Tectonic Potentials of Earthen Materials
Post-tensioned Structures

JOY SAMUEL LABIB MAHER

June 2024

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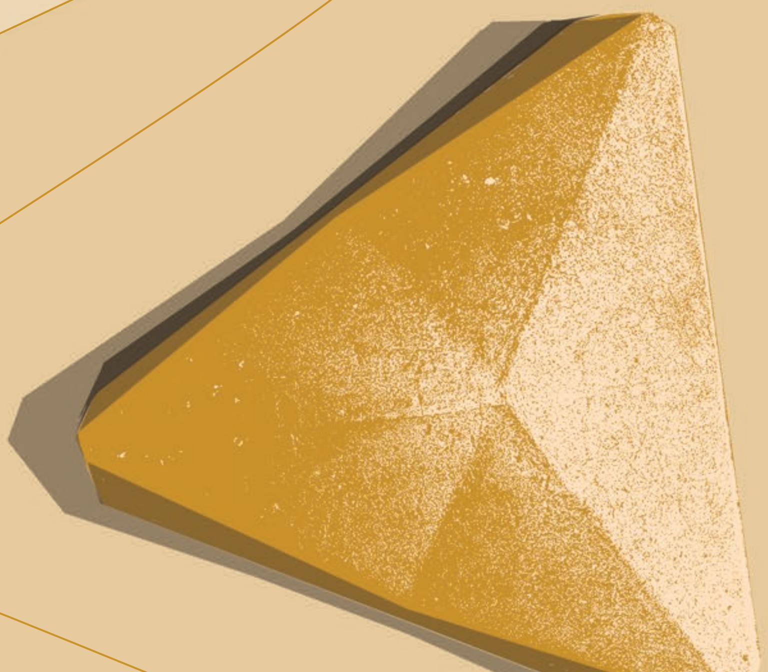

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

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Doctoral thesis

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"For of Him, and through Him, and to Him, are all things. To Him be the glory forever! Amen." (Romans 11:36)

Dedicated to the great memory of my number one supporter,

Rev. Fr. Father Samaan Ibrahim,

whom I dearly miss every day. His unwavering support was the cornerstone of my journey, providing me with guidance, encouragement, and strength through every challenge and triumph.

Fr. Samaan was not only a supporter but also a role model in all aspects of life. His exemplary character, wisdom, and dedication inspired me to strive for excellence and integrity in everything I pursued.

I am forever grateful for his great care, both spiritually and personally. His kindness, empathy, and compassion touched the lives of many, including mine, leaving an indelible mark of love and warmth. His advice were invaluable treasures that I will cherish forever. Whether it was in matters of faith, academics, or personal growth, his words of wisdom were a guiding light, steering me towards the path of success and fulfillment.

Though he may no longer be with us in person, his spirit and legacy continue to live on, guiding me each step of the way. Fr. Samaan›s impact on my life is immeasurable, and I dedicate this thesis to his memory with profound gratitude and love.

To my beloved family, whose boundless love and support have been a constant source of strength throughout this journey. My heartfelt gratitude to my father, **Dr. Samuel Maher**, my mother, **Mary Samaan** and my sister, **Joanna Samuel** for their unwavering support and continuous encouragement, which have been the pillars of my perseverance. Their love, and understanding have been my guiding light, I owe a debt of gratitude beyond words.

I extend my heartfelt appreciation to my esteemed supervisors, **Dr. Fernando Vegas López-Manzanares, Dr. José Manuel Pagés Madrigal, and Dr. Camilla Mileto**. Their guidance, expertise, and unwavering support have been invaluable throughout the course of this thesis. Their dedication to excellence and their willingness to share their knowledge and insights have enriched my understanding of the subject matter and elevated the quality of my research.

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_ Joy Samuel, 2024

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ABSTRACT

Over the years, numerous building materials have undergone experimentation and technological enhancements to meet their intended purposes and remain competitive in the construction industry.

In an era marked by escalating climate change concerns, the selection of low-carbon footprint building materials is paramount. However, local materials like earth lack the necessary technical advancements and structural integrity to garner widespread adoption among architects and society.

While earth-based materials offer undeniable environmental benefits, including low embodied energy and carbon emissions, doubts persist regarding their technical performance and structural reliability. Architects and builders often prefer conventional options perceived as more dependable.

The thesis seeks to explore the architectural possibilities of earthen materials, examining ways to integrate them into various architectural elements and proposing innovative design approaches, such as post-tensioned structures, to enhance their usability and broaden their applications. The objective is to capitalize on the unique qualities of earth materials and challenge the prevailing notion of them as standardized, flat forms while addressing feasibility concerns.

The research methodology employs a concurrent mixed method, combining experimental data with observations of material behavior to derive outcomes. Through a three-phase experimentation process, variables such as mold materials, earth mixtures, and post-tensioned structures are rigorously tested. Iterative design and meticulous testing

refine fabrication techniques, ensuring the robustness of the research design.

In summary, this thesis significantly advances contemporary building materials and architectural engineering. Through innovation and interdisciplinary collaboration, it facilitates the creation of functional, aesthetically pleasing structures that seamlessly integrate with their environment while pushing the boundaries of conventional design paradigms.

Keywords

Earthen materials; post-tensioned structure; tectonics; modular; mold design; connection.

ABSTRACT (SPANISH)

A lo largo de los años, numerosos materiales de construcción han sido objeto de experimentación y mejoras tecnológicas para cumplir con sus propósitos previstos y mantenerse competitivos en la industria de la construcción. En una era marcada por crecientes preocupaciones sobre el cambio climático, la selección de materiales de construcción con bajo impacto de carbono es fundamental. Sin embargo, materiales locales como la tierra carecen de los avances técnicos y la integridad estructural necesarios para lograr una adopción generalizada entre arquitectos y la sociedad.

Si bien los materiales a base de tierra ofrecen beneficios ambientales innegables, como baja energía incorporada y emisiones de carbono, persisten dudas sobre su rendimiento técnico y su fiabilidad estructural. Los arquitectos y constructores a menudo prefieren opciones convencionales percibidas como más fiables.

La tesis busca explorar las posibilidades arquitectónicas de los materiales de tierra, examinando formas de integrarlos en varios elementos arquitectónicos y proponiendo enfoques de diseño innovadores, como estructuras postensadas, para mejorar su usabilidad y ampliar sus aplicaciones. El objetivo es capitalizar las cualidades únicas de los materiales terrosos y desafiar la noción predominante de ellos como formas estandarizadas y planas, abordando las preocupaciones de viabilidad.

La metodología de investigación emplea un método mixto concurrente, que combina datos experimentales con observaciones del comportamiento del material para derivar resultados. A través de un proceso de experimentación de tres fases, se prueban rigurosamente variables como materiales de moldeo, mezclas de tierra y estructuras postensadas. El diseño iterativo y las pruebas

meticulosas refinan las técnicas de fabricación, asegurando la solidez del diseño de investigación.

En resumen, esta tesis avanza significativamente los materiales de construcción contemporáneos y la ingeniería arquitectónica. A través de la innovación y la colaboración interdisciplinaria, facilita la creación de estructuras funcionales y estéticamente agradables que se integran perfectamente con su entorno, al tiempo que empujan los límites de los paradigmas de diseño convencionales.

ABSTRACT (VALENCIAN)

Al llarg dels anys, nombrosos materials de construcció han sigut objecte d›experimentació i millores tecnològiques per a complir amb els seus propòsits previstos i mantindre›s competitius en la indústria de la construcció. En una era marcada per creixents preocupacions sobre el canvi climàtic, la selecció de materials de construcció amb baix impacte de carboni és fonamental. No obstant això, materials locals com la terra manquen dels avanços tècnics i la integritat estructural necessàries per a aconseguir una adopció generalitzada entre arquitectes i la societat.

Encara que els materials a base de terra ofereixen beneficis ambientals innegables, com baixa energia incorporada i emissions de carboni, persisteixen dubtes sobre el seu rendiment tècnic i la seua fiabilitat estructural. Els arquitectes i constructors sovint prefereixen opcions convencionals percebudes com més fiables.

La tesi busca explorar les possibilitats arquitectòniques dels materials de terra, examinant maneres d›integrar-los en diversos elements arquitectònics i proposant enfocaments de disseny innovadors, com ara estructures postensades, per a millorar la seua usabilitat i ampliar les seues aplicacions. L›objectiu és capitalitzar les qualitats úniques dels materials terris i desafiar la noció predominant d›ells com a formes estandarditzades i planes, abordant les preocupacions de viabilitat.

La metodologia de recerca empra un mètode mixt concurrent, que combina dades experimentals amb observacions del comportament del material per a derivar resultats. A través d›un procés d›experimentació de tres fases, es proven rigorosament variables com ara materials de motlleig, mesclades de terra i estructures postensades. El disseny iteratiu i les proves meticuloses refinen les tècniques

de fabricació, assegurant la solidesa del disseny de recerca.

En resum, aquesta tesi avança significativament els materials de construcció contemporanis i l›enginyeria arquitectònica. A través de la innovació i la col·laboració interdisciplinària, facilita la creació d›estructures funcionals i estèticament agradables que s›integren perfectament amb el seu entorn, alhora que impulsen els límits dels paradigmes de disseny convencionals.

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This chapter discusses the research background and motive, aims and objectives, research question, methodology and research framework.

Part 1

INTRODUCTION AND STATE OF ART

Chapter 01

INTRODUCTION

"The word of the Greek TECTON; a context-dependent bringing together of aesthetics and technique implied in the notion of TECTONICS" -Tectonics in Architecture book

01 INTRODUCTION

Tectonic Approach

In architecture, the activity we carry out in order to process a material is the technique, the technical processing. In this context, technique refers to human beings joining means of work, objects of work and manpower in the work process.

At the same time, technical processing is the stage which decisively separates culture from nature. Only then can we talk of architecture. Consequently, the forms created by technique are always significantly different from the forms found in nature. No matter how much we struggle and strive, it is always obvious when human intelligence and skills are behind the production of a specific physical form. Nature has its forms, just as culture has its forms.

The three parameters, material, technique and form, are common features. They form one combined set, which constitutes one of the smallest elements of architecture: an axiom. The term "tectonics" as a conceptual framework that seeks to define a close relationship between material, technique and the resultant form (Christiansen 1997).

Tectonics is connected to architecture in a similar way. Etymologically, the concept of tectonics never primarily describes an aspect of form. Instead, it always describes the circumstances that create the form, its premise: The craftsman, the artist who processes a material, the person who manufactures something, composes something, builds and creates something (Christiansen 2015).

Tectonics indicate the schemer and the poet, who both create based on nothing, even though it is in particular the parameters that bring about the art of building as art,

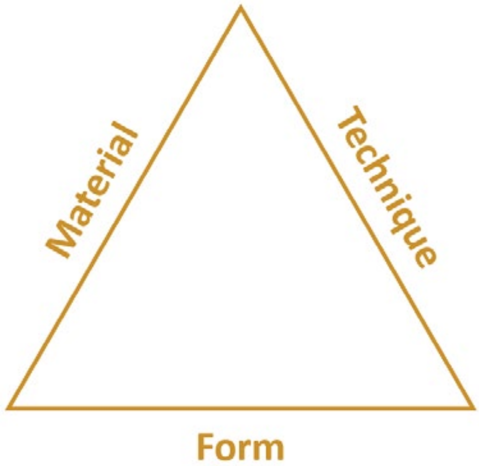


Figure 1 _ Material Tectonics Concept (Christiansen 1997)

as architecture, which are in focus etymologically. Form is created on the basis of its premise(s). In this way, form is created from the inside out. Tectonics is a product of the genes (Beim and Madsen 2014).

Many building materials have gone through different experimentation and technological investments and enhancements along centuries meet the role that they were manufactured for. Knowing the various economic, environmental and social benefits of earthen materials, this building material was totally neglected for years. It was a left behind during the modernism era as a result of many factors that include social perception, poor maintenance, etc. However, nowadays, architects, engineers and researchers are starting to give more and more attention to the earthen materials as a solution to face the increasing climate change and to promote the use of sustainable building materials and achieve the net-zero and energy plus strategies.

Other reasons are, the vision of the planet reviewed the environmental problems, and this fact obliged us to look at the past. Second, the research was able to propose valid alternatives able to meet the requirements of better result from a technical, environmental, and formal perspectives. Third, some architects got the possibilities to propose alternatives for the contemporary architecture based on vernacular or regional architectures as well as the insertion of the earthen materials in the contemporary architecture in western cultures.

As discussed, the essential basic relations between the three elements of tectonics are crucial so that something can be described as architecture. Historically, the term tectonics can be observed in architecture as vernacular architecture which means that the material choice is used efficiently and locally selected. Then, this material is manufactured by innovative local craft technique to result in a meaningful efficient form.

Earthen Materials in Contemporary Architecture

Earthen material is one of the oldest building materials known to humanity and was used for centuries in Africa and the Middle East to build houses, stables, mosques, and palaces. It became almost forgotten with industrialization, material mass production, and the prevalence of concrete, and even today it has a reputation as a transient and inferior building material. The design and construction possibilities of earth have always been severely limited: although it can withstand compressive forces, it is unable to absorb tensile forces. It also takes time to dry and harden, which makes it impossible to ram curved or vaulted shapes directly on site[1] (Schläfli 2014).

1 Check ETH article: https://ethz.ch/en/news-and-events/eth-news/news/11/2014/unique-rammed-earth-domes-at-hoenggerberg.html

Limitations of the earth usage

1. Structurally, this material can withstand compressive forces, it is unable to absorb tensile forces.
2. Constructive process: The time was a factor in the construction management with a progressive importance in the contemporary civilization. Earth constructions take generally more time than other materials to dry and harden. This factor is essential in the necessary timings to ram curved or vaulted shapes directly on site.
3. The economic factor in such western cultures, where the labor costs are high when compared with other regions.
4. Although the traditional building materials are highly sustainable, contemporary materials such as bricks and concrete are more dominant. The main social reason is the poor image of earth buildings. They are referred to as short durable material. There is a persistent need for an improved building technique that provides durability as well as comfort (Maher and Madrigal 2021).

Earthen materials suffered from lack of potential exploration when other contemporary materials such as concrete and fired bricks were in a continuous upgrade production process. Recent enhancement was the pre-production which has greatly helped in material quality control and reduced manufacturing time. (Rauch, 2017) (Heringer et al., 2019) However, the limited material architecture application in contemporary practice, where the addition of Euclidian geometrical elements makes up rectangular casting molds/ formwork which present a geometric restriction to the inherent isotropy of earth. All form creation techniques currently developed always introduce earthen materials to the society as a poor restricting building material. For this reason, the thesis wants to prove the capacity of different formal expressions, (not only formal) to consider new understanding of the tectonic of the material. The contribution of the Computer Numerical Control (CNC) technologies can be considered, even. These technologies are to be spread now in so many countries in Africa. And they open other ways for the serial production with infinite number of applications everywhere.

Some attempts are now being experimented in making the earthen materials more technologically advanced such as using robotic and virtual reality (VR) aid in construction, prefabrication and assembly. The impact of these attempts is very limited as they require complex and expensive machines which require very skilled engineers. Moreover, they neglect one of the important aspects of the earthen material which is the simplicity and low-tech construction process that promotes the participation of different society members in the building execution. People with low skill can contribute to the construction process, which create sense of belonging to the built environment.

In a time of the increasing climate change, the choice of low carbon footprint building material is crucial. However, local building materials such as earth are not enough technically and structurally enhanced to attract the architects and the society to use it.

While earth-based materials offer undeniable environmental advantages, including low embodied energy and carbon emissions, their utilization often faces skepticism due to perceived deficiencies in technical performance and structural integrity. Architects and builders may hesitate to incorporate these materials into their projects, opting instead for conventional options perceived as more reliable and robust.

However, it›s crucial to recognize that advancements in technology and construction methodologies have significantly enhanced the viability of earth-based materials in modern architectural practice. Innovative techniques such as stabilized earth, rammed earth, and adobe construction have emerged, addressing concerns related to durability, stability, and resistance to environmental factors.

Domes and Shell Structures

Domes and shell structures throughout history represent a diverse array of architectural styles, materials, and purposes. Ancient civilizations, such as the Romans, Byzantines, and Islamic cultures, all contributed significant examples of dome architecture. Roman domes, exemplified by the Pantheon in Rome and the Baths of Diocletian, showcased their mastery of concrete construction. In Byzantine architecture, the Hagia Sophia in Istanbul stands as an iconic example of dome design, featuring a massive central dome supported by pendentives. Islamic architecture, characterized by intricate geometric patterns, produced notable domes like the Dome of the Rock in Jerusalem, symbolizing spiritual significance.

During the Medieval and Renaissance periods, dome construction continued to evolve. In Italy, the Renaissance saw a resurgence of interest in ancient architectural forms, leading to masterpieces like the Florence Cathedral›s dome, designed by Filippo Brunelleschi. Meanwhile, in India, Mughal architecture flourished, resulting in the majestic domes of structures like the Taj Mahal in Agra, showcasing intricate marble inlay work and symmetrical design.

Moreover, the modern era brought innovations in dome and shell structures, driven by advancements in engineering and materials science. Buckminster Fuller popularized the geodesic dome, known for its efficient use of materials and structural strength, exemplified by the Montreal Biosphere. Thin-shell structures, such as the Sydney Opera House designed by Jørn Utzon, demonstrated the aesthetic possibilities of concrete construction. Membrane structures, like the Allianz Arena in Munich by Herzog & de Meuron, utilized lightweight materials and innovative forms to create dynamic spaces.

In contemporary architecture, sustainability and advanced design techniques have become prominent themes. Solar domes, designed for sustainability, are exemplified by projects like the Sustainable Bioenergy Research Consortium›s pilot project in Masdar City, Abu Dhabi. Parametrically designed domes, utilizing computational design tools, are showcased in iconic structures like the Beijing National Stadium (Bird›s Nest) by Herzog & de Meuron and Ai Weiwei, demonstrating the fusion of art, technology, and environmental consciousness.

These examples represent a fraction of the rich history and innovation in dome and shell structure design, highlighting the enduring appeal and versatility of these architectural forms.

When discussing the state of the art in domes and shell structures, several key advancements and trends emerge:

1. Digital Design and Fabrication: Utilizing advanced computational tools like parametric design software and digital fabrication techniques such as 3D printing and robotic manufacturing has revolutionized the design and

construction process. Architects and engineers can now create intricate geometries and optimize structures for efficiency and performance.

2. Material Innovation: Advances in materials science have led to the development of new lightweight and high-strength materials such as carbon fiber, glass-fiber reinforced polymers (GFRP), and engineered timber. These materials offer greater flexibility in design and improved structural performance.

3. Sustainability and Environmental Considerations: With growing concerns about climate change and environmental impact, there is a greater emphasis on sustainability in dome and shell structure design. This includes incorporating renewable materials, optimizing energy performance, and integrating passive design strategies for natural ventilation and daylighting.

4. Structural Engineering Advances: Innovations in structural analysis and engineering techniques have allowed for the design of more efficient and structurally sound dome and shell structures. Advanced finite element analysis (FEA), computational fluid dynamics (CFD), and performance-based design methods enable engineers to optimize designs for various loads and environmental conditions.

5. Biomorphic and Organic Design: Inspired by nature, architects are exploring biomorphic and organic design principles to create structures that mimic natural forms and systems. This approach often results in visually striking and structurally efficient domes and shells.

6. Adaptive and Responsive Structures: The integration of sensors, actuators, and smart materials enables the development of adaptive and responsive dome and shell structures that can adjust their form and behavior in response to changing environmental conditions or user requirements.

7. Prefab and Modular Construction: Prefabrication and modular construction techniques offer advantages such as faster construction times, reduced waste, and improved quality control. These methods are increasingly being applied to dome and shell structures, particularly in projects where rapid deployment or scalability is important.

8. Interdisciplinary Collaboration: Collaborative approaches involving architects, engineers, material scientists, and other specialists are becoming more common in the design and construction of complex dome and shell structures. This interdisciplinary approach allows for the integration of diverse expertise and the exploration of innovative solutions.

These advancements represent the cutting edge of dome and shell structure design and construction, pushing the boundaries of what is possible in terms of form, function, and sustainability.

In recent years, research institutes and groups have increasingly turned to constructing pavilion-scale mock-ups as part of their experimentation and testing processes. The selection of pavilion scale, particularly emphasizing shell or vault structures, has emerged as a practical intermediate for material experimentation. Positioned between individual modules or scaled models and full-scale buildings, pavilions strike a balance between various constraints such as time, budget, and space, making them a sensible option for research pursuits.

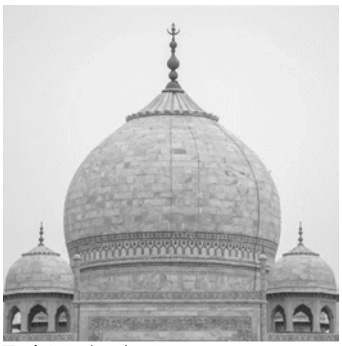
Shell and vault structures, prominently featured in these pavilion-scale experiments, offer notable material efficiency (Veenendaal and Block, 2014). By focusing on these forms in pavilion-scale mock-ups, researchers can delve into and analyze structural and material behaviors within a controlled environment.

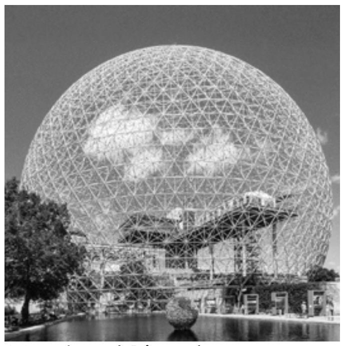

Pantheon, Rome


Hagia Sophia, Istanbul


Dome of the Rock, Jerusalem

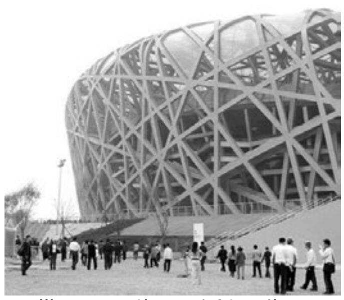

Florence Cathedral, Florence


Taj Mahal, Agra


Montreal Biosphere


Sydney Opera House


Allianz Arena


Beijing National Stadium

1.1. Context

There are many aspects to assess material material's sustainability as per Akadiri & Olomolaiye (Akadiri and Olomolaiye 2012). These aspects are divided into three main categories: environmental, socio-economic and technical. This study is focusing on two aspects in the sustainability perspective of the earthen material: the aesthetics (socio-economic) and the buildability (technical).

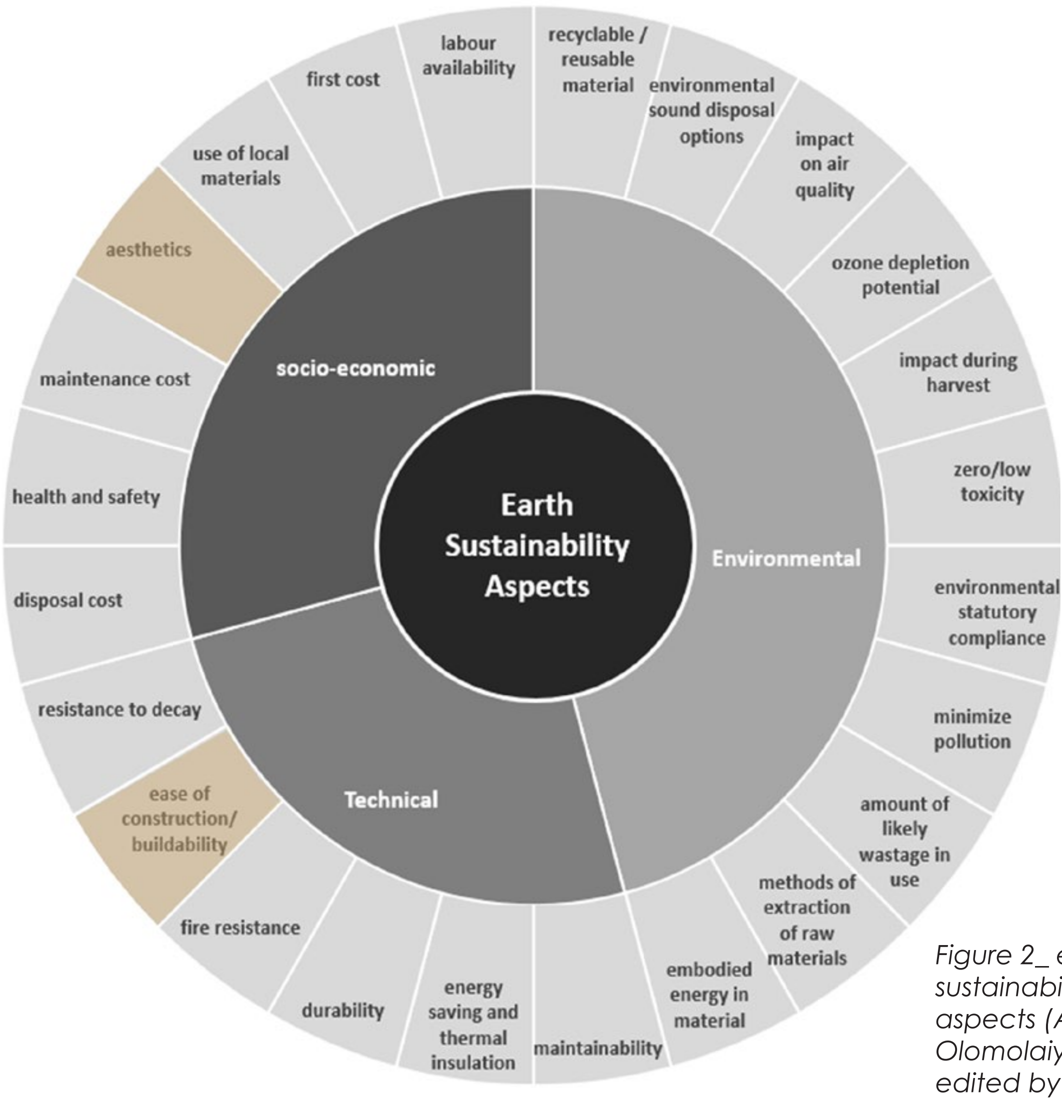


Figure 2_ earth sustainability aspects (Akadiri and Olomolaiye 2012); edited by author)

Potentials and Challenges of Earthen Materials

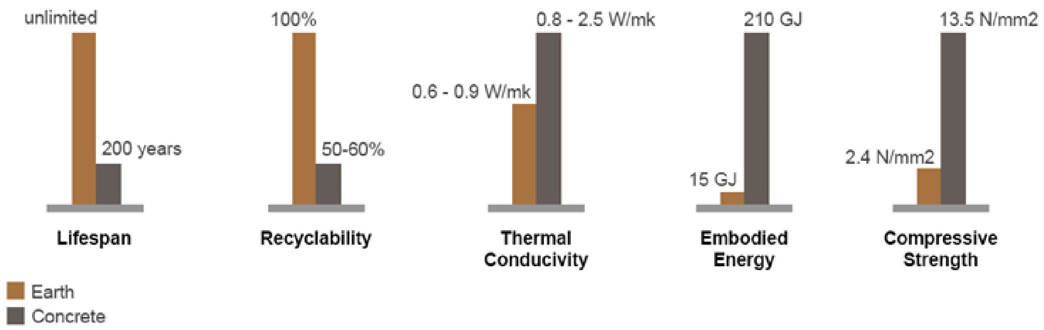


Figure 3_ Different aspects of Earth (Heringer, Howe, & Rauch, 2019)

• Lifespan (durability) and Recyclability

The meaning of durability when referring to earth construction is different from concrete. Earth is an aging material; this means that year after year and season after season; it starts to have some wrinkles, the same as a human's face. In a TED talk in April 2017, Anna Heringer explained that if a wall in her METI school has any kind of time deterioration or the edges are not sharp as before, the broken part is taken and made wet and mixed then put back on thev wall. Recyclability of earth walls, as example, is total. It can be turn into a garden or get fully recycled without any loss in the material. There is no other building material with %100 recyclability and environmentally friendly. Waste accumulation from building materials are increasing every year.

• Indoor Air Quality

Earth has a huge impact on the indoor air quality. It works as humidifier for the building due to its moisture content. It also works as a thermal mass so it works best with hot days and cool nights. It stores heat during the daytime since it has relatively high heat capacity, then it releases it during night flushing. This is a passive cooling technique that helps remove accumulated indoor heat at night, particularly in regions where night temperatures drop significantly compared to daytime temperatures.

• Embodied energy

When compared with concrete and red brick, earth does not involve any firing or excessive energy during its production. When produced locally, earth does not require even transportation and fuel consumption zero if the soil is excavated on-site without adding materials from outside the site; however, concrete is being exported from other countries. Moreover, in the rural context, the mixing and production of the material will be by local workers and builders so this does not require any intensive machinery and electricity.

• Compressive Strength

Despite the fact of earth having many potentials, there are challenges that the material faces when being compared by the other building materials like concrete. Although, adobe walls compressive strength is relatively low. Adobe brick can be used for load-bearing walls up to several stories high, like Shbam's buildings in Yemen, for example.

Figure 4_ Shbam's buildings, Yemen (Getty Images)

The Shebam's buildings are 8 stories high and inalterable for centuries. They were built in the 16th century and lasted for only 500 years. The problem is apparently more related to the perception of the people and the skill of the architect/ designer rather than the capability of the material.

In order to connect the tectonic realm and the sustainability, aesthetics is an integral part in the material socio-economic sustainability. Earthen materials (material) are well known for its remarkable texture and color variation. This aesthetics is enhanced through technical advancements and craftsmanship (technique). In contrast to other contemporary materials, earth is usually employed as basic standard walls (form) in the building construction.

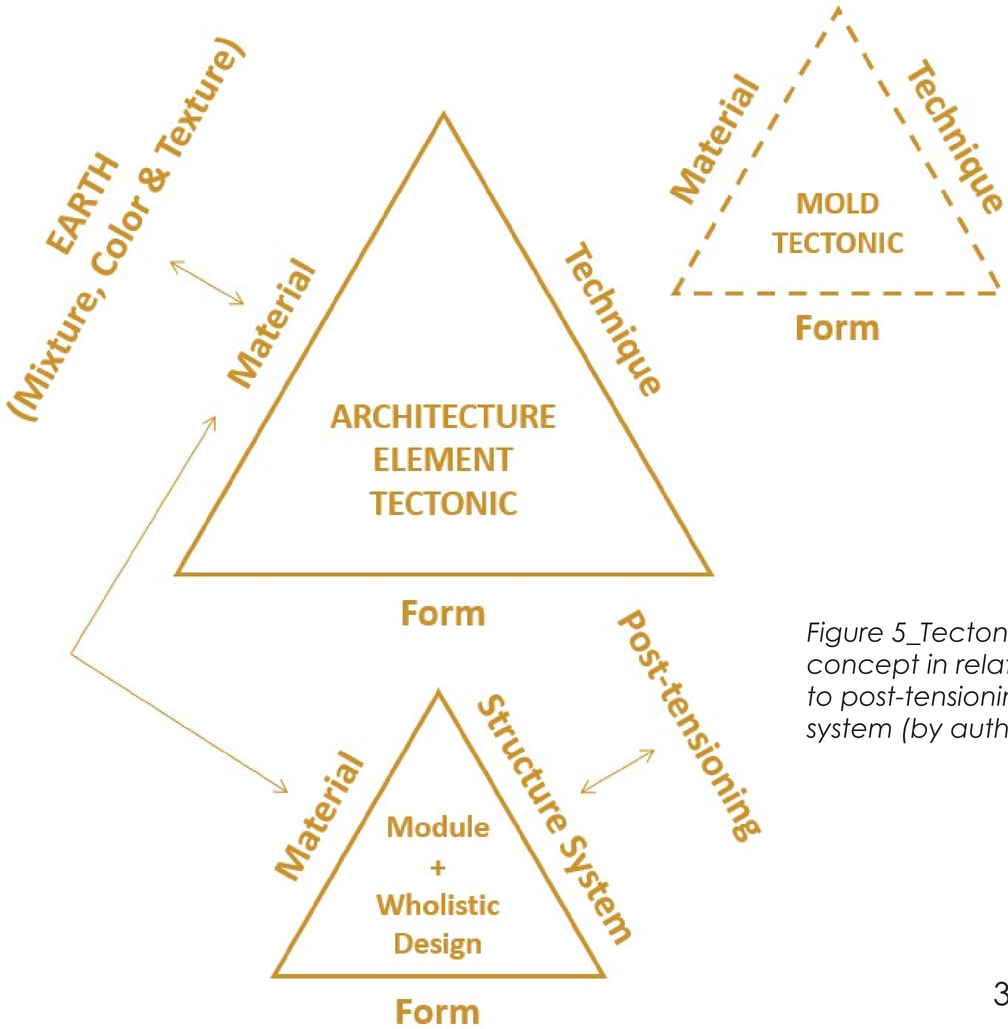


Figure 5_Tectonic concept in relation to post-tensioning system (by author)

In the PhD thesis of Ole Pedersen (Pedersen 2013), his findings were that the concrete tectonics involves another sub tectonic approach method for the mold. In this study, the material is changing to earthen materials. Therefore, the mold tectonics need to be studied as well along with effect of adding post-tensing system to the structure design which involves a modified conceptual configuration.

1.2. Research Objectives

The aim of the thesis is to explore the tectonic potentials of the earthen materials in construction investigate the potential integration of earthen materials in various architectural elements, and propose innovative design approaches, such as post-tensioned structure, to increase its usability and broaden its area of application. It is the ambition of the research to take advantage of earth spectrum qualities and to challenge the prevailing design of earthen elements as standardized, flat, rectilinear forms while addressing key feasibility issues.

The main objective of the thesis is to define new horizons and potential for the earthen materials integrated in the sustainable construction processes, to improve the quality of life of wider population sectors.in order to increase its usability and broaden its area of application.

The research is exploring applying new technologies to the earthen materials for developing new tectonics and structural systems that have never been constructed by this material. It is also very connected to developing the current building industry from both perspectives; sustainable and technical. Besides, it also solves the presence of false social perceptions and technical restrictions in the material appearance, application, and form.

To achieve this goal, the following specific objectives are proposed:

- Evaluate existing (historical) earth construction material mixture, techniques and common form.
- Analyze the contemporary earth construction tectonic practices.
- Identify the current practices for the use of post-tensioning system with earthen materials.
- Identify shell structure advancements built with non-earthen materials.
- Extract the advancements that align with earth values and can enhance the earth material.
- Design post-tensioned earth structure that integrate material, technique, and structure framework.
- Detail the earthen elements to withstand structural loads, achieve the intended form and meet the challenges of the assembly process.
- Build and examine the different structures.

These aims and objectives are tacking the following questions:

- **What historical trials and techniques have earthen materials undergone in tectonic construction?**

- **How can earthen materials be integrated into different architectural elements beyond basic walls?**

- **What innovative design approaches can enhance the usability and sustainability of earthen materials in construction?**

- **What tectonic advancements can facilitate the integration of earthen materials in contemporary building techniques?**

This question leads to secondary questions in relation to post-tensioned structures:

- What are the most effective techniques to upgrade the tectonics of the earthen materials?
- How does the technique affects/ changes the form?
- How can the post-tensioning structure can contribute to upgrade of the earthen materials?
- Connection and module design influence the wholistic structure design?

The integration of earthen materials in contemporary building techniques can be enhanced through innovative design approaches and technological advancements such as post-tensioned structures, leading to sustainable and aesthetically pleasing architectural solutions.

1.3. Research Methodology

The study first starts with descriptive research where the secondary data collection includes different case studies in two focuses: the tectonic innovation in earth construction and the recent advancements in the commonly used contemporary materials.

The data collection for the earth tectonics is based on three focal points: the history of the earth tectonics, the advancements that the material has gone through and the different practices where the material was post-tensioned. The history research is important to identify the base of the concept through different practical examples. The modern practices are determining the current state of art which cast more the shadow on the research gap and displays recent tolls and technologies in the field. Furthermore, the post-tensioning of earth is an integral data for informing the experimental methodology with the detailing, technical considerations, and the effects of this hybrid structural enhancement. The data is a selection of case studies that show an innovation in one or more of the anchors of tectonics: material, technique, and form. These data is a secondary data that is derived mainly from previous literature review.

Second, the data for the advancements in the contemporary materials is collected based various case studies for concrete and brick. The cases are chosen so that the domes, shells, or pavilions have a tectonic advancement in both of the two aspects: the module design and wholistic structure design. The main categories are the technique, and form. On the other hand, the sub aspects are the mold tectonics and the connection tectonics. These case studies directly inform the research experimental methodology in an attempt to identify the effective potential research areas for earth material upgrade. These data is a secondary data that is derived mainly from previous literature review and architects interviews.

The second part of the study implied experimental research where the primary data collection is obtained by lab testing (quanititative data) along with experiments observations (quantitative data). The research methodology is a concurrent mixed method it emplys experimental hands-on methods. Besides, the data, from the experiments, are derived from observations of the material structure behavior which form an important method of obtaining outcomes.

To achieve an experimentation that embodies the true essence of tectonics, it is imperative to delve into the interconnected relationship between materials, techniques, and forms. When exploring a material such as earth to realize a specific form, previously tested with concrete, the fabrication technique emerges as a pivotal variable. Employing Rhinoceros modeling software, a meticulous 3D model of the entire dome is crafted, ensuring precise measurements of the intended earthen element.

The fabrication technique, however, is intertwined with mold tectonics, encompassing the material, technique, and form of the mold itself. Thus, the experimentation is structured to address these variables across three distinct phases: mold experimentation, earth mixture definition, and detailing for mock-up execution. In the initial phase, known as mold tectonic experimentation, three different mold materials – cardboard (paper), wood, and metal – are rigorously tested to fabricate adobe and rammed earth elements, each employing a unique fabrication technique.

Subsequently, the focus shifts to mixture definition, where adobe and rammed earth techniques are explored across three varied earth mixtures: unstabilized, stabilized, and hybrid mixtures. Following the drying period, they undergo flexure strength testing, with data collected via video documentation of the crushing process and detailed notes for each specimen.
The final phase entails detailing the earthen elements for assembly into different mock-ups, where two post-tensioned structure systems – external and internal – are put to the test. These mock-ups consist of approximately six elements derived from the predefined molds and mixtures. The stability of these mock-ups serves as a litmus test for the success of the experimentation. If the mock-ups stand steadfast, it signals positive results, underscoring the efficacy of the chosen materials, techniques, and forms in achieving the inclusive meaning of tectonics.

The thesis is divided into the following main three parts:

// PART 1: INTRODUCTION AND STATE OF ART

Chapter One | Introduction

This chapter discusses the research background and motive, aim and objectives, research questions, methodology, and conceptual framework.

In part 1, the introduction chapter is showing a broad overview on the earth practices and discussing the different misconceptions about the earthen materials. Besides, it casts the shadow on the tackled research gap aims and objectives. It also raises research questions that address the possibilities of upgrading earthen materials using new tectonics to broaden its area of use. This chapter as well highlights the thesis hypothesis that contemplates that innovative design methods and technological progress like post-tensioned structures can amplify the incorporation of natural materials like earth in modern construction practices, resulting in eco-friendly and visually appealing architectural solutions.

In the following chapters 2 and 3 the state of art is researched to review two main aspects. First, the history and best practices of earthen materials tectonics when used with post-tensioning structure and as slabs/ roofs. Second, the tectonic advancements of other contemporary materials in the realm of tectonics with special focus to module design and holistic structure.

Chapter Two | Earth Material Tectonics

In this chapter, the rich history, and diverse techniques of using earth as a building material, exploring its evolution from ancient practices to modern innovations. The discussion has been structured around three key factors: the earthen mixture, construction techniques, and form upgrades. In addition to the modern upgrading practices review.

Chapter Three | Other Materials Tectonic Advancements

Different contemporary building materials have encountered technological and tectonic advancements specially the contemporary building materials such as concrete and bricks. Different tectonic innovations are displayed in this chapter and are analyzed by the module design and the holistic structure design.

Form part 1, the state of art and the literature are reviewed. These three chapters inform and structure the experimentation methodology in two ways. First is to maintain the integral existing sustainability aspects of earth construction. Second in to inform the earthen material upgrading with the modern tectonic practices that were done previously with other materials.

// PART 2: EXPERIMENTATION

In this section, the hypothesis from the introduction chapter will be tested to be applicable of not.

Chapter Four | Experimentation Methodology

In the methodology section, the research design is discussed in relation to the identified research problem, objectives, and existing literature. The research is characterized as applied research, focused on the process of integrating post-tensioned structure with earthen materials to develop new processes or systems.

This innovative research methodology employs an experimental approach to explore the possibilities within the field of earthen materials. Its primary objective is to construct an external shell structure using post-tensioned techniques, showcasing a fresh application of established construction methods.

Of particular significance is the adaptation of the post-tensioning structure system, typically utilized in concrete construction, to earth-based structures. This innovative approach not only pushes the boundaries of structural engineering but also offers valuable insights that could potentially transform sustainable and eco-friendly construction practices.

Chapter Five | Experimentation: Results and Discussions

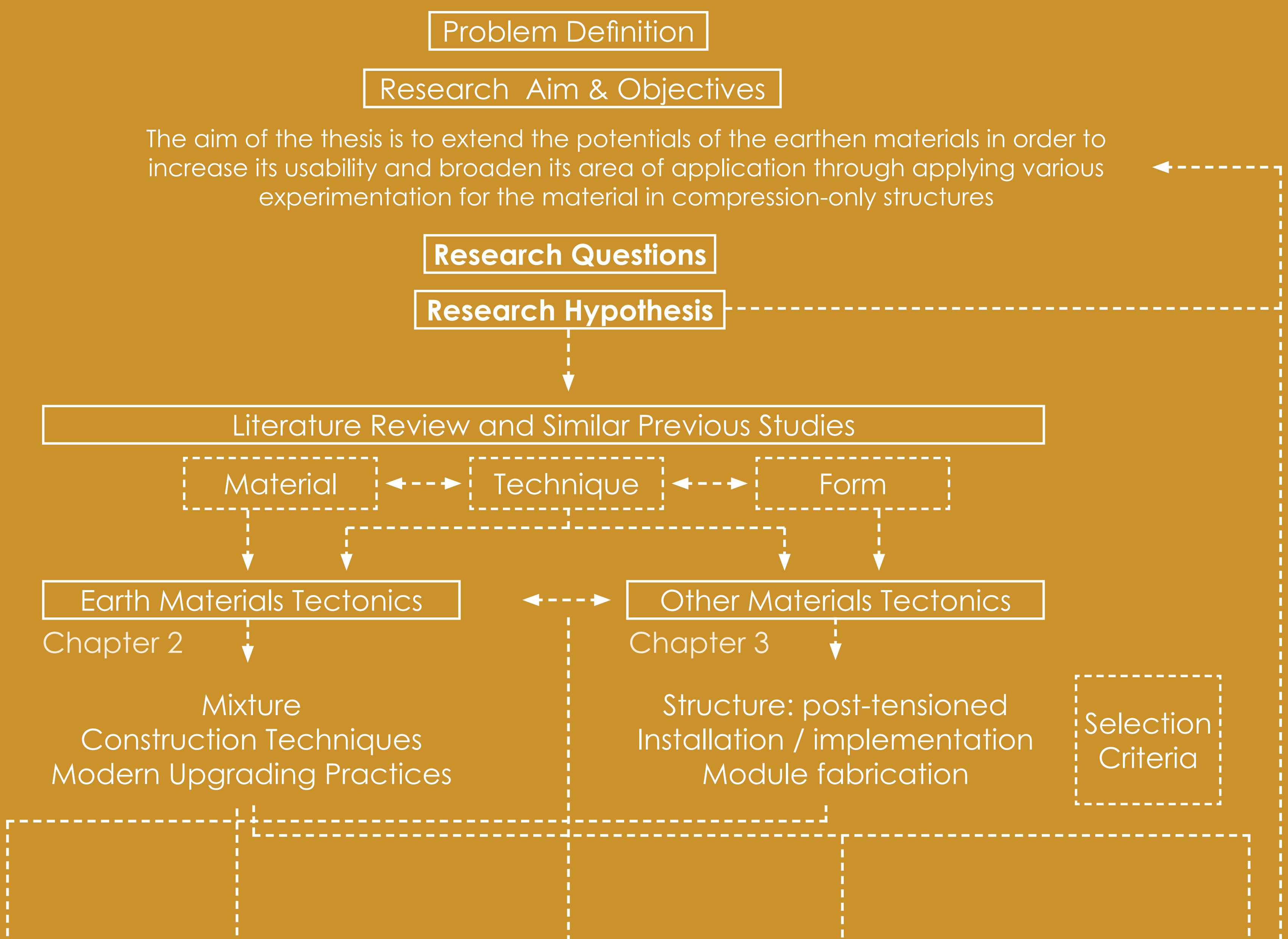
In this chapter the results of each part of the methodology is discussed and linked to the literature and findings are achieved. Results are obtained from the experimentation methodology which employed different field and material lab testing including flexure test. This chapter as well leads to different insights on the potentials of upgrading the tested technique with earthen materials.

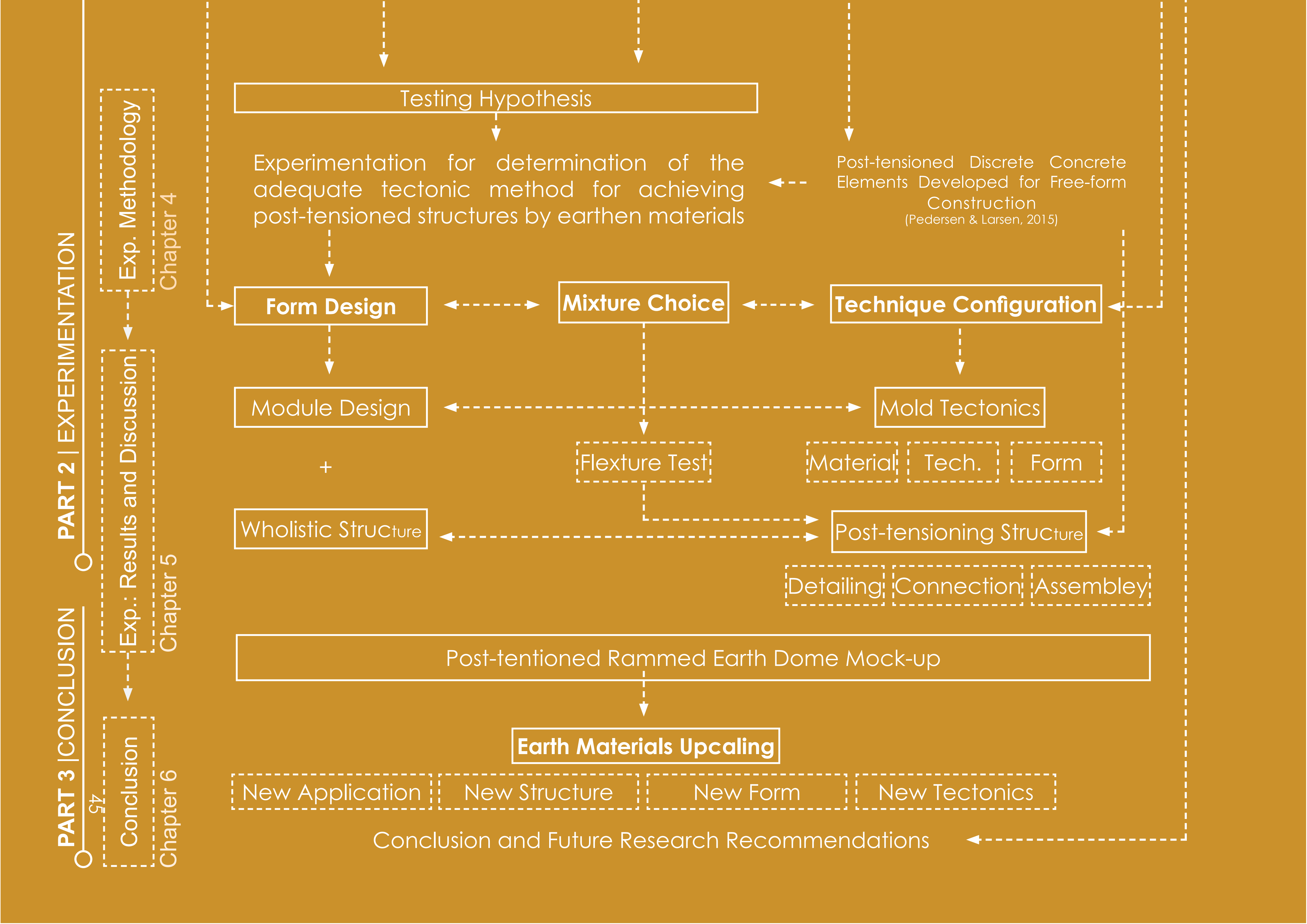
// PART 3: CONCLUSIONS

Chapter Six | Conclusion

Figure 6_Theoretical Framework

TECTONIC POTENTIALS OF EARTHEN MATERIALS: POST-TENSIONED STRUCTURES



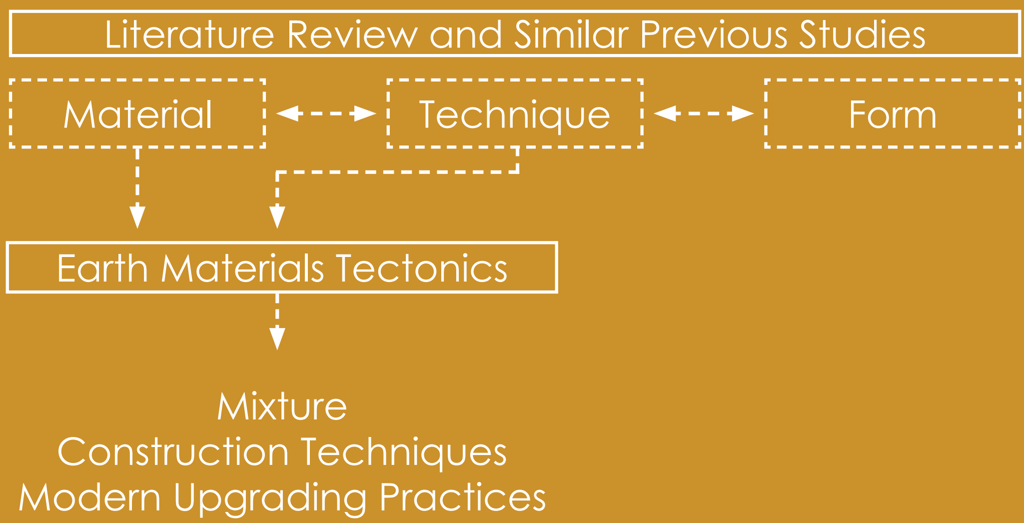


PART 2 | EXPERIMENTATION
Exp. Methodology
Chapter 4
Exp.: Results and Discussion
Chapter 5
PART 3 |CONCLUSION
Conclusion
Chapter 6
Testing Hypothesis
Experimentation for determination of the adequate tectonic method for achieving post-tensioned structures by earthen materials
Post-tensioned Discrete Concrete Elements Developed for Free-form Construction
(Pedersen & Larsen, 2015)
Form Design
Mixture Choice
Technique Configuration
Module Design
Mold Tectonics
Flexture Test
Material
Tech.
Form
+
Wholistic Structure
Post-tensioning Structure
Detailing
Connection
Assembley
Post-tentioned Rammed Earth Dome Mock-up
Earth Materials Upcaling
New Application
New Structure
New Form
New Tectonics
Conclusion and Future Research Recommendations

Chapter 2

State of Art

This chapter discusses the previous and current applications that tackled the earthen materials structural properties in relation to its aesthetics.



Chapter 02

EARTHEN MATERIALS TECTONICS

"An ecology of tectonics embeds the concept of buildings as parts tied together as a whole in a broader context of natural and cultural systems"
-Anne Beim

02 EARTHEN MATERIALS TECTONICS

Earth or soil is a very old building material. Many cultures have used earth as their main building material in order to build their civilization. This can be because it is simply an available material so various trials have been carried out on the material to fulfill different needs and produce spectrum of forms. Humans and even animals have experimented different methods for using earth for building shelters, ranging from underground burrows, Termites mounds to masonry walls and domes. Not to mention, that those way back practices are a long tradition for the evolvement of earth material tectonics.

As discussed before, the tectonic of a material is a system that consists of three main factors: material, technique and form. Therefore, in this chapter the earthen materials will be discussed from these three factors to see the previous applications and techniques that were performed on this material before that resulted on the current practices that we see now. The study is classified into the following categories:

- **Historical/ conventional methods**
  - Mixture
  - Technique
  - Form (domes & shells)

- **Modern upgrading practices**
  - Mixture
  - Technique
  - Form (domes & shells)

- **Post-tensioning of Earth**
  - Walls
  - Slabs and roofs

History of Earth Tectonics

Mixture

Unstabilized
Stabilized
(+additives)

Technique

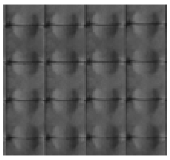
Rammed Earth
Adobe
Cob
CEB

Form

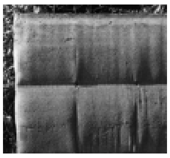
Hollow Cell Vaulting, Tunisia
Beehive Domes, Syria
Musgum houses, Cameroon

Modern Upgrading Practices

Mixture & Technique



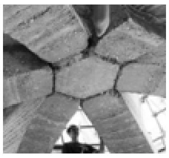
CEB Special Module Fabrication: Omar Rabie



Fabric Formwork

Prefabrication Rammed Earth

Form



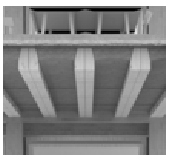
Rammed Earth dome: ETH students (BRG)

Post Tensioning Earth

Wall

Kiln Tower for the Brickworks Museum

Roofs & Slabs



Holz-Lehm-Decke

Floor ceilings load-bearing clay arches

Figure 7_State of Art three Pillars (by author)

2.1. History of Earthen Materials Tectonics

Throughout history, the concept of tectonics has manifested in architecture through vernacular practices. Vernacular architecture emphasizes the efficient use of locally sourced materials, which are often selected with careful consideration of their availability and suitability for the environment. These materials are then crafted using innovative local techniques, resulting in structures that not only serve a functional purpose but also embody a deep connection to their cultural and environmental context.

This approach to architecture demonstrates a harmonious integration of materiality, craftsmanship, and cultural identity. By leveraging locally available resources and traditional building methods, vernacular architecture showcases the ingenuity of communities in adapting to their surroundings while also promoting sustainability and resilience. Moreover, the emphasis on meaningful and efficient forms reflects a sensitivity to both practical needs and aesthetic considerations, contributing to the enduring appeal of vernacular architectural traditions across different cultures and regions.

2.1.1. Earthen Mixture

The mixture of earthen material is an important factor in the success and the strength of an earthen wall. Usually, it is not a mixture in the sense of adding ratios to each other like in concrete. It is more the soil components where the building element will be produced. Since the earthen elements are dependent on the soil type, the building plot soil content is thoroughly tested using field and/or laboratory tests. These tests are important to understand the soil coherence, grain size distribution, water content and more properties. In most cases, the site soil may need enhancements to improve its characteristics or make it suitable for a specific use either by increasing the ratio of one of its components or an external material for stabilization.

Additives

The use of stabilizers such as cement has derived out a need to improve wet strength and erosion resistance in exposed walls (Houben & Guillaud, 1994). However, in Australia and USA, cement stabilization has become accepted routine practice in rammed earth construction irrespective of application. In many situations, the use of cement and other stabilizers can be avoided by good design and construction appropriate to earth building. The main categories of binders used for earth construction are (Standards Australia, 2002; (Houben and Guillaud 1994); SAZS 2001 ,724:2001) Portland cement, lime, bitumen, natural fiber and chemical solutions such as silicates.

However, in Germany, stabilization of the material is not a very accepted practice. It is not because technical consideration against stabilizers. It is more about to preserve the material as natural as it is. Martin Rauch[1] and Anna Heringer[2] argue that stabilizers make earth lose it recyclability characteristic. In addition, they believe earth can have a great performance when the mixture's components are accurate, and the design of the building is protecting the

1 Lehm ton Erde
2 Anna Heringer Studio

earthen walls from erosion (Howe, Heringer, and Rauch 2019). This can be achieved using “a good hat and a good boots” for the walls, extruded roof and a foundation, and by adding erosion checks in rainy climatic zones.

According to Auroville Earth Institute the following tables show the stabilization material suitable for the type of soil:

It depends of the type of stabiliser:

Cement stabilisation: It is more sandy than clayey.	Gravel	Sand	Silt	Clay
	15%	50%	15%	20%

Lime stabilisation: It is more clayey than sandy.	Gravel	Sand	Silt	Clay
	15%	30%	20%	35%

Suitability of stabilisers and their percentage for CSEB

It depends on the soil quality and the particular requirements. The average stabilizer proportion is rather low: 5% for cement and 6% for lime. These low percentages are part of the cost effectiveness of CSEB and stabilised rammed earth.

	SUITABILITY	MINIMUM %	AVERAGE %	MAXIMUM %
Cement	Mostly for sandy soil	3%	5%	No technical maximum Economic maximum: 7 - 8 %
Lime	Mostly for clayey soil	2%	6%	10%

Table 1 _ Stabilization application and percentages (Auroville Earth Institute)

For compressed earth blocks (CSEB) and rammed earth, the most common stabilizers are cement and lime. Cement or lime stabilization of soils are proven to increase a lot the strength, and stabilized earth could be exposed to water or even immersed (Minke 2006).

To make a stabilized mix which has improved technical and mechanical properties, some additives can be added to the mixture. Those additives are classified as artificial and natural stabilizers (Van Damme and Houben 2018)(de Pádua et al. 2016). Here are some case study projects that have incorporated artificial stabilizers in the earth mixture:

In contemporary earth construction, adding a small percentage of cement to the earth mixture can enhance its compressive strength and durability. For example, the «Pak Suan Earth Community» project in Thailand incorporates a small amount of cement into the earth mixture to create stabilized earth blocks for construction. This allows for the creation of load-bearing walls with improved structural integrity.

Moreover, the restoration of historic adobe structures in the southwestern United States often involves the addition of gypsum to the earth mixture. Gypsum helps to stabilize the clay soil and reduce shrinkage, preventing cracks from forming in the walls. For instance, in the restoration of the San Miguel Mission in Santa Fe, New Mexico, gypsum was added to the adobe bricks to improve their durability and resistance to weathering.

Furthermore, the «Chateau de Guedelon» project in France utilizes lime as an additive in the earth mixture for constructing a medieval-style castle using traditional techniques. Lime acts as a binder, enhancing the cohesion of the earth mixture and improving its workability. By adding lime to the clay soil, sand, and straw mixture, the construction team is able to create sturdy walls that replicate the architectural techniques of the Middle Ages.

The artificial stabilizers, such as cement, are not environmental since they emit carbon and consume huge amount of energy during construction. Moreover, they are proven to reduce the recyclability of the earthen building elements which hinders one of the most important benefits of the material due to the chemical reaction between the different components of the material.

On the other side, there are natural stabilizers such as lime, straw, carob tannins (Clausell et al. 2020) and more. Here are some case study projects that have incorporated natural stabilizers in the earth mixture:

The «EcoARK Pavilion» in Taiwan incorporates straw as a reinforcing additive in the earth mixture used for constructing the pavilion›s walls. By mixing straw with clay soil, sand, and water, the resulting material becomes stronger and more resistant to cracking. The use of straw also helps to improve thermal insulation and reduce the overall weight of the walls, making the pavilion more sustainable and energy-efficient.

Additionally, the «Earthship Biotecture» projects designed by Michael Reynolds often utilize natural fibers such as recycled tires, cans, and bottles as additives in the earth mixture. These fibers are incorporated into rammed earth or adobe walls to provide reinforcement and improve structural stability. By using recycled materials as additives, Earthship Biotecture promotes sustainability and reduces construction waste.

Finally, in Japan, the «Wachigaiya» tea house in Kyoto incorporates rice husks as an additive in the earth mixture used for constructing the walls. Rice husks, a byproduct of rice milling, are mixed with clay soil and water to create a lightweight and insulating material. The use of rice husks not only enhances the thermal performance of the walls but also contributes to the sustainability .

These examples illustrate the diverse applications of additives in earth construction, from traditional techniques to innovative approaches that prioritize sustainability and performance. Each additive serves a specific purpose, whether it›s improving strength, durability, insulation, or sustainability, demonstrating the versatility of earth as a building material.

2.1.2. Earth Construction Techniques

The range of technical and architectural possibilities offered by raw earth is large and varied. The traditional and modern ways of using this material is a catalyst for how to use this material in the future. There is a diverse collection for earth construction techniques documented by CRAterre[3] and was first published in Treatise in Earth Construction (1989). Earth has more than 12 construction techniques (Figure 8), which can be divided into three groups. In the first, earth is used to create a preliminary load-bearing structure. In the second, it is used as a monolithic mass. In the last, it takes the form of multiple smaller masonry elements (Dethier 2020).

Not all of the earth construction techniques are common internationally nowadays. However, there is a selection of techniques that have been used more often in various modern projects, such as: rammed earth, compressed earth blocks, cob and adobe.

3 CRAterre is an international institution that work in the context of earth architecture to preserve the material and educate people to use it.

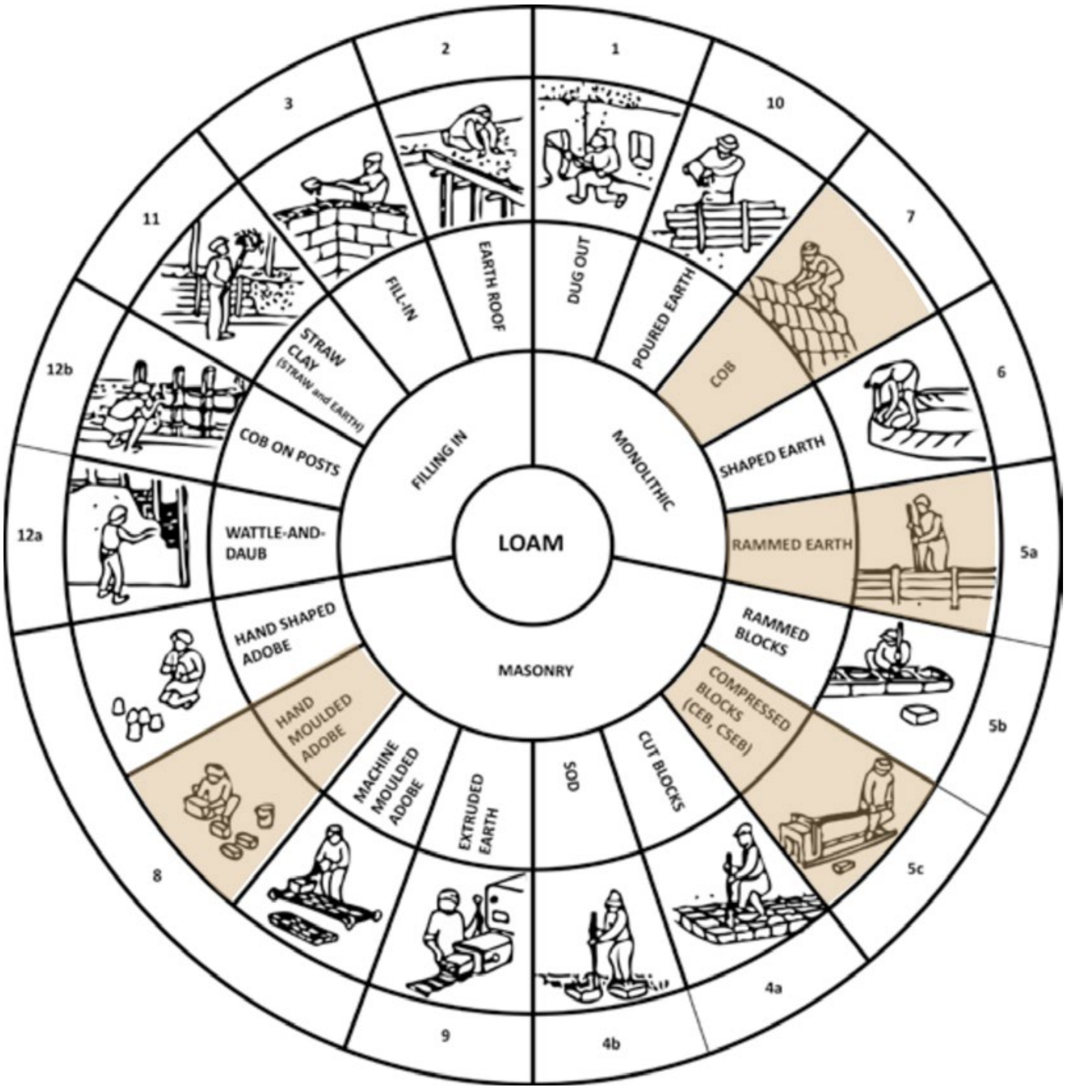
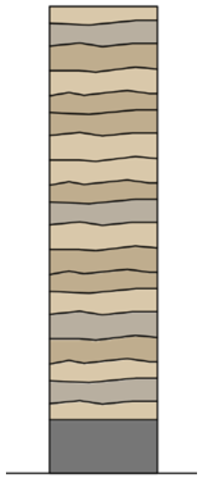


Figure 8_Earth Construction Techniques (CRAterre)

Rammed Earth and Compressed earth blocks are modernized techniques which have recently drawn the attention of many researchers, engineers and architects nowadays. Rammed earth is not new it was used in the Great Wall of China but it is now being reused, but CEB is relatively new. The mixture preparation for these techniques does not require many days to be ready for construction since no fermentation is needed. However, the construction process may require either mechanization or relatively a lot of time. Rammed earth for example does not require mechanization for implementation by the ramming process require time and effort while densifying the wall so in some cases pneumatic rammers or specialized machines are preferred to speed up the process. On the other hand, it is only possible to produce compressed earth blocks using special manual or electrical machines. Many companies nowadays are working on upgrading those machines to speed up the process.

Cob and Adobe’s processes are totally traditional even when being used in recent times. Straw is usually added to the mixture to increase its tension ability. The mixture requires fermentation which makes it a bit challenging than the other two techniques. Besides, the construction is very simple which requires simple wooden mold in case of the adobe. The mixture in these techniques is simply stacked over each other or poured in a mold in contrast to the other two techniques where the compaction of the soil is essential which has an impact on the performance of the walls.

Rammed Earth

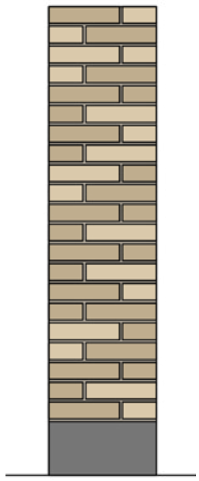


Rammed earth (RE), also known in French as pisé de terre or pies, has been used since ages worldwide like many other earth techniques. The earth is mixed thoroughly with water to get a homogeneous humid mix but it does not reach plastic state. This humid earth is poured in a form in thin layers and then rammed to increase its density. This density increases as well as the compressive strength and the water resistance. Ramming was traditionally done by hand. Since a few decades, ramming is being done mechanically with pneumatic rammers (Rauch 2017).

RE is considered the most susceptible to variation in quality due to variations in soil quality and homogeneity as compared to adobe and CEB (Houben and Guillaud, 1994; Standards Australia, 2002). Moreover, during the lifetime of the structure, RE then CEB is considered less costly compared to adobe due to the less regular maintenance requirements related to their enhanced durability. Examples of this kind of buildings are: Alnatura in Germany (2019 – 2015); Ricola building (2014) and Haus Rauch (2008 – 2005) in Switzerland by Lehm Ton Erde.

Compressed Earth Blocks (CEB)

The soil (with or without stabilizer) is slightly moistened, poured into a steel press and then compressed either with a manual or motorized press (Minke 2006). After the first attempts of Cointeraux[1] , one had to wait until 1950 in Colombia for a housing research program to improve the hand-moulded bricks (BASEhabitat 2018).



The result of this research and development was the Cinvaram, the ancestor of the steel manual presses, which could make very regular blocks in shape and size, denser, stronger and more water resistant than the common adobe. CEB technology has been a great mean for the worldwide renaissance and promotion of earth construction in the 20th century.

Examples for this kind of buildings: Pan African Institute by ADAUA Burkina (1984); Gando Primary School (2001) by Francis Keré in Burkina Faso; Center for the Blind (2001) by Mauricio Rocha in Mexico.

1 François Cointeraux (1830 – 1740) was a French architect. He «discovered» pisé de terre architecture in the Lyon region and promulgated its use in Paris.

COB

Plastic soil, with or without fiber integration, is usually formed in balls, which are freshly piled upon each other. This technique has been used a lot long ago in Europe, where it was named cob in England and bauge in France. This technique is still used a lot in Africa, India and in Saudi Arabia, where beautiful examples can be seen (Gauzen-Muller 2017).

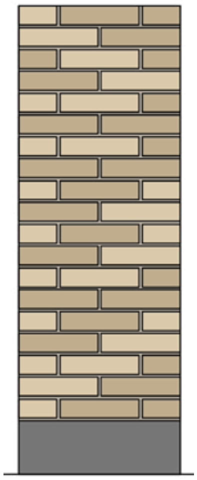
The most impressive examples are encountered in Yemen in Shibam, a UNESCO world heritage site. This old historic capital of Southern Yemen has been named “The Manhattan of the Desert. The sometimes 13 storey buildings were built with a combination of cob and adobe. Recently, cob is getting known again with some development in USA, as well as in other parts of the world (Howe, Heringer, and Rauch 2019).

Example of these buildings can be: METI School by Anna Heringer in Bangladesh; City of Shibam in Yemen; Najran Palace in Saudi Arabia.

Figure 9_METI School, Anna Heringer (source: Kurt Hoerbst)

Adobe

Sun dried clay brick, named Adobe, is undoubtedly one of the oldest building materials used by mankind. According to the historical overview in the literature about the Earth construction techniques, the only construction technique was Adobe bricks (sun-dried mud bricks).



Adobe is made of thick malleable mud, often added with straw. After being cast they are left to dry under sun. They are traditionally either hand shaped or shaped in wooden moulds. The adobe technique is known for its flexibility with respect to the type of soil used (Standards Australia, 2002).

Figure 10_Mud brick at the time of the Ancient Egyptians. (Levantine Asiatics making bricks (Illustration from N. D. G. Davies, Paintings from the Tomb of Rekh-Mi-Rē [New York: Metropolitan Museum of Art, 1935], pl. 17)

Review on the four Different Techniques

Rammed Earth and Compressed earth blocks are modernized techniques which have recently drawn the attention of many researchers, engineers and architects nowadays. Rammed earth is not new it was used in the Great Wall of China but it is now being reused, but CEB is relatively new. The mixture preparation for these techniques does not require many days to be ready for construction since no fermentation is needed. However, the construction process may require either mechanization or relatively a lot of time. Rammed earth for example does not require mechanization for implementation by the ramming process require time and effort while densifying the wall so in some cases pneumatic rammers or specialized machines are preferred to speed up the process. On the other hand, it is only possible to produce compressed earth blocks using special manual or electrical machines. Many companies nowadays are working on upgrading those machines to speed up the process.

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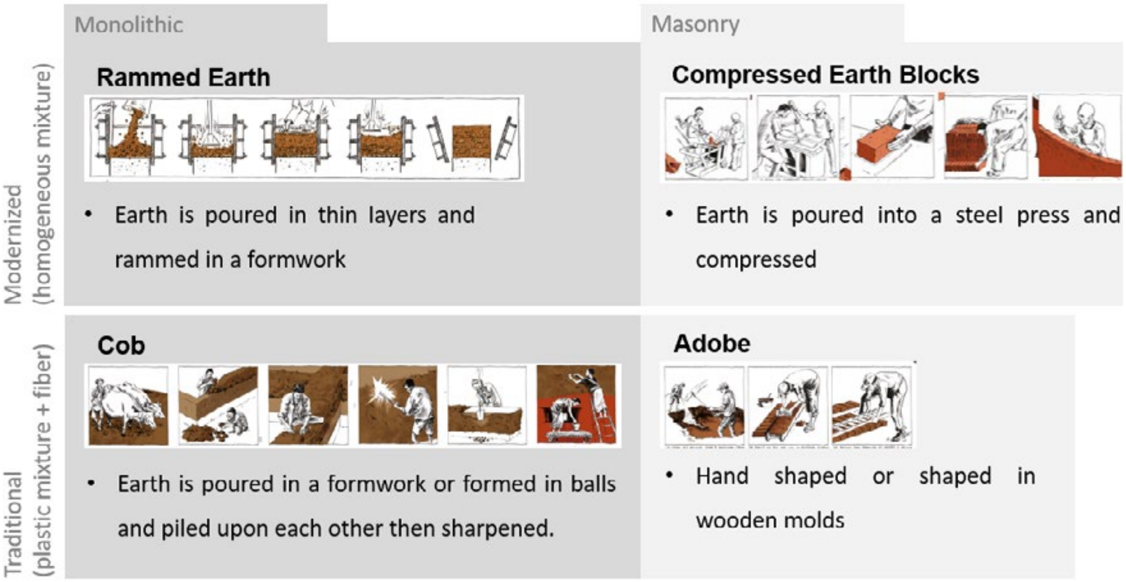


Figure 11_classification for four earth techniques (by author; adapted from CRAterre; pictograms source: Architecture en Terre d›Aujourd›hui)

Hybrid Technique

Various construction methods incorporate raw earth alongside other materials. One such technique, wattle and daub, utilizes a blend of clay, water, and straw to fill voids in a load-bearing wooden structure, positioned both above, below, and to the right. This method was prevalent across Europe from ancient Roman times until the Renaissance, contributing to the development of ‹half-timbering›. Presently, remnants of this technique can be spotted in rural regions of Europe, Africa, Asia, and Latin America, as well as within historic buildings in European towns, notably in France, Britain, Germany, and Scandinavia (Rauch 2017).

The concept of half-timbering has further evolved into ‹light earth› construction, where raw earth is combined with plant fibers like straw or hemp and wood shavings. These materials enable the prefabrication of construction elements like floor slabs and insulating panels for walls and roofs. Additionally, such mixtures can be applied under high pressure onto a metal framework, as demonstrated in an experiment conducted in Chile. In Spain, compressed earth bricks are occasionally integrated within a framework of fired bricks (to the right below). Moreover, in early 20th-century Germany, families collaborated to produce earth bricks using the Dünne loam-loaf technique before commencing construction (Dethier 2020).

2.1.3. Vernacular Earth Forms

Raw earth domes exhibit various forms such as hemispherical, segmental, pointed, or faceted, and their construction demands advanced technical expertise. They are particularly prevalent in the Islamic architectural tradition. For instance, in southwest Iran, expansive icehouses known as yakhchal were capped with pointed domes crafted from layered earthen bricks (Dethier 2020).

In religious edifices like chapels, churches, mosques, and temples, as well as in mausoleums, domes are often elevated on a drum. However, more intricate designs may feature domes supported by pendentives or, in the Byzantine tradition, squinches. In Egypt, the technique of constructing Nubian vaults emerged, characterized by brick courses sloping slightly inward and built without external support. This method was modernized by the Egyptian architect Hassan Fathy around 1948 (El-Shorbagy 2010).

Various other vernacular traditions can be found across Africa, such as the Musgum houses of Cameroon.

Hollow Cell Vaulting, Tunisia

On the Tunisian island of Djerba, the ancient Roman technique of hollow-cell vaulting has been meticulously preserved. The pottery workshops of Guellalah specialize in crafting wedge-shaped clay cells that, when assembled atop a centering, form an arch. The convex tops of these cells provide stable support, especially once a mortar topping has been applied. The sizes of these cells vary, allowing for flexibility in adjusting the span and rise of the vaulting within practical limits. For dome construction, the square plan is transformed into an octagon using squinches, while open sides are reinforced with supporting arches. The clay cells are then stacked to form intersecting arches, with any remaining spaces filled in with debris and mortar (Ragette 2003).

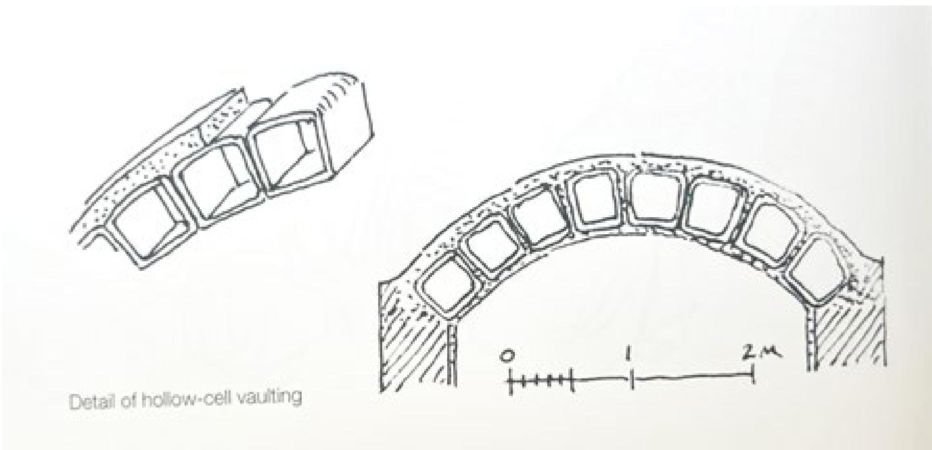


Figure 12_Detail for the Hollow Brick (Ragette 2003)

The advantages of this technique are manifold:

- Lightweight construction leading to efficient material usage.
- Rapid construction compared to methods requiring movable centering.
- Excellent thermal insulation due to the presence of voids within the structure.

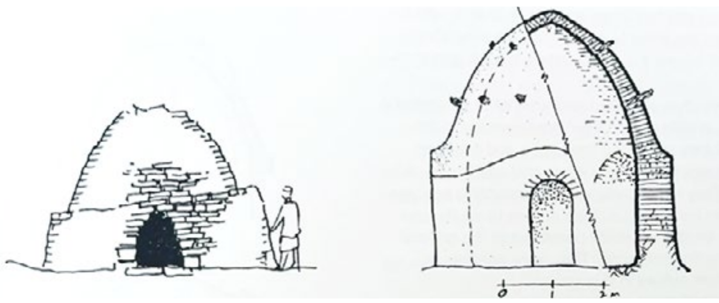
Beehive domes, Syria

Beehive construction is well-suited for both mud bricks and flat, slab-like fieldstones. The building process involves arranging courses in concentric circles, either horizontally or with a slight inward inclination, until they converge at the apex. This results in a domed roof with a pointed arch cross-section. The inherent stability of the structure is provided by the conical ring action of the courses, reducing the necessity for additional counterweights. To enhance stability, the walling typically begins with a thick base, often tapering back at around 1.5 meters in height to serve as a working platform for the upper sections. In some instances, the courses are laid in concentric spirals.

In regions like the Emirates and Oman, beehive stone structures, used for tombs, have endured for approximately 5000 years. These structures still function as shelters for herdsmen in Mediterranean countries. The beehive construction principle obviates the requirement for formwork during construction and has been implemented in large-scale structures, possibly even in the construction of the Hagia Sophia in Istanbul (Ragette 2003).

Vaulting technology was swiftly mastered in the ancient Near East, with evidence of domed roofing dating back to Tell Halaf around 5100 BCE. This architectural innovation has been a staple of traditional Syrian rural architecture for centuries. Over time, earthen-domed houses evolved as a result of a willingness to adapt and refine solutions to meet human needs while working with available environmental resources.

Figure 13_Beehive dome of mud with timber pieces for scaffold, Syria (Ragette 2003)



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Earthen domes offer several advantages over flat roofs, particularly in regions where timber is scarce. Their construction is more cost-effective, and they provide better resistance against rain leakage. Additionally, they minimize the surface area exposed to the intense summer sun, thus reducing solar radiation and creating favorable climatic conditions within interior spaces. As a result, earthen domes have become a preferred architectural choice, offering practical solutions to environmental challenges.

Musgum houses, Cameroon

The Musgum people of Cameroon have innovated a distinct form of housing known as the tolek (pictured on the right and opposite). French colonists coined the term «case bus» after artillery shells due to its resemblance in shape. What sets this vernacular architecture apart is the ingenious logic behind its construction.

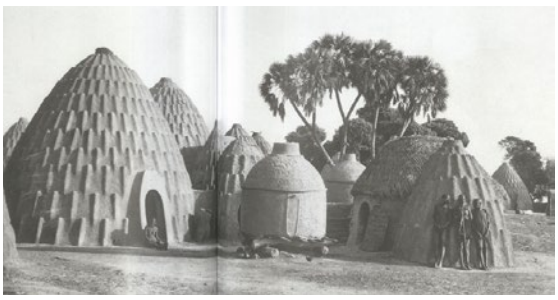


Figure 14 _ Cameroon Domes (Dethier 2020)

Toleks, which can tower up to 8 meters in height, are crafted akin to coil pots. Thick cylinders of raw earth, fortified with plant fibers, are layered in circular formations, gradually thinning from a base thickness of 35 centimeters to a mere 10 centimeters at the apex. This method yields a load-bearing structure that optimizes material usage for exceptional stability and durability.

The exterior of the tolek is adorned with a repeating motif in vertical relief, often depicting an inverted V, arranged in a uniform pattern. This decorative feature serves multiple purposes: reinforcing the load-bearing structure, providing ample footholds for easy access to all exterior sections for construction or maintenance tasks, and proudly proclaiming the cultural identity of the village it represents (Dethier 2020).

Material Failure

Despite all the earthen materials successes along the years, some (technical) failures have resulted in earth poor image. “Poor imagery” is a term that is usually being used when the subject of Earth is raised to discussion. People perceive earth as a building material for the tombs and the material for the poor. Even when architect Hassan Fathy chose a name for his book “Architecture for the Poor” representing the economic benefits for building with earth. However, no one wants to be described as “poor” so people in the villages nowadays want to have a new image and build with conventional materials ignoring all the drawbacks of these materials. It is the challenge of the architects to do “modern” earth architecture with implementation to new technologies and interesting architectural tectonics to be able to transform these perceptions about the material.

New Gourna, Luxor, Egypt (1946)

New Gourna or Gourna El-Gedida village was designed by the Egyptian architect Hassan Fathy. It was partially built between 1945 and 1948, lying roughly midway between the Colossi of Memnon and el-Gezira on the Nile (Ahmed & El-Gizawy, 2010). He discovered not only building with mud, as a material and technique of building, but more importantly as a part of a philosophy of interaction between man and his environment.

‹The experiment back then was unique, beautiful, and comfortable…but now there are negatives. The architecture is falling apart because of the increase in groundwater, the lack of a sewage system, and absence of a proper drainage system for agricultural lands.› _ Hassan Fathy

Unfortunately, the year 1948 witnessed a dramatic end to Fathy's experience of New Gourna where the pressure that had been increasing from endless problems and setbacks finally reached a breaking point. Cracks began to appear in all buildings ruining many of them. Ultimately, the village was abandoned in its state of partial disrepair. (Ahmed & El-Gizawy, 2010)

The lack of sewage system has raised groundwater level which resulted in moisture and salt migration, contributing to the disaggregation of limestone within foundations and de-cohesion of mud bricks. In walls, this results in significant erosion, destroying the outer coat of earthen bricks. The lower courses show efflorescence, and also the failure of the physical-chemical matrix forms deepening concave features at the wall base. The degradation compromises structural integrity, thereby reducing the load bearing capacity of foundations and lower storey walls. Structural cracking was observed in buildings with domes where weight distribution was uneven, especially around voids such as windows and doors. Its supporting walls, especially in the corners, appeared thicker. ("New Gourna Village: Conservation and Community," 2011)

On the other hand, the lack of good insulation technologies and the choice of roofing materials and techniques were the main reasons for the poor imagery and deterioration of earth in the modern era. Moreover, the current initiatives for using earth nowadays are well perceived by users and clients and the earth service providers are getting more projects after their consecutive successes. However, those recent practices are lacking the vertical extension. They are only one floor high and the rural context's needs requires material boundary expansion.

2.2. Modern Upgrading Practices

Most earth construction techniques are very old as displayed in the previous section. Building with earth started with the human urge to find or construct a shelter. As the human lifestyle and needs have changed, his shelter must be upgraded too to fulfill these needs. Material upgrade is an evolvement process that material must undergo to meet social, economic, and technical changes in the different societies and cultures. This may require enhancement in the material strength, appearance, application and more. In the case of the earthen materials, the upgrade is essential to promote the use of such sustainable to be able to continue to compete in the current building industry.

2.2.1. Mixture and Technique

Earth has gone through tectonic upgrading processes. These processes have contributed to broadening the application and area of use of this technique in the modern building industry. They have transformed the material from the basic wall to a spectrum of textures that made the formwork an integral part of the fabrication process.

CEB Special Module Fabrication: Omar Rabie

Since the fact that CEB is a commonly used technique in comparison to the other earth construction technique, it has undergone various experimentation to upgrade its tectonics thus increase its use.

In an interview with architect Omar Rabie he mentioned that while he was moving from Egypt to Auroville city in India, he found himself surrounded with a different culture that is clearly visible in many aspects of the city. The people's clothes, building facades and many more have a common feature that is the excessive details. In the era of globalization, the buildings in different parts of the world are tending to look the same.

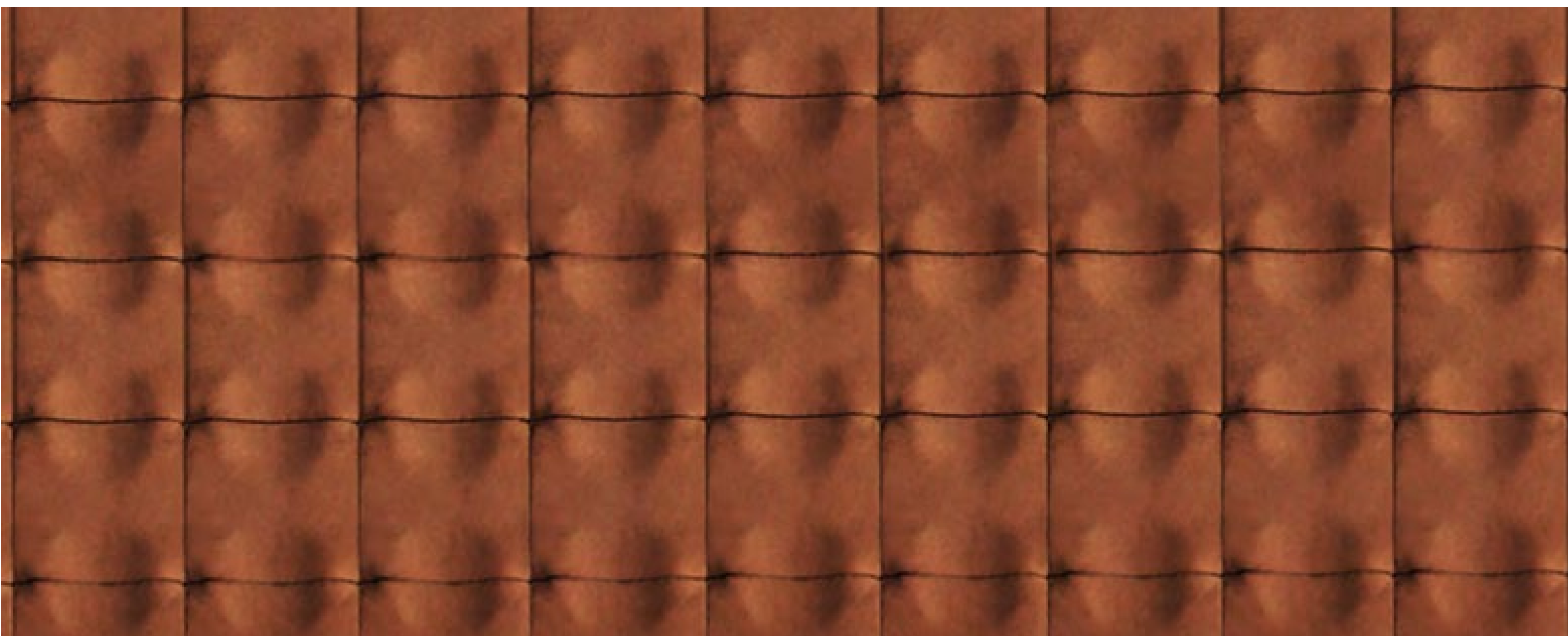
Rabie was assigned as an architect to a project where he started to explore the potential of earth architecture in preserving the identity of the city but in the same way add a value to it through upgrading the material tectonics.

This involved not only to design the building from an air-conditioned office but rather to work with his hands as a mason to experiment has a feeling to the material characteristics (O. (MIT) Rabie 2015; O. Rabie 2008).

This was clear when he said:

> ***"While working on the production of Compressed Earth Blocks on site, I had a deeper understanding of the process of the material production, as well as the capabilities of the machines, tools, and craft workers."***

Figure 15 _ CEB special brick workflow (O. (MIT) Rabie 2015; O. Rabie 2008)



He started by a very simple curve using his material-educated understanding to produce several experimental blocks and walls. He utilized this curve to construct the first block and wall, inverted the curve to make the second, and then used both simultaneously to make the third while working with the carpenter to carve additional wooden shapes to be added to the machine. When being exposed to natural light, the walls› look drastically changed. He intended to use such a textual undulated earth walls in the natural resort, in order to promote a feeling of connection to typically unnoticed natural phenomena, like the movement of sunlight on surfaces. (O. (MIT) Rabie 2015; O. Rabie 2008)

At some point in his thesis, he used the example shown in figure 15 as evidence of the opportunities, such a material manufacturing process, can offer to the designer. The process is completely controlled by the architect using affordable tools and raw materials. Rabie mentioned that:

"I discovered that I can reveal the nature of a material through understanding and practicing its production process, and here we compress soil returning it to its original primordial stony state. Thus I emphasized a feeling of compressibility and sculpturally."

Rammed earth special module fabrication: Lee

The potential to improve the aesthetical and functional quality of rammed earth is highlighted through the utilization of fabric formwork, where the installation of steel reinforcement bars becomes a crucial aspect. The compaction process during ramming causes the fabric to bulge, necessitating careful pre-planning for controlling this bulging with frames, such as steel bars in this construction. This consideration significantly influences the design of the fabric formwork. Two distinct types of fabric-formed rammed earth were created: fully unstabilized rammed earth and proportionally stabilized rammed earth. (Lee 2021)

In the construction of unstabilized rammed earth, the moisture content of the earthen mixtures exceeded that of typical rammed earth construction. However, this elevated moisture content did not pose any issues in the final outcome, as excessive moisture and air were effectively extracted through the permeable fabric. After seven days, when the fabric formwork was removed, the rammed earth walls showcased exceptional appearances with delicately undulated forms and textured surfaces. A careful examination of the models reveals a gradual undulation in the surface, with greater intensity at the bottom and subtler undulation as one moves upwards. This variation is attributed to the differential weight distribution on each soil layer, with more load applied to the lower part of the rammed earth walls causing greater fabric bulging.

Additionally, fabric introduces new possibilities for material-driven design, such as enhancing aesthetic quality and potentially improving rainwater drainage. In fabric-formed rammed earth, patterns can be easily created based on the arrangement of frames like timber, bamboo, or steel bars. These arrangements can be schematically designed, taking into account both design and environmental considerations. Consequently, fabric formwork allows for the production of bespoke shapes of rammed earth that reflect local conditions and fully exploit the qualities of these materials (Lee, 2021).

Figure 16_ Fabric mold for rammed earth (Lee 2021)

Prefabrication of Rammed Earth

Prefabrication represents a new paradigm in rammed earth construction. It takes the practice to a new level. Rather than employing a team of laborers to ram the earth in site, gradually putting up the building over time, cranes can quickly mount the finished elements in accordance

with the demand of tight schedule. In contrast, technical implementation has become much simpler: prefabricated details are standardized and can be put in place by unskilled labor. This technique was started by Lehm Ton Erde in 1997. The first large scale project was an office building for Gugler Printers in Pielach. It took three months to finish the 160 pieces required for the project, then these pieces were put in place over the course which took more two weeks to be completed.

Based on the literature, due to improved workflow and increased production speed compared to the 1990s, the current ratio of production to installation in prefabricated parts in approximately 3:1. The number of projects constructed with prefabricated materials have grown significantly: walls can be produced efficiently regardless of weather conditions and schedules are simpler to coordinate (Rauch 2017)(Gauzen-Muller 2017).

In order to develop prefabrication and further improve its efficiency, several new inventions have been required. The most strenuous task is filling the formwork with the material and compacting the mixture. A machine therefore was developed to address this particular challenge by automatically distributing the earth within the formwork and mechanically compacting it by a moving rammer. (Rauch 2017)

2.2.3. Form (domes & shells)

There is not a lot of modern projects that use earth as a roof or slab due to its weak characteristics when bearing tensile loads. Besides, the domes in its traditional forms are associated for many people with the tomes design.
Recently, hybrid construction is the favorable choice. In this case, the earth is used as the material form the walls but the roof and even the building structure is concrete or wood.

Figure 17 _ Prefabricated walls waiting to be shipped. Source Ricola (Handmade Ricola, 2014)

There are many examples for this to name a few:

- Sihlhölzli Sport Complex, Swizerland; concrete slab for rammed earth walls in by Martin Rauch
- AlNatura Campus, Darmstadt; rammed earth façade, wooden beams, concrete columns
- Chapel Reconciliation, Berlin: organic rammed earth walls and wooden roof.

Below, a research mock-up by ETH students will be displayed, since it is one of the very few rammed earth roofs projects.

Rammed Earth dome: ETH students (BRG)

The construction of roofs or arches was previously limited to the use of earth bricks and mortar. Salis highlights, «The possibility today of prefabricating rammed earth elements opens up an entirely new range of applications.» Thanks to innovative construction methods, earth can now be employed as a robust building material, presenting numerous advantages over concrete. It is readily available, requires no chemical curing, possesses minimal grey energy content, ensures an excellent indoor climate, and can be naturally recycled by dissolving in water (Schläfli 2014).

The material›s potential in terms of construction and design underwent exploration through two course seminars. Following the completion of a rammed earth wall in Austria by an initial group in 2012, another 26 students, working in groups of three or four, conceptualized seven diverse designs for a unique construction project: a rammed earth dome. The initial models were constructed using earth sourced from Hönggerberg. Martin Rauch, an expert with over 30 years of experience in working with earth, was on standby to provide assistance. Eventually, a design was chosen for practical implementation.

During a two-week workshop supported by the ETH Innovedum fund, students completed 19 rammed earth elements in the workshop of Rauch's company, Lehm Ton Erde GmbH. These elements were intended to be assembled later as domes and arches. Robust wood formworks were filled with layers of earth from the Laufen region, which was then compressed using pneumatic rammers. "The students learned on-site how to transform their plans into reality with their own hands," says Salis (Schläfli 2014).

This summer, after a two-month drying period, the students assembled the elements at the Hönggerberg campus using a pneumatic crane. Despite incorporating some conventional materials, such as a concrete foundation and a metal plate to protect the roof from rain, the objective was not to eliminate the use of concrete entirely but to use it only where absolutely necessary. Salis emphasizes the importance of keeping the core of the rammed earth building dry for stability (Schläfli 2014).

Georg Bachmann, a Master's student in the Department of Architecture, assisted during the two-week construction period. He marveled at the ease with which flaws, such as chipped edges, could be touched up by applying moisture, pressing it down with earth, and lightly tapping the area with a hardwood board and hammer. Bachmann found the hands-on experience valuable, noting the significance of architects understanding how their designs are actually

built, an aspect often overlooked in their training.
Salis underscores the teaching aspect of making students aware of the relationship between materials, design, form, and architectural expression. The dome will serve as a research object, providing insights into the weathering and long-term stability of prefabricated rammed earth elements. The project aims to cultivate a young generation of innovative architects who understand the intricate connections between materials and design (Block Research Group 2012).

The teaching and research project›s aim was to convey the theoretical and practical relationship between material, construction, form, and architectural appearance. The task was to develop a pavilion with space-spanning constructions made of rammed earth. Since rammed earth can only absorb compressive force, the students collaborated with experts to design suitable structures. It was discovered that prefabricated elements could be used, and one design was selected for further elaboration. The elements were rammed by students in a workshop, with vaulted roofs rammed resting on their faces and then rotated during the assembly process. This innovative technique was the first time load-bearing rammed-earth vaulting was constructed using prefabricated elements.

Figure 18 _ Rammed Earth dome by ETH students (BRG) © Gian Salis (Schläfli 2014)

2.3. Post Tensioning Rammed Earth

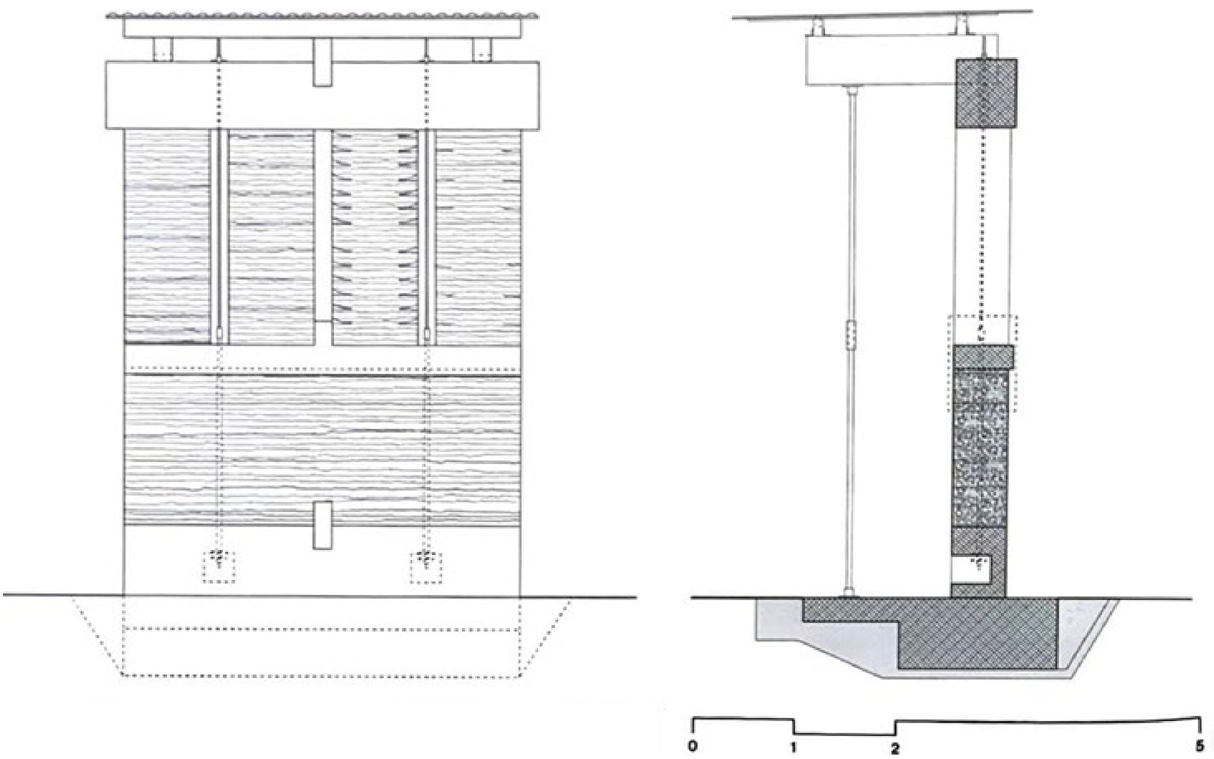
Post-tensioning in general, which is a form of prestressing, is a method that is commonly applied on concrete construction members. It is used for its advantage over standard reinforcing method (rebars) such as: reduction or elimination of shrinkage cracking-therefore no joints, or fewer joints, are needed. Moreover, cracks that do form are held tightly together. Besides, It allows slabs and other structural members to be thinner and gives the possibility to design longer spans in elevated members, like floors or beams (ConcreteNetwork.com 1999). On the other hand, post tensioning for rammed earth is used to improve the wall›s capacity to withstand lateral loads without failing in tension (Ward and Grill 2006).

In a research experiment by Roger Boltshauser at EPFL Lausanne, he worked on developing innovative hybrid construction in an attempt to extend and simplify future possibilities of earth construction. The aim was to challenge the established standards of today›s construction industry using intelligent hybrid solutions as well as to enable scale jumps in rammed earth construction. During summer school at the end of August 2017, architecture students built a mock-up of their selected project design. They have completed of the mock-up›s rammed earth elements in less than two weeks time. The earth mixture is mostly not standard since material properties are strongly dependent on the earth conglomerates used on site. It is therefore necessary to examine the material properties of rammed earth used on every building site, especially with regard to its compressive strength.

The post-tensioning structural system was examined in this mock-up. As shown in figure 19, The post-tensioning rods are secured to a concrete footing and a concrete beam where the rammed earth wall is placed between the two concrete members. A nut is threaded upon each rod and tightened against the top and bottom concrete members to draw the rod into tension. Thus compressed, the rammed-earth wall is less susceptible to tension failure.

Concerning the prestressing procedure, the initial step involved ramming the lower section of the wall onto a concrete plinth in the conventional manner. Additionally, two steel tubes were incorporated into the wall to accommodate the steel cables required for prestressing at a later stage. Simultaneously, the upper portion of the

Figure 19 _ Elevation and section of the RE post-tensioned mock-up (Boltshauser 2018)

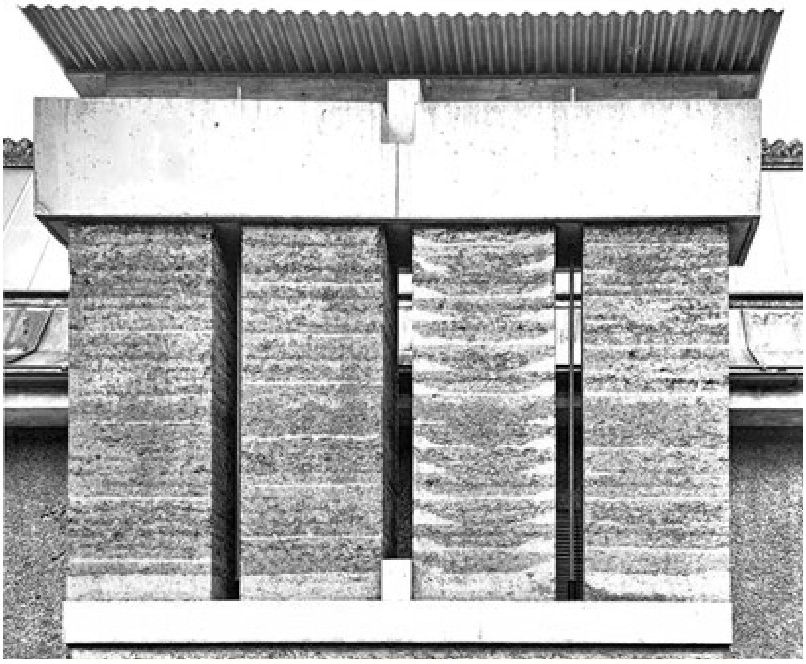


wall, comprising four earth pillars, was rammed into the form of eight premanufactured elements. Subsequently, following an approximate drying period of six weeks, the premanufactured elements were relocated to the lower section of the wall. At this juncture, a concrete slab was introduced, serving as both the lowermost component and the central element into which the upper anchors for prestressing were integrated. Comprising threaded rods and nuts, the subsequently integrated prestressing system effectively fastens the upper concrete slab to the foundation, imparting adequate rigidity to the supporting framework (Boltshauser 2018).

In alignment with the initial design envisioned for the pavilion prototype, the integration of two threaded rods serves the purpose of transmitting prestress to the earth in the mock-up. Considering the natural tendency of earth to undergo shrinkage during the drying process and to exhibit initial creep when subjected to constant stress, it was determined that the mock-up should be prestressed without the final composition. This approach allows for subsequent post-tensioning to compensate for any decrease in pretension over time.

It is worth mentioning that the trass lime layers within each of the earth pillars exhibit variations in both spacing and form. Monitoring of the erosion of these elements isan ongoing process over long period of time. Additionally, the mock-up incorporates several technically detailed solutions, including diverse material transitions between concrete and earth, with or without the use of trass lime. These integrated features facilitate the examination of the effects of weather conditions such as humidity, rainfall, snow, and frost on the structure.

In an ideal scenario, prestressing can enhance the bending load capacity of the mock-up›s wall by approximately 70 percent. This signifies that it is possible to withstand 70 percent higher wind loads, or alternatively, increase the wall›s height by 30 percent in comparison to a non-prestressed wall (Figure 20).



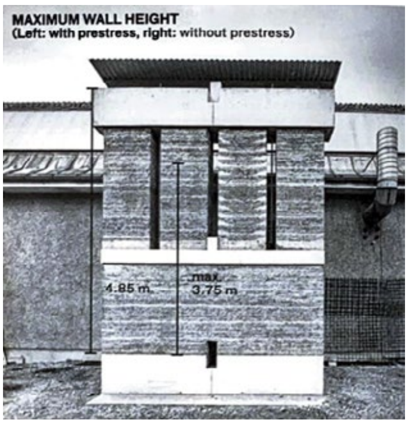


Figure 20_ Experimentation for rammed earth corners durability (Boltshauser, 2018)

2.3.1. Walls: Upscaling prestressing in earth: Kiln Tower for the Brickworks Museum

In a subsequent project, students from Studio Boltshauser, under the guidance of visiting professor Roger Boltshauser, embarked on the planning of an approximately nine-meter-high tower constructed from rammed earth. This distinctive tower was intended for the Cham Brickworks Museum, situated at the Technical University of Munich and ETH Zurich. One noteworthy element of the design involved the aspiration to engage in a self-construction endeavor, which was incorporated into a summer school program in the summer of 2019.

The primary objective was to provide these students with practical experience in rammed earth construction, a hands-on DesignBuild project. Through this initiative, students were not only able to partake in the process of innovation but also gain insights into how architectural creations can emerge from raw, unfired earth materials.

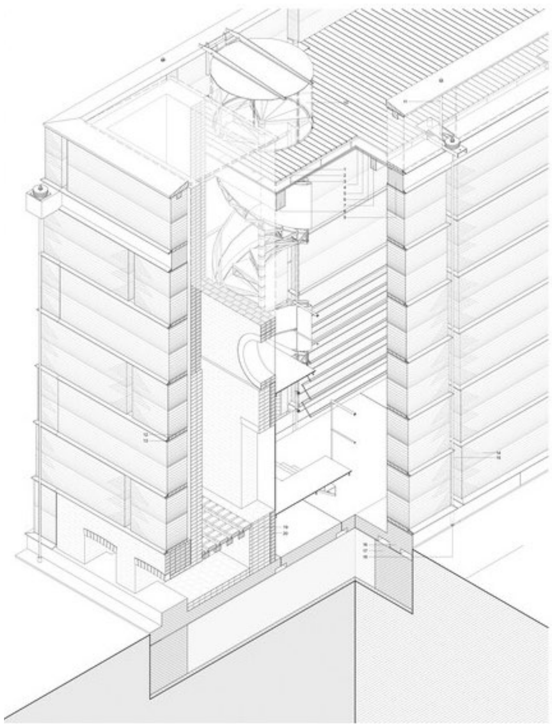


Figure 21_ Kiln Tower for the Brickworks Museum / Boltshauser Architekten (archdaily)

The project›s foundation lies in technical innovation, where rammed earth wall elements are prefabricated by students and subsequently assembled on-site. The incorporation of prestressing techniques involves tension rods embedded within the walls, creating a robust static system that enables the construction of a nine-meter-high building without the need for a false ceiling. This pioneering approach, spearheaded by Roger Boltshauser, was tested through post-tensioning in the walls at ETH Zurich and the Kiln Tower for the Brickworks Museum (Boltshauser, 2018). Boltshauser›s method reinforces the walls between two beams, with only a minimal use of concrete in the edges, addressing their critical strength and durability requirements. Additionally, erosion control measures are employed to mitigate the impact of rainwater on the external surface of the walls (Pintos 2021).

2.3.2. Rammed Earth in Roofs/ Slabs

Earth is an ancient building material with roots dating back centuries, has a rich history in the construction of houses, stables, mosques, and palaces in Africa and the Middle East. Despite its once-prominent role, the advent of industrialization and the widespread use of concrete led to the gradual neglect of earth. Even today, it contends with a reputation as a transient and subpar building material.

Throughout history, the application of earth has been constrained by inherent limitations in design and construction. While it exhibits resilience against compressive forces, its inability to absorb tensile forces has curtailed its versatility. Additionally, the protracted drying and hardening process of earth pose challenges, rendering it impractical for the direct on-site ramming of curved or vaulted shapes.

As modern construction methods continue to evolve, there is a growing awareness of the potential inherent in earth, prompting a reevaluation of its attributes. By acknowledging its historical significance and addressing its limitations through innovative techniques, there is a renewed opportunity to unlock the full potential of earth in contemporary architectural practices. Efforts to enhance its structural capabilities and streamline its application processes could position earth as a sustainable and culturally significant building material for the future. (Howe, Heringer, and Rauch 2019).

Resource-efficient construction, sustainable lifestyles, and adherence to the circular economy principles have gained unprecedented importance in our contemporary context. Many construction techniques currently under consideration actually have historical roots in traditional building methods. These encompass a range of designs such as ribbed ceilings, classic wooden beam ceilings, Hourdi ceilings, Koensche cove ceilings, and capped ceilings.

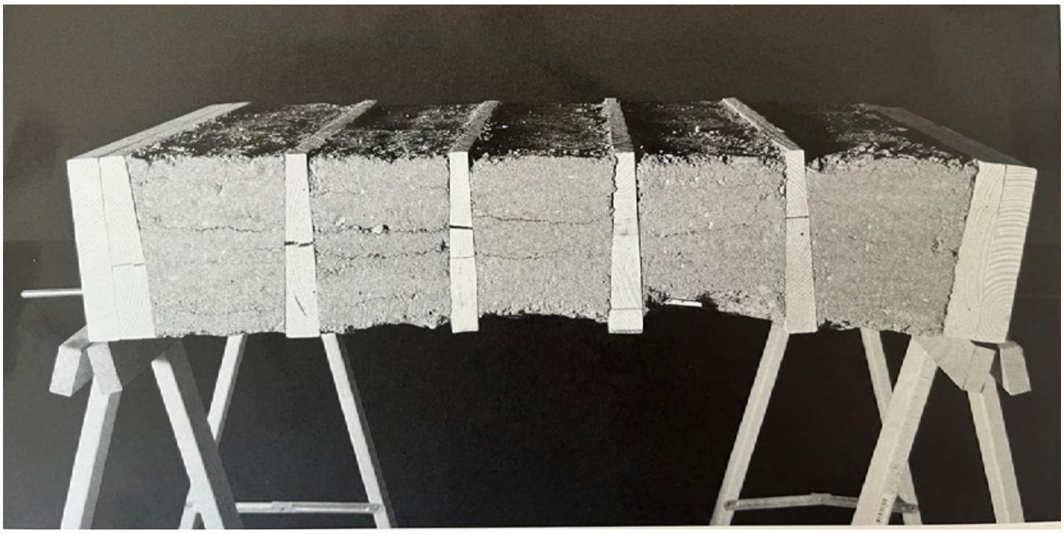
While pure wooden beam ceilings are recurrent, they often fall short of meeting minimum acoustic standards and can exhibit vibrations. Their inherent lightweight nature and a lack of (thermal) mass might necessitate additional measures, such as subsequent weighting. This is where incorporating ecologically friendly materials becomes crucial. Considerations lead us to materials like clay, a natural substance that not only offers the needed weight but also aligns with ecological principles.

In essence, the exploration of traditional construction methods provides numerous opportunities for advancing and refining current practices. By integrating eco-friendly materials and emphasizing the importance of sustainable construction, we pave the way for a future where structures are not only functional but also aligned with the principles of environmental responsibility and resource conservation.

Early Trials of Timber Lehm Slabs

Is it possible to reinforce rammed earth in a manner similar to concrete? The primary distinction lies in the close synergy between concrete and reinforcement steel, which is much more significant than what can be achieved with rammed earth. Another factor to consider is that concrete provides protection against corrosion for the reinforcement steel, which is an advantage that rammed earth cannot offer.

Figure 22 _ Earth as slab experiment using wood as a connecting material (Boltshauser 2018)



However, it is conceivable to envision a broader-scale synergy between timber structures and rammed earth. In this scenario, timber could serve as a reinforcement for rammed earth walls. One could envision placing a timber structure within the wall and covering it with rammed earth. It is crucial that the timber is resistant to moisture, as expanding wood can disrupt the surrounding earth cladding. Nevertheless, a sufficiently thick layer of rammed earth can mitigate this issue.

The challenge that remains is the higher shrinkage rate in rammed earth, approximately %1. If not addressed, this shrinkage can lead to cracks in rammed earth, allowing unwanted moisture to enter the building interior. A more promising approach in this context is prestressing rammed earth. Concentrated anchor forces can be applied to rammed earth through steel or concrete distribution plates. The use of corrosion-resistant tendons allows for post-tensioning at any time. This can effectively compensate for the loss of compressive strength due to shrinkage and creep in rammed earth.

Recent research project: Holz-Lehm-Decke

After the lockdown measures were imposed, the transition to online sessions occurred. During this period, the Zero Pavilion (ZPF) introduced a ceiling analysis, and Martin Rauch from ‹Lehm Ton Erde› joined the project. Within a few weeks, a fundamental structural concept was formulated: a wooden support frame construction with minimal adhesive elements, incorporating spruce beams, clay vaults, solid wood panels, sand infill, and oak floorboards. The specifications of the timber beams dictated a maximum span of nearly six meters. Nico Ros emphasizes, «Unusually, the design process here unfolded from the selection of materials to the construction methods and, ultimately, to the architectural design. This sequencing, if one seeks to achieve genuine sustainability, is indeed the correct approach.»

Alexander Franz, an Associate at Herzog & de Meuron, observes, «In this project, architects, engineers, and building technicians collaborate as equals.» This approach stands in stark contrast to the conventional linear model where design and engineering phases are distinctly separated. While this direct-order approach may pose challenges from a competitive perspective, it fosters a culture of open discussion during meetings, eliminating the traditional divisions between disciplines. It is impressive how these fragmented construction disciplines converge in the pursuit of climate objectives, with the team successfully constructing a mock-up in a matter of months.

The construction of the mock-up was entrusted to ‹Lehm Ton Erde,› a company based in Schlins, Vorarlberg. Comprising approximately two dozen employees, the company led by Martin Rauch has been involved in numerous clay construction projects across Europe. This underscores the underappreciated role of clay as a building material. Jomo Zeil, overseeing the project, notes, «Apart from wood, very few manufacturers today employ natural building materials. The time for industrialization has arrived.»

The potential of clay as a construction material is substantial. In timber construction, particularly in the creation of structures with significant heights and spans, there is a demand for mass to meet fire protection and thermal storage requirements. The use of concrete in laminated timber slabs is suboptimal, whereas clay, being both ecological and locally available, presents an attractive alternative. Clay possesses the ability to regulate humidity levels in indoor spaces, enhancing its utility in conjunction with wood, which cannot perform this function. Additionally, clay is effective in absorbing and releasing heat, insulating against both airborne and structure-borne noise, and is even believed to have antiseptic properties.

Figure 23_ Holz-Lehm-Deck Mock-up (Petersen 2021)

The underlying principles of this approach are not entirely novel. As Jomo Zeil notes, «There have been some instances of similar ceilings in the domain of self-made, alternative architecture, but these were often labor-intensive and prone to instability.» Scaling up this concept represents a significant departure from previous endeavors. The innovation lies in achieving a high level of product maturity: the resulting ceiling is fire-resistant and economically viable, with a cost per square meter estimated to be below 500 Swiss Francs (Petersen 2021).

Floor ceilings made of load-bearing clay arches

Martin Stumpf, managing director of wh-p Ingenieure (Basel) and professor of structural design at the University of Applied Sciences in Stuttgart, challenges the conventional use of reinforced concrete flat slabs in multi-storey buildings. While these slabs have dominated construction for years due to their versatility and ease of installation, Stumpf emphasizes the need to reconsider these choices in the face of resource conservation and a reduction in concrete use.

Motivated by this perspective, Stumpf and his team embarked on a research project exploring load-bearing clay arches as an alternative structural solution. Stumpf acknowledges the historical use of various arch shapes from different materials, with clay being a notable omission. Unlike rammed earth, which has limitations in absorbing tensile forces and compressive stress, the objective of their work is to demonstrate the load-bearing capabilities of clay.

Nico Ros, an engineer passionate about ecological construction, points out the paradox in the industry›s reluctance to invest slightly more for significantly more ecological practices. Despite this, Stumpf›s team proceeded to construct clay arches, creating a support line within the material to accommodate various load cases. The resulting arch boasts a 3.50 m span and a 54 cm stitch height.

In ERNE Holzbau production halls, she built a 1:1 mock-up of the arches with two adjacent arched fields. The arches, constructed from rammed earth, benefited from the company›s experience gained during the construction of its new office building.

Drawing inspiration from the company›s use of clay blocks for climbing zones in their office building, the researchers devised a method to build the arch formwork as a curved wall. The loose clay material was poured layer by layer into the formwork, compacted by hand, and removed after a six-week drying period. The project represents a departure from traditional construction methods, showcasing the potential of clay as a viable and environmentally friendly alternative to reinforced concrete in structural design (Dietsche 2023).

Figure 24_ Rammed earth segmental arch roof/ slab (Dietsche 2023)

Chapter Conclusion

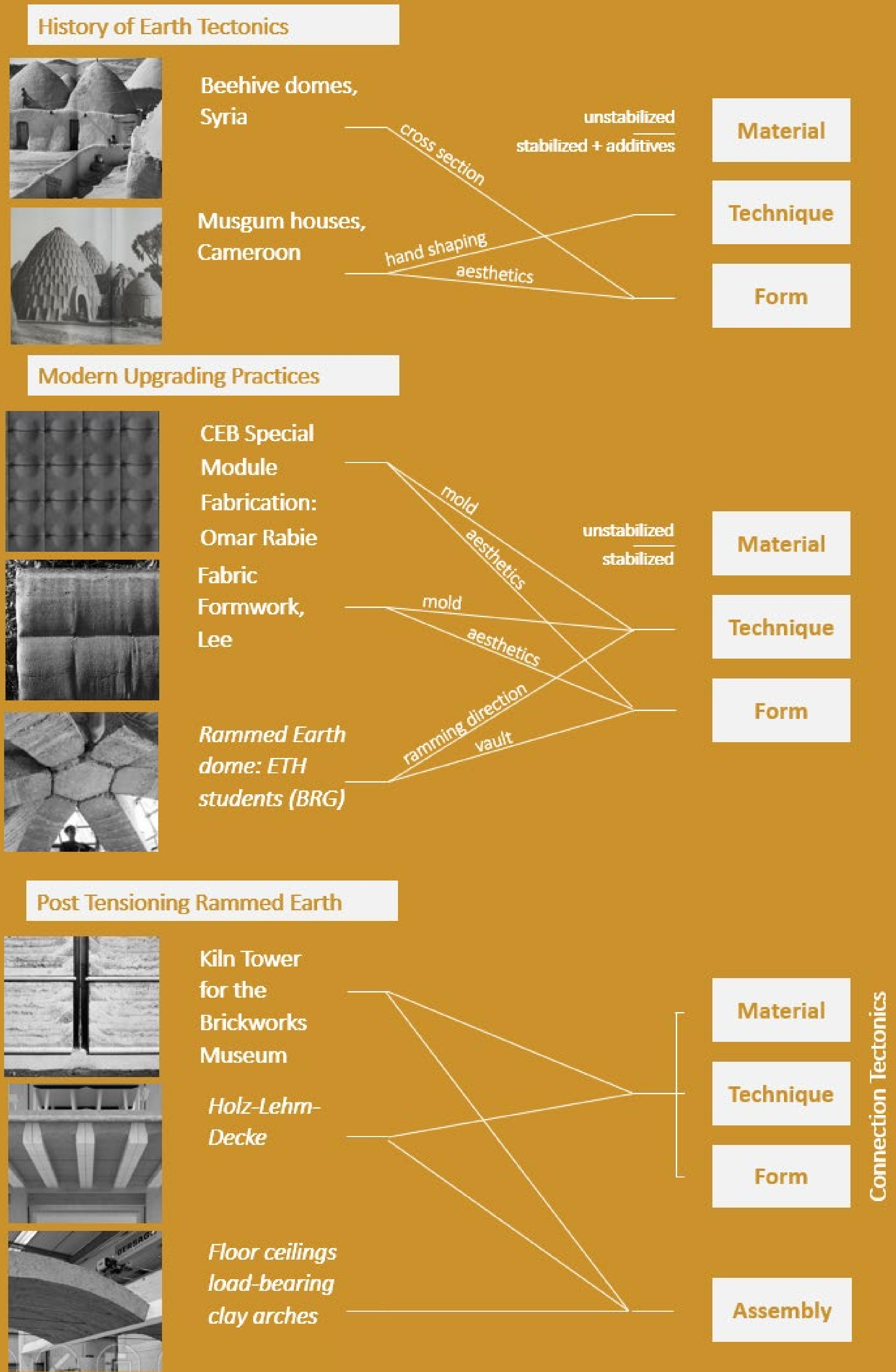
In this chapter, the rich history and diverse techniques of using earth as a building material, exploring its evolution from ancient practices to modern innovations. Earth, or soil, has been a fundamental component of human shelter since ancient times, with various cultures harnessing its versatility and abundance to construct their civilizations. From underground burrows to towering structures, the utilization of earth in construction has shaped architectural traditions across the globe.

The discussion has been structured around three key factors: the earthen mixture, construction techniques, and modern upgrading practices. The earthen mixture, crucial for the strength and durability of earthen walls, involves careful consideration of soil composition and potential additives for stabilization. While some regions have embraced the use of stabilizers like cement, others prioritize maintaining the natural characteristics of the material, highlighting the debate between technical considerations and environmental sustainability.

Exploring earth construction techniques reveals a rich tapestry of traditional and modern methods, from rammed earth and compressed earth blocks to cob and adobe. Each technique offers unique advantages and challenges, influencing architectural possibilities and shaping the built environment. Rammed earth and compressed earth blocks, in particular, have seen a resurgence in interest due to their sustainable nature and potential for modernization.

In the realm of modern upgrading practices, architects and researchers are pushing the boundaries of earth construction, seeking to enhance its strength, appearance,

Figure 25_Chapter 1 findings diagram


History of Earth Tectonics
Beehive domes, Syria
Musgum houses, Cameroon
cross section
hand shaping
aesthetics
unstabilized
stabilized + additives
Material
Technique
Form
Modern Upgrading Practices
CEB Special Module Fabrication: Omar Rabie
Fabric Formwork, Lee
Rammed Earth dome: ETH students (BRG)
mold
aesthetics
mold
aesthetics
ramming direction
vault
unstabilized
stabilized
Material
Technique
Form
Post Tensioning Rammed Earth
Kiln Tower for the Brickworks Museum
Holz-Lehm-Decke
Floor ceilings load-bearing clay arches
Material
Technique
Form
Connection Tectonics
Assembly

and application. Innovations such as fabric formwork, prefabrication, and post-tensioning techniques are expanding the possibilities of earth architecture, enabling the creation of intricate designs and structurally robust buildings. These advancements not only improve the performance of earthen structures but also contribute to their broader acceptance in the contemporary building industry.

Moreover, the case studies presented, including Omar Rabie›s exploration of CEB special module fabrication and Roger Boltshauser›s experiments with post-tensioning rammed earth, exemplify the intersection of traditional wisdom and modern ingenuity in earth construction. These projects demonstrate how a deep understanding of materials and innovative construction techniques can result in sustainable, aesthetically pleasing, and structurally resilient buildings.

As we look to the future, the continued exploration and refinement of earth construction methods hold great promise for addressing contemporary challenges such as sustainability, affordability, and resilience. By embracing the lessons of the past and embracing cutting-edge technologies, we can usher in a new era of earth architecture that not only honors ancient traditions but also embodies the spirit of innovation and adaptation. Earth, with its timeless appeal and inherent sustainability, remains a cornerstone of architectural excellence, offering boundless opportunities for creativity and exploration in the quest for a more harmonious built environment.

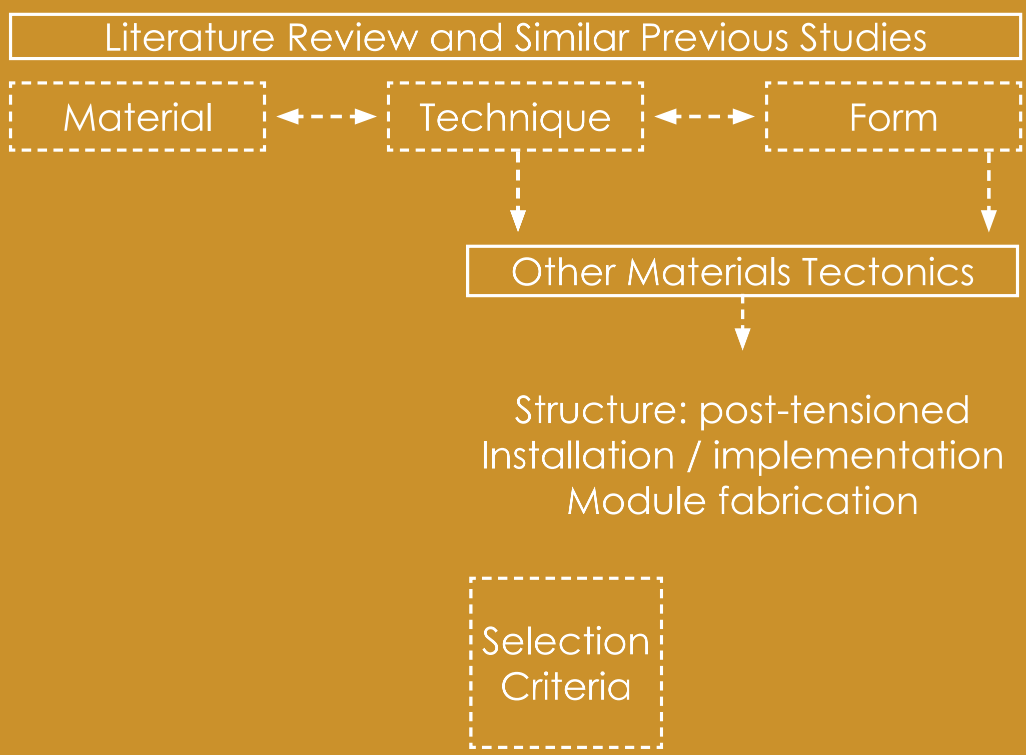
A new significant aspect is starting to appear from the literature: the connection tectonics. The post-tensioning structure implies the design of a connection between the different elements. The connection on its own has material, production technique and form.

In conclusion, the journey of earth from ancient origins to its renaissance in modern construction practices exemplifies the cyclical nature of architectural innovation. Despite facing challenges and neglect in the wake of industrialization, the inherent qualities of earth have sparked a renewed interest in its potential as a sustainable and culturally significant building material.

The ongoing exploration of traditional construction methods, coupled with innovative techniques and interdisciplinary collaborations, heralds a promising future where eco-friendly materials like earth play a central role in shaping the built environment. By embracing the lessons of history and leveraging the latest advancements in design and engineering, we can pave the way for structures that not only meet the functional needs of society but also honor the principles of environmental responsibility and resource conservation.

Chapter 3
State of Art

This chapter shows some shell structure implementations by different materials to understand the various parameters of the structure.



Chapter 03

OTHER MATERIALS TECTONIC ADVANCEMENTS

"As the complexity of the building industry continuous to grow, the question of the relationship between architecture and engineering is increasing in relevance" -Tectonics in Architecture book (Beim and Madsen 2014)

03 OTHER MATERIALS TECTONIC ADVANCEMENTS

In contemporary architecture, the building materials tectonics becomes an important part of the architectural expression. Materials' properties, textures, colors, and structural capacities of the commonly used materials are being deeply and thoroughly developed along many centuries. This includes experimenting with different construction methods, connections, and detailing to highlight the unique characteristics of conventional materials such as concrete and brick. This results in buildings that not only serve their practical purposes but also convey a sense of craftsmanship, innovation, and aesthetic richness.

In this context, material tectonics is about exploring and expressing the language of construction, celebrating the beauty and functionality of materials in architecture. This approach often leads to designs that are not only visually compelling but also deeply rooted in the physical and tactile experience of the built environment. Tectonics, in this context, relates to the science or art of construction and is concerned with the way buildings are put together (Beim and Madsen 2014).

- **Material**

- **Form**

- Holistic Structure Design
- Module Design

- **Technique**

- Mold Tectonics

Pavilions – "Compression-only" Structures

In recent times, there has been a noticeable trend among research institutes and research groups to construct pavilion-scale mock-ups as part of their experimentation and testing processes. The choice of pavilion scale, particularly showcasing shell or vault structures has emerged as an efficient intermediate scale for materials experimentation. Positioned between single modules or scaled models and full-scale buildings, pavilions balance between various factors such as time, budget, and space, making them a pragmatic choice for research endeavors.

Shell and vault structures, featured prominently in these pavilion-scale experiments, offer exceptional material efficiency (Veenendaal and Block 2014). Focusing on these forms in pavilion-scale mock-ups allows researchers to explore and analyze the structural and material behaviors in a controlled environment.

However, realizing shell and vault structures at this scale often encounters a substantial challenge—the dependency on custom-fabricated falsework. Exceptionally, some vaulting techniques does not necessarily require falsework such as the Nubian vault which depends on a supporting wall from one side and a slanted angle for the brick courses. Other technique also is the self-supporting tile vaults when connected by gypsum or quick cement.

Falsework, a temporary structure used to support the construction of an arch or vault until it is self-supporting, plays a crucial role in achieving the desired geometries of these structures. Unfortunately, the production of such bespoke falsework poses significant challenges and acts as a hindrance to the feasibility of architectural shells, primarily due to its associated costs in terms of material, time, and labor.

The costliness of falsework extends beyond the monetary aspect, encompassing both physical and intellectual resources. The labor-intensive nature of fabricating custom falsework requires skilled craftsmanship, contributing to the overall expenses. Moreover, the intellectual investment in designing and engineering falsework tailored to unique geometries adds another layer of complexity, making the realization of these structures a resource-intensive undertaking.

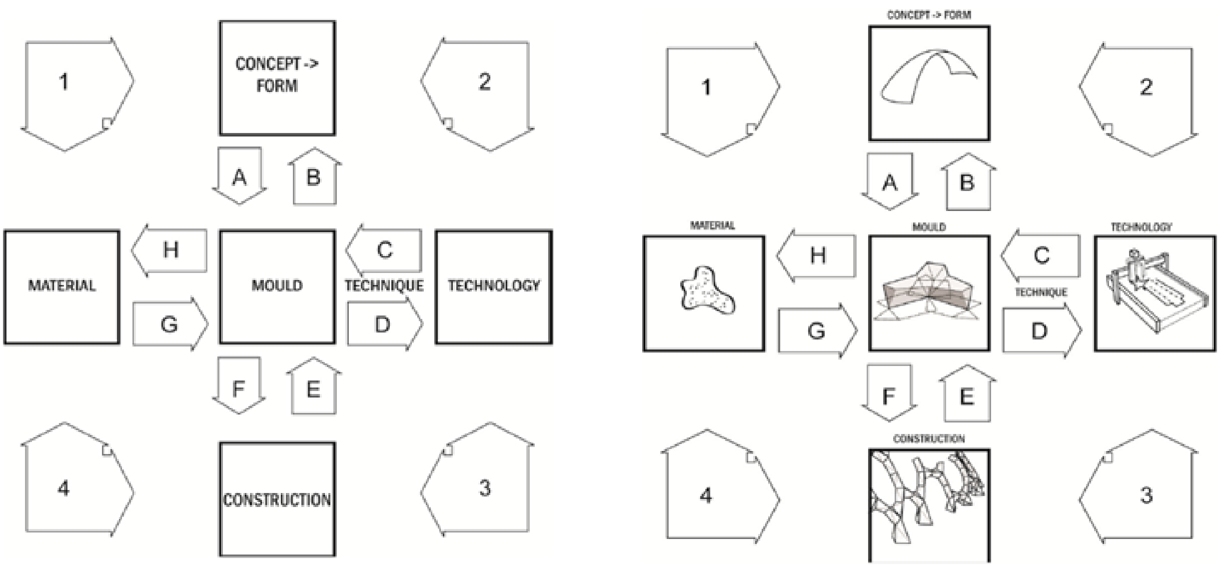
Despite the challenges posed by falsework, the investment in pavilion-scale mock-ups remains a valuable avenue for researchers. These scaled experiments provide an opportunity to refine design principles, optimize material usage, and overcome challenges associated with construction processes. The insights gained from pavilion-scale testing contribute to the advancement of knowledge in structural engineering and architecture, potentially paving the way for more feasible and sustainable approaches to the realization of shell and vault structures in future construction projects.

Tectonics Concept Integration

The concepts of ‹New Production Philosophy,› ‹Mass-customization,› and ‹Digital Tectonics› are essential terms to establish a framework for exploring their application in concrete production. Central to this investigation is the utilization of digital modeling and simulation as a dual-purpose tool for contemplating both geometry and manufacturing processes concurrently.

In order to achieve a holistic integration of tectonics, the theory of tectonics has to serve as a conceptual apparatus, guiding decisions in the development of the concrete casting method. Tectonics, in this context, is defined as the interplay between material, technique, and form (Christiansen 2015 ,1997).This understanding finds its roots in the theories of the German architect and theorist Gottfried Semper, who characterizes tectonics as the unity between idea, action, and construction, or more broadly, the amalgamation of means and ends (Frampton 1995; Semper 1851).

Figure 26_ A relational model that places the mould in the centre of a realisation process addressing complex shaped constructions (Larsen and Pedersen 2013)



To effectively investigate the intricate relationship between geometry and techniques associated with concrete casting, the study introduces the MTF-model. This model (Figure 26) incorporates construction and the mold, with a central emphasis on the mold as the element directly responsible for generating form. The MTF-model represents an extension built upon a series of prior investigations and physical experiments conducted as part of Ole Egholm Pedersen›s Ph.D. research, as documented in works such as Larsen and Pedersen in 2013, Larsen, Pedersen, and Pigram in 2012, and Pedersen and Larsen in 2015.

The inclusion of the mold as a central element in the MTF-model reflects its pivotal role in concrete casting processes. It highlights the interconnectedness of form generation, construction methods, and material behavior. By incorporating this comprehensive model, the study aims to provide a holistic framework for researchers and practitioners to understand and navigate the intricate landscape of digital tectonics and concrete production. This approach aligns with the broader exploration of innovative techniques and philosophies in construction, setting the stage for advancements in both theory and practice within the field.

3.1. CONCRETE TECTONICS

Concrete tectonics, a term that encompasses the structural and aesthetic exploration of concrete as a building material, represents a convergence of engineering principles and architectural design. At its core, concrete tectonics delves into the inherent qualities of concrete, harnessing its plasticity, compressive strength, and adaptability to create structures that are not only functional but also visually compelling. This approach emphasizes the expression of form, texture, and materiality, highlighting the intrinsic beauty of concrete in its raw state or as a finished surface. Concrete tectonics often involves innovative construction techniques, such as formwork manipulation, precasting, and post-tensioning, to push the boundaries of what is achievable with this versatile material. From iconic landmarks to contemporary architectural marvels, concrete tectonics continues to shape the built environment, offering endless possibilities for creative expression and structural innovation (Orr, Nicholas, and Tringali 2012).

3.1.1. Free-form Concrete Shells

This section discusses a significant study initiated by the PhD thesis of Ole Egholm Pedersen from Aarhus School of Architecture, outlined in Pedersen›s work in 2013 (Pedersen 2013). The study has evolved through subsequent trials and publications involving other co-authors, including Larsen and Pedersen in 2013, Larsen, Pedersen, and Pigram in 2012, and Pedersen and Larsen in 2015 (Larsen and Pedersen 2013; Larsen, Pedersen, and Pigram 2012; Pedersen and Larsen 2015). Together, they have developed a novel relational model that forms the methodological foundation of the research, providing a framework to identify crucial parameters governing geometrical consequences when altering materials or techniques.

The primary objective of this relational model is to discern possible connections between a conceptual idea, the chosen material (concrete), and the technique applied (involving a mold material subjected to a specific technology), all within the context of the final construction outcome. The arrows within the model serve to illustrate essential considerations when making decisions about which forms, materials, and techniques to employ. The model aids in navigating the intricate relationships between these elements, facilitating a systematic approach to the selection of construction methods.

The research presented in this section centers around three case studies that explore how these identified relations can unveil innovative approaches to casting concrete in complex shapes, aligning with the mode of production suggested by available technologies, as outlined in the work of Larsen and Pedersen in 2013 (Larsen and Pedersen 2013).

The methodological approach adopted in the study focuses on understanding the relations between material (concrete), mold geometry, and technology. The choice of laser cutting technology is significant due to its digital controllability, providing precision and flexibility in shaping the molds. Additionally, the decision to work with molds of complex geometry is driven by the inherent fluidity of concrete, allowing it to take on virtually any form. The method embraces folding as a logical means to generate three-dimensional forms from flat sheets, a process that can be parametrically controlled.

By leveraging these considerations and methodological choices, the study aims to push the boundaries of conventional concrete casting techniques. The exploration of the relationships between concept, material, and technique not only contributes to a deeper understanding of the interplay between these elements but also opens up new possibilities for creating intricate and complex concrete structures that align with the capabilities of contemporary technologies.

++ Module Fabrication

The mold material utilized in this method is PETG plastic, a member of the PET plastic family commonly used for containers like soda bottles. PETG stands out for its recyclability, as it can be easily melted down at °260C, evaporating only CO_2 and water in the process. From a cradle-to-cradle design perspective, PETG is considered a technical nutrient and should ideally remain in a closed recycling loop without degrading (McDonough and Baumgart, 2002). Thus, the casting principle employed in this project presents the opportunity for zero-waste production, as the plastic sheets used for molds can be melted and reused indefinitely.

Concrete, being a material that adopts the surface properties of its mold, yields a highly glossy surface when cast in plastic, resembling polished stone. To achieve the necessary crease angles for producing components suitable for this construction method, PETG sheet thicknesses of around 1mm are typically used. However, when exposed to fluid concrete material, PETG foil tends to undergo significant deformation. This challenge is addressed by reinforcing edges with folds, triangulating large areas, and limiting the area of planar surfaces. These measures contribute to the highly specific set of aesthetic characteristics associated with this method.

The production process involves setting up a production line with various stations for folding the PETG, riveting parts together, and adding features such as reinforcement. Each component undergoes meticulous assembly, ensuring that it meets the required specifications and structural integrity. Through this systematic approach, the method facilitates the efficient and precise production of concrete components with distinctive aesthetic qualities.

Overall, the utilization of PETG plastic as a mold material in this construction method not only enables sustainable and zero-waste production but also contributes to the creation of visually striking concrete elements with unique surface characteristics. The combination of recyclability, precision engineering, and aesthetic appeal makes this method a promising avenue for innovative construction practices.

Figure 27_ Prototype of Y-shaped concrete component and template of PETG plastic (Larsen, Pedersen, and Pigram 2012)

Similar module fabrication technique

The Concrete Tectonics Studio 2012, led by Associate Professor Kirsten Orr at the University of Technology, Sydney, was a research-based design studio comprising sixteen Master of Architecture students. This studio aimed to bridge the gap between analogical and digital realms of architectural research by exploring innovation in precast concrete through material experimentation and parametric design.

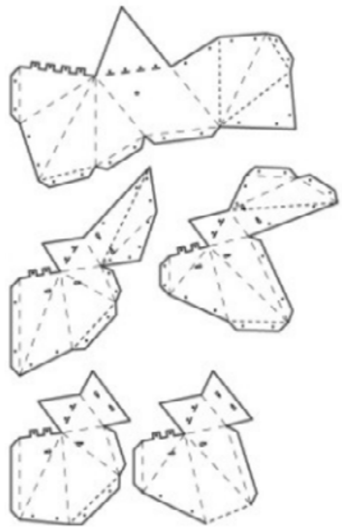


Figure 28_ Similar module fabrication technique(Orr, Nicholas, and Tringali 2012)

The studio›s approach involved an iterative process that transitioned from analogue methods to digital tools, culminating in an investigation of scale. Through multi-scalar prototype-based research, students delved into innovative fabrication techniques, pushing the boundaries of precast concrete in terms of scale complexities, dimensional tolerance, materiality, and mass-customization principles.

Practical and hands-on material testing and prototyping were integral components of the studio, supported by a parametric scripting tool developed by Supermanoeuvre. This dynamic process of oscillating between analogue and digital platforms allowed students to actively engage with the design process while grappling with the disparities between digital simulations and physical artifacts.

By dissecting the design process into various scales, the studio provides a comprehensive understanding of the complexities involved in working with precast concrete, from conceptualization to realization. This approach fosters a holistic exploration of architectural tectonics, encouraging students to push the boundaries of conventional design practices and embrace innovation in material and fabrication techniques. (Orr, Nicholas, and Tringali 2012)

Molds crafted from readily available materials like polypropylene balls, nylon and PETG pipe, plastic funnels, and plastic drinking cups were utilized in the fabrication process. Additionally, various shapes including pyramid, wedge, and egg crate were meticulously constructed using plywood, masonite, and foam. These diverse forms were chosen deliberately to explore the potential of each configuration in optimizing solar performance.

Through the utilization of KT-EWE, a specialized Grasshopper

script, a comprehensive solar analysis was conducted to evaluate the efficacy of each void configuration in harnessing direct solar radiation. The panels were subjected to rigorous testing in both south and west orientations to facilitate a thorough comparison. Panels exhibiting reduced direct solar radiation during summer months were identified as advantageous, indicating potential benefits in terms of thermal comfort and energy efficiency.
Furthermore, surface area calculations were performed to ascertain the panels› ability to dissipate accumulated heat, thereby enhancing their thermal performance during nighttime hours. This holistic approach aimed to identify panels capable of efficiently radiating or flushing out heat, thereby mitigating the urban heat island effect and improving occupant comfort.

Among the various patterns tested, the wedge and pyramid configurations emerged as particularly promising candidates warranting further investigation. Their lightweight nature, coupled with the potential thermal benefits observed, underscores their viability as sustainable design solutions for optimizing solar performance in architectural applications.

In conclusion, the meticulous exploration of diverse mold materials and panel configurations, coupled with comprehensive solar analysis, has yielded valuable insights into enhancing the thermal performance of architectural panels. These findings lay the groundwork for future research and development aimed at optimizing energy efficiency and occupant comfort in the built environment (KieranTimberlake 2012).

++ Holistic Structure Design

Trial 1 >>
'Worst-Case' Prototype Test

Given the slender nature of the elements utilized in this method, ensuring precise construction to match the computationally determined form is paramount to maintain load paths within the sectional profile. Additionally, as is customary in non-tile vaults, the structure lacks stability in an incomplete form, necessitating the use of formwork to position and support each component during assembly.

Similar to the precast components, each scaffolding element is custom-designed to accommodate the unique characteristics of the structure. The scaffolding, typically crafted from recyclable cardboard, is laser cut and assembled into triangular tubes, which are then clustered into larger formations resembling hexagonal geometries mirroring the plan of the concrete structure (Figure 29). Beyond providing support during construction, the scaffolding serves the critical role of ensuring precise positioning of components, as even minor deviations from spatial geometry can hinder assembly.

Before commencing production of the final construction, a ‹worst-case› test construction was conducted to identify constraints that would inform the final method. This prototype, based on a triangular mesh transformed through dynamic relaxation, served to unveil key insights into the structural behavior. Through Finite Element Analysis, it became evident that the initial design approach, which generated the hexagonal geometry from a triangular mesh, resulted

in deviations from the optimized shape larger than what component joints could accommodate. Consequently, the approach was revised to define the base geometry as hexagons, aligning more directly with the final structure.
The prototype test underscored the critical role of connections in ensuring structural integrity. Correct positioning of each element proved challenging without addressing shear forces between elements. These challenges highlights the risk of the assembled form deviating from computed load paths, rendering the construction susceptible to collapse due to inadequate tensile resistance at joints.

In essence, meticulous attention to detail in both construction methodology and structural analysis is essential to realize the envisioned form while ensuring stability and load-bearing capacity. The iterative process of prototyping, analysis, and refinement plays a crucial role in overcoming design challenges and ultimately achieving a successful outcome.

Figure 29_ First trial for free form concrete pavilion (Larsen, Pedersen, and Pigram 2012)

Trial 2 >>
PreVault Pavilion (2011)

PreVault was designed around the application of small-scale components with triangulated surfaces and a small casting height, in order to eliminate deformations due to the hydrostatic pressure of concrete. The case study was carried out at Aarhus School of Architecture in the fall of 2011 (Figure 30). Over the course of three weeks the authors, with the aid of Civil Engineers Jacob Christensen, and Ronni Madsen and 12 Master of Architecture students, designed and built a 16 square meter by 2 meter tall pavilion consisting of 110 discrete concrete elements, cast in PETG.

The final pavilion structure comprised 110 components, which were nested on sheets of PETG, laser cut, folded and reinforced. The PETG moulds were fixed to a blueprint, generated from the digital model, which enabled positioning of the ends of the three component arms with a tolerance of less than one millimetre. Flaps added to the ends dictated the angle of the component arms. A prototype test disclosed that precise falsework would be important to position the components correctly in the compressive arc. This falsework was generated directly from the spatial components model using Grasshopper, a generative modelling plugin for Rhinoceros, and laser cut from recyclable cardboard (Figure 30, bottom right) (Larsen, Pedersen, and Pigram 2012).

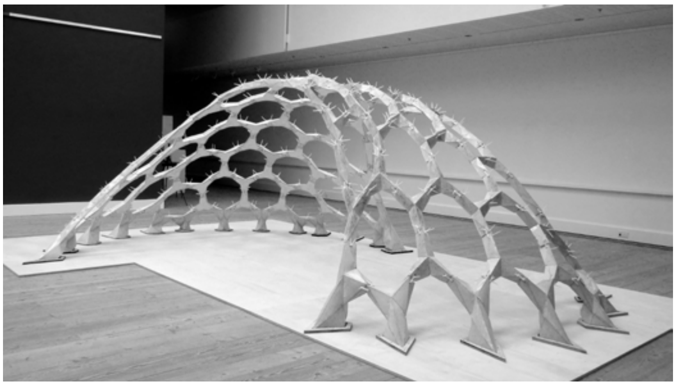


Figure 30_ Pre-Vault Pavilion and the extensive formwork needed (Larsen, Pedersen, and Pigram 2012) (Pedersen and Larsen 2015)

Trial 3 >>
PlayVault Pavilion (2012)

The PlayVault project, spearheaded by Ole Egholm Pedersen as a workshop at the Royal Academy of Fine Arts in Copenhagen, Denmark, engaged 40 students over a two-week period (Figure 31). This case study served a dual purpose: to assess the method›s applicability in an industrial production setting beyond the laboratory and to explore its potential in handling a more intricate overall form.

The workshop provided an invaluable learning experience for first-year students, allowing them to swiftly grasp the workflow of drawing a mesh, performing dynamic relaxations, and generating components. The efficient workflow facilitated the rapid proposal and evaluation of numerous designs, with Civil Engineer Jacob Christensen overseeing the process.

During the fabrication of the second prototype, an unexpected challenge arose as a faulty laser-cutter necessitated the manual drawing and cutting of the cardboard falsework. This introduced a level of imprecision and led to folding and mirroring errors that could have been avoided with digitally controlled cutting and marking. Consequently, the construction of the falsework became notably intricate.

The case study pavilions, constructed in a remarkably short timeframe and at a low cost, demonstrated that the integration of algorithmic form-finding techniques, CNC fabrication workflows, and innovative PETG folded mold techniques allows for the practical realization of complex, freeform geometry as precast concrete element structures.

Figure 31_ A complex grid shell structure made up of 190 discrete concrete elements (Larsen and Pedersen 2013)

While the PreVault case study achieved success in terms of precision and structural performance, the PlayVault case study highlighted the method›s capability to generate more complex forms. However, it also revealed the method›s sensitivity to imprecision, particularly when dealing with the accumulation of dimensional variances at scale.

In essence, the PlayVault case study showcased the practical application of the proposed method in an industrial context, emphasizing its flexibility in generating complex forms. It also underscored the importance of precision and highlighted the method›s sensitivity to imprecision and scale. This hands-on exploration provided valuable insights into the practical challenges and potential of the methodology, contributing to the ongoing refinement, and understanding of the approach.

Trial 4 >>

Discontinuous Post-Tensioning: External

The introduction of discontinuous post-tensioning marks a significant innovation, allowing tension to be distributed through the connections and expanding the formal possibilities of the system beyond compression-only funicular forms. This approach introduces a new dimension to the structural system, enhancing its versatility and potential applications.

The external post-tensioning concept is designed to connect all joints and component centers with steel cables running both above and below the construction. By attaching the cables outside the concrete, the cross-sectional integrity remains intact, and the details are easily accessible during assembly. The assembly procedure was meticulously planned to enable the assembly of six concrete parts with tightened wires before lifting them into place.

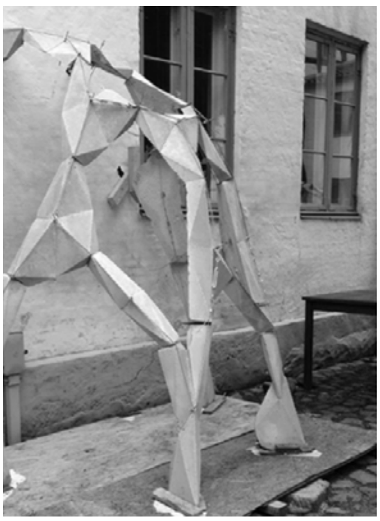


Figure 32_ Full-scale prototype assembly of external post-tension system (Beim and Madsen 2014; Pedersen and Larsen 2015)

As shown in Figure 32, this approach proved effective in assembling a full-scale prototype, showcasing the feasibility of the external post-tensioning system. Subsequently, two ends of a large structure were constructed without the need for falsework, although substantial support was still necessary. However, challenges arose during the process, particularly with the weight of the sections and difficulties in achieving uniform tensioning of the wires, especially in ensuring equal tension both at the top and bottom.

Despite the successful assembly of the prototype, it was concluded that the external tensioning system, as described, was not a viable solution for entirely avoiding the use of falsework in the construction process. The complexities associated with the weight of the sections and the challenges in achieving consistent tensioning posed practical limitations, highlighting the need for further refinement in the methodology.

In a personal interview with one of the study authors, Prof. Niels Martin Larsen, the professor indicated that the incompleteness of this external post-tensioning prototype was due to administerial issue not mainly structural failure from the conceptual point of view.

This exploration into discontinuous post-tensioning and the external tensioning concept demonstrates the innovative thinking behind the structural system. While it opens up new possibilities for formal expressions and construction techniques, the practical challenges encountered underscore the importance of continued research and development in the quest for efficient and reliable construction methodologies that push the boundaries of traditional approaches.

Trial 5 >>

Discontinuous Post-Tensioning: Internal | Utzon: 40 Pavilion (2013)

The Utzon:40 Pavilion, erected in Sydney to coincide with the Utzon Symposium at the Sydney Opera House in March 2014, stands as a testament to innovative construction methods. Designed with 62 discrete concrete elements and 130 timber pieces, the structure posed unique engineering challenges, particularly in counteracting thrust forces and ensuring structural integrity.

To address the thrust forces, a network of 20mm wide and 2mm thick aluminum bars was connected to the bottom of each base element. This network effectively distributed horizontal forces to the other bases, maintaining equilibrium within the system. Additionally, the aluminum network served as a set out mechanism, guiding the positioning of the base elements during assembly.

The construction process unfolded in three distinct steps. First, the aluminum tension floor was assembled. Second, the concrete elements were added, with particular attention given to forming trusses above the openings to ensure structural stability during construction. Notably, this step provided conclusive evidence of the method›s success in eliminating the need for falsework. Temporary propping was required at various stages, especially above openings, to support the cantilevering concrete elements.

The final step involved mounting the timber components, which distributed forces across the top of the structure. Although timber did not form an integral part of the method, its inclusion in this case study pavilion served to test the system›s ability to interface with other materials. The timber elements, created with precision using a high-end gantry -5axis CNC router, demonstrated the concrete components› accuracy, with assembly tolerances within +/- 5mm.

However, the case study also highlighted areas for improvement. The corners of concrete elements tended to be crushed due to their sharp edges and small dimensions. To address this issue, a chamfer of approximately 5mm needs to be added to the component design, enhancing durability and structural integrity.

Overall, the Utzon:40 Pavilion exemplifies the successful application of innovative construction methods, combining precast concrete elements with aluminum reinforcement and timber components. Through meticulous planning and execution, the project achieved structural stability, precision, and aesthetic appeal, setting a benchmark for future architectural endeavors.(Larsen and Pedersen 2013; Larsen, Pedersen, and Pigram 2012; Pedersen and Larsen 2015)

OTHER MATERIALS TECTONIC ADVANCEMENTS

Figure 33_Different similar experimentations that were performed by researchers in Aarhus School of Architecture (Larsen & Pedersen, 2013) | Utzon: 40 pavilion (supermanoeuvre)

3.1.2. CAP Fellow’s Experiment on Concrete Debuts at Architectural Mecca (2019)

The exploration of 3D printing in the realm of precast concrete by Battaglia represents a cutting-edge application of automation to a traditional building material. The overarching goal is to revolutionize precast concrete, making it more versatile, attractive, sophisticated, and efficient.

Traditionally, precast concrete products have been limited to basic and straightforward forms such as wall panels, blocks, pillars, and girders. The feasibility of creating complex forms was hindered by the practical and economic challenges associated with the substantial time, labor, and skill required, especially for one-off pieces. Battaglia›s project, however, defies these limitations by employing 3D printing technology to produce 110 unique concrete panels, each curving in two directions. The result is a structure that assembles like a giant three-dimensional puzzle.

++ Module Fabrication

Materials - Laticrete MD3 31-D Printable Mortar; Laser cut painted steel; Steel; EcoVantage Thermally Modified Ash Wood; Greensand Mix (Bentonite Clay, Medium Sand). The innovative use of 3D printing not only allows for intricate and custom designs but also addresses structural efficiency. The strategic placement of holes in the panels serves to allow natural light and air to permeate the structure. These openings, where concrete would have served minimal structural purpose, contribute to lighter

Figure 34_ Concrete pavillion of CAP fellows. Photo by Hadley Fruits

and more manageable panels, lower material costs, and a reduced carbon footprint. Additionally, the holes add an ornamental aspect to the structural form, enhancing the overall aesthetic (Werner 2020).

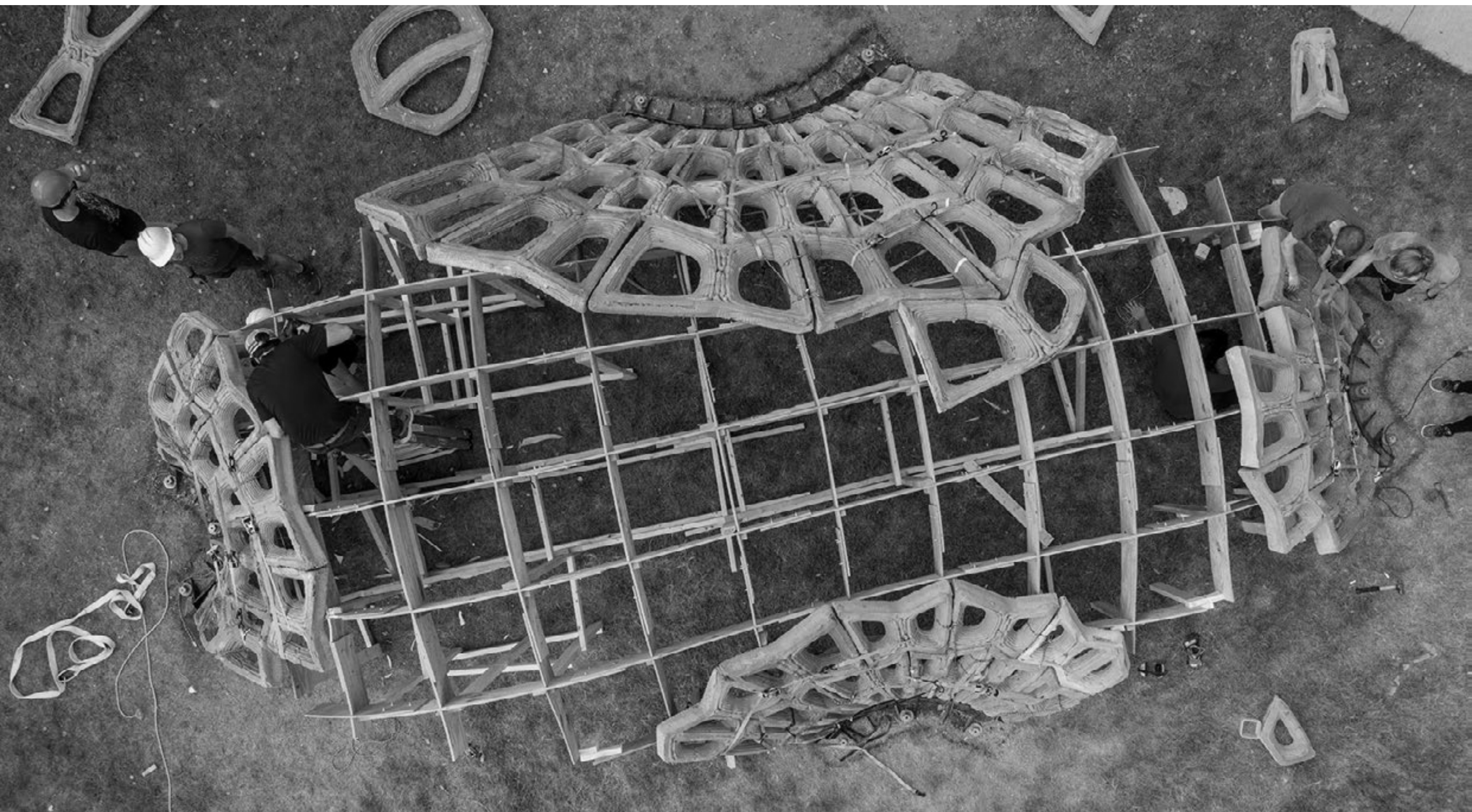
++ Holistic Structure Design

During the assembly process of «DE|stress,» the concrete panels were held in place by temporary wooden scaffolding. The wood supported the weight of the structure until the final keystone panel could be inserted, at which point the scaffolding was removed, relying on compression to maintain the structural integrity. However, challenges emerged during the assembly, with excess concrete interfering with the precision of joints. The need for on-site improvisation and adaptation to unexpected details highlighted the realities of translating a design from theory to practice.

Despite the challenges, Battaglia and his team, including graduate students and colleagues, overcame these issues with traditional methods, showcasing the resilience required in pioneering research. The project was completed in October, remaining on-site until December 1 for Exhibit Columbus. Afterward, «DE|stress» was disassembled and relocated to the headquarters of Laticrete in New Haven, Connecticut, a material sponsor for the project, where it is now on permanent display.

«DE|stress» stands as a testament to Battaglia›s conviction that automation technology can breathe new life into the built environment. This 3D-printed concrete shell exemplifies a sustainable, formally responsive, and flexible approach to construction, creating a vaulted space that invites community collaboration and activities while providing a visually stunning architectural piece framed by its arches. The collaborative design effort with Martin Miller of Cornell University further enriches the project›s depth and innovation (Werner 2020).

Figure 35_ Excessive formwork and different modules assembley. Photo by Hadley Fruits



3.2. BRICK TECTONICS

> *You say to brick, "What do you want, brick?" Brick says to you, "I like an arch." if you say to brick, "arches are expensive, and I can use a concrete lintel over an opening. What do you think of that, brick?" Brick says: "I like an arch." And it's important, you see, that you honor the material that you use. —Louis Kahn (Lesser 2017)*

Masonry stands as one of humanity›s most enduring building materials, with brick being the oldest manufactured product still in use today. However, its longstanding prominence faced significant challenges due to two pivotal events in history (Meiss 2013) (Kara, Selçuk, and Akan 2021):

Firstly, doubts arose regarding its structural capacity following the completion of the Monadnock Building in Chicago in 1891. This iconic skyscraper, constructed primarily of masonry, led to massive walls that its width can reach 2 meters.

Secondly, the devastating San Francisco earthquake of 1906 exposed the vulnerabilities of brick buildings in earthquake-prone regions. The widespread collapse and damage inflicted upon brick structures during the seismic event underscored the urgent need for structural reinforcement (Gu et al. 2014).

In response to these challenges, the construction industry introduced steel reinforcement to enhance masonry structures› ability to withstand shear and tensile stresses. The incorporation of steel elements provided much-needed stability and resilience, effectively addressing the structural shortcomings highlighted by both the Monadnock Building and the San Francisco earthquake.

These advancements in structural engineering marked a transformative moment for masonry construction, ushering in a new era of innovation and ensuring its continued relevance in modern architecture. By integrating steel reinforcement, masonry structures could now achieve greater heights and withstand the rigors of seismic activity, reaffirming their place as enduring symbols of strength and durability in the built environment (Trubiano, Dessi-Olive, and Gentry 2019).

Eladio Dieste: Innovation in Structural Art

The resistant virtues of structures that we make depend on their form: it is through their form that they are stable and not because of an awkward accumulation of materials. There is nothing more noble and elegant from an intellectual viewpoint than this, resistance through form. (Dieste 1996b).

Eladio Dieste made significant contributions to brick tectonics, particularly in the realm of roof structures. Through his innovative use of reinforced brickwork, Dieste pioneered new thin-shell structural typologies, revolutionizing traditional construction methods. One of his most notable achievements in this regard is the Church of Cristo Obrero y Nuestra Señora de Lourdes in Atlántida, Uruguay, designed and built between 1956 and 1960. This architectural marvel, later declared a UNESCO World Heritage Site in 2021, stands as a testament to Dieste›s visionary approach to engineering and design (Lammers 2019).

The Church of Cristo Obrero y Nuestra Señora de Lourdes represents the culmination of Eladio Dieste›s experimentation with reinforced brickwork, showcasing innovative thin-shell roof modules characterized by continuous gaussian vaults. These unique structural elements, along with the ruled surfaces adorning its lateral walls, demonstrate Dieste›s mastery of form and construction techniques. By marrying tradition with ingenuity, Dieste was able to achieve architectural feats previously thought impossible (R. F. Pedreschi 2015; Remo Pedreschi 2000)(Palma 2007)(R. Pedreschi and Theodossopoulos 2010).

Figure 36_ Cristo Obrero Church in Uruguay

The construction of the church was facilitated by the adaptation of traditional building practices to suit Dieste›s visionary designs. Mobile frameworks and other on-site innovations allowed for the realization of the continuous gaussian vaults, laying the groundwork for subsequent advancements in structural engineering. Notably, the continuous gaussian vaults pioneered by Dieste served as precursors to the discontinuous vaults that would later dominate architectural discourse. These discontinuous vaults, characterized by skylights interrupting the roof modules and enabling larger spans, represent a natural evolution of Dieste›s groundbreaking work. (Anderson 2004)

In essence, the Church of Cristo Obrero y Nuestra Señora de Lourdes stands as a testament to Eladio Dieste›s unparalleled contributions to brick tectonics and architectural innovation. Through his visionary designs and ingenious construction methods, Dieste reshaped the architectural landscape, leaving behind a legacy that continues to inspire architects and engineers to this day (Melachos et al. 2023).

Use of brick

Dieste was renowned for his ingenious use of brick as the primary structural material in his architectural endeavors. This choice was not arbitrary; rather, it stemmed from a profound understanding of the material›s inherent benefits, especially within the context of Uruguay›s landscape and resources.

Bricks, being indigenous to Uruguay and abundantly available, presented a compelling advantage over concrete. One of the key advantages lay in their lighter weight compared to concrete, resulting in the need for less reinforcement and formwork in structures. This characteristic not only streamlined construction processes but also contributed to cost efficiency.

Moreover, the unique properties of bricks, particularly in the context of vault construction, offered significant advantages. In a brick vault, a remarkable %90-80 of the material is already hardened, facilitating swift structural stability. Additionally, the hygroscopic nature of bricks naturally draws moisture from the mortar, hastening the stiffening of the vault. Consequently, formwork could be removed earlier compared to traditional concrete structures, expediting the overall construction timeline.

Furthermore, brickwork inherently requires less cement than concrete, aligning with principles of sustainability and resource optimization. This not only reduced environmental impact but also enhanced the economic feasibility of Dieste›s projects.

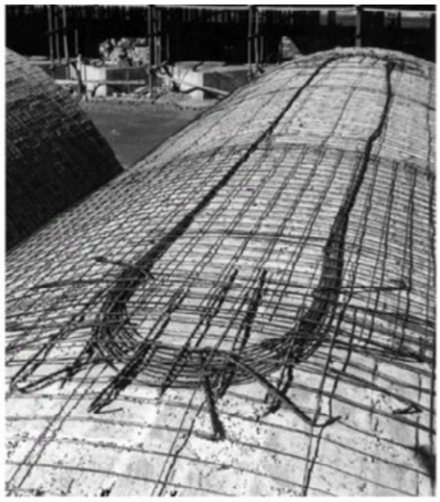
Another noteworthy aspect of Dieste›s approach was his utilization of various types of bricks, tailored to the specific requirements of each structure. From solid handmade bricks to hollow clay pots, Dieste demonstrated a nuanced understanding of material properties and structural needs, ensuring optimal performance and aesthetic appeal in his designs.

In essence, Dieste›s mastery of brick as a structural medium exemplified a harmonious integration of tradition, innovation, and environmental consciousness in architecture. His legacy continues to inspire architects and engineers worldwide, emphasizing the timeless relevance of thoughtful material selection and meticulous craftsmanship in shaping the built environment. (Remo Pedreschi 2000)

Prestressing in Dieste’s Work

Dieste y Montañez, under the leadership of Eladio Dieste, left an indelible mark on South American architecture, having constructed over 1.5 million square meters of buildings across Uruguay region. Among their notable contributions were the numerous thin brick vaults, predominantly in single or double curvature, integrated into a variety of structures including warehouses, factories, gymnasiums, and workshops. One particular innovation that stands out is the Free-standing Barrel Vault, a testament to Dieste›s commitment to both economic efficiency and architectural expression.

These distinctive vaults, born out of the necessity for cost-effective industrial construction, exemplify Dieste›s ingenuity in design and construction techniques. The evolution of these vaults, intricately intertwined with Dieste›s inventive approach, is characterized by innovative construction methods such as looped pre-stressing. This technique, pioneered by Dieste, not only enhanced the structural efficiency of the vaults but also accentuated their aesthetic appeal.



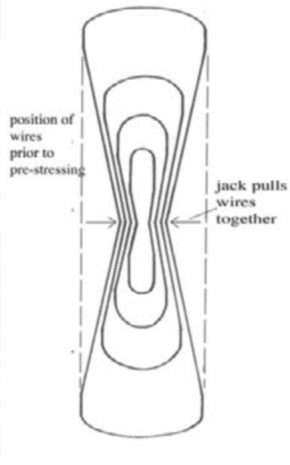


Figure 37_ Cristo Obrero Church roof layers prestressed (Warmburg 2017)

Figure 38_Loops of prestressing steel in the church roof (R. F. Pedreschi 2015)

The Free-standing Barrel Vault, along with its counterpart the Gaussian vault, capitalized on surface form optimization, with the directrix defined by the geometry of the catenary. To minimize thickness while achieving large spans, Dieste employed advanced pre-stressing techniques to counteract tensile stresses induced by bending. In the case of a double cantilever vault, for instance, primary bending action creates a hogging moment over central columns (Dieste 2007).

Dieste›s method of pre-stressing, utilizing welded loops of steel anchored along the crown of the vault, epitomized simplicity and effectiveness. The process involved pinching the wires together at midpoints, stretching them into configurations to pre-compress the vault (figure 38 ,37). The desired pre-stress level was achieved by adjusting the length of loops and the distance between their long sides. Once tensioned, metal clamps secured the wires in place, after which a thin concrete screed covered them (R. F. Pedreschi 2015; Remo Pedreschi 2000).

This straightforward pre-stressing technique offered several advantages, including the even distribution of prestress force at anchorage points, containment of prestress within the vault›s topping thickness, and the use of a simple jack for tensioning, without the need for complex hydraulic systems. Such innovations not only exemplified Dieste›s mastery of structural engineering but also underscored his commitment to practical, efficient, and elegant solutions in architectural design.

Figure 39_ Manzanet Memorial Pantheon (Vegas and Mileto 2016)

3.2.1. Family Soriano – Manzanet Memorial Pantheon (2014)

The mausoleum of the Soriano Manzanet family in Villareal, Castellón province, Spain, serves as a multi-layered narrative, intertwining the legacies of José Soriano, the visionary founder of Porcelanosa; Rafael Guastavino, the pioneering architect who popularized the tumbrel vault technique in the United States; and the collaborative efforts of family members, architects, and craftsmen who brought the mausoleum to life.

In 1956, at just 25 years old, José Soriano established Porcelanosa, propelling it to become a global leader in ceramic tile manufacturing. Following his tragic passing in a car accident in 2000, the family honored his memory with the creation of this mausoleum in the Villareal cemetery. In commemorating Soriano, they also pay homage to Rafael Guastavino, whose introduction of the tumbrel vault to America elevated Valencian and Mediterranean building techniques to international acclaim.

The impressive vault, a collaborative masterpiece envisioned by architects Fernando Vegas and Camilla Mileto and brought to life by Salvador Gomis under the careful supervision of Salvador Tomas, stands as a testament to both the rich heritage of ceramic craftsmanship in the region and the ingenious tile vault technique prevalent in Eastern Spain›s history. Inspired by the legacy of Valencian architect Rafael Guastavino, whose influence resonated among Modernist luminaries like Gaudi and extended across the Atlantic to become synonymous with innovative construction in the United States, this vault embodies a fusion of tradition and innovation.

The architects entrusted with realizing the family›s vision, Camilla Mileto and Fernando Vegas, possess an intimate understanding of Guastavino›s work, having extensively studied his contributions. Through collaborative dialogue among the clients, architects, craftsmen, and builders, a shared vision emerged, culminating in the manifestation of a collective endeavor.

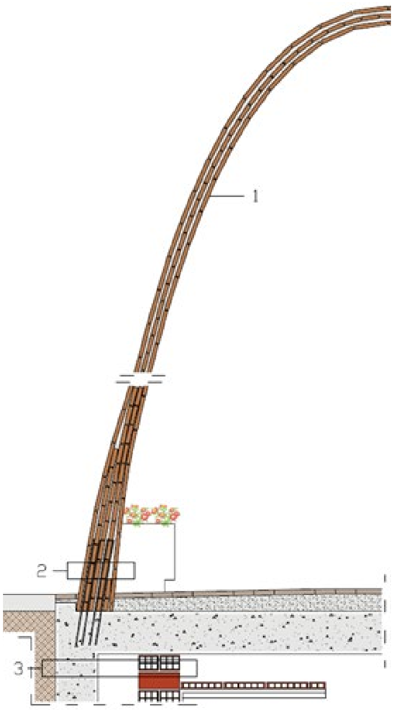
Designed to reflect José Soriano›s persona – sociable, honest, open-minded, and humble – the mausoleum embodies warmth and accessibility. Its design, characterized by clean lines and unadorned simplicity, mirrors Soriano›s integrity and modesty. The portico, featuring a single vault composed of interlinked hyperbolic paraboloids crafted from layers of terracotta tiles, exudes fluidity and grace, concealing the meticulous craftsmanship and attention to detail required for its construction.

Figure 40_ Section detail showing construction method (Mileto and Vegas 2016c)

++ Module Fabrication

Handcrafted ceramic tiles, meticulously produced with input from the architects and family, adorn the structure, while local artisans skilled in the traditional tumbrel vault technique brought the design to fruition without the need for formwork. The materials, including terracotta, gypsum, and white cement, were selected for their quality and durability. Fiberglass rods were integrated only in the connection between the foundation and the springing of the vault, not in the whole structure for seismic resilience.

The mausoleum›s interior, adorned with cenia stone floor tiles and ceramic embellishments by acclaimed ceramist Enric Mestre, offers a serene sanctuary for reflection. Beneath the surface lies a crypt lined with Porcelanosa tiles, symbolizing continuity and preservation of Soriano›s legacy.



Through explicit references to Guastavino and the region›s rich building traditions, as well as the utilization of local craftsmanship and materials, the mausoleum celebrates a profound connection to Valencia›s heritage. This deep-rooted love and pride in one›s homeland, shared by Guastavino and Soriano, facilitated the dissemination of their respective legacies, enriching the global architectural landscape with the timeless beauty and craftsmanship of their native land.

Nearly 20,000 artisanal ceramic tiles, meticulously tested for clay composition, texture, durability, and aging properties, were employed in construction. Each tile was carefully calibrated in size and thickness to conform to the graceful contours of the vault, while three ceramic layers were strategically positioned to counteract wind suction effects. The vault›s composition, comprising four interlinked hyperbolic paraboloids, not only achieves remarkable lightness but also boasts exceptional resilience, obviating the need for conventional formwork and relying solely on metal guides to maintain precise curvature (Mileto et al. 2018)(Vegas and Mileto 2016)(Vegas and Mileto 2016).

Moreover, beyond its structural ingenuity, the vault serves as a beacon of sustainability and environmental consciousness in construction practices. By employing locally-sourced materials and traditional craftsmanship techniques, it reduces the carbon footprint associated with transportation and manufacturing processes. Additionally, the minimal use of reinforced concrete only in the underground, not only conserves resources but also mitigates the environmental impact associated with its production, a process notorious for its high energy consumption and greenhouse gas emissions.

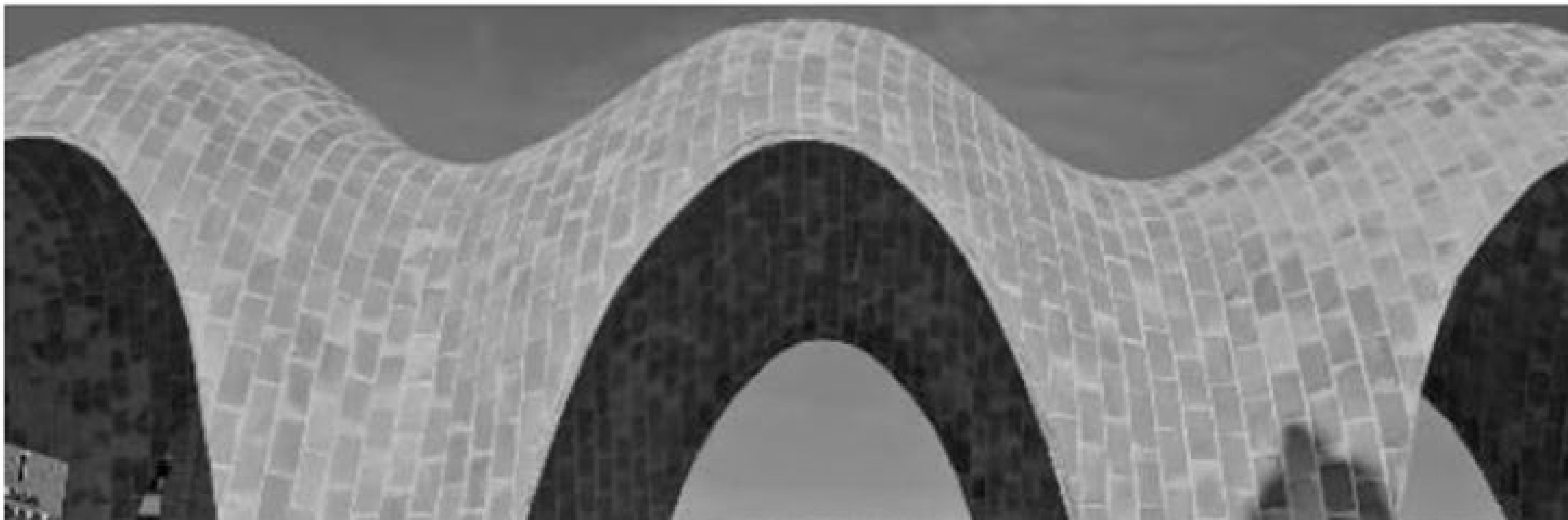
The vault›s cultural significance extends beyond its technical achievements, serving as a symbol of cultural preservation and architectural innovation. By revitalizing traditional building techniques and paying homage to the region›s ceramic heritage, it not only enriches the architectural landscape but also fosters a deeper appreciation for local craftsmanship and cultural identity.

Figure 41_ Close-ups from the Manzanet Memorial Pantheon by Vicente A. Jiménez (Mileto and Vegas 2016a)









++ Holistic Structure Design

Crafted with meticulous attention to detail, the pantheon›s design underwent an iterative process, with specialized 3D software utilized to refine its aesthetic and structural integrity through 23 consecutive variations. The intricate curves adorning the vault were meticulously crafted using catenary profiles, representing a mathematical and graphical challenge in achieving optimal structural performance.

Innovatively, the entire structure, devoid of reinforced concrete, was constructed using only brick, plaster, and white cement, with meticulous planning ensuring minimal wastage and a seamless integration of materials. Despite its lightweight nature, the vault is engineered to withstand seismic forces, with fiberglass rods strategically integrated to absorb shear stresses at key points.

Remarkably, the total weight of the vault stands at a mere 12.5 tonnes, a fraction of the mass typically associated with conventional brick and concrete constructions of similar volume, which could weigh upwards of 190 to 250 tonnes. These figures underscore not only the substantial savings in energy and materials but also the inherent adaptability and efficiency of the tile vault technique compared to traditional building methods.

In essence, the mausoleum of the Soriano Manzanet family is more than a mere structure; it is a testament to the enduring power of architecture to transcend time and space, weaving together the stories of individuals, communities, and cultures. As visitors pass through its vaulted portico and explore its intricacies, they are invited to contemplate not

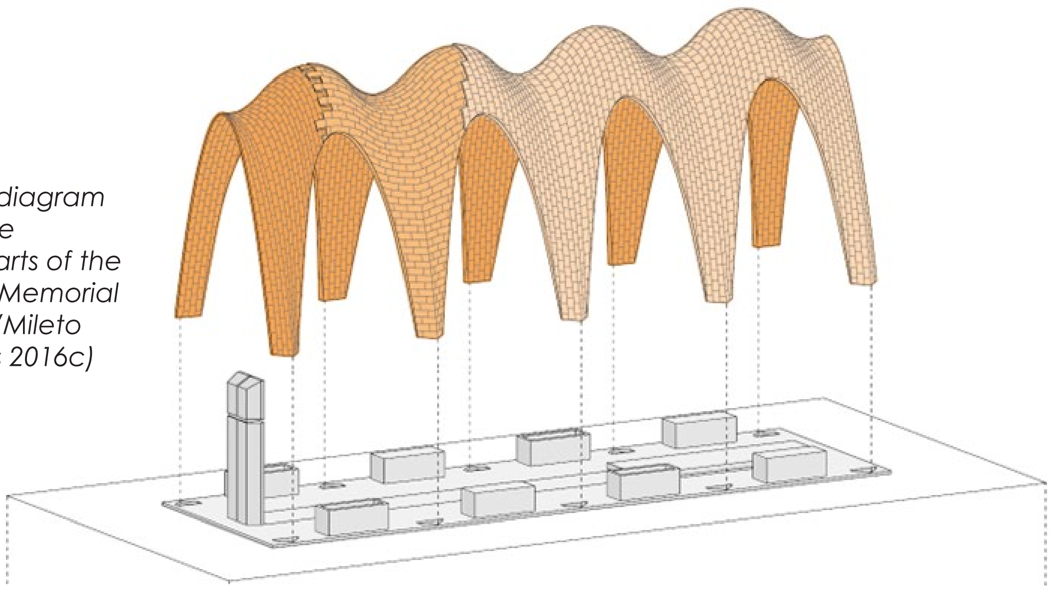


Figure 42_ diagram showing the different parts of the Manzanet Memorial Pantheon (Mileto and Vegas 2016c)

only the life of José Soriano but also the timeless beauty and resilience of the human spirit. In doing so, they become part of a larger narrative—one that celebrates the power of creativity, collaboration, and commemoration to shape our shared human experience (Mileto and Vegas 2016c).

This experimentation was repeated by Block Research Group (BRG) at ETH Zurich and a multidisciplinary team assembled by the Norman Foster Foundation, with support from the LafargeHolcim Foundation for Sustainable Construction. Together, they constructed a full-scale earthen masonry shell at the 15th International Architecture Exhibition «La Biennale di Venezia,» under the curatorship of Alejandro Aravena: «Droneport» concept. (Philippe Block et al. 2010) (Lammers 2019) (Philippe Block et al. 2010)(Maniatidis and Walker 2003)(P Block and Rippmann 2013; Michael H. Ramage, John Ochsendorf, Peter Rich, James K. Bellamy 2010) (Michael H. Ramage, John Ochsendorf, Peter Rich, James K. Bellamy 2010)

3.2.2 Armadillo Vault, Venice, Italy, 2016

The Armadillo Vault took center stage as the focal point of the «Beyond Bending» exhibition during the 15th International Architecture Exhibition - La Biennale di Venezia, curated by Alejandro Aravena. Held in Venice, Italy, from May 28 to November 2016 ,27, this groundbreaking exhibition showcased innovative architectural designs that pushed the boundaries of traditional construction methods. Amidst a backdrop of artistic ingenuity and visionary concepts, the Armadillo Vault stood as a testament to the possibilities of architectural innovation and structural daring.

++ Module Fabrication

Constructed from 399 individually cut limestone pieces, the Armadillo Vault is a remarkable feat of engineering, boasting a span of 16 meters with a minimum thickness of merely 5 cm. Notably, this awe-inspiring structure is assembled without the use of mortar, relying solely on the precise interlocking of its constituent elements to achieve structural integrity.

++ Holistic Structure Design

With its unique funicular geometry, the structure of the discrete shell stands resiliently in pure compression, while tension ties effectively balance the form, ensuring structural equilibrium. Rooted in the same foundational principles that guided the construction of historic stone cathedrals, this intricate form is a testament to the fusion of tradition with cutting-edge computational design and optimization methodologies pioneered by the project team.

The engineering behind the discrete shell involved pioneering computational approaches to evaluate stability under diverse load conditions. Each stone voussoir embodies a careful balance of structural integrity, precise fabrication requirements, and adherence to the constraints imposed by its historically protected environment. Additionally, considerations such as time, budget, and construction limitations played a pivotal role in shaping the design process.

Figure 43_ Freen form stone vault in Venice Biennale 2016 (Philippe Block et al. 2018)

To streamline fabrication and assembly, the voussoirs are meticulously crafted to exhibit planar exteriors, eliminating the need for complex flipping during machining. The interior surfaces, characterized by doubly curved geometry, are achieved through a process of rough cutting. Rather than conventional milling techniques, excess material is expertly hammered off, resulting in distinctive grooves that serve as an expressive feature of the finished structure. This approach not only enhances the aesthetic appeal but also underscores the meticulous craftsmanship and innovative spirit inherent in the project.

The distinctive appearance of the shell, characterized by its scale-like texture on the exterior and softly curving surface on the interior, serves as a tangible manifestation of the project›s inherent constraints. Remarkably, the structure stands without the need for reinforcement, achieving a proportional thinness akin to that of an eggshell. This expressive interplay of form challenges conventional notions, demonstrating that complex, freeform geometry can be realized without sacrificing efficiency or resorting to excessive material usage. In essence, the Armadillo Vault embodies a harmonious fusion of structural innovation and aesthetic elegance, showcasing the transformative potential of visionary architectural design (Calvo Barentin et al. 2016)(P. Block et al. 2016)(Van Mele et al. 2016)(Philippe Block et al. 2016)(Philippe Block et al. 2018).

3.2.3. Basuna Mosque dome by Waleed Arafa[1]

"Bridging the gap between labor experience and what you want through a solution you provide" Waleed Arafa (Abdrabou 2020)

Situated in the sweltering and arid village of Basuna, Sohag, Egypt, the Basuna Mosque occupies a site surrounded by a cacophony of noise, dust, and densely packed structures. Encroaching residential buildings, a bustling cemetery, and the constant movement of cattle along the nearby road add to the bustling atmosphere, compounded by a weekly makeshift market right outside the mosque›s main entrance. In the face of these challenges, the design of the new building must prioritize providing a sanctuary of peace and tranquility for its users. To achieve this, several key requirements had to be carefully addressed.

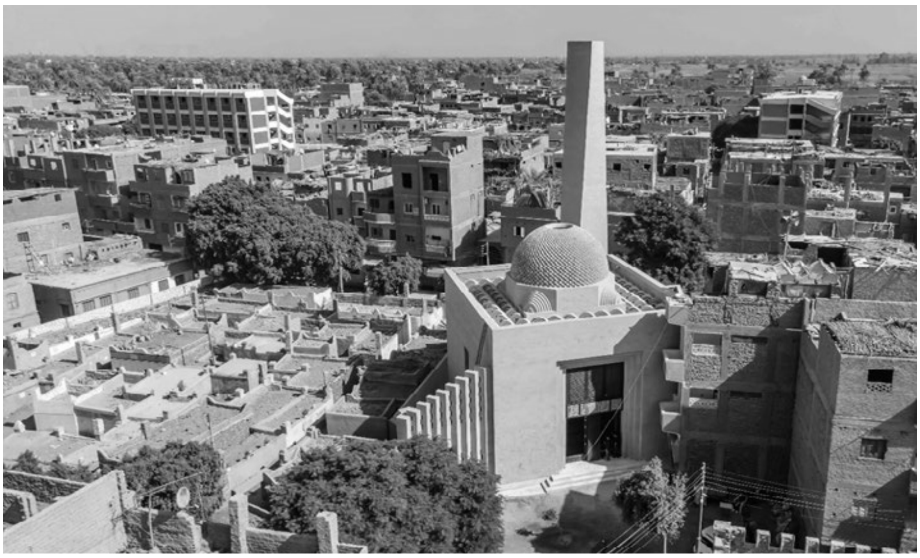


Figure 44_ Arieal View for Basuna Mosque (Dar Arafa)

1 https://www.dararafa.com/project/1

++ Module Fabrication

The main dome of the Basuna Mosque showcases innovative construction techniques, utilizing Egyptian-made light blocks composed of sand, lime, and air. With a density of just 0.5 ton/m3, these blocks offer exceptional thermal conductivity ranging from 0.136 to 0.132 W/m2.°K and boast a fire rating of 7-4 hours relative to thickness. Additionally, they provide sound insulation capabilities ranging from 37 to 48 dB. The remarkable lightness of these blocks not only reduces the building›s overall weight but also allows for smaller dimensions of reinforced concrete elements throughout the structure (Abdrabou 2020).

Measuring 100x200x600 mm, the dimensions of these blocks are ideally suited for implementing an original aesthetic vision that complements the conceptual scheme of the mosque. Through meticulous planning and execution, a special cutting list and a simple staggered tessellation pattern were employed to achieve a visually striking effect. To ensure precise spatial positioning of each block, regardless of the mason›s skills or accuracy, a special steel compass was devised. This innovative tool guaranteed the exact placement of every single block, contributing to the architectural integrity and cohesive design of the mosque›s main dome.


Figure 45_ Basuna Mosque Dome and its construction process (by Essam Arafa)

++ Holistic Structure Design

Waleed Arafa meticulously devised a cutting list for each concentric circle of the Basuna Mosque›s dome, recognizing the necessity for precise sizing of every block, even with slight variations of a few millimeters. Originally measuring 201060cm, each block was uniformly cut by masons to dimensions of 201038cm. As the circles decrease in diameter vertically, one dimension of the blocks is gradually reduced from 20cm on the outermost circle to 5cm on the innermost circle. This strategic dimensioning ensures a seamless fit within the dome›s evolving curvature, with the 38cm depth allowing for both interior and exterior protrusion, adding to the architectural intricacy.

Furthermore, Arafa ingeniously devised a steel compass to calculate the tilt of the blocks within each circle, precisely detecting their X, Y, and Z axes. This innovative tool facilitated the orientation of the blocks, ensuring optimal positioning and alignment throughout the dome›s construction process.

In the construction of the Basuna Mosque, careful consideration was given not only to architectural design but also to industrial processes and material selection. The sand blocks utilized in the mosque, sourced exclusively from «Delta Sand Bricks,» a prominent Egyptian company, are composed of sand, lime, water, sponging agent (such as powder aluminum), and a small proportion of cement. This unique composition results in lightweight blocks that significantly impact both the structural integrity and environmental sustainability of the building (Abdrabou 2020).

Chapter Conclusion

Different contemporary building materials have encountered technological advancements specially the contemporary building materials such as concrete and bricks. Shell structures as a compression only structures and highly experimented in pavilion medium scale prototypes by various research groups.

The displayed projects in this chapter are analyzed by the module design and the holistic structure design. As the M-F-T tectonic concept is applied, the module design focuses on the individual components or units that make up the overall structure. It is affected and affects the module own tectonics. This modular approach allows for flexibility in design and construction, as well as easier assembly and disassembly of components.

Meanwhile, the holistic structure design considers the entire system as a unified whole, taking into account factors such as load distribution, stability, and overall aesthetic coherence. In this approach, the interaction between different components and their integration into the overall structure is crucial for achieving structural integrity and architectural harmony.

The application of the M-F-T (Material-Form-Technique) tectonic concept further enhances the integration of module design and holistic structure design. It emphasizes the synergistic relationship between the material properties, the form or shape of the structure, and the construction techniques used. By considering these three elements together, architects and engineers can optimize the performance and efficiency of the building material while achieving innovative and visually striking designs.

Figure 46_ Concrete and brick advancement practices relation to tectonics (by author)

In the context of shell structures, which rely on the inherent strength of their curved or domed shapes to distribute loads in compression, the M-F-T concept can lead to groundbreaking advancements. By carefully selecting materials with the right structural properties, shaping them into optimized forms, and employing advanced construction techniques, researchers and designers can push the boundaries of what is possible in terms of structural efficiency, sustainability, and aesthetic expression.

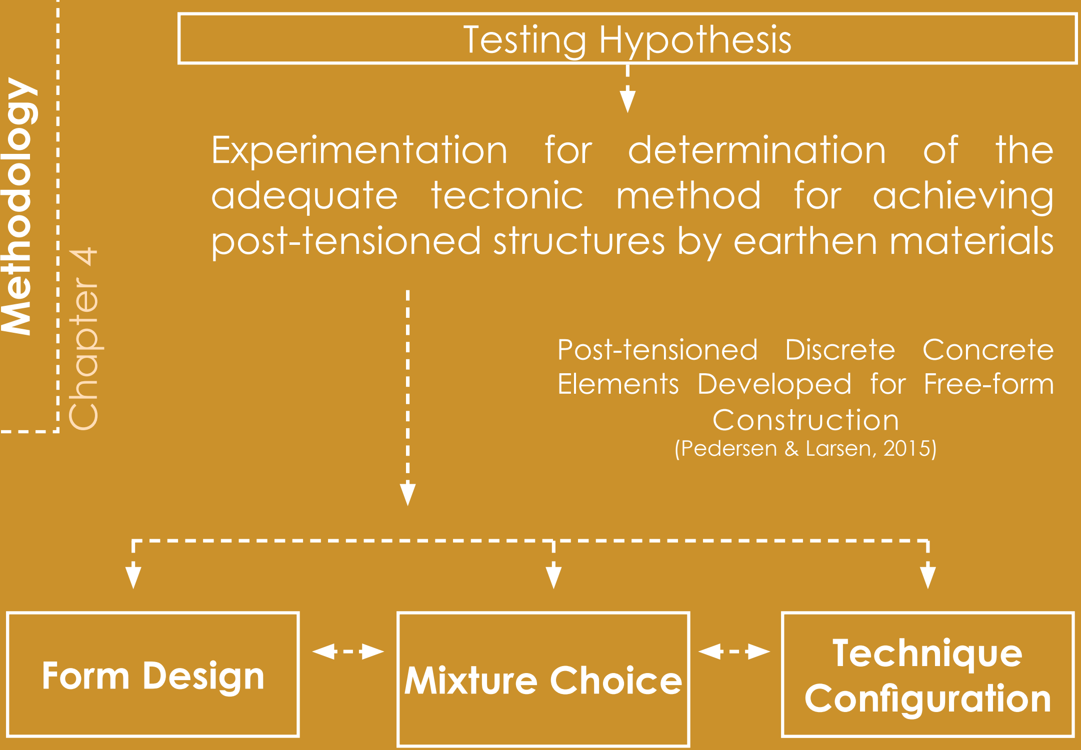
The pavilion-scale prototypes mentioned in the chapter serve as experimental prototypes for exploring these ideas in practice. Through iterative design, analysis, and construction processes, researchers can refine their understanding of how to best apply the M-F-T concept to create shell structures that are not only structurally sound but also beautiful, adaptable, and environmentally responsible.

Overall, the integration of module design, holistic structure design, and the M-F-T tectonic concept offers a powerful framework for advancing the state of the art in contemporary building materials and architectural engineering. By embracing innovation and interdisciplinary collaboration, designers can continue to push the boundaries of what is possible in architecture and construction, creating structures that are both functional and inspiring.

Methodology

Chapter 4

This chapter discusses the methodology design and data collection methods.



Part 2
EXPERIMENTATION

Chapter 04

EXPERIMENTATION METHODOLOGY

"As the complexity of the building industry continues to grow, the question of the relationship between architecture and engineering is increasing in relevance"
-Tectonics in Architecture book

04 EXPERIMENTATION METHODOLOGY

According to the previously discussed research problem, objectives and literature, this chapter outlines the choice of research methodology from the different commonly used research design methods. This depends mainly on the research aim and objectives.

4.1. Research Type

There are many different types of research, according to its application, objectives, and strategies. This research type is applied research that is designed to solve practical problems of the real world, rather than to exclusively acquire knowledge. It involves the use of some technology in the development of new processes or systems, and it is connected to development (R&D).

It is described as original work undertaken primarily to acquire new knowledge with a specific application in view. It is undertaken either to determine possible uses for the findings of basic research or to determine new ways of achieving some specific and predetermined objectives.

The research is exploring applying new technologies to the earthen materials for developing new tectonics and structural systems that have never been used by this material. It is also very connected to developing the current building industry from both perspectives; sustainable and technical. Besides, it also solves the presence false social perceptions and technical restrictions in the material appearance, application, and form. From another perspective, the research is trying to apply structures that have been tested on other materials to the earth material.

Certainly, the research at hand not only serves as an exploratory endeavor but also delves into uncharted territory within the realm of shell structures constructed using earthen materials. This study is driven by the overarching goal of venturing into novel avenues and pushing the boundaries of conventional knowledge. The specific objective revolves around investigating the viability and potential applications of earthen materials in the creation of shell structures, an area that has been relatively unexplored or has seen limited experimentation.

In essence, the research seeks to unravel the untapped potential inherent in the fusion of shell structures and earthen materials, presenting an opportunity to contribute groundbreaking insights to the existing body of knowledge. By venturing into uncharted domains, the study aims to shed light on the practicality, structural integrity, and aesthetic possibilities that may arise from this innovative amalgamation. The scarcity of prior research in this domain emphasizes the novelty and significance of the current exploration, positioning it as a pioneering effort within the broader landscape of architectural and construction research.

As the research unfolds, it is expected to offer a comprehensive understanding of the challenges and opportunities associated with utilizing earthen materials in the construction of shell structures. By addressing gaps in current knowledge and testing unexplored materials, this exploration holds the promise of not only expanding the theoretical framework but also contributing valuable insights that may have practical implications for sustainable and innovative construction practices. In essence, this research endeavors to transform a relatively obscure niche into a well-informed and potentially transformative area of study within the field of architecture and construction.

4.2. Methodology Design

This innovative research methodology follows an experimental approach that pushes the boundaries within the realm of earthen materials. The central objective of the experiment is to construct an external post-tensioned shell structure using these unconventional materials, presenting a novel application of established construction techniques.

Building upon the foundation laid by preceding chapters, the research delves into various aspects, including earthen material techniques, tectonics, and upgrading practices. By exploring the recent advancements in tectonics seen in traditional materials such as concrete and bricks, the study aims to bridge the gap between conventional construction methods and the unique challenges posed by earthen materials.

The methodology is particularly significant as it adapts the post-tensioning structure system, a technique previously employed in the realm of concrete construction. This time, however, the focus is on the distinctive properties and characteristics of earthen materials. By experimenting with the application of post-tensioning to earth-based structures, the research not only pushes the boundaries of structural engineering but also contributes valuable insights that could potentially revolutionize sustainable and eco-friendly construction practices.

The methodology employed interdisciplinary aspects draws upon various fields, including structural engineering, architecture, and craftsmanship, to explore the sustainable utilization and enhancement of traditional earthen and even wooden construction techniques. By integrating insights from these diverse disciplines, the research aims to develop innovative approaches that not only strengthen the structural integrity of buildings but also enhance their aesthetic appeal, form, and cultural significance.

• Structural Engineering for Material Strength

Structural engineering principles are leveraged to analyze the mechanical properties and strength characteristics of earthen and wooden materials. This involves conducting laboratory tests, such as compression and tensile tests, to assess material behavior under different loading conditions.

• Architecture for Form, Aesthetics, and Proportion:

Architectural design principles guide the exploration of form, space, and proportion in the context of sustainable construction. This involves studying vernacular architecture and indigenous building traditions to extract design elements that can be adapted to contemporary contexts.

Digital fabrication technologies are employed to generate innovative architectural solutions that integrate cultural heritage with modern design sensibilities. This includes the development of customizable models for earthen mock-up, allowing for variations in form and aesthetics.

• Craftsmanship for Employing and Upgrading Traditional Techniques:

Craftsmanship plays a central role in the implementation of traditional construction techniques, requiring a deep understanding of material properties and construction methods. This involves hands-on experimentaion and skill development.

Traditional building techniques are revitalized and upgraded through the integration of modern tools and technologies. This includes the development of innovative construction methods. This fosters a holistic approach to sustainable construction, where traditional wisdom is combined with contemporary expertise to create resilient and culturally sensitive built environments.

By embracing an interdisciplinary methodology that combines structural engineering, architecture, and craftsmanship, this thesis aims to contribute to the advancement of sustainable construction practices while preserving and celebrating the rich cultural heritage embodied in traditional earthen. Through collaborative research and innovation, it seeks to address the complex challenges facing the built environment and promote a more inclusive and environmentally responsible approach to building design and construction.

Title of the experiment

Determination of the adequate tectonic method for achieving post-tensioned structures by earthen materials.

4.3. Classification, and Description of the Experiment

The focus of the experimentation process shifts to the meticulous detailing and execution of mock-ups. This phase is crucial as it bridges the gap between theoretical concepts and practical application, aiming to validate the feasibility of the proposed tectonic approach. To design an experimentation that truly achieves the inclusive meaning of tectonics, it has to address the interrelated connection between the element: material, technique and form.

In the case of testing a specific material, which is earth, to achieve a certain form, that was previously tested by concrete, the technique is then the most important variable. To achieve a cohesive integration of material, technique, and form, the detailing process involves enhancing the precision of the 3D model derived from Rhinoceroses for the whole dome to be able to get the exact measurements of the intended earthen element. This includes fine-tuning the design to accommodate the intricacies of the chosen fabrication materials and techniques. The detailing phase also considers factors such as structural integrity, surface finish, and overall aesthetic coherence.

However, the fabrication technique is directly influenced with the mold tectonics which has again the material, technique and form of the mold. Therefore, the experimentation is designed to tackle those variables in three phases of experimentation respectively: **mold experimentation, earth mixture definition and detailing for mock-ups execution.** In this phase, the attention is directed towards refining the fabrication techniques based on the insights gained from the mold and mixture experiments. The goal is to optimize the process for creating full-scale earthen elements that align with the intended form. The selected mold materials from the first phase, namely cardboard, wood, and metal, will be further assessed in terms of their suitability for large-scale applications.

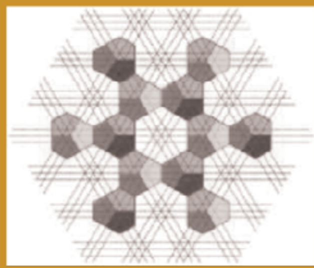
The first phase, which is the mold tectonic experimentation, will put three mold materials into test: cardboard (paper), wood and metal to fabricate adobe and rammed earth elements. For each material a different fabrication technique will be performed. For cardboard, sheets of 1.5 mm are cut by laser cutting machine then the pieces are folded and glued. On the other hand, wood has a different technique where a piece of 15*40*40 cm is engraved using a 3D CNC machine. Finally, the metal 3mm thick sheet is cut using digital machine, folded and welded. Accordingly, 6 specimens are produced and assessed for their accuracy in achieving the intended form.

Once the detailed design is established, the execution of mock-ups begins. Each mock-up serves as a tangible representation of the theoretical framework, allowing for real-world observation and analysis. The fabrication process is closely monitored to ensure adherence to the defined techniques, and any deviations are documented for further evaluation. Throughout the execution of mock-

Mold

Form A *Core Earth Elements Structure*

	Paper (cardboard)	Wood (CNC)	Metal (folding)
Rammed Earth	trial 1	trial 2	trial 3
Adobe	trial 4	trial 5	trial 6



Mixture

Mixture Variants

	Unsabilized	Stabilized	Hybrid
Rammed Earth	Specimen 1	Specimen 2	Specimen 3
Adobe	Specimen 4	Specimen 5	Specimen 6

Compressive strength test

Detailing + Production of all Earth Elements
Connections fabrictions + Construction of the Dome

If "Form A" was not successful, repeat with "Form B"

Mold

Form B *Earth + Timber Structure*

	Paper (cardboard)	Wood (CNC)	Metal (folding)
Rammed Earth	trial 1	trial 2	trial 3
Adobe	trial 4	trial 5	trial 6

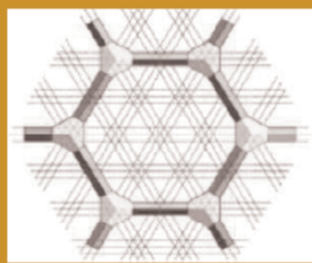


Figure 47_ Specimens Trials Road map (by author)

ups, a comprehensive record is maintained, capturing data on the challenges encountered, adjustments made, and unexpected observations. This documentation aids in refining the process iteratively, fostering a dynamic and adaptive approach to the experimentation.

Upon completion of the mock-ups, a thorough assessment is conducted to evaluate their success in achieving the intended tectonic goals. This evaluation encompasses not only the visual and structural aspects but also considers the practicality and sustainability of the chosen earth mixture. The data collected from this phase contributes valuable insights for potential future applications and further iterations of the tectonic experimentation.

The second phase is the mixture definition where adobe and rammed earth techniques will be tested across three different earth mixtures: unstabilized, stabilized and hybrid mixtures. Three specimens will be constructed for each technique and mixture which in total are 18 specimens. All specimens will be left to dry for 29 days and will be flipped on different sides to make sure that they are evenly dried. After that, they will be crushed for flexural strength test. The data will be collected by a video for the crushing machine and notes recorded for all the specimens. An average from the 3 specimens of each mixture will be taken to get the most accurate result that resembles the reality. Moreover, any data that is oddly far from the rest, will be excluded.

Flexural strength testing, often referred to as the «flexure test» or «bending test,» is a widely used mechanical test to evaluate the ability of a material to withstand bending or flexural loads. It is an essential parameter in assessing the performance of materials, particularly in applications where the material must endure bending forces, such as beams, bars, or components subjected to bending loads. Here is an overview of flexure strength testing with some key references:

1. ASTM C78 / C78M - Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading): This is a widely recognized standard test method for determining the flexural strength of concrete. The American Society for Testing and Materials (ASTM) publishes this standard (ASTM International 2019).

2. ASTM D790 - Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials: This ASTM standard outlines procedures for determining the flexural properties of various plastic materials, including modulus of elasticity and flexural strength (ASTM International 2017).

3. ISO 178 - Plastics - Determination of Flexural Properties: This ISO standard provides guidelines for the determination of flexural properties of plastics, including flexural modulus and flexural strength (International Organization for Standardization 2019).

4. ASTM E290 - Standard Test Methods for Bend Testing of Material for Ductility: While this ASTM standard focuses on bend testing rather than pure flexural strength, it is relevant when assessing the ductility of materials (ASTM International 2014).

5. ACI 14-318: Building Code Requirements for Structural Concrete: This reference is specific to concrete design and construction, providing guidelines and standards for the use of concrete in structural applications, including

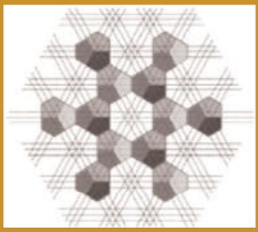
requirements related to flexural strength (American Concrete Institute 2014).

When conducting flexural strength tests, it is essential to adhere to the relevant standards and guidelines to ensure accuracy and consistency in results. Depending on the material being tested (e.g., concrete, plastics, metals), different standards and procedures may apply, as indicated by the references above.

The final phase is the detailing of the earthen elements to be assembled in different mock-ups where two post-tensioned structure systems will be tested: external and internal. The mock-ups will be composed of around 6 elements from the previously defined mold and mixture. If the mock-ups successfully stand stable then the results are positive.

In summary, the three-phased experimentation process—mold tectonic experimentation, earth mixture definition, and detailing for mock-ups execution—provides a comprehensive framework for investigating the inclusive meaning of tectonics. Through rigorous testing and analysis, this approach aims to push the boundaries of conventional design paradigms, fostering innovation in the realm of architectural experimentation with earthen elements.

Figure 48_ Experimentation Design (by Author)

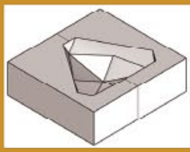


Form A Core Earth Elements Structure

Mold Experimentation

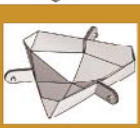
→ **Mold 1**: Cardboard

- *Cardboard sheets*
- *Laser cutting machine*



→ **Mold 2**: Wood

- *Wood sheets*
- *CNC machine*



→ **Mold 3**: Metal

- *Metal sheets (3mm)*
- *Metal cutting and folding machine*

Earth Mixture Definition

→ **Unstabilized**: ratio from literature and field tests

- *3 Rammed Earth specimens*
- *3 Adobe speciments*

→ **Stabilized**: cement, lime and carob tannins

- *3 Rammed Earth specimens*
- *3 Adobe speciments*

Materials Lab: Compressive Strength Test

→ **Hybrid**: Unstabilized + stabilized in defined areas

Materials Lab: Compressive Strength Test

Detailing

→ **Earthen elements detailing**: bolts, connectors

→ **Many assembley mock-ups**: internal/ external post-tensioning

→ **Design the Base and Top sections**

Production

→ **Manufacturing Selected Mold**: 8 Molds (2 for each raw)

→ **Production of 56 earth units**

→ **Manufacturing Base and Top sections**

- *Wood sheets*
- *Wood lab*

→ **Assembley**

- *Area for assembley*

***Earthen material components supply is needed in all the different stages of the experiment*

If «Form A» was not successful, repeat with «Form B»

Form B Earth + Timber Structure

4.4. Variables that intervene in the process, and description

Variables play a crucial role in the examination of observation units. These entities possess certain characteristics that define their significance in the research process:

1. Observability: Variables must be observable, ensuring that researchers can measure and analyze them effectively.
2. Variability and Interdependence: Variables exhibit variability and interdependence, encompassing covariance, dependence, influence, and other related attributes.

Variables can be categorized based on various factors:

- Nature: Qualitative or quantitative.
- Number of Elements: Individual or collective objects.
- Abstraction Level: General, intermediate, indicators, or empirical.
- Scales or Sets: Nominal, ordinal, interval, or ratio.
- Research Position: Intervening (dependent or independent) and confounding.

In the context of experiments assessing form, technique, and material consecutively, it is imperative to consider and test different variables that influence the outcomes. Mold tectonics, which comprises form, technique, and material, is a set of variables that significantly impact the results. Additionally, variables such as structure system, assembly technique, module detailing, and others play crucial roles in determining the experimental outcomes.

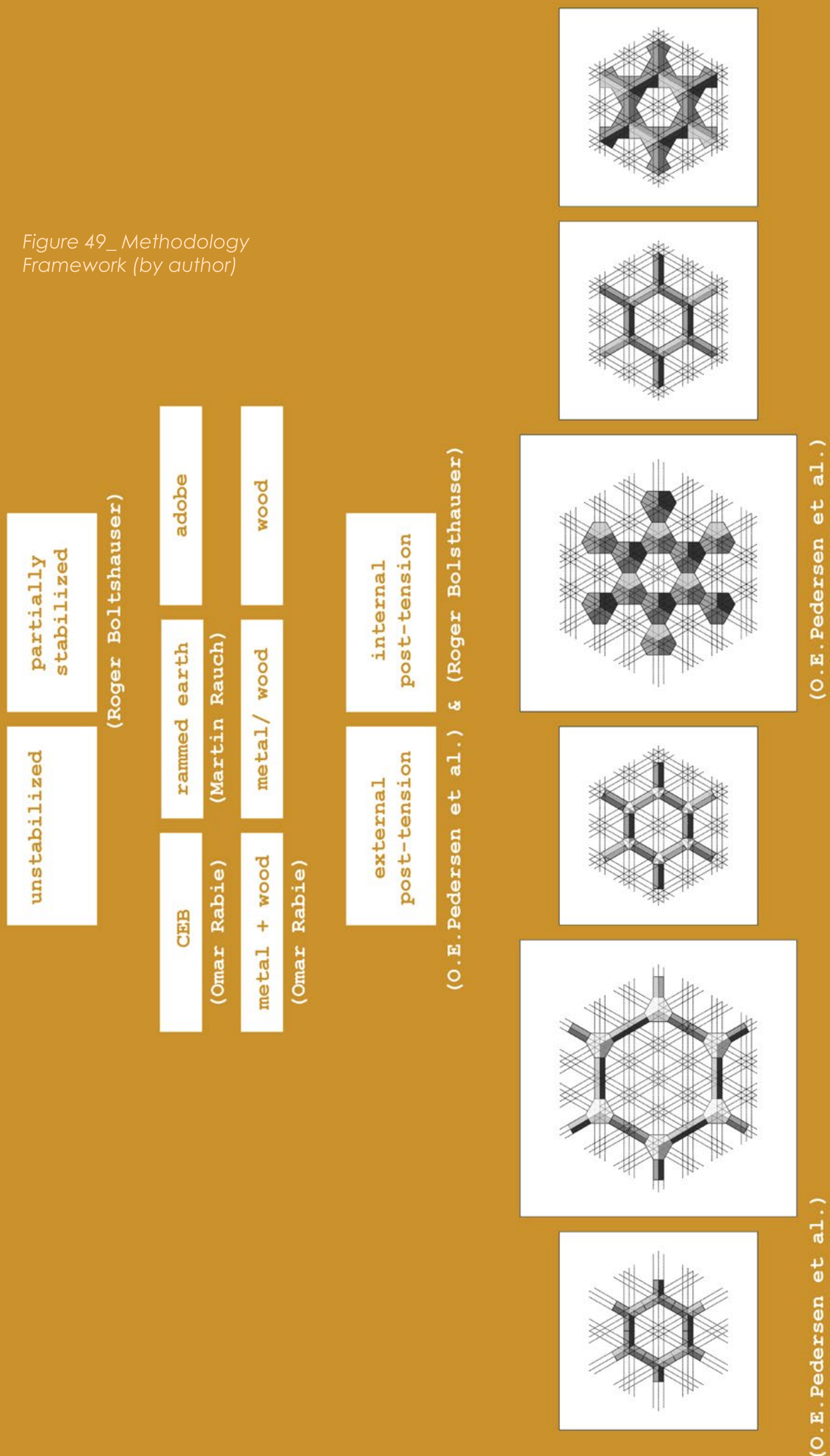
During the drying process, it is essential to be mindful of confounding or external environmental variables that may affect the results. To mitigate this, elements under observation should be placed outdoors, avoiding direct sunlight and providing protection from rain.
One specific variable that requires attention is "Module Neatness." This variable, encompassing the organization and cleanliness of modules, can have a substantial impact on the overall experiment.

Chapter Conclusion

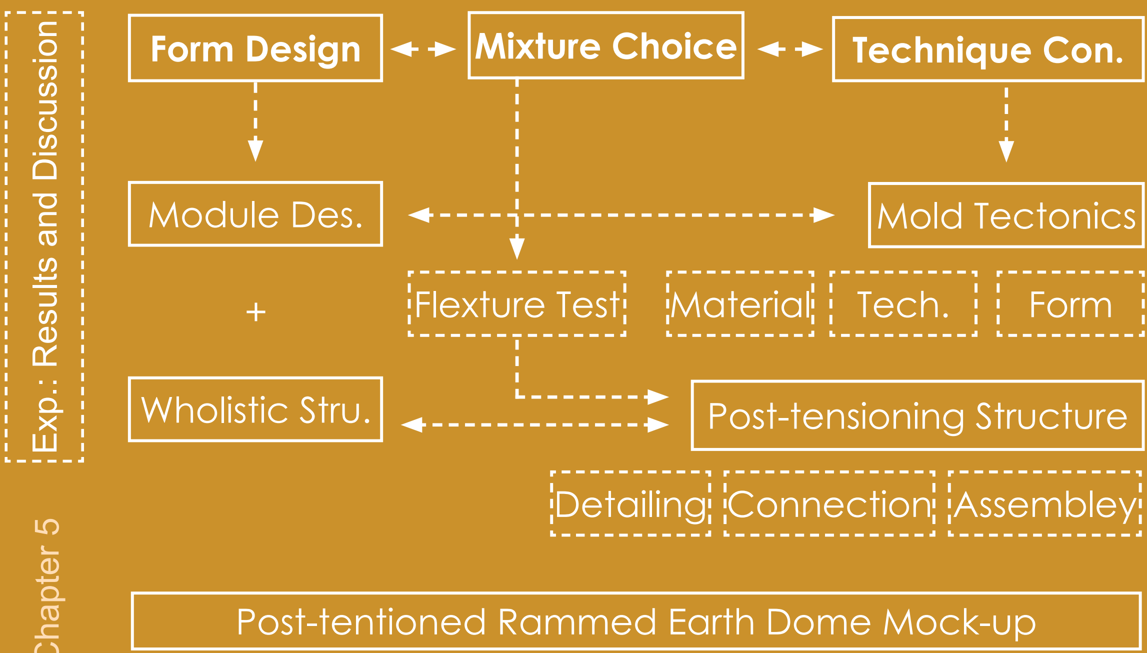
In the methodology section, the research design is discussed in relation to the identified research problem, objectives, and existing literature. The selection of the research methodology is contingent upon the research aim and objectives. The research is characterized as applied research, focused on addressing real-world problems and integrating technology to develop new processes or systems. Specifically, it explores the application of new technologies to earthen materials for the development of innovative tectonics and structural systems. The research also delves into the exploration of shell structures with earthen materials, an area with limited existing knowledge, categorizing it as exploratory research.

This design is employed to create an external post-tensioned shell structure using earthen materials, aiming to determine the most suitable tectonic method for achieving such structures. The experimentation process unfolds in three phases: mold tectonic experimentation, earth mixture definition, and detailing for mock-ups execution. These phases involve meticulous testing of variables such as mold materials, earth mixtures, and post-tensioned structure systems. Attention is given to the interrelated connection between material, technique, and form, with a focus on refining fabrication techniques based on insights gained from experimentation. The comprehensive framework aims to push the boundaries of conventional design paradigms, fostering innovation in architectural experimentation with earthen elements. The thorough examination of variables, including the critical consideration of external environmental factors, underscores the robustness of the research design.

Figure 49_ Methodology Framework (by author)



This chapter discusses the experimentation and its results in details in reference to the literature.



Chapter 5

Chapter 05

Experimentation: Results and Discussions

"As the complexity of the building industry continues to grow, the question of the relationship between architecture and engineering is increasing in relevance"
-Tectonics in Architecture book

05 EXPERIMENTATION: RESULTS & DISCUSSIONS

The methodology being employed in this research is rooted in the experimental approach, particularly as it pertains to the utilization of earthen materials. The uniqueness of this study lies in its endeavor to create a post-tensioning structure using earthen materials, a relatively unexplored domain in the realm of construction materials. The inspiration for this experimentation draws from Larsen's innovative work in concrete experimentation, as documented in Pedersen's seminal work in 2013.

The experimental nature of the research is crucial, as it involves navigating uncharted territories in the construction field. The use of earthen materials presents distinct challenges and opportunities that diverge significantly from conventional construction materials like concrete or steel. Earthen materials, with their diverse composition and natural variability, require a specialized understanding of their structural behavior, necessitating a departure from traditional tectonic design methodologies.

In developing the post-tensioning structure with earthen materials, the research team is delving into unexplored engineering intricacies. The novel approach demands an in-depth analysis of the material's mechanical properties, structural integrity, and long-term durability. The experimentation encompasses various stages, from material sourcing and preparation to the actual construction process, all of which contribute to a comprehensive understanding of the feasibility and performance of earthen materials in structural applications.

Moreover, the study extends beyond the mere application of earthen materials in construction. It delves into the intricacies of post-tensioning, a technique commonly associated with traditional construction materials but relatively uncharted in the context of earthen structures. This integration of post-tensioning techniques with earthen materials not only adds an innovative dimension to sustainable construction practices but also requires a meticulous adaptation of design principles.

In essence, the research is pioneering a paradigm shift in construction methodologies by pushing the boundaries of materials traditionally considered for structural applications. The insights gained from this experimental approach will not only contribute to the scientific understanding of earthen materials but also open up new avenues for sustainable and eco-friendly construction practices. As the experiment unfolds, it is expected to provide valuable data that can inform future architectural and engineering practices, potentially revolutionizing the way we conceptualize and construct structures using alternative materials.

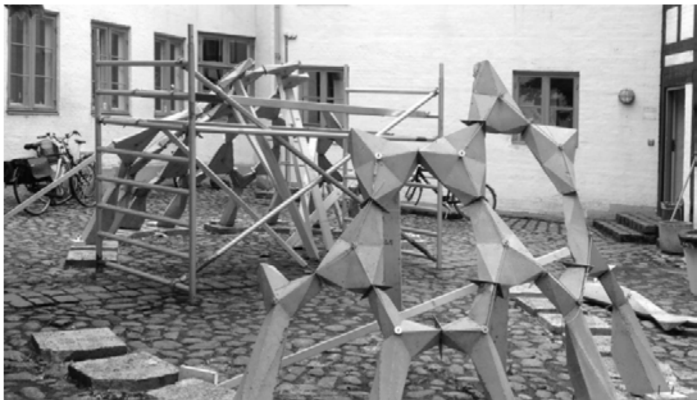


Figure 50_ Full-scale prototype assembly of external post-tension system (Beim and Madsen 2014; Pedersen and Larsen 2015)

As discussed in the literature chapter 3, this is one of the experimentations that post-tensioned structure was experimented with concrete modules. The structure here was external post-tensioned structure which put the main structural elements under compression. Since earthen materials are good in compression, so this compression-only structure was very promising choice for the structure. Moreover, the structural triangular form had more potential to be tested on earthen materials more than the other "Y" forms tested in other experimentations since it is more compact with less free-standing arms that may experience possible cracks.

However, there were many other factors that require tectonic configuration when changing the material to earth. These variables are construction technique, mixture composition, mold tectonics, connections, detailing, fixations, assembly and much more. These factors can be classified in the following sub-topics:

- Holistic structure design
- Module design
- Flexure test (mixture choice)
- Mold tectonics
- Post-tensioning structure

These factors are going to be discussed in this chapter showing the different experimentations of solution trials and their reflections.

The main aim of this experiment was not just to explore the rammed earth tectonic potentials but also to make use to keep the values of the earth materials as they are.

Rammed earth is known to be recyclable so that the earthen element can be easily dismantled and return to a garden soil without changing any of its properties. This can be preliminary achieved through mechanical fixations that does not involve adhesives or complex connections that deprive the building material to return easily to its original state. Earth is also simple in terms of construction that involves low tech tools and machinery which promotes participation of unspecialized people to the construction site. Furthermore, the process has also to be kept with low carbon footprint as possible.

5.1 Form:

The experimentation involves a multi-faceted process, beginning with the selection and preparation of earthen materials. Unlike conventional construction materials that undergo standardized manufacturing processes, earthen materials introduce an additional layer of complexity due to their natural variability. The research team meticulously analyzes different types of earthen materials, considering factors such as composition, moisture content, and particle size distribution, to ensure a comprehensive understanding of their characteristics and behaviors.

Furthermore, the construction of the post-tensioning structure demands a thoughtful adaptation of tectonic design principles. Earthen materials possess unique structural properties, and their response to loads, pressures, and environmental conditions requires a nuanced approach. The research team is actively exploring innovative design strategies that can harness the inherent strengths of earthen materials while addressing potential weaknesses.

To ensure the success of the experiment, the construction process involves careful monitoring and iterative adjustments. Real-time data collection, including stress and strain measurements, enables the researchers to assess the structural performance of the earthen material post-tensioning system. This data-driven approach facilitates continuous refinement of the construction methodology, ensuring that the final structure not only meets safety standards but also maximizes the efficiency and sustainability of earthen materials.

Collaboration across disciplines is a key aspect of this research initiative. Structural engineers, material scientists, and architects work in tandem to integrate their expertise and insights. This interdisciplinary collaboration is vital for overcoming the challenges associated with working with earthen materials and post-tensioning techniques, fostering a holistic understanding of the project from both a material and structural standpoint.

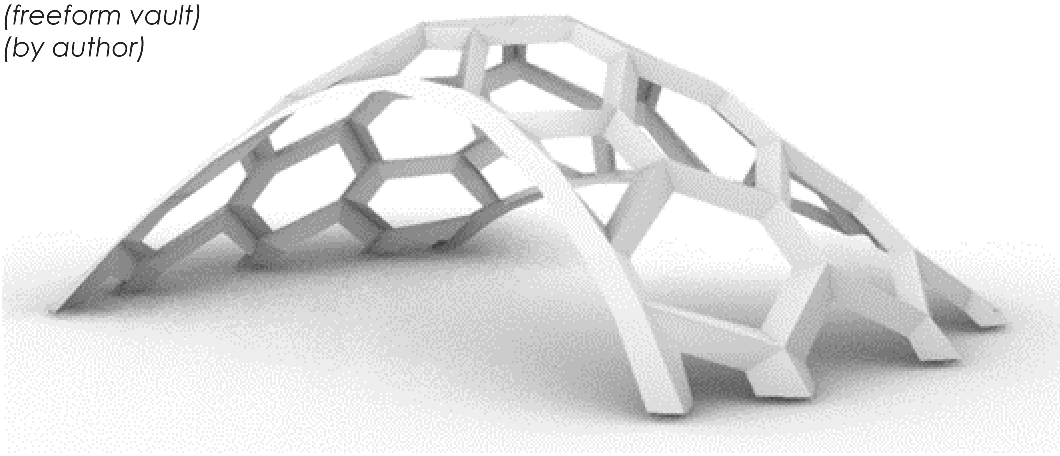
Moreover, the research extends its focus beyond the immediate structural implications. Sustainability is a core theme, with an emphasis on eco-friendly construction practices. Earthen materials, being abundantly available and environmentally friendly, hold the potential to contribute significantly to sustainable construction. The research team is keen on understanding not only the structural feasibility but also the environmental impact and life cycle analysis of the earthen material post-tensioning system.

In summary, the experimental methodology being pursued in this research is comprehensive and intricate, involving a systematic exploration of earthen materials and the integration of innovative design and construction techniques. The collaborative and interdisciplinary nature of the project positions it at the forefront of sustainable construction research, with the potential to revolutionize the way we conceive and construct structures using unconventional yet environmentally conscious materials.

5.1.1. Holistic Structure Design

Different design iterations were meticulously explored through the utilization of a customized script within the «Rhinoceros» 3D program, employing commands like «flow on surface.» The initial experiment revolved around a freeform vault design, seeking to achieve a captivating aesthetic. However, it soon became apparent that this approach compromised the inherent modularity and cost-efficiency associated with traditional earthen structures. Consequently, an alternative design concept was experimented – the modular dome employing triangular form modules. This approach not only preserved the

Figure 51_ First attempt for the pavilion form (freeform vault) (by author)



modularity reminiscent of earthen structures but also offered the advantage of improved cost-effectiveness, ensuring that the project remained economically viable without compromising on the Catalan dome›s timeless appeal.

In the realm of architectural innovation, the design of the Catalan dome represents a fascinating fusion of traditional craftsmanship and cutting-edge technology. To optimize structural integrity, the module thicknesses were inspired from load-bearing buildings of yesteryears, envisioning a dome that is thick at the base and gradually thins as it ascends, mirroring the principles seen in load-bearing structures of historical significance. This approach not only pays homage to the past but also pushes the boundaries of modern architectural design.

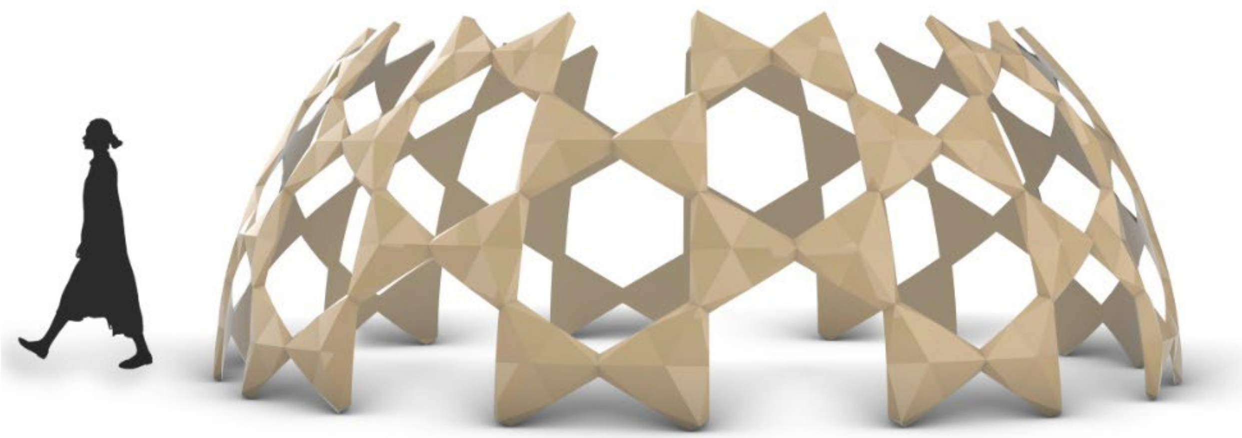


Figure 52_ Second attempt for the pavilion form (modular dome) (by author)

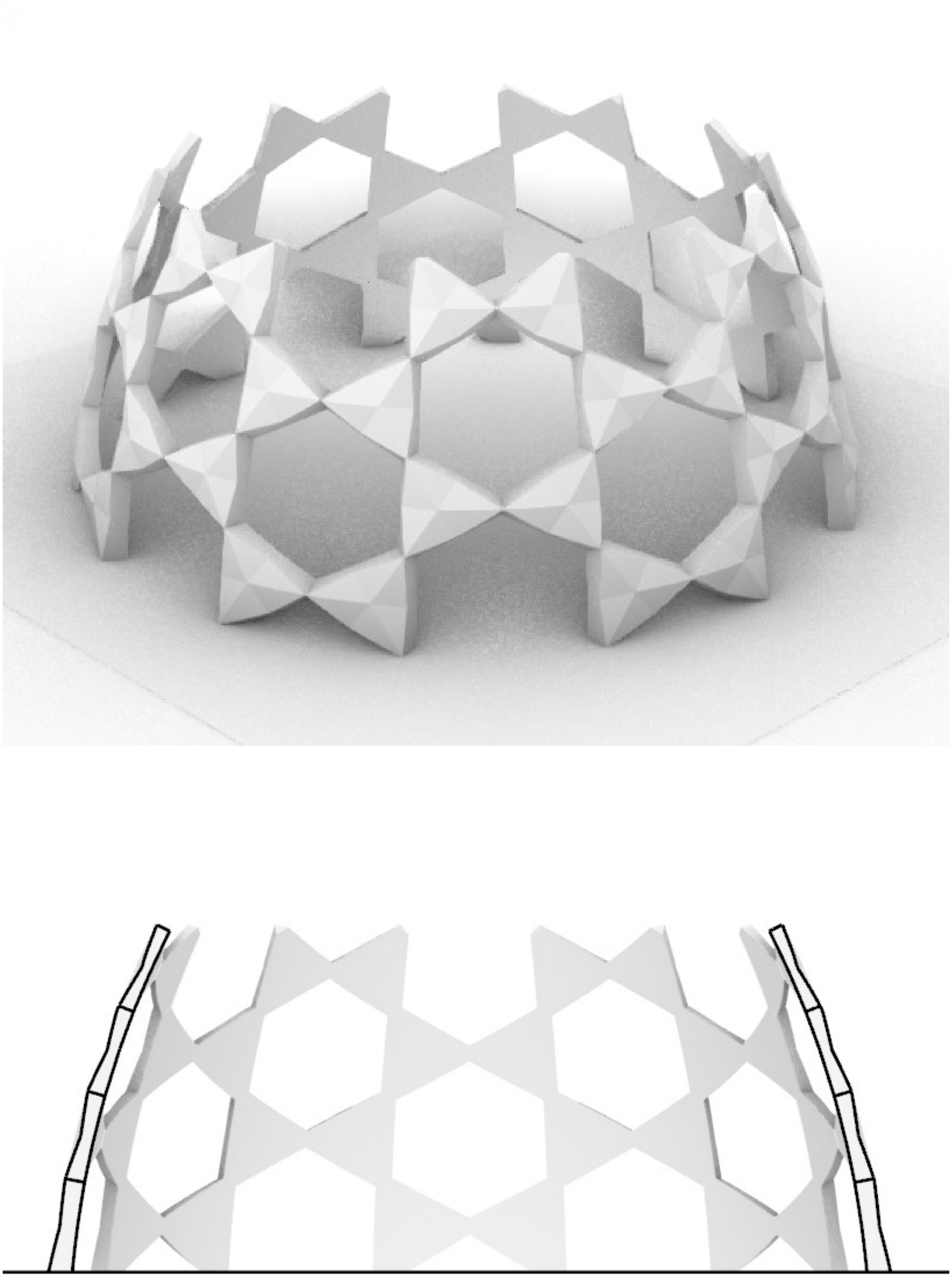


Figure 53_ Module thickness decrease as the level increase (by author)

5.1.2. Module Design

After interviews with the designers and the engineers who constructed the concrete mock-ups, Prof. Niels Martin Larsen[1] and Prof. Dave Pigram[2], some insights were obtained regarding the cluster unit of the form. More than six different alternatives were tried to act as alternations plans for the construction mockup. They are variations for the connection and module design. In some of the clusters the connection is in the middle between three modules and in other the connection only connects two units in the leg of the cluster (Figure 54). This was put to test to figure out earth module structural behavior in the connection.

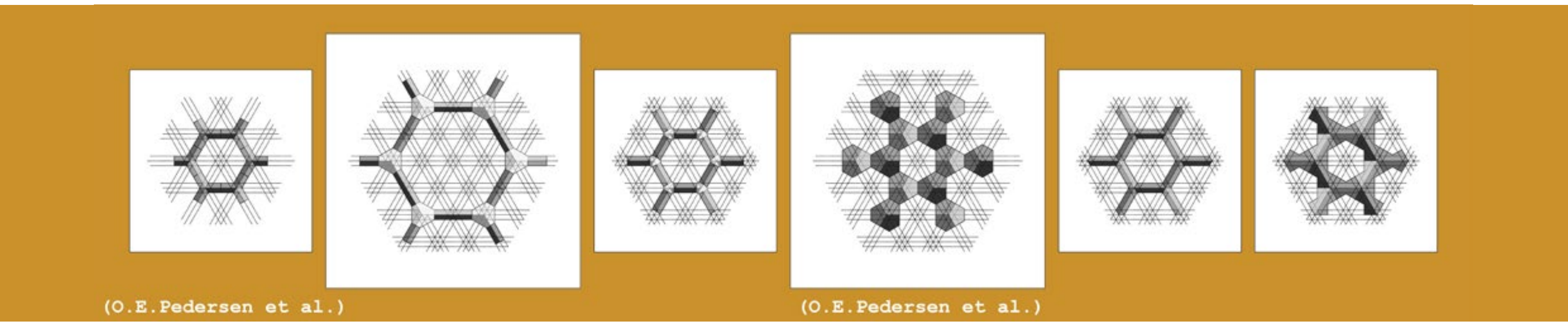


Figure 54_ Different design alternatives (by author)

The module design underwent continuous refinement throughout the project›s development, reflecting the dynamic nature of the design process. The original

1 Prof. Larsen is an associate professor at Aarhus School of Architecture, Denmark

2 Prof. Dave is director of Supermanoeuver and senior lecturer at University of Technology Sydney

concrete elements were initially substantial, presenting challenges in terms of handling and integration with the mold tectonics. Recognizing the need for adaptability, the process embraced a mindset of constant evolution, adjusting the module design to align seamlessly with the evolving mold tectonics. This iterative approach allowed for the optimization of both form and function, ultimately ensuring that the construction process could proceed smoothly without compromising the structural integrity or aesthetic vision of the mockup.

5.2. Mold Tectonics:

In tandem with the dynamic evolution of the earthen structure itself, a parallel and equally intricate set of tectonics governs the mold used in crafting the earthen modules. This interplay of mold tectonics exerts a profound influence on the overall design and characteristics of the earth modules, adding a layer of complexity to the construction process. The careful manipulation and consideration of these mold-based dynamics play a pivotal role in determining the final form, structural integrity, and functional aspects of the modules, thereby facilitating a seamless integration between the raw earth material and the precision of the mold.

The mold, in essence, becomes a silent orchestrator in the creation of the earthen structure, guiding the shaping and molding of the material into a cohesive and purposeful form. The geometrical intricacies, surface textures, and even the structural properties of the earthen modules are intricately linked to the design and characteristics of the mold. Engineers and artisans working on this project engage in a meticulous dance with the mold, experimenting with various configurations, sizes, and compositions to optimize the interaction between the mold and the earthen material.

This thoughtful synergy between the two sets of tectonics – the inherent properties of the earthen material and the dynamics of the mold – is paramount to achieving a successful and cohesive outcome in earthen construction. The craftsmanship involved in manipulating the mold tectonics is a blend of traditional knowledge and cutting-edge technology. It involves a delicate balance between the artisan›s expertise in working with earthen materials and the precision afforded by advanced molding techniques.

The mold, as a tool in this creative process, not only imparts a structured form to the earthen material but also influences the aesthetic and tactile qualities of the final product. The intricate patterns, textures, and surface finishes that emerge from this dance of mold tectonics contribute to the visual appeal and uniqueness of the earthen structure. It is a testament to the fusion of human ingenuity and technological innovation, where craftsmanship and technology intersect to produce structures that are not only enduring in their strength but also captivating in their aesthetic appeal.

In conclusion, the dual narrative of tectonics – one governing the earthen structure and the other guiding the mold – underscores the complexity and sophistication of earthen construction. This holistic approach, where the manipulation of mold dynamics is as integral as the understanding of earthen material properties, ensures that the resulting structures stand at the intersection of tradition and modernity, embodying a harmonious blend of craftsmanship and technological precision.

- **First trial:**

Material: **Cardboard + Cement**
Form: **Triangular**
Technique: **Pouring**

The construction process involved the definition of four distinct molds, each accompanied by its respective mirrored counterpart. These molds were meticulously unfolded and transferred onto sturdy cardboard sheets, serving as the framework for cement pouring. The initial idea was to do the formwork from the cardboard only without cement but the soil densification of the rammed earth requires a strong formwork.

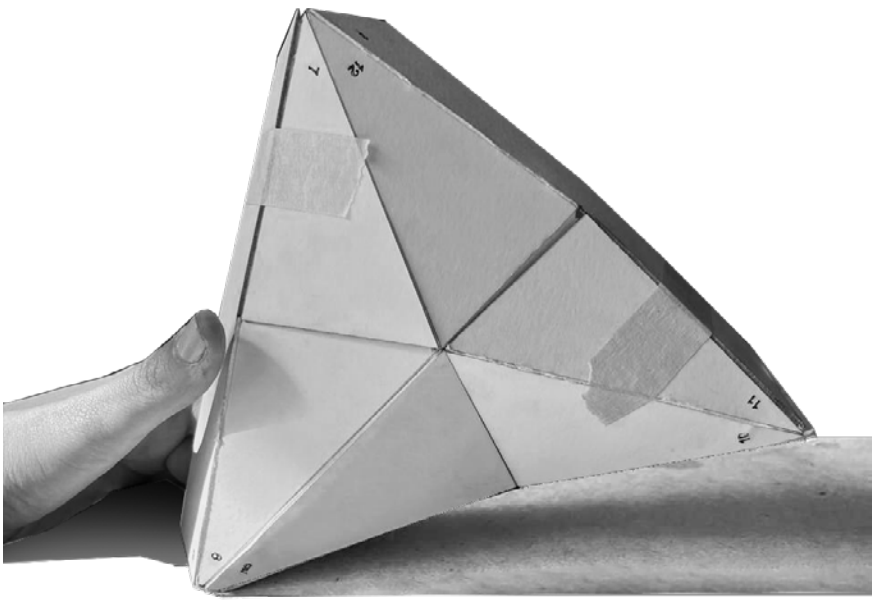
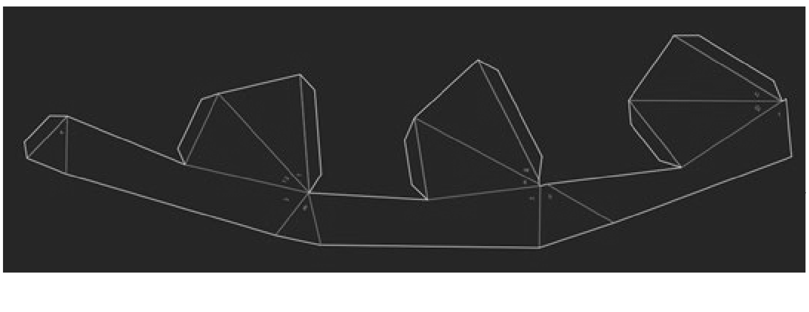


Figure 55_ AutoCAD laser file for cardboard mold (by author)



To ensure a smooth release of the cement, a layer of oil was generously applied to the interior of the molds, preventing any unwanted adhesion. The cement mixture was poured in sections, with each portion being gently vibrated to eliminate air bubbles and ensure optimal compactness. However, one challenge encountered during the process was the limited structural integrity of the cardboard, which struggled to withstand the moisture content in the cement mixture. Therefore, a course of red brick was added to the edges of the form to offer the required strength (Figure 56).

Despite careful execution, achieving precise form accuracy proved to be a challenge due to the pouring direction and the absence of clamps to secure the molds firmly in place. As a result, the final product exhibited minor deviations from the desired specifications. This can also be because of the water content in the cement that has caused deformations in the cardboard.

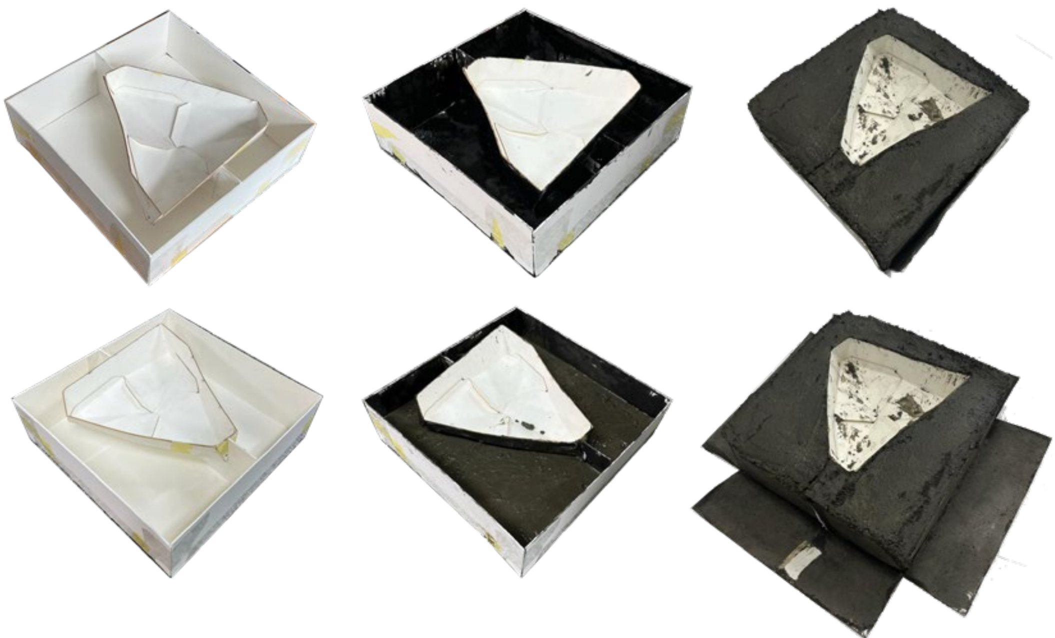


Figure 56_ Cement pouring in cardboard mould (by author)

The earth mixture itself consisted of a straightforward blend of clay, sand, and gravel, fine-tuned through the ball field test. While this mixture yielded a robust final product, it displayed a slight fragility at the corners, highlighting the delicate balance between strength and structural integrity in the construction process.

Figure 57_ ramming earth in the cement mold (by author)

- **Second trial:**

Material: **Cardboard**
Form: **Triangular**
Technique: **Folding**

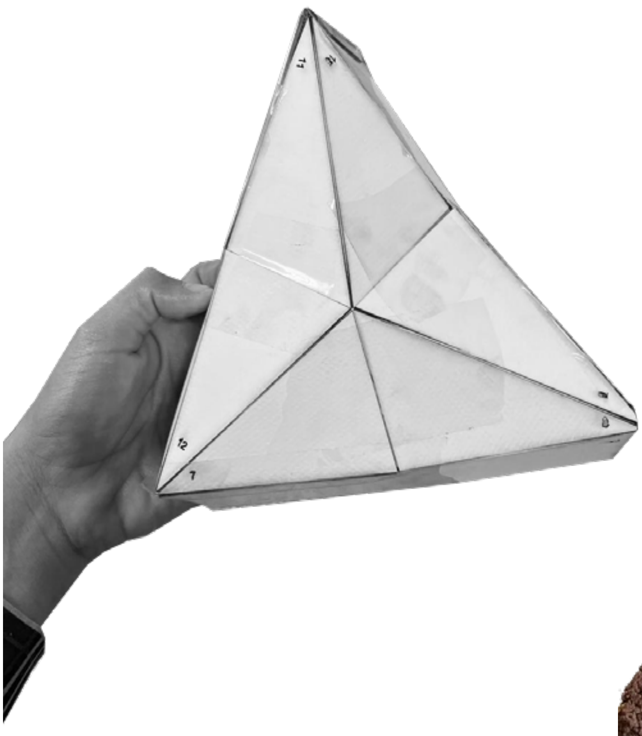
This trial was as attempt to use an earth construction technique that does not require a string stiff mold. Therefore, the adobe technique was chosen so that the that earthen material will be poured without additional need for densification for the material. The adobe mixture that was used in the construction primarily comprised sand, clay, and straw, with a key element being the use of vibration to enhance the cohesion of the materials and eliminate air pockets. However, despite careful execution, certain challenges arose during the process.

One notable issue was the presence of occasional air holes in the final product. This irregularity was likely attributed to variations in the mixture›s consistency, possibly resulting from an inconsistent distribution of water within the blend. Achieving a uniform mix of these materials proved to be a crucial but challenging aspect of the construction process. Besides, the straw also was in many cases protruding from the triangular form resulting in a non-smooth surface.

Additionally, the choice of cardboard as a construction material was found to be less than ideal. The cardboard proved to be ill-suited for the adobe construction process, as it struggled to withstand the weight and moisture content of the adobe mixture. This led to the unfortunate flattening of the form during the construction process, affecting the overall accuracy of the final structure (Figure 58).

Alternative mold material or structural support may need to be considered to ensure the success and integrity of the adobe construction module.

Figure 58_ Adobe mixture and the cardboard mold and adobe module imperfections (by author)



- **Third trial:**

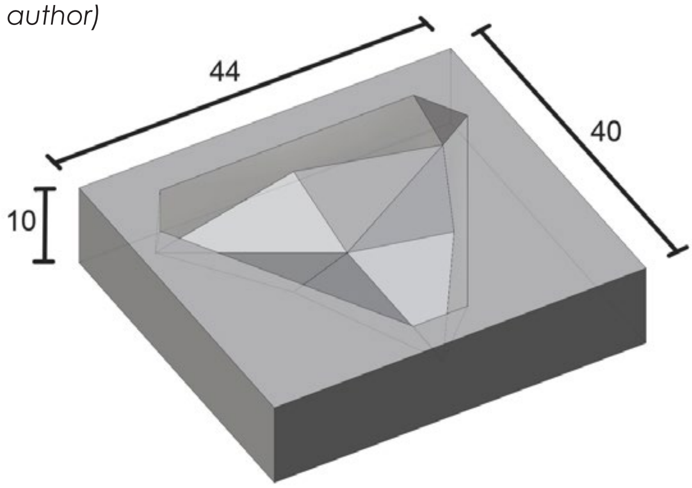
Material: **Wood**
Form: **Triangular**
Technique: **Router CNC drilling**

The process was initiated with the creation of a digital model for the mold (Figure 59), and a decision was made to slightly increase the earth module size, thereby ensuring an overall increase in thickness during the final detailing phase. This crucial modification was undertaken to achieve the desired structural integrity and aesthetics in the final structure. During this particular stage, special attention was given to the corner of the triangles, introducing a deliberate inclination. This design choice would provide a solution for achieving the curvature of the dome when the individual elements were assembled.

The wood mass measures were dimension 10*40*44 cm and is of the Swedish/Finland type, typically chosen for its quality and durability. To achieve the desired form from this wooden block, a CNC router machine is employed, and the process is typically divided into two main phases.

The first phase involves cutting the main bucks or rough shaping of the form. During this stage, the CNC router carefully removes excess material, gradually revealing the intended shape of the wooden element. However, it is crucial to note that vertical cutting techniques can sometimes introduce unintended changes to the element's form. These deviations can occur due to the nature of the cutting process and may require additional refinement.

Figure 59_ digital 3D model for the wooden mold (by author)



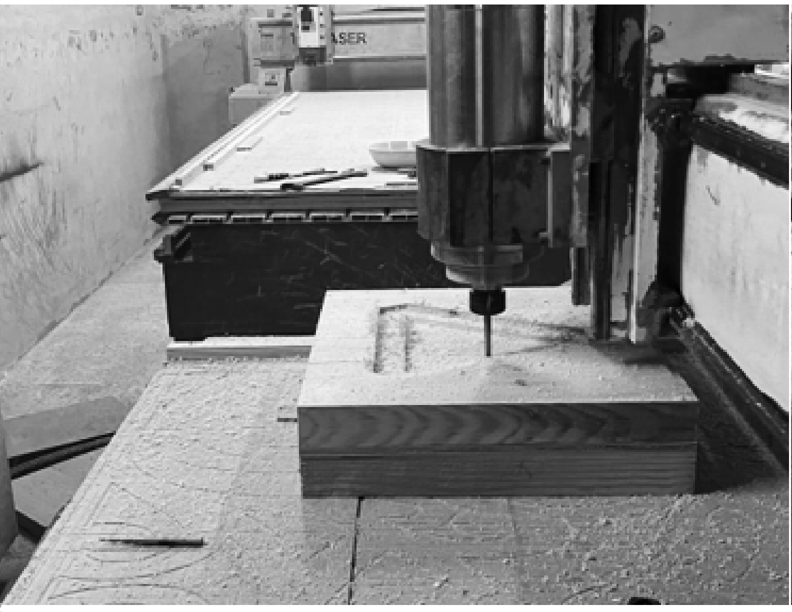
A wooden cuboid was carefully positioned on the CNC router machine, where it underwent precision engraving using a specialized **perpendicular-only** engraving tip. The meticulous craftsmanship of the CNC router brought forth the idea that eliminating the inclination in the corner triangles would better align with the modular concept characteristic of rammed earth construction. This approach paralleled the principle often seen in traditional arch construction, where special bricks are not required; instead, adjustments are made using mortar. In our case, the wooden connectors in the forthcoming assembly phase would serve a similar function, allowing for fine-tuned adjustments.

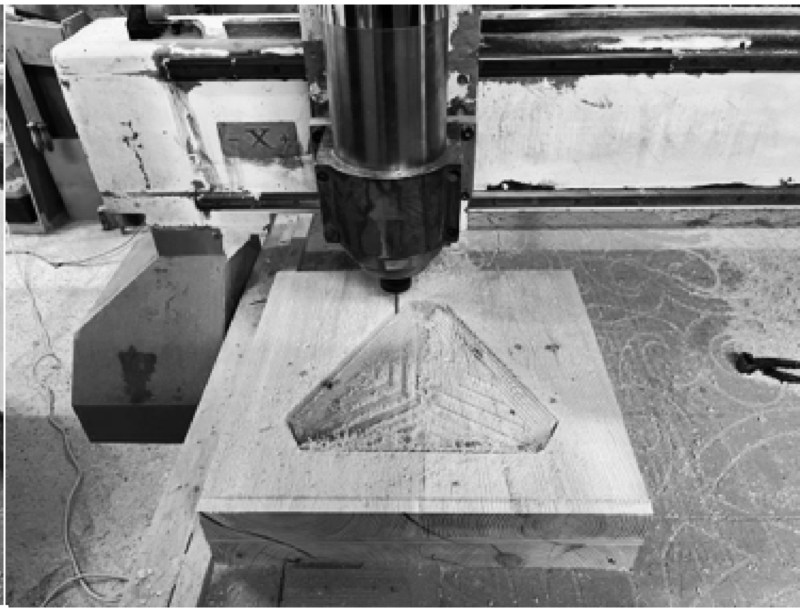
Following the CNC machining, further manual modifications may be necessary to achieve the desired level of precision and smoothness. This can involve sanding the surface to eliminate any imperfections or irregularities, ensuring the final wooden element meets the necessary standards for aesthetics and functionality. These meticulous manual adjustments serve to enhance the overall quality and finish of the wooden components, aligning them with the project›s design and structural requirements. Subsequently, the mold underwent a meticulous detailing phase, as showcased in the attached photos. This phase was crucial to ensuring the mold›s precision and consistency, which are paramount to the success of the entire construction project. The attention to detail, combined with the strategic adjustments made throughout the process, would ultimately contribute to the realization of a remarkable and harmonious architectural masterpiece.

Remarkably, the principle of maintaining the element›s form irrespective of changes in the dome›s size or shape is reminiscent of traditional brick construction. Much like bricks that retain their uniform shape regardless of the overall structure›s dimensions, these wooden elements adhere to a consistent design concept.

The ramming process was initiated and progressed successfully until a point where patience wore thin. It couldn›t be resisted to unveil the partially dried structure, but this impatience resulted in the mixture adhering to the sides of the mold, ultimately leading to the unintended cracking of the element. However, this step, though unfortunate, proved invaluable in identifying the weak areas within the form. This knowledge would play a pivotal role in refining the mixture in the subsequent stage.

Figure 60_ CNC machine perpendicularly engraving the wood block in several stages (by author)





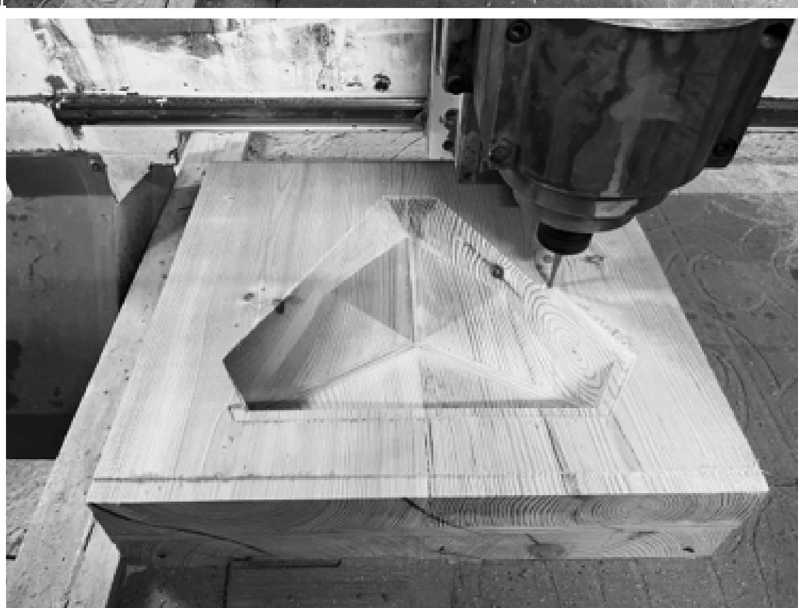


Figure 61_ Detailing the wooden mold after the CNC engraving (by author)

Figure 62_ Mixture adhesion to the mold causing cracks (by author)

In response to this setback, the decision was made to repeat the ramming process, but this time, a very thin plastic bag was introduced underneath the mixture to prevent it from sticking to the mold. This innovative approach, while effective, could potentially be replaced with the use of oil as a mold lubricant in future attempts. The newly rammed structure was then left to dry overnight, allowing the elements to settle and solidify.

Ultimately, persistence and the lessons learned paid off. The form was successfully achieved with its distinct and well-defined angles, marking a significant milestone in the construction process. These challenges and adaptations along the way were utilized as valuable experiences, contributing to the refinement and ultimate success of the mockup.

Figure 63_ CNC successful mold technique (by author)

5.3. Mixture & Technique

This phase is not about determining the material since the tested material is the earthen materials from the start of the study. However, it is more about putting different mixtures of earth under the test of tension or bending stresses to answer two questions. The first question is related to the form and eventual application which is a shell/ dome structure.

To which extent can the earth bear radial loads?

The second question is related to the earth mixture:

which earth mixture can enhance the earth structural performance to bear these loads?

The needed rammed earth specimens for the flexural strength testing were fabricated. A total of eight specimens were prepared, covering four different mixtures, ensuring two specimens were available for each mixture for control purposes. The mixtures tested were as follows:

1. **Unstabilized earth** (ratio 3 sand: 2 clay: 0.75 gravel), suitability tested using the drop ball field test.

2. **Lime stabilized earth** (clayey earth; ratio 2.5 sand: 3 clay: 0.75 gravel: 0.3 lime) in accordance with the Auroville Earth Institute guidelines.

3. **Cement stabilized earth** (sandy earth; ratio 3 sand: 1.5 clay: 0.75 gravel: 0.25 cement) following the Auroville Earth Institute recommendations.

4. **Fiber (straw) stabilized earth** (ratio 3 sand: 2 clay: 0.75 gravel: 0.5 straw), suitability tested using the drop ball field test. The choice of straw was made due to its tensile strength potential, which could enhance the overall tensile strength of the earthen element.

The hybrid mixture was challenging to be achieved due to the relatively small size of the earth module and the different curing processes between the different mixtures. Each specimen consisted of three to four layers, and the time allocated for each triangle was almost 35 minutes. The specimens were left to dry for 28 days and every one or two days a damp cloth was put on the cement and the lime specimens for curing.

The flexure test was conducted on the earth specimens, which were subjected to a compression-testing machine. The machine was capable of accommodating samples with dimensions of 20*20*20 cm, and its units of measurement included Kgf, cm, and C. The tests adhered to the following conditions:

- Prisms were thoroughly dried before testing.
- The masses of the triangles were determined prior to testing.
- Precise measurements of the triangles were taken before testing.
- Prisms were positioned centrally in the machine and loaded until complete failure.
- Metal prism was added on top of the triangle centered accurately on the triangle center point to ensure uniform load distribution across the specimens.
- The triangles were placed on a one fixed on a metal plate parallel to one of the triangle's sides. The opposite corner of this side was placed to a roller hinge cylinder so it can simulate the forces directions in the dome.
- The hinges were covered with a lubricating oil to minimize possible friction between the specimens and the hinges.

Figure 64_ Eight specimens for Flexture test (by author)

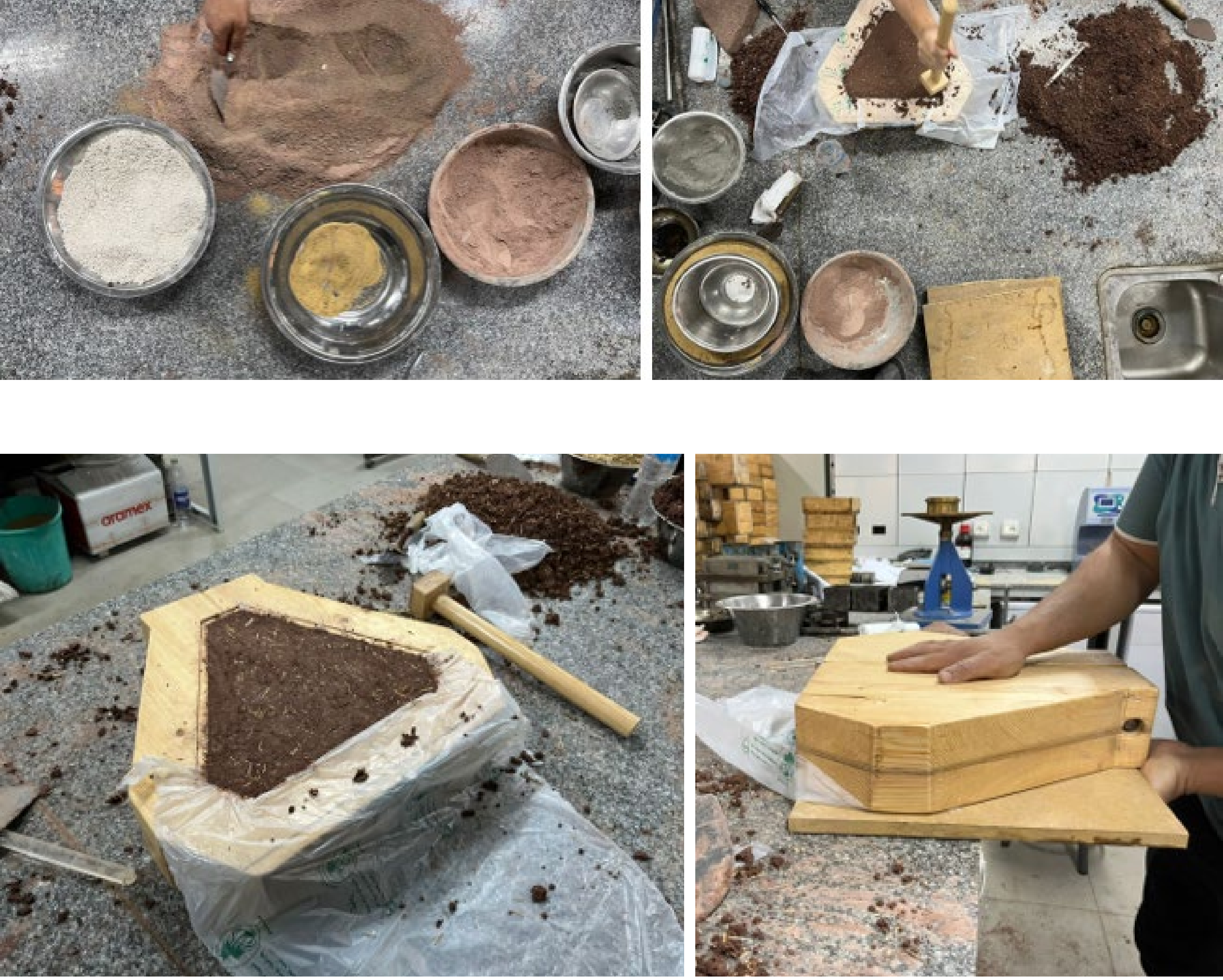
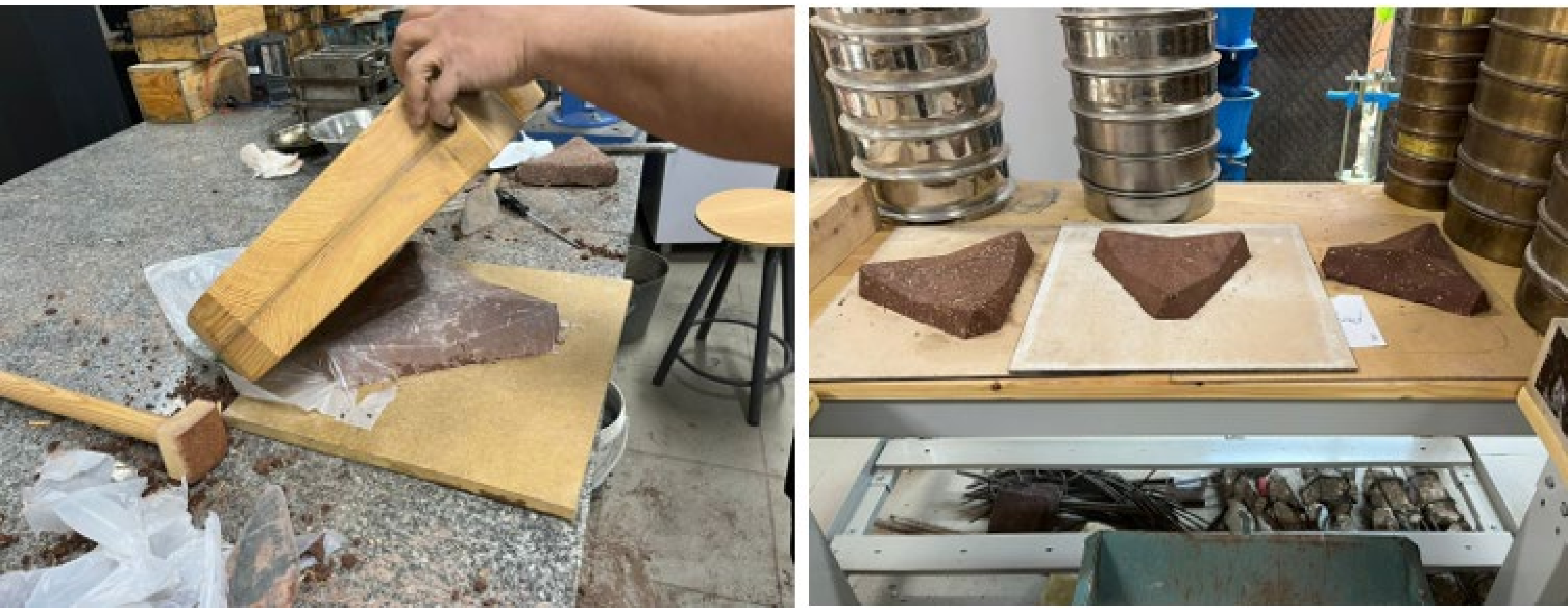


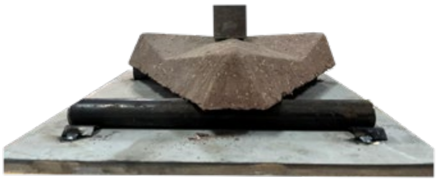
Figure 65_ specimens mixing, ramming and curing processes (by author)



In addition to utilizing the compression machine, an important supplementary tool known as a gauge was employed as part of the testing methodology. This gauge played a crucial role in determining the stress-strain curve of the techniques being investigated. It's important to note that this specific approach was not applied to all specimens but was selectively employed for a subset of cubes. The selection process for these cubes was conducted with careful consideration, taking into account their ability to represent various mixtures used in the study. In essence, this additional testing method and the selection of specimens aimed to provide a comprehensive understanding of how different mixtures and materials behaved under the applied loads.

The results from the flexure test are of great significance as they shed light on the strength characteristics of diverse earth materials and composite mixtures when subjected to a specific type of mechanical loading known as flexural stress. In a flexure test, a test specimen, typically a rectangular or prismatic shape, is subjected to a bending force rather than direct compression. This methodology allows researchers to assess the material's flexural strength and its behavior under conditions that mimic scenarios involving bending or bending-related stress. The results mentioned in your description are quantified in kilograms-force (Kgf), offering a measure of the maximum stress that the material can endure before reaching the point of failure within the flexural test. Understanding these results is crucial for assessing the suitability of different earth materials and composites for various applications, particularly in situations where flexural strength is a critical consideration.

Figure 66_ Flexure test setup (by author)



1. Unstabilized Earth:

- Failure Stress: 40 Kgf and 80 Kgf

Unstabilized earth, as the name suggests, is subjected to the test without any added stabilizing agents like fibers, lime, or cement. The results indicate that this material is characterized by a relatively low failure stress, with one specimen failing at 40 Kgf and another at a higher stress of 80 Kgf. The variability in results might be attributed to the inherent heterogeneity of natural earth materials.

2. Earth with Fiber:

- Failure Stress: 60 Kgf and 60 Kgf

Earth with fibers added is a composite material that is typically associated with improved tensile and flexural strength. In this case, both specimens were observed to have the same failure stress of 60 Kgf, which suggests that the addition of fibers has led to an enhancement in the material's resistance to bending. The consistent results may indicate that the fibers have been well mixed and distributed within the earth.

3. Earth with Lime:

- Failure Stress: 70 Kgf and 60 Kgf

Earth mixed with lime is often seen to exhibit improved strength and durability. The higher failure stress of 70 Kgf in one specimen suggests that the material's flexural strength has been positively influenced by lime. The lower value of 60 Kgf in the other specimen could be attributed to variations in lime content or differences in mixing procedures.

4. Earth with Cement:

- Failure Stress: 40 Kgf and 40 Kgf

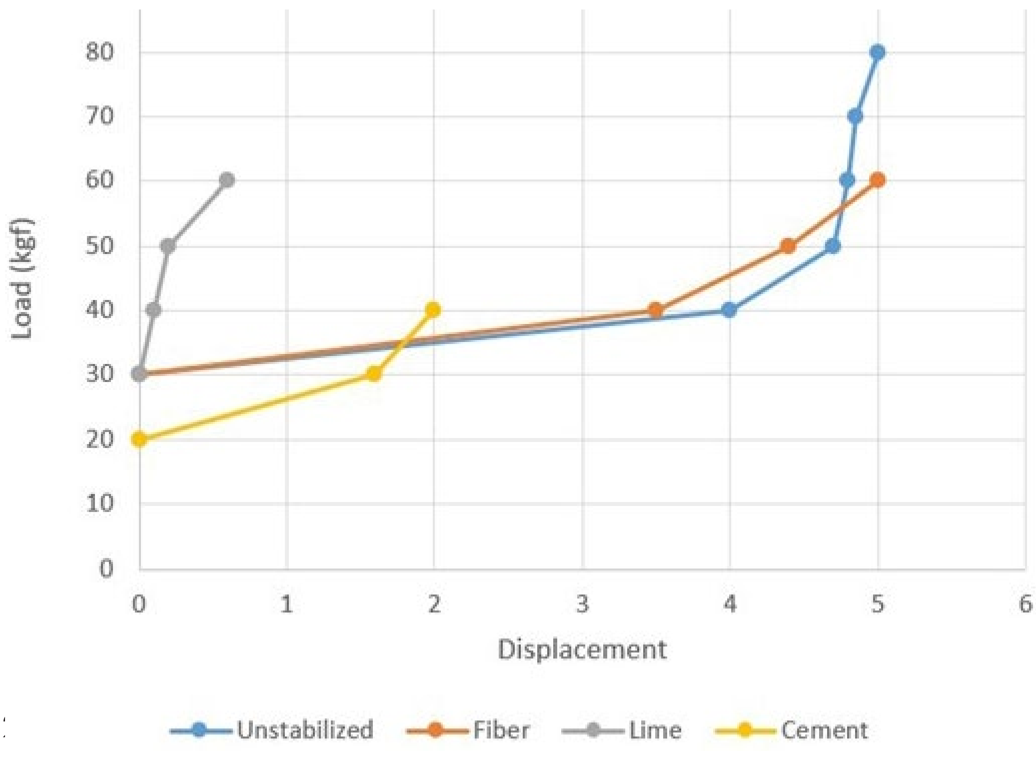
Earth mixed with cement is commonly used to stabilize earth materials. Surprisingly, it was observed that both specimens in this case exhibited a failure stress of 40 Kgf, which is the same as that of the unstabilized earth. This might indicate that the cement used did not effectively enhance the flexural strength of the material, or issues with the mixing process or curing may have been experienced.

	Unstabilized		Fiber		Lime		Cement	
	1	2	1	2	1	2	1	2
Weight/ mass (kg)	3.32	3.3	3.34	3.3	3.2	3.36	3.42	3.34
Side Length	25.2	25.2	25.1	25.1	25.1	25	25	25.3
Failure Stress (Kgf)	40	80	60	60	70	60	30	40
	Load	Displacement	Load	Displacement	Load	Displacement	Load	Displacement
	30	7	30	11	30	8.2	20	9
	40	11	40	14.5	40	8.3	30	10.6
	50	11.7	50	15.4	50	8.4	40	11
	70	11.85	60	16	60	8.8		
	80	12						
		5		5		0.6		2

Figure 67_ Flexure test results (by author)

In summary, the flexure test results suggest that the flexural strength of the earth material has been improved to varying degrees by the addition of fibers and lime, while no significant improvement in flexural strength was observed with the addition of cement. The variations in the test results can be attributed to factors such as material heterogeneity, mixing quality, and the effectiveness of the stabilizing agents used. Further analysis and experimentation may be required to optimize the earth-stabilizing process for specific applications. However, in general the results' values achieved by the tests are significantly low which indicate the necessity of using the post-tensioning system when using the earth in shell/ dome application. Therefore, for the next stage of the experiment, the neural unstabilized mixture was used since that it is the default mixture with no adidtives.

Figure 68_ Stress-strain curves of the different earth mixtures (by author)



5.4. Post-tensioning Structure

In order to achieve the proposed modular dome design, a partial dome mock-up that consists of one complete structure hexagon is designed and built. After producing the needed six modules for the mock-up, they were left to dry. Meticulous attention was paid to environmental conditions such as temperature and humidity, factors that play a vital role in the curing process. This precision in monitoring environmental variables guarantees the optimal development of material strength and cohesion within each module, laying the groundwork for a durable and stable final structure. Once the modules reached the desired level of dryness and curing, the assembly phase commenced. The next crucial step involved allowing them to undergo a thorough drying and curing process. This pivotal phase ensures the structural integrity and resilience of each component, setting the stage for a seamless assembly. The diameter of the mock-up structure is around 1.2 meters.

Structure Detailing

The assembly of several triangulated rammed earth modules was the most challenging part of the experiment. It has gone through various phases which in this experiment have gone relatively in parallel. First was the design of the mockup which involved defining tectonics of the different elements such as the module itself, the intermediate connections, the base and its connection as well.

Similar to the mold tectonics, the mock-up detailing also involved modulation that was different from that of the original concrete experiment. Since that the earth module form was influenced by the mold tectonics and now the triangle corners are perpendicular without any inclination that used to form the curvature of the dome, the proposed wooden connection has to take this role. Therefore, in contrast to the original concrete experiment where the connecting element was a flat metal element, the connection has to be wooden, and it needs to compensate the module corner angles[1]. Several trials were produced using the digital models to achieve the exact angles . The connection was designed also to have a recessed part in the middle to prevent the earth modules from huge movements in the assembly phase. However, it required many trials and errors to reach the adequate size of the recess.

1 The exact wooden connection dimensions can be found in the annexes.

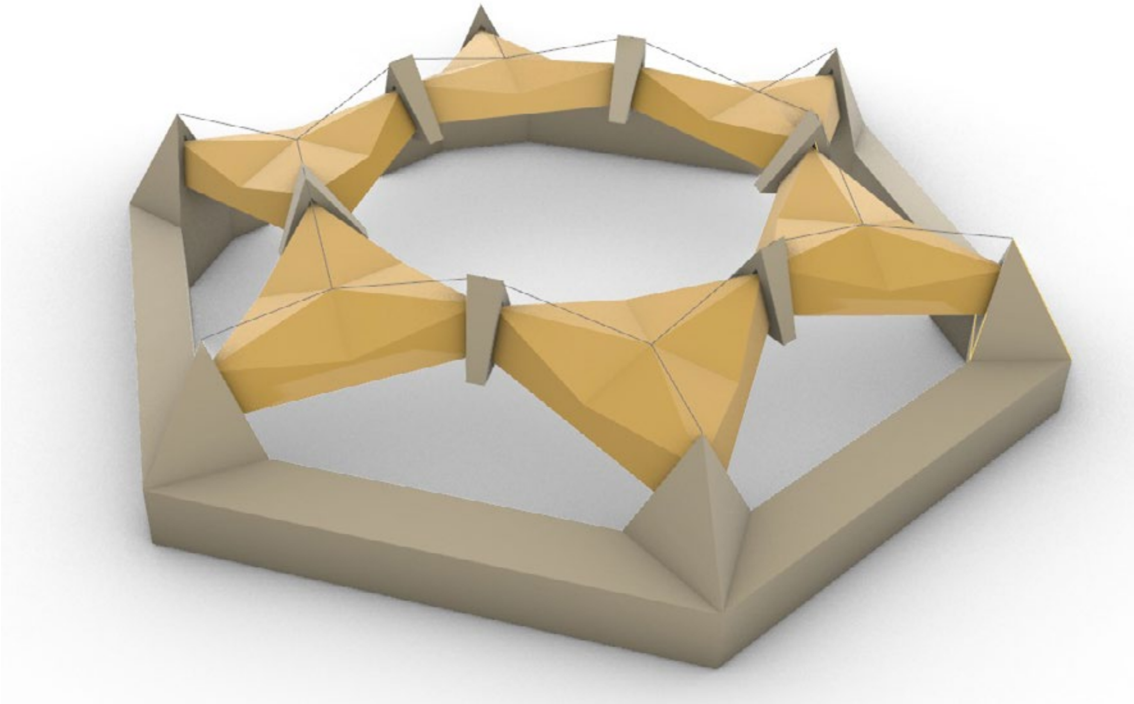
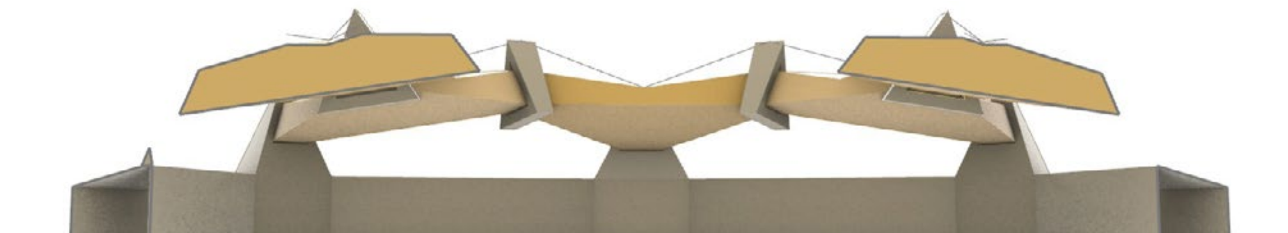


Figure 69_ Hexagon earth mock-up design using digital model (by author)



Additionally, holes punching through the wooden connection for the passage of the connecting wires was also challenging and had its own tectonics as well. The drilling machine was perpendicular, and the triangle has three different corner angles. Therefore, the connection was rested on another connection with opposite dimension so that it is drilled perpendicularly.

Figure 70_ Wooden connection and base fabrication (by author)

The incorporation of a tie beam in the base design adds a crucial element to the overall stability and cohesion of the modular dome mock-up. Much like the flooring mesh structure in traditional concrete constructions, the tie beam serves as a unifying force, connecting and reinforcing the entire assembly. This tie beam not only facilitates a robust connection between the earth modules but also mimics the well-established design principles of the original concrete structure. Its role in distributing and transmitting loads ensures a balanced distribution of forces throughout the mock-up, contributing to the overall strength and durability of the dome. The design of the connections between the earth modules and the tie beam is particularly noteworthy. The integration of drilling and a recessed central area in these connections enhances not only the structural integrity but also the visual cohesiveness of the dome. This meticulous attention to detail ensures that each module fits seamlessly into the larger structure, creating a unified and aesthetically pleasing whole.

Furthermore, the intentional elevation of the entire structure from the ground through the base design serves a dual purpose. Firstly, it allows for thorough testing of the mock-up's load-bearing capacity, providing valuable insights into its structural performance when assembled. Secondly, this design feature anticipates real-world scenarios where the structure may need to withstand varying ground conditions, showcasing a forward-thinking approach to the modular dome's adaptability and resilience. As the base lifts the structure, it establishes a clear separation between the dome and the ground, minimizing potential vulnerabilities and enhancing the overall reliability of the assembly. This holistic design approach not only ensures the immediate success of the modular dome mock-up but also sets a solid foundation for the scalability and applicability of this innovative design in broader architectural contexts.

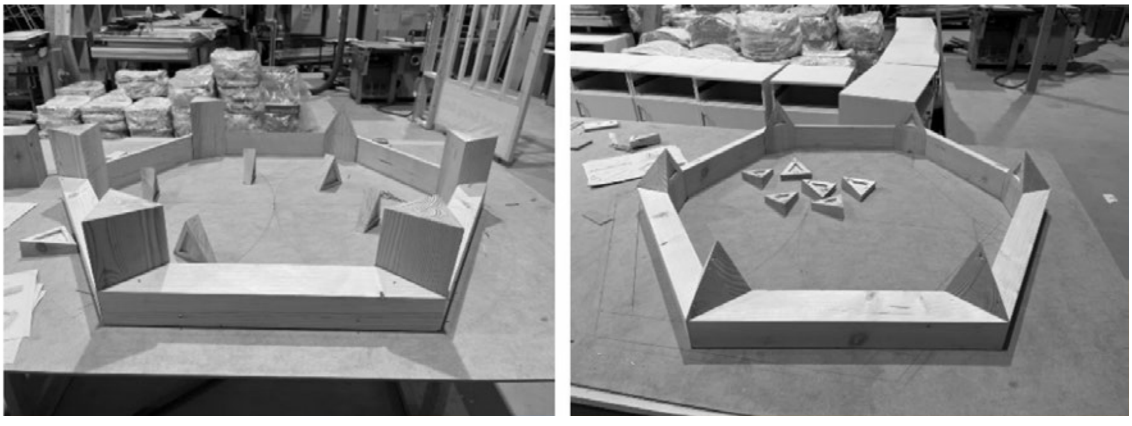


Figure 71_ Wooden base fabrication (by author)

Post-tensioning System

An external post-tensioned shell structure was previously done with concrete, but it was not successful when it came to the assembly of the different parts (Pedersen & Larsen, 2015). According to the authors:

> **"It was possible to use this approach to assemble a full-scale prototype assembly. Two ends of a large structure were subsequently made without falsework, though considerable propping was necessary. However, due to the weight of the sections and difficulties in tightening the wires, it was not possible to continue to mount sections of six preassembled parts."**

Moreover, when an interview was held with Prof. Larsen by the author, the professor clarified that this conclusion was reached due to a logistic/ administrative reason that deprived the team from completing this external post-tensioning mock-up. As a continuation for this research project, the authors had the chance to exhibit their work as a pavilion celebrating the 40th anniversary of Jorn Utzon's magnificent Sydney Opera House. The pavilion was called "Utzon 40" where they reconstructed the same previous mock-up idea but using internal post-tensioning structure and it worked successfully. However, not all of the structure was designed and constructed out of concrete. The upper part was built out of wood which raises some questions related to the ability of the concrete post-tension system to be assembled or work as integrated structure in these areas.

In the context of earthen materials, the utilization of the external post-tensioning method confers a significant advantage by effectively segregating tensioning cables from the primary structural module elements. This meticulous separation not only enhances the material's recyclability but also preserves it in its optimal condition for potential reuse without any loss in material or waste. Furthermore, the ramming technique employed in the formation of earthen modules necessitates a comprehensive densification process, requiring the entire element to undergo ramming. The introduction of tunnels within the ramming mold in the case of internal tensioning, however, introduces intricacies that may impede the process. There is a palpable risk of misplacement during densification, and conversely, the ramming around the inserted reinforcement may lack the desired precision.

An alternative approach for internal tensioning involves completing the earthen modules before drilling three longitudinal openings. Regrettably, this method compromises the overall stability of the element, posing challenges to its structural integrity. In contrast, the deployment of external post-tensioning permits the ramming of the entire earthen element with minimal openings, resulting in a substantial augmentation of structural strength. This innovative approach facilitates the independent production of earthen modules, decoupling the production process from the intricacies of assembling detailing, which can be seamlessly orchestrated at a subsequent stage without compromising the structural integrity of the elements.

Earthen Module Detailing

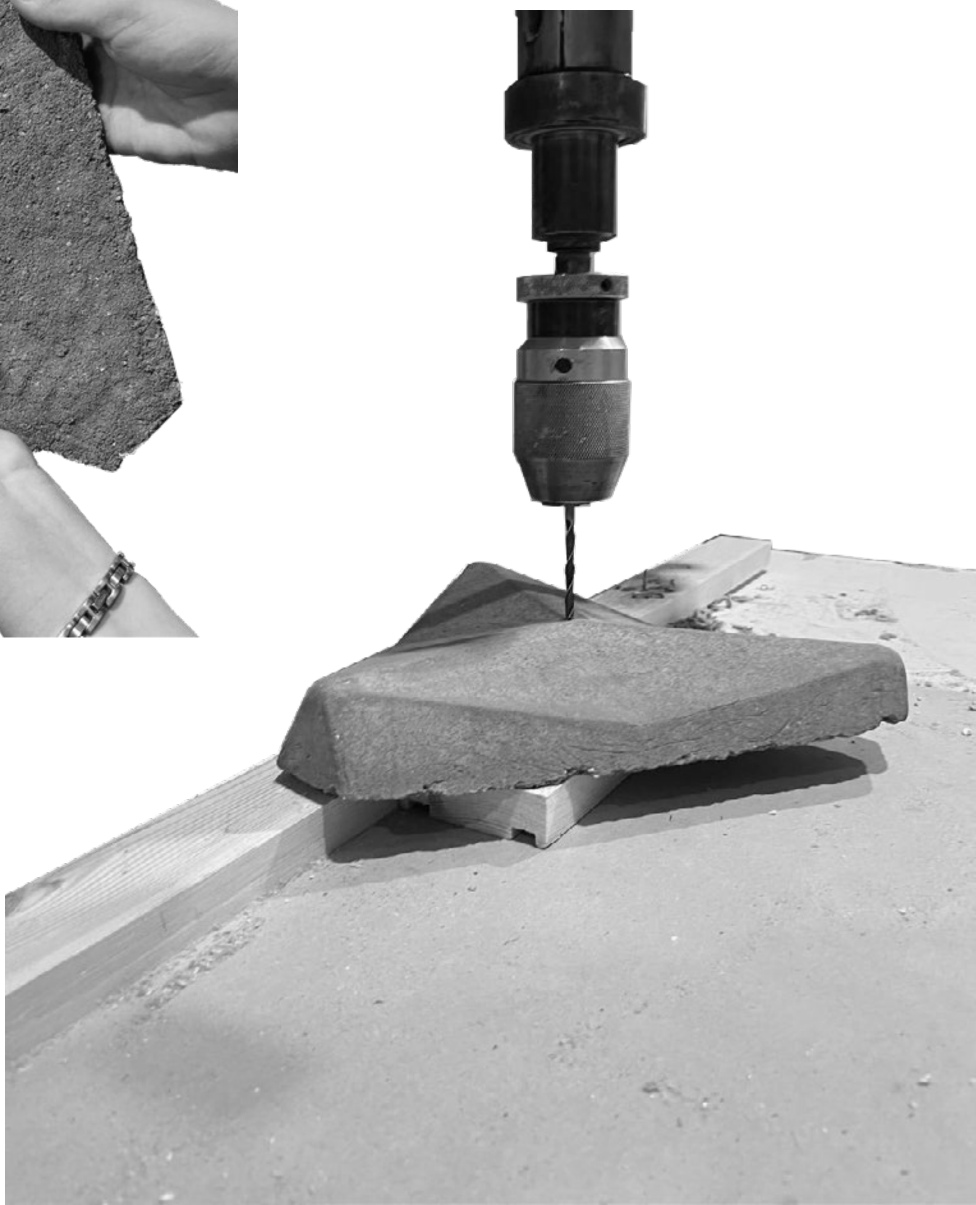
According to the external post-tensioning structure choice, the earthen module is detailed so that the system can be ready to work together as one holistic structure. This involved trials as it can be seen in figure 72. The modules were drilled from the exact middle by a perfectly perpendicular driller. This hole is created so that the element can be fixed with the connection wooden element and the base by the metal cable.

Assembly

The assembly process of the earthen structure unfolded methodically over two consecutive days, guided by a meticulous sequence that dictated each step of the construction. The narrative of these two days reveals a carefully orchestrated progression that sheds light on both the intricacies of the experiment and the challenges encountered during its execution.

The commencement of the experiment on the initial day was marked by the placement of three units. The active involvement of the author and two volunteers in this foundational stage underscores the hands-on nature of the construction process. This collaborative effort not only

Figure 72_ Earth Module Detailing and hole drilling (by author)



speaks to the practicality of involving individuals with diverse skill sets but also emphasizes the collaborative spirit inherent in experimental construction endeavors.

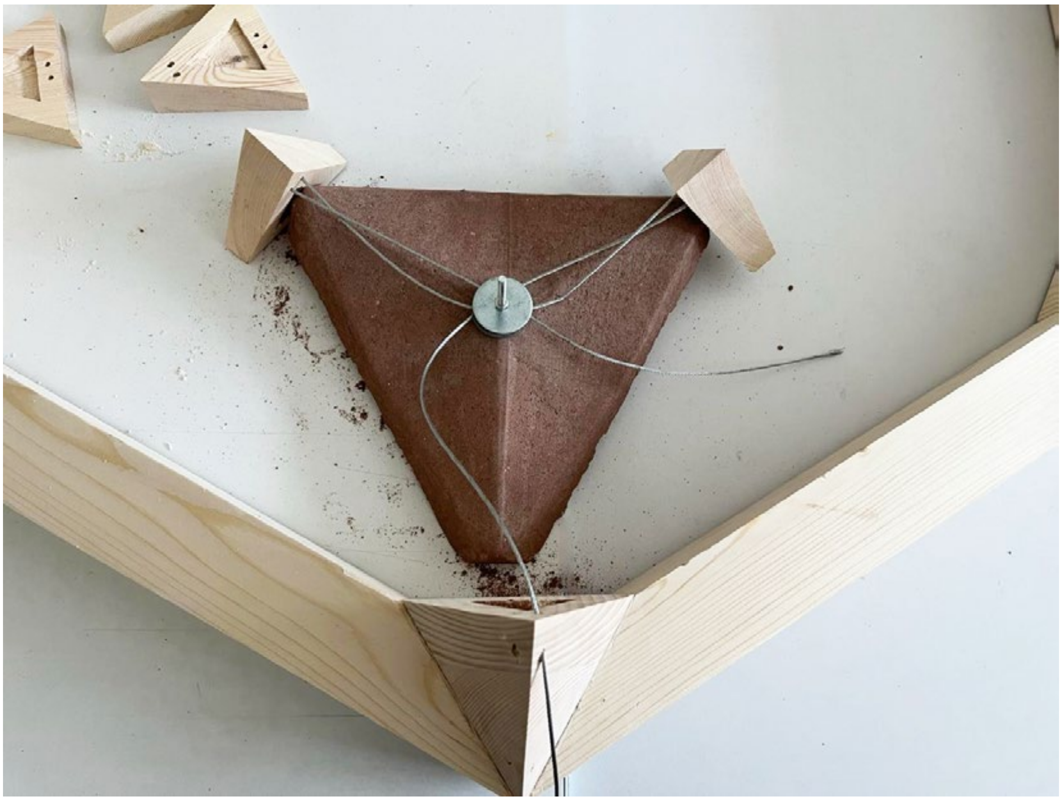
An interesting challenge that manifested early in the process was related to the wire connection. The task of securing both ends of the wire while the earthen element remained unplaced introduced a layer of complexity to the construction sequence. This challenge required a thoughtful and innovative approach, as the successful fixation of the wire connections was essential for the stability and integrity of the structure.

The intricacies of wire connection management reveal the nuanced nature of working with earthen materials and the need for adaptability in the face of unexpected challenges. The experiment›s transparency about encountering difficulties adds a realistic dimension to the narrative, portraying the construction process as an evolving and dynamic endeavor.

The outcome of the initial day›s efforts resulted in the successful fixation of only three elements. This limited progress underscores the careful and deliberate pace at which the experiment unfolded. It speaks to the commitment to precision and thoroughness, prioritizing the quality of construction over speed. The acknowledgment of the complexity faced on the first day sets the stage for a deeper exploration of the adjustments and optimizations that may be necessary in subsequent stages of the construction.

In summary, the two-day assembly process is characterized by a meticulous and collaborative approach, revealing both the successes and challenges encountered during the experiment. The focus on wire connection intricacies and the deliberate pace of construction emphasize the dedication to methodical experimentation and the pursuit of valuable insights into the behavior of earthen materials in structural applications.

Figure 73_ First assembly trial (by author)



An intriguing development emerged as the assembly unfolded, where the corners of the triangles attached to the wooden base underwent thinning due to multiple fixation attempts as shown in Figure 74. This nuanced issue highlighted the dynamic nature of the assembly process and underscored the importance of iterative adjustments to ensure structural integrity. The process of the first day can be shown in figure 75.

For 1st assembly day time laps, scan the QR code ..

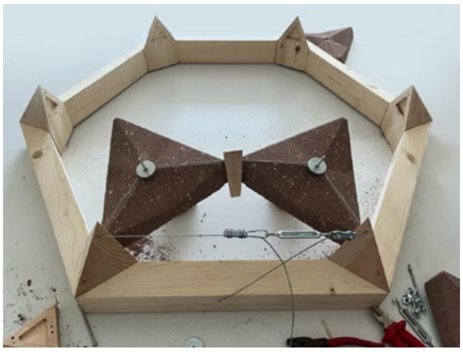


Figure 74_ Module corner thinning due to multiple fixation attempts (by author)

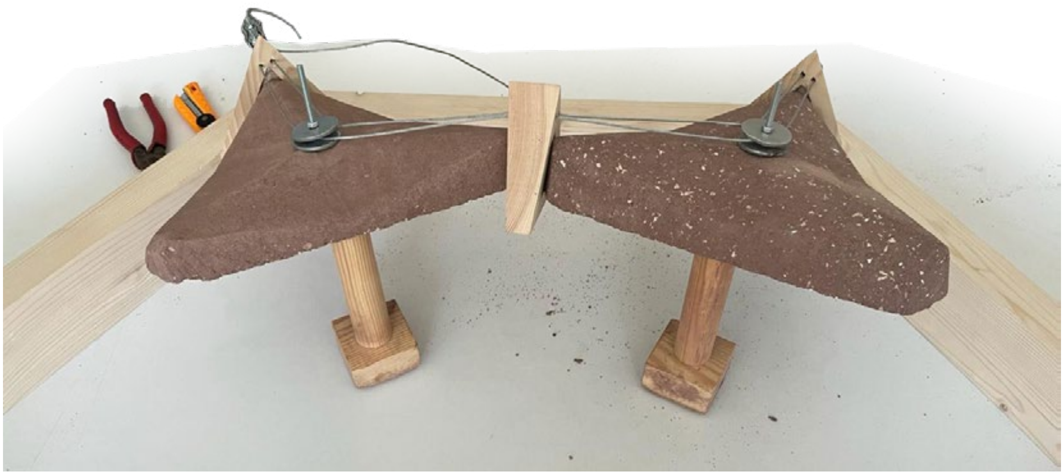


Figure 75_ Earthen modules ready to be assembled (by author)

As the experiment progressed to the second day, the remaining three earth modules found their designated positions, completing the assembly. Notably, a minimalistic support approach was adopted at the inception of the assembly, providing foundational stability for the earthen modules. However, as the process advanced, it became evident that not all units required continuous support, given their secure fixation with other modules and the wooden base. The supports were intricately cut at an angled orientation, mirroring the eventual triangle placement angle.

A pivotal aspect of the first day's proceedings involved the Intricate process of tying the metal endings in parallel with tightening the wire. This step, central to the assembly methodology, demanded precision and coordination among the three individuals involved. The sequence of events, from the initial wire connection challenges to the strategic placement of supports and the subsequent thinning of triangle corners, intricately woven together to form a comprehensive narrative of the

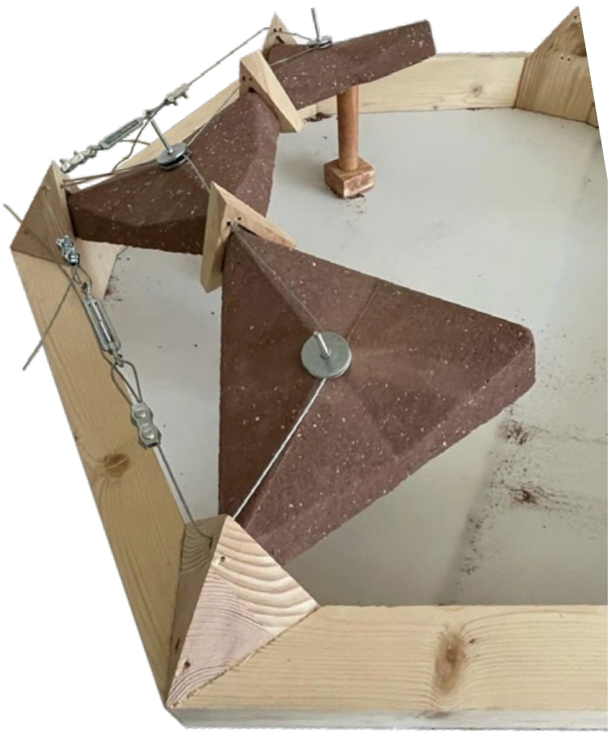


Figure 76_ First three units assembley (by author)

For 2nd assembly day time laps, scan the QR code ..

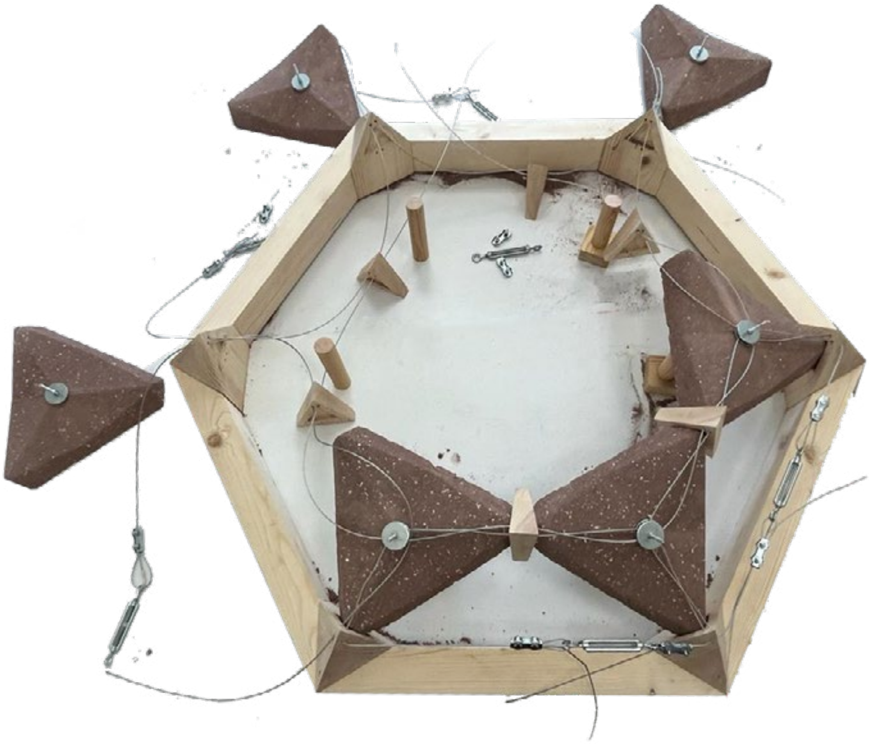
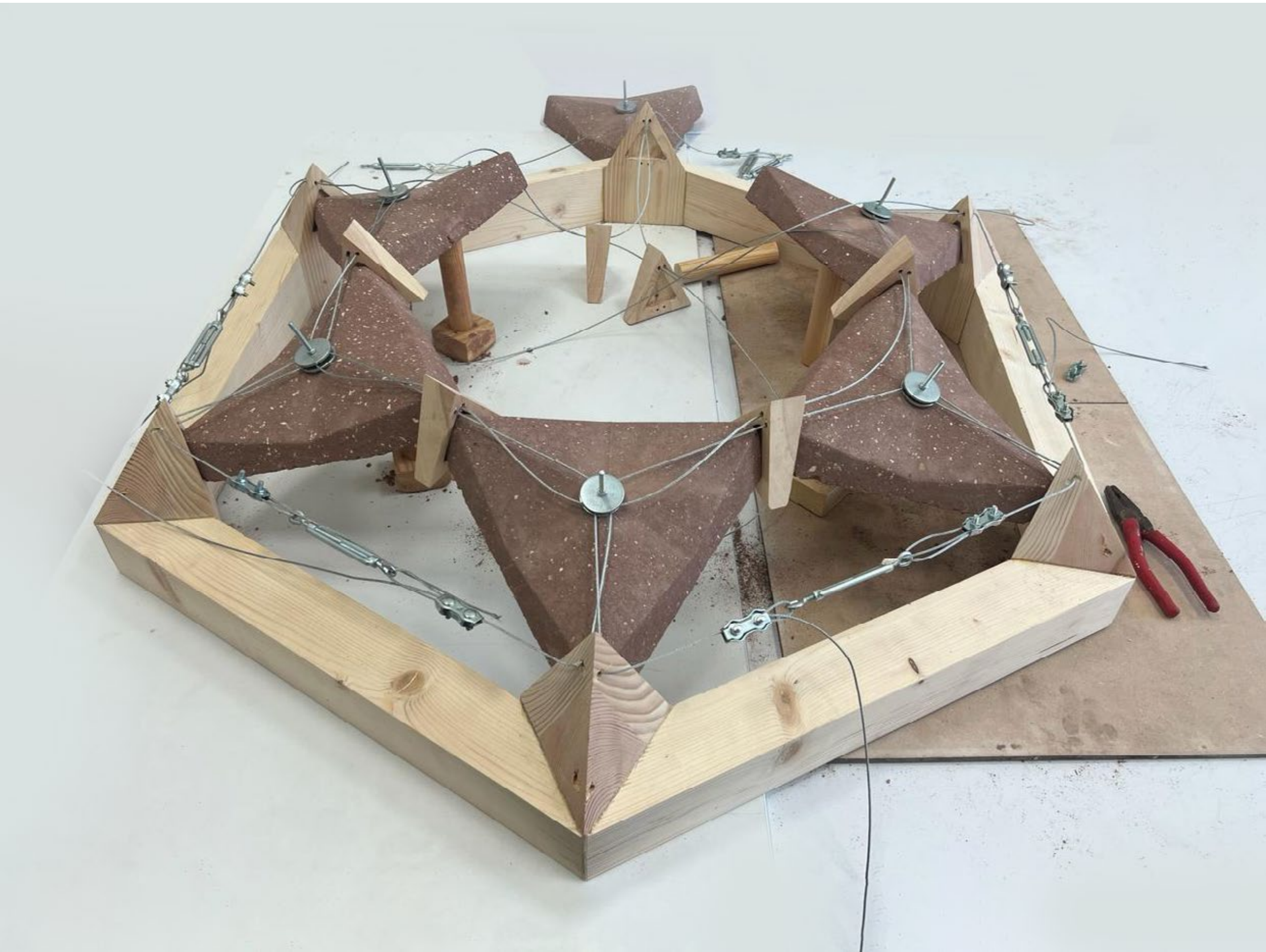


Figure 77_ Second day of mock-up assembly process (by author)



assembly process over the two days. This detailed account sheds light on the nuanced challenges encountered and the adaptive measures undertaken to achieve a successful and structurally sound outcome.

The process started by the first unit and the second units are tightened up as shown in Figure 75. Every two units are connected with a metal cable and when all the units are in place, all the connections and the units were closely connected with another cable in a closed loop. The process of the second day can be shown in figure 78.

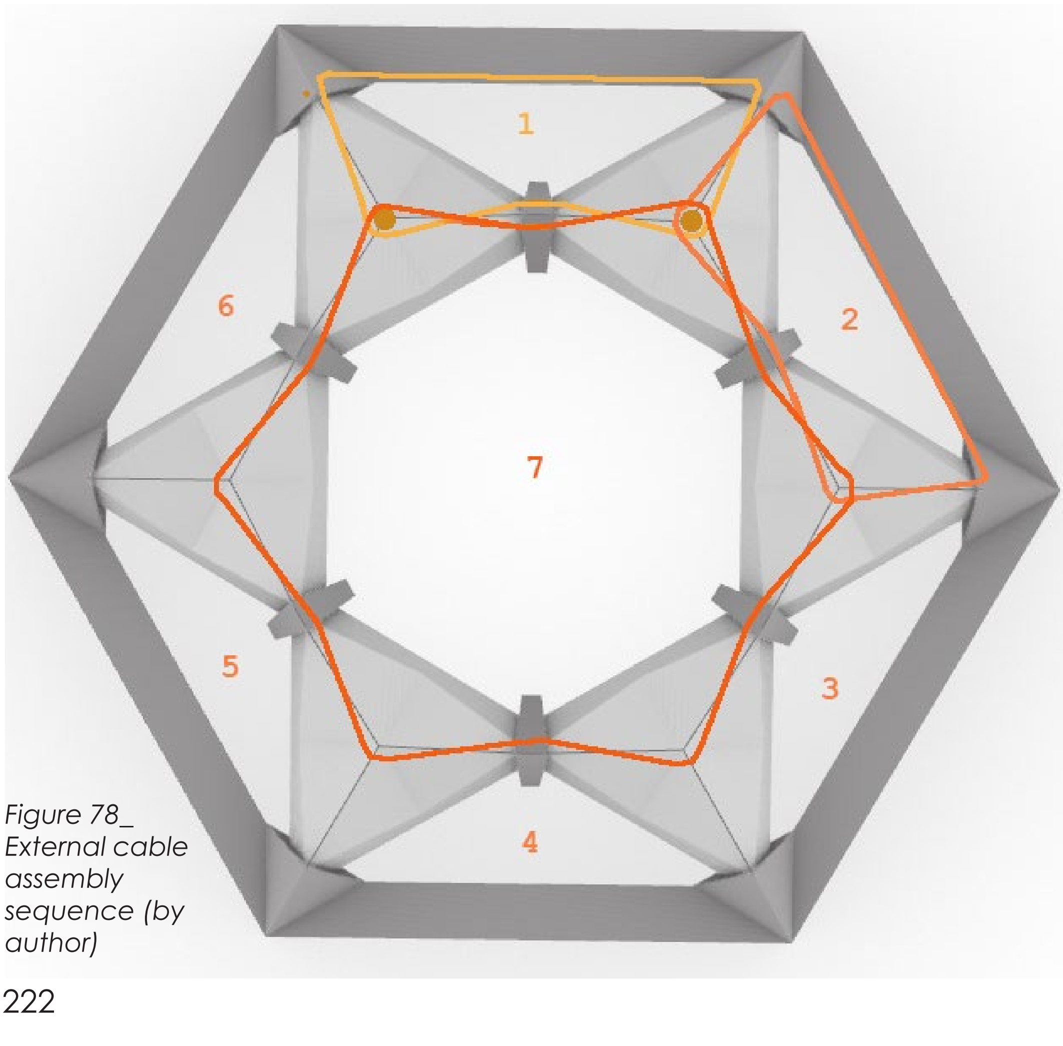
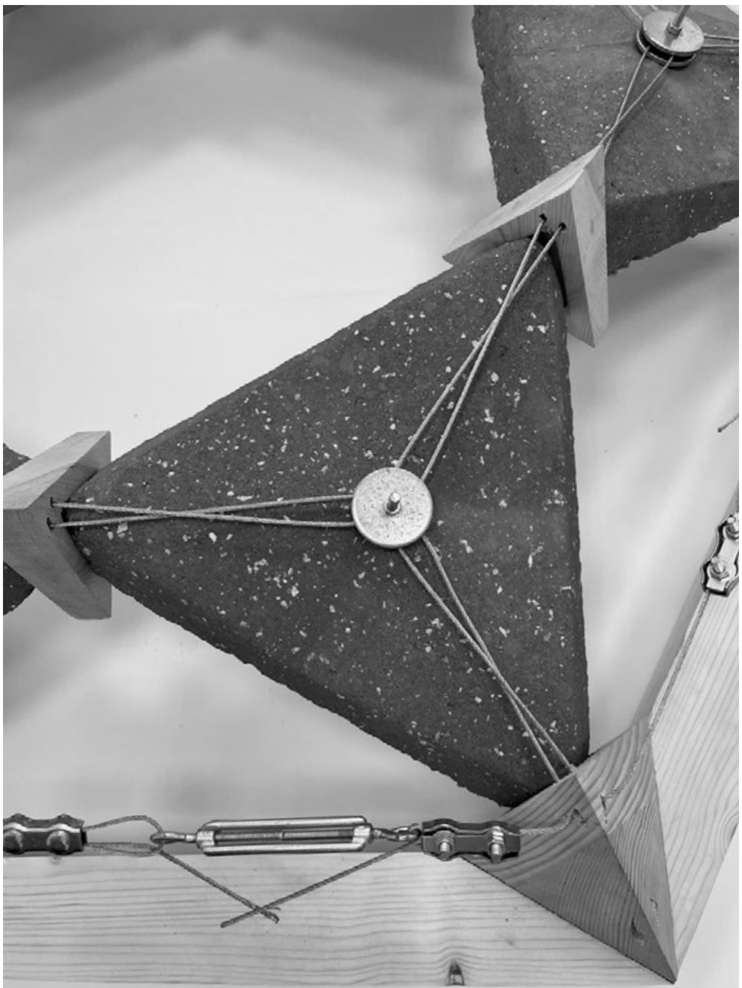
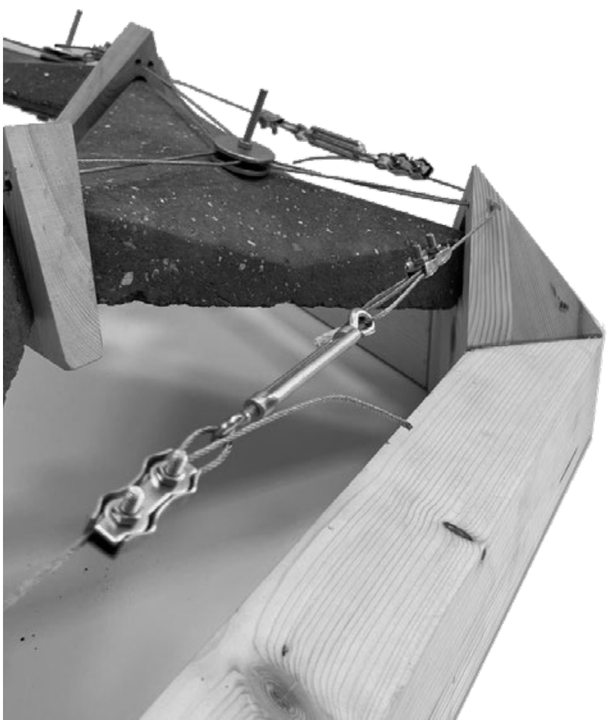


Figure 78_ External cable assembly sequence (by author)





Upscaling

The potential scalability of this experiment introduces a realm of possibilities, allowing for not only an enlargement of the overall scale but also the replication of the process with an increased number of elements. This adaptability aligns with the evolving demands of construction projects, providing a modular framework where every six elements can be meticulously assembled and prestressed together. Once prestressed, these consolidated units can be efficiently transported to the site, where they seamlessly integrate with another set of six units. This modular approach not only streamlines construction logistics but also facilitates the construction of larger structures with enhanced efficiency and structural integrity.

In essence, the experiment transcends its immediate applications, offering a blueprint for construction methodologies that balance adaptability, sustainability, and aesthetic considerations. The progressive integration of modular assembly, water preservation measures, and future-oriented design possibilities positions this experiment at the forefront of contemporary construction practices, poised to shape the future of architectural innovation.


RESULTS AND REFLECTIONS

The final design and the applied connection system guaranteed the possibility of reusing the single segment units to suit further construction designs and other constellations. This was set in the initial design phase to guarantee a closed-material cycle of the constructed temporary building. In Figure 22, the panels were flattened to suit a façade cladding system, showcasing this possibility.

Figure 79 _ Results and reflection of a similar pavilion (Dahy, Baszyński, and Petrš 2019)

As the main structure assumes a pivotal role, its versatility becomes increasingly evident. Beyond its primary function, the shell can be repurposed as a shading element, adding an additional layer to its multifunctionality. Looking towards the future, the prospect of infill elements emerges as an exciting avenue for architectural innovation. These infill elements, thoughtfully designed to fill the spaces between hexagons, could incorporate advanced materials such as glass panels or straw pattern. This forward-thinking approach not only enhances the aesthetic appeal but also augments the structural and thermal properties of the construction, paving the way for sustainable and technologically advanced architectural solutions.

Shell structure are special because of its wide span covering using very small material cross section. There for most of the stadiums are coverd using shell structures. Since that earth was not tested for roofing such big spans, the upscaling of the structure cans start by small size rooms roofing to medium scale to big scale buildings.

The structure was tested into mock-up in a dome orientation to test its structural performance. However, its application is vast when explored as commercial or office buildings› secondary shading façades can be as a great protection from direct sunlight and ensure better indoor quality.

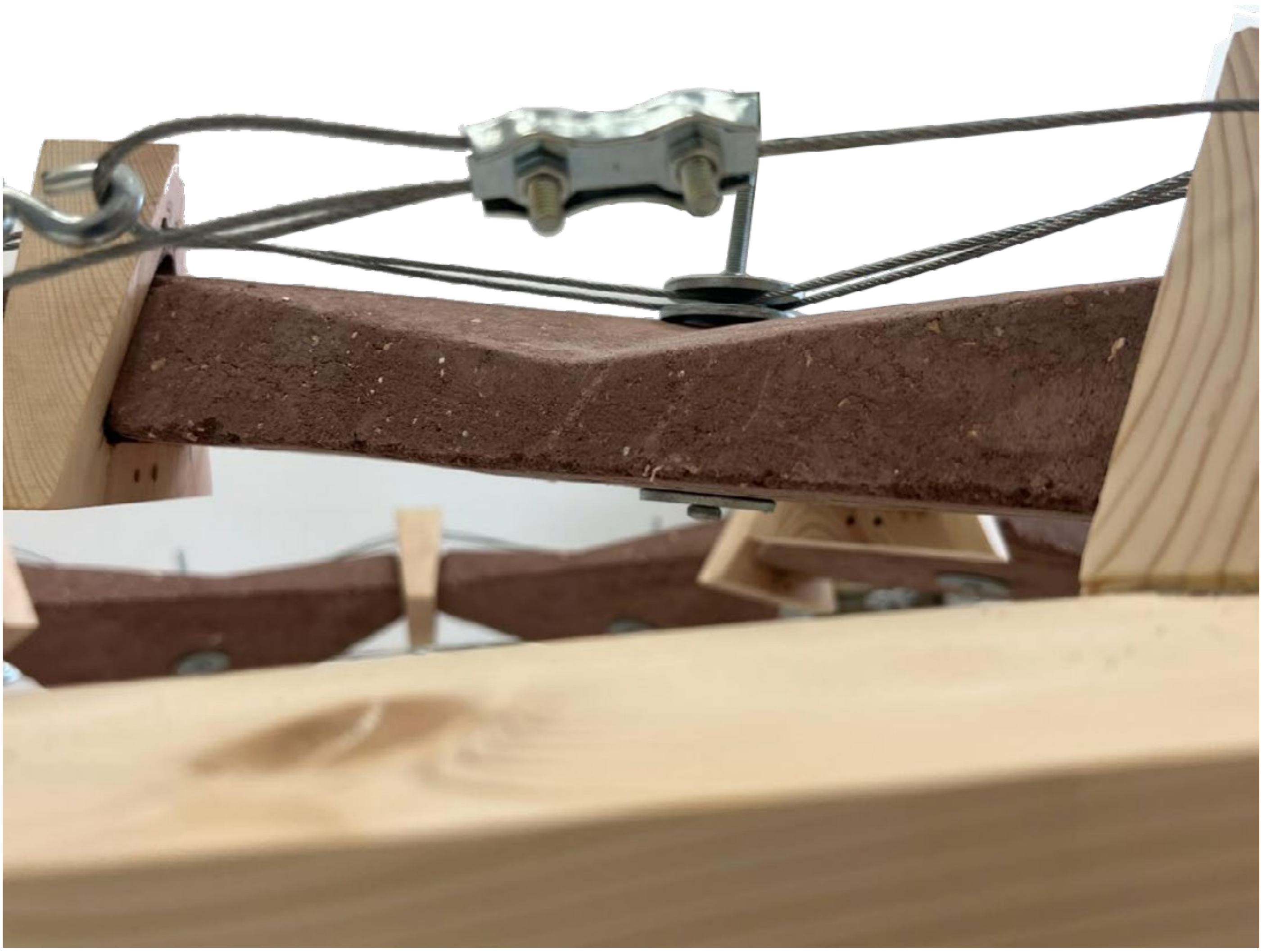
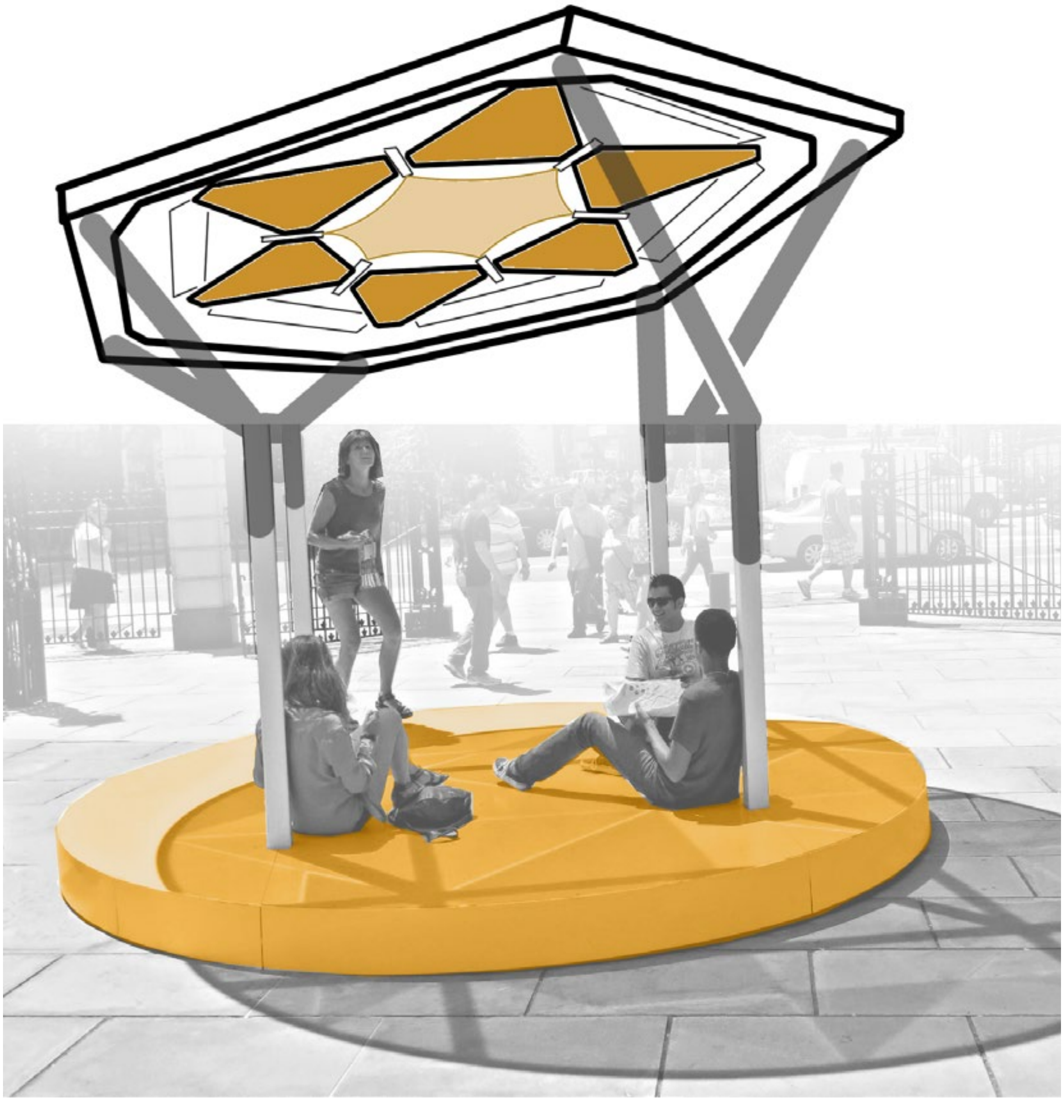
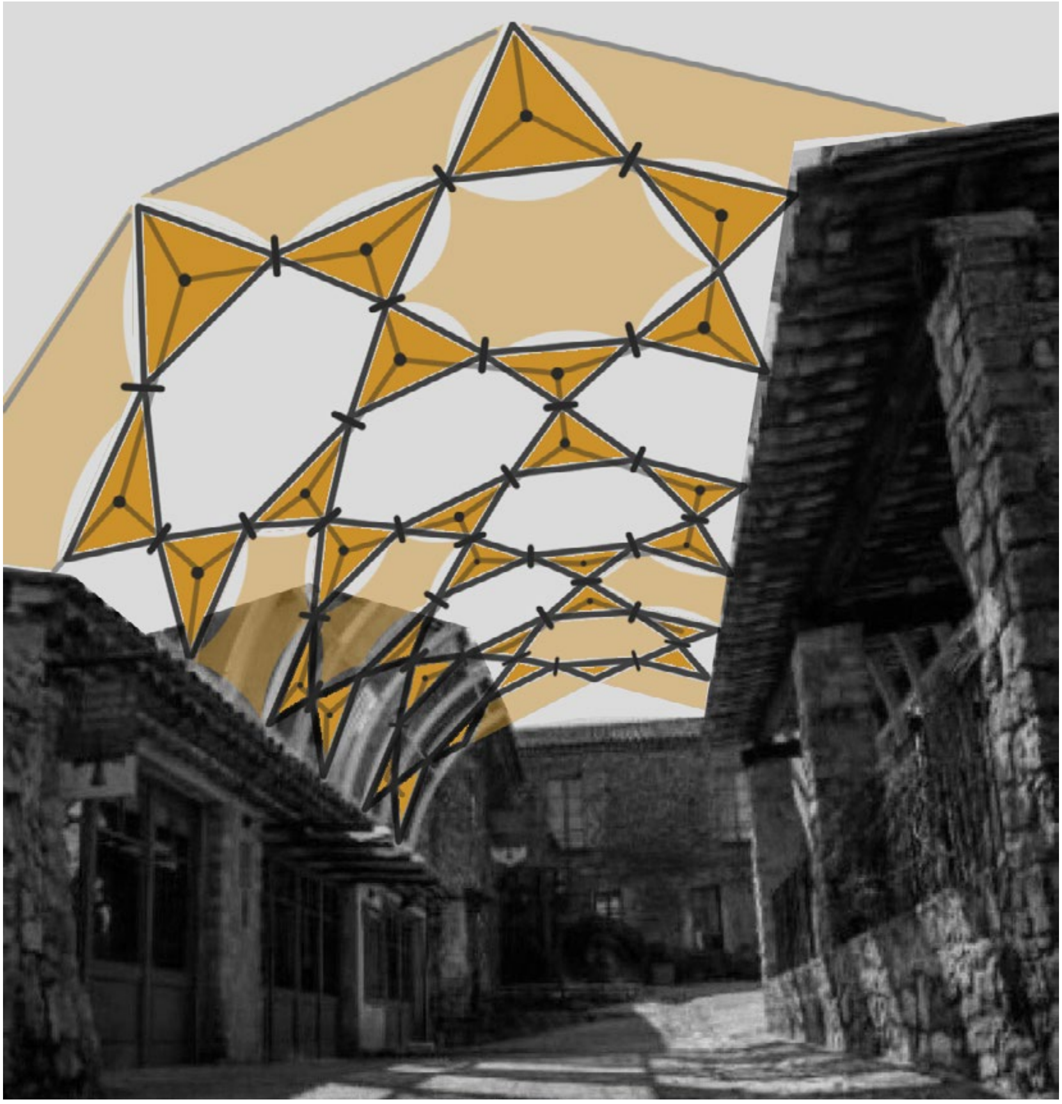


Figure 80 _ Final Mock-up detILS (by author)



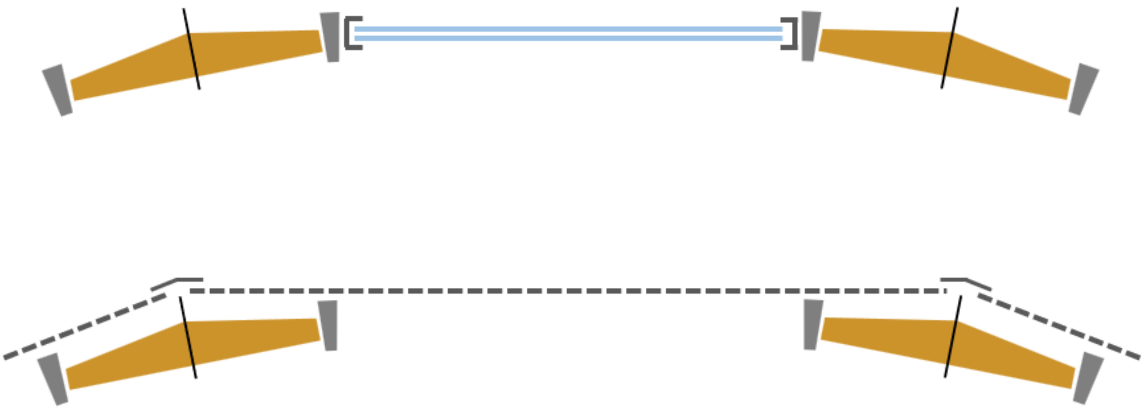
SCALABILITY |
TEMPORARY STRUCTURE |

First Scale: Urban furniture



SCALABILITY |
OUTDOOR (COURTYARD) |

Second Scale: Small spans



SCALABILITY |
INDOOR |

Third Scale: Big spans

_ Building Dome (Factory)
glass infill/ Fabric/
Corrugated sheets

SCALABILITY |
OUTDOOR |

Fourth Scale: Big spans

_ Building Dome (Stadium)
Cushion roof

Figure 81_ Final Mock-up (by author)

Chapter Conclusion

In this research, an experimental approach is taken to develop a post-tensioned structure using earthen materials, inspired by Larsen›s concrete experiments. The design focuses on an external post-tensioned structure to leverage the strength of earthen materials in compression. The chosen triangular structural form is preferred for its potential stability and reduced risk of cracks compared to other forms. The transition from concrete to earthen materials requires adjustments in various tectonic aspects, including construction technique, mixture composition, mold design, connections, detailing, and fixations. These factors are systematically explored and experimented with in three phases: mold tectonic experimentation, earth mixture definition, and detailing for mock-up execution. The objective is to uncover rammed earth tectonic potentials while maintaining the recyclability and simplicity of earthen materials in construction, with considerations for mechanical fixations and a low carbon footprint.

A new significant aspect is being conformed from the experimentation: the connection tectonics. The post-tensioning structure implies the design of a connection between the different elements. The connection on its own has material, production technique and form.

The experimentation focuses on form, module design, and mold tectonics. The form design evolves from an initial freeform vault to a modular dome with a triangular structure, balancing aesthetics, modularity, and cost-effectiveness. Continuous refinement occurs in module design, incorporating insights from interviews and adapting to mold tectonics. Mold tectonics are explored through

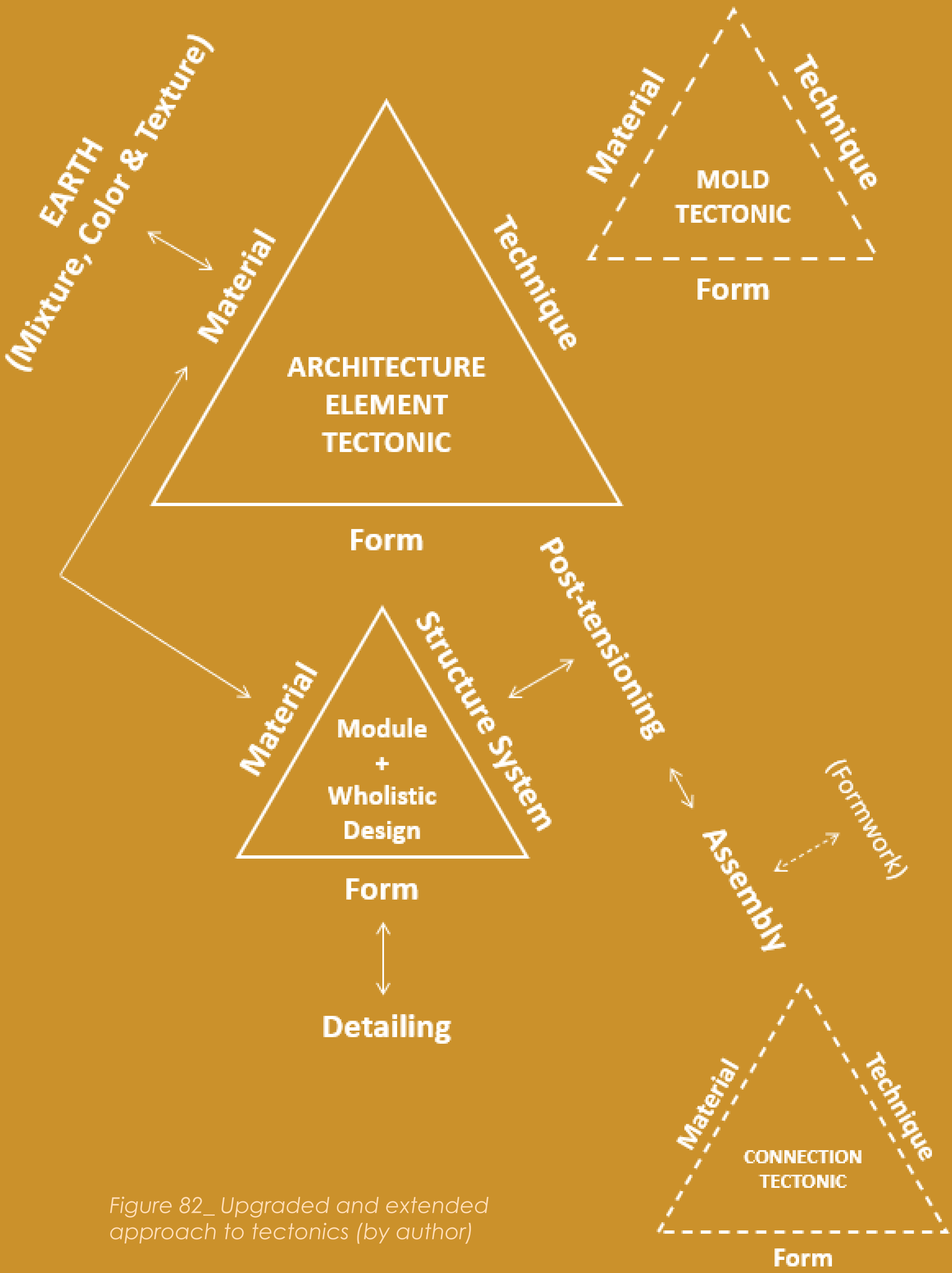


Figure 82_ Upgraded and extended approach to tectonics (by author)

three trials using cardboard, adobe, and wood, revealing the intricate interplay between mold design and earth material characteristics. Challenges related to structural integrity, form accuracy, and adaptability are addressed, with innovative solutions proposed. The iterative approach, combining traditional craftsmanship and technological advancements, showcases a commitment to pushing the boundaries of architectural design with earthen elements.

The research employs an experimental methodology to explore the use of earthen materials in constructing post-tensioned structures, drawing inspiration from Larsen›s concrete experiments. The study covers various aspects, including holistic structure design, module design, mold tectonics, post-tensioning structure, and the mixture of earthen materials. Holistic structure design shifts from an initial free-form vault to a modular dome with triangular forms, ensuring modularity and cost-effectiveness. Mold tectonics, vital for shaping earthen modules, undergo trials using different materials, highlighting challenges and improvements. The mixture phase involves flexural strength testing of diverse earth mixtures, revealing variations in flexural strength based on the mixture. The post-tensioning structure phase explores an external post-tensioning system, emphasizing recyclability and structural strength. The assembly process, using metal cables, demonstrates the feasibility of the proposed modular dome design, concluding with discussions on scalability and future applications in larger construction projects.

Conclusion

Chapter 6

Earth Materials Upcaling

New Application	New Structure	New Form	New Tectonics

Conclusion and Future Research Recommendations

Part 3
CONCLUSIONS

Chapter 06

CONCLUSION

06 CONCLUSION

The untapped potential of earthen materials in accommodating various advanced forms and applications stands as a testament to their remarkable structural abilities. In a paradigm shift that challenges conventional perceptions, designers and engineers are discovering the extraordinary versatility of these age-old materials. The realization that earthen materials possess the capacity for innovative applications, previously unimagined, underscores the transformative journey unfolding in the field of construction.

What sets this exploration apart is not only the inherent potential of earthen materials but also the merging of historical tectonic knowledge, traditional handcraft techniques, and an unwavering will and dedication to embrace new possibilities. The integration of these elements forms the cornerstone of the material's tectonic upgrade—a departure from the familiar to a realm of uncharted possibilities.

Earthen materials, often associated with traditional and vernacular construction, are now being reimagined with a contemporary lens. The understanding of their previous tectonic knowledge, rooted in centuries-old building practices, serves as a foundation upon which new design principles are being built. The evolution from traditional tectonics to modern applications requires a careful reinterpretation of historical practices, blending them with cutting-edge engineering and architectural innovations.

Handcraft, another critical element in this transformation, brings a human touch to the process. The tactile expertise of artisans in working with earthen materials, improved over generations, plays a pivotal role in shaping the material into forms that defy conventional expectations. The synergy between technology and craftsmanship becomes apparent as traditional handcraft techniques are refined and complemented by contemporary tools, ensuring precision and finesse in the execution of complex forms and designs.

Perhaps the most influential factor in this recovery of earthen materials is the spirit of experimentation—the strong will and dedication to endeavor beyond established norms. The willingness to embrace the unknown, coupled with a determination to challenge preconceived limitations, propels designers and engineers to push the boundaries of what earthen materials can achieve.

This proactive approach to experimentation not only results in novel applications but also contributes to a broader shift in the construction paradigm. Earthen materials are no longer confined to the margins of traditional construction; they are emerging as viable contenders for sustainable and innovative architectural solutions. The material's tectonic upgrade is a dynamic process driven by a collective vision of creating structures that not only perform exceptionally but also contribute to a more sustainable and resilient built environment.

In summary, the newfound potential of earthen materials, coupled with a reevaluation of tectonic knowledge, handcraft traditions, and a spirit of experimentation, is ushering in a new era in construction. The journey from historical practices to modern applications is marked by a commitment to explore the uncharted, transforming earthen materials into a dynamic and versatile resource for designers and engineers eager to redefine the possibilities of sustainable architecture.

The development of the thesis aims to validate the hypothesis that by leveraging historical tectonic knowledge, traditional handcraft techniques, and modern engineering innovations, earthen materials can be transformed into dynamic and versatile resources for sustainable architecture.

In conclusion, chapter 2 in this thesis has thoroughly investigated the trials and techniques undergone by earthen materials in construction, showcasing their evolution from basic walls to integrated slabs and roofs. Through a synthesis of human creativity and technological progress, significant advancements have been made in employing earthen materials across various architectural elements.

In chapter 3, the examination of contemporary building materials, particularly concrete and bricks, has revealed substantial technological progress. Shell structures, explored as compression-only structures, have been extensively experimented with in pavilion-scale prototypes by numerous research groups, marking a significant advancement in architectural innovation.

The experimentation, in the methodology chapter 4, presented in this chapter were analyzed through the lenses of module design and holistic structure design. The adoption of the M-F-T (Material-Form-Technique) tectonic concept has enabled a modular approach, enhancing flexibility in design and construction, while ensuring structural integrity and aesthetic coherence at a holistic level.

Furthermore, the application of the M-F-T concept has propelled the development of shell structures, leveraging the synergistic relationship between material properties, form, and construction techniques. This approach has led to groundbreaking advancements in structural efficiency, sustainability, and aesthetic expression, pushing the boundaries of conventional design paradigms.

In the methodology section, the research design was meticulously tailored to address real-world problems and integrate technology for innovative tectonics and structural systems. Applied and exploratory research methods were employed, with an experimental approach focused on developing external post-tensioned shell structures using earthen materials.

The experimentation process, conducted in three phases, rigorously tested variables such as mold materials, earth mixtures, and post-tensioned structure systems. Iterative design and meticulous testing ensured the refinement of fabrication techniques, underlining the robustness of the research design.

In summary, this thesis has contributed significantly to advancing contemporary building materials and architectural engineering. Through a combination of innovation and interdisciplinary collaboration, it has paved the way for functional, inspiring structures that seamlessly integrate with their environment while pushing the boundaries of conventional design paradigms.

Limitations

The partial completion of the dome structure introduces intriguing questions regarding the assembly process and the requisite falsework needed for its construction. The decision to construct only a portion of the dome not only adds an element of curiosity but also highlights the deliberate and phased nature of the thesis, emphasizing a meticulous approach to experimentation and testing.

One of the primary inquiries arising from the partial construction is related to the structural assembly strategy. Understanding how specific segments of the dome were selected for construction provides valuable insights into the engineering considerations and design rationale. Whether driven by material testing, prototype development, or other factors, this selective approach to assembly raises questions about the iterative nature of the construction process.

Moreover, the mention of needed falsework adds an additional layer of complexity to the structural puzzle. Falsework, essential for supporting and stabilizing structures during construction, becomes a critical element in the methodology employed. Questions may arise regarding the design and implementation of the falsework system—how it was tailored to accommodate the unique characteristics of earthen materials and the specific challenges posed by the dome's unconventional geometry.

The decision to leave certain portions incomplete may also be rooted in a desire to evaluate the structural performance under different stages of construction. This phased approach allows researchers to assess the material's behavior and the structural integrity of the dome at various stages, offering valuable data for refining the construction methodology and informing future projects.

Additionally, the partial construction prompts considerations about the aesthetic and functional aspects of the completed structure. How will the unfinished sections integrate with the final design? What impact will the phased construction have on the overall appearance and functionality of the dome? These questions open avenues for exploring the interplay between form and function in the context of earthen construction.

The deliberate choice to leave parts of the dome unfinished may also have educational implications. It provides a tangible learning experience for researchers, students, and professionals involved in the project, offering opportunities to analyze and understand the evolving dynamics of earthen structures throughout the construction process.

In essence, the decision to partially construct the dome structure not only raises questions about assembly techniques and the role of falsework but also invites a deeper exploration of the iterative nature of the construction methodology. It underscores the commitment to a systematic and thoughtful approach, where each phase of construction serves as a valuable learning opportunity, contributing to the ongoing evolution of knowledge in the domain of earthen architecture.

Future Research

Navigating the complexities of water resistance, especially in the context of roofing applications, prompts an in-depth exploration of earth water preservation methods within the scope of this experiment. Recognizing the shell's predominant role as a roofing structure, the research takes a comprehensive and strategic approach to investigate and implement effective erosion checks. This dedicated exploration aims to fortify the material's resilience against water-induced degradation, ensuring that it can withstand environmental challenges over the course of time.

The choice of a shell as a roofing structure underscores the importance of addressing water resistance, as roofs are particularly vulnerable to the detrimental effects of moisture, rainfall, and other environmental elements. Unlike conventional roofing materials, earthen shells require a specialized understanding of water preservation techniques that align with their unique composition and properties.

The holistic approach adopted in this experiment encompasses a multifaceted examination of earth water preservation methods. This involves investigating various treatments, coatings, and additives that can be applied to the earthen material to enhance its resistance to water infiltration. Additionally, the experiment explores innovative design features aimed at redirecting and mitigating water runoff, reducing the potential for erosion and water-related damage.

The strategic consideration of erosion checks is crucial for ensuring the long-term durability of the earthen roofing structure. By implementing effective measures to counteract erosion, the experiment aims to prolong the life cycle of the material, minimizing the need for repairs and maintenance. This not only contributes to the economic viability of earthen roofing solutions but also aligns with sustainable construction practices by reducing the overall environmental impact associated with frequent repairs or replacements.

Moreover, understanding and implementing erosion checks contribute to the broader goals of environmental conservation. By mitigating water-induced degradation, the experiment strives to create roofing structures that are not only durable but also environmentally friendly. This is particularly relevant in regions where water scarcity or irregular weather patterns pose significant challenges to traditional construction materials.

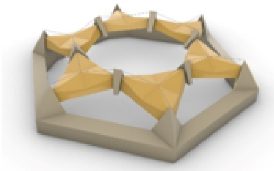
Another solution can be the same as the one adopted in ETH earth dome presented in chapter 2. The climate in Switzerland is usually experiences excessive rain and the dome mock-up is outdoor. Therefore the research team used a permanent cover on the upper parts of the dome to prevent the water from reaching the earthen structure.

Besides, the prototype needs to undergo different weathering tests, earthquake and fire resistance tests in an attempt to measure its durability. These tests will also promote this structural validity and further develop the experimentation in real building application.

The dedicated exploration of earth water preservation methods, with a focus on effective erosion checks, underscores the commitment of this experiment to address the unique challenges posed by water resistance in earthen roofing applications. The holistic approach adopted in the research not only aims to enhance the material's resistance to environmental factors but also aligns with sustainable construction practices, promoting the development of resilient and environmentally conscious building solutions.

COMPARATIVE ANALYSIS

TECHNICAL



	EARTH POST_TENSIONED	EARTH VERNACULAR	CONCRETE POST_TENSIONED
Design Flexibility	Compression and tension (live load)	Compression only	Compression and tension
Openings	Maximum/ flexible	Minimum	Maximum/ flexible
Cross-section	Till 10%	Standard	Till 10%
Material efficiency	Minimum use	Standard	Minimum use
Own weight	medium	heaviest	low

ENVIRONMENTAL

	EARTH POST_TENSIONED	EARTH VERNACULAR	CONCRETE POST_TENSIONED
Recyclable	Completely and easily	completely	Partially / not recyclable
Waste Accumulation	no	no	yes
Embodied Energy	low	Very low	High heated to about 1450°C
Indoor Air Quality	Positive/ partial depends on the infill	positive	negative
Material availability	everywhere	everywhere	Cement: mines and quarries

Declaration of generative AI and AI-assisted technologies in the writing process. During the preparation of this work the author used AI tool in order to refine written text style. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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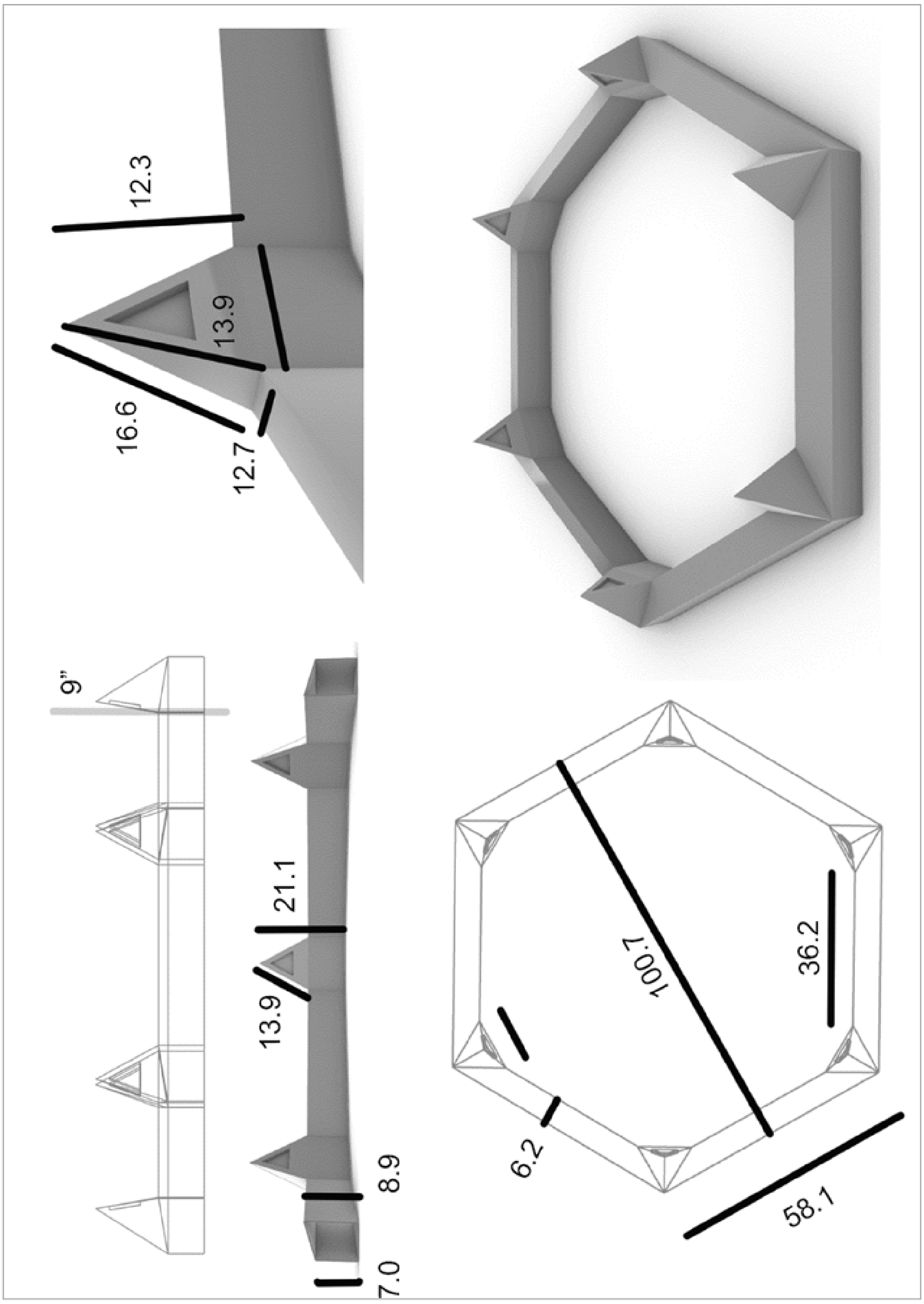
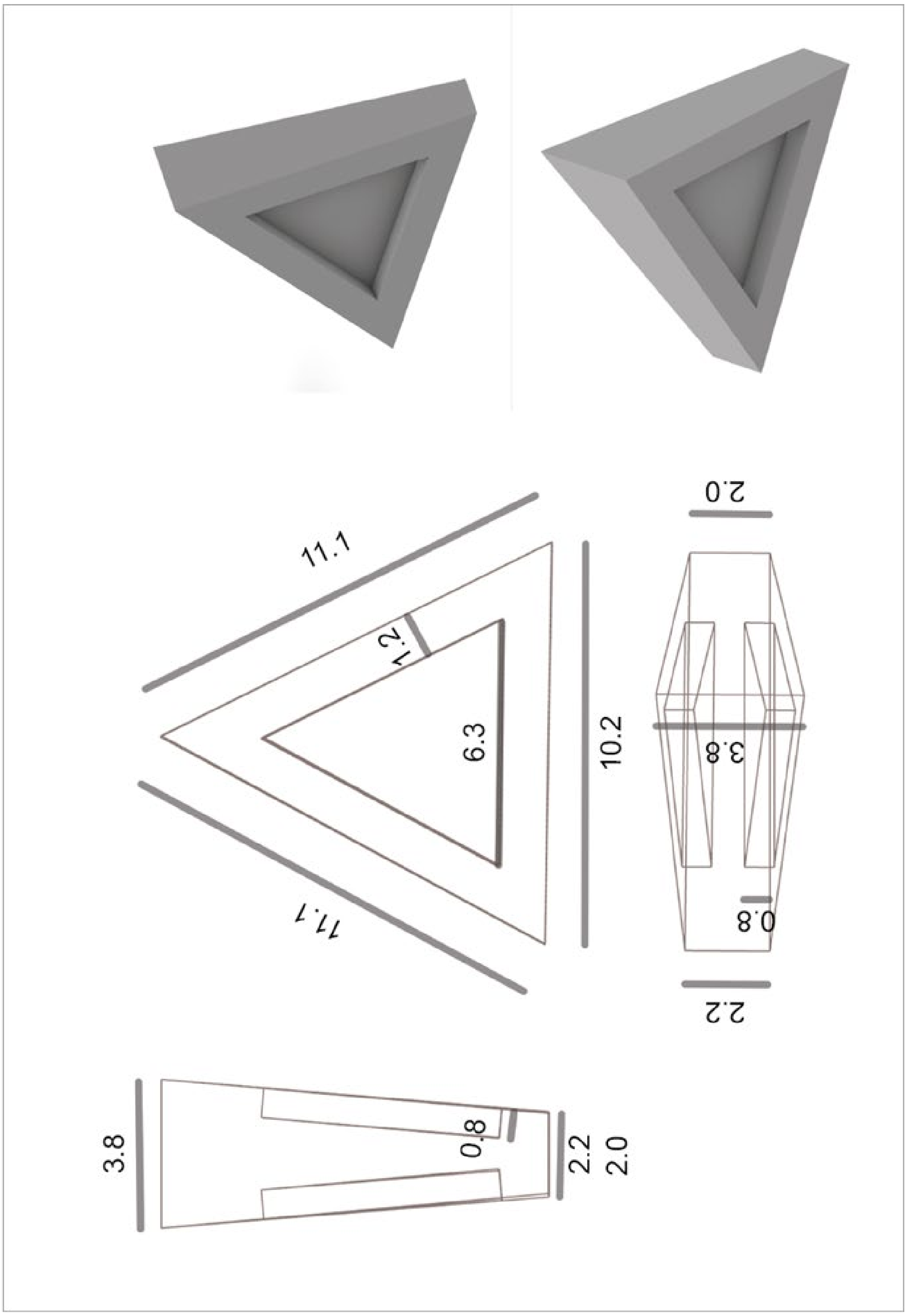
ANNEXES

Technical Drawings to the wood factory for the wooden base and connection.

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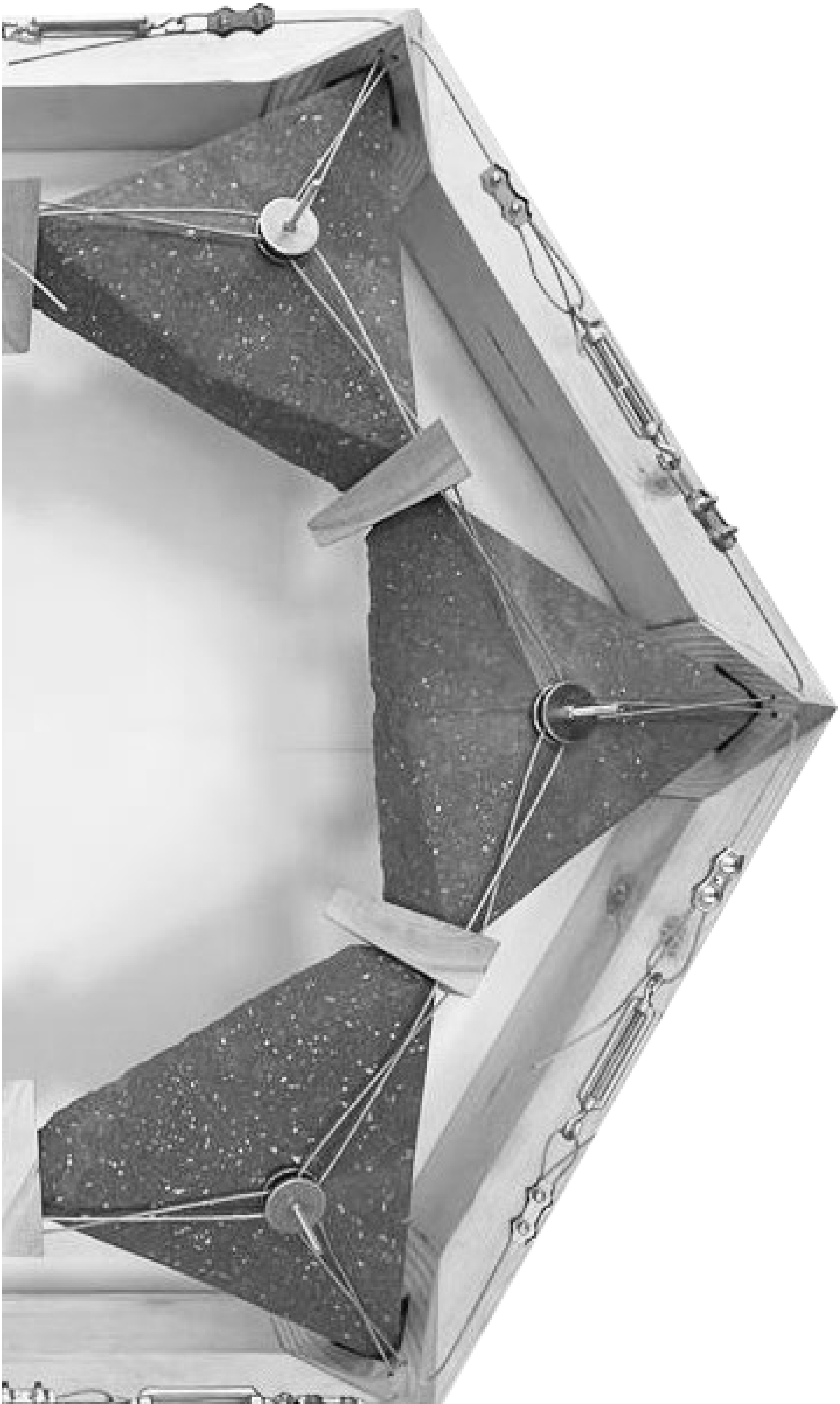

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