STRUCTURAL TRANSFORMATION:
DESIGNING STRUCTURAL BUILDING ELEMENTS
INFORMED FROM BONE MORPHOLOGY

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

ŞEVVAL ÇÖLOĞLU

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
BUILDING SCIENCE IN ARCHITECTURE

DECEMBER 2022

Approval of the thesis:

STRUCTURAL TRANSFORMATION:
DESIGNING STRUCTURAL BUILDING ELEMENTS
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submitted by **ŞEVVAL ÇÖLOĞLU** in partial fulfillment of the requirements for the degree of **Master of Science in Building Science in Architecture, Middle East Technical University** by,

Prof. Dr. Halil Kalıpçılar
Dean, Graduate School of **Natural and Applied Sciences** ________________

Prof. Dr. F. Cana Bilsel
Head of the Department, **Architecture** ________________

Prof. Dr. Arzu Gönenç Sorguç
Supervisor, **Architecture, METU** ________________

Examining Committee Members:

Asst. Prof. Koray Pekeriçli
Architecture, METU ________________

Prof. Dr. Arzu Gönenç Sorguç
Architecture, METU ________________

Asst. Prof. Zelal Öztoprak
Architecture, TOBB ETU ________________

Date: 28.12.2022

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name : Şevval Çöloğlu

Signature :

ABSTRACT

STRUCTURAL TRANSFORMATION: DESIGNING STRUCTURAL BUILDING ELEMENTS INFORMED FROM BONE MORPHOLOGY

Çöloğlu, Şevval
Master of Science, Building Science in Architecture
Supervisor : Prof. Dr. Arzu Gönenç Sorguç

December 2022, 80 pages

The population growth and the pace of urbanization lead to increasing demand for infrastructure and new buildings and increased consumption of products and services. Eliminating waste by developing more sustainable and durable solutions to build without overusing resources and minimizing environmental impacts has come to mean rethinking the way we design, build, use, maintain and operate our buildings.

In this vein, together with the increasing importance of lightweight structural design, material efficiency and other environmental issues, this thesis aims to provide a framework for the design of structural load-bearing elements derived from bone morphology, that is controllable, adaptable to different loading conditions and environmentally controllable. When design parameters such as light weight, durability and efficiency are sought, the potential of lattice structures as an attractive solution is quite high rather than conventional design alternatives.

The thesis values bone as a source of information model to structural transformation processes in design. Bone as one of the cellular materials found in nature, has anisotropic material properties, reproducing and reshaping itself in response to mechanical stresses and load. It is, therefore, one of the most important examples of structurally efficient, strong, optimized and lightweight natural systems.

This thesis explores the potential to design modular and material-informed building components that can be programmed according to bone morphology. Material, structure, form and performance are key concerns in exploring architectural possibilities and designing transformable interfaces. It aims to integrate generative logic, algorithmic and computational design with emerging technologies, fabrication technologies and biomimetic design principles to find new tectonic and material conditions to design modular, scalable and transformable structural building elements.

Keywords: Biomimetics, Bone Morphology, Structural Design, Computational Design, Circularity.

ÖZ

YAPISAL DÖNÜŞÜM: KEMİK MORFOLOJİSİNDEN ÖĞRENİLMİŞ YAPI ELEMANLARININ TASARLANMASI

Çöloğlu, Şevval
Yüksek Lisans, Yapı Bilimleri, Mimarlık
Tez Yöneticisi: Prof. Dr. Arzu Gönenç Sorguç

Aralık 2022, 80 sayfa

Nüfus artışı ve kentleşme hızı, altyapı ve yeni binalara olan talebin artmasına ve ürün ve hizmet tüketiminin artmasına neden olmaktadır. Kaynakları aşırı kullanmadan ve çevresel etkileri en aza indirerek inşa etmek için daha sürdürülebilir ve dayanıklı çözümler geliştirerek israfı ortadan kaldırmak, binalarımızı tasarlama, inşa etme, kullanma, bakımını yapma ve işletme şeklimizi yeniden gözden geçirmek anlamına gelmeye başlamıştır.

Bu doğrultuda, hafif yapısal tasarım, malzeme verimliliği ve diğer çevresel konuların artan önemi ile birlikte, bu tez, kemik morfolojisinden türetilen, kontrol edilebilir, farklı yükleme koşullarına uyarlanabilir ve çevresel olarak kontrol edilebilir yapısal yük taşıyıcı elemanların tasarımı için bir çerçeve sağlamayı amaçlamaktadır. Hafiflik, dayanıklılık ve verimlilik gibi tasarım parametreleri arandığında, geleneksel tasarım alternatiflerine kıyasla kafes yapıların cazip bir çözüm olma potansiyeli oldukça yüksektir.

Tez, tasarımda yapısal dönüşüm süreçleri için kemiği bir bilgi modeli kaynağı olarak değerlendirmektedir. Doğada bulunan hücresel malzemelerden biri olan kemik,

anizotropik malzeme özelliklerine sahiptir, mekanik gerilimlere ve yüke yanıt olarak kendini yeniden üretir ve yeniden şekillendirir. Bu nedenle, yapısal olarak verimli, güçlü, optimize edilmiş ve hafif doğal sistemlerin en önemli örneklerinden biridir.

Bu tez, kemik morfolojisine göre programlanabilen modüler ve malzeme bilgisine sahip yapı bileşenleri tasarlama potansiyelini araştırmaktadır. Malzeme, yapı, biçim ve performans, mimari olasılıkların keşfedilmesinde ve dönüştürülebilir arayüzlerin tasarlanmasında temel kaygılardır. Modüler, ölçeklenebilir ve dönüştürülebilir yapısal yapı elemanları tasarlamak üzere yeni tektonik ve malzeme koşulları bulmak için üretken mantık, algoritmik ve hesaplamalı tasarımı yeni teknolojiler, fabrikasyon teknolojileri ve biyomimetik tasarım ilkeleriyle bütünleştirmeyi amaçlamaktadır.

Anahtar Kelimeler: Biyomimetik, Kemik Morfolojisi, Yapısal Tasarım, Hesaplamalı Tasarım, Dairesellik.

To my beloved family.

ACKNOWLEDGMENTS

I would like to express my greatest gratitude my mentor and supervisor Prof. Dr. Arzu Gönenç Sorguç for her advice, criticism, encouragements and insight throughout the research. This research would not be possible without her guidance, motivation, and criticism. She not only enlighten me along the way but also showed me the way to conduct research.

I also want to express my appreciation and gratitude to the examining committee members Assist. Prof. Dr. Koray Pekeriçli and Assist. Prof. Dr. Zelal.

I want to thank to my parents Asuman Yancı and Hakan Çöloğlu for their continuous support and understanding from the day that I was born. Also, thanks to my dearest family members; Berkay, Koray, Filiz, Hatice Çöloğlu and Yurdanur Yancı for their motivational support. I would like to thank especially my dearest nieces Buğra, Bora and Hira Çöloğlu.

I would like to show my sincere appreciation to Digital Design Studio and METU Design Factory Team for their support and hospitality. I especially want to thank to Dr. Müge Kruşa Yemişcioğlu, Ozan Yetkin and Anıl Koç for their comments and guidance during this process, as well as for their constant support and motivation.

Last but not least, I cannot express my gratitude enough for my friends Okay Tutar, Ceren Su Yılmaz, Ekin Güneş, Çağatay Kamalı, Kerem Gürdallı, Furkan Uluocak, Yağmur Köseoğlu and Aslı Zeynep Doğan for their invaluable love, encouragement, and support throughout my path. None of my accomplishments would be possible without them.

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CHAPTER 1

INTRODUCTION

1.1 Background Information

One of the biggest challenges of 21st century is the overconsumption of resources. The current economy, which is based on using non-renewable energy resources and consuming materials in a linear "take-make-waste" path, has a huge detrimental impact on our environment (Kubbinga et al., 2018).

Environmental problems such as global warming, waste pollution, energy crisis, depletion of natural resources and greenhouse gas emissions have been a source of great concern all over the world. The population growth and the pace of urbanization lead to increasing demand for infrastructure and new buildings and increased consumption of products and services (Xing et al., 2018). Given this situation, buildings become one of the most critical intervention points for reducing the impact on the environment. (Kubbinga et al., 2018).

Recent studies have highlighted that the construction industry is one the world's largest consumer of natural resources and energy, as well as the largest producer of waste. Considering the resource consumption of the construction industry alone, building materials should be evaluated not only in terms of energy consumption but also in terms of reuse, recycling, and upscaling potential in a circular design. Smart material selection, using less material and reusing structural components beyond their traditional life cycle can significantly reduce the environmental impact of buildings.

Eliminating waste by developing more sustainable and resilient solutions to construct without excessive use of the resources and with minimal environmental impact also means to reconsider the way we design, construct, occupy, maintain and operate our buildings (Mazzoleni, 2013). Since the 1950s, conceptual frameworks have been introduced to try to reduce the environmental impact we leave behind, such as Biomimicry, Performance Economy, Bio-Based Economy, Cradle-to-Cradle, Green Economy, Blue Economy, Regenerative Design, and Industrial Ecology (Amory, 2019). Many of these ideas are also included in the Circular Economy model.

In this context the key strategy shifts are discussed with the concepts of sustainability and circularity. When we look at the concept of circularity, it is possible to talk about an analogy to nature. The most obvious link between nature and the circular economy is the recognition that there is no waste in nature, as well as, from the production and use of materials to the organization of entire populations, it has many examples of survival with minimal energy use (Vincent, 2002). As Mazzoleni (2013) indicates nature has a very complex structure and depends heavily on closed-loop cycles. Circular design model's main purpose is to close the cycles of material, structure and form, as in nature, in order to prevent the depletion of resources by changing the relationship between man and nature.

In this regard, sustainability cannot be considered simply as reducing the impacts of human activities on the environment or reducing the consumption of resources, but also as developing ways of integrating, cooperating, and learning, from nature. Nature is a dynamic and adaptive system; thus, it is open for regeneration. Mazzoleni (2013) states, the paradigm shift will happen if architecture moves beyond formal and sustainability concerns and begins to connect with nature on a direct performative level.

Frank Duffy introduced the idea of "Shearing Layers" with 6S framework -site, skin, structure, services, space plan, and stuff- to indicate that building elements change at different rates regarding their function and should be designed accordingly (Brand, 1994). He also stated that they are all part of a circular system which consists of products, components and materials (Kubbinga et al., 2018). Brand also refers to harmony in nature and attributes it to the small feedback-loop adaptations which occur constantly. Additionally, the structure is vital due to its close relation with environment and human as well as performance and safety of the building.

However, a review of the literature shows that adaptation studies in the field of architecture are generally limited to the building envelope. When we look back at Brand's shearing layers, we see that the structure is the most decisive element of a building's lifespan.

In conventional design practices, structural design is based on static calculations of the services of the building will serve throughout its lifetime and the loads it will withstand (Chen et al., 2018). The durability of a building, and therefore how well it can withstand wear and tear, depends on the structural construction, materials, its environment and the socio-economic context. Together, these factors determine how long a building will last (Galle et al., 2019). This study addresses the importance of structure and their capacity in extending the life spans of buildings. It is focused on the analogies between nature and architecture.

The capacity to recover from a change and/or respond according to changing conditions is associated with resilience. In nature, resilience is achieved by applying adaptation strategies - the process by which an organism becomes better adapted to its environment, a principle that is fundamental to sustainability and survival in the short and long term (Badarnah, 2018).

Bone has always been considered as an adaptive and strong material due to its micro-structure. It is one of the significant examples of a natural system that is structurally efficient, strong, and lightweight. It has anisotropic material properties; it forms and is remodeled in response to mechanical stresses and loading it experiences. Trabecular bone architecture experiences adaptive changes according to the loads it is subjected to, achieving maximum mechanical efficiency with minimum mass. The extensive use of the analogy of the bone-like structures can be traced through many built and unbuilt examples and research in the literature.

This study aims to learn lessons from nature to increase capacity of buildings with designing future-proof "structures". The morphological strategies from nature, especially bone, have been recognized as a source of information for designing structural elements that facilitate adaptation to different environmental conditions, withstanding forces while using materials efficiently.

1.2 Problem Definition

With cost and sustainability issues becoming increasingly important, the standard tradition of using materials and constructing buildings is changing. Eliminating waste by developing more sustainable and durable solutions to build without overusing resources and minimizing environmental impact is of increasing interest. As a result, as Mazzoleni (2013) states the "RE-" movement :reduce, recycle, repair, rethink, reimagine and reuse, has been among the most frequently discussed topics.

Buildings are complex systems consisting of layers and sub-systems with a variety of performance and functional requirements, which are formed by the combination of a large number of materials. These systems are composed of interrelated layers, of which the structure, is the most decisive element in terms of the life cycle of buildings durability, reliability, stability and load bearing.

In this vein, sustainability and the expectations of high-performance buildings in contemporary architecture have begun to be discussed in terms of performance, optimization and adaptation, however the traditional design and construction processes have not substantially changed in recent years.

In this sense, it is of great importance for a sustainable built environment that building structures can be recycled, repaired and intervened. This problem needs to be addressed, examined and a model should be generated to transfer the knowledge gained from the biological model: bone morphology.

1.3 Hypothesis & Research Questions

In nature, bone have evolved variety of systems capable of adapting its structural and material properties, to the loads under which it is placed. They can adapt their internal structure to deformations without the need of classical engineering-like adjustments or joints. The adaptation strategy of bone has the potential to be used in building constructions to increase structural thickness and weight, stiffness against changes in loading conditions, with material saving, economic and environmental advantage. Within this framework, the hypothesis of this research can be defined as follows:

Bone morphology is an instructive model for obtaining structurally, environmentally and functionally efficient material systems and fabrication technologies with the goal of lightweight structures and material efficiency while providing high mechanical performance in design of structural elements in architecture.

Q1: How the structural properties of bone can be transferred to structural design elements? In which scale?

Q2: Can we redefine adaptiveness, resilience and performance in architecture in terms of biomimetics, learning from the morphology and performance of bone structures in nature?

Q3: Can the structural, generative, responsive, adaptive and self-healing, performance criteria that architecture aims for in the design processes be learned from bone morphology and transferred to design processes and fabrication methods?

1.4 Aim and Objectives of the Research

This research aims to develop new approaches to the design of structural building elements by taking bone morphology as an instructive model. It explores the potential to design modular and material-informed building components that can be programmed according to bone morphology. Materials, structure, form and performance are primary concerns in exploring architectural possibilities and designing transformable interfaces.

It aims to integrate generative logic, algorithmic and computational design with emerging technologies and biomimetic design principles to find new tectonic and material conditions to design modular, scalable and transformable structural members.

The main objectives of this study are:

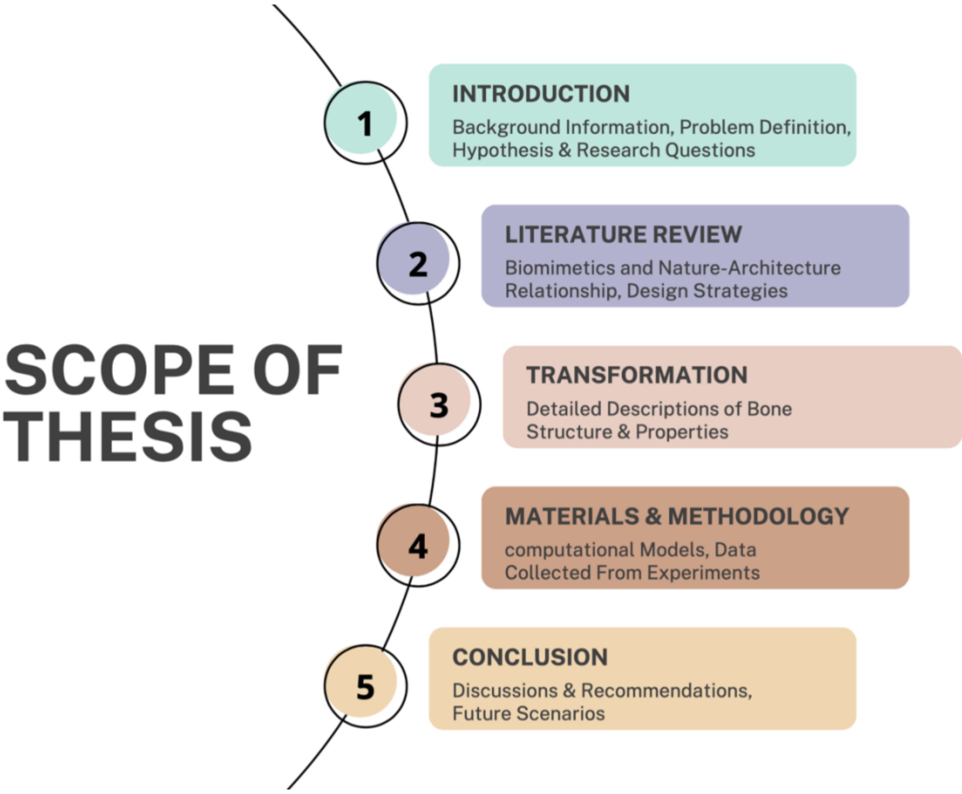
- To examine the potential of bone morphology to inform the development of new construction techniques to design lightweight and material efficient structures.
- To create a framework for designing structural building elements by examining the relation between structural properties, material anisotropy and deforming forces of the bone morphology.
- To examine the potential of the self-healing mechanism learned from bone morphology for structural strengthening/healing of buildings

1.5 Scope of the Thesis

- Chapter 1 gives background information about the topic, the problem statement, hypothesis, research questions, aims and the research objectives.
- Chapter 2 introduces circular design concepts, biomimetics and nature-architecture relationship then reviews previous works done in the literature before.
- Chapter 3 presents detailed description of bone and its properties, materials, forces to inform architecture in structural design.
- Chapter 4 materials and the methodology of the research and provides a detailed description of the results and discussion. The experimental work that was conducted during the project, the data collected from the experiments,

computational models and the analysis of the research are presented in this part.

- Chapter 5 is the conclusion part, includes summary of the research and provides a space for limitations, and recommendations for future works.



CHAPTER 2

LITERATURE REVIEW

The requirements that modern buildings have to meet today are very complex, often challenging and they need to be adapted throughout their life cycle for social, economic, ecological, and structural reasons. Considering current challenges regarding the development and optimization of structures, materials and components nature can make an important contribution to design of adaptive, functional and efficient structures with mimimal environmental impact.

In this vein, architecture and nature are similar in many ways that they are part of a process subject to constant change and adaptation. They differ from most engineering sciences, which usually focus on fixed boundary conditions and clearly defined optimization processes. In nature, all living things are made of materials with fragile properties and can adapt to environmental stresses and conditions. Thanks to geometric and hierarchical material organization, robust structures can be built with fragile materials. They can optimize material structures according to required functions by adjusting the mechanical properties of the material and adapting to internal/external forces. This process plays an important role in transformation processes in nature.

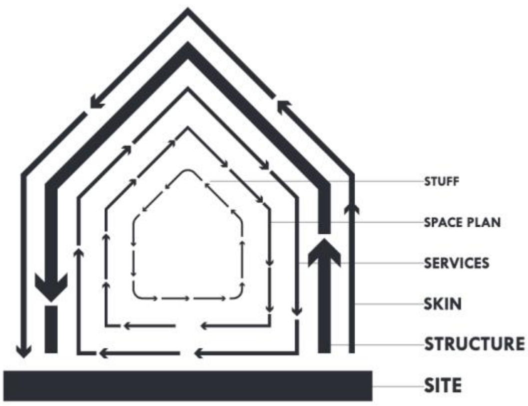
A building has to be, robust, reliable and withstand various loads thus here, the most important role falls to the structural system of the building. Lightweight cellular structures with porous material properties and controllable mechanical properties have the potential to help overcome many of the structural challenges we face in architectural applications today.

This thesis argues that structural building elements should meet an expected performance from the design phase to the after-life cycles of the building. It explores the possibility that it can respond to its environment by transforming into a heterogeneous, differentiated open system that can adapt to changing conditions within and around it, as in nature, in bone structures.

2.1 Buildings as Layers : "*Shearing Layers*"

The concept of layers, introduced by Frank Duffy, recognizes that building elements have different life spans and should be constructed separately. He argues that buildings should be measured in terms of time rather than in material terms (Duffy, 1990). He refers nature

"In **nature** you've got continuous **very-small-feedback-loop adaptation** going on, which is why things get to be harmonious. That's why they have the qualities that we value. If it wasn't for the **time dimension**, it wouldn't happen. Yet here we are playing the major role in creating the world, and we haven't figured this out. That is a very serious matter." (Brand, 1994)



Shearing Layers
"Because of the different rates of change of its components a building is always tearing itself apart."

Shearing layers	Description	Typical lifespan/activity
Site	Location and context	Permanent
Structure	Bones	30-300 years
Skin	Envelope	20+ years
Services	Lifeblood	7-20 years
Space plan	Interior layout	3 years
Stuff	Furniture and equipment	Under 3 years
Souls	People	Daily

Figure 1 Shearing Layers (Brand, 1994).

In his book “How Buildings Learn: What Happens After They're Built.” Stewart Brand (1994) expanded Duffy’s model of “four S’s” to cover a broader interpretation of the layer concept and added site, and skin. According to him, geographical setting, the *site* is permanent and eternal; the foundation and load-bearing elements, the *structure* last 30-300 years; exterior surfaces and its components, the *skin*, last 20+ years; technical installations, electrical wiring, communications wiring, sprinkler system, plumbing, ventilating, heating and air conditioning, the *services* are replaced after 7-15 years; the layout of interior, including ceilings, walls, doors, floors etc.; the *space plan*, can be replaced every 3 years and finally furniture, chairs, desks, etc., the *stuff*, are usually replaced every 1-5 years (Figure 1) (Brand, 1994).

The adaptability of a building can also determines the physical *flexibility* of a building and should be considered with the required durability of that building over its lifetime. James Douglas (2006) defines flexibility in architecture as adjusting a building to adapt to new requirements or conditions in order to change its capacity, function and performance. Although sustainability has been targeted in buildings constructed over many years, adapting to the changing needs of building users still remains a major challenge. When the scope of optimization studies across current structural design practice, is evaluated in general, it is seen that it is most concerned with the skin. Therefore, the ultimate longevity and value of a building to a large extent depends on the main element of the building, the structure, whether it can be easily preserved and replaced during its service life-span and adapt to environmental changes.

2.2 Life-Long Design Strategies

The idea of sustainable development has recently been a hot topic among entrepreneurs in various sectors. With these ideas, attention is drawn to design strategies that are gaining importance. Design for Adaptability, Design for Material Efficiency, and Design for Disassembly can be considered one of the most important design strategies that have come to the fore. The concept of the "Design for

Adaptability" methodology is based on the hypothesis that a product reaches the end of its product life due to its inability to adapt to changing demands (Pinder et al., 2017). The DFA strategy aims to prevent the environmental and material impacts of resource consumption, building obsolescence, and the accompanying material waste. Furthermore, as Graham (2005) states, how sustainable a building is not measured by how long it stands, but by how much it can adapt to change. Adaptability also requires that the structure is strong enough to withstand different load scenarios during its lifetime. In this case it is important to design long-life span layers according to durability and short-life span layers according to the principles of flexibility (Graham, 2005).

The adaptability of a building can also determines the physical *flexibility* of a building and should be considered with the required durability of that building over its lifetime. Design for Adaptability provides theoretical and methodological framework for designing flexibility. What the building needs, whether spatial, structural or material flexibility, should be decided in the early stages of design as Durmisevic and Brouwer (2001) explains.

- *"Spatial transformations* – ensuring continuity to make the space useful
- *Structural transformations* – ensuring continuity in the use of building layers and components through reuse, recovery and replacement
- *Element and material transformations* – ensuring continuity of access to building materials for recycling and reuse (Durmisevic and Brouwer, 2001)."

Another important point is to design the fast-cycle materials in such a way that they can be changed without damaging the slow-cycle materials. With this design strategy, the total service life of the building can be extended.

Most buildings today are designed for an end-of-life scenario for assembly, and factors such as possibility of disassembly and reuse of components are not considered. (Durmisevic & Yeang, 2009). Design for Disassembly aims to redesign a building with building components that are dismantled at the end of their life cycle. In this way, building components that can still function can be prevented from becoming waste and reused in other buildings (Guy & Ciarimboli, 2005). Designing for disassembly can also minimize the impact on the environment by ensuring that building components can be used not just for one life cycle, but two, and even more if they are still suitable for reuse. In this way, the most appropriate future scenario can be obtained by returning building components into new cycles of life.

Designing for material efficiency is one of the critical steps to ensure the implementation of circularity in the building sector. Design for Material Efficiency claims that several strategies can be used throughout the life cycle of a building to reduce the amount of materials needed and environmental impact (Munaro et al., 2020). It is important to use efficient construction methods during the construction and deconstruction phases and to properly maintain the materials to preserve the values during the use phase. However, as Morseletto (2020) points out, the design is the most important phase of implementing it. In the preliminary design phase of the project, material choices should be made by considering the environmental impacts of these materials.

2.3 Potentials of Nature-Informed Design in Sustainability

In the theoretical introduction and above , the terms and design methodologies for a more sustainable environment have been defined and discussed. As the world has become increasingly complex in the last century, the problems it faces have also become more complex with dynamics of interrelated social, economic, ecological, and cultural issues. Thus, the question about how to develop models for sustainable environment in building construction sector has been a prominent topic in many studies recently.

The paradigm shift in architecture and design, the return to nature, is not only about understanding and imitating natural forms, but also about deeper research into processes from natural phenomena from which designers can derive *models* and *methods* (Steadman, 2008). Nature consists of complex and dynamic systems and information derived from these systems can lead to construction of sustainable, effective and optimized buildings. Multi-functionality in natural beings can provide to control the many design parameters that must be considered and integrated in sustainability such as: structural support, acoustic and sound insulation, material optimization, heat insulation etc. (Pohl & Nachtigall, 2015).

2.4 Nature - Architecture Relationship

Humankind has always been in search of solutions from nature in order to tackle life's challenges. The close relationship between form and function, the balance of natural forces and the geometric solutions found in nature have always inspired architecture. Archetypes such as caves and trees have been used as models for architectural design thus countless analogies inspired by nature can be observed in structures throughout history from Acanthus plant inspired Corinthian columns to flying buttresses (Figure 2).

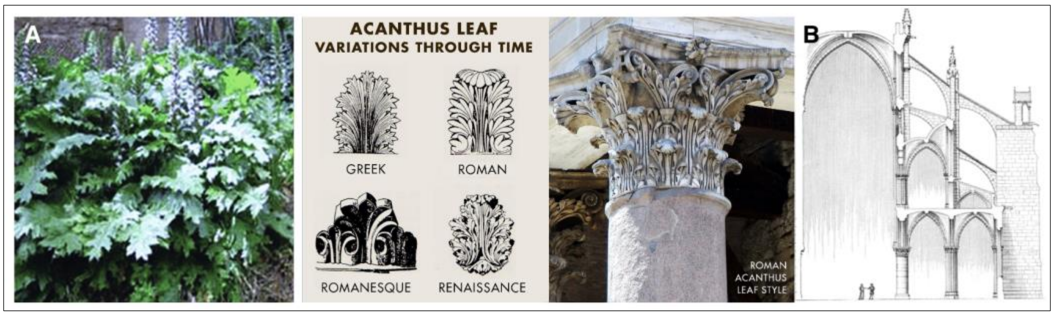


Figure 2 (a) Plant of Acanthus; and Corinthian column head in Pantheon, Rome built in 126 AD. (b) The gothic flying buttresses in Notre Dame. Source: (Aziz, M. S., & El Sherif, A. Y., 2016).

Vitruvius in "The Ten Books of Architecture" gives one of the seminal examples of architecture's inspiration from nature as an attempt to derive the use of ratios in buildings, especially for the orders of columns, by observing the system of proportions in the human body (Picon, 2018).

Biomimetics or "learning from nature for technical solutions" started with Leonardo da Vinci (1452-1519). Thus Mazzoleni (2013) positions Leonardo da Vinci as the first biomimetic designer in his book "Architecture Follows Nature-Biomimetic Principles for Innovative Design". Leonardo da Vinci studied geometries in nature, has drawn numerous observations from the human body, animals, insects and plants. He studied the anatomy and wings of birds tried to understand aerodynamics and made notes and sketches of his observations to make human flight possible (Figure 3) (Mazzoleni, 2013).

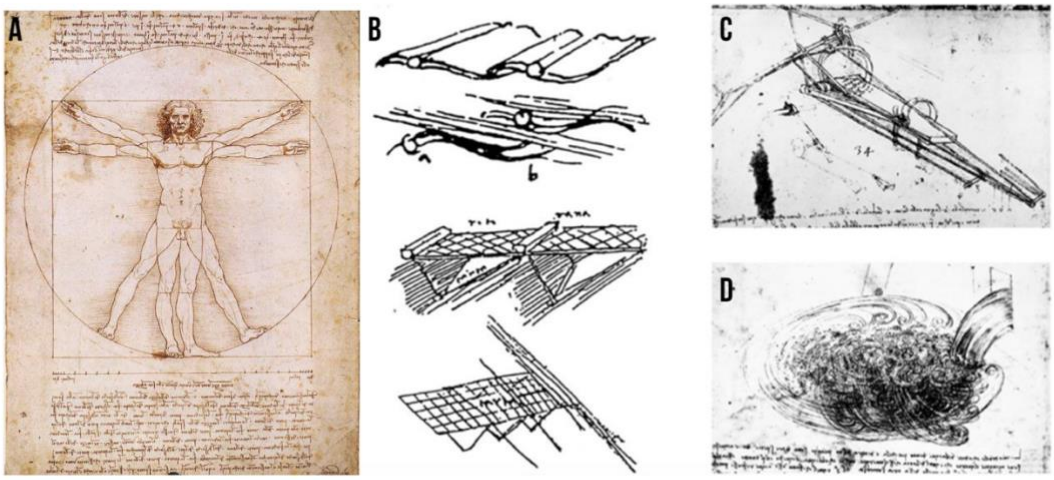


Figure 3 a) Vitruvian Man, 1487 b) Leonardo da Vinci: sketches about bird anatomy and wings c) Design for fly machine inspired by bird wings, 1490. d) A sketch of flowing water by Leonardo da Vinci around 1508. (Gruber, 2010)

Although Leonardo da Vinci's works are considered as first biomimetic studies, the term biomimetic, also known as biomimicry, originates from the 1960s and only gained importance with the biologist Janine Benyus's "Biomimicry - Innovation Inspired by Nature" book in 1997. For the biomimicry term, Vincent (2006) indicated that the "mimicry" part is not intended to be a copy of organisms but an interpretation, adaptation, or derivation from biology. Benyus (1997) defined biomimicry as "a new discipline that studies nature's best ideas and then imitates the designs and processes to solve human problems."

Biomimetics uses the processes, mechanisms, strategies, functional properties, and information obtained from nature. The concept of biomimetics is rooted in realizing that through selection and interaction, organisms in nature can adapt their characteristics to meet challenges in the environment by regenerating multi-functional resolutions during evolution (Knippers & Speck, 2012).

Since ancient human civilization, nature, as archeological sites have verified, has been a source of inspiration and motivation for designing (Mazzeloni, 2013) The need for shelter of humankind has emerged simultaneously with observing nature and the structures in nature and trying to learn from them.

Human beings, who learned to live in communities, observed the formations in nature with the need for shelter, used the materials obtained from nature, and started to build the first building techniques by learning or imitating the constructions in nature (Figure 4). However, until the industrial revolution the nature-informed design was generally limited to the form. With the industrial revolution and developments in computer and information technologies that followed it, the way architecture engages material, form, and structure is altered completely. (Arslan Selçuk, Gönenç Sorguç, 2013)

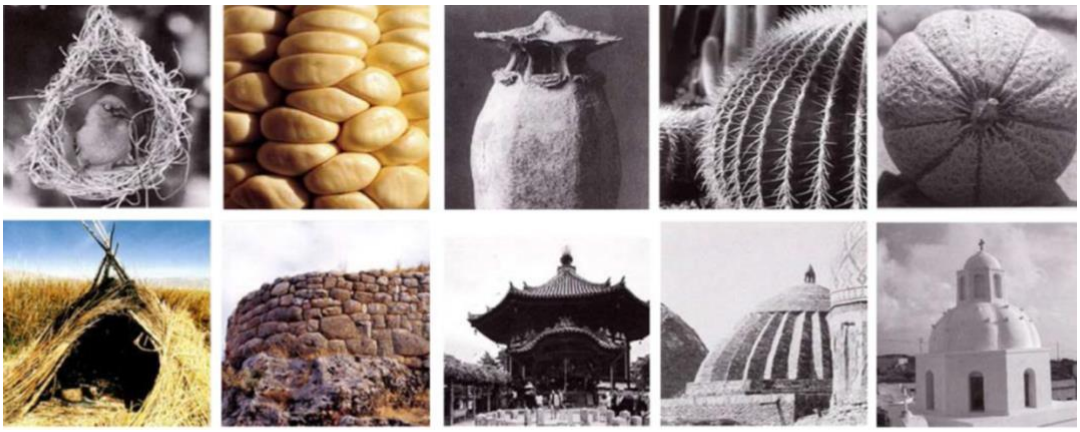


Figure 4 Some examples on analogies of nature inspired architecture. (Arslan Selçuk, Gönenç Sorguç, 2013)

The biomimetic approaches as a design process as defined in Biomimicry Guild (2007) can be divided into two: Defining the design problem or human need and look for its solution in nature to solve, "design looking to nature" or selecting a certain feature, function or behavior in organisms or ecosystems and transferring that information to design, referred as "biology influencing design."

Through the literature, biomimetic applications were also approached with various terminologies by different researchers such as “Solution Driven & Problem-Driven Biologically Inspired Design” (Helms, Vattam & Goel, 2009) and “Bottom-Up & Top-Down Approach” (Knippers & Speck, 2012), which all meaning the same.

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 5 The Application of Biomimicry Framework (Zari 2010).

Biomimetics approaches can be categorized in three levels as described by Zari (2010) (Figure 5) : form, process and ecosystem to apply to a design problem. The first level of biomimetic application is the organism level. This type of mimicking is to copy an organism for its morphological appearance such as its components, form and structure. The second level is mimicking the processes level. This level aims to reproduce a biological organism’s emergence, behaviors and processes within its environment. The third level is mimicking the ecosystems. This process can also be more complicated. When mimicking the ecosystem level, it is necessary to consider the design in a wider perspective (Zari 2010).

2.5 Building Methods Analogous to Nature

Structures in nature have aesthetic, functional, and structural advantages. Many studies throughout history have examined how optimization processes in biological structures are possible role models for producing optimized architectural forms and structures. It has been observed that designers and engineers use theories, analogies and methods inspired by biological principles to develop solutions to technical problems.

With digital design and fabrication techniques, it became possible to design forms and processes found in nature. Architecture's relationship with nature has changed from taking nature as a metaphor to taking it as a model, mentor, and measure (Benyus, 1997). The structures informed/inspired/adapted from nature can be classified into six categories (Figure 6): tree-like branching structures, pneumatic structures, cellular structures, shell-like structures, web-like structures, and skeleton/bone-like structures (Arslan Selçuk, 2009).

Tree-like branching structures are one of the most common nature-inspired analogies in the history of architecture. The physical, mechanical, and biological functions of trees have been a structural model that inspires designers beyond plant and branching patterns in architectural ornamentation (Arslan Selçuk et al., 2022). Trees, with their trunks, branches, and leaves, have guided architects and designers with the balance they provide, especially in transferring vertical and horizontal loads (López et al., 2016; Pawlyn, 2019). While branched tree-like structures were first encountered in the ribs of gothic style buildings, nowadays, they are mostly seen in three-dimensional structural support systems that can be used in concrete, wood and steel buildings (Arslan Selçuk, 2009). As one of the pioneering designers, Frei Otto analyzed the branching structure of trees to cross large spans with little interference with the ground, focusing on load and stress distribution (Arslan Selçuk et al., 2022). It is possible to come across many tree-like structures in many of Antonio Gaudi's works. The geometry of the many of the Sagrada Familia Basilica pillars are inspired by tree trunks. Stuttgart Airport Passenger Terminal roof, designed by von Gerkan and Marg, is one of the contemporary examples of a tree-like structure with its tree-like columns. Besides those examples, it is possible to give many others.

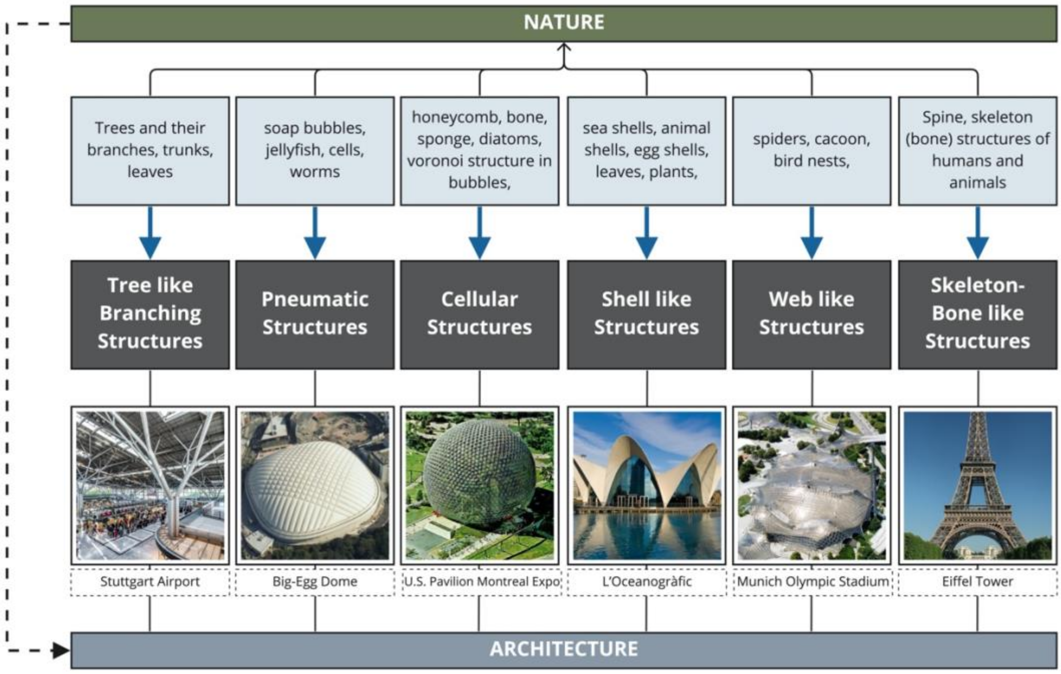


Figure 6 Classification of architectural structures inspired by natural structures adapted from Arslan Selçuk (2009), (developed by author).

Pneumatic structures can be defined as tension-resistant, flexible membranes inflated to gain rigidity. *Pneu* can be defined as "a system in which a layer stressed only in tension envelopes a medium," (Bach et al., 1976 as cited in Velikov at al., 2014). A wide variety of formations of pneus can be observed in animate/inanimate world such as; caterpillars, frogs, snails, living cells and liquid membranes (water drops, soap bubbles), bones, nets, vessels. The earliest applications can date back to development of hot air balloons 1709 (Herzog,1977; Forster, 1994; Arslan Selçuk, 2009). Frederick William Lanchester was the first to come up with the idea of supporting tents with internal air pressure in 1917. Frei Otto (1960-1980) conducted a series of soap-bubble experiments that use the surface tension of a liquid in his form-finding processes to cover a closed shape with find the minimum surface (Lopes at al., 2014). After that pneumatic construction techniques became a part of architecture. They are mostly used for large roofs, and openings as they provide a solution, extremely lightweight. They provide most efficient structural system in terms of span/weight ratio. Tokyo Big-Egg Dome Stadium by Forster, Atoms for Peace Pavilion, Archipelago by Architects of Air, Roman Arena in Rome by Nimes can be listed as some of the pneumatic structure examples. Mostly they can be observed in temporary building scale by economic reasons.

In the field of architecture **Cellular Structures** or cellular solids are referred as structures based on an interconnected network of solid edge or face cells joined together to fill a space (Gibson and Ashby, 1997; Naboni 2017). Cells, the basic forms of life, are the basic building blocks of natural organisms and have been used in many different disciplines since their discovery. Their arrangement can be in a regular or irregular manner; honeycomb, foams, cancellous bone, wood, sponge, cork, iris leaf, skeletons of diatoms can be listed as some of the cellular structures found in nature (Gibson and Ashby, 1997). In architecture cellular structures in nature attract attention of designer with its good mechanical properties, optimal morphology, efficient and functional integration they provide at the lightweight.

One of the most common and most efficient structural elements observed in nature are shells due to their minimal material, durability, high resistance, shelter function and large span structural properties (Melaragno,1991; Arslan Selçuk, 2009). Eggs, seashells, nutshell, snails, scallops, turtle shells, and skulls are some of the notable examples that are studied with **shell-like structures**. Shells found in nature have particularly influenced architecture in terms of geometry, mathematics and shelter capacity. As classified by Melaragno (1991), pneumatics, membranes, slabs and folded plates are also among the shell-like/surface structure systems. The discovery of cement, which made reinforced concrete possible, can also be considered as the beginning of shell structures in architecture. The advent of using concrete as a new building material made it possible to build vaults and domes with less thickness and weight. With the development of building technologies, it is now possible to construct roof structures made of reinforced concrete steel or wood with long span. The Sydney Opera House by Peter Hall, L'Oceanogràfic by Felix Candela, Wyss Garden Center by Heinz Isler can be listed as some of the examples of shell-like structures seen in architecture.

Lastly, the skeleton/bone-like structures seen in the spine and skeletal structures of vertebrate animals have often been used in architecture as a source of inspiration for constructing buildings. However, the skeleton/bone-like structures will be examined in detail in the next chapter since they are the main research topic of this thesis.

2.5.1 Bone-Like Structures

The process of drawing inspiration from nature when designing is a long-lasting approach that dates to the beginning of architecture. Anatomy has been of interest to architects and engineers throughout history as it deals with issues such as static problems, strength, and distribution of weight (Steadman, 2008). Each bone of the skeleton and the skeletal system itself show that nature has created a sophisticated, light and rigid structure that is perfectly suited for structural design (Selçuk, 2009). Bone and skeleton-like structures are analogies that are among the nature-inspired structures that attract and inspire designers we frequently encounter throughout the history of architecture.

The developments of natural sciences since the 17th century have enabled the architecture discipline to develop individually and collectively, especially with methods, concepts, scientific language, and systematic and taxonomic approaches (Hensel, 2012). The French naturalist Georges Cuvier conducted the first systematic review of fossil finds at the beginning of the 19th century, and his disciple Henri Milne Edwards analyzed life forms as man-made machines in order to understand how living things in nature emerged (Collins, 2008). Gottfried Semper stated that the concepts underlying Cuvier's classification of animals underlie the typology of architectural form today (Steadman, 2008).

Over the centuries, there have been many studies on how to put animal and human physiology into a purely mechanical worldview and draw analogies from nature to architecture and engineering. However, of all biological studies, perhaps D'Arcy Thompson's book "*On Growth and Form*" has most directly inspired architects especially with its mathematical descriptions, scientific explanations of growth processes and, analogies between anatomy and building construction (Steadman, 2008).

Thompson argued the role of physical and mechanical forces in the development of the morphology of organisms with a new critical point of view to evolution (Thompson, 1917). In addition to explaining the relationships between morphology and physical conditions on form with numerous examples and analogies, he developed a simple and powerful descriptive graphical method for the theory of "*Transformations* or *Comparison of Related Forms*", using a grid to show the geometric transformation in the shape differences of related animals (Figure 7) (Hensel, 2012).

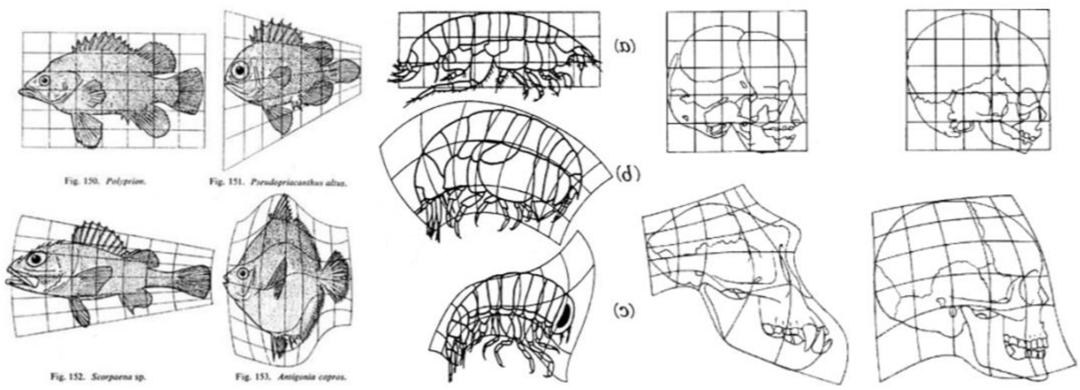


Figure 7 Examples from "*On Growth and Form*" (Thompson, 1917)

Steadman (2008), states analogy from nature to architecture can be at multiple levels of information and formation. Throughout history, it is possible to observe that bone-like structures have approached nature with two different approaches; one visual appearance or composition, the other functional.

It can be given as the first example of the structural analogy of the buildings to animal skeletal forms is based on J.R. Perronet's comments on Gothic cathedrals as early as 1770. Bartholomew's diagram (Figure 9a) comparing the human skeleton with counter-abutments of Gothic vaults has been used repeatedly through the next hundred years with the classification of bone-like structures (Bartholomew, 1840; Steadman, 2008)

The Forth Railway Bridge, which Mainstone (1975) calls the most successful structural masterpiece of its period, can also be found in Thompson's *Growth and Form* with various analogies from nature. According to him the pipes which the bridge is built correspond to the structure of cylindrical plant stems and their reinforcing rings to the joints in the bamboo stems, one of the strongest of plants in structural means (Figure 9b). Additionally, while pointing to a visual analogy of the integration of the bridge's double cantilever system with the skeleton of a heavy bison, he also matches the structural elements carrying the bridge with the bones of the bison (Günaydın, 2019).

Eiffel Tower built in 1889 by Gustave Eiffel and his team. In this team Maurice Koechlin, structural engineer and assistant of the chief engineer was also a student of Karl Culmann. Karl Culmann was an engineer and also the author of the book "Graphical Statics" in which he explained how the transmission of stresses in structures can be determined using graphical analysis (Adhikari, 2017) The approach of Culmann's calculation of stress trajectories of the bone and the crane (Figure 8) inspired structural engineer Koechlin in designing Eiffel Tower. The femur, the lightest and strongest bone, provides stiffness and flexibility in the skeleton and optimizes the use of building materials. The outer structure of the bone, also known as cortical, is hard and compact, while the inner structure is known as spongy trabecular bone. While the hard part acts as a pillar, the spongy part forms the supporting structure of the main bone, allowing it to respond equally to the compression and tension forces that bone constantly experiences (Steadman, 2008; Selçuk, 2009)

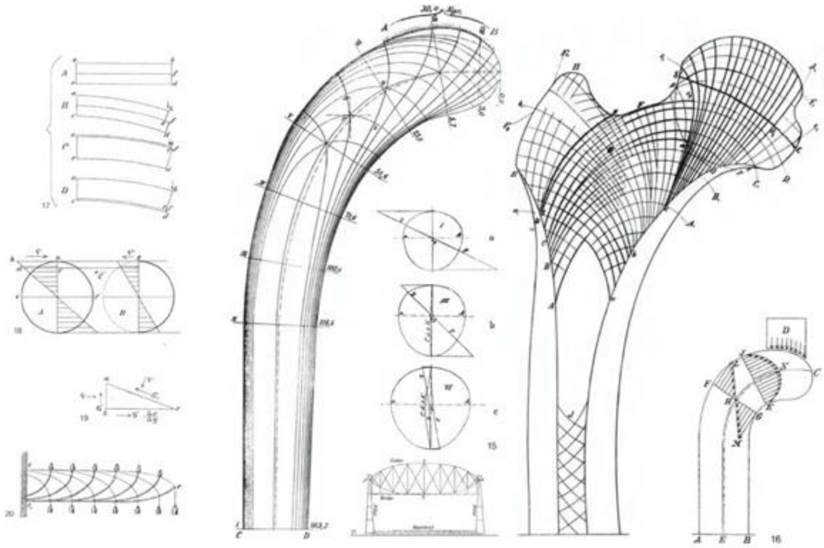


Figure 8 Sketches of Culmann's Fairbairn crane and representation of the stress trajectories of the internal architecture of long femur and its mathematical significance. (Wolff, 1986)

Gaudi was one of the most important architects of his time who knew how to observe and interpret nature. Gaudi observed how structures in nature withstand dynamic and static loads in order to achieve distinction and aesthetics in his buildings and to construct structural systems suitable for these designs. His analogies with skeletal systems and bones played an important role in the design of his buildings. Together with these examples the architect and engineer Santiago Calatrava, particularly famous for his "biomorphic" designs, was inspired by nature and to a large extent by the bone and skeletal system. He stated that he believes that understanding geometry is as essential to understanding architecture as understanding structure, and that both, along with the materials properties and the constructions of nature, are sources of inspiration for him.

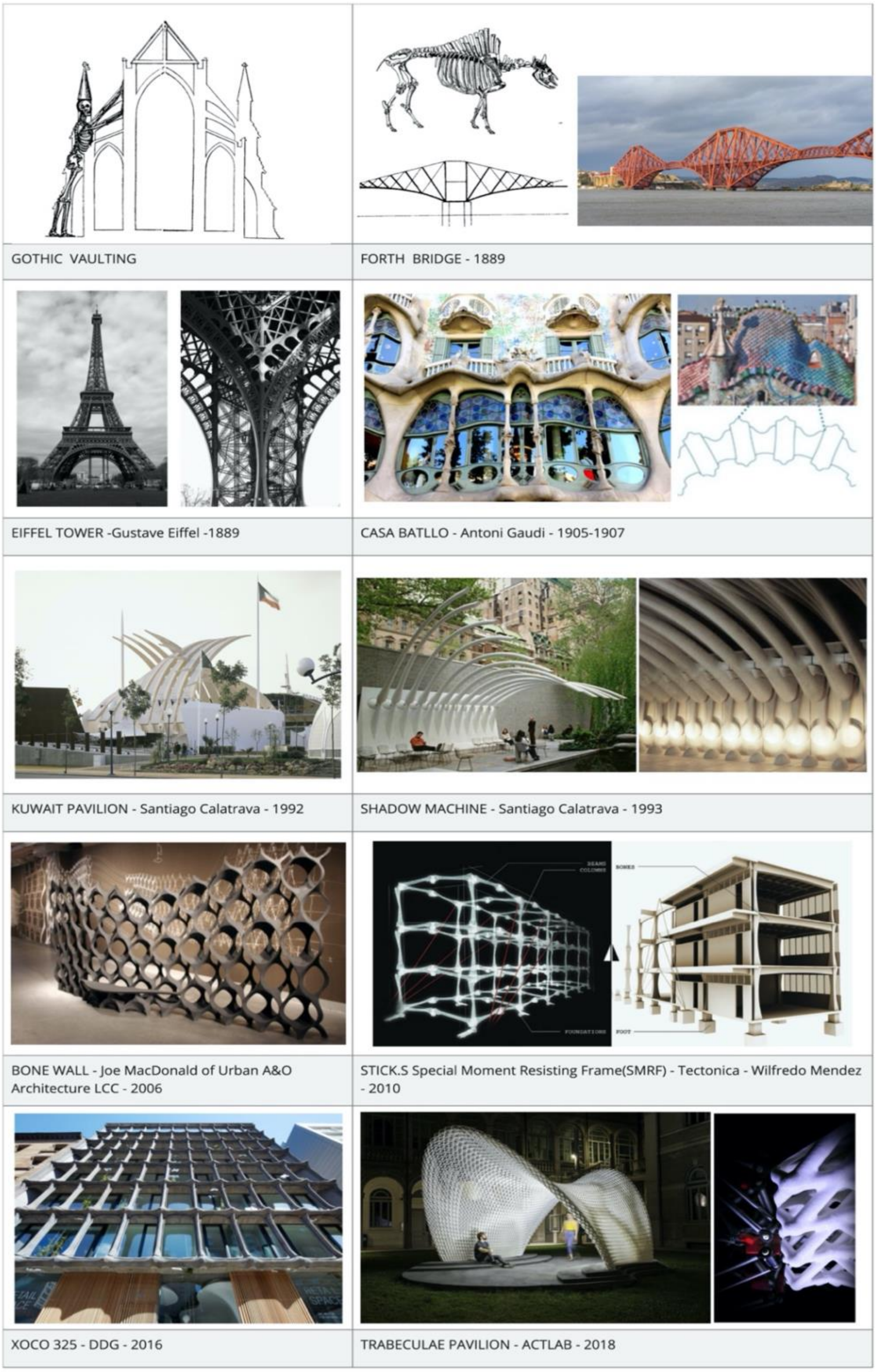


Figure 9 Architectural structures inspired by bone/skeleton through time (developed by author)

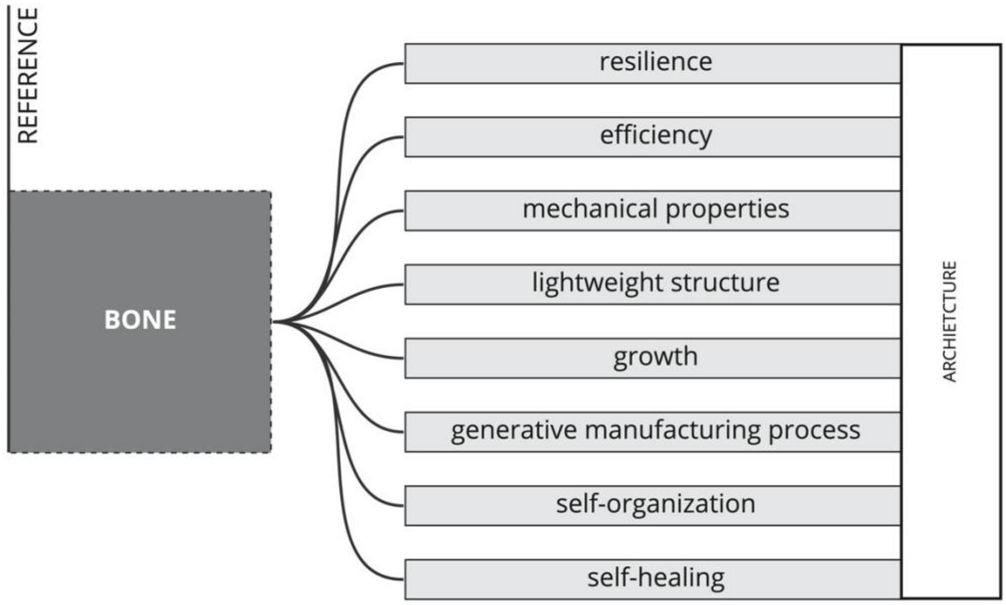


Figure 10 Possible information transfer form reference to architectural domain (developed by author).

2.6 Biomimetic Design Principles

At first glance, architecture and biology appear to be different from each other, both are based on materiality and organization and are related to morphology and structuring (Wiscombe, 2005).

2.6.1 Adaptation

Adaptation is the first principle as it is one of the fundamental properties of a biological phenomenon. Adaptation can be defined as the complexity and variety of living systems developed in response to changing environmental conditions (Hensel, Menges & Weinstock, 2010).

In nature's adaptation processes, the input from a given starting condition never repeats the same output. The processes, repeated many times and involve small random mutations, can reveal something that bypasses standardized material components' limits and develop an important "evolutionary" strategy for architecture, design, and engineering (Hensel et al., 2010). Gruber & Imhof (2017) also indicated that adaptation could completely transform materials and structures by widening the use of local supplies by dynamically changing conditions.

In the book "Architecture Follows Nature - Biomimetic Principles for Innovative Design," Mazzoleni (2013) has discussed "adaptation" in detail. While noting that the concept of "adaptation" has not traditionally been at the center of architectural practice, he stated that this needs to be taken into account in order to improve the ecological footprint.

2.6.2 Material Systems

Hensel et al. (2010) indicated that biological forms' evolution should not be considered as distinct from their structure and materials. All living forms in nature are made of materials with subtle properties, and they can change and adapt to environmental stresses.

The self-assembled geometrical and hierarchical material organization can make a stronger structure with fragile materials. The process uses only four polymer fiber components, collagen in animals, cellulose in plants, silks in spider's webs, and chitin in insects to construct its structure. These materials have much lower densities than many engineering materials, and their dynamic response and properties can be very different from human-made structures.

The material performances emerge from the hierarchical composition. Material, structure and form influence each other, and the behavior of all three acting on each other cannot be understood by analyzing them separately.

As Hensel et al. (2010) stated in their book, "Emergent Technologies and Design," the solutions material systems provide as listed below,

- In order fibers to not experience compressive loads pre-stress the tension fibers
- In order fibers to help carry compression loads, add high-modulus minerals to connected phases
- Cross connect fiber network to improve lateral stability
- Change fiber orientation so that compressive loads do not move through the fibers." (Hensel et al., 2010, p.16)

can inform the material strategies of architectural engineering and construction.

2.6.3 Evolution

Evolution can be described as the change in the genetic composition of a population across sequential generations. This process is assumed to result from natural selection, which affects genetic variation between individuals and results in the development of new species over time (Hensel, 2006).

Additionally, Hensel et al. (2010) indicated that every living organism emerges from two processes: the first and the fast process is; the embryological development from a single cell to mature, the second and the slow process is; the evolutionary process of various species' forms over many generations. The biological evolution of plants and animals can be seen in fossil findings as a range of differentiation from simple cell organisms to higher complexity. O'Reilly, Hemberg & Menges (2004) noted that complicated natural systems and forms emerge from evolutionary processes. The process intertwines the genotype, genetic constitution of specific species, and phenotype; outcome of environment-genotype interaction.

Frazer (1995), in his book "An Evolutionary Architecture," mentioned that with many developments, nature has evolved to a wide variety of species that are in balance with their environment. Besides, he emphasized the importance that buildings in contemporary architecture should share some of these characteristics. Evolutionary architecture's analogy should not be attracted from only the form, but other sides of evolution, such as self-organization, natural processes such as metabolism, the operation of thermodynamics' laws, principles of morphology, morphogenetics, and symmetry breaking. (p.12)

2.6.4 Emergence

The term "emergence" originates from system theory. It defines the features of a system that cannot be separated from the sum of its parts. The notion is generally correlated to complexity theory, the study of nonlinear behaviors, and self-organizing systems (Hensel et al., 2010). Additionally, Wiscombe (2005) indicated, other than the glossary definition of "emergence," it refers to a particular scientific phenomenon: the indivisible and irreversible whole such as structures, organizations, behaviors, or properties.

Finally, in the paper "Emergent Processes," Wiscombe (2005) remarked that emergence could lead designers to think differently about how diverse agents and disciplines exhibit generative and collective behavior in architectural design. Emergence uses the evolutionary development process, the material characteristics, the ability to adapt to environmental changes, the metabolism of organisms to develop new design strategies.

It also describes how natural systems evolve and protect themselves against challenging environmental conditions. It provides a set of models for the design fabrication of architectural forms that can display complex behavior and perhaps even real intelligence (Hensel et al., 2010).

2.6.5 Form & Behavior

All living forms in nature can be thought of as a system, and these systems derive their complex forms and behavior patterns from the interactions of their components. Behavior and form of living things emerge as the result of a process that produces, elaborates, and maintains the structure as well as a form of biological (or non-biological) things. In this sense, behavior and form are intertwined, and the process is created from the exchanges between organism and environment. (Hensel et al., 2010)

The form of a living being has an influence upon its behavior in the environment and will produce different results when a particular behavior is performed in different environments or with different forms in the same environment. (Hensel et al., 2010) strategies to improve their material characteristics from micro to macro levels.

2.7 Critical Review of Literature

This chapter is designed to examine the architectural literature so far in the literature on structural design, biomimetic and structural design, bone-like structures in architecture systematically. The analysis approached through a semantic and critical review of the literature.

The proposed research is started by searching the following keywords: "learning from nature", biomimetic, bio-inspired, structural design, bone structure, architecture, architectural design in Web of Science database. As a result of the raw data obtained as a result of the search words, it was seen that there are 200,482 publications in the WOS database. Further to refine the initial findings in order to retrieve building and structure related studies, the results are filtered with the categories "Architecture", "Civil Engineering", and "Construction Building Technology". In these findings, there were 98,218 publications in the field of architecture with the largest percentage, 91,270 in the field of civil engineering and 57,872 in the field of construction building technology (Figure 11). In order to reduce all these data to a more specific level, a filtering was performed again under the title of "design & manufacturing" and 5,964 publications were found. Iteratively there have been filtering to obtain more specific data. Structural design and biomimetics cover a huge area in the literature. Therefore, a network diagram based on keywords of publications in this literature using Vosviewer (https://www.vosviewer.com) was used to explore the relationships between studies.

Figure 11 Web of Science database search distribution of subjects according to their fields (Source: WOS last update: 23.12.2022).

Within the scope of this thesis, the search was further narrowed to investigate what kind of studies have been conducted in the literature on design, learning from nature and structural design (Figure 12). As a result of the first search based on keywords, it was observed that the words nature, structure, process, sustainability were particularly emphasized. If it is necessary to make a correlation among keywords in terms of structural design with nature learning, it is possible to observe that studies are more focused on plants. However, it should be added that spine is one of the keywords that stand out in relation to the word’s nature and structure.

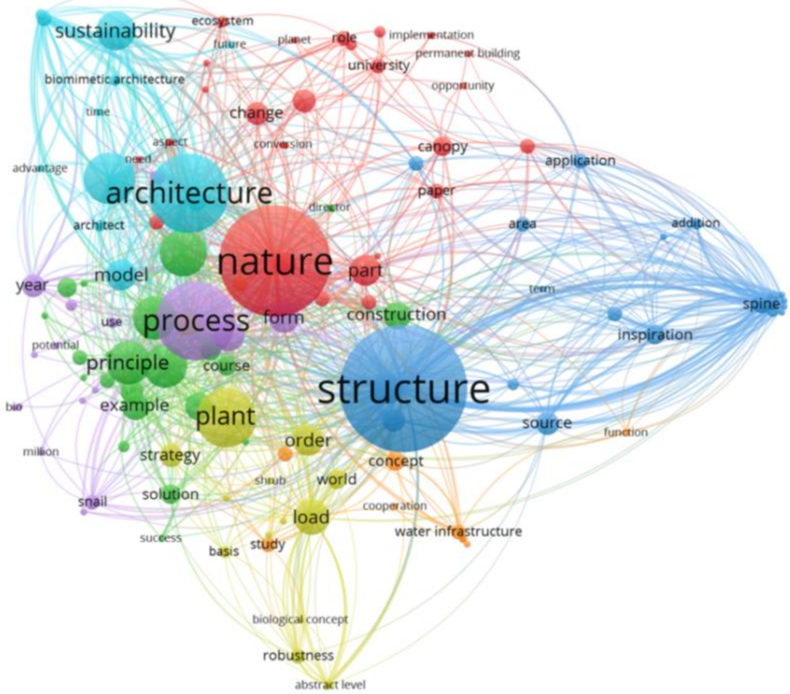


Figure 12 Network Graphic of Keywords : “structural design”, “biomimetics”, “learning from nature” (last update: 23.12.2022).

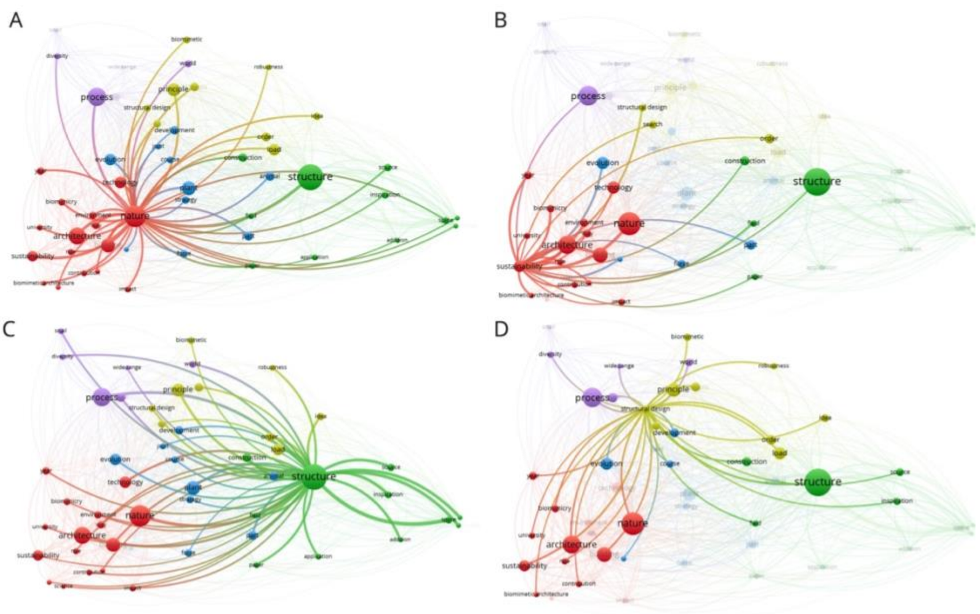


Figure 13 Network Graphic of Keyword Correlations: a) nature , b) sustainability, c) structure, d) structural design. (last update: 23.12.2022).

In order to gain a more comprehensive understanding of the literature, the keywords selected from this thesis were then filtered again and correlation network graphs were extracted from Vosviewer. In these studies, the interest towards sustainability stands out with its relation with many aspects in nature and structural design. It is noteworthy that the relationship of structural design with nature has always been linked to keywords such as sustainability, optimization and spine.

"Structure" has always been the most critical focus in architectural design, especially a major driver behind the engineering application in Architecture. At this point, if we need to bring a critical perspective to the literature, as it is seen in line with the research and readings, the literature on structural design that we know conventionally is an endless sea.

This thesis values structural design for the purpose of integration solutions, adaptation strategies and optimization processes learned from bone morphology. While there is a lot of work in the literature on optimization, this thesis aims to find unconventional ways to learn and transfer the behavior learned from bone. The answer to the question of whether adaptive structures that can integrate more harmoniously into the form are possible is sought.

CHAPTER 3

MATERIAL, FORCES, AND INFORMATION : TRANSFORMATION

This chapter is dedicated to the discussions on potentials of bone morphology to inform the structural design elements in architectural design. An iterative design process that integrates material, form and structure as in nature has the potential to unfold new design and construction strategies.

3.1 Nature's Design Strategy: Cellular Materials

> *"When modern man builds large load-bearing structures, he uses dense solids: steel, concrete, glass. When nature does the same, she generally uses cellular materials: wood, bone, coral. There must be a good reason for it (Ashby 2000)."*

Cellular structures provide material with good mechanical properties at the lightweight (Gibson & Ashby, 1999). Biological materials such as bone, wood, cork, sponges, plant stem, coral, and bird beaks; use this beneficial strategy. Cellular biological materials have complex internal structures that self-organize itself in hierarchies to produce differentiation, redundancy, and modularity. (Weinstock, 2006). All materials in nature are composed of fibers, so their multi-functionality occurs at nano-macro scales within different levels of connectivity. They make material configuration and allocation strategy according to performance requirements. The material is sparse in areas where stiffness is not required and concentrated where high strength is required. Therefore the shape of matter is therefore directly related to the forces acting on it (Oxman, 2010).

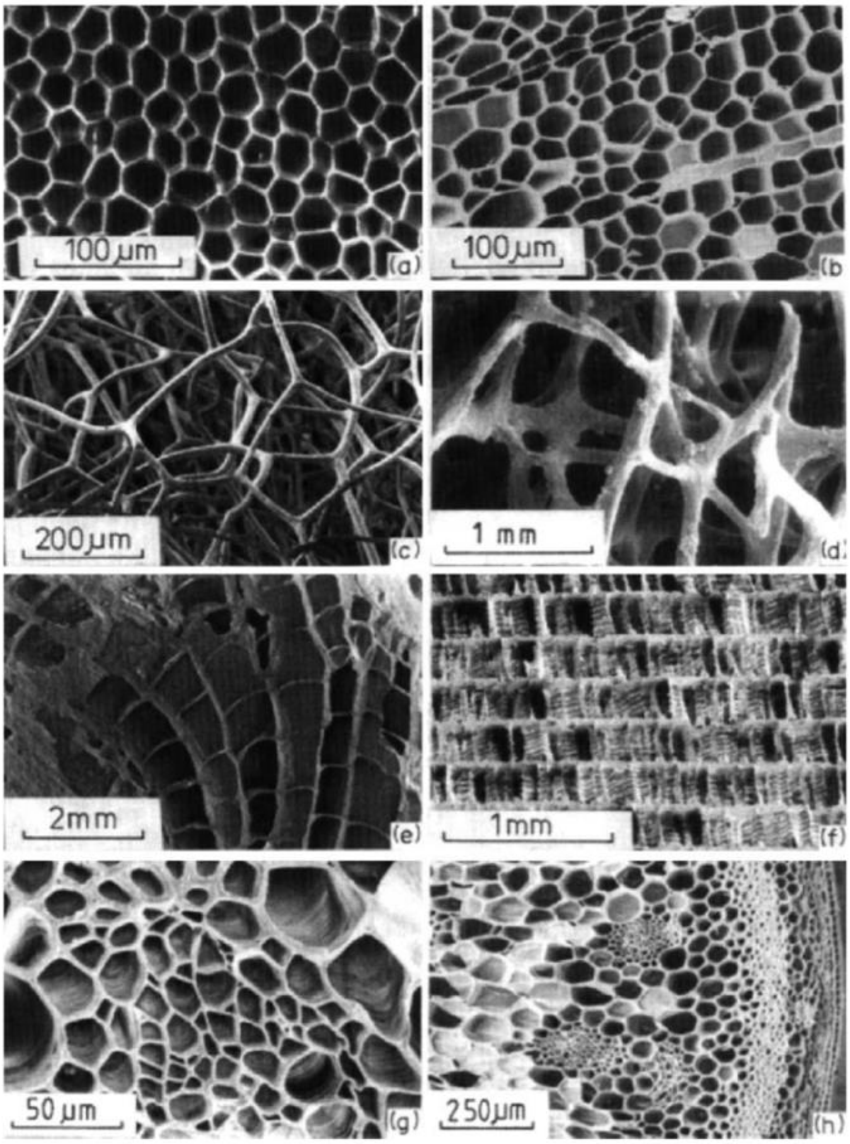


Figure 14 Natural cellular materials. a)cork, b)balsa, wood, c) sponge, d) trabecular bone, e) coral, f) cuttlefish bone, g) iris leaf, h) stalk of a plant (Gibson & Ashby, 1997)

In nature, material is known to be cheap because it is efficiently shaped and effectively structured. Nature can simultaneously model, simulate and reproduce material configuration with external requirements. Oxman (2010) emphasizes, nature has reversed the hierarchical order of "form-structure-material" from bottom to top, because material informs structure, and structure informs the shape of naturally designed specimens. In most cases the material comes first. For example, bone and other cellular structures in nature; the shape of matter is directly determined by the material from which they are made of.

Weinstock (2006) states, cellular materials' foam geometries are a source of appealing research area for developments in structural systems in architecture/engineering and material sciences. The foam geometries offer porous and ductile structural systems that are durable and strong.

Therefore, investigation of cellular solids with porous architectures and controllable mechanical characteristics as a tectonic system in architecture can provide material minimization in structural building elements.

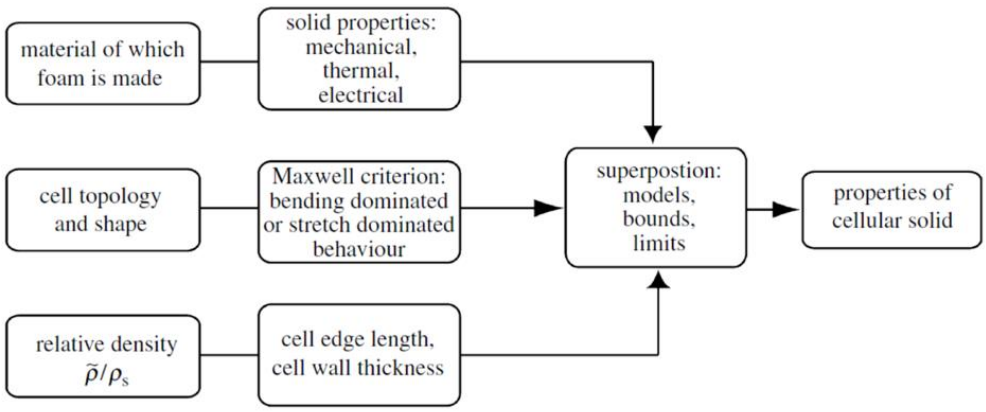


Figure 15 Design variables of cellular solids as explained by Ashby (2006).

3.1.1 Bones

Bone refers to a family of materials whose building block is the collagen fibril, each with a slightly different structural pattern. It consists of fibrous protein in a structural form, which is also found in tendons, skin, and various other soft tissues (Weiner & Wagner, 1998). Despite having meager building blocks such as minerals and proteins, bone has a complex inner structure that features exceptional mechanical properties (Cuneo et al., 2022). The formation and behavior of the bone are related to its structure, material, and form. The structural properties of bone follow the behavior of the elements and their properties (Oxman, 2010).

As Oxman (2010), states differentiating between biological materials of members of the bone family can also vary by the way their building blocks are arranged into higher-order structures. Bones have very complex inner structures and can be described into 7 hierarchical levels of organization (Figure 16). These materials have the ability to transform their own internal structures to perform various mechanical functions, in time (Weiner & Wagner, 1998).

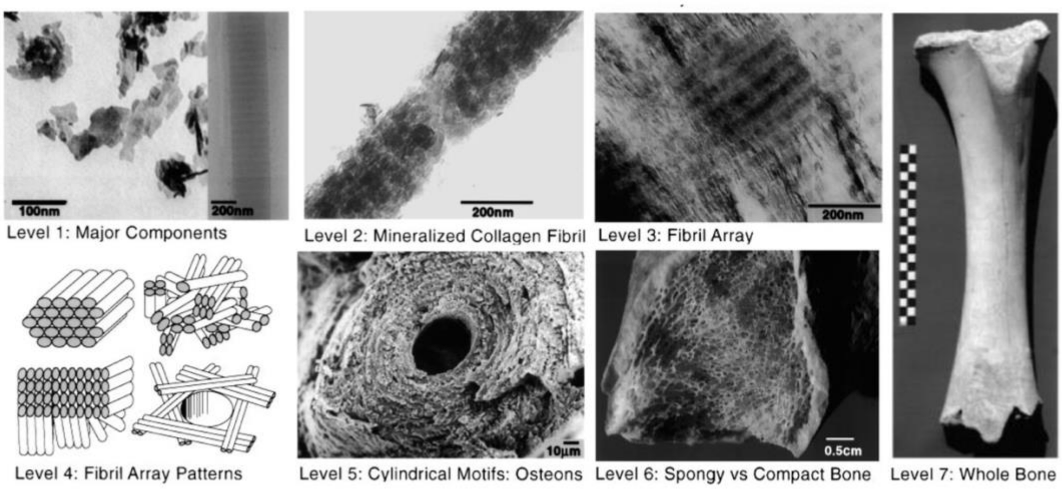


Figure 16 Bone material family showing 7 hierarchical levels of organization (Weiner & Wagner, 1998).

In his book “On Growth and Form”, D’Arcy Thompson (1942) defined the abstract mathematical systems underlying the structural formations and its transformations in nature. He sought to define form by understanding the forces acting upon it and worked on the correlations between mechanical influences and biological form. He especially drew attention to the feature of the bone structure showing equal strength against both compression and tension forces.

Bone is one of the significant examples of a natural system that is structurally efficient, strong, and lightweight. It has exceptional material and structural properties, making it almost as good as a tie or a strut, so much so that it can withstand tearing asunder, rupture or crushing. It has anisotropic properties which consists of a system that organizes matter, both structure and material, consistent with the lines of stress patterns across scales (Figure 17)

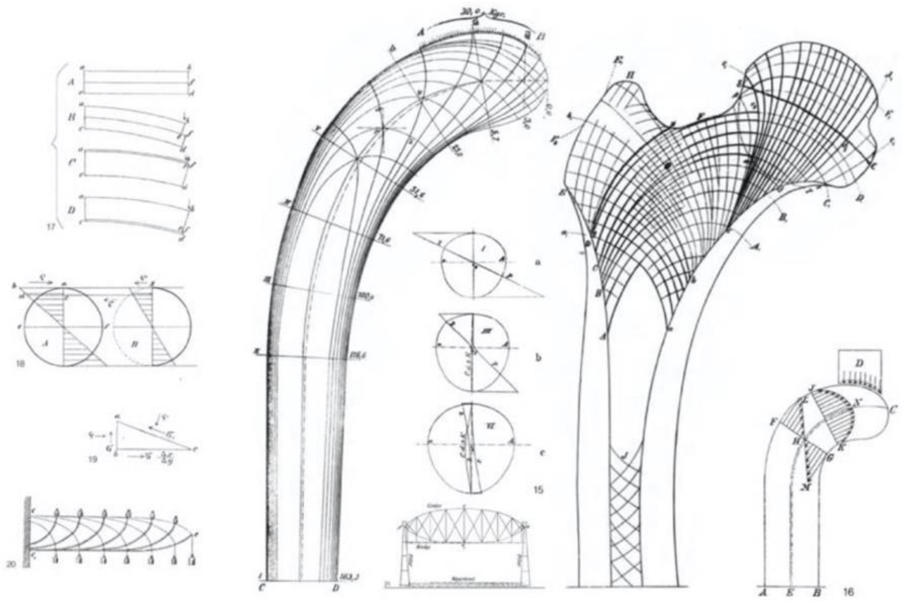


Figure 17 Sketches of Culmann’s crane and representation of the stress trajectories of the internal architecture of long femur and its mathematical significance. (Wolff, 1986)

As defined by Wolff's Law, it forms and remodels in response to mechanical stresses and the loads to which it is subjected (Figure 18) (Wolff, 2010). Wolff (1986), who described the theory of trajectories of trabecular orientation, suggests that bone achieves maximum mechanical efficiency with minimum mass and that trabecular bone architecture undergoes adaptive changes.

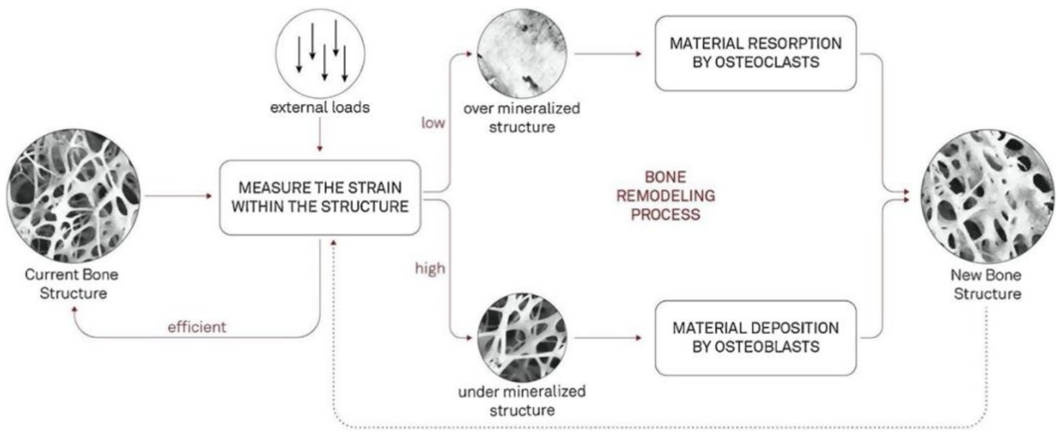


Figure 18 Algorithmic pipeline diagram of the bone remodeling process adapted from Turner (2012), (Naboni, 2019).

3.2 The Effect of Scale

Scale has a very important place in architectural design. Especially in nature-informed design. Every living organism in nature, from smallest to the largest, developed and adapted different working principles based on their scale. Therefore the material transformations, adaptations and size changes determines significant changes in natural organisms' function, structure and evolution in nature (Perricone et. al, 2021).

As Perricone et. al (2021) states, in biomimetic studies size and scaling rules should also considered as a remarkable point when transferring one solution obtained from nature to another dimension. The biomimetic principles generally work at very small scale, transferring the information from micro/nano scale to macro scale is not always possible (Perricone et. al, 2021). It can be seen that many biological structures lose their functionality while transferring information from one scale to another. This can best explained by Galileo's concept of *similitude* which first explained in his book "Two New Sciences". Similitude term is often used in physics, mathematics and engineering to test the properties, accuracy and precision of the model. However in biological context Galileo explains scale factor with the drawings showing two bones of different lengths (Figure 19), but strong enough to support loads proportionally to their linear dimensions. He tried to understand how the strength of structural elements is centrally related to the dimensional scaling. And it can be seen that the longer bone is more bulky (Steadman, 2008). It is by the reason of the fact that when we scale the dimensions of a matter by two it does not mean the volume is doubled. Rather the volume rises by a factor of eight (Leach, 2017).

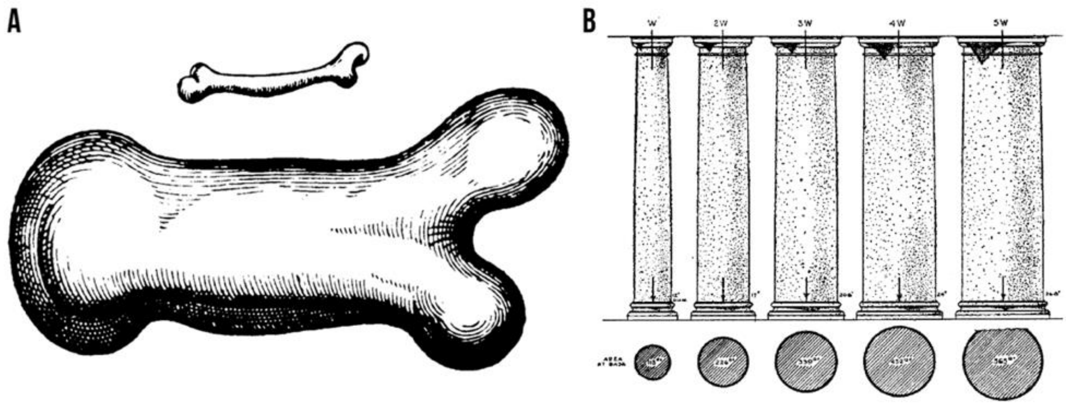


Figure 19 (A) Diagram of Galileo Galilei, different proportions of bones, to illustrate the "*principle of similitude"*. (B) Changing column ratios according to the different loads applied (Steadman, 2008)

One of the most important features of natural structures is their complex structure, formed by the highly differentiated combination of simple and basic molecular components, leading to structures that are multilayered, hierarchically structured, fine-tuned and characterized by multiple network functions.

Recent advances in computational design, simulation and fabrication technologies offer new options for transferring these principles to the macro scale of building construction and other technology fields. The aim of this nature-informed research is not only to improve performance of structures, but also to transfer the unique characteristics of natural structures, mainly the efficient use of limited resources and closed material cycles, their transformation processes and self-healing properites, and thus contribute to sustainability in architecture and technology.

CHAPTER 4

MATERIALS & METHODOLOGY

This part focuses on the materials and method of the research. How data is gathered, and analyses of data will be included. In this thesis, various research methods were used to explain, develop and illustrate the framework and to answer the three research questions.

At the initial stage, a literature survey is conducted to understand the relationship between circular economy and biomimetics by highlighting the obvious links between the two (Figure 20). Besides, the recognition that there is no waste in nature, as well as the many examples of survival with minimal energy use, from the production and use of materials to the organization of entire populations, illustrate this. Then after, in the light of this analogy, circular design strategies, nature-architecture relationship and building methods analogues to nature are examined (Figure 21).

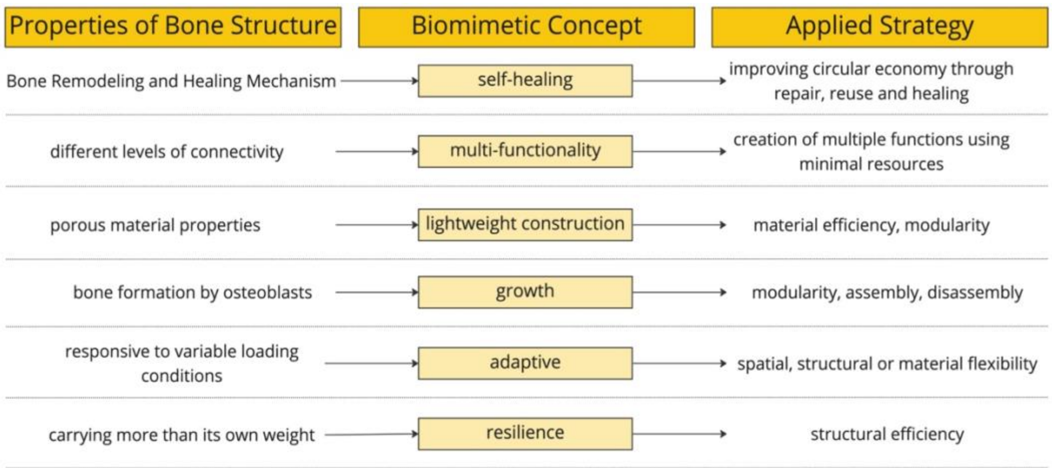


Figure 20 Properties of bone structure and its possible application scenario to improve circular design strategies (developed by author).

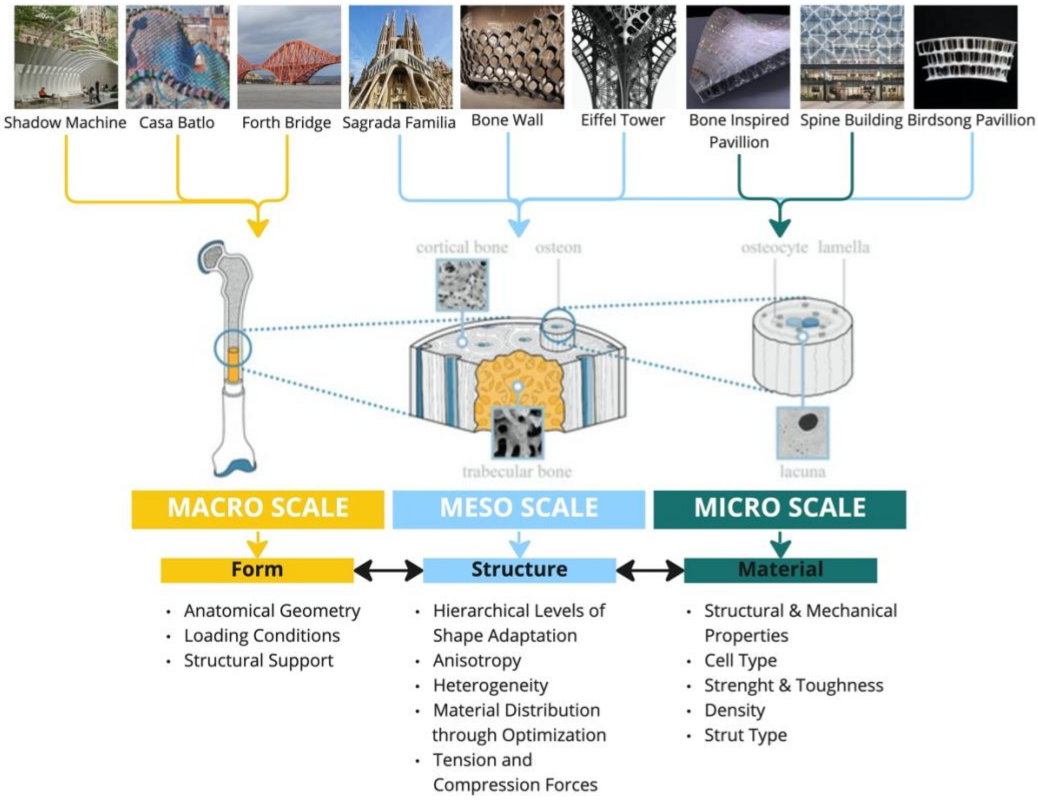


Figure 21 Level of information transfer from micro to macro scale application of bone inspired design in architecture (developed by author).

The research methodology includes case studies corresponding to different typologies of lattice structures derived from bone structure and comparing their properties. It includes analysis and evaluation steps, including the development of performance-based models learned from bone morphology for the design of structural elements, optimization and structural analysis to support optimized structural forms. It aimed to investigate the mechanical behaviors (i.e. strength, stiffness and bending) of different types of 3D printed truss structures under compression loading. The built-in static structural analysis design space of Autodesk's Fusion 360 was used to analyze the stresses of different unit-based lattice structures with the same dimensions under the same loading conditions for optimized design alternatives.

This study aimed to learn from the mechanical and material properties of bone structure to develop a different perspective on conventional ways of building structures. At this stage, it mapped the properties learned from bone morphology to lattice structures and conducted experiments on them. Taking the discussion further, argued that the anisotropic properties of bone tissue can also be used in building structures by calculating them according to the load distribution. The detailed method and methodology can be seen in the pipeline diagram in Figure 22.

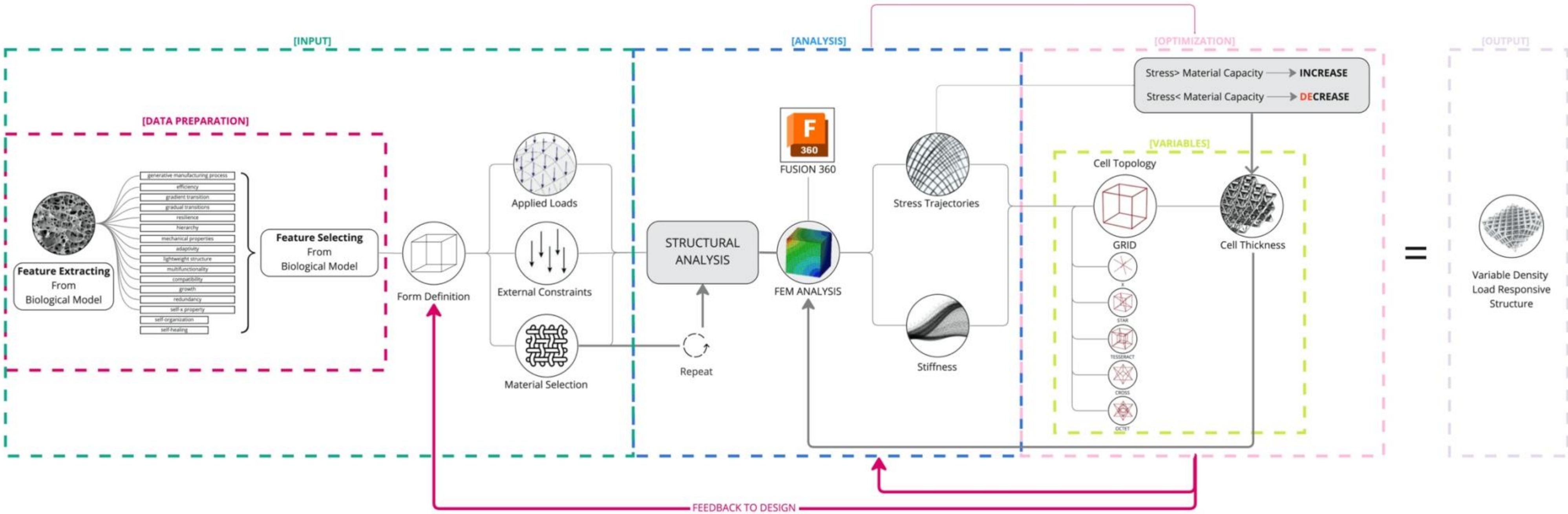


Figure 22 Pipeline diagram of the thesis (developed by author).

4.1 Lattices for Load-Bearing Structures

In nature, there are numerous cellular and lattice structures characterized by a high strength-to-weight ratio, such as the trabecular structure of bone. The idea of designing a material from the micro-scale to the macro-scale has been a long-standing goal, especially with engineering applications. Lattice structures are often used to reduce weight while maintaining structural performance. Since periodic lattice structures have more degrees of connectivity, they are successful in providing stiffness and strength at lighter weight and lower density. Periodic cellular lattices are formed by repetition of a singular unit cell with set dimensions (Lu, 2020). By controlling unit cell properties and their spatial distribution and arrangement can achieve superior mechanical properties as in bones. In various applications they can be used such as biomaterials, mechanical and aerospace engineering and medical purposes (Xu, et al., 2016).

Lattice structures can be formed in different types, their connectivity of strut node network can vary as strut based, surface based (triply periodic minimal surfaces), planar based (d) stochastic such as Voronoi lattices.

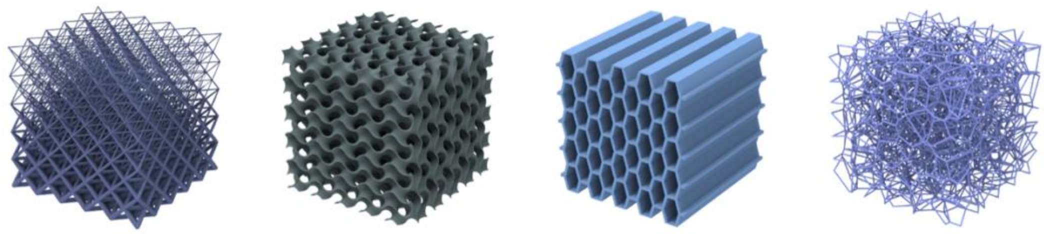


Figure 23 Examples of different lattice types. (a) strut based, (b) triply periodic minimal surfaces, (c) plate lattice (d) stochastic lattice (Voronoi). (retrieved from https://ntopology.com/blog/guide-to-lattice-structures-in-additive-manufacturing/ on 25.11.2022)

Factors affecting the mechanical performance of lattice structures can be listed as the dimensions and type of unit cell used, the porosity of structure, pore size, strut thickness, relative density, and the type of material used. Considering this method in a structural context gives the result that the forces to be carried more optimized way due to the density of the roads and the buckling resistance of the structural elements is increased. For the purpose of designing structural elements learned from bone lattice structures have been used as a basis for the extraordinary material and structural properties.

- **Unit Cell Generation**

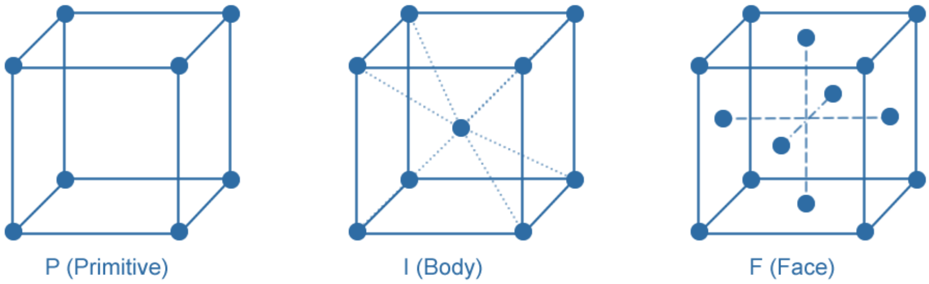


Figure 24 Bravais Lattice Structure generation methods (developed by author)

A lattice structure can be constructed from an array of unit cells according to the repetitions of the unit cells in three dimensions, determined in the direction of the x, y and z axis. Their configurations can be primitive, face centric and body centric.

Three different lattice typologies were selected, and simulations and analyses were performed on them in order to reach the load carrying capacity of the bone. In the quantitative comparison, periodic cellular lattices are generated with different unit cell structures were developed using Rhino3d and Grasshopper and analysed with Autodesk Fusion 360's built-in simulation environment. In the first stage, stress graphs of each of them under the same parameters were analyzed to test which would be the optimal unit cell to produce the lattice structures for load-bearing purposes. Structural steel, a type of steel commonly used as a construction material, was chosen as the material from Fusion 360's material library, as can be seen in Table 1.

Table 1 Material Selection and Properties of Steel (Fusion360 Material Library).

Material	Steel
Density	7.85E-06 kg / mm^3
Young's Modulus	210 GPa
Poisson's Ratio	0.3
Yield Strength	207 MPa
Ultimate Tensile Strength	345 MPa
Thermal Conductivity	0.056 W / (mm C)
Thermal Expansion Coefficient	1.2E-05 / C
Specific Heat	480 J / (kg C)

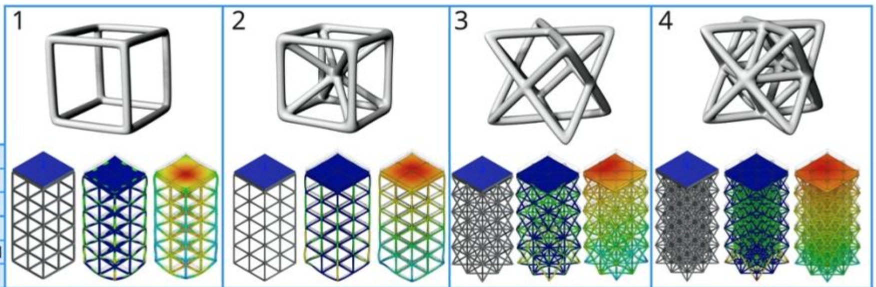
Table 2 Stress analysis of different type of unit cells under the same loading condition (developed by author).

Unit Cell Type	Unit cell length (mm)	Material	Force	Fixed Points / Loads	Safety Factor Per Body	Stress - Von Mises	1st Principal	3rd Principal	Total Displacement
Octet Cubic	20x20x20	Steel	500N						
Body Centered Cubic	20x20x20	Steel	500N						
Simple Cubic	20x20x20	Steel	500N						

The use of the Finite Element Model allowed to see how the structural performance of truss structures changes for different physical and mechanical changes and loading conditions. The load-bearing capacity of each unit in can be seen in Table 2 with Von Mises stress factor.

In this analysis, the following settings are used. The force is a static load equal to 500 N applied from the top surfaces. The material used is Structural Steel where the density is equal to 7.85E-06k/mm3, young’s elasticity is equal to 210 GPa, the Poisson ratio is equal to 0.3 and tensile strength is equal to 345 MPa.

Table 3 Stress analysis of different type of lattice structures with same volume under the same loading condition. 1) grid, 2) star, 3) cross, 4) octet (developed by author).



Type	Force
Magnitude	1000 N
X Value	0 N
Y Value	0 N
Z Value	-1000 N
Force Per Entity	No

	1		2		3		4	
Name	**Minimum**	**Maximum**	**Minimum**	**Maximum**	**Minimum**	**Maximum**	**Minimum**	**Maximum**
Safety Factor								
Safety Factor (Per Body)	0.2538	15	0.1592	15	0.03916	15	0.01696	15
Stress								
Von Mises	0.1236 MPa	815.6 MPa	0.04286 MPa	1300 MPa	0.4103 MPa	5286 MPa	0.0202 MPa	12209 MPa
1st Principal	-90.04 MPa	302.3 MPa	-401.7 MPa	546.3 MPa	-1329 MPa	1423 MPa	-4534 MPa	2816 MPa
3rd Principal	-922.9 MPa	24.13 MPa	-1510 MPa	34.78 MPa	-6578 MPa	114.5 MPa	-17667 MPa	243.7 MPa
Normal XX	-169.5 MPa	133.9 MPa	-563.7 MPa	295.8 MPa	-2795 MPa	567.4 MPa	-7535 MPa	1387 MPa
Normal YY	-172.1 MPa	130.2 MPa	-568.3 MPa	276.8 MPa	-2540 MPa	559.3 MPa	-7570 MPa	1339 MPa
Normal ZZ	-919.3 MPa	150.6 MPa	-1502 MPa	453.4 MPa	-5844 MPa	1181 MPa	-13760 MPa	2010 MPa
Shear XY	-67.91 MPa	128.8 MPa	-182.7 MPa	145.1 MPa	-657.5 MPa	685.8 MPa	-1565 MPa	1590 MPa
Shear YZ	-186.9 MPa	229.3 MPa	-498.2 MPa	378.2 MPa	-1999 MPa	906.5 MPa	-4288 MPa	4175 MPa
Shear ZX	-204.9 MPa	199.4 MPa	-543.4 MPa	287.1 MPa	-2367 MPa	764.7 MPa	-4202 MPa	3913 MPa
Displacement								
Total	0 mm	0.05922 mm	0 mm	0.0439 mm	0 mm	0.08336 mm	0 mm	0.07668 mm
X	-0.006962 mm	0.007596 mm	-0.01012 mm	0.004123 mm	-0.02326 mm	0.01668 mm	-0.00911 mm	0.004893 mm
Y	-0.005741 mm	0.008773 mm	-0.006866 mm	0.007544 mm	-0.01485 mm	0.01677 mm	-0.004879 mm	0.004997 mm
Z	-0.0592 mm	0 mm	-0.04373 mm	1.881E-04 mm	-0.08081 mm	0 mm	-0.07636 mm	0 mm
Reaction Force								
Total	0 N	258.4 N	0 N	271.7 N	0 N	299.1 N	0 N	292.7 N
X	-36.92 N	36.86 N	-58.27 N	70.79 N	-106.4 N	94.43 N	-104 N	103.4 N
Y	-37.52 N	37.42 N	-61.62 N	70.91 N	-101.1 N	98.7 N	-103.3 N	103.9 N
Z	0 N	253.4 N	0 N	255 N	0 N	260.7 N	0 N	253.6 N
Strain								
Equivalent	7.665E-07	0.004809	3.153E-07	0.008533	2.192E-06	0.03767	1.302E-07	0.09411
1st Principal	-4.708E-06	0.00313	-9.817E-06	0.006858	-1.675E-05	0.01897	-1.652E-05	0.04536
3rd Principal	-0.005345	-3.543E-07	-0.008897	-2.064E-07	-0.04173	2.257E-05	-0.1058	6.32E-06
Normal XX	-4.92E-04	9.164E-04	-0.0016	0.001652	-0.006033	0.00517	-0.01236	0.01211
Normal YY	-4.926E-04	9.602E-04	-0.001036	0.001476	-0.006454	0.005747	-0.01305	0.0125
Normal ZZ	-0.004056	7.873E-04	-0.006516	0.001749	-0.02353	0.007297	-0.05124	0.0125
Shear XY	-8.408E-04	0.001595	-0.002262	0.001796	-0.008141	0.008491	-0.01937	0.01969
Shear YZ	-0.002315	0.002839	-0.006168	0.004683	-0.02475	0.01122	-0.05309	0.05169
Shear ZX	-0.002537	0.002469	-0.006728	0.003554	-0.0293	0.009467	-0.05203	0.04845

At this stage the challenge was to select the most appropriate lattice unit and deciding densities and design space to ensure structural integrity. In this sense, series of tests were conducted to see which truss unit typology is more robust and reliable against the load imposed on structures within the same volume. Periodic cellular lattices, grid, star, cross and octet were generated with Rhino/Grasshopper. The structures with a volume occupied of 8000mm^3 have proportions of 20x20x100 mm. After equalizing the volume, the strut thicknesses were adjusted to provide the same volume. The results show that the highest deformation observed is in the Cubic lattice structure and the least deformation is in the octet lattice structure.

After the analyses were completed, the octet truss unit cell was preferred for the most suitable for designing load responsive lightweight structure.

4.1.1 Octet-Truss Lattice Frame Structure Analysis

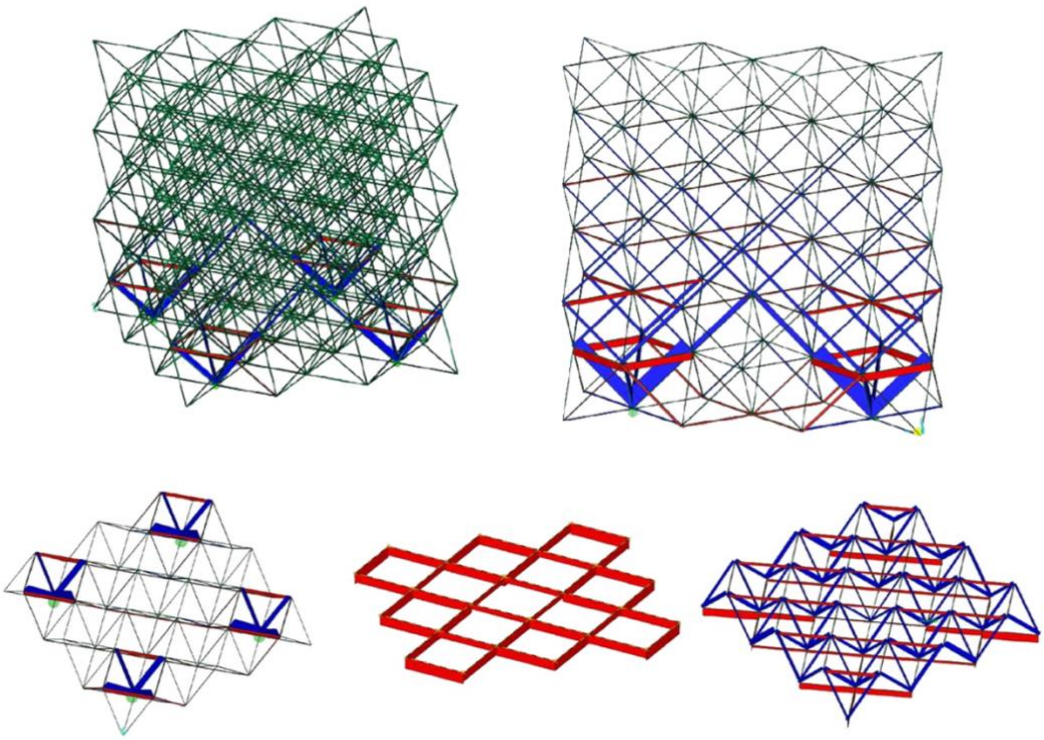


Figure 25 Initial wireframe test case and the analysis results.

In the first stage to test some parameters for the designed model, an octet-truss unit cell was selected. One reason for this symmetrical lattice selection is to be able to perform wire-diagram analysis with conventional trusses simulation applications. The lattice structure were comprised of 2x2x5 array of octet-truss unit cells. In the unit cell selection, the octet truss with pyramidal and tetrahedral core, which are particularly successful in preventing stress-dominated truss deformations, was chosen.

According to the results of the analysis, it is seen that the axial load distribution on the elements is shown in the screen images above. All elements are assumed to be of the same steel profile dimension. Since the stresses will be directly proportional to the axial loads in the elements with the same cross-section, it can be assumed that the stress distribution will be parallel to the axial load distribution. Blue color represent compression loads and red color represent tension loads. As expected, the loads concentrate and increase in the elements close to the bearings we have defined. The study was carried out under vertical loads and with four bearings defined at the lowest level. The load distributions obtained from different slices of the structure are also seen in the Figure 25. The information learned after conducting the analysis on this wireframe structure was the first step in determining the load distribution occurring in the bone and revising the design of new structural elements according to these load distributions.

4.1.2 Variable Density Lattice Structures

The hypothesis of this thesis suggests that there is a potential link between the process of bone remodeling and adaptation for the healing, repair, strengthening and load bearing capacity of existing building structures through advanced technologies. As observed in physical and digital tests, lattice structures can manage to minimize the use of material under the same boundary conditions and loads compared to a solid model. However, taking this optimization one step further will be possible with an in-depth study of the morphological structure of the bone structure and its adaptation process under different loads.

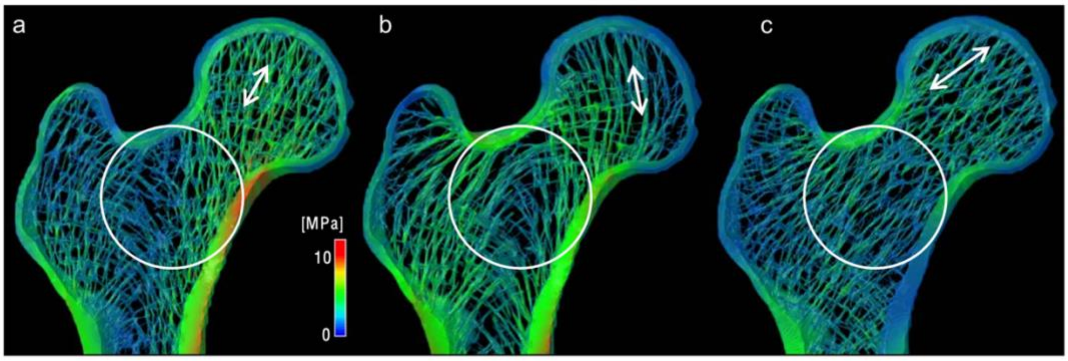


Figure 26 Simulation image representing the adaptation of the trabecular structure of the bone with the corresponding load direction (Tsubota et al., 2009).

If we look back at the simulation image representing the adaptation of the trabecular structure of the bone with the corresponding load direction (Figure 26) we can clearly see the optimization process to the load upload and how the internal structure changes in time. As can be seen in the first image, the areas highlighted in red are the areas on the bone where the most stress is observed. In the images that follow, bone structure adapts to the areas of greatest stress and changes its internal structure. This self-optimization process of the bone structure under changing external conditions and varying loads has great potentials if it can be applied structurally to architecture.

For a system aiming to achieve the most structurally optimized solution, the key feature of the proposed idea should be the ability to adapt and reconfigure according to changing loading conditions as in the reference model, bone. The process of creating maximum form diversity using minimum resources, defined as the concept of anisotropy in nature as Oxman (2010) states. It can be defined as the difference in the physical properties of the material such as hardness, strength, porosity, density, etc. when measured along different axes.

In light of all this, the non-uniform gradient distribution of mechanical properties along different axes of new type of structural components also has the potential to overcome many structural defects when combined with additive manufacturing technologies. For this case, a Grasshopper-based algorithm has been developed that optimizes itself according to the load distribution. The thickening algorithm can be controlled by points or lines. It is set to be point/curve-controllable, so that it can work harmoniously with point or line graphs extracted from structural analysis programs.

With the possible variations in cell geometry, a computational algorithm was developed to determine material placement, balancing stiffness and load distribution across the structure while achieving deflection limits

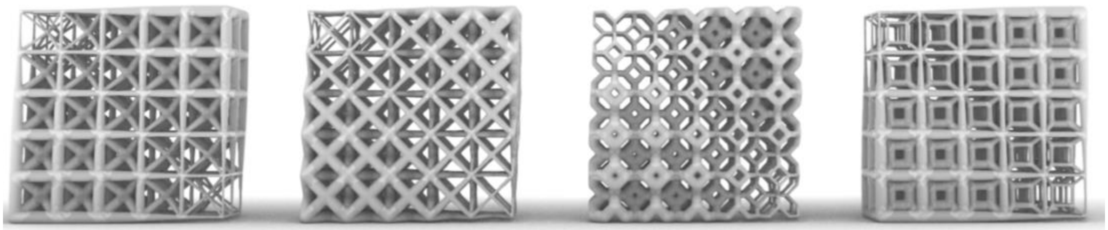


Figure 27 Variable density different type unit cell structures (developed by author).

- **Octree Algorithm**

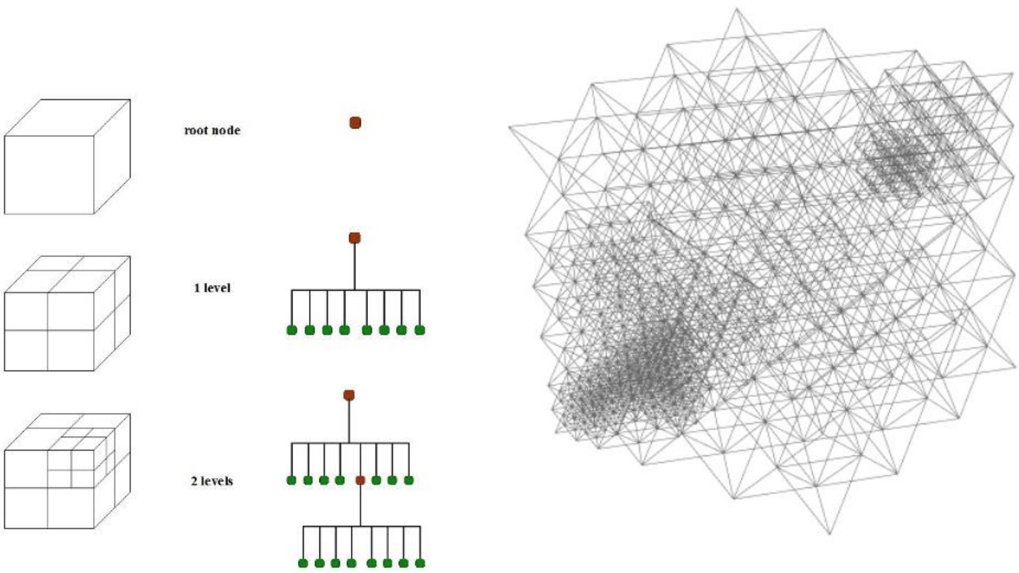


Figure 28 Octree algorithm logic and the octet truss octree model (developed by author).

Another approach for cells to adapt themselves according to the stress distribution was thought to be possible with the Octree algorithm. The logic of this algorithm is similar to bone's adaptation processes. Octree is a tree data structure where most often used to recursively subdivide a three-dimensional space into smaller parts. The resulting data, in this case, maximum stress levels. It is transferred, and then used to redistribute by cells, adding new ones where necessary. The size of the cells also varies in response to the amount of stress. This is done through an Octree algorithm, with 4 different scales of cells. Once printed, the smallest voxel becomes the densest one.

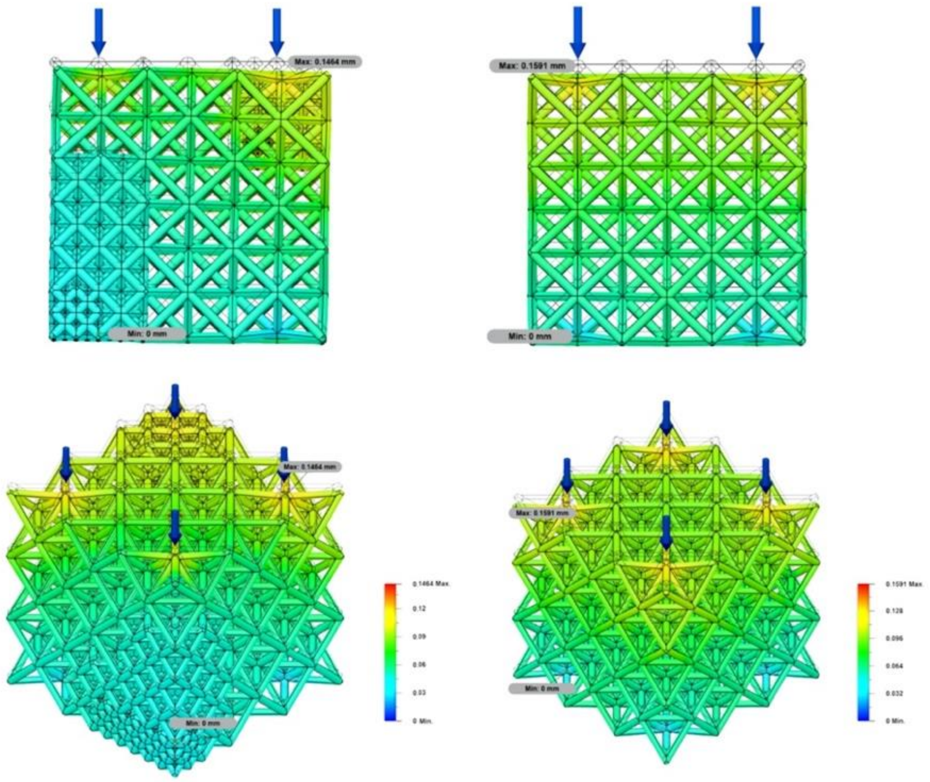


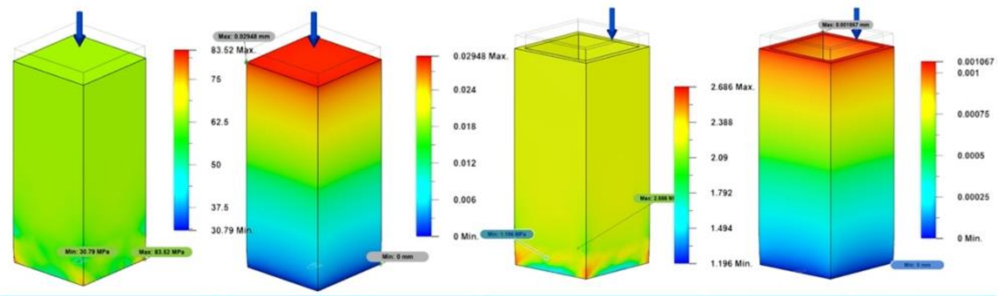
Figure 29 Comparison of uniform lattice structure and lattice generated by octree algorithm (developed by author)

To test whether the Octree algorithm can confirm the hypothesis, a pairwise comparison test was conducted with the same material properties under the same loads. As a result of the analysis, it was seen that calculating the stress load distribution using the algorithm and simultaneously controlling the number of cells can ensure that the structure is optimized according to the load and simultaneously increase its strength. While it is seen that the color distribution differs in places where the number of cells becomes denser, it is also observed that there is an increase in the numerical values of the strength in the graphs.

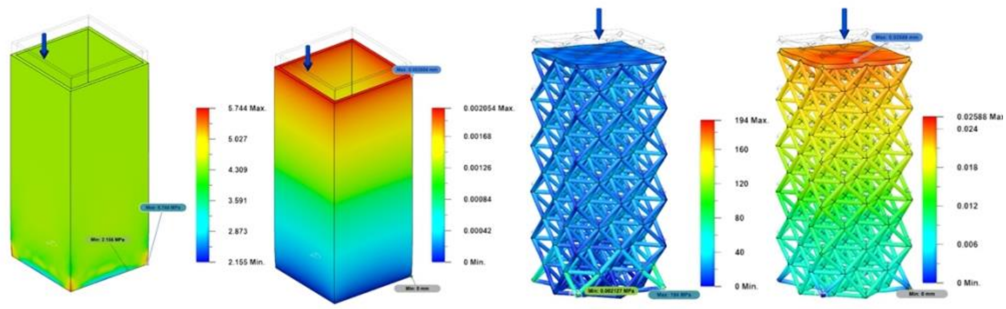
- **Comparison of Solid and Hollow Solid Structure with Cellular Lattice Structure**

Test cases were generated to compare the proposed cellular structures with the solid load-bearing structures used in conventional fabrication techniques and to use as benchmarks to optimize the system. First, the response of a completely solid structure under 1000N load was measured, then this structure was gradually hollowed out and measured under the same loads. Finally in order to make a comparison of the proposed cellular truss structural systems with a hollow solid structure and an octet truss lattice structure were generated. Models with a volume of 23,000mm^3 and dimensions of 40x40x100 mm were produced, to ensure that the dimensions of the design space and the material used were equal in volume. In the results obtained, it is seen that lattice structures are quite high in terms of load carrying capacity withstanding 194 MPa. The difference in load carrying capacities can also be seen in Von Mises Stress graphs, which represent a scalar field derived from the volume distortion energy density and used to measure the stress state.

Table 4 Comparison of Hollow Solid Structure & Cellular Lattice Structure



Name	Minimum	Maximum	Name	Minimum	Maximum
Safety Factor			Safety Factor		
Safety Factor (Per Body)	2.478	6.723	Safety Factor (Per Body)	15	15
Stress			Stress		
Von Mises	30.79 MPa	83.52 MPa	Von Mises	1.196 MPa	2.686 MPa
1st Principal	-32.89 MPa	10.88 MPa	1st Principal	-1.216 MPa	0.379 MPa
3rd Principal	-122.4 MPa	-50.6 MPa	3rd Principal	-3.781 MPa	-1.871 MPa
Normal XX	-46.58 MPa	10.15 MPa	Normal XX	-1.44 MPa	0.374 MPa
Normal YY	-46.58 MPa	10.34 MPa	Normal YY	-1.44 MPa	0.3721 MPa
Normal ZZ	-108.7 MPa	-50.54 MPa	Normal ZZ	-3.495 MPa	-1.837 MPa
Shear XY	-4.221 MPa	2.73 MPa	Shear XY	-0.1434 MPa	0.1404 MPa
Shear YZ	-22.48 MPa	22.06 MPa	Shear YZ	-0.6 MPa	0.6278 MPa
Shear ZX	-23.11 MPa	22.42 MPa	Shear ZX	-0.6068 MPa	0.6008 MPa
Displacement			Displacement		
Total	0 mm	0.02948 mm	Total	0 mm	0.001067 mm



Name	Minimum	Maximum	Name	Minimum	Maximum
Safety Factor			Safety Factor		
Safety Factor (Per Body)	15	15	Safety Factor (Per Body)	1.067	15
Stress			Stress		
Von Mises	2.155 MPa	5.744 MPa	Von Mises	0.002127 MPa	194 MPa
1st Principal	-2.854 MPa	1.052 MPa	1st Principal	-87.94 MPa	53.16 MPa
3rd Principal	-8.905 MPa	-3.496 MPa	3rd Principal	-259.8 MPa	7.797 MPa
Normal XX	-3.528 MPa	0.9458 MPa	Normal XX	-141.8 MPa	32.63 MPa
Normal YY	-3.528 MPa	0.9434 MPa	Normal YY	-140.3 MPa	33.1 MPa
Normal ZZ	-8.231 MPa	-3.356 MPa	Normal ZZ	-201.3 MPa	24.88 MPa
Shear XY	-0.3392 MPa	0.3384 MPa	Shear XY	-46.31 MPa	47.1 MPa
Shear YZ	-1.341 MPa	1.348 MPa	Shear YZ	-81.59 MPa	82 MPa
Shear ZX	-1.345 MPa	1.341 MPa	Shear ZX	-81.05 MPa	83.09 MPa
Displacement			Displacement		
Total	0 mm	0.002054 mm	Total	0 mm	0.02588 mm

- **Comparison of Truss System & Cellular Lattice Structure**

At the end of all these proposed structural cases and methods, a comparison with truss systems used in traditional lightweight construction was deemed appropriate to test the robustness of the new generation of cellular structures. For this system, two structures covering the same volume and using the same amount of material were produced. The volume covered by the structures measuring 60x60x200mm was determined as 45.000mm^3. As can be seen in Table 4, the cellular structure was able to withstand a load of 1123 MPa, while the truss system was able to withstand a force of 194.3 MPa. This difference between these two structures, which are equal in terms of the volume used and the design area they occupy, has been very significant point in terms of evaluating their load-bearing capacity.

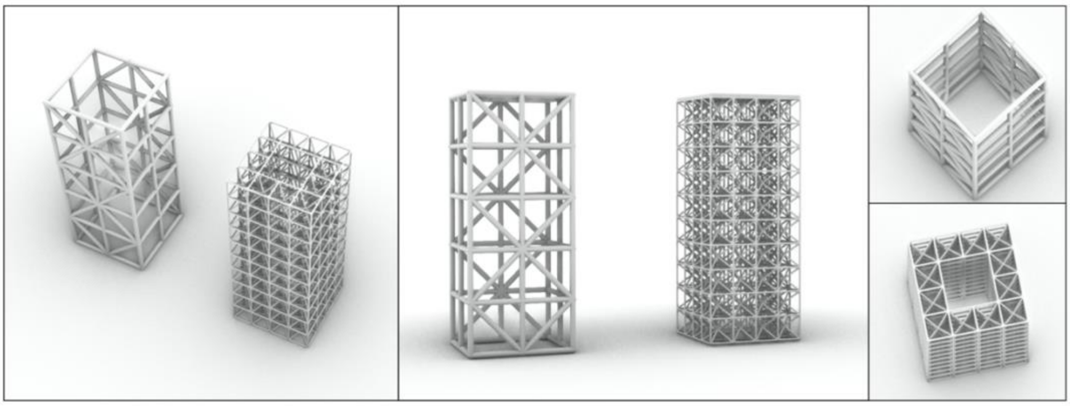
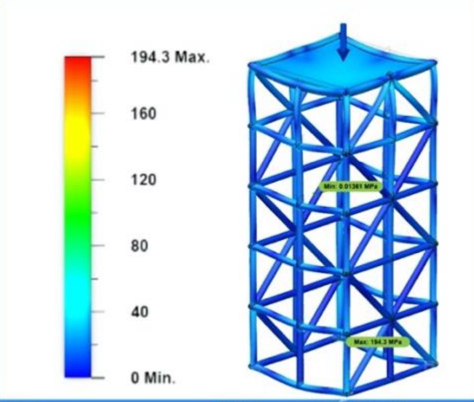
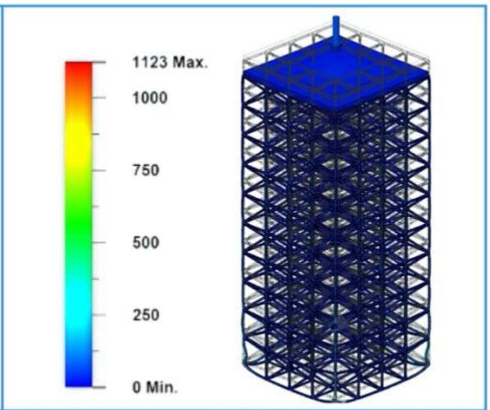


Figure 30 Truss System and Proposed Cellular Structure (developed by author).

Table 5 Comparison of Truss System with Proposed Cellular Structure





Name	Minimum	Maximum	Name	Minimum	Maximum
Safety Factor			Safety Factor		
Safety Factor (Per Body)	1.065	15	Safety Factor (Per Body)	0.1844	15
Stress			Stress		
Von Mises	0.01361 MPa	194.3 MPa	Von Mises	0.01143 MPa	1123 MPa
1st Principal	-105.9 MPa	81.5 MPa	1st Principal	-340.8 MPa	315.1 MPa
3rd Principal	-304.8 MPa	14.29 MPa	3rd Principal	-1537 MPa	25.18 MPa
Normal XX	-110.1 MPa	27.07 MPa	Normal XX	-481.6 MPa	249.8 MPa
Normal YY	-118.3 MPa	51.12 MPa	Normal YY	-675.5 MPa	283.3 MPa
Normal ZZ	-297.9 MPa	79.83 MPa	Normal ZZ	-1297 MPa	147.3 MPa
Shear XY	-17.88 MPa	15.41 MPa	Shear XY	-164 MPa	152.3 MPa
Shear YZ	-73.01 MPa	57.87 MPa	Shear YZ	-340.5 MPa	445.5 MPa
Shear ZX	-64.83 MPa	62.29 MPa	Shear ZX	-324.2 MPa	371.6 MPa
Displacement			Displacement		
Total	0 mm	0.06508 mm	Total	0 mm	0.0413 mm
X	-0.009447 mm	0.009367 mm	X	-0.004642 mm	0.004581 mm
Y	-0.01937 mm	0.01394 mm	Y	-0.004708 mm	0.005682 mm
Z	-0.06496 mm	0 mm	Z	-0.0413 mm	0 mm

4.2 Digital and Physical Tests and Outcome of the Process

- **Development of a Study Model**

Development of a model informed from bone morphology starts from design phase, which includes of design, test and validation processes of lattice structures with different types and parameters. There are several applications for the creation of lattice structures, in this thesis Rhinoceros3D and Grasshopper modeling environments, were used for the parametric model. Grasshopper plugins "Intralattice" and "Dendro" were used to create lattice and variable density lattice structures. While Intralattice plugin makes it possible to create different lattice typologies, Dendro algorithm was used to create variable, parametric and adaptive structures that respond to the load distribution with certain parameters according to the stress loads on the lattice structure. Depending on the values chosen, the volume of the structure can be reduced/increased, and the thickness of its elements thinned/thickened. After that , the process continues with the analysis, production and compression testing of the produced models and comparison of their load carrying capacities. The process is described in more detail in the following sections with case studies.

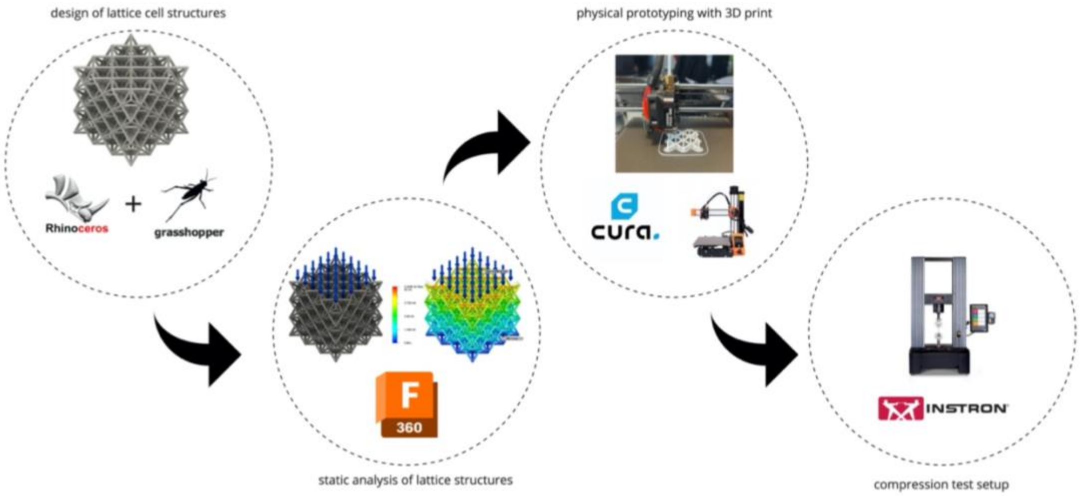


Figure 31 Development scheme of the model-test-validation process (developed by author).

- **3D Printing**

For physical testing 3D models are printed using with PLA filaments with Fused Deposition Modeling (FDM) printer which enabled rapid prototyping. The mechanical behavior of 3D printed lattice structures under compression is studied, focusing on failure mechanisms and main mechanical properties such as strength, durability.

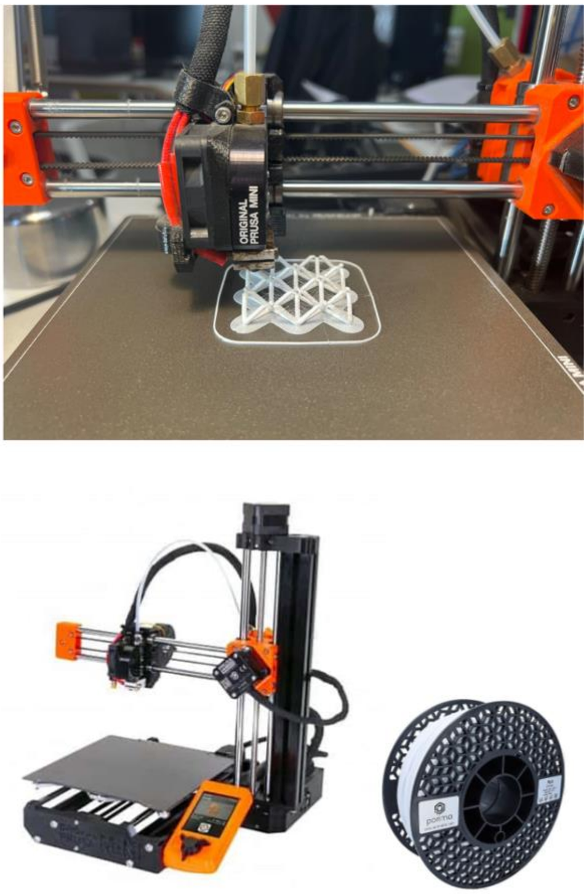


Figure 32 Original Prusa Mini Fused Deposition Modeling (FDM) printer and Porima PLA filament used for the 3D Models (Photographs taken by author).

FDM has the limitation of printing with horizontally parallel layers. Since the strut thickness is not evenly distributed along the various parts of the structure, the unit cell typology selection becomes important point in the design decisions. At this stage, many attempts were made and with failed models had to be returned to the earlier stages of the design. It is very difficult to produce strut thicknesses that vary especially vertically with 3D printers that produce layer by layer. In some places, the model needs to be printed in air due to varying strut thicknesses. This will require a more comprehensive understanding of the behavior of 3D printing, as well as revisiting the models to have more control with the material used for printing.

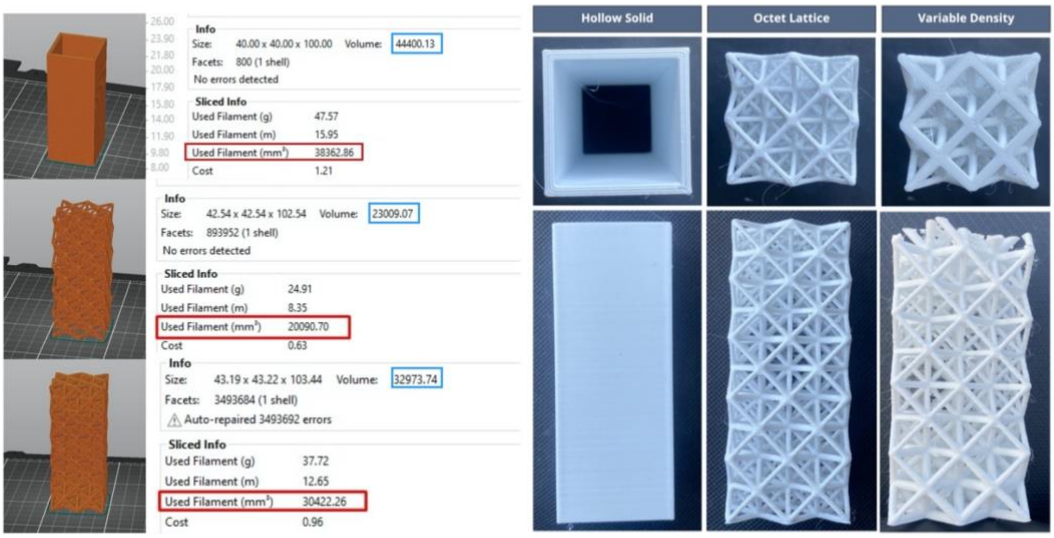


Figure 33 3D models prepared using Fused Deposition Modeling (FDM) printer with PLA filaments (photographs taken by author).

As marked in Figure 33, the variation in the amount of filament used for the tested specimens is quite remarkable. It is observed that the solid hollow sample has the highest volume with 44400 mm^3 and uses the most filaments, while the uniform lattice structure has the lowest volume with 20090 mm^3 and filament usage. At this point, it can be said that the uniform lattice structure saves almost more than half the material compared to a hollow solid structure under the same boundary conditions with the same thickness of struts and wall. In addition, it is noteworthy that there is an increase in the volume occupied by the variable density structure and the amount of filament used. However, it should be noted that the only purpose of performing these experiments is not only to save material but also to make a comparison in terms of strength.

- **Compression Test**

As the next step after the analysis, the compression tests were conducted on a universal testing machine (Micro Analiz) that can perform tensile - compression - bending tests, allowing the determination of life and maximum strength of the materials such as polymer, plastic, composite, metal etc. The machine can be programmed according to the desired conditions, sample size, test type, speed and controlled/monitored by its own built-up computer program.

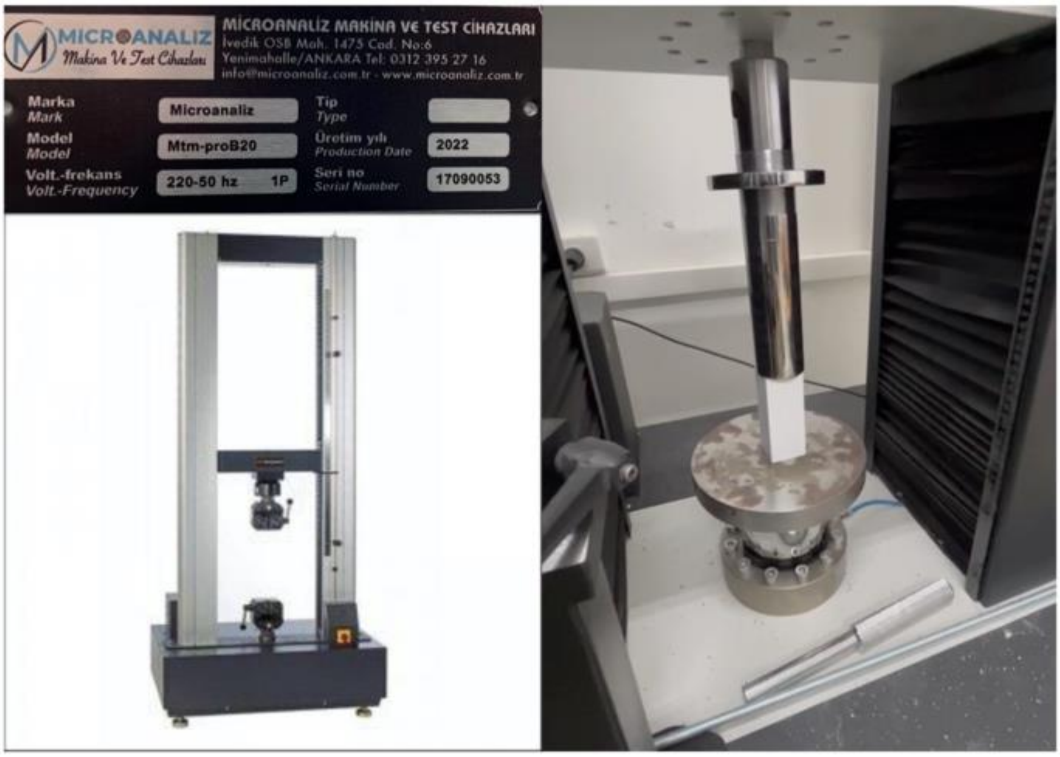
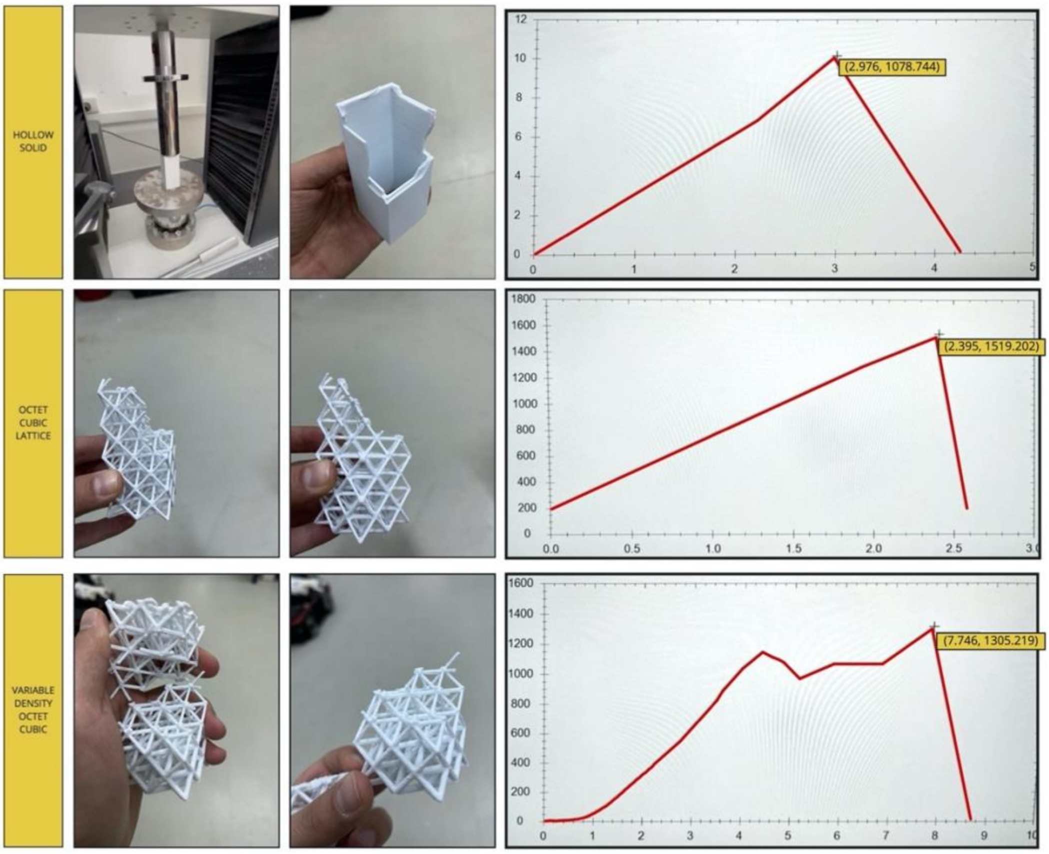


Figure 34. Compression test setup and its specifications (photographs taken by author).

Physical compressive buckling testing was carried out with generated lattices, to record mechanical properties of strength, stiffness, first failure force, and peak failure force, and failure displacement. A solid hollow rectangular prism with the same bounding proportion is tested as a control. Lightweight cellular lattice structures made with 3D printed Polylactic Acid (PLA) are subjected to axial compression tests. The axial deformation and force values of the specimens obtained from the experiments are recorded with the computer program and the force-displacement curves are drawn using the data obtained from the experiments, as shown in (Table 6). This leads to promising findings for the use of lattice/cellular structures for load bearing purposes with more detailed investigations in future studies.

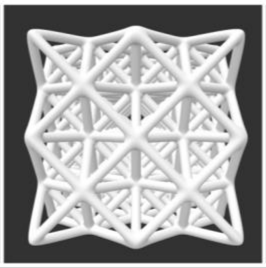
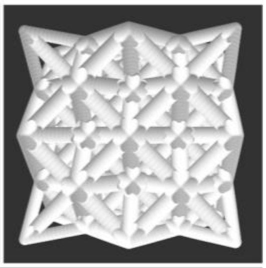
Table 6 First trial of test cases and their force/deformation graphics.



After the experiments were carried out, the uniform lattice between the specimens provided strength up to 1519.202 N force as can be seen in table 6 prepared with the data. The bone-informed variable density specimen was the second strongest, reaching a strength of 1305.219 N. At this point, it should be noted that the tested specimen was damaged due to the 3D printer from the fabrication stage. Nevertheless, the data it has shown is very promising. It is predicted that if its defects are minimized in the future stages, it can become more optimized than the uniform one. Another interesting thing in the extracted data form force-displacement graphs how the curves changes with the geometry and material usage. At this point, further tests should be conducted to better understand the behavior learned from the bone.

It is important to keep in mind that although this thesis uses 3D printed and octet truss lattice structures by FDM printers using PLA as proof of concept, the method itself is not limited to this specific lattice geometry or these specific materials. 3D printing often has the capacity to speed up the production process compared to traditional manufacturing techniques. However small 3D printers using PLA material are not very powerful in reflecting the bearing capacity of a structure in terms of material, additionally it should be noted that this thesis, in this stage, investigates structural possibilities in terms of behaviors not the material itself.

Table 7 Comparison of the compression test (developed by author).

case study **comparison chart**			
unit cell type	hollow solid	uniform octet truss	variable density octet truss
volume (mm3)	44400 mm3	20090 mm3	32973 mm3
dimensions (mm)	40x40x100	40x40x100	40x40x100
filament used (g)	47.57	24.81	37.72
filament used (mm3)	38362 mm3	20090 mm3	30424 mm3
cost	1.21	0.63	0.96
failure displacement	4.1mm	2.6mm	8.7 mm
first failure force (N)	700 N	1800 N	1100 N
peak failure force (N)	1078.744 N	1519.202 N	1305.219 N

CHAPTER 5

CONCLUSION

5.1 General Discussion, Limitations and Recommendations for Future Work

The concept of developing highly automated tools and techniques for application in construction has not yet been put into much practice. However with the rapid prototyping, information technologies and computer-aided design (CAD), advances in digital design and fabrication integration are motivating a shift in architecture and design towards the production of fully integrated buildings. The industry is currently evolving towards new design and production processes through better integration of materials, form, structure and construction.

With computer-aided design combined with additive manufacturing technologies, the design and fabrication of complex structures became possible. 3D printing technologies' potential to enable us to simultaneously consider structural, material and fabrication constraints while giving high level of shape control on producing highly complex and precise geometries, in a cost-effective manner, is very promising way to improve the performances.

In this thesis, a biomimetic design methodology has been introduced with the information gained from biological, structural and material properties of bone. An experimental investigation of the compressive response of lattice structures and variable density lattice structures informed from bone morphology has been presented. The possibility of applying the knowledge gained from bone morphology was investigated and the possible impact on the strengthening, ease of assembly-disassembly and hence repair of the structure was analyzed.

In contrast to the current materials and manufacturing technologies used, the method proposed enables efficient and lightweight structures, providing advantageous structural efficiency and ease of comprehensive control over complex geometries with special precision. Optimization of this new system will enable the concept of sustainability, integrating material composition, information of heterogeneous components with geometry information, and assigning different spatial properties according to requirements.

Optimizing analysis programs that provide live feedback while exploring geometry or other design features in structures, while also considering load calculations and scenarios, can also foster a new generation of building construction. Structures derived from continuously self-optimizing materials and construction techniques can enable an architecture based on a dynamic and adaptive system for building longevity, strength and durability.

A self-repairing load-responsive building system can be integrated into the construction sector enables optimization and adaptation over time, while increasing lifespan, providing material self-repair, preventing demolition and reducing CO2 emissions and therefore construction waste.

A solid and an octet truss lattice, one variable density, have been fabricated. It has been observed that the overall performance of the structural elements designed using lattice structures has significant enhancements compared to the conventional ones. However, using FDM technology to fabricate these lattice structures has some limitations, as indicated in Figure 35, the elements marked in red cannot be fabricated using FDM. At this stage, it is necessary to re-evaluate the lattice typologies and manufacturing technologies used for future phases. For future phases given the relatively small number of tests performed for both the test series and the different lattice structures, further testing and analyzing with different approaches are recommended.

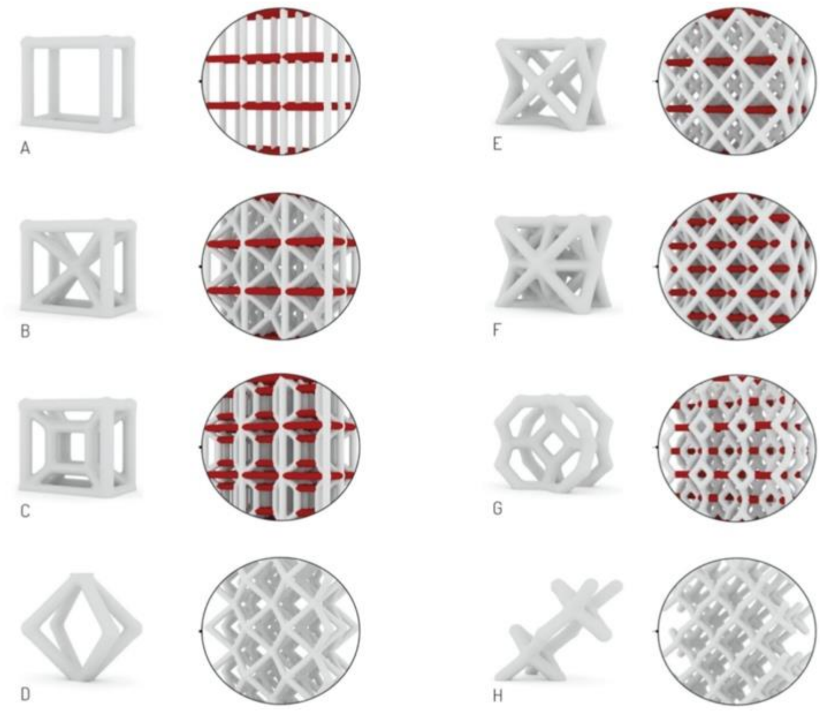


Figure 35 Elements highlighted in red indicates lattices that cannot be produced with FDM (Naboni, 2017).

Additionally to general discussion some scenarios and future uses can be listed as:

- Modularity

Modularity is a design principle that divides a structure into smaller parts, called modules, that can be independently built and stacked to create the desired structure. Using unit-cell based lattice structures for load-bearing approach also becomes extremely valuable for construction systems based on modularity and prefabrication. It facilitates ease of assembly and disassembly and facilitates circular economy by allowing cyclical material and structure repair and reuse. Lattice structures can use modular growth systems derived from nature to apply endless scalability, and freedom for the future of architecture. The logic behind the processes are that the resulting designs were capable of spanning, climbing, turning corners, closing spaces and creating new kinds of architectural spaces. It can both test the limits of the matter and data while turning algorithm into real spaces and objects.

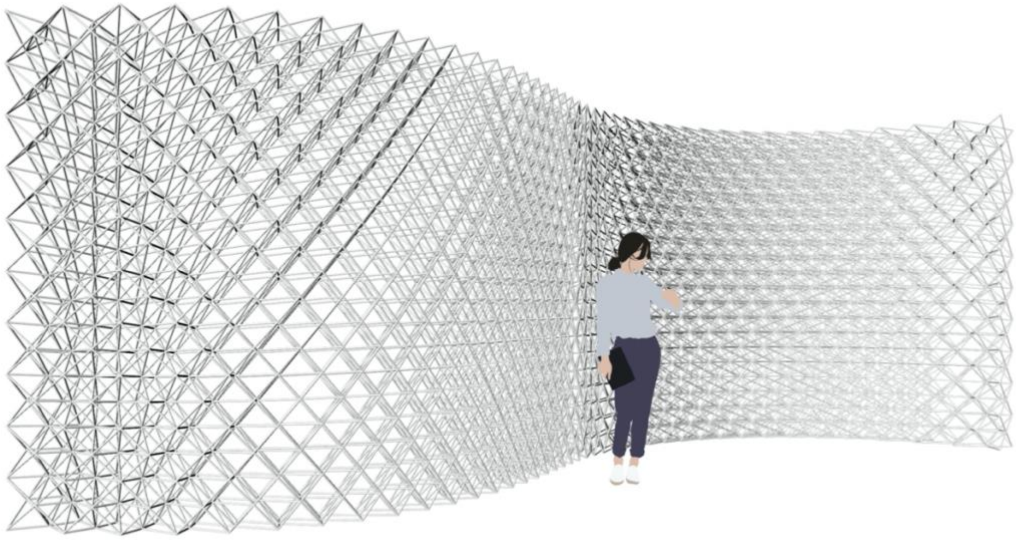


Figure 36 Future use scenario of lattices for modular structural elements (developed by author).

- Self-Healing

Concrete is one of the most widely used materials in the construction industry and it has significant contribution to environmental issues, such as global warming, CO2 emissions and material consumption. It is a semi-brittle and crack-prone material that has high strength in compression but poor strength in tension.

It is inevitable that there is a paradigm shift in architectural design from material and resource consumption to sustainability, which has also made sustainability a major concern for existing buildings. Extending the lifespan of existing buildings in the built environment, improving their performance, repairing and healing them, taking measures against possible defects or re-functioning them becomes a design concern. Structure mainly contributes to the overall performance of the building with durability, strength, reliability.

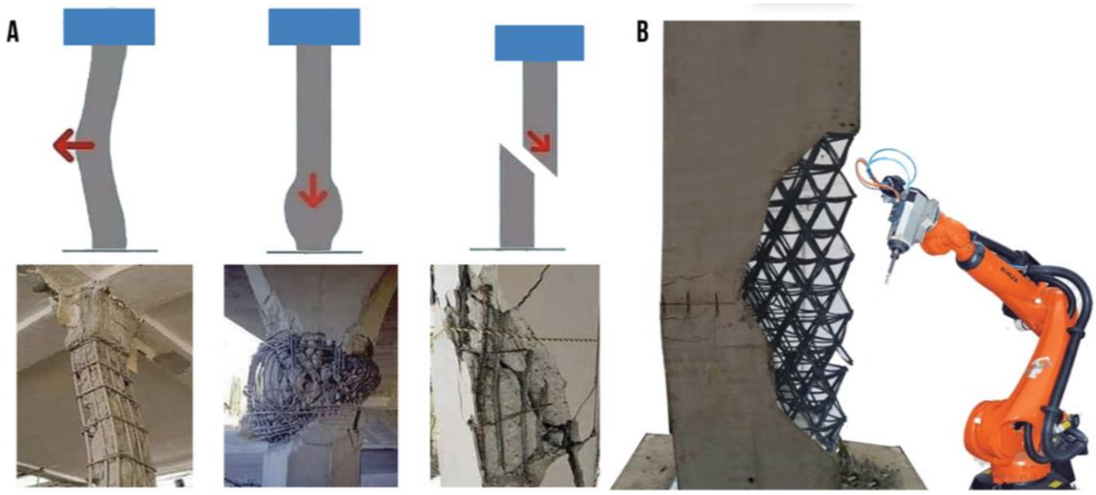


Figure 37 Structure- robot collaboration scenario (developed by author).

Instead of building components such as concrete, which are difficult to intervene later, it will be possible to optimize and adapt buildings with new generation fabrication and construction techniques, steel and perhaps biological materials in the future.

As a result of all these studies, in order to take the discussion further, it has been concluded that it may be enlightening for future studies to reconsider the production of traditional lightweight building truss systems with the cellular lattice structures proposed in this thesis with fabrication on an architectural scale, using real construction materials and different production techniques from FDM printers.

Also recent advances in artificial intelligence (AI) and machine learning (ML) can offer a way forward, connecting the power of performance-driven structural design with information obtained from biological models. Biological models of bone and simulations can be analyzed using machine learning methods to employ properties of bone to design processes to optimize the structures in future studies.

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