kinds of economical silos for the storage of grain (Fig.52). [38]

Figure 52: Water-cooling towers for thermal power stations and silos for the storage of grain

As branches of computational mechanics continued to develop, such as the finite element method, "a kind of numerical methods in which various mechanics problems are solved by discretizing related continuums" [40], architectural design has evolved substantially, gaining more and more freedom in shaping and form finding. This has eased the construction of shells to a great extent, and made a tremendous number of bionic design applications possible.

Shells in biology are very common structures, found typically in eggs, crustacea, and tortoises. In order to transfer the functional principles of such biological structures into their architectural analogs, studies are conducted on numerous natural systems. In early 2020, Schmier et al. published a study that aimed to qualitatively analyze and visualize the functional morphology of the coconut endocarp with the purpose of evaluating its toughening mechanisms more precisely. The outcome of the study was the identification of eight hierarchical levels of the ripe coconut ranging from the organ level of the fruit to the molecular composition of the endocarp components. All levels were confirmed to have an influence on the crack development, hence, contribute to the fracture toughness of the endocarp. "By providing relevant morphological parameters at each hierarchical level with the associated toughening mechanisms, this lays the basis for transferring those properties into biomimetic technical applications" [41].

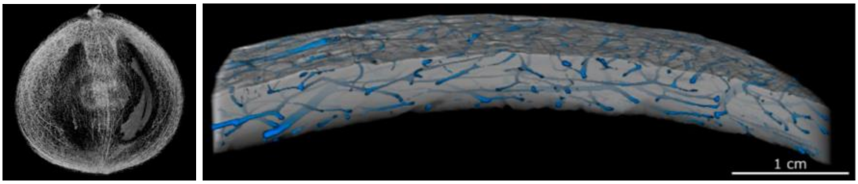


Figure 53: µCT reconstructions of a coconut fruit scanned at two resolutions

Nachtigall exhibits a few examples of biological shell constructions, such as the prosoma, the head region of the *Limulus* horseshoe crab (Fig.54). This rigid molded bowl enables the animal to plow through the superficial mud layers of the sea floor with little resistance [34].

He also displays the abdomen of the *Cnemidotus caesus* water beetle as an example of a buckling and pressure resistant shell construction assembled from different elements (Fig.54). The two wing covers, called elytra, fold laterally into one abdominal piece called the sternum, carrying cavities and representing a form of lightweight construction. The elytra and the sternum form a closed, statically stable shell construction, while the back piece, called tergum, remains tender and does not play any special static role [34].

Figure 54: The horseshoe crab and the water beetle

A few other shell structures of particularly high strength and pressure resistance were showcased by Nachtigall. The permanent eggs of moss animals (Fig.55), for example, are reportedly so pressure resistant that ice formation cannot harm them when they float in the water during the overwintering stages in autumn, due to the rigidity of the external shell. The shell of sea urchins (Fig.55), which consists of double rows of interlocked lime slabs, is considered pressure resistant as well. [34]

Figure 55: The moss animal and the sea urchin

The shell of a chicken egg also shows extreme resistance against loads parallel to the longitudinal axis and cannot be crushed between the thumb and the index finger; it only breaks when subjected to astonishingly high loads (Fig.56). Moreover, the eyes of numerous insects incorporate hexagonal cornea lenses that form a relatively stable and bulge-resistant shell (Fig.56). This shell plays an important role in protecting the sensitive eye, besides its primary function of collecting light from all sides and letting it fall onto the sensory cells via crystal cylinders. [34]

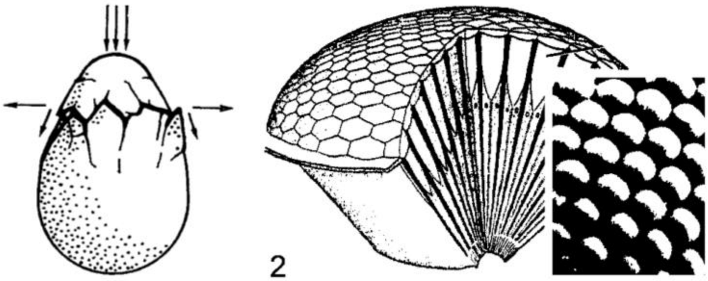


Figure 56: The chicken egg and the cornea lenses in the eyes of insects

With the abundance of shell structured organisms in nature and the availability of the necessary technological tools along with effective strategies that facilitate the collaborative work of architects and biologists, the bionic design approach has been successfully delivering highly renowned products throughout the years. Based on the results of thorough analogies, technical principles inspired by natural systems, like urchins and insects, that contribute to their stability and load resistance in particular, are translated into both aesthetically and structural-functionally remarkable buildings, halls, and high-rises, all in the form of bionic applications. After assessing the main concepts and methodologies behind their development process, the following chapter will present a number of examples to further illustrate what is considered a new science that could potentially change the face of architecture.

3 Catalog of biomimetic shell structured buildings

There are several ways to categorize bionic applications in architecture. As this chapter mainly assesses buildings that fall into the category of shell structures, a classification based on the building material is chosen. The first section sheds light on concrete buildings, while the following sections address masonry, steel, and timber constructions, occasionally in combination with plastic and glass elements. Within each example, the three steps of Nachtigall's method, mentioned in 2.5.3, are distinguished. The biological system from which the structure is inspired is displayed, the abstracted principles taken into the design concept are highlighted, and the resulting structure in which these are implemented is demonstrated. Related examples that show similarities in form, function, or inspiration with the assessed primary example are exhibited and illustrated as well.

3.1 Concrete structures

"Concrete is a material of possibility", states Gabriel Tang [42]. One of the biggest advantages of concrete is the ability to take any shape or form given by the designer as long as adequate formworks can be provided. Not only does he believe that "mouldability renders concrete an ideal material for shell construction", he also thinks that the perfect shell, theoretically having axial and shear in-plane forces, is best constructed with a material that favors the surface transfer of forces, like concrete, allowing shell structures to have a slenderness ratio of above 1:500 [42]. Reinforced concrete suits this type of in-plane force transfer perfectly due to its positive behavior towards compressive loads. According to Ramm and Mehlhorn, "for RC shells the ideal situation is of course a stress state of pure compression" [43].

The "golden age of concrete shell construction" lasted from the 1920s until the early 1960s [44], where countless factories, warehouses, metro stations, grandstands, theatres, restaurants, and houses roofed with concrete shells were built around the world [42]. However, multiple factors were not in favor of this trend and led to a noticeable decrease in the interest of architects in concrete shells, which also affected the number of research papers on their design methods and construction techniques.

Christian Meyer and Michael H. Sheer took the initiative of interviewing several engineers and architects in order to explore these factors. Almost unanimously, the biggest issue they related to concrete shells were labor costs. To erect the necessary shoring and formwork, highly skilled labor is required due to the level of accuracy needed in the construction of shells, especially the geometrically challenging ones. Domes, for example, are more difficult to build compared to surfaces with straight generators that can be formed using nearly flat panels, such as cylinders and hyperbolic paraboloids. When it comes to thin shells, “small errors in thickness and reinforcing steel placement can have significant effects on internal forces as well as global stiffness and stability”. Structural engineer Edward DePaola, who shares this opinion, believes, however, that the development of innovative, flexible, and easily adjustable forming systems could solve this problem and lower the expenses of building such complicated shapes. [44]

Ricardo Bitella, also a structural engineer, considers the lack of flexibility in the final form one of the detrimental characteristics of concrete. Building thin shells with concrete, according to him, limits the architectural design to a certain degree and does not provide the same freedom to make geometric changes as structural steel, for example. Architect Gregory Waugh thinks that concrete shells have a “brutalistic feel of heavy masonry” and their aesthetics are part of the problem, although Isler’s shells, for instance, demonstrate the exact opposite (Fig.57). Architect Michael Flynn argues that “thin shells are no longer used for arenas and stadiums because the architectural focus of these buildings has shifted” from the structure itself to their actual use. Arenas’ roofs are now “cluttered with lights, catwalks, screens, scoreboards, and banners”, which only calls for “unexciting utilitarian construction systems” like steel trusses, bar joists, and metal decks. [44]

Figure 57: Heinz Isler's shell structures

Another reason that could have contributed to the popularity drop of concrete shells, according to Meyer and Sheer, is the lack of expertise in shell structures among the younger generation of engineers. They claim that most designers of iconic shell constructions are no longer alive, thus, much of their knowledge in shell design is lost. Based on a survey of current curricula, they also state that “none of the departments in the top of the U.S. News and World Report list of America’s best colleges offered special courses on shell structures”, which could have influenced the interest as well as the expertise in this type of design. [44]

On the other hand, thin concrete shells present numerous advantages and benefits that support their competitiveness with other materials, besides mouldability. Meyer and Sheer highlighted “the efficient use of materials; relatively low cost and general availability of materials (concrete and reinforcing steel); their fire, blast, and impact resistances that provide safety and may lower insurance costs; energy efficiency; clean and uncluttered interior and exterior surface appearance; and the possibility of many visually interesting geometries”. Moreover, construction technology and concrete material science in particular are experiencing a substantial development that could have a positive impact on shell construction. Some would even argue that referring to the 1960s when evaluating the potential of thin concrete shells is “improper”. “Better shotcreting technology, stiffer fabric forms, and novel forms of fiber-reinforced cement composites” are now in disposition of shell designers. These material advancements along with new methods of construction, such as the use of air-inflated forms and modular formwork, help lower the labor costs drastically and achieve larger and more unique shapes. Improving the concrete reinforcing technology and using alternative solutions like steel or glass fibers can eliminate the need for costly and delicate-to-place reinforcing bars. Through high-performance fiber-reinforced cement composites, it is possible to reach strain hardening comparable to that of structural steel, and to obtain “fracture properties and energy absorption capacities... at least one order of magnitude larger than those of regular fiber-reinforced concrete”. [44]

According to the architects and designers interviewed by Meyer and Sheer, modern techniques able to reduce the construction costs of concrete shells should be popularized in order to reintroduce this type of building to the engineers of this era. “By giving thin concrete shells another look, educating the public in general and the building community in particular about the innovations made possible by recent advances in concrete technology, maybe great designers will revive a tradition that produced some of the most magnificent architectural landmarks of the 20th century”. [44]

In an attempt to assess Heinz Isler’s Sicli SA Factory Shell in Geneva built in 1969 (Fig.58), Chilton and Chuang used the finite element analysis to evaluate the Von-Mises stress and total deformation values of this structure under self-weight and a uniform vertical load of 2.000 Pa. They then compared them with a digitally form-found surface derived using the hexagonal mesh. Both models showed relatively low values (Fig.59-60) [45]. They related the structural efficiency and the elegance of Isler’s work to its “close association with doubly-curved forms found in nature, which are generated by the laws of physics and strive to minimize the energy required in their formation” [45].

Figure 58: Heinz Isler’s Sicli SA Factory Shell in Geneva

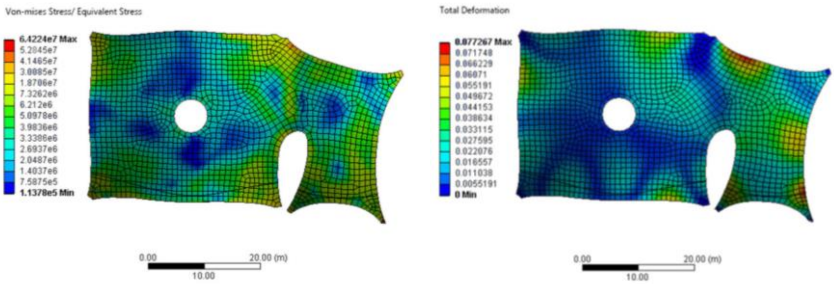


Figure 59: Von Mises stresses and deformation of the Isler shell

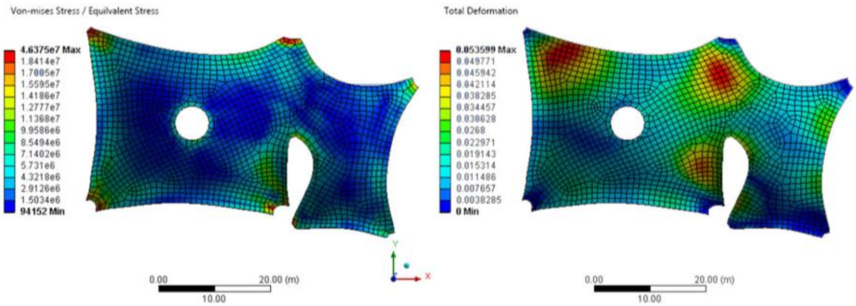
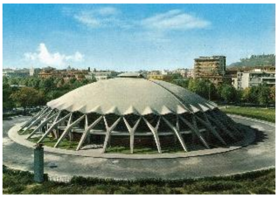


Figure 60: Von Mises stresses and deformation of the digitally form-found shell

As unique as Heinz Isler’s work is known to be, the tendency to imitate natural forms and curvatures in concrete shell constructions was displayed by several other engineers and designers as well, such as Félix Candela, Pier Luigi Nervi, and Eduardo Torroja. This section of the catalog assesses examples of biologically inspired shell structures that were built mainly with concrete, and the structural-functional aspects learned from nature that contributed to their stability and sustainability are highlighted. The selected buildings for the entire chapter are listed in the following table (Fig.61).

Overview

 **Palazzetto dello Sport** Rome, Italy	 **Norfolk Scope Arena** Virginia, USA	 **Terme di Chianciano** Siena, Italy
 **Zoology Lecture Hall** Freiburg, Germany	 **Gatti Wool factory** Rome, Italy	 **Palazzo del Lavoro** Turin, Italy
 **Los Manantiales Restaurant** Xochimilco, Mexico	 **Submarine Restaurant of L'Oceanogràfic** Valencia, Spain	 **Zarzuela Hippodrome** Madrid, Spain
 **Royan Market Hall** Royan, France	 **National Circus of Bucharest** Bucharest, Romania	 **King's College Chapel** Cambridge, England

 **Peterborough Cathedral** Peterborough, England	 **The Gherkin** London, England	 **Hearst Magazine Tower** New York, USA
 **CCTV Building** Beijing, China	 **Lotte Super Tower** Seoul, South Korea	 **The Technosphere** Dubai, UAE
 **CITIC Financial Center** Shenzhen, China	 **The Eden Project** Cornwall, England	 **The Water Cube** Beijing, China
 **Roskilde Domes** Roskilde, Denmark	 **Dome of Visions** Copenhagen, Denmark	 **The Vessel** New York, USA

Figure 61: Overview of the assessed buildings in chapter 3

3.1.1 Palazzetto dello Sport, Rome - Italy

1957, Pier Luigi Nervi

Figure 62: Palazzetto dello Sport

Biology

The leaf of the giant Amazon water lily, also known as *Victoria Amazonica* [46], has a network of veins that stiffen the leaf without adding excessive thickness [47]. Despite its 2m diameter, the leaf is only 2mm thick and can carry a weight of up to 60 kg [26]. Its massive surface area needed for maximum sun exposure for photosynthesis makes it difficult to keep afloat, especially when vertical loads are applied by animals using these leaves to cross the river. Therefore, a ribbed, girder-like support structure is found on the underside to help bear the weight [48, 49].

Figure 63: The giant Amazon water lily

Based on David Attenborough's work, Alexandra Ralevski, science director at the biomimicry institute in Seattle, explains how a main rib runs along the center, from which additional ribs radiate and bifurcate incrementally along the leaf. She describes them as flat and wall-shaped, with decreasing thickness towards the edge. Filled with air, they help reduce the total weight of the structure, which keeps the leaf floating on water. Adjacent ribs connected to each other in a pattern of radial webbing form concentric circles that provide additional structural support without adding excess weight. [48, 49]

Zhao et al. classify these ribs into major, minor, and diagonal ribs. The major veins growing from the stalk center to the leaf edge are mainly responsible for carrying loads. To keep the leaf flat and stiff, the minor veins establish a network with the major veins. The diagonal ribs are a result of the intersection of the fiber bundles with each other in diagonal directions (Fig.64). [50]

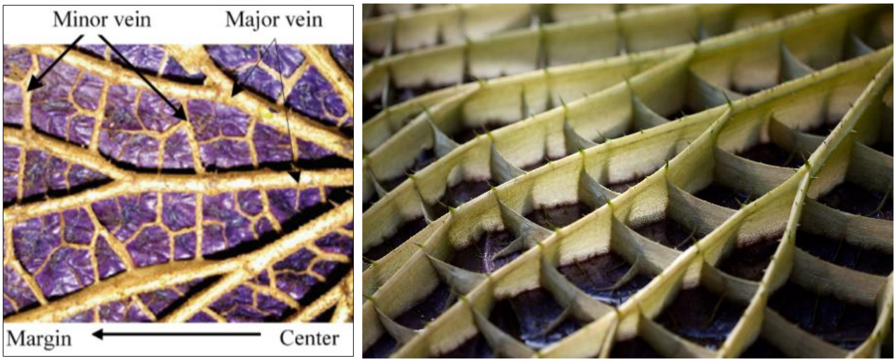


Figure 64: The ribbed structure of the water lily

Abstraction

The main structural aspect observed in the understructure of the water lily leaf is that properly distributed, lightweight ribs help support a relatively heavy upper structure by scattering the applied load into a mesh of almost equidistant force resultants. These resultants run through a network of supporting bifurcated ribs built radially following the direction of force distribution. This allows a reduction in the spanning distance of the outer surface [51] and the total weight of the structure, providing a fully functional system with evenly distributed loads and minimal material consumption. Outlining the abstracted principle, Pawlyn states that "radial bifurcating ribs reduce the distance over which the outer surface must span, while the outer surface in turn connects all the ribs together, so loads are more evenly distributed” [16].

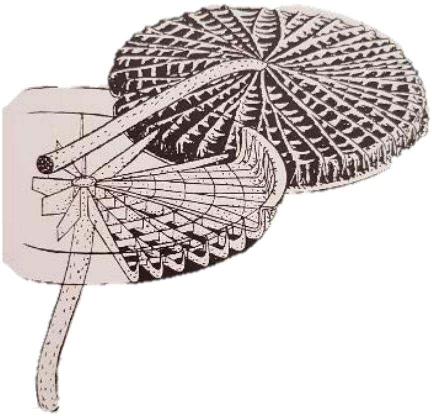


Figure 65: The understructure of the water lily

Transfer

This principle was employed by Pier Luigi Nervi in the roof construction of Rome’s Palazzetto dello Sport, completed in 1957 with architect Annibale Vitellozzi [45]. Combined with the benefits of shell structure behavior, he used ribs “to give effective structural depth to a thin planar surface” [16].

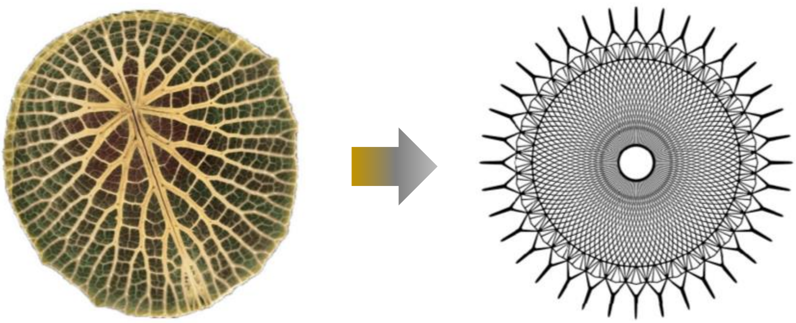


Figure 66: From the Amazon water lily to the roof structure of the sports arena

The 60m spanning cupola consists of two sets of intersecting ribs that follow the technical necessity of bending stiffness to prevent buckling [52]. Nervi’s redistribution of material through this method provided a significant enhancement of stiffness using the invention of “ferrocement” [52] or “ferro-cemento” [36]. This “new revolutionary material” [51] was formed using thin, flexible, and elastic steel mesh as the core, brushed with layers of cement mortar [36]. Its ability to withstand great strains enabled Nervi to address the problem of stress and static equilibrium more freely in terms of design [36].

Figure 67: The roof of Palazzetto dello Sport

GRAPH link + link

Analogous to Amazon water lilies, the ribbing allowed for a thinner ceiling [53]. Nervi designed a roof structure covered with corrugations of around 2,5m span divided into 4m long units. The precast units made from ferrocement were less than 5cm thick and were joined together using poured-in-place concrete at the peak and troughs of the corrugations [42]. These rhombic prefabricated elements (Fig.68) filled with concrete in situ became an integral part of the final structure [52].

Figure 68: Construction of Palazzetto dello Sport

The forces transmitted through the ribs were collected by 36 Y-shaped buttresses that are inclined following the angle of thrust lines (Fig.69). An underground prestressed ring of 80m diameter bears the horizontal component of the buttress forces [52]. The rippling edge stiffening, where the buttresses meet the dome, helps reduce the thickness of the shell [45].

Figure 69: Y-shaped buttresses supporting the roof

Through the design of Palazzetto dello Sport, Nervi was able to mimic the combination of strength and lightness found in nature, using ribs to span wider spaces with less material [54], a principle that he learned and abstracted from the biological system of the giant Amazon water lily, demonstrating a typical example of the three-step bionic design. He even took the inspiration a step further and suggested innovative solutions that eased the construction of concrete shells, such as the use of ferrocement for the ribs to make them as light as the natural system, and the alternative plaster molds method instead of traditional timber formwork to reduce the cost of the project, which also “allowed the building to become one cohesive unit” [36].

Related examples

Comparable to this example is Nervi’s Norfolk Scope Arena in Virginia, USA. It was built in 1970 and shows a similar implementation of interior ribs and buttresses to obtain long span concrete domes [55].

Figure 70: Norfolk Scope Arena in Virginia, USA

Another example of Nervi’s ribbed shells is the Terme di Chianciano in the province of Siena, Italy. In 1952, based on the same principle, he designed the ceiling of the hall that was later named the “Salone Nervi” hall in his honor. One unique aspect of this ceiling is the daylight provided by the openings between the ribs [52].

Figure 71: Terme di Chianciano in Siena, Italy

3.1.2 Zoology lecture hall, Freiburg - Germany

1968, Hans-Dieter Hecker

Figure 72: Zoology lecture hall

Biology

“There are two types of bone”, state Drake et al., namely compact, also called cortical, and spongy, also called trabecular or cancellous [56]. “Compact bone is dense bone that forms the outer shell of all bones and surrounds spongy bone. Spongy bone consists of spicules of bone enclosing cavities containing blood-forming cells” (Fig.73) [56]. Felix W. Wehrli believes that “both trabecular and cortical bone contribute to bone strength” [57]. One of the bones in the human body exemplifying this combination, of which the internal structure draws considerable attention, is the femur, the only bone forming the thigh (Fig.74) [58].

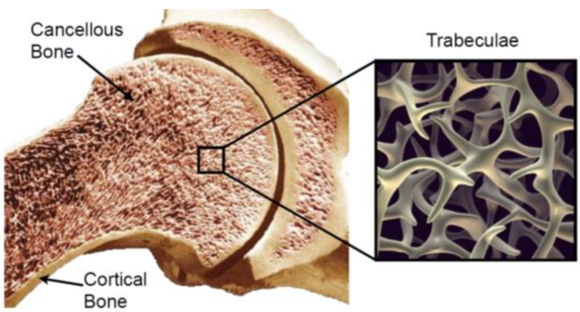


Figure 73: Trabeculae of cancellous bone

According to Dr. Henry Gray, "The femur is the longest, largest, and strongest bone in the skeleton, and almost perfectly cylindrical in the greater part of its extent" [58]. The weight bearing and weight transmission functions of the upper end of the femur, a major concern in this particular bone, are strongly related to the trabecular arrangement, as emphasized by Sinha, since "the disposition of the trabeculae is directly influenced by the mechanical requirements of the bone" [59].

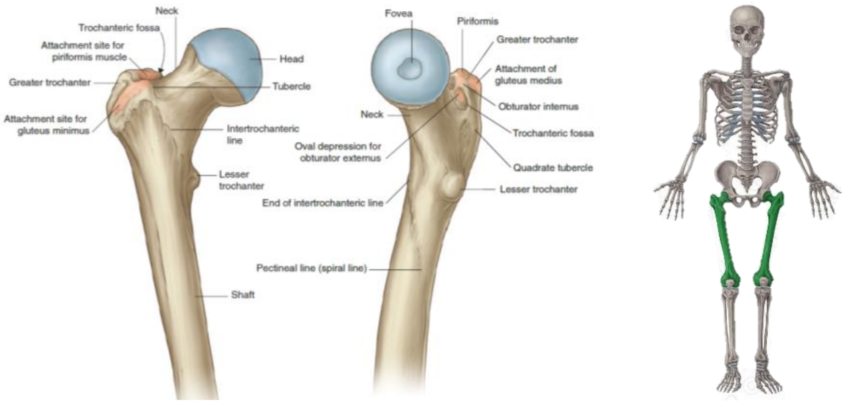


Figure 74: The femur

Clinton T. Ruben expresses it more generally, saying "bone is a tissue that adjusts its architecture in relation to its functional load bearing" [60]. Nachtigall clarifies that trabeculae orient themselves by following the trajectories of stress, namely the direction of main pressure and tension stresses [5]. Sinha explains it by the formation of two sets of bony lamellae in the structure of cancellous bone: pressure lamellae related to compression forces, and tension lamellae related to tensile forces [59]. Based on optical stress recordings, Nachtigall describes these supporting features as spatially twisted surfaces that intersect at right angles everywhere [26].

The following cross-section shows a reconstruction of the stress trajectories in a normal femoral neck, where pressure trajectories are represented by continuous lines, and tension trajectories by dashed lines (Fig.75). The bundle of cancellous bone elements parallel to the compressive stress trajectory, ascending "right" from the compacta and running somewhat parallel to the direction of loading R, is crossed at right angles at every point by the bundle of the cancellous bone elements rising from the "left", through the shaft, and then bending over to the right-bottom, following the tension trajectory [34].

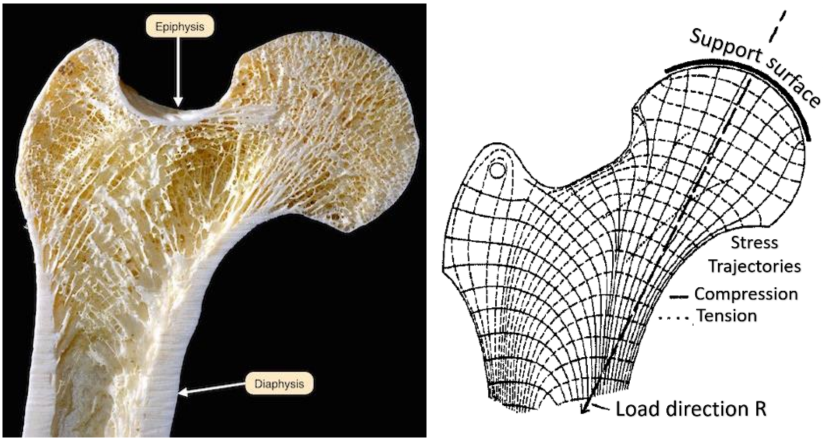


Figure 75: Stress trajectories in the femoral neck

To prove the structural adaptation of the femur's structural pattern to changes in the load direction, Nachtigall exhibits a few pathological deviation cases that, when affecting the femur, may transform or reshape the stress trajectories that run through the cancellous bone, and rearrange the trabeculae accordingly. In the case of coxa valga deformity in the hip, where the angle between the femoral shaft and the femoral neck is increased, "the estimated overall loads were found to be more vertical" [61]. While, in the normal femoral neck, the resultant R of body weight and muscle forces runs obliquely to the central axis of the femoral neck, a particularly steeply erect femoral neck is observed in the case of coxa valga. The unchanged resultant R now runs at a smaller angle to the axis, in the limiting case even parallel to the axis. As a result, the cancellous structure changes: the trabecular tracts parallel to the compressive stress trajectories are now parallel to the neck axis in the direction of the resultant, the arch systems of the bars parallel to the tension trajectories are missing, and the latter systems now run from edge to edge across the head and neck. According to Nachtigall, the orangutans have a steeply erect femoral neck that corresponds to a "physiological coxa valga" and shows a stress trajectory image comparable to the one described (Fig.76). A different pattern is shown when the trajectory-parallel trabecular tracts undergo a transformation due to the pathologically almost vertical resultant R, and a clear functional attitude towards the applied stress can be observed in Fig.76. [34]

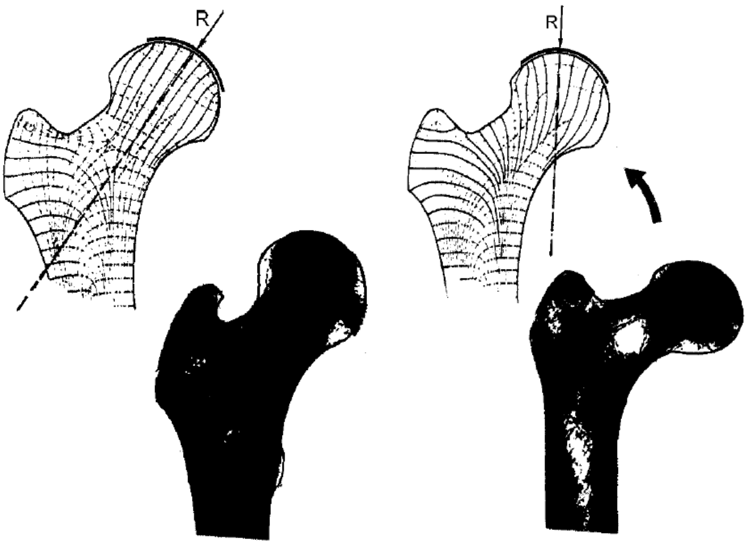


Figure 76: Trabecular tracts parallel to the stress trajectories

Besides the orientation of trabeculae in the direction of stress lines, Michael Pawlyn points out an additional aspect observed in the inner structure of femur bones, namely the proportionality of the density of bone filaments to the concentration of stresses. He does so by displaying an X-ray image that matches the stress lines diagram in terms of density and demonstrates that "where there is high stress, there is a proliferation of material and elsewhere there is a void" [16].

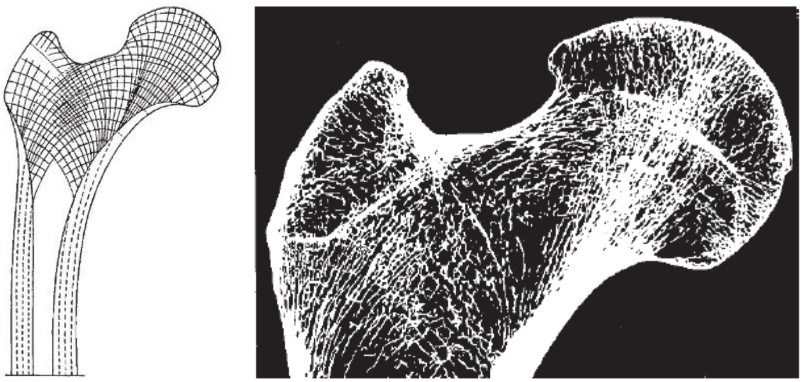


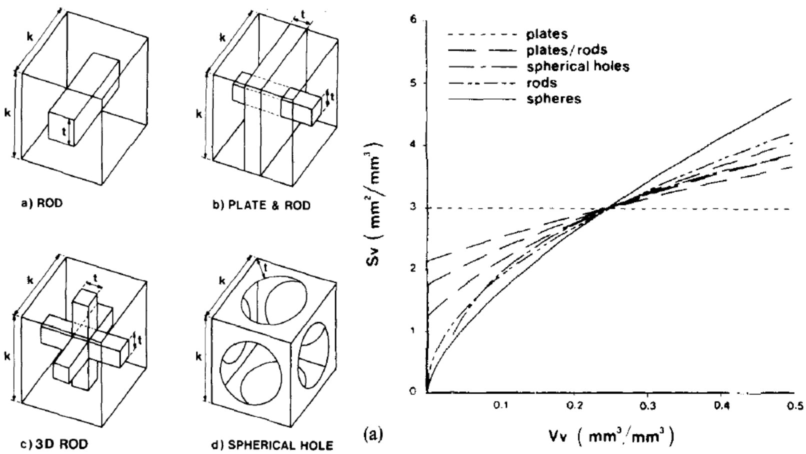
Figure 77: X-ray image showing the density of bone filaments matching the stress lines diagram

Abstraction

In order to support dead weight and dynamic loads, the structure of the supporting body is built exclusively, or at least mainly, in the direction of the loads, following the compressive and tensile stresses' trajectories. This allows the structural elements running in line with these trajectories to "relieve themselves mutually of bending stresses" [5]. This principle relies on the material's response to compression and traction forces. Whether it is bony trabecular meshwork or technically manufactured material, sufficient strength and precise design are needed to minimize bending stresses, as well as material consumption, without endangering the structure.

German civil engineer Karl Culmann was reportedly the first one to notice this particularity in bone structure during a lecture given by von Meyer in 1866 [62]. He described it mathematically in 1875, which formed a basis for the scientific work of anatomist and surgeon Julius Wolff later in 1877. He postulated Wolff's law, "a theory which describes the form-function-relationship between bone geometry and mechanical loading on bone", and facilitated the transfer of this principle into several bionic design applications in lightweight architecture ever since [63].

Among the numerous assessments and numerical analyses of the bone architecture's adaptation to physical function as Wolff's law states, Fazzalari et al. evaluated the surface to volume relationships in the femoral head and described the trabecular bone structure using mathematical modelling. According to Fazzalari et al., "a single measure of mineralized bone volume per unit volume of structure (V_v) and the surface area of mineralized bone per unit volume of structure (S_v) does not identify a particular architecture in any detail", yet "the way in which S_v changes in relation to V_v does provide this information as the structure remodels" [64]. They were able to demonstrate the "increase in the rate of change of S_v with respect to V_v" that results from the structure's tendency "to minimize surface for a given V_v" (Fig.78) using analytically studied abstracted models of the trabecular bone structure simplified into cubic unit cell structures containing basic combinations of rods, plates, and spheres (Fig.78) [64]. They also described each of these mathematical models with relation to the trabecular thickness t, the marrow space width w, and the length of one side of the unit cell k, along with the "least squares regression fit on derived data from the model formulae" (Fig.78) [64]. The formulation of the mathematical models as such allows for the analytical comparison with experimental data and the reproduction of similarly built structures with similar mechanical behavior.



Physical model	Mathematical model	Regression
Plates	$Sv=2/k$	$Sv=3.0*Vv^{0.0}$
Plates & rods	$Vv=(k*t^2-t^3+k^2*t)/k^3$ $Sv=(2*k^2+4*k*t-6*t^2)/k^3$	$Sv=3.3*Vv^{0.08}$
Plates/rods 1	$Sv=2*(1+4*Vv)^{0.5}/k$	$Sv=4.0*Vv^{0.18}$
Plates/rods 2	$Sv=2*(1+2*Vv)^{0.5}/k$	$Sv=4.5*Vv^{0.27}$
Plates/rods 3	$Sv=2*(1+4*Vv/5)^{0.5}/k$	$Sv=5.5*Vv^{0.43}$
3D rod network	$Vv=(3*k*t^2-2*t^3)/k^3$ $Sv=(12*k*t-12*t^2)/k^3$	$Sv=4.0*Vv^{0.33}$
2D rod network	$Vv=(2*t^2*k-t^3)/k^3$ $Sv=(8*k*t-6*t^2)/k^3$	$Sv=4.9*Vv^{0.38}$
Rods	$Sv=4*Vv^{0.5}/k$	$Sv=6.0*Vv^{0.50}$
Spheres	$Sv=6*Vv^{2/3}/k$	$Sv=7.6*Vv^{0.67}$
Spherical holes	$Vv=(pi*w^3/3-3*pi*k*w^2/4+(1+pi/4)*k^3)/k^3$ $Sv=(3*pi*w*k-2*pi*w^3)/k^3$	$Sv=5.3*Vv^{0.46}$

Figure 78: Four of the models of trabecular bone structure studied analytically leading to their mathematical formulations

In a more recent approach, Rapisarda et al. "addressed the problem of determining, with reasonable accuracy, the values of the parameters of a mathematical model for bone mechanics and bone cell populations dynamics" [65]. Based on their mathematical model and the ordinary differential equations (ODEs) that describe "the evolution of cell densities and bone tissue density", using the stimulus function defined by $S(x,t)$ and the equilibrium equations that involve the deformation gradient F, the Green-Saint-Venant strain tensor G, and the strain energy U, they estimated and verified the model's parameters with numerical simulations, delivering a table of values that would facilitate future attempts to remodel bone structures [65]. The detailed elaboration of the mathematical expressions is found in Abali's 2020 publication, which comes in response to the "insufficient interaction between mathematical and mechanical literature on one side and biological researches on the other", when it comes to bone mechanics and bone architecture [65].

The system of ODEs:

$$\frac{\partial x_k}{\partial t} = -\beta_k X_k + \gamma_{bk} x_b \mathcal{K}(\varphi),$$

$$\frac{\partial x_b}{\partial t} = -\beta_b X_b - \gamma_{bk} x_b \mathcal{K}(\varphi) + \alpha_b S^+ x_k$$

$$\frac{\partial x_c}{\partial t} = -\beta_c X_c + \gamma_c x_c \mathcal{K}(\varphi) + \alpha_c S^- x_k$$

$$\frac{\partial \rho}{\partial t} = (a x_b - b x_c) H(\varphi)$$

The threshold functions $\boldsymbol{X_i}$:

$$X_i = \begin{cases} x_i, & \text{if } x_i > \tilde{x}_i \\ 0, & \text{if } x_i \leqslant \tilde{x}_i \end{cases} \qquad i = k, b, c$$

The Stimulus function $\boldsymbol{S(x,t)}$:

$$\boldsymbol{S(x,t)} = \left(\frac{\int_{\mathcal{B}} \boldsymbol{U(y,t)\eta x_k(y,t) e^{-\frac{\|x-y\|^2}{D^2}} dy}}{\int_{\mathcal{B}} \boldsymbol{e^{-\frac{\|x-y\|^2}{D^2}} dy}} \right) - \boldsymbol{S_0(x,t)}$$

The deformation gradient F, its determinant J, and the Green-Saint-Venant strain tensor G:

$$\boldsymbol{F} = \nabla \chi, \qquad J = \det \boldsymbol{F}$$

$$2\boldsymbol{G} = \boldsymbol{F}^T \boldsymbol{F} - \boldsymbol{I}$$

The Lamé parameters λ and μ:

$$\mu = \hat{\mu}(\rho(t), x), \quad \lambda = \hat{\lambda}(\rho(t), x)$$

The relation of Young's modulus $\boldsymbol{Y}$ and Poission ratio ν to the Lamé parameters:

$$\lambda = \frac{Y\nu}{(1+\nu)(1-2\nu)}$$

$$\mu = \frac{Y}{2(1+\nu)}$$

The Young modulus assumed for the bone tissue:

$$Y = Y_{mb} \left(\frac{\rho}{\rho_{\max}} \right)^{\omega_b}$$

The strain energy:

$$U(\boldsymbol{G}, \rho, x) = \mu \mathrm{tr}(\boldsymbol{G}^2) + \frac{\lambda}{2} (\mathrm{tr}(\boldsymbol{G}))^2$$

The equilibrium equations:

$$\mathrm{Div}\boldsymbol{T} = \mathrm{Div}\left(\boldsymbol{F} \cdot \frac{\partial U}{\partial \boldsymbol{G}} \right) = -\boldsymbol{b}^{ext},$$

$$\boldsymbol{T}[\boldsymbol{N}] = \boldsymbol{F} \cdot \frac{\partial U}{\partial \boldsymbol{G}} \cdot \boldsymbol{N} = \boldsymbol{f}^{ext},$$

ρ_0	physiological cortical bone density	g/mm^3	1.6×10^{-3}
ρ_{max}	maximum cortical bone density	g/mm^3	2×10^{-3}
Y_p	physiological cortical bone Young modulus	GPa	18.6
Y_{mb}	maximum cortical bone Young modulus	GPa	28
ν	cortical bone Poisson coefficient	-	0.14
D	osteocytes range of influence	mm	0.1
x_{k0}	physiological density of osteocytes	1/mm^2	316
x_{b0}	physiological density of osteoblasts	1/mm^2	17
x_{c0}	physiological density of osteoclasts	1/mm^2	3
$\tilde{x}_k$	lower threshold for osteocytes density	1/mm^2	31.6
$\tilde{x}_b$	lower threshold for osteoblasts density	1/mm^2	1.7
$\tilde{x}_c$	lower threshold for osteoclasts density	1/mm^2	0.3
a	rate of bone synthesis for one osteoblast	g/day	4.6×10^{-10}
b	rate of bone resorption for one osteoclast	g/day	2.6×10^{-9}
β_k	death rate of osteocytes	1/day	2.5×10^{-4}
β_b	death rate of osteoblasts	1/day	0.015
β_c	death rate of osteoclasts	1/day	0.099
γ_{bk}	rate of differentiation from osteoblasts to osteocytes	1/day	1.8×10^{-3}
γ_c	proliferation rate of osteoclasts	1/day	0
α_b	production rate of osteoblasts	1/day	1
α_c	production rate of osteoclasts	1/day	1.2
S_0	reference value of the stimulus	-	0.0344
L	longitudinal length of the sample	mm	1
l	width of the sample	mm	0.2
h	thickness of the sample	mm	0.01
L_m	average load	N/mm	2

Figure 79: Summary of the mathematical formulae leading to the equilibrium equations and the table of values and definitions of the parameters proposed in the paper of Rapisarda et al.

Transfer

The ceiling of the former zoology auditorium in the University of Freiburg, designed by German architect Hans-Dieter Hecker in 1968, represents a classic application of the abovementioned abstracted principle. Since concrete is highly resistant to pressure forces, and steel to tension forces, reinforced concrete is qualified to play the role of cancellous bone in this analogy, and it is possible “to accept higher pressure- or also tension-stresses for the benefit of reduction of bending stress” [5].

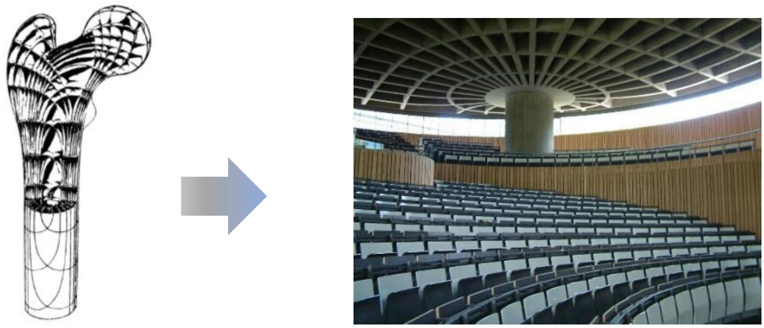


Figure 80: From the femur bone to the lecture hall

Hecker developed a non-symmetric design for the ceiling that covers the large lecture hall without resorting to space and vision compromising indoor columns, as shown in the following schematic drawing (Fig.81), thanks to its isostatic ribbed structure driven by three main support elements: one hollow reinforced concrete pillar and two curved wall supports [63]. The diameter of the ribbed slab measures 23,86m [66].

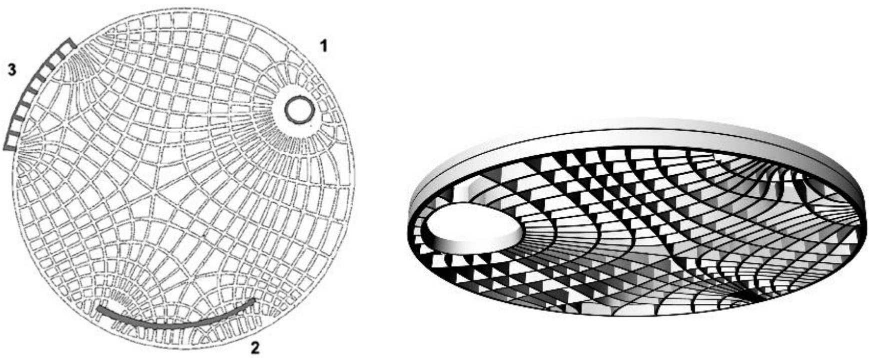


Figure 81: Schematic drawing of the isostatic ribs

The state of equilibrium achieved by the design of the ceiling rests on the fact that the reinforced concrete ribs follow the stress trajectories, the same way bone trabeculae are built in the femur [63]. Analogous to bone architecture, this has also helped “build a slab of maximum strength by using as few building material as possible” [63].

Figure 82: The ceiling of the zoology lecture hall

Olga Speck et al. classified Hecker’s approach, based on a decision tree, as a “functional biomimetic and biomorphic product” (Fig.84), which corresponds to a transfer of principle, morphology, and function, without direct use of living organisms [66]. According to Speck et al., Hecker expressed that the ribs in the lecture hall slab share the same function with the cancellous bone trabeculae of the femur. They believe the geometrical arrangement of the isostatic ribs, led by the given structural conditions, “guarantees the most possible stability together with the lowest possible material input” [66].

Figure 83: Scale model of the slab with isostatic ribs

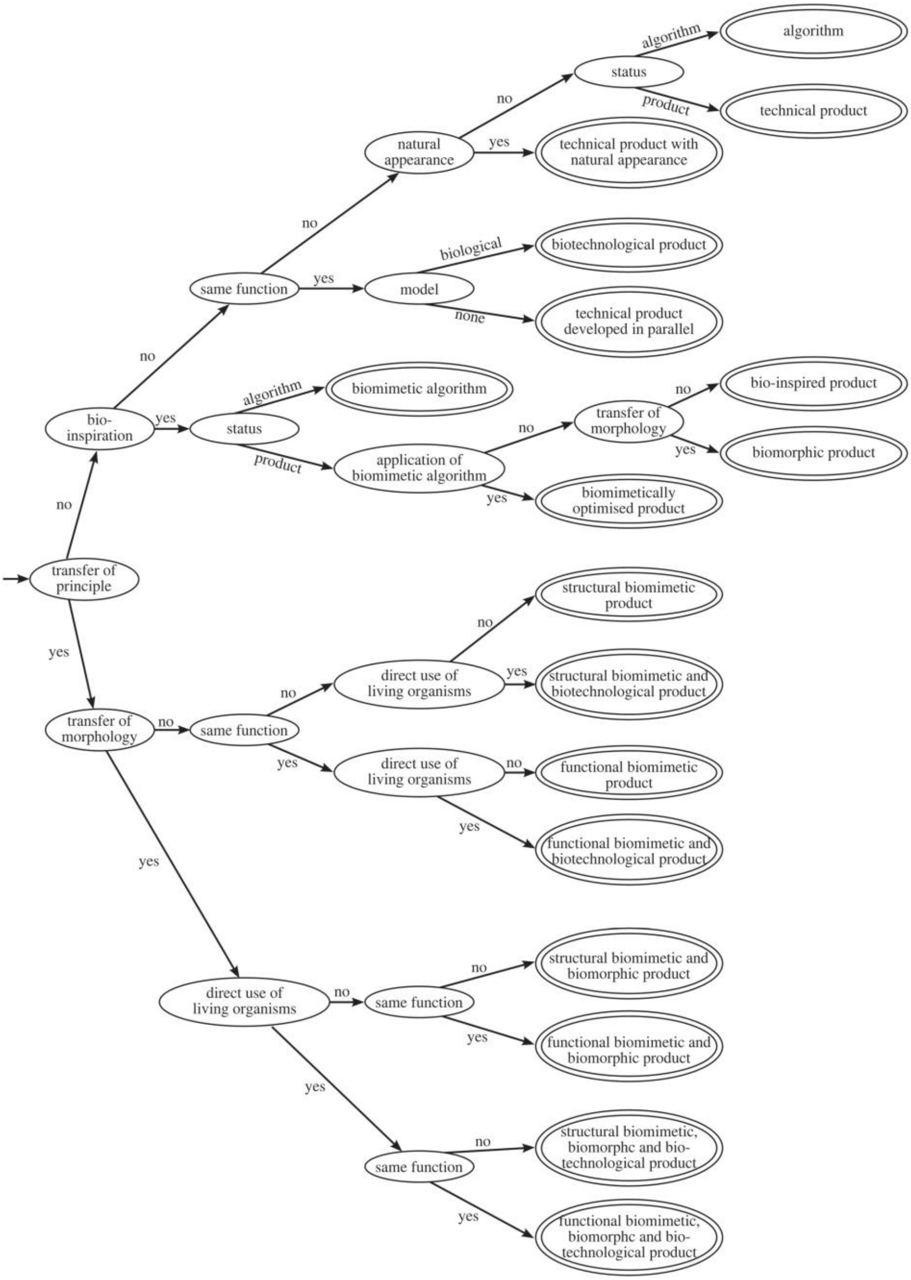


Figure 84: The decision tree used by Speck et al. to classify biology-derived and technology-derived products and algorithms

Related examples

In 1953, Pier Luigi Nervi used the same principle in the design of the Gatti Wool Factory in Rome, where "the ribs and downstand beams... precisely follow the lines of principal stresses" [16].

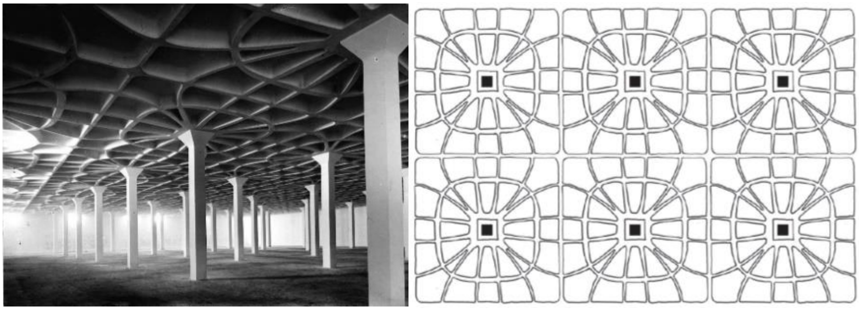


Figure 85: Gatti Wool Factory ribbed floor system

According to Rossmann and Tropea, the layout of the ceiling soffits in this building shows an identical course as the theoretical load bearing lines, and the concrete beams highlight the increase of the shear force distribution towards the supports [12].

Halpern et al. presented an evaluation of Nervi's ribbed floor slab systems, including the example of the Gatti Wool factory, and suggested different numerical methods that deliver the necessary stress analysis to find adequate rib arrangement patterns. According to Halpern et al., Nervi's work utilized the strain gauge methods, which "rely on devices capable of measuring strain via mechanical, optical, electrical, acoustical, and pneumatic methods, to determine the displacements and stresses at points on a small-scale model"; and the photoelasticity experiments, which help visualize stress distribution and generate isostatics [67].

In order to analyze the 5 by 5 meter slabs supported by one central column each, determine the corresponding principal bending moment trajectories, and obtain the primary and secondary bending moment angles, Halpern et al. evaluated a quarter of a slab using a software called Isostatic Line Tool. They displayed the result of the analysis in the following figure, where the primary isostatics that correspond to maximum principal bending moments are represented by red lines, and the secondary isostatics that correspond to the minimum principal bending moments by blue lines [67]. "The grey and white outline shows an approximate plan of the Gatti Wool Factory floor, to illustrate the correlation between the theoretical isostatics and the as-built rib pattern" [67].

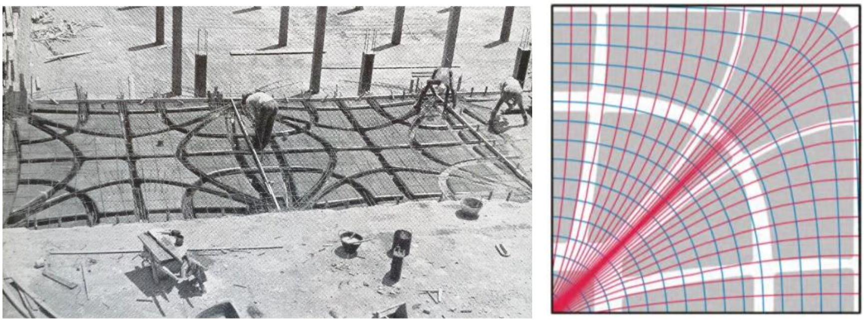


Figure 86: Gatti Wool Factory quarter slab analysis

A similar representation was made for another example of ribbed floor constructions designed by Nervi in 1961, namely the Palazzo del Lavoro (Palace of Labor) in Turin. A strong correlation "between the theoretical primary and secondary isostatics and the as-built plan" is similarly demonstrated in this case [67].

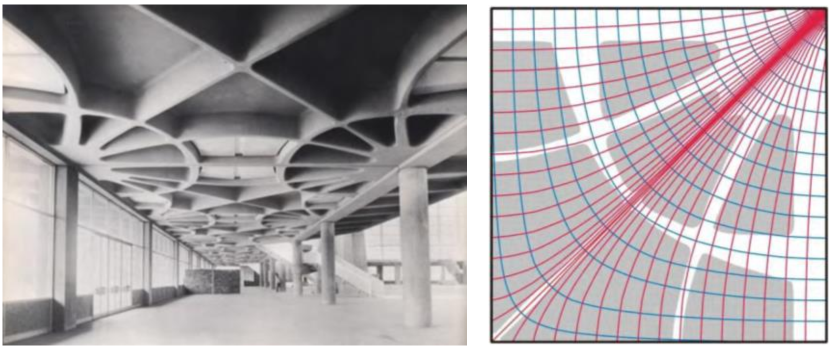


Figure 87: Palace of Labor quarter slab analysis

3.1.3 Los Manantiales restaurant, Xochimilco - Mexico

1958, Félix Candela

Figure 88: Los Manantiales restaurant

Biology

According to Nachtigall, nature makes ample use of highly pressure-resistant yet material-saving shell shapes in plants and animals. One example he highlights and considers extremely resistant to compression loads is the *Tridacna* shell, also known as the giant clam [34]. The giant clam is characterized by the hyperbolic paraboloids forming both valves, with a radius that extends “from the umbo to the periphery of the generating curve” [68]. Besides the sheer mass factor that builds a “strong overall system” [69], the oval curvature of the clam’s valve gives the system a larger range of resistance to vertical compressive loads in terms of bending stress when compared to flatter shells with larger radii.

Figure 89: The giant clam Tridacna

Abstraction

With the use of the right material and adequate thickness, hyperbolic paraboloidal structures can be particularly stable and pressure-resistant. The intersection of multiple hyperbolic paraboloids extending along quasi-concentric directions enables a conservation of the load-bearing behavior of curvatures with smaller radii, while keeping the entire structure flat and compact.

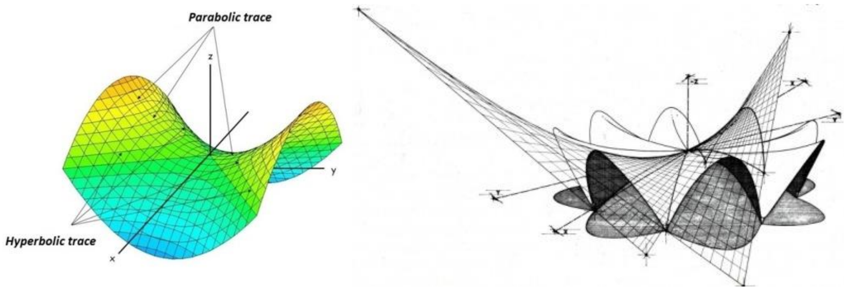


Figure 90: Hyperbolic paraboloidal structures

Transfer

The Tridacna-like hyperbolic paraboloid structure inspired Félix Candela to design the “Los Manantiales” restaurant in Xochimilco, Mexico City. Implementing nearly the same geometric properties and using the benefits of arched concrete shells in terms of load bearing capacity, he was able to obtain a long-spanning, self-supporting shell structure that had a thickness of only 15mm [8].

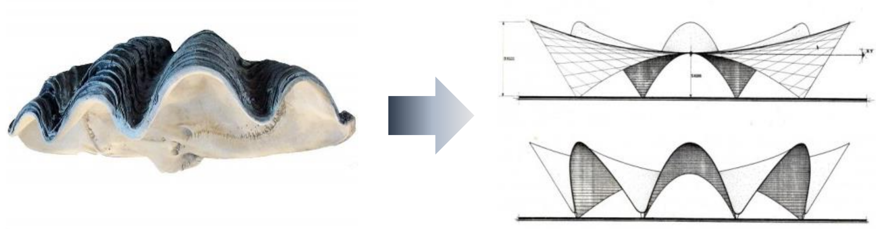


Figure 91: From the giant clam to the restaurant

While Gruber describes Candela's project as "a cross vault consisting of four connecting hyperbolic paraboloids", which she considers different from natural shells where "curves are focused on a single center" [33], Aziz reports that the form was generated by "eight separated hyperbolic forms connected to each other along the shared valley joint" [70]. David P. Billington, who organized a conference in 1972 at Princeton University with the participation of Félix Candela himself, states that the roof of Los Manantiales was "made up of eight hyperbolic paraboloidal vaults arranged on a circular ground plan of about 140 feet in diameter" [71], which corresponds to 42,7m.

Figure 92: The structure of Los Manantiales restaurant

Related examples

Shortly before his death, Candela designed a very similar structure in Valencia in 1997 called the Submarine Restaurant of L'Oceanogràfic. Tomás and Martí gave an overview of the main geometric details constituting this fiber-reinforced concrete structure: The height that reaches 12,27m at the free edge, the thickness that increases gradually from 0,06m to 0,225m at the intersection of the ribs, the measures of the octagon base, and the angles of axes forming the plane that characterizes the hypar each lobe belongs to. There are eight radially symmetrical lobes of which the "groined vault system" of the restaurant is composed [72]. Domingo et al., who assisted with and contributed to the design of the building, published the following scheme based on Candela’s blueprints and ideas (Fig.93) [73].

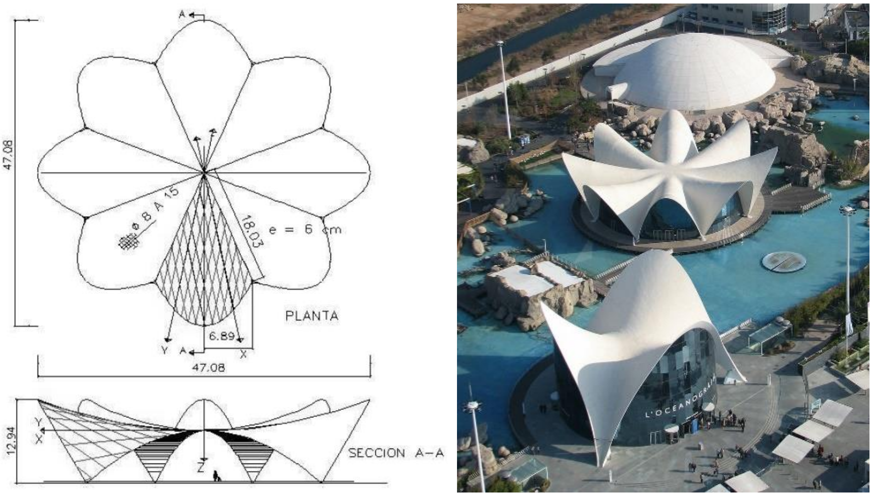


Figure 93: The structure of the Submarine Restaurant of L’Oceanogràfic

According to Tovar, two types of ribs were used to stiffen the thin shell of concrete: Main ribs that spread from the support to the center of the structure, and other ribs that surround the small central hole made in the shell to avoid “meshing problems arising from the distortion of the elements generated” in that area with very acute angles [74]. The following sequence of pictures demonstrates the building process of the underwater restaurant, or the “JChypar roof,” as Domingo et al. refer to it [73].

Figure 94: The formwork of the Submarine Restaurant of L’Oceanogràfic

Figure 95: The Submarine Restaurant of L'Oceanogràfic in Valencia

The idea of building linked hyperbolic paraboloids was manisfested before in the design of Madrid's Zarzuela Hippodrome, only with parallel extruded arches. This project was realized in 1935 by Eduardo Torroja, one of the elite engineers that marked the history of reinforced concrete thin shell construction. The 13m long cantilevered canopies were 60 to 145mm thick. [45]

Figure 96: The Zarzuela Hippodrome in Madrid

Mentioned by Nachtigall as another inpiration from the clam's shape, the Royan Market Hall in France presents a form of radial wave roof [75] with a span of 52,4m [34]. It was designed by engineer René Sarger and architects Louis Simon and André Morisseau, and was completed in 1956 [76].

Figure 97: The Royan Market Hall in France

Another example highlighted by Pohl and Nachtigall that showcases the same principles and is characterized by a Tridacna-like roof structure is the National Circus of Bucharest, built in Romania in 1960 by architects Porumbescu, Pruncu, and Ruleahe, and spanning a distance of 66,6m [8].

Figure 98: The National Circus of Bucharest

3.2 Masonry structures

3.2.1 King's College Chapel, Cambridge - England

1515, John Wastell

Figure 99: King's College Chapel

Biology

Another biological system characterized by its ribbed structure is the pilgrim's scallop *Pecten jacobaeus* [8], also called the Mediterranean scallop [77]. This bivalve mollusk can have a width of up to 10cm [8] and displays regularity in the folding angles and distances between the ribs. With the rigidity of its shell, the scallop possesses a strong and compact structure that has drawn the attention of multiple engineers and designers, including Robert Le Ricolais, who had particular interest in spatial structures and put effort into finding suitable analogies in natural systems, like the skeleton of Radiolaria in the 1940s [75].

Figure 100: The pilgrim's scallop Pecten jacobaeus

Abstraction

Equidistant ribs constitute a statically stabilizing type of structure that adds significant strength and rigidity to the system. In some cases, these ribs have a nearly sinusoidal curvature and parallel arrangement, in others they are arranged concentrically with constant angles between the ribs forming radially alternating waves as seen in the scallop's shell. The first case reminds of Le Ricolais's abstraction of this principle to conceptualize "a structural system consisting of perpendicularly crossing corrugated panels", which he called "isoflex" (Fig.101) [8]. The second case recalls a scaffolding technique used in the construction of thin-shell masonry buildings.

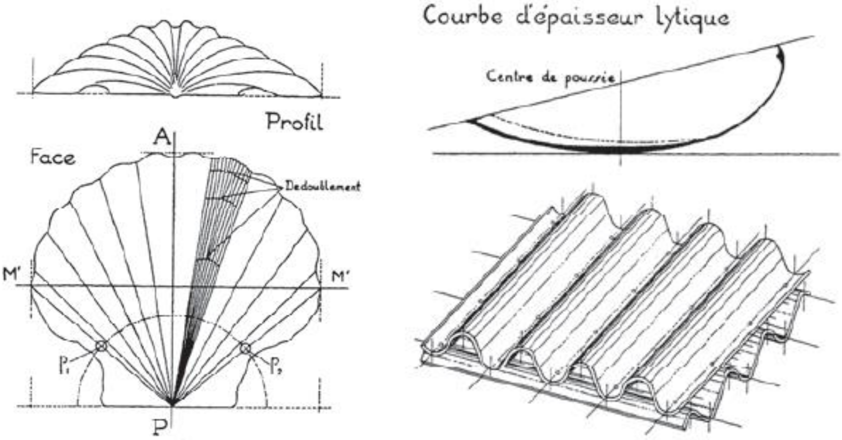


Figure 101: "Isoflex" abstraction from the pilgrim's scallop

Transfer

This technique was used in the roof structure of King's College Chapel in Cambridge, England. "The fan vaults at King's College are the largest in the world, spanning 12,66 meters", with 10cm of thickness in the panels [78]. They were built by master mason John Wastell, and the chapel was completed in 1515 after sporadic periods of construction. This roof represents an obvious match to the Mediterranean scallop in terms of geometry and shape, but it also implements the same structural behavior of the ribs observed in the biological system, and benefits similarly from the added rigidity and strength. These ribs are either carved directly from the voussoirs of the conoids, or "set back with a shelf on the upper side of the vault to receive the panels of the vaulting conoids," depending on their location [78].

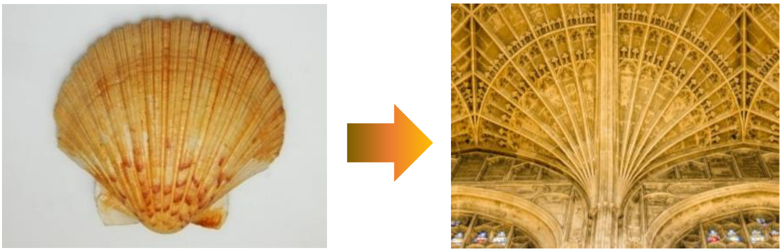


Figure 102: From the pilgrim's scallop to the scaffolded ceiling

Based on Block and Davis's assessment of this scaffolded ceiling, the vaulting quadrants are composed of a central spandrel panel and four quarter fans. A transverse arch separates each two successive quadrants, and a transverse ridge is found at the intersection of the fans where weight from the upper side is applied, while a longitudinal 88,5-meter long ridge runs along the entire axis dividing the chapel in half [78].

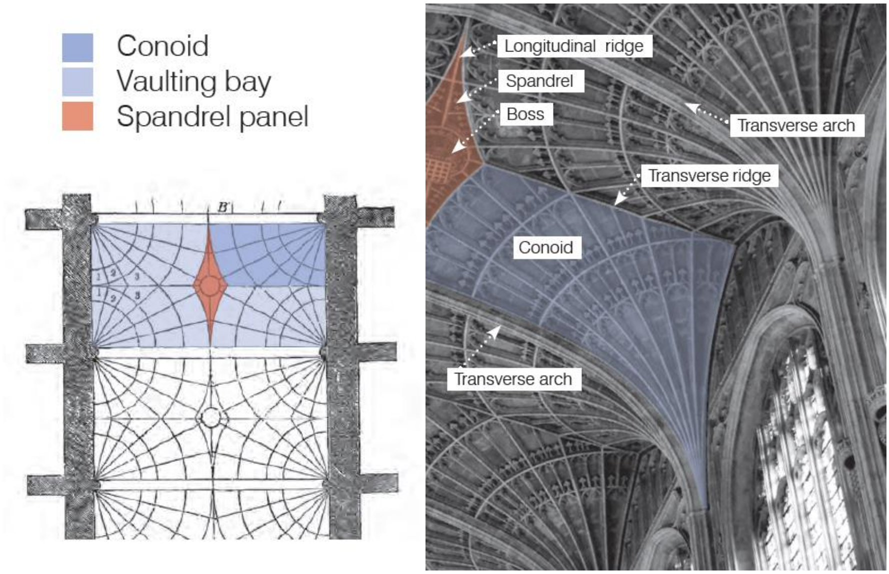


Figure 103: The structure of the fan vaults

The high horizontal thrust of the vaulting is contained mainly by the fill at the edges. A truss that includes steel tension ties is installed over each transverse arch that is "supported with sizable masonry columns, which carry the pinnacles and convey the thrust vertically down through the fan", and over each transverse ridge that is "supported by a relieving arch, which distributes the load of the vault and roof truss along the wall" [78].

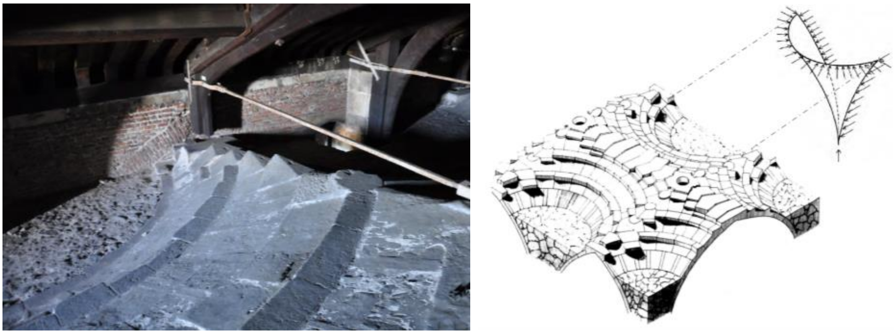


Figure 104: The roof area above the vaulting system

Philippe Block believes “the added weight of the transverse ridges is critical to maintaining equilibrium of the vault system, so that the thrust of the fan conoids stays with the area of the fill” [78]. The access to the roof has reportedly been limited in order to protect the precariously thin vaulting, since, according to Block and Davis, “the 10 centimeter thick panels of this 12,6 meter span vaulting easily transmit the vibration of the average-weighted footstep” [78].

Figure 105: The ceiling of King's College Chapel

With the forces running along the thin roof structure transmitted towards the side walls, a compensating vertical load is needed to adjust the direction of the line of action of the resultant force so it lies “within the cross-sectional thickness of the Chapel buttresses”. For this reason, masonry towers and pinnacles were added to the design. Their weight equilibrates “the thrust of the large-span and extremely horizontal vaulting”, as according to Block and Davis [78].

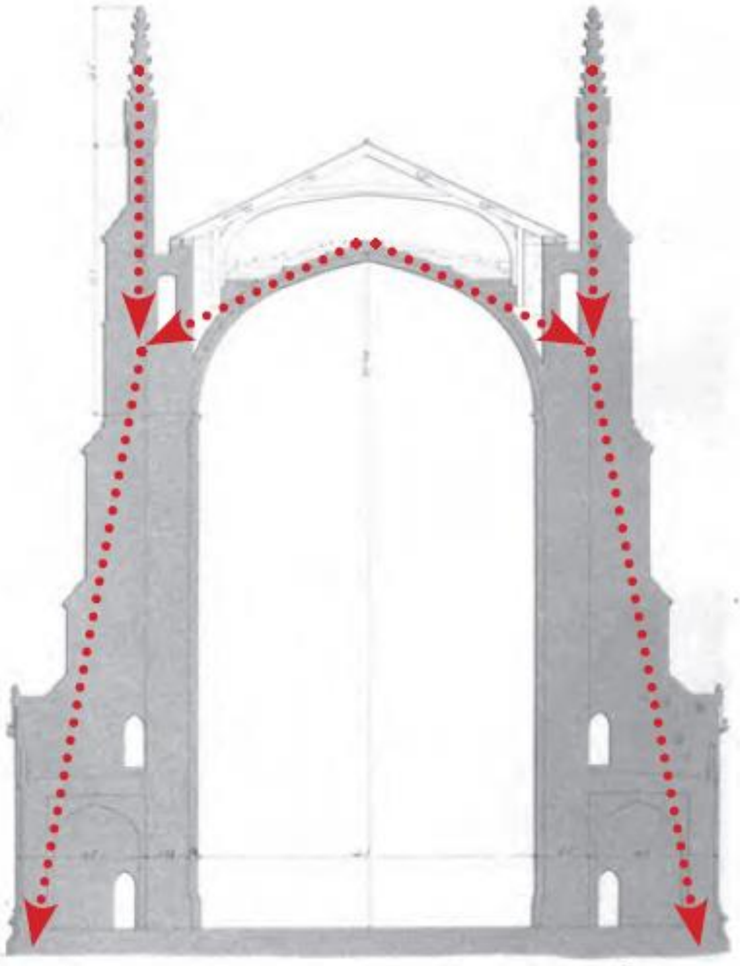


Figure 106: The line of action of the resultant force lying within the cross-sectional thickness of the Chapel buttresses

Related example

About 65km away from King's College Chapel, an almost identical roof structure is found at the new retrochoir of the Peterborough Cathedral, built between 1460 and 1515, most likely by John Wastell as well. The only visible difference between the two buildings is the absence of transverse ribs in the latter. [78]

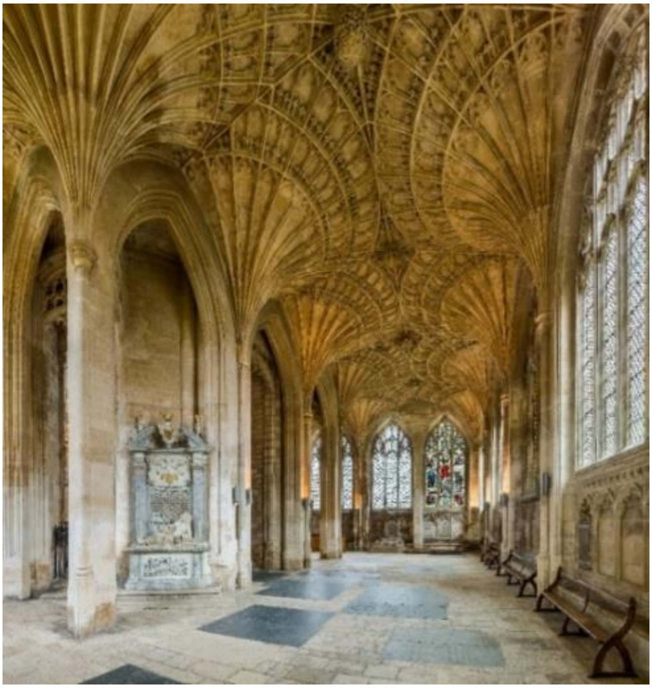


Figure 107: Peterborough Cathedral

A particularity of these fan conoids is that their geometry “can be rotated about a vertical axis with no change in curvature”, unlike typical quadripartite vaults (Fig.108) [78]. In the words of Sugár et al., their shape is “reminiscent of a shellfish or palm leaf” [79], which aligns with its comparison to the Pecten jacobaeus, like for King’s College Chapel.

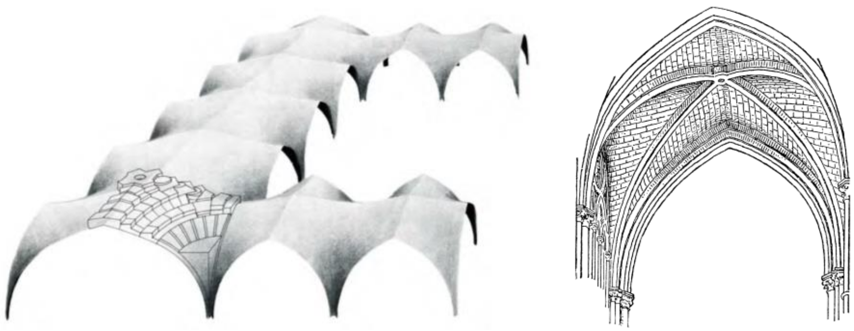


Figure 108: Peterborough Cathedral's fan conoids

3.3 Steel structures

3.3.1 The Gherkin, London - England

2003, Norman Foster

Figure 109: The Gherkin

Biology

The glass sponge *Euplectella aspergillum*, assessed previously in 2.8.1, is a sediment-dwelling marine sponge “that is anchored into the sea floor by a flexible holdfast apparatus consisting of thousands of anchor spicules (long, hair-like glassy fibers)”, as expressed by Monn et al. [80]. Internally, each spicule embodies “a solid core of silica surrounded by an assembly of coaxial silica cylinders”, of which the thickness downsizes gradually towards the periphery. Monn et al. hypothesized this de-escalation in thickness as “an adaptation for redistributing internal stresses, thus increasing the overall strength of each spicule” [80].

Figure 110: The glass sponge Euplectella aspergillum

Through their 2014 study, they were able to confirm this hypothesis by building a spicule structural mechanics model with fixed silica cylinders radii that maximize the transmitted forces "from the surface barbs to the remainder of the skeletal system" [80]. The resulting values of load capacity and measured radii showed great correlation with the biological model. This, as they concluded, highlights the benefits of the sponge's "elastically heterogeneous lamellar design strategy" and provides "potential design insights for the fabrication of high-strength beams for load-bearing applications through the modification of their internal architecture, rather than their external geometry" [80].

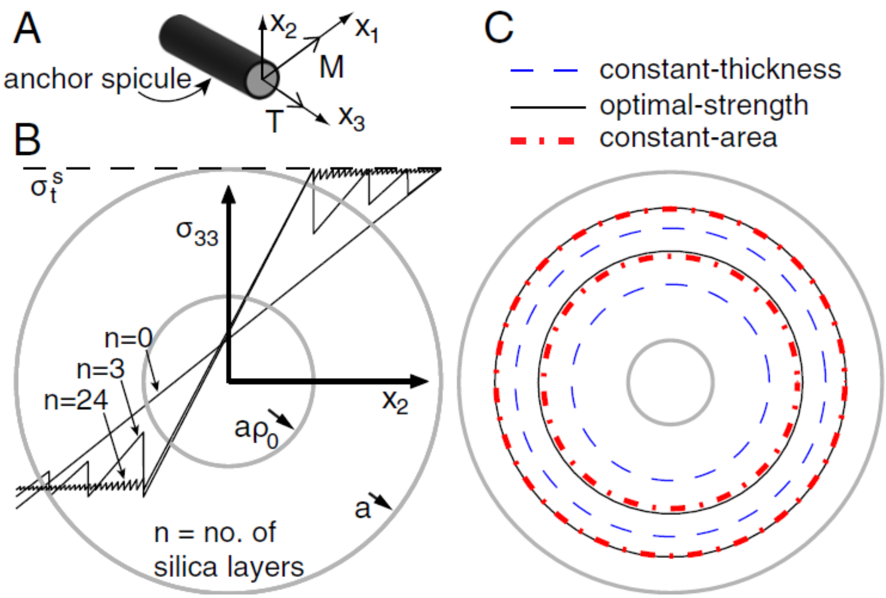


Figure 111: Study of the spicule model

According to Aizenberg et al., "the assembly of these spicules into bundles, affected by the laminated silica-based cement, results in the formation of a macroscopic cylindrical square-lattice cage-like structure reinforced by diagonal ridges", a design that demonstrates remarkable mechanical rigidity and stability [81]. A principal contributor to the structure's stability and its resistance to tensile and shearing stresses in particular is the beams' arrangement "in a rectangular lattice with ancillary crossbeams". Aizenberg et al. highlight that "the cylindrical structure is reinforced by external ridges that extend perpendicular to the surface of the cylinder and spiral the cage at an angle of 45°" (Fig.112). The diagonal elements are observed in every second square cell, in a grid of cemented parallel struts, in both vertical and horizontal directions. [81]

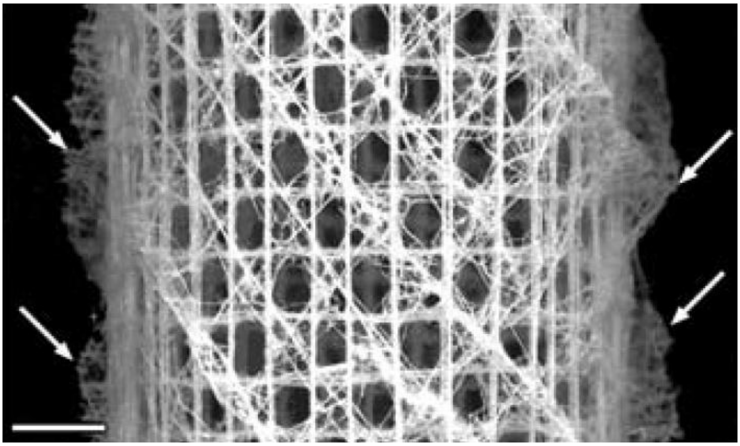


Figure 112: Fragment of the glass sponge's structure showing the square-grid lattice of vertical and horizontal struts with diagonal elements

Abstraction

The "gridded and braced layout" [16] observed in the walls of the Euplectella presents a structural model in terms of load bearing behavior. One of the main lessons learned from this biological system is that, for a structure that is subjected to dynamic lateral loads, water currents in the case of the glass sponge and wind in the case of high-rises and buildings, the "lattice-like exoskeleton and round shape help disperse those stresses in various directions" [82].

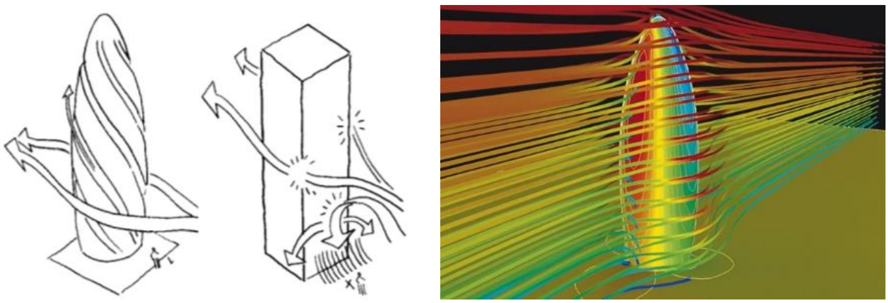


Figure 113: The wind flow patterns around a round shaped structure

More specifically, a "diagrid system" consisting of multiple diagonal grids on the coating surface of a structure exhibits "greater structural effectiveness in comparison with the traditional diagonal bracing located within the cavity of central cores or in the facade" [83]. Feng Fu studied this type of bracing system and summarized its main structural benefits as follows: "The triangular geometry of diagrid structures can effectively prevent structural failure as a result of lateral loads. Compared to conventional external bracing, it considerably minimizes numbers of columns, especially less requirement for corner columns. Diagrid structures can also resist shear distortion through the axial resistance of diagonal members. The combination of an interior core and the external diagonal bracing provides extra stiffness, therefore enabling greater heights". [83]

In a study conducted by Robson Brown et al. on the structural efficiency of the Euplectella aspergillum skeleton, which showcases the displacement resultant at different simulation times using a finite-element model and a scaled 3D printed construct (Fig.114), it was proven that "the compression response of the closed cell lattice arrangement was largely governed by the structure" rather than the material properties [84]. The results displayed by the biological specimen were, in fact, compared to engineering analogues and "a very similar initiation and propagation failure pattern" was demonstrated when subjected to compression loading [84]. This strongly defends the legitimacy of the abstraction of the sea sponge's structural behavior and its potential in biomimetic design. Monn et al. also consider it a "bio-inspired design strategy" that has a significant impact on the "new generation of man-made structural materials" [80].

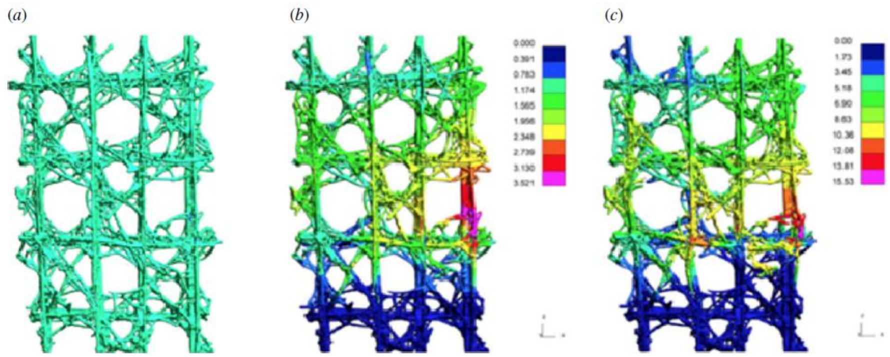


Figure 114: Finite-element simulation on 3D printed skeleton

Transfer

Arguably the most common reference when it comes to the application of this bio-inspired structural design is the 30 St Mary Axe skyscraper, known as the Gherkin, located in the City of London, and standing at 180m tall [83]. It was designed by Foster & Partners architects with Arup in structural engineering, and was completed in 2003.

Figure 115: From the glass sponge to the Gherkin

Singh and Nayyar describe the Gherkin as "an elongated, curved shaft with a rounded end,... sheltered uniformly around the outside with glass panels and... rounded off at the corner" [85]. According to Aldersey-Williams, the building's analogy with the marine organism is indicated by the external lattice similar to an exoskeleton that consists of "a steel structure running in three interlocked directions to form a rigid framework", instead of the rigid silica tracery [86].

Figure 116: The external lattice structure of the Gherkin

Terri Meyer Boake, professor at the University of Waterloo, assessed the Gherkin from a structural point of view, along with multiple other diagrid structures, considering how it “defined the high-rise diagrid building typology”, being the first tower of its kind. The “unusual geometry”, in the words of Dominic Munro, required several specific design solutions in order to adjust to a number of constraints, such as the variation of “the floor span, orientation, and intersection angles of the floor with the perimeter façade” along the entire building [87]. For the floor plan, a “six-finger” arrangement around a circular core hub in the center was chosen (Fig.117). Yet with the presence of a diagrid structure, the core was not necessary for wind forces resistance, which allowed its design “as a steel structure based on an open plan to provide flexible space planning”. Boake also believes that foundation loads were reduced due to the transfer of “responsibility for wind resistance and lateral stability from the core to the perimeter diagrid”. She explains that implementing the column-free principle of the floor areas was aided by the inclined placement of these “in the perimeter double façade zone that is situated between the exterior curtain wall glazing system and the interior glazing system”, as they form the diagonal members of the diagrid system. [87]

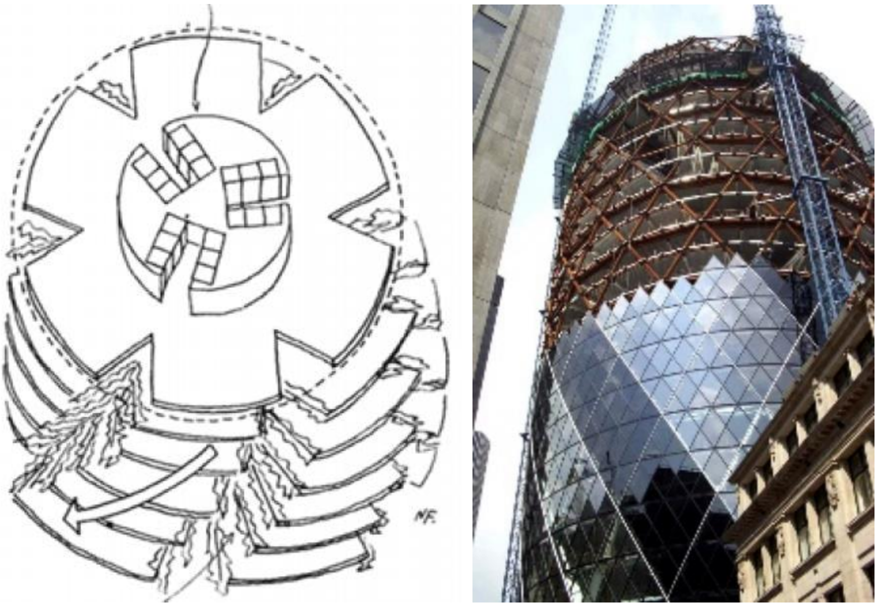


Figure 117: The six-finger arrangement around a circular core hub in the center

The columns rise from the six finger base, spiral up around the building, and form a symmetrical diagrid, leaving six triangular voids used for ventilation. According to Boake, the triangulation of the tapering diagrid and the twisting of the floor plan at every floor level following the diagrid's helical lines "avoided the need for large cantilevers in the floor slabs and balanced the diagrid structure". [87]

At this point, the diagrid consists of diagonal members that are connected by nodes at alternating floors. Due to gravity loads, these diagonal elongated columns are subjected to an outward push that needs to be restrained. In order to accomplish that, Arup added horizontal rods to the design, referred to as "hoops", which connect the nodes and "resist the forces arising from the curved shape" [87]. Another significant "outward thrust around the mid-height of the building", caused by the tilt of the columns on a three-dimensional level, is contained by these hoops. As expressed by Boake, "the hoops act as tension rings for the middle and lower sections of the tower", while "at the top of the tower, where the loads are lighter and the diagonals more steeply inclined, the rings act in compression". Further, she emphasized the hoops' contribution in the stability of the tower and its resistance against asymmetrical or horizontal loading conditions, by turning the diagrid "into a very stiff triangulated shell". [87]

Figure 118: The horizontal rods connecting the nodes and resisting the forces arising from the curved shape

In addition to the resulting diagrid pattern of large diamonds at the intersections of tapering columns in opposite directions, a curtain wall system of smaller scaled diamonds and triangles was used to better fit the opted curvature of the tower. At entry points at the base of the building, “large sections of the diagrid break away” from this curtain wall, creating a colonnade as shown in Fig.119. According to Boake, “this release of the structure from the building enclosure accentuates the strength of the diagrid as a structural system”. As observed in the glass sponge, the structure “tapers inward at the base” unlike the majority of tall buildings that “use an enlarged base for rigidity”. [87]

Figure 119: The base of the building

Related examples

The concept of diagrid structures has been implemented in the design of many other high-rises across the world in the last few years. One that emphasizes the triangular arrangement of glass panels in a more obvious way and tends to “accentuate the expression of the diagrid on the building” [87] is the Hearst Magazine Tower, built in Midtown Manhattan, New York City, in 2006. After the Gherkin, the architects of Foster & Partners decided to use the diagrid structure approach once again to “provide sufficient stability on the perimeter without requiring additional columns between the exterior wall and the core”. One of the challenges that spurred the designers to make that decision was the obligation to “push the core towards the backside of the building” due to the street exposure of the site on three of its four faces, which lessens the role of primary stability provider for the building. Therefore, the ability of diagrid structures "to carry both gravity and lateral loads without needing to rely on the core to resist lateral loading" was called for. The core was ultimately built "as a braced frame steel structure to assist with carrying the lateral loads", and a composite concrete-steel structure was added to the lowest 10 floors to provide a safer load transfer between the columns, braces, and the upper part of the building. [87]

Figure 120: Hearst Magazine Tower, New York, USA

Although a dominant number of diagrid structures cited in literature are considered frame structures, such as the CCTV Building in Beijing and SOM's design proposal of the Lotte Super Tower in Seoul, their load transferring behavior through the surface of the outer "shell" represents technical common ground with typical forms of shell structures. This explains the application of this principle in the design of domes, roofs, and long span thin structures, as seen in the Technosphere of Dubai (Fig.121).

Figure 121: CCTV Building, Beijing - Lotte Super Tower, Seoul - The Technosphere, Dubai

A more recent project of Skidmore, Owings & Merrill (SOM) that demonstrates a comparable approach for tall buildings, in which the outer surface plays the major role in load transfer, is the CITIC Financial Center in Shenzhen, China. Designed in 2019, this building exemplifies the concept of Michell structures, formulated by Ostoja-Starzewski as a way to create “a minimum-weight design of a planar truss that transmits a given load to a given rigid foundation with the requirement that the axial stresses in the bars of the truss stay within an allowable range $\sigma_0 \leq \sigma \leq \sigma_0$” [88].

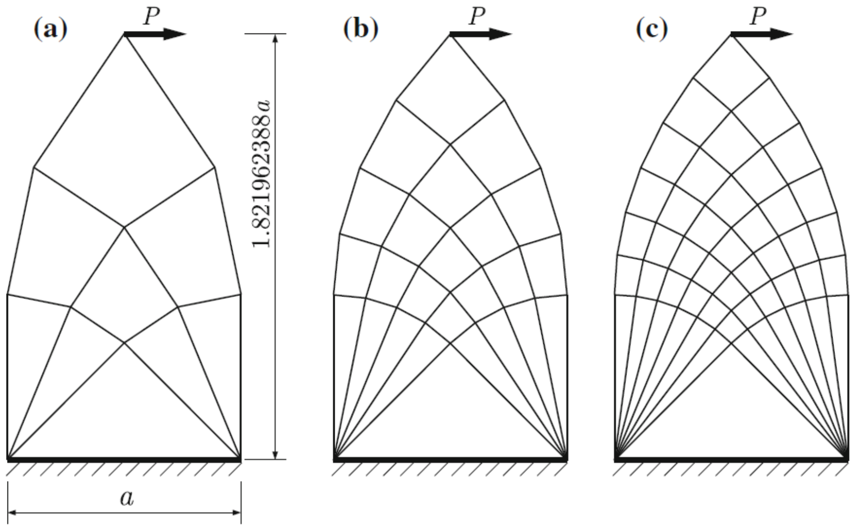


Figure 122: Michell structures - Three suboptimal designs of the least volume trusses transmitting a given force to a straight rigid support

Lewiński et al. stated that “the layout of bars of these structures follows the trajectories of specific strain fields” [89], which, based on the previous findings of this thesis, is a very common structural principle in biological systems. In their assessment of the equilibrium problem of Michell structures in a plane loading case, a fundamental consideration they made was the fact that the parametrizing lines coincide with the trajectories of principal stresses, and the edges A1A2 and A2A3 are subjected to tractions of intensity p, as represented below (Fig.123) [89].

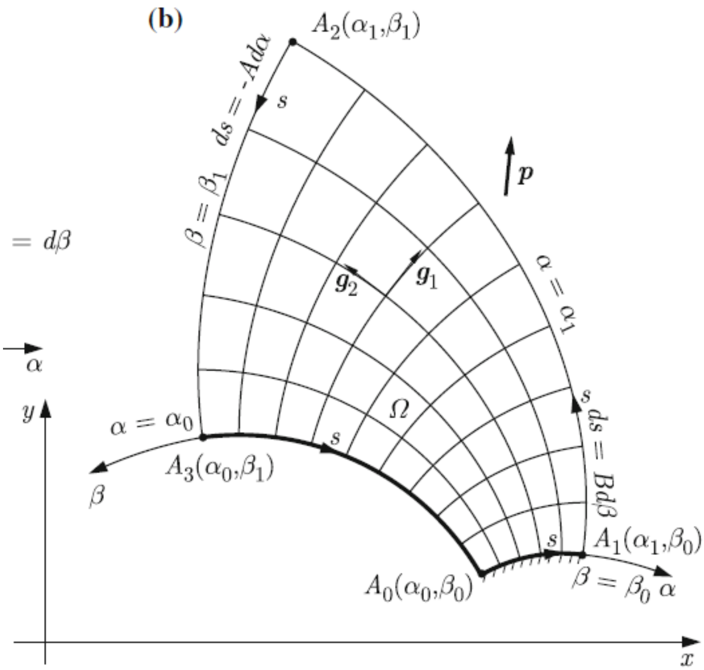


Figure 123: The design domain and its parameterization

In a biomimetic context, the design of the CITIC Financial Center, using the Michell structure approach, was inspired by the understructure of the tree leaf, as according to Professor Zhou Ying, vice director of the International Joint Research Laboratory of Earthquake Engineering at Tongji University.

Figure 124: The structure of the tree leaf

It was during a personal visit to the shaking tables laboratory at the Siping campus of Tongji that Professor Zhou presented the following miniature of the CITIC tower, on which the seismic design efficiency of the building was tested (Fig.125).

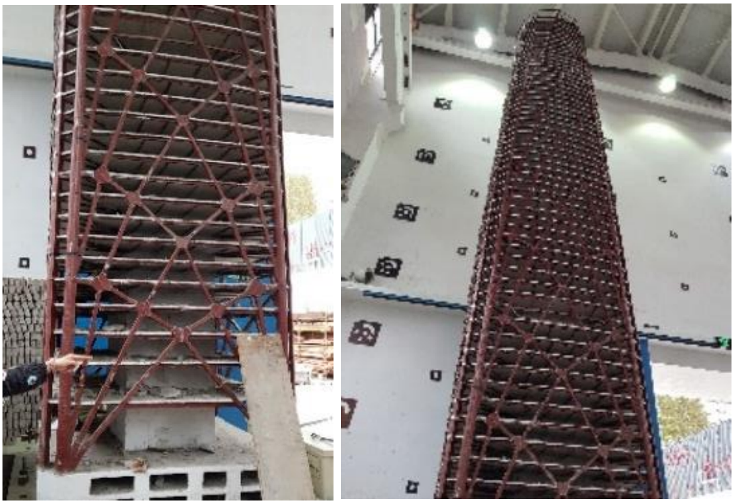


Figure 125: CITIC tower miniature at the shaking tables laboratory of Tongji University

The project consists of two towers that are 200 and 300 meters high and "include external bracings strongly inspired by Michell cantilevers". While the lower tower shows a "simplified layout of the optimal cantilever with only two members at each level", the higher tower uses three parametric lines for the discretization of its cantilever layout. The principal benefit of this particular design is the significant resistance to "seismic loading acting at structure base and wind loading prevailing at structure top". [89]

Figure 126: Design concept of the CITIC Financial Center in Shenzhen, China

3.3.2 The Eden Project, Cornwall - England

2001, Nicholas Grimshaw

Figure 127: The Eden Project

Biology

Belgian physicist Joseph A.F. Plateau was "the first person to have studied the geometry of soap bubbles", state Almgren and Taylor [90]. Based on Plateau's study, three basic rules governing the geometry of soap bubbles were introduced: "First, a compound soap bubble or a soap film spanning a wire frame consists of flat or smoothly curved surfaces smoothly joined together. Second, the surfaces meet in only two ways: Either exactly three surfaces meet along a smooth curve or six surfaces (together with four curves) meet at a vertex. Third, when surfaces meet along curves or when curves and surfaces meet at points, they do so at equal angles" [90].

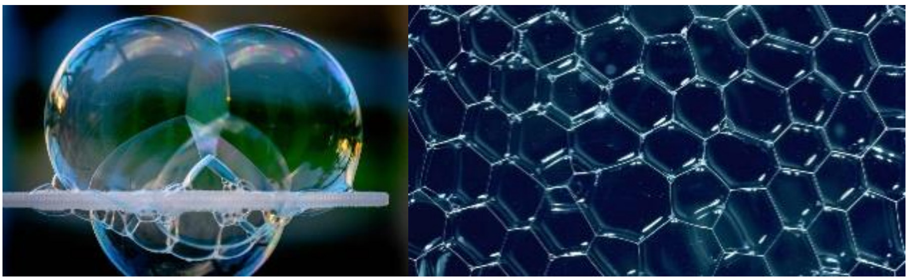


Figure 128: Soap bubbles

According to Almgren and Taylor, these three rules mathematically result from an area-minimizing principle, which is stimulated by the presence of unbalanced attractive forces between the molecules. In reaction to these forces and “in the absence of gravity and differences in air pressure”, the tendency of the liquid surface to “act as an elastic membrane” is manifested by a minimization of its surface area, resulting in the minimization of the surface energy [90]. Consequently, “when three surfaces meet along a curve, they do so at angles of 120 degrees with respect to one another, and when four curves meet at a point, they do so at angles of close to 109 degrees”, as displayed in Fig.129 [90]. The 109-degree angle is known as the tetrahedral bond angle and can be easily calculated using basic trigonometry rules (Fig.130).

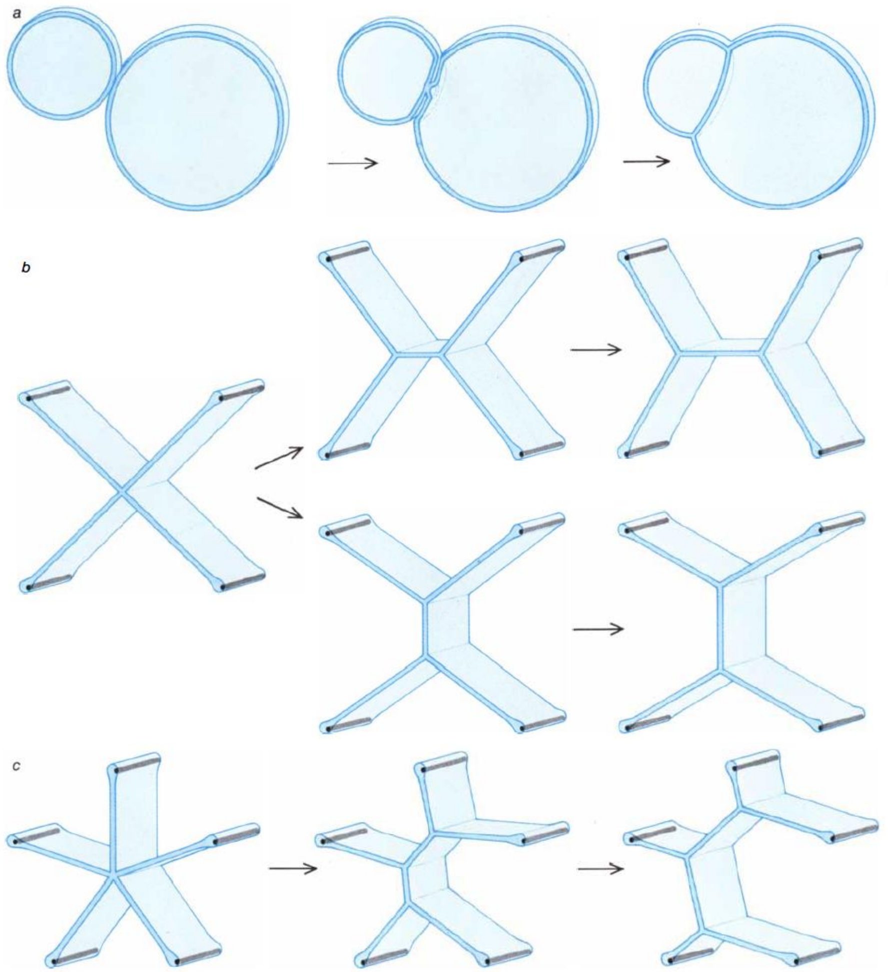


Figure 129: Cross-sectional illustration of bubbles meeting at angles of 120 degrees

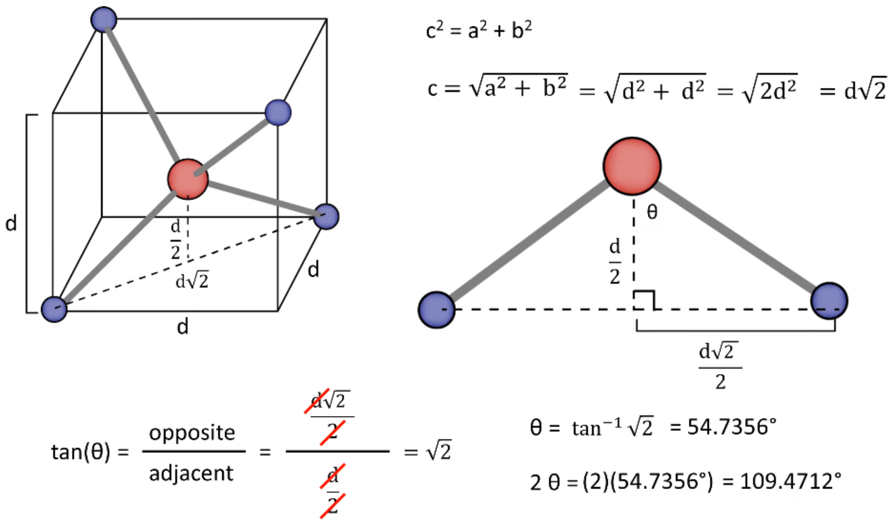


Figure 130: Calculation of the 109-degree tetrahedral bond angle

Andrew Borgart addressed the “bubble cluster method” with regard to radiolarians and the way they “condense their structure according to the flow of forces by controlling the diameter of the individual bubbles intersecting the surface of the global sphere which forms the radiolarian” [91]. The bubble clusters with smaller bubbles, reportedly showing larger amounts of membrane surface, display denser skeleton structures. Borgart believes the density “reflects the amount of stress that can be carried within the structure”, which explains the radiolarians’ strategy to adjust their skeleton grids geometry “according to the magnitude and the direction of the applied loads”. [91]

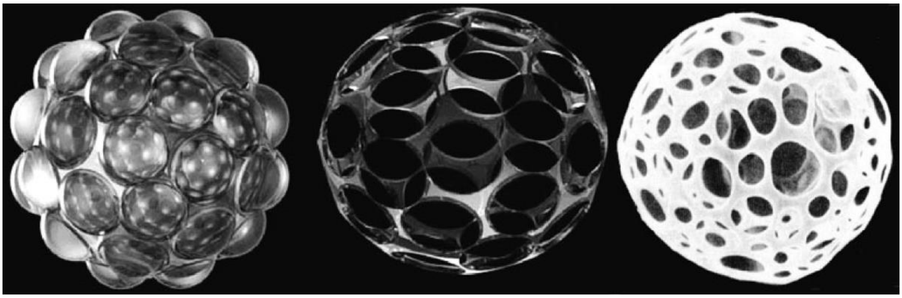


Figure 131: Bubble clusters, intersection of bubbles with sphere, and Radiolarians

Abstraction

Borgart abstracted this phenomenon into an optimization algorithm for Radiolaria-like structures. A division of the initially unloaded structure into "equal sized spheres in their closest packing" puts each sphere in the middle of six other spheres forming a hexagonal grid (Fig.131). Like a soap bubble, each sphere displays a state of membrane stress that verifies the Laplace-Young equation $P = 2\sigma / r$, with P the internal air pressure, σ the membrane stress, and r the radius. Due to the uneven variation of the internal stress when the structure is loaded, and because the goal is to keep the membrane stress constant, "the radius of each bubble will change according to its pressure". The smaller the radius, the higher the internal air pressure and accordingly the carriable loads. A simplified scheme exhibited by Borgart clarifies this concept of optimization (Fig.132). [91]

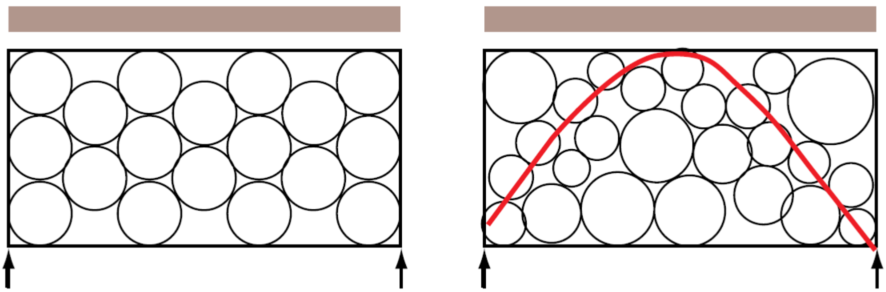


Figure 132: First and final step of the optimization

Transfer

Based on this optimization method and the equilibrium achieved by the hexagonal-framed configuration of adjoining bubbles, resulting from their area-minimizing process, Nicholas Grimshaw was able to design a complex in Cornwall, consisting of two artificial enclosures of spherical shape, known as the Eden Project. According to Nkandu and Alibaba, "each enclosure emulates a natural biome", which is defined as "a natural occurring community of flora occupying a major habitat" [82]. The Eden Project comprises a humid tropic rainforest and a Mediterranean biome. The first compartment is 240 meters long, 55 meters high, and 110 meters wide, while the smaller Mediterranean one has 135 meters of length, 35 meters of height, and 65 meters of width [82].

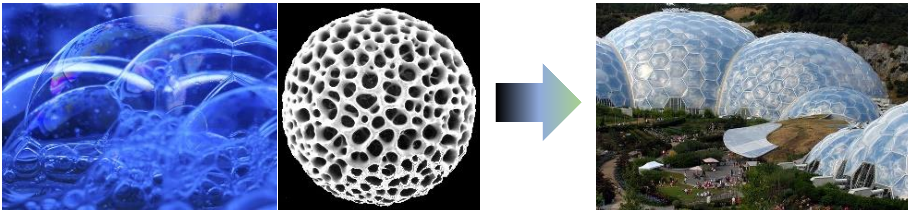


Figure 133: From the soap bubbles and radiolarians to the Eden Project domes

The structure of each biome consists of a series of geodesic domes. The domes are built with webs of interlocking steel tubes, and hexagonal pillows made from three layers of Ethylene Tetrafluoroethylene (ETFE), a light and strong material that allows the use of lighter steel frames [82].

Figure 134: Structure of the Eden Project biomes

Llorens states that "the structure of the biome domes in the Eden Project in Cornwall is optimized by using hexagonal frames to enclose the maximum surface area within the minimum contiguous boundaries" [92].

Figure 135: The hexagonal structure of the biomes

Related example

Another way of optimizing bubble clusters, according to Borgart, is the stimulation of foam. Based on Lord Kelvin's suggestion in 1887, "foam could be represented as a space partitioned into cells of equal volume with the least area of surface between them by a 14-sided space-filling tetrakaidecahedron (a truncated octahedron with 6 square sides and 8 hexagonal sides)" [91]. In 1993, Weaire and Phelan developed the Weaire-Phelan structure of artificial foam using an extended version of the optimization algorithm, which includes Boyle's law to allow deformations, volume change, and pressure change. This structure was later the basis for the design of Beijing's National Aquatics Center, known as the Water Cube. [91]

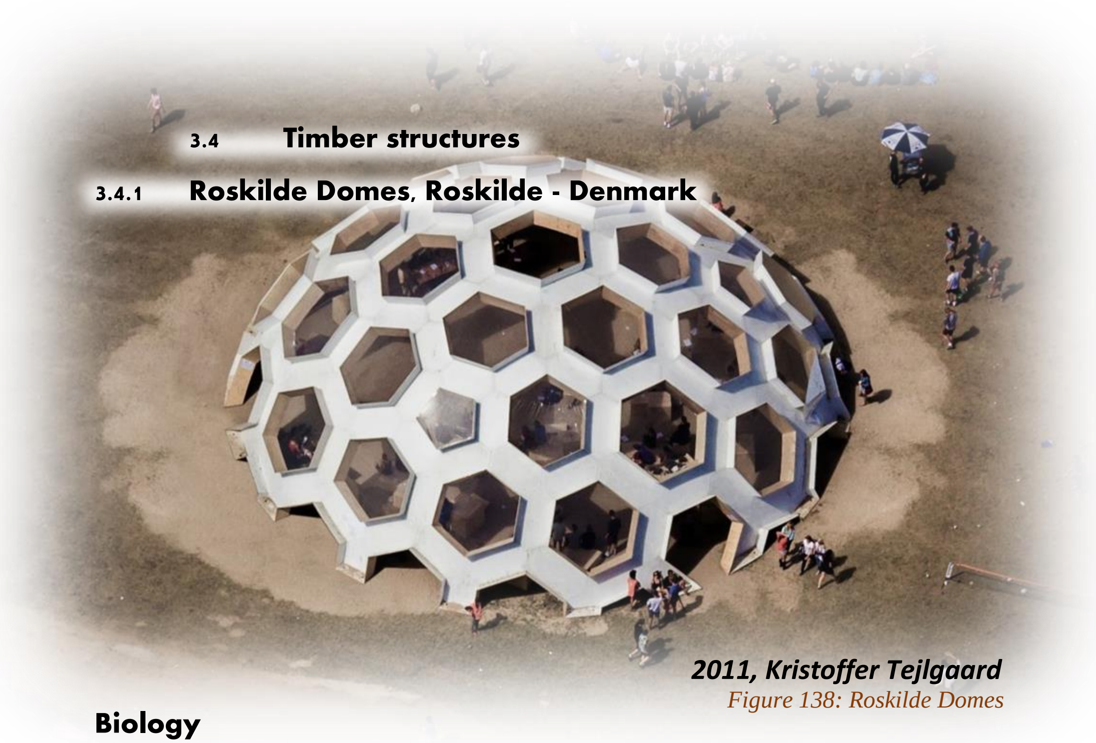
Figure 136: Beijing's National Aquatics Center, known as the Water Cube

The project took place in 2003 and was led by Arup, PTW Architects, and China Construction Design International (CCDI). It required 22.000 steel members and 12.000 nodes for the frame structure. The engineers opted for the use of ETFE panels instead of glass in order to reduce the supported weight and improve the seismic performance of the building [93]. The Water Cube is one of the most obvious implementations of the hardened foam structure in architecture, which Nachtigall and Blüchel described as an optimal lightweight structure with optimal angles that lead to high inherent stability [26].

Figure 137: The structure of the Water Cube

3.4 Timber structures

3.4.1 Roskilde Domes, Roskilde - Denmark



2011, Kristoffer Tejlgaard

Figure 138: Roskilde Domes

Biology

While layers of soap bubbles display a combination of irregular hexagonal shapes, “the honeycombs have an array of a perfectly hexagonal cross-section with a precise thickness and equal angles of 120 degrees between them” [94]. Compared to triangle and square sections, Kim and Park believe the hexagonal cells form walls of minimal total area [94], lightening the panels of the beehive while improving its structural resistance, and making it able to support about 45 times its own weight, as highlighted by Llorens [92].

Figure 139: Honeycombs

According to Nachtigall, the hexagonal honeycombs of the western honeybees *Apis mellifica* have a two-layer structure and meet in an intermediate layer in which the ends of the honeycomb are joined together in a geometrically favorable manner. They form a system of rhombic dodecahedra and the hexagonal edges are slightly stiffened. Nachtigall claims that this system is considered “the” lightweight prototype, in which a particularly large number of units fit in the same surface with the minimum possible use of materials. [34]

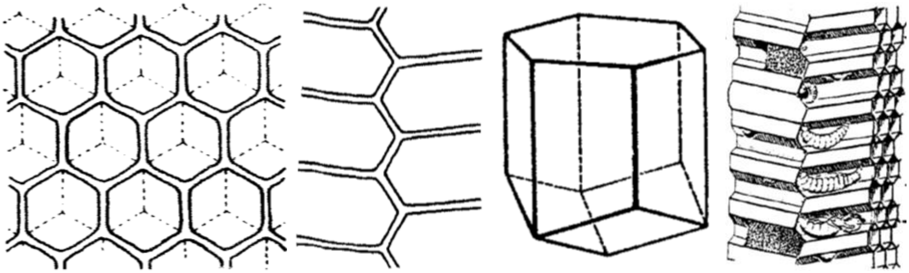


Figure 140: The structure of honeycombs

Abstraction

Gibson and Ashby studied the structures and properties of cellular solids, and assessed the mechanics of honeycombs on several levels. They believe that the honeycomb’s structure, consisting of a “regular array of prismatic hexagonal cells, epitomizes a cellular solid in two dimensions”, and thereby provides a basic structural model that helps better understand “the mechanics of... more complex three-dimensional foams” and “load-bearing structures” [95]. Gibson and Ashby also claim that understanding structural properties of honeycombs facilitates the assessment of comparable natural materials like wood, cancellous bone, and cork [95].

Due to the two-dimensional plate-like geometry of the honeycomb, a distinction between in-plane and out-of-plane loading has to be made. While “the out-of-plane stiffnesses and strengths (those in the X3 direction) are much larger because they require the axial extension or compression of the cell walls”, the in-plane stiffness (X1-X2) is lower due to the bending caused in the cell walls (Fig.141). After the linear elastic deformation due to the bending induced by compressive loads, and “depending on the nature of the cell wall material”, the deformation behavior of these walls then corresponds to either elastic buckling, plastic yielding, or brittle fracture (Fig.141). [95]

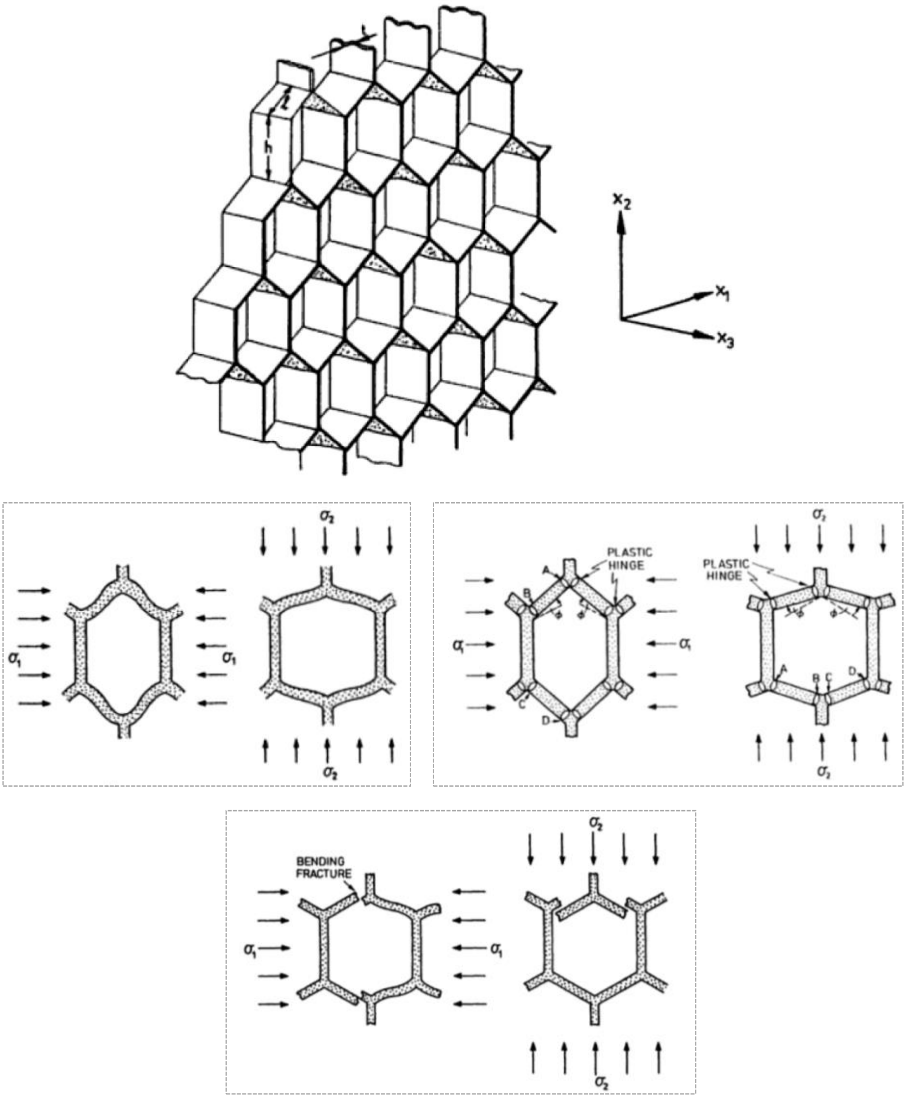


Figure 141: The deformation behavior of the honeycomb's cell walls (elastic buckling, plastic yielding, and brittle fracture)

In the case of in-plane biaxial loading (Fig.142), the linear-elastic response remains the same, while the three deformation modes that subsequently occur are slightly different from the those of the uniaxial loading cases shown above. Substantial changes influencing the stress required to cause buckling are observed in the elastic buckling mode, an increase of the plastic collapse stress “by a factor of 100 or more” leading to an elongated yield surface occurs in the plastic yielding scenario, and extreme failure surface shapes strongly depending on the stress state are likely to result from brittle fractures. [95]

In the case of out-of-plane loading, “the cell walls are extended or compressed (rather than bent) and the moduli, for hexagonal honeycombs, are much larger than those calculated... for in-plane loading” [95]. Additional moduli are needed as well for the description of out-of-plane deformations compared to in-plane, including “Young’s modulus E3* for normal loading in the X3 direction” [95].

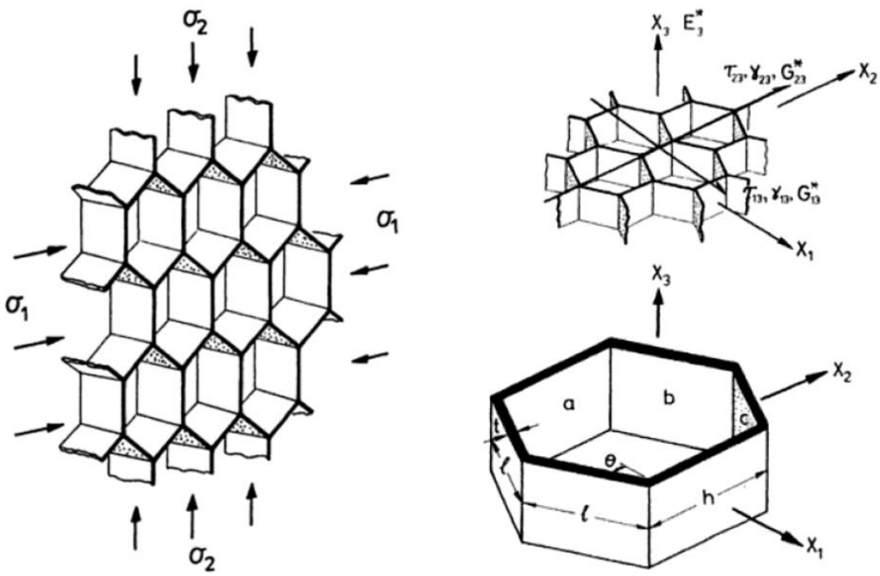


Figure 142: In-plane biaxial loading and out-of-plane loading

In a study by Hu et al. about the effect of cell wall angles on in-plane crushing behavior of hexagonal honeycombs, the relationship between the three main factors affecting the mechanical properties of honeycombs was described. These are “the cells’ configuration, the crushing velocity, and the honeycomb’s relative density” [96]. Hu et al. state that “the higher the impact velocity, the more obvious the effect of the honeycomb’s relative density, and... the lower the impact velocity, the more obvious the effect of the cell’s geometric configuration”. This statement is an interpretation of the following diagram that studies the “dependence of the normalized crushing strength on the cell-wall angle of honeycombs under x-directional crushing”, where the dashed curve of normalized density, which is defined as “the ratio of the honeycomb's density to the density of the regular hexagonal honeycomb", reaches its minimum value at an angle of 30 degrees before increasing rapidly with the cell angle [96]. Consequently, for the biaxial loading case, the regular geometric arrangement of honeycombs with 30-degree cell wall angles presents a suitable solution to achieve stability in both axes in the design of lightweight shell structures with hexagonal patterns.

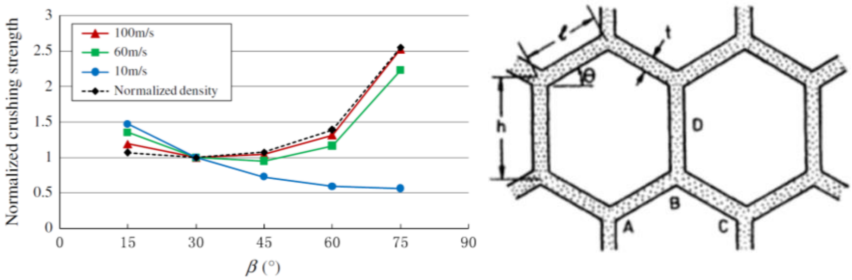


Figure 143: The dependence of the normalized crushing strength on the cell-wall angle

Transfer

One example of the more complex three-dimensional structures [95], of which the mechanical properties represent an extended version of the hexagonal honeycomb, is "the C240 giant fullerene cage" [97], a molecular allotrope of carbon characterized by its highly stable structure [98], which inspired the design of Kristoffer Tejlgaard's domes in Roskilde, Denmark.

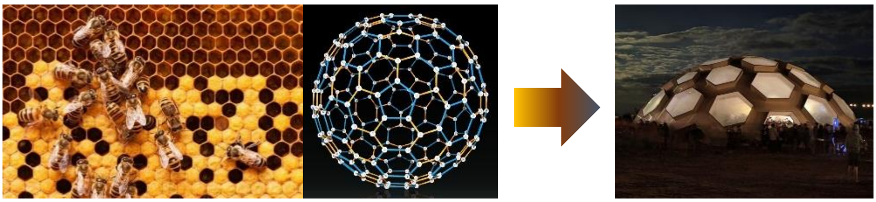


Figure 144: From the honeycomb and the C240 giant fullerene to the Roskilde domes

For the Roskilde Festival in 2011, Tejlgaard designed a 4,4-meter high geodesic dome that was built on site using prefabricated plywood elements. According to Henrik Almegaard, structural engineer on this project, the structure was considered a "frequency 4 Class II" hexagonal dome, meaning the overall geometry was "a spherical cap".

Figure 145: The 2011 Roskilde dome

Almegaard reported that “the final structural model had three levels”: the dome shell structure, the plate shell subdivision, and the grid shell structure [99].

At the first level, the structure was viewed as a dome shaped membrane shell, requiring the support of the edge to be unidirectional, with the exception of three points that necessitated bidirectional support. A ring beam was added to sustain the horizontal thrust. [99]

At the second level, Almegaard stated that “although the shell surface consists of a grid with either pentagonal or hexagonal holes, called openings, it was chosen to consider it as a plate shell structure... because this would ensure the spatial stability of the shell surface”. He explained that the elements around each opening were “considered as a planar frame having substantial rigidity in the tangent plane of the dome”. [99]

The third level was “used for the structural analysis, calculation of dimensions, and documentation of the load bearing capacity”. Two main conditions had to be checked so the local buckling capacity would be acceptable: The sufficiency of “the bending capacity in a tripod consisting of three elements connected at the top... to carry the self-weight of the three elements plus the design load of the wind pressure on the tripod”, and that “the deformations from normal forces in a hexagonal frame and the six connected elements under full design load” are insignificant enough that the load bearing capacity remains unaffected. [99]

Figure 146: Construction of the 2011 Roskilde dome

With generally the same structural concept, except for a few adjustments regarding the edge ring, a larger and taller dome was built in 2012 reusing elements from the 2011 dome and doubling the total surface area. The edge elements were provided with foot plates and pinned into the ground, making the ground an “edge beam and anchoring for uplift at the same time”. The ground was also “leveled with a thin layer of gravel” first, in order to achieve more precision in the assembling process. [99]

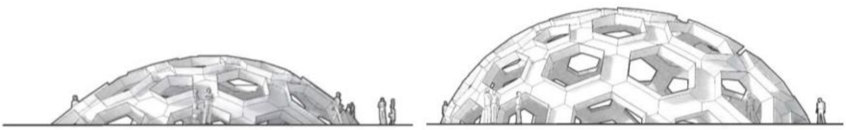


Figure 147: Comparison of the 2011 with the 2012 dome

Figure 148: The 2012 Roskilde dome

Related examples

In cooperation with Benny Jepsen, the same architect Kristoffer Tejlgaard used the hexagonal arrangement principle of shell elements to design a dome-shaped polycarbonate shield with a wooden support grid underneath, covering a two-person dwelling in Copenhagen referred to as the Dome of Visions [100]. This construction can also be related to the previous example inspired by soap bubbles.

Figure 149: The Dome of Visions, Copenhagen

On a larger scale and using different materials, the Vessel in Hudson Yards, New York City exemplifies the adaptability of the honeycomb structure in architecture. Designed by Thomas Heatherwick and completed in 2019, this 16-story steel skyscraper is 46 meters high, has a diameter of 15 meters that widens to 46 meters at the top, and comprises around 2.500 stainless steel steps along one-mile long stairways [101].

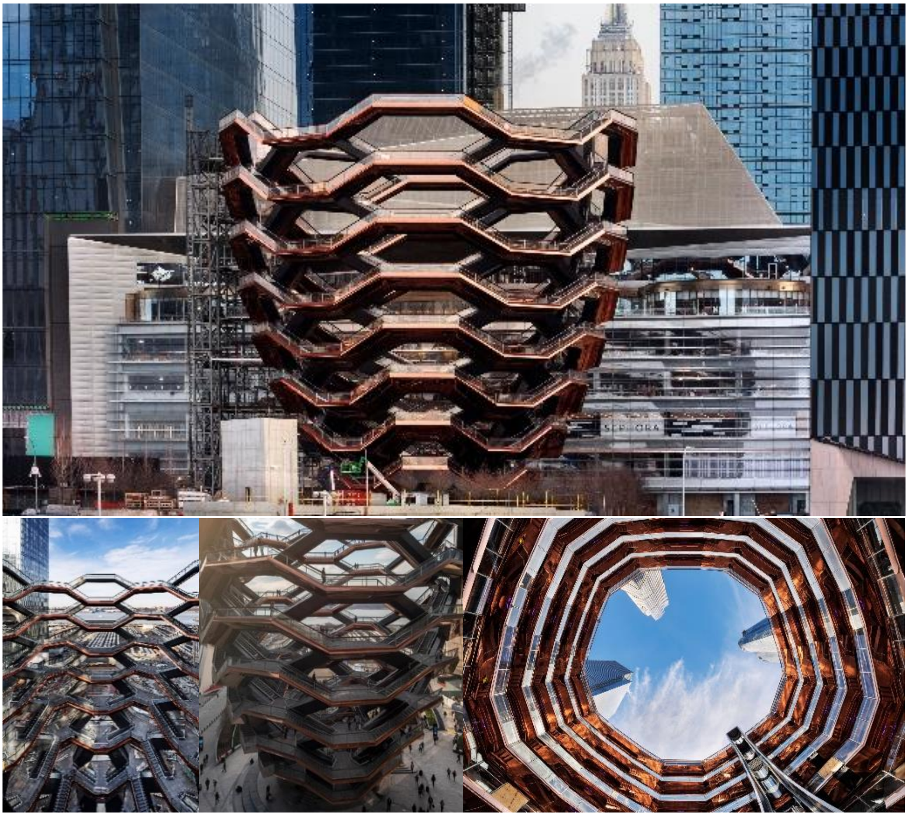


Figure 150: The Vessel, New York, USA

4. Conclusion

This thesis aimed to demonstrate the impact of turning the inspiration from nature from a simple subjective motivation into an organized process, according to which a building is designed. Based on the assessed bionic design projects, the implementation of structural properties that are found beneficial in natural organisms in architectural design has been shown to have comparable effects on the structural properties of buildings.

After determining the analogy between a biological system and an envisioned technical system, the designer abstracts the observed phenomena and key characteristics into generalized rules and principles, before applying them accordingly in the design process, in order to obtain a similar effect in terms of structural performance. The research emphasized these three steps of the transfer process in each of the studied examples to explain and illustrate how the analysis of structural models provided by nature can lead to structural efficiency in buildings.

Reviewing literature from different scientific disciplines, including biology, architecture, physics, chemistry, medicine, and structural engineering, with various perspectives on the concept of bionics, delivered a theoretical foundation needed to better understand practical examples of this modern design approach. The focus on shell structures allowed for a more specific assessment of biologically inspired projects, and demonstrated the level to which the analogy between nature and technology can be relevant and the transfer of abstracted principles can impact design. This research also highlighted the potential of concrete structures to ensure better stability and load bearing capacity when using adequate natural models. The compatibility of the bionic design approach with masonry, steel, and timber constructions was exhibited and shown profitable as well.

The multidisciplinary aspect of bionics, and the fact that it has only been introduced as an organized scientific branch a few decades ago, denotes a tremendous potential of improvement and certainly a wide range of research possibilities. Besides the environmental impact and the energy efficiency related benefits of new bionic projects, which are assessed in a dominantly large number of articles, civil engineers and architects may find further research addressing the efficiency of bionic design on a purely structural level particularly interesting. Other types of structures besides shell structures can be evaluated for possible correlations with certain biological systems.

Beyond its technical aspect and theoretical research input, bionics as a concept defines a new way to observe nature, which goes from being a generator of physical resources to a model from which structural solutions and technological innovations can be inspired. The noticed relevance of the smallest similarities in form and function with technical systems and the adaptability of biological principles in industrial design, draws the motivation to explore the natural models surroundings us with an entirely different vision, and leverage them with consciousness and belief that they might just provide solutions scientists have long been looking for.

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List of figures

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The manner in which bionics will mark its greatest contribution to technology is not through the solution of specific problems or the design of particular devices. Rather it is through the revolutionary impact of a whole new set of concepts, a fresh point of view.

Jack E. Steele

Bionic Design

Architectural Innovations Inspired by Nature with a Focus on Concrete Shell Structures

September 2020