



**DIGI-BRICKS: REVISITING ELADIO DIESTE'S WALLS THROUGH
DIGITAL DESIGN AND SIMULATION TECHNOLOGIES**

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BY

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IN
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ETHICAL STATEMENT

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Ceyda ELDEMİR KARA

11/05/2022

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(M. Sc. Thesis)

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ABSTRACT

Developed in the past two-decade, computational design and manufacturing tools/technologies, automation in construction and robotics have been changing the paradigms in architecture. All these developments have also been changing the designers' attitude towards architectural material. The oldest man-made material, "brick" has a unique place in the history of architecture and architects/masons have developed various tectonics through a single unit and created masterpieces over the centuries. Brick is still seen today as a tool and medium for architects using digital technologies, where they can design creative and innovative forms / tectonics and allow them to think, experiment, explore and produce. The potentials of brick are being rediscovered through computation, and new understandings of masonry are beginning to emerge. From this point of view, in this thesis, it is aimed to (re)discover the potential of brick units and masonry techniques with digital design and simulation tools to create complex surfaces by questioning them. For this purpose, first of all, a literature review was conducted to reveal the development of brick masonry in architecture. Then, recently developed digi-brick approaches are presented and evaluated. Finally, it is questioned how a brick can be used to create complex surfaces/envelopes with the help of computational design tools. For this purpose, complex surfaces/walls constructed by Eladio Dieste using the principles of 'resistance through form' were examined, and it was investigated how geometry was manipulated to shape the building and provided robustness to the building and provided an efficient and expressive architecture. A wall of the Atlantida Church, which was chosen as a case study to understand the techniques and methods used in the buildings he designed, was modeled with a unit brick and bricks of different geometries, the structural behavior of the wall was simulated and the principle of 'resistance through form' was re-evaluated and discussed with today's technologies.

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DİJİ-TUĞLALAR: DİJİTAL TASARIM VE SİMÜLASYON TEKNOLOJİLERİ
YOLUYLA ELADIO DIESTE'NİN DUVARLARINI YENİDEN
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ÖZET

Son yirmi yılda geliştirilen, hesaplamalı tasarım ve üretim araçları/teknolojileri, inşaat ve robotikte otomasyon, mimarideki paradigmaları değiştiriyor. Tüm bu gelişmeler, tasarımcıların mimari malzemeye karşı tutumunu da değiştirmektedir. İnsan yapımı en eski malzeme olan “tuğla”, mimarlık tarihinde eşsiz bir yere sahiptir ve mimarlar/masonlar, yüzyıllar boyunca tek bir birim üzerinden çeşitli tektonik geliştirmiş ve başyapıtlar yaratmışlardır. Tuğla, günümüzde de, dijital teknolojileri kullanan mimarlar için yaratıcı ve yenilikçi formlar / tektonikler tasarlayabildikleri, düşüncelerine, denemelerine, keşfetmelerine ve üretmelerine izin veren araç ve ortam olarak görülmektedir. Tuğlanın potansiyelleri hesaplama yoluyla yeniden keşfedilmekte ve yeni duvar örme anlayışları ortaya çıkmaya başlamaktadır. Bu açıdan bakıldığında, bu tezde, tuğla birimlerinin ve yığma duvar tekniklerinin potansiyellerinin sorgulanarak, karmaşık yüzey oluşturmak amacıyla dijital tasarım ve simülasyon araçlarıyla (yeniden) keşfedilmesi amaçlanmıştır. Bu amaçla öncelikle tuğla duvarcılığın mimarideki gelişimini ortaya çıkaran bir literatür taraması yapılmıştır. Daha sonra son zamanlarda geliştirilen diji-tuğla yaklaşımları sunulmuş ve değerlendirilmiştir. Son olarak, hesaplamalı tasarım araçları yardımıyla kompleks yüzeyler/zarflar oluşturmak için bir tuğlanın nasıl kullanılabileceği sorgulanmıştır. Bu amaçla Eladio Dieste'nin ‘biçim yoluyla direnç’ ilkelerini kullanarak inşa ettiği karmaşık yüzeyler/duvarlar incelenmiş, geometrinin yapıyı şekillendirmek için nasıl manipüle edildiği ve yapıya sağlamlık kazandırdığı, verimli ve dışavurumcu bir mimari sağladığı araştırılmıştır. Tasarladığı yapılarda kullandığı teknik ve yöntemleri anlamak için alan çalışması olarak seçilen Atlantida Kilisesi'nin bir duvarı birim tuğla ve farklı geometrilerdeki tuğlalarla modellenmiş, duvarın yapısal davranışı simüle edilerek ‘biçim yoluyla direnç’ prensipi günümüzün teknolojileri ile yeniden değerlendirilmiş ve tartışılmıştır.

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SYMBOLS AND ABBREVIATIONS

In this study, the used symbols and abbreviations are explained below.

Symbols

Definition

cm

Centimeter

m

Meter

Abbreviation

Definition

2D

Two-dimensional

3D

Three-dimensional

CNC

Computer Numerical Control

HRZ

Horizontal

1. INTRODUCTION

Developments in architecture in the last twenty years such as digital architecture, construction automation and robotic technologies have brought together design and production cooperation. Current developments in contemporary architecture have become inevitable and play an important role in architecture. With the work done in this field, researchers are experimenting to replace many traditional methods established with digital design tools. Computational design offers important possibilities for architecture by going beyond the traditional design field that focuses on the creation of complex geometries (Menges, 2016: 76-83). Thanks to these possibilities created by digital design tools, the production of non-standard forms can be improved today. The advancement of complex geometric form formation relative to material compositions has led to the consideration of the material's potential in most digital design processes. Oxman and Oxman (2010) argues that researching and understanding the role of material in architecture, the ability to design with materials, and digital tectonic techniques to manipulate representations of material structures have become an evolving part of the foundation of architectural knowledge and one of the most important areas of research (pp. 14-23). These developments have increased the studies on materials in architecture, and the brick material has gained an important place in these studies.

Brick material is the oldest building material manufactured throughout the history of construction. The history of brick is based on its use as adobe in Ancient Egypt and Mesopotamia civilizations. Later, this adventure continued by spreading from the Romans to Europe and from Europe to the world (Kroger, 2005: 1-24). Over time, brick has evolved in terms of its production and joining techniques and has evolved to this day and continues to be used today. Thanks to the advantageous form of the brick, construction compositions have been created by the architects / designers / stone workers by developing construction techniques / tectonics and its potential has been evaluated over the years.

Brick is a design tool as well as a construction material. Throughout the history of architecture, the compositions created by the brick in the building have created unique tectonic effects, ensuring that the brick maintains its importance both in terms of structure and aesthetics, and has been effective in the production of new forms. "Brick is both

symmetrical and reproducible and therefore easily meets the needs of assembly. However, in its simplicity, this basic unit allows for a variety of forms simultaneously through the increasing complexity of unit-to-unit connections” (Collier, 2016: 1-2). When the brick masonry applications are examined in the buildings that have been applied throughout history, it is seen that the brick is suitable for many forms in terms of its geometry. However, complex forms made of bricks made the laying process of brick difficult over time. Until recently, this process has been a manual process, mostly labor. Today, architects are investigating robotic production techniques to create new forms of brick and analyze the production process of brick, and experiment with advanced digital production technologies to build on-site to complete the masonry process that cannot be done correctly with traditional methods.

This study tries to predict how we can make use of the brick material in complex forms in a more innovative way by using the computer aided environment. In this direction, this thesis creates and evaluates the production of brick material and laying it in complex forms through digital media in order to see the potential of a single unit. For this purpose, in the last part of the thesis, one of the complex brick masonry structures, a wall of the Atlantida Church, built based on the principle of ‘resistance through form’ put forward by Uruguayan architect/engineer Eladio Dieste was reproduced in digital environment and analyzed by simulation software. Then, the brick material’s place in contemporary architecture was reinterpreted through these digital techniques.

Background and problem definition

In the research, the answer to the question “How recent computational technologies supports creation and exploration of complex forms derived from a single brick unit and process of generating novel masonry work for architectural design” was sought principally.

To answer the main research, question the following sub-questions have also been answered:

- How has the brick material been used through the history of architecture?
- What are the potentials of using a brick unit in the formation of architectural components?

- For what purpose and how has the brick unit been used in complex forms/structures throughout history?
- What are the future scenarios created by technological developments in building structures with brick units?
- What is digital tectonics and how does it benefit the architectural structure?
- How do digital technologies and brick architecture benefit from each other?

Research hypotheses

Within the scope of this research, following hypotheses have been tested.

- Revisiting Eladio Dieste's complex masonry works through computational design and manufacturing technologies can stir up new design approaches for brickwork.
- Form-structure-material relationship, which has been further developed thanks to digital tools, can create tectonically successful structures.
- Brick material can make comeback as a contemporary material in architecture with the new methodologies.

Research aim

Nonstandard structures result from innovative architectural approaches, digital technologies, new materials and novel structural forms. They not only generate new processes of design and construction, but also prompt architectural thinking to step off beaten paths and expand traditional perspectives. This is the lasting effect of innovative forms of architectural practice that owe their existence to the introduction of nonstandard technologies.

The first aim of the study was to understand how to use brick in complex surface formation by using computational design tools and to examine the potentials of brick. To understand how to combine brick walls that have formed complex forms, different digital manufacturing techniques, local masonry methods and automation technologies *etc.* it is aimed to revisit through the digital tools.

Significance of study

This thesis revisits the brick walls of Eladio Dieste through digital technologies and simulation technology, announcing a new order that enables us to see the potential of brick material through form and the importance of architectural technologies in design and construction. With the introduction of digital technologies, existing parameters have changed. The old model and existing traditional design processes are no longer sufficient, so new technologies in architecture are trying to improve traditional techniques; contemporary architectural practice tries to reach the optimal form by using various software programs to create personalized, non-standard, complex forms. This thesis contributes to understanding the change in design and production technologies and questions the position and potential of brick as a contemporary material in this digitization. Through the walls of Eladio Dieste, the study evaluates historical texts, contemporary practices and analyzes them through digital tools to show the effect of the manipulation of geometry on brick material.

Limits of the study

In this thesis, a digital discovery of the brick unit was made through the structural strength information obtained by reconsidering the complex form wall of the Atlantida Church, which is one of the tectonically strong examples of brick architecture built in the middle of the 20th century. Instead of the original brick model of the complex wall created within the scope of the study, new digital bricks were created within the framework of the limitations of the add-ons, for example, brick typologies. Future studies require further investigation of the bricklaying logic and more unique brick typologies that can interact each other on the complex geometries.

Methodology

In this thesis, the Atlantida Church wall, built by Eladio Dieste, was chosen to explore the potential of brick material in masonry building systems. First of all, one wall of the church was digitized via SAP2000 and Rhinoceros 6, Grasshopper. Then, as observed in the structures of Dieste, the structural behavior of the wall was reviewed with the aid of a pre-tensioned cable for highlighting the effectiveness of his methods. Moreover, with the help of today's digital technology, new digitally created brick units were transferred to the wall

with the help of plug-in called, Starfish. The performance of the created wall was tested with the Alpaca4d plugin on Grasshopper by entering the material information. Thus, the complex geometry of the wall was revisited with new polygon digital brick units. Throughout this study, the process continued as digital modeling, analysis then obtaining a new digital model on the same model and reanalyzing it. Each analysis obtained as a result of this research was compared and evaluated. The flow chart of the thesis is visualized below.

Table.1.1. Thesis flowchart

Section / Title	Research Questions	Research Method
1 Introduction		
2 Literature Review and Theoretical Background	<ol style="list-style-type: none"> 1. How has the brick material been used through the history of architecture? 2. What are the potentials of using a brick unit in the formation of architectural components? 3. For what purpose and how has the brick unit been used in complex forms/structures throughout history? 4. What are the future scenarios created by technological developments in building structures with brick units? 5. What is digital tectonics and how does it benefit the architectural structure? 6. How do digital technologies and brick architecture benefit from each other? 7. What is the place of digital tools in brick masonry construction and what provide? 	literature review
3 Case Study	<ol style="list-style-type: none"> 1. How Eladio Dieste achieved such complex forms through the construction technologies of 1950's? 2. What is the impact of digital tools in materialization process of complex forms? 3. Could changing the brick units of Eladio Dieste's structure through computational design and simulation technologies help increase the potential of the brickwork? 	parametric modelling and performance evaluation revisiting brick unit
4 Evaluation of Findings	<ol style="list-style-type: none"> 1. How do the form of the brick unit and tessellation affect the building statically during the brick wall formation process? 2. What is the place and importance of digital technologies in the design of non-standard forms? 	analyses of the obtained data
5 Conclusion and Future Remarks		

2. LITERATURE REVIEW AND THEORETICAL BACKGROUND

In this section, it is aimed to examine the theoretical definitions and concepts that form the background of the thesis. First, the historical background of the brick material, its current applications and future scenarios were researched, and then the concepts that emerged in the discipline of architecture were examined, their definitions and examples were given and the interaction of these concepts on the brick was explained. Finally, with the development of information technologies in recent years, important examples of brick applications showing the integration of material, form and structure are presented.

2.1. Development of Brick Tectonics in Brick Architecture

Brick is a universal building material that has been frequently used in buildings for thousands of years (Afsari, Swarts, and Gentry, 2014: 225-247). The main reason for that, brick is a low-cost material and requires little qualification (Yenice and Park, 2019). Other advantageous aspects of the brick such as accessibility, geometry, production techniques have enabled brick to be accepted as a common building material today. Another aspect that distinguishes the brick from other materials, especially with the way the brick is laid, strongly affects the appearance of the monolithic surface, to which it gives the monolithic surface style and character. According to Massoud (2018), the versatility of brick does not just have an aesthetic effect; it can also affect the budget, the structure, and the method of construction itself. All these effects created by the brick have led to the fact that the brick has been a frequently used material in the process of creating building elements for many years, and has served many different purposes in the building (Figure 2.1). It has been a frequently used material in building walls in structure.

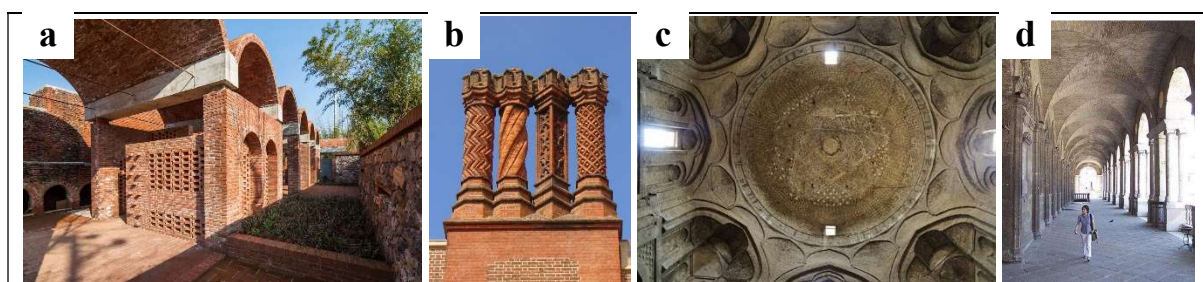


Figure 2.1. Brick applications; brick arches (a) (URL-1), brick chimneys (b) (URL-2), Brick dome (c) (URL-3), Brick vault (d) (URL-4)

Brick firstly used in Babylon and its use has survived to the present day by being influenced by different cultures and different techniques. The simple geometry of the material, easy accessibility to its raw material and the ease of production technique allow it to create a wide variety and economical structures in architecture. By means of the potential of the unit's geometry as well, different laying techniques have been tried and aesthetically unique structures have been obtained. All these features have made the brick an indispensable building material until today. Thus, brick has been used more widely than other building materials for many years. This long history of brick use offers architects/builders/engineers a wide spectrum to analyze the possibilities of the material in the brick building process.

Brick is a building material as well as a tool that can create different design typologies. It is seen that the brick is more suitable for many forms in terms of its geometry compared to the building materials used in ancient times. Therefore, this material can be used in various ways in the construction cycle of the structure. "Bricks have been the building blocks of many of the world's great treasures, including the pyramids of Giza, the Roman Coliseum, and the Taj Mahal, whose interior walls are lined with brick walls" (URL-5). Thanks to its effective geometry, the brick has the potential to create strong tectonic effects in the structure. For this reason, it is still accepted as a contemporary material and continues to be used by being interpreted with the technology of the new century. In particular, new construction methods are being developed thanks to algorithmic design approaches that have become widespread in architecture. In other words, the developing/changing brick tectonics over time is being re-evaluated with today's technology. In this way, the potential of the brick material is rediscovered. For this purpose, in this section, the history, applications and future potentials of brick are mentioned in order to better understand the changes that brick has undergone from past to present.

2.1.1. The history of brick

Brick material is a well-known/experienced building material, the production and use of which dates back to ancient times and has been used in buildings for at least 10,000 years, sharing its origins with the beginning of civilization (Kroger, 2005: 1-24). The reason for this is that this material is a building material with abundant raw materials and its production technique is based on simple principles. Basically, brick is produced by mixing ground clay with water, shaping the clay into the desired shape and firing it or using natural methods to

dry (Figure 2.1) (Brick Industry Association, 2006: 1-7). At the same time, brick is a building unit with effective geometry and easy to handle by a builder/mason. This feature has led brick to be one of the building materials that is frequently used in creating many building elements such as walls, arches, vaults and in building special forms.

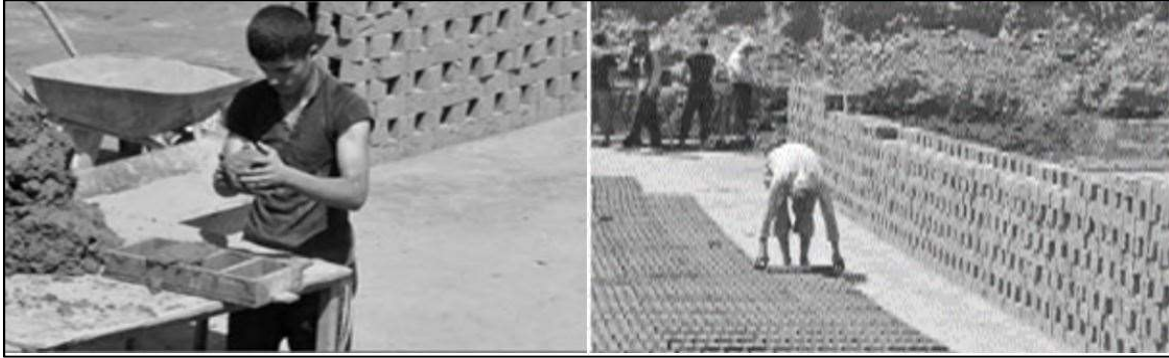


Figure 2.2. Traditional brick making processes molding and drying (Dalkılıç, Nabikoğlu, 2017:346-353)

5000 years after the discovery of the brick, the first molded brick was invented in Mesopotamia (Kroger, 2005: 1-24). Initially, bricks made from "clay" or "mud" were used as building materials in the New Stone Age (6000-8000 BC). The method of mixing straw or manure with clay or mud was followed to strengthen the building unit at that time. These bricks, which are handmade and dried using natural methods without firing, are called "adobe bricks". For this reason, it is possible to see the first unique examples of brick structures in regions with more temperate and arid climates due to the ease of drying process. It is seen that the use of these bricks continues today. Thanks to important inventions over time, brick has developed in terms of production and application methods, has started to be used widely and has taken its place as an important building material today (Figure 2.2).

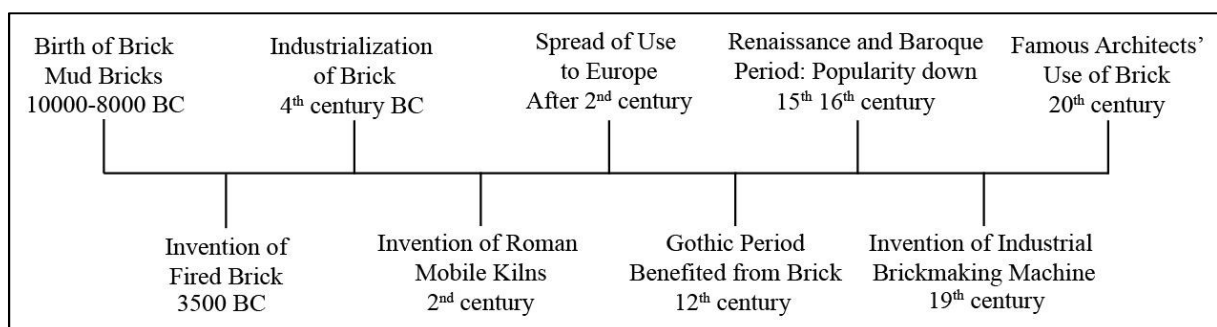


Figure 2.3. Important events that contributed to the development of brick material, (Kroger, 2005: 1-24; Little, 2006: 6-28;Kline;2017: 23-35)

1500 years after the invention of molded bricks, there was a development that changed the character of the bricks and the brick material became a stronger building unit (Zumthor, 1998; Little, 2006: 6-28). The invention of this brick type coincides with 3500 BC. Due to technical inadequacies in ancient civilizations, civilizations lived in large river basins suitable for alluvial sediment deposition and brick making, but with the invention of firebrick, this was no longer a necessity and brick material became a more accessible material (Lynch, Roundtree, and Architects, 2009: 4-12). Ziggurat at Ur, constructed at 2100 BC, is one great example of the use of baked and mud bricks (Figure 2.4).



Figure 2.4. Ziggurat at Ur, 2100 BC (left) (URL-6)

The type of brick that was first used prefabrication through the use of molds appears at Ishtar gates in Babylon around 580 BC (Figure 2.5). The most distinctive feature of these gates is that they have three-dimensional lion reliefs made of many ceramic pieces stacked in regular vertical layers (Kline, 2017: 23-35). Kroger (2005) shared the following information for the bricks found in the Babylonian excavations: "Excavations of Babylon, one of the great cities of Mesopotamia, showed that the city had a high mastery of fired and glazed bricks, but there are no records of its methods"(pp. 1-24). After the process of the development of the brick, brick material started to produce industrially. "The first industrial fired bricks were produced and used by the Lydians in Anatolia in the 4th century BC." (Görçiz, 1996; Dalkılıç and Nabikoğlu, 2017:346-353).

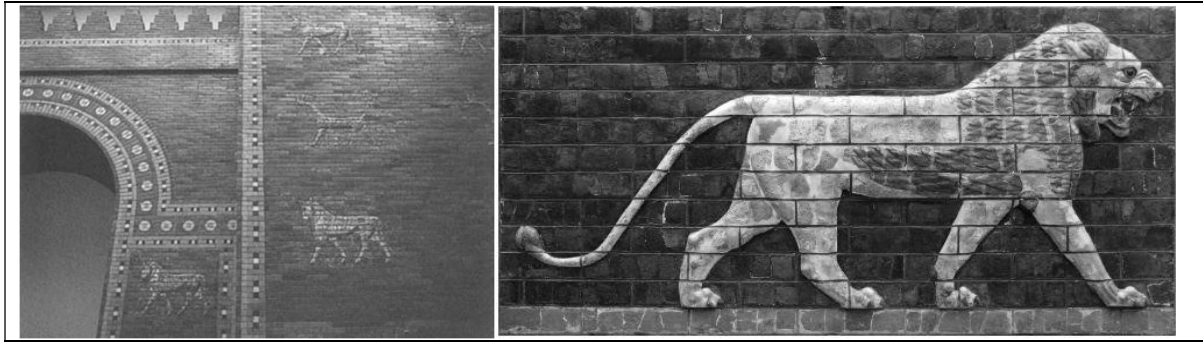


Figure 2.5. Ishtar Gate, 575 BC (left) (Kroger, 2005: 1-24), Ishtar Glazed Lion Ornament (right) (Kline, 2017: 23-35)

The use of clay bricks increased during the Roman period and these bricks were customized with new production techniques to maximize their benefits (Fernandes, 2010). It was carried out by the Romans to obtain a stronger material by burning or firing bricks through the mobile kilns (Figure 2.6). Thus, this material subsequently spread throughout Europe (Lynch *et al*, 2009: 4-12). The use of firebrick in construction spread to a wider geography and its use increased in the 1st century AD, and as a result, it led to the development of the brick industry in the Roman Empire. Thus, brick factories with kilns became widespread for the production of firebrick, which was widely used in the 2nd century (Kroger, 2005: 1-24). This industry, which flourished in the Roman empire, left behind the problem of limiting brick production to warmer climates or summer months. In this way, brick making spread all over the ancient world (Colefield, 2018). With these developments, brick has been used as a building material in almost every geography and has managed to survive until today.



Figure 2.6. Brick firing process (URL-7)

The use of fired bricks developed by Roman civilization and frequently used in construction, spread throughout the entire Roman Empire until the 2nd century AD. In the Roman period, the post and lintel building technique used in Greek civilization was replaced by arches and vaults that could be easily built from bricks, with the increase in the use of bricks. These practices are especially evident in aqueducts and baths, are also included in the Roman Colosseum (Figure 2.7) (Kroger, 2005: 1-24).



Figure 2.7. Brick in Colosseum (Kroger, 2005: 1-24)

One of the basic rules of Roman Architecture is to use local resources whenever possible. For this reason, brick building technique is highly developed especially in Eastern Rome (Radivojević and Kurtović-Folić, 2006: 692-699). According to the Byzantine building tradition, the upper parts of the vaulted structures were made of bricks due to the lightness of the brick. With the advancement of brick masonry in Byzantium and Western Rome over time, the extraordinary use of brick can be found in Hagia Sophia, whose dome was built of brick in 537 AD (Figure 2.8).



Figure 2.8. Hagia Sophia (Little, 2006: 6-28)

The incentive to develop firebrick has been the need to construct highly robust tall buildings. Firebricks allow the construction of permanent structures because the manufacturing process of firebricks gives brick the durable properties of stone while giving its users greater flexibility in creating and using a range of architectural surfaces (Little, 2006: 6-28). Other reasons why these bricks are preferred over sun-dried bricks are that they provide higher compressive strength, higher resistance to fire and weather conditions, and better heat and sound insulation. Therefore, fired bricks are more suitable to use than sun-dried bricks (Shakir and Mohammed, 2013).

The firing process of clay bricks dates back to more than 5000 years. This process is today a sophisticated and highly controlled manufacturing process. Still, the principle of incineration to transform clay into a more stable, durable, low-maintenance ceramic material has remained unchanged to this day. Firebricks appear to have held a large place in the history of masonry because firing is an easy technique for drying brick and provides ample resources for construction. For this reason, brick material has always been seen as a good alternative in case of scarcity of materials such as stone and timber, which are often used in buildings (Ganobjak and Carstensen, 2019). With these developments, mankind has continued to build with bricks for centuries and to use bricks as structural and decorative. In this process, while the Great Wall of China was built with unbaked bricks, many important and solid structures such as Hagia Sophia were built with baked brick materials (Figure 2.9).



Figure 2.9. The Great Wall of China (Left)(Little, 2006: 6-28) Hagia Sophia (right)(URL-8)

After the invention of the firebrick, the developments in the Renaissance period not only affected the manufacturing process of the brick, but also changed its use. In this process, building with brick material has become more cost-effective and more socially accepted

(Little, 2006: 6-28). Since the Renaissance, a variety of brick making styles and techniques have been continuously developed around the world, and new and innovative strategies have often been used in the brick building process (Figure 2.10). Although production techniques have improved greatly from hand forming to mass production, no major improvements have been seen in the basic geometry of the brick unit (Andreani and Bechthold, 2014: 797-806).

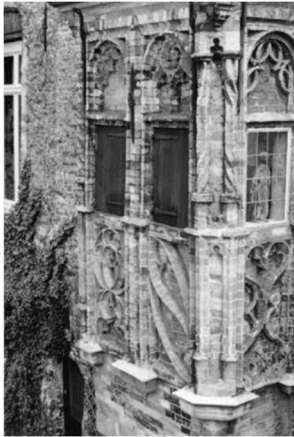


Figure 2.10. Brick facade from the 15th Century (Lynch *et al.*, 2009: 4-12)

Brick was used in the construction of the dome in Florence Cathedral, which was built in Italy during this period, and it showed its importance again (Figure 2.11) (Kroger, 2005: 1-24). This material continued to be used in buildings throughout the Renaissance period. In the Gothic period, architects and builders used brick to achieve more complex geometries. To obtain these geometries, bricks were used to emphasize the architectural features in the structure, especially in this period (Lange and Holohan, 2019: 103). These compositions created with bricks have progressed further and revealed their effect on design in building applications.



Figure 2.11. Florence Cathedral, 15th century (Kroger, 2005: 1-24)

Another successful example of brick applications can be found in Islamic buildings. According to Islamic belief, it is not appropriate to use spiritual beings as motifs in sacred buildings, and this has led to the application of geometric patterns in Islamic architecture. With the characteristics of the brick, geometric patterns were successfully created in the structures made of adobe and fire bricks in Islamic architecture, and a few of these structures have been preserved until today (Kroger, 2005: 1-24). The brickwork method commonly used in early Islamic architecture was to arrange the bricks horizontally and vertically, but later decorative facades were obtained using complex geometries (Figure 2.12) (Kharazmi and Topoi, 2016: 301-308).

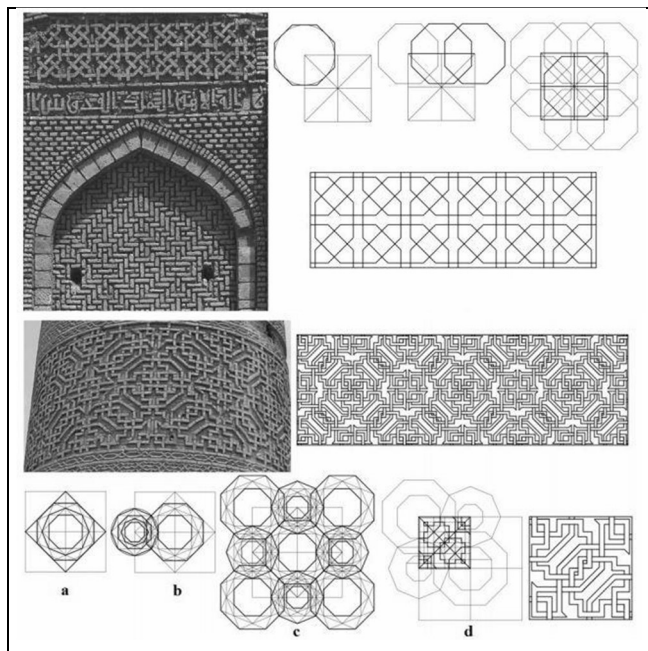


Figure 2.12. Islamic brick tiling (Kharazmi and Topoi, 2016: 301-308)

A major development after the Renaissance period was the invention of brick making machines in the second half of the 19th century. With this development, a great improvement was made in the manufacturing process and machine-made bricks were started to be used (Figure 2.13) (Brick Industry Association, 2006:1-7). With the industrialization process, the replacement of standard bricks by hand-made ones has brought some design restrictions in their applications in architecture. While hand-made bricks affect the design by forming various units, after the industrialization process, this aesthetic effect has been tried to be achieved by the diversity of the standard brick arrays (Jose Pedro Sousa, Varela, and Martins, 2015).

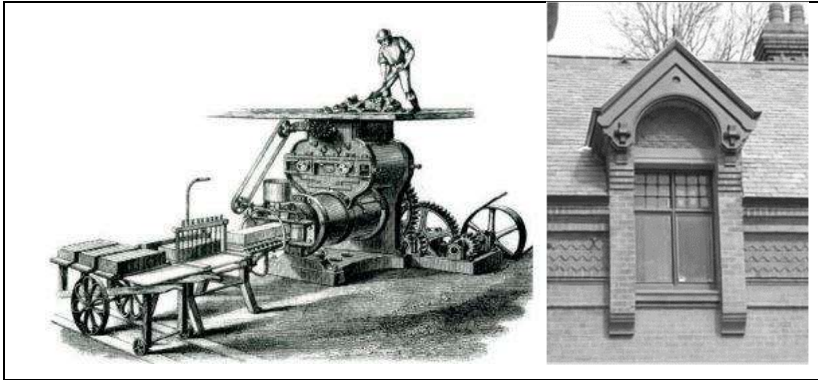


Figure 2.13. Steam-driven stiff-mud brick making (Left) (Andreani and Bechthold, 2014: 797-806), The Red Stables, St Anne's Park, Raheny, Dublin, built in 1886 of machine-made brick from the Portmarnock Brickworks (Right) (Lynch *et al.*, 2009: 4-12)

Thus, enormous structures such as factories and residential blocks emerged with brick, but the material started to give way to different materials in terms of statics with the technological advancements. Thus, this period resulted in the use of brick as a coating material due to its properties, because the brick served as a fire protection for materials such as steel, which were frequently used in construction in this period (URL-9). Rafael Guastavino, on the other hand, used the ceramic tile as a structural system instead of using it as a coating system, taking into account the non-flammability potential of the brick as well as other properties (Figure 2.14) (Kline, 2017: 23-35).



Figure 2.14. Guastavino Tiles, Manhattan Municipal Building (right) (URL-10) City Hall Subway Station, New York, 1904, by Guastavino (left) (URL-11)

One of the most well-known structures built in this period, where brick was evaluated from a static point of view, was designed by Burnham and Root was “The Monadnock Building” (Figure 2.15). To support the walls that continue across the 16 floors, the walls on the ground floor were built approximately 180 cm thick (Little, 2006: 6-28).

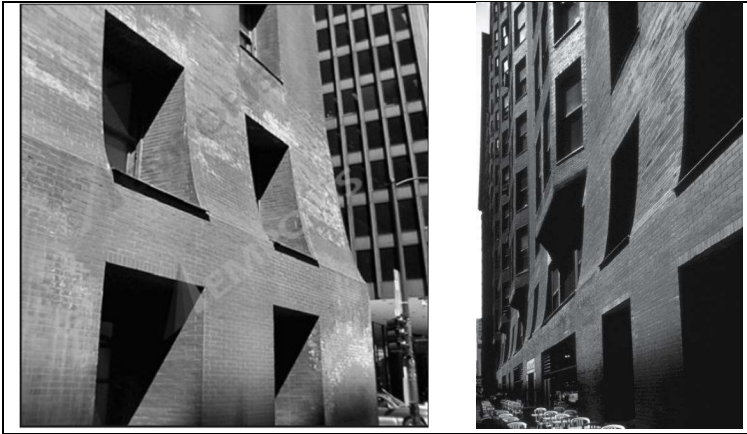


Figure 2.15. The world's tallest self-supporting brick facade: Monadnock Building (Left) (Little, 2006: 6-28) (Right) (Söffker and Deplazes, 2005: 27-30)

More complex and impressive structures have emerged with the techniques developed in the following years. When the structures of famous architects and engineers are examined such as Raul Hestnes Ferreira, Eladio Dieste, Antoni Gaudi, Eduardo Torroja and Louis Kahn, it is seen that they created traditional construction methodologies and tectonics in this area (Figure 2.16). However, despite their remarkable work, the application of the irregular geometries they created is very difficult to achieve with traditional manual methods and requires serious static calculation and labor force (Jose Pedro Sousa *et al.*, 2015). As Oliveira and Sousa (2016) argue: "Brick building has a strong tectonic tradition in architecture, and this material is used as both a structural and expressive material." (p. 123). Considering the irregular geometries created by this construction process, it is seen that it is very difficult to achieve these structures with traditional manual methods without unique construction techniques.



Figure 2.16. National Assembly Building, Dhaka, Bangladesh, 1982, by Louis I. Kahn (URL-12)

According to Kroger (2005), “The Study of how brick was formed and put together in the past provides an understanding of where the strengths and weaknesses of the material are and where they are. provides information on how to get the most out of it” (pp. 1-24). In the past century, many brickworks seem to have been carefully constructed by architects and builders (Jose Pedro Sousa *et al.*, 2015). The enormous number of brick-structure precedents has created a wealth of resources for contemporary architects to rely on as a design technique that has its origins in ancient history.

While brick manufacturing techniques continued to be developed, at the beginning of the 20th century, the development of new building materials as a result of the Second Industrial Revolution and the absence of brick in the philosophy of modern architecture led to the decline of the popularity of brick material (Imbern, 2014: 211–220). There have been great developments in the last 60 years in the evolution of brick material, which has been used for 10,000 years. Revolutionary approaches have been developed with the use of brick, especially in the 21st century, with the developing digital technologies (Fiala, Mikolas, and Krejsova, 2019: 1-4). The manufacture of brick material has seen many innovations throughout history, but the forming process has remained dependent on the molding or extrusion system (Figure 2.17) (Peters, 2017: 433-434). Brick, which is a strong building material whose development has been observed historically, has provided architects, engineers and designers with a wide range of knowledge with its many applications and has turned into a modern material suitable for re-evaluation due to its properties.

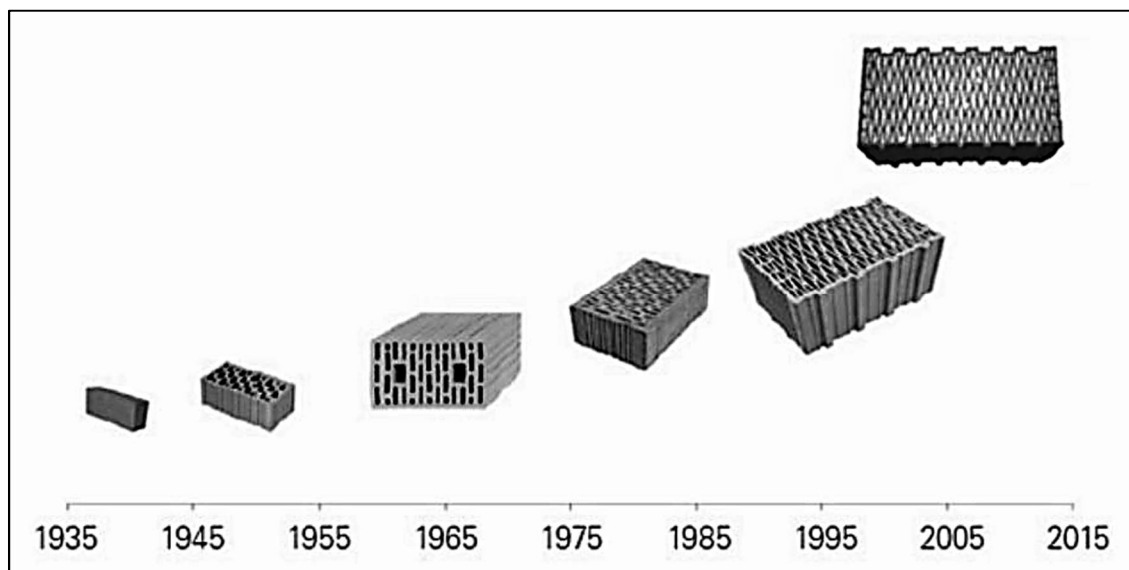


Figure 2.17. Full brick timeline (Fiala *et al.*, 2019: 1-4)

Consequently, the architect/engineer/designer can leverage traditional brick making techniques to create new construction methodologies. Today, many researchers are trying to integrate new technologies with materials, inspired by successful works created with bricks. Materials re-evaluated by today's technology have the potential to create a new impact. Brick material, on the other hand, is an indispensable material to be evaluated both structurally and aesthetically, thanks to its tectonic tradition. For example, Dieste's buildings have complex walls produced with different construction techniques. The challenge for Dieste has been to create a structure language that is contemporary and modern, but not dependent on the technology of the developed world, more suited to Uruguayan conditions. The brick material provided this language with the unique tectonic effects it created. In order to define the geometry of these walls, Dieste renewed existing construction methodologies and introduced an innovative construction technique. It is an inevitable fact that these unique methodologies have the potential to set a precedent in today's technological developments.

Traditional construction systems have been influenced by technological dimensions and material availability over time. Especially industrially produced and standardized bricks, manually placed and pasted modules to maintain stability, have enabled the brick to survive until today. This modularity has enriched the forms and styles in brick structures. (Kroger, 2005: 1-24). Thanks to these rich forms, the brick has brought many benefits to the structure and most importantly, the building has benefited in a static sense. For this reason, architects and engineers have taken advantage of the rich forms and tectonics created by the brick and evaluated it with today's technology. Alia Bengana and Jacques Kaufmann once again emphasize the rich form effect of brick with the installation exhibited in a gallery in Paris in 2016 (Figure 2.18).

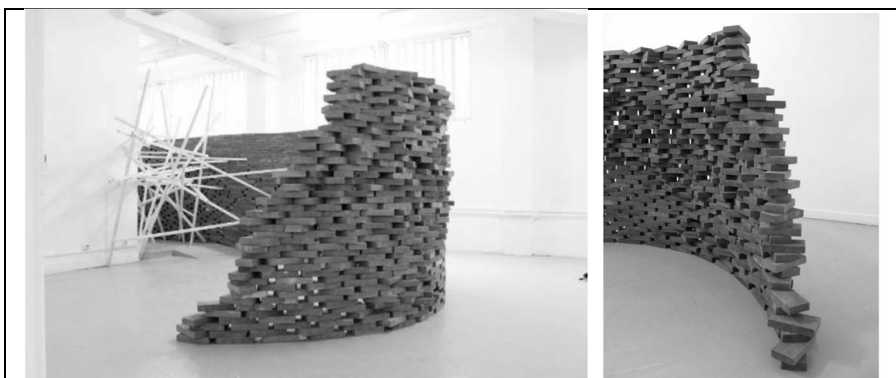


Figure 2.18. Innovative use of unfired earth bricks, Terres by Alia Bengana and Jacques Kauffman, 2016 (URL-13)

Brick is a material whose structural potential has been forgotten due to new materials that have emerged since the 20th century and is mostly used as a cladding material. The transformations brought about by the uninterrupted construction process created by digital tools in relation to the formation of the structural setup, created a paradigm shift in architecture and caused the material-form and structure relationship to be reconsidered. As history of brick applications show, the tectonic impact of brick reveals and encourages innovative applications and methodologies. Today, digital tools help to overcome the problems experienced in the brick building process and discover the potential of brick with innovative methodologies.

2.1.2. The use of brick in complex forms

Brick material is one of the most successful materials that can be used to create efficient structural forms thanks to the geometric combinations it creates. Building straight, curved, double-curved walls, domes, and vaults that are as light as they are inexpensive demonstrates brick's immense form abilities (Abdelwahab and Elghazi, 2016: 1102-1103). For this reason, many successful compositions have been created with brick material throughout the construction history, and the form capabilities of the brick have been frequently used in the building in terms of static and aesthetics. This benefit is clearly observed through the structures of Rafael Guastavino. "Historical and traditional construction has made use of bricks in arches, vaults and shells, leading to thin, light and ingenious solutions whose strength is often guaranteed by the curved shape, such as those built by Spanish architect Rafael Guastavino" (López-Almansa *et al.*, 2010: 1799-1814). This shows that the brick material has the potential to create strong tectonic effects in the structure.

It is observed that the building envelope has changed significantly with the effect of technology in buildings from ancient times to the modern age (Grobman, 2013:951-963). Pedreschi (2008) observes that the work of a number of designers from the early to mid-20th century sought opportunities to create innovative structural forms with new and old materials (pp. 12-19). While creating these forms, the architect succeeded in obtaining innovative forms in the building by producing new methodologies. Most of the works of architects/engineers of that period symbolize 'structural art' by revealing the structure-material-form relationship. According to Oxman (2010), architectural engineering, which Pedreschi calls structural art, has traditionally been characterized by the sequential

development of 'form, structure and material'. In the 20th century, a successful building that achieved a non-standard form with the composition of brick material is Atlantida Church (pp. 14-23). The undulating brick walls that stand out in this building not only create a dynamic space in Dieste's structure, but also make the structure efficient. The double curvature form that Dieste uses in its structure (Figure 2.19) is an efficient structural form. The undulating form serves as the sole support for the brick, vaulted roof and lateral loads, rather than the visual it creates. (Kroger, 2005: 1-24).



Figure 2.19. Church of Atlantida: Construction phase and built version (URL-14)

Freeform structures with high geometric complexity are playing an increasingly important role in contemporary architecture (Pottmann, 2013). Ensuring good form of the structure brings optimal benefits to the structure. In addition to the advantages of brick masonry today, a disadvantage of the traditional brick wall construction process is that brick masonry is time consuming and labor intensive. In brick structures, after a period of development with the turning point in the work of Guastavino and Dieste, the construction of ceramic structural surfaces has become difficult and their formation today is almost unobservable (Imbern, 2012: 315-321). Oswald (2013: 8-26) talked about the strength of the wall built with bricks in his thesis and emphasized that it was used to build many buildings for many years due to this durability. When looking at the brick applications created in this process, structural forms with strong tectonics are encountered. Even, detailed ornamentation with brick is possible (Figure 2.20). However, Oswald also mentioned that building with bricks today also raises questions about the value of human labor, the meaning of craft, and even the

importance of permanent construction in our increasingly ephemeral society. Brick's strong tectonic tradition has caused difficulties in the bricklaying process, however, difficulties in construction processes are tried to be solved with digital technologies in the 21st century.



Figure 2.20. Wall relief no:1, Rotterdam, 1955, by Henry Moore (URL-15)

Complex forms have an important role in this regard, and the use of digital design tools has become inevitable for the construction of these beneficial forms. In recent years, there has been a shift from the modern orthogonal building envelope to more elaborate curved and folded forms (Jonas *et al.*, 2014: 513-522). Today, many parameters (such as heating, cooling, natural ventilation, lighting need, static) are evaluated in the digital environment in order to cope with the increasing performance demands while the building envelope is being created (Grobman, 2013:951-963). Thus, the form of the structure corresponds to these performance parameters. According to Nilsson (2007), "non-standard architectural solutions, not only expand the possible experience of the structures built for the users and customers, but also open up potentially profitable and structurally efficient spaces" (pp. 1-4). Brick, which has maintained its importance throughout history, continues to play a functional and creative role in the construction of contemporary architecture in the twenty-first century. For this reason, it is at the center of new ways of thinking today (Abdelwahab and Elghazi, 2016: 1102-1103). According to Ding (2016), the topics of form, structure, and material each involve various methodologies, but together they form a continuous series to discuss how new brick architecture can be built using form-finding methods (pp. 9-11). Today's digital design tools offer new opportunities for the architect to take part in the structural process, thus providing a strong link between form, structure and material. Thus, with the understanding of this process, it was possible for the conceptual design process to reach a better form-material unity. Brick is a strong building material ready to be evaluated in line with this relationship. Thanks to the bond enabled by digital technologies, today the

brick is ready to show its potential by creating complex forms again. Thus, the re-evaluation of brick material, which is suitable for use with digital technologies, according to the needs of the age, has started to question the potential of brickwork in the future (Figure 2.21).

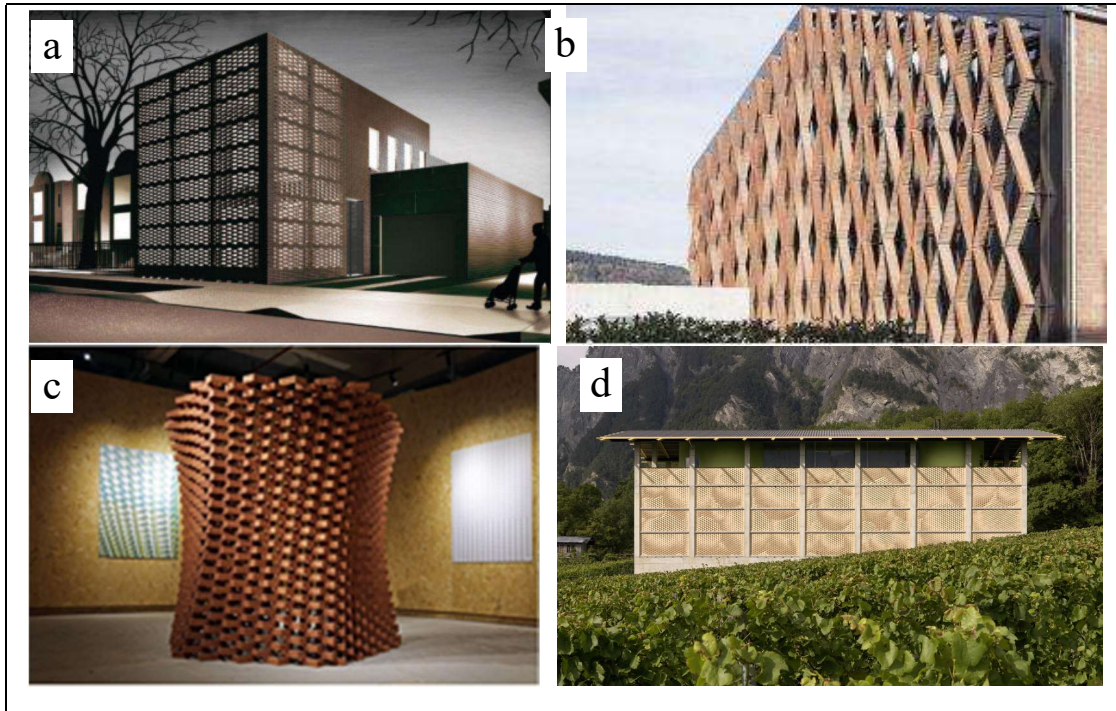


Figure 2.21. Walled Garden House (a), (Kolarevic and Klinger, 2013: 6-20) Ofenhalle Keller AG Ziegeleien, Gramazio and Kohler (b), (Kalkatechi, 2016: 45), Ceramic InFormation Pavillion, Lange and Holohan (c), (Lange and Holohan, 2019: 111), Winery Gantenbein, Gramazio and Kohler (d), (Bonwetsch, 2015)

Brick applications created with today's technology show the importance of integration of technology with existing materials. Brick occupies an important place for reevaluating technology-existing material relationship. Therefore, developments and research show that the future potential of brick is promising in creating non-standard forms and in this way meeting the need for construction.

2.1.3. Future potentials of brick

Re-evaluation of material impact has an important place in meeting today's construction demands. In the recent past and today, the current use of brick has been limited by considering it as the cladding material and outer layer of the building wall on a decorative scale, but due to the properties of the brick, the question of what the potential of bricks for the future is and what causes innovation with bricks has become one of the important

research topics of architecture (Sunguroglu, 2008: 64-73). As the interest in building techniques created with brick increases, innovative design ideas are needed to meet today's demands (Yenice and Park, 2019). Brick material is a material whose potential is ready to be explored because in many ways, especially its geometry, it is a suitable material for today's digital design tools, and some precedents with strong tectonic impact created with brick in the past also include algorithm logic for the digital environment (Figure 2.22).



Figure 2.22. Dieste's Tiles (left) (Jonas, Penn, and Shepherd, 2014: 513-522) Armadillo Vault (right) (Block *et al.*, 2020: 66-72)

The use of digital tools in design has allowed new methodologies to create new forms in contemporary building applications. New manufacturing techniques are changing the understanding of ceramic material properties and its structural function (Kline, 2017: 23-35). Thus, building materials experience new compositions with the help of digital tools and sometimes even turn into a new material. Looking at the research in this field today, it is observed that the existence of many different types of bricks has been established because the possibilities enabled by new production techniques have opened new research paths for the architect to re-evaluate the brick material (Little, 2006: 6-28).

With the developments experienced, some performance-oriented fundamental innovations that can start the era of building a new building with bricks have been created and these innovations have begun to replace traditional methods (Sunguroğlu, 2008). According to the claim of Wu and Roe (2006), building materials such as brick create new compositions through digital media, pushing the boundaries of form and creating building systems that give optimal benefit (pp. 8-13). Advances in brickwork techniques tend to be driven by structural and aesthetic goals that support the realization of majestic brick walls, arches or

vaults, as well as decorative surface effects (José Pedro Sousa, 2017: 73-83). The work of companies such as Office dA, SHoP Architects, Gramazio and Kohler exemplifies groundbreaking contemporary brickwork through digital processes (Figure 2.23) (Ambrose, Callam, Kunkel, and Wilson, 2009: 5-12).

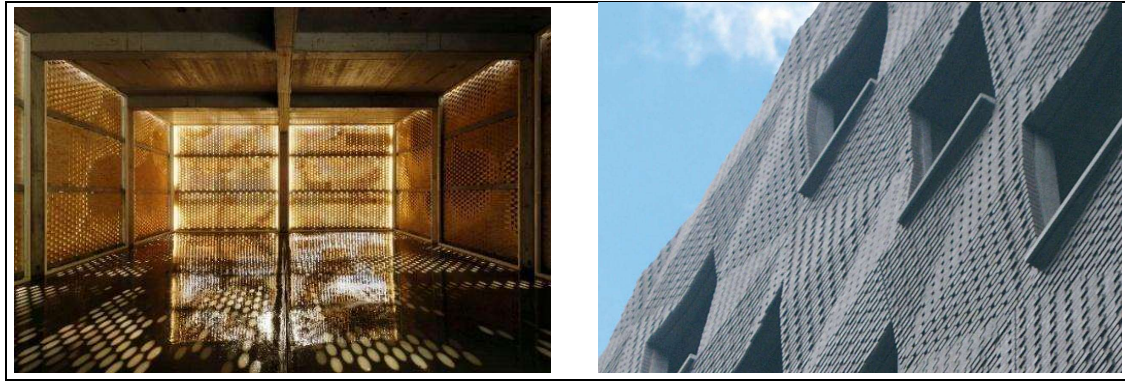


Figure 2.23. Gantenberg Winery Interior, Gramazio and Kohler (left) (URL-16) 290 Mulberry House, Shop Architects (Right) (Sharpless, 2009)

With its new techniques and methods, digitally-enabled making reintroduces long-forgotten craft concepts that stem from the desire to bring out the unique qualities of the material and use them to a particular effect. Therefore, examining the mutual relationship of material and digitality is the main point to be investigated to achieve the purpose of the design (Kolarevic and Klinger, 2013: 6-20).

Brick's many properties have made it unique for re-evaluating the brick material and exploring its potential in the construction industry. While its design responds to the technological and sustainable demands of our contemporary world in terms of both style and assembly, it integrates the historical context and features of the brick with today's design (Kroger, 2005: 1-24). Brickwork is still constrained by formal constraints, although new digital techniques are constantly expanding the expressive and stylistic possibilities of curved shapes. Although there are some examples of brick structures that successfully overcome this problem in today's architecture, experiments with complex geometry are still problematic, especially in building scale projects where radii of curvature are smaller and mortar cannot absorb irregularities, and research continues in this area. (Imbern, 2014: 211–220).

Although technology still provides significant advances in architecture, design and materials science, research on ceramics as a basic building material can be increased and further restored. In recent years, with important developments in the relationship between ceramics and architecture, this cooperation promises a long and exciting future (Kline, 2017: 23- 35).

2.2. The Place of the Brick in Digital Design

Since the early 1990s, computer aided design has been used in buildings, and digital tools have been used for structurally informed architectural design. Today, it is seen that the use of digital tools is often used to guide design and they have an enormous effect on form, structure and material integration. Those developments in architecture are caused emergence of the term digital architecture. Grobman's (2008) related work on digital architecture successfully defines digital architecture (pp.21-26). According to Grobman (2008), two aspects of digital architecture can be identified: the first is the semantic/semiotic aspect and the second is the practical/technological aspect (pp. 21-26). The concept of "digital architecture", and especially the word "digital", means being creative and up-to-date, one step ahead of the "analogue" associated with modernism and the beginning of the 20th century. Therefore, modern architecture literally means modern and creative architecture from a semantic point of view. First, it reflects on the creation and representation of architecture. According to this approach, digital architecture uses the computer not only as a drawing and rendering tool, but also as a modeling tool. This means that architectural design tools should help architects make decisions during the design process. The second has to do with the shape of the building or the geometric complexity of computer-designed projects. According to this explanation, digital architecture is understood to be based on free-form, curvilinear and other complex geometries that cannot be developed, represented and/or constructed without computer assistance.

According to Dunn (2012), with the increasing prevalence of computers and advanced modeling software, an environment has been provided for architects and students alike to design and build designs that would be very difficult to develop using traditional methods. It is observed that objects and structures produced before the development of CAD-CAM systems are mostly created in simpler shapes, avoiding geometric shapes. This is due to the high cost of geometric complexity and diversity. Architects, who left this problem behind with the development of digital production methods, started the process of discovery of

complex forms. This non-standard production technique allowed and enabled non-standard objects and structures.

The use of digital technologies by designers in the early stages of design in order to provide optimal benefit in the designed structure is a newer issue in architecture (Mousavian and Casapulla, 2020: 448-468; Zboinska, 2019). In the process of creating the structure for which optimal benefit is to be created, technical requirements are becoming more and more complex, and therefore more and more special solutions are being developed (Helm, Ercan, Gramazio, and Kohler, 2012: 169-172). The requirements of complex structures are tried to be met with today's technology. With the new techniques and strategies of digital technologies, architects can now work efficiently with sophisticated and complex forms. Working with these forms has not been the only concern in today's architecture. This situation has led architects to question the potential of constructing complex forms (Saridal, 2007). As a result, the complexity of modern freeform architecture has been a driving force for the development of new digital design processes in recent years (Flöry and Pottmann, 2010:103-209).

When brick masonry practices are examined throughout history, brick has been frequently used to create complex structures instead of other materials. However, creating complex forms from bricks resulted in difficulties in the bricklaying process, and this problem has been tried to be solved with digital technologies today. In order to understand the impact of digital developments on the use of brick materials, in this part of the thesis, the development of materials and geometry in building through digital is examined.

2.2.1. Digital tectonic

The concept of tectonic has an important place in architecture and has a long history. According to Oxman's (2012) definition, tectonic is a seminal term that describes the essence of the connection between the structural and material properties of architectural design. In architecture, the term tectonic often refers to a way of building that transcends only the functional structure, that is, it deals with the building aesthetically, as well as the opposite aesthetics structurally (Garritzmann, 2018: 72-73). This concept is widely used in the architectural discourse of recent years, which was put forward in the context of "critique of modern technology" and "results of mass production" (Nilsson, 2007: 1-7). Today, there are

developments that encourage a new tectonic form by manipulating the geometry of the structure, thanks to new techniques that enabled by digital tools (Figure 2.24). Thus, these tools created paradigm shift in architecture.



Figure 2.24. Integration of traditional and digital structure in brick structure (Imbern, 2012: 315-321)

Today, the term tectonic has once again become a stimulating and operational design phenomenon, thanks to computational processes that strengthen the relationship between "form, structure and material" properties. The revolutionary transformation of traditional tectonic relations now allows form, structure and material to be directly related thanks to the digitalization process and thus to consolidate this relationship from the idea process in construction to the creation process (Figure 2.25) (Oxman, 2012: 427-455). All these developed relationships reveal the concept of "Digital Tectonics" in architecture. According to Balinski and Januszkiewicz (2016), "Digital tectonics is an evolving methodology that integrates the use of design software with traditional construction methods". With details and components directly related to contemporary construction, digital tectonic design has been accepted as a systematic use of geometric and spatial components (Beesley and

Seebohm, 2000: 287-290). Today, traditional construction methods was replaced and developed with this term.

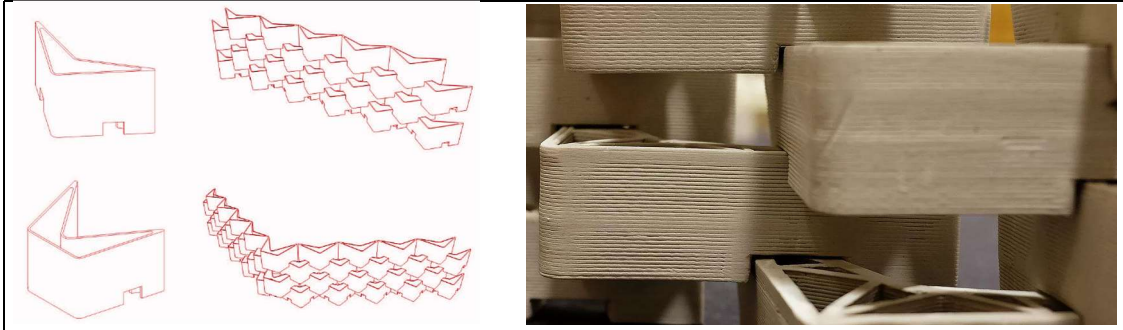


Figure 2.25. V Brick from ACLAB (URL-17)

Digital tectonics focuses on the role and application of materials and technology in the creation of contemporary architecture. The relationship between tectonic and digital design tools increases the performance of the building, and in line with this relationship, today's construction demands are tried to be met (Baliński and Januskiewicz, 2016: 1504-1508). According to Kolarevic (2001), "Digital-driven design processes, characterized by dynamic, open-ended and unpredictable yet consistent transformations of three-dimensional structures, are opening up new architectural possibilities".

In short, the use of digital design tools creates a new tectonic effect in design. New technologies can contribute to rethinking or updating architectural traditions by opening up new design and construction opportunities. For this reason, it becomes an important subject to examine this contribution in today's research (Oliveira and Sousa, 2016: 123-131). Most importantly, digital tectonics today is increasingly enriched by technological evolution based on scientific knowledge in design and production, taking architects from the design of static forms to the design of the material process (Varela, Paio, and Rato, 2013).

2.2.2. The role of material in design

Thanks to the developments in the digital age, the relationship between form, structure, material, production and construction is being reformulated. The return of concepts to their material origins, through material design and production, is a cultural design process that raises questions about the fundamental ideas of design patterns. This shift towards a new

material interest in architecture has begun to contribute significantly to material design theories through the tectonic principle (Oxman, 2012: 427-455). The importance of materials in digital manufacturing has increased as tangible artifacts from the early years of machine-based structured work were prototyped on intangible simulated platforms of modeling software and inevitably took real material limitations into account (Fure, 2011:90-97).

Advances in technology today lead architects and designers to material exploration, thereby expanding the available material palette. The convergence of digital design, materialization and manufacturing technology is creating a change in research and practice in materials design. Technology, which contributes to the rediscovery of materials in architecture, acts as a catalyst, changing the roles of architect and designer and directing modern architecture. In addition, it allows the existing material to become better. Architects and designers are exploring unconventional applications and methodologies for traditional and non-traditional materials to find new ways to push current constraints in materials space (Figure 2.26) (Little, 2006: 6-28). While technologies allow complex geometries to be realized, designers are limited by the properties of materials, not by the problem of defining designs (Marin, Liveneau, and Blanchi, 2012: 137-150).

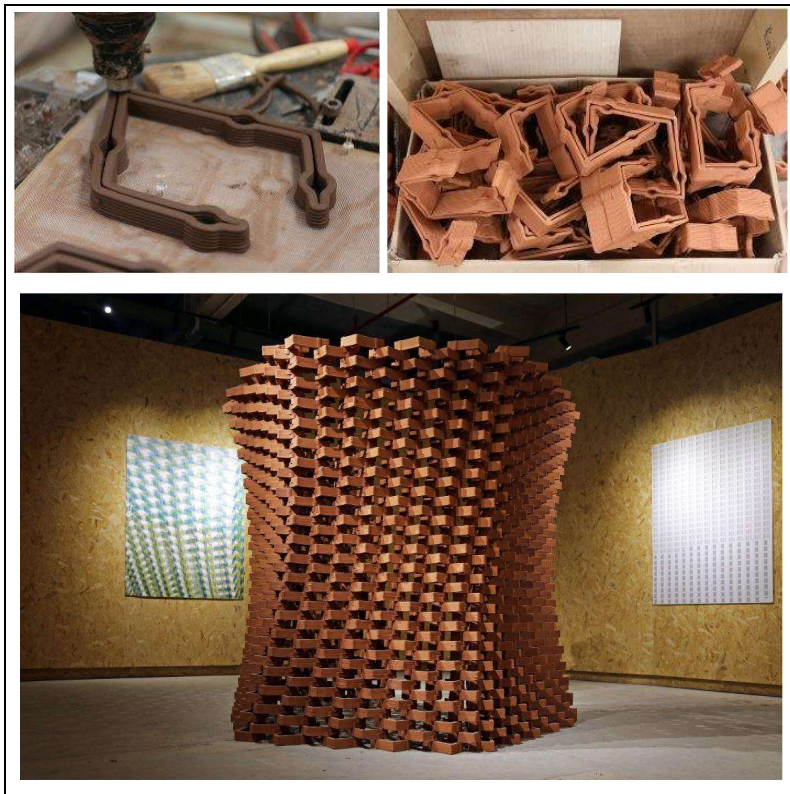


Figure 2.26. 3d printed brick units and brick composition (Lange and Holohan, 2019: 111)

Selecting a material and designing it according to its properties, applying it in a structure and detailing it for a particular project requires understanding the spirit of the material, including its limitations and visual possibilities. By understanding the specific properties of the material, it is possible to provide an economically, structurally or aesthetically successful structure. Hence, material-driven architecture provides the basis for structural tectonics. Oxman (2010) argues that investigating and understanding the role of material in architecture, manipulating the representations of material structures and techniques via digital tectonic to change representations of material structures has become an evolving part of the foundation of architectural knowledge and one of the most important research areas today (Figure 2.27) (pp. 14-23). As Oxman (2010) states, “With the developing manufacturing technologies, the effect of material on architectural form has become one of the important factors in architectural design” (pp. 14-23).

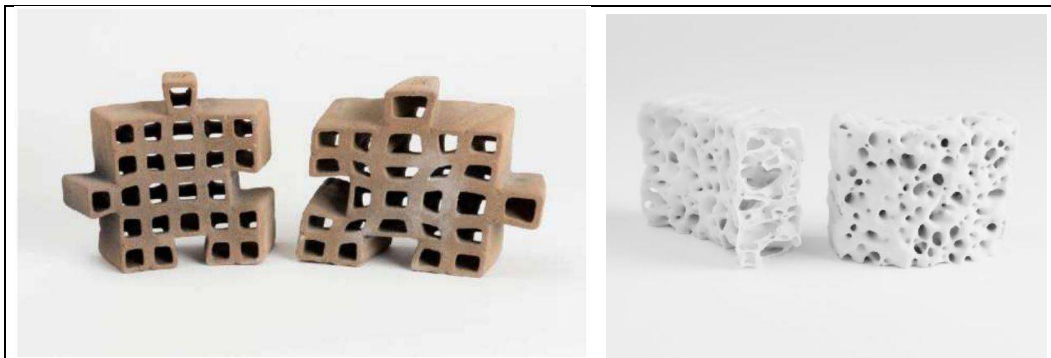


Figure 2.27. 3d Printed Brick (Rosenwasser, Hamada, Luo, and Sabin, 2018: 205-206)

Creating design with materials in architecture can inspire and enhance an architectural concept. Many architects today are experimenting with the potential of a material by building on what it "wants to be", keeping in mind the integrity of the materials. It is believed that every material has a specific nature and intrinsic properties that can be expressed, revealed or hidden depending on its application. Architects are constantly working on ways to push the boundaries of materials and their applications in the built environment, hoping to reinvent a material for future use in design and construction. Therefore, they are increasing their role in the construction and construction process by exploring new ways to process and apply these materials to buildings (Little, 2006: 6-28).

According to Castellon's (2012) definition, form is defined by the combination and arrangement of non-standard components. Digital tools enable the design of complex and

interesting forms. However, the main difficulty lies on the way to their realization. “As a result, material emerges as a contemporary interface between material knowledge (digital) and material performance (analog) and environment (digital and physical) and form.” (Castellon, 2012:277-282). The importance of materials in digital production has increased with the shift from the software-only-based formal experiments of the early years, which took place on the intangible, virtual platforms of design software, to the prototyping of physical artifacts that are necessarily considered (Fure, 2011:90-97). According to Castellon (2012), a good example of material evolution from traditional techniques to contemporary technologies is ceramics and especially brick construction. Brick construction can be considered as a traditional example of component-based systems and thus brick can be seen as one of the first industrial systems produced for construction. The repeatability of brick wall construction and its cost-effective solutions in construction provide a suitable environment for digital design (Bechthold, 2004: 88-89).

2.2.3. Discovery of the geometric boundaries in form

The investigation of the relationship between structural form and strength began with the understanding of the catenary and its correspondence to the arch in the 17th century (Pedreschi, 2008: 12-19). In the light of developing technologies throughout the history of architecture and construction, techniques have been developed by architects and engineers to overcome geometric limitations in the building. The structures that emerged in these years have become a guide for contemporary architecture today, and in the research of Adiels (2021), “Is it possible to learn from masters like Guastavino in a modern context using contemporary geometric knowledge and digital tools” posed the question.

In the 1940s, with the works of great names such as Pier Luigi Nervi, Eladio Dieste, more studies began to be carried out on the role of geometry in structure. The work of a number of designers from the early to mid-20th century aims to express structure with new materials and to develop methods for creating structural forms. Most of these structures symbolize 'structural art', which has an important place in architectural discourse (Pedreschi, 2008: 12-19). Master builders/structural artists at that time pushed the boundaries of structural engineering and provided significant gains to architecture with the unique geometric forms they created (Block *et al.*, 2020: 66-72).

According to Dunn (Dunn, 2012:6-14), objects and structures produced before the development of CAD-CAM systems were created in a simpler way, avoiding complex forms. This is due to the high cost of geometric complexity and diversity. Architects, who have overcome this problem with the development of digital production methods, have unprecedented opportunities compared to previous architects. This non-standard production technique allowed non-standard objects and structures and enabled their construction. In the pre-digital age, structural performance-based methods that contributed to the engineer's architecture served as a validation tool to enable architects to better understand and respond to the structural situation (Madeo and Schnabel: 433-442). At the beginning of the 20th century, building-based form-finding efforts were seen in the work of master engineers and architects, while at the end of this century, another great innovation, the use of computers, emerged. "The use of computers has been a catalyst that defines structure and form. This has opened up new possibilities for the building designer and created a boom in both the design and production process." Today, while formal sensibility re-evaluates complex curved geometries, digital tools for design and fabrication have the ability to reduce technical limitations and make structural surfaces reworkable (Figure 2.28) (Bechthold, 2004: 88-89).



Figure 2.28. Re-vaulting example, Brick-topia by Manuel de Lozar and Lopez Barba (López, Domenech, and Palumbo, 2014: 33-40)

According to Parigi (2014), algorithmic control allows the exploration of more complex relationships between design variables and performance analysis that cannot be evaluated by manual control. For this reason, digital technologies, which play an active role in the design and production phase, enable the (re)appearance of complex forms in architecture. In such complex structures, architects and designers benefit from the solutions created by digital architecture. Therefore, digital architecture is one of the most important research areas to shape the architectural discourse of today and the future. Digital technologies

increase the capacity for accurate representation and error-free production of the designed and enable the production of complex shaped forms, intricately articulated surfaces, facades and structures (Kolarevic and Klinger, 2013: 6-20).

Techniques that continue to be specialized in line with technology and developments in geometry have provided architects with a way of originality and freedom in their designs and have had a great impact on issues such as structural calculations and performance analyzes of architectural structures. Throughout the history of architecture, geometry and architectural form have passed through various periods. With these developments, the understanding of design in architecture has been affected. According to Terzi (2009), "While Euclidean geometry, the precision of which could not be disputed for many years, was considered a revolution, non-Euclidean geometries formed the basis of many computer software" (pp. 1-8). While the development of curvilinear forms poses significant challenges for most architects trained in the precision of Euclidean geometry, computer-based digital architectures are changing design processes (and construction processes) (Kolarevic, 2000: 98-103). Along with computational techniques, the relationship between geometry, mathematics and architecture was re-established. Thus, the architectural design is freed from the constraints of Euclidean geometries, allowing to work with non-standard geometries (double curved surfaces, *etc.*). (Saridal, 2007: 2-6).

According to Ding (2016), understanding the relationship between form and structural behavior through digital technologies not only helps to solve seismic problems, but also triggers new inspirations for design. The critical difference between the use of computer technology and structure-based forms is the ability to directly translate the surfaces of an abstracted volume into a digital surface map and create shapes without predefined conditions. As a result, geometry is the common language that connects our various industries, but traditional design methods are no longer sufficient to manage it and new alternatives are required for both structural design and analysis (Block *et al.*, 2020: 66-72). According to Pedreschi (2008), "Technology can now resolve what has always been a point of contention between the pragmatic and the simply possible" (pp. 12-19). The relationship between construction and design has become more efficient with the integration of digital tools into the design process and benefits architectural practice.

2.2.4. Digital tools and brick integration

The long-term development process of the brick has led to various uses of the brick in construction; however, the material's versatility opens endless possibilities, and as technology advances, it gives designers more options for its use. The geometry of the brick material makes it a suitable material for digital fabrication methods. Along with progress in digital design and parametric form creation in architecture, the discussion about the robotic assembly process of brickwork, an accurate digital fabrication method, and its applicability for complex non-standard brickwork is helping architects today explore the potential of brickwork (Xu, Luo, and Gao, 2019: 83-92).

The manufacturing process system of brick material with traditional methods is based on the formation of brick material by first molding the moist clay by hand, then forming the clay and then drying the shaped moist clay in the sun, as is still a practice in some arid climates (Lynch *et al.*, 2009: 4-12). Today, this system has shown some changes over time. Basically, there are five main processes in traditional brick production and they are extraction of raw material, forming process, drying, cooking and packaging and distribution. With advancing technologies, some projects have supported both the production of brick material and the construction process with new systems and more advanced construction methods used to produce brick walls such as digital templates, robotic assembly and 3d printed brick panels. (Massoud, 2018). In these new production processes, systems such as "CNC Milling, 3D Printer and Robotic Arm" are used.

In the discipline of architecture, it is quite difficult to define a robot. This term includes the concept from robotic arms to CNC milling and 3D printers in architecture (Figure 2.29) (Rahman, 2019). What a robot needs to do in architecture is to create a more efficient system and process that will reduce time and construction costs. The introduction of robotic assembly in brickwork begins as a cost-effective alternative to traditional assembly (Zandavali and García, 2019: 217-226). Brick construction offers strong potential to be automated, as it relies on the repeated assembly of many small and identical physical units. (Jose Pedro Sousa *et al.*, 2015). According to Willman's (Willmann *et al.*, 2012: 439-459) claim, "It not only saves time and cost, but also connects digital design data directly to the production process, enabling the construction of non-standard structures".

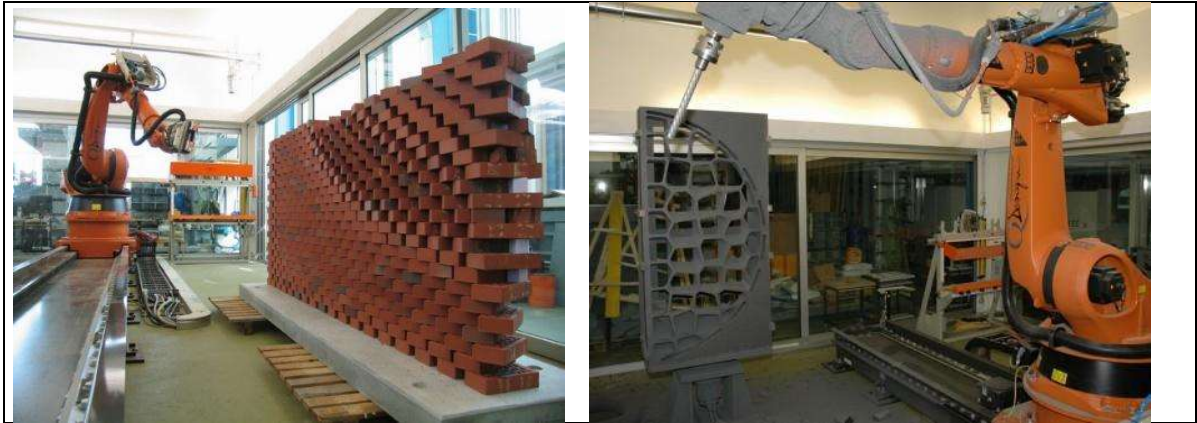


Figure 2.29. Robot Laying Non-standard Wall (left) (URL-18) / Robot act like milling machine (right) (URL-19)

Existing technologies, such as CNC, robotic arm, strengthen the design-construction relationship, and as a result, the relationship of architecture with tectonic contributes to the development of the architect-engineer relationship. Using design data directly in production brings the structure-architecture relationship closer and liberates the architect and designer in the context of form. The fact that everything can be produced and built forces the architect/designer to evaluate what is produced and what is not (Paşaoğlu, 2016).

Robot arms are currently the most common form of robotics used in architecture (Rahman, 2019). Robot arms provide convenience to the designer in the production phase in terms of the ability of a robot to handle a higher workload as well as the ability to place each brick differently without extra effort. Thus, with this benefit, the designer can handle complex forms more efficiently (Bonwetsch, Gramazio, and Kohler, 2007: 1-5).

Building a brick wall is a manual process that requires labor. Building a non-standard brick wall is a time-consuming process as well as requiring skilled craftsmanship. With the development of technologies, Gramazio and Kohler began to use robotic technologies to perform the assembly of brick structures more efficiently. Thus, a ground-breaking development in brick masonry has been caused in the creation of brick walls with the help of robotic arms (Figure 2.30). As a result, robot arms have the potential to be a solution for both standard, repetitive and non-standard variable design scenarios (Oliveira and Sousa, 2016: 123-131).

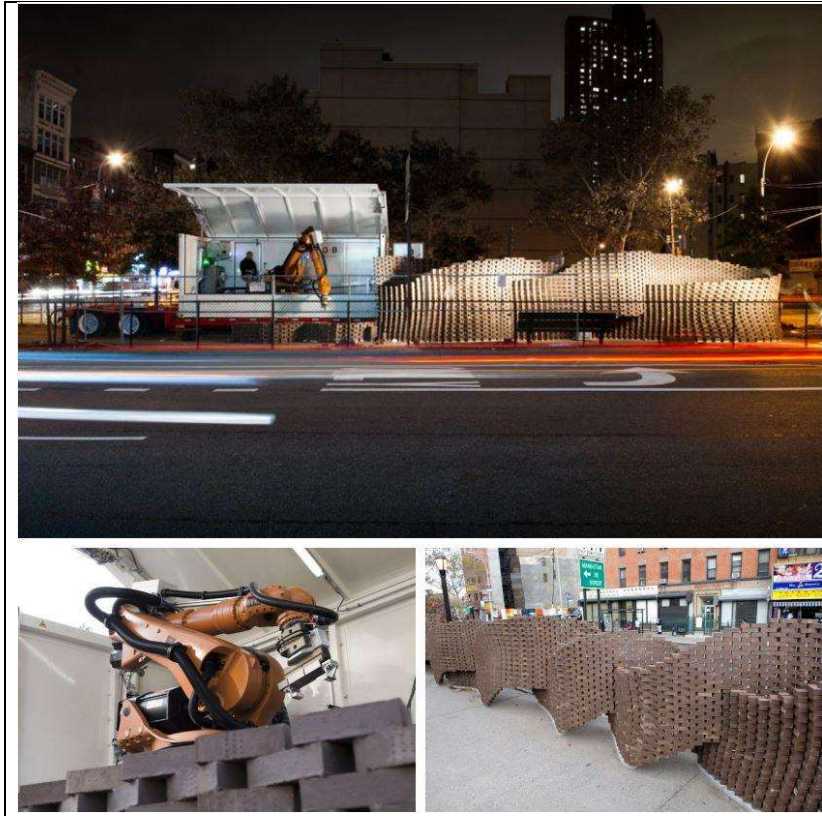


Figure 2.30. Pike Loop by Gramazio and Kohler (Rahman, 2019)

Among the various manufacturing techniques used in architecture, Additive Manufacturing (AM), like other manufacturing techniques, offers a new freedom in creating form and finding creative solutions in architecture. Additive manufacturing technologies are considered a revolutionary technology that expands the possibilities for the design, production and performance of construction systems and their materials, and most importantly, can change the paradigm of the forms in which we can be produced (Paoletti, 2017: 1150-1159). As Attaran (Attaran, 2017: 677-688) argues, “AM has five key advantages over traditional manufacturing: cost, speed, quality, innovation/transformation, and impact. Currently, additive manufacturing enables and facilitates the production of products in medium to large quantities that can be individually customized.” The Additive Manufacturing concept can be turned directly into a final product in the form of a computerized 3D solid model, without the use of external equipment and cuts. This allows the creation of components with complex geometry that can be obtained (Bandari, Williams, Ding and Martina, 2015).

There are still several challenges ahead of making 3d architecture widely available. With ceramic additive manufacturing of structures, the building industry has had unique

opportunities when researching and integrating components with complex design features. Today, with great encouragement, the limits of what can be achieved with masonry are tried to be redefined and expanded. For this reason, it has been researched those new solutions can be produced from the integration of AM technologies with brick material (Figure 2.31) (Cruz, Knaack, Figueiredo, and Witte, 2017: 1-2).

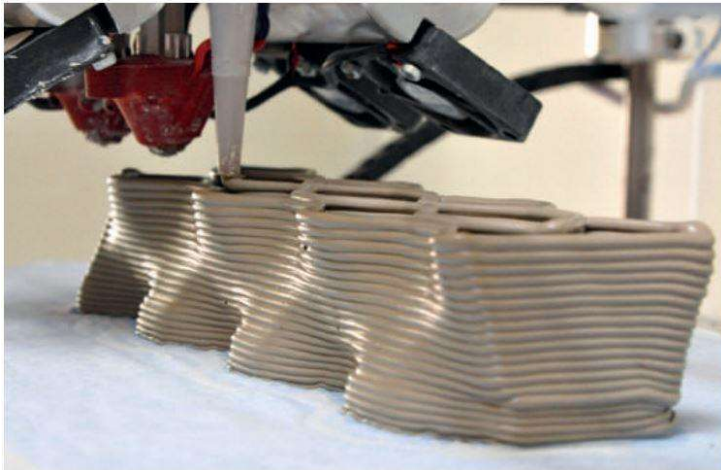


Figure 2.31. 3d printing ceramic unit (Peters, 2013: 433-434)

CNC cutting or 2D manufacturing is the most widely used manufacturing technique (Kolarevic, 2001: 268-278). CNC machines provide designers with a precise production in a very short time with the help of CAD/CAM systems (Kolarevic and Klinger, 2013: 6-20). Digital production and traditional techniques are compatible and complementary to each other. These two techniques sometimes form a hybrid toolkit for architects. In this respect, CNC Milling can be the most convenient system to use in this hybrid process. In the study of low-tech masonry construction techniques conducted by Vazquez, CNC has been a technology used to create negative templates for entire rows, unit templates for individual bricks, and gap templates to control gaps between bricks (Vazquez, Diarte, and Gursoy, 2018: 3-8). In Vazquez's work, the double curved form is primarily constructed using traditional construction techniques, using the string frame method created by Eladio Dieste. Then, to create a special wavy wall with bricks, some templates were created with the help of CNC and leveled surfaces were created (Figure 2.32) (Vazquez, Diarte, and Gursoy, 2018: 3-8).

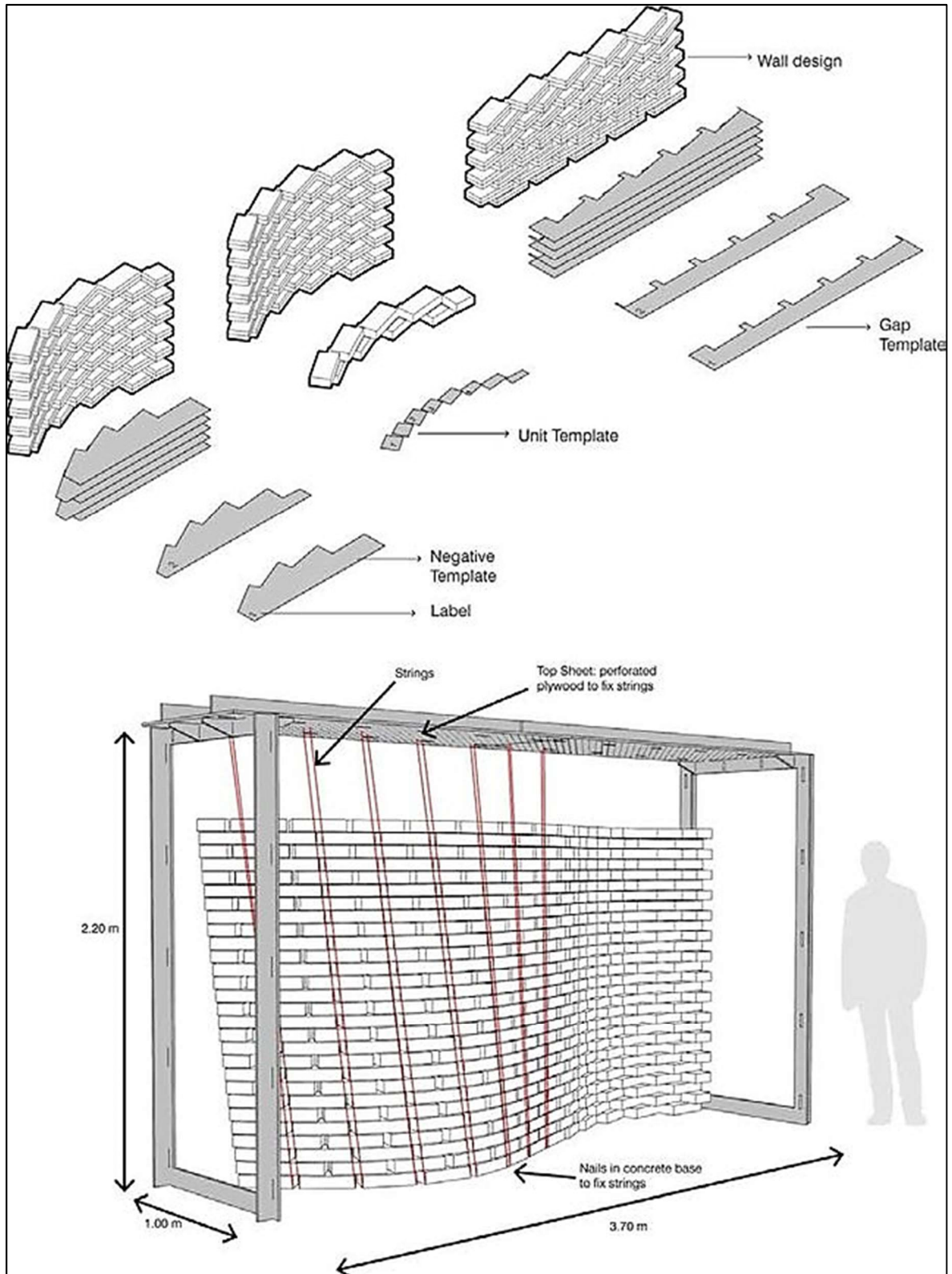


Figure 2.32. Negative template system for bricklaying (Vazquez *et al.*, 2018: 3-8)

CNC machines perform the production based on two-dimensional production and extraction. CNC milling requires monolithic, moldable materials that can be systematically engraved

with machining tools. Today, special cutting and shaping of traditional materials with Computer Numerical Control (CNC) fabrication equipment creates innovative materials in the field of architecture (Figure 2.33) (Fure, 2011: 90-97). Thus, CNC machines are frequently used to create brick structures.

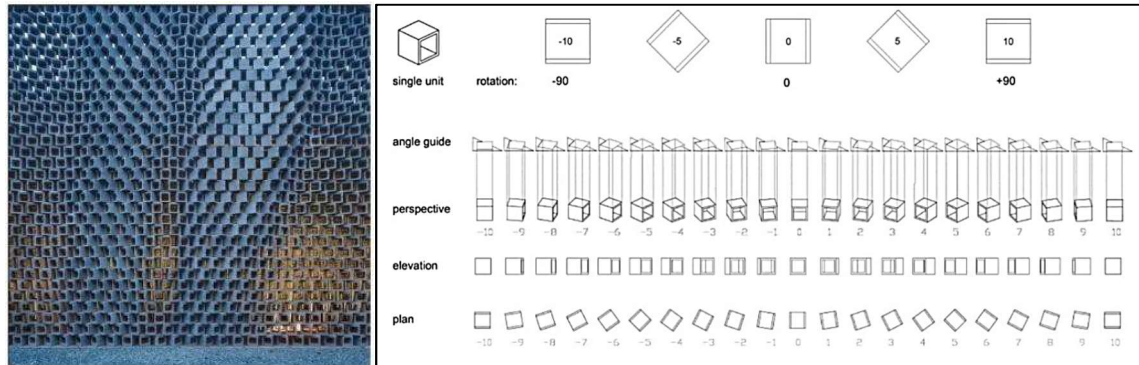


Figure 2.33. Template system for bricklaying (Yuan, Zhang, and Han, 2013 :139-148)

Today, with the research on brick, it has been tried to understand how the brick material can be improved through today's technology. As research show, brick is a ready-to-develop material compatible with digital applications and studies on it continue today.

3. MATERIAL AND METHOD

In the 20th century, masters such as Dieste, Isler and Candela pushed the limits of structural engineering with the techniques they used in their structures, and their efforts to reach the concepts of efficiency, economy and beauty in this way created the motivation of these structures. At the same time, limitations such as financial and cosmic economics have enabled the development of ground-breaking innovations and new structural systems. In this period when new materials and technologies are costly, it has been observed that effective projects in terms of structural and material efficiency have been developed significantly (Block *et al.*, 2020: 66-72). In these projects, awareness of form has been the main factor that provides this efficiency. With the form-making process being inseparable from the materialization process, masters such as Dieste and Isler gave importance to the integration of form and material. Thus, examples of successful architectural structures in terms of structural, economic and aesthetic were formed (Figure 3.1).

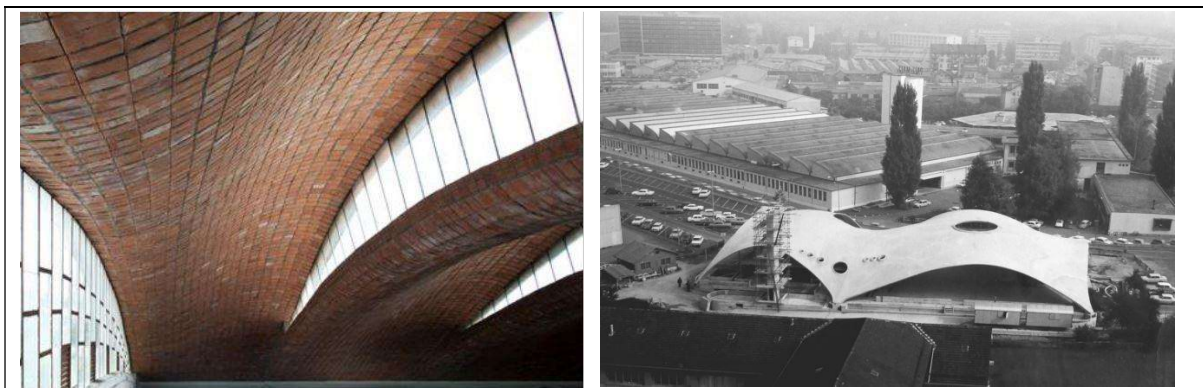


Figure 3.1. Citricola Saltena, Eladio Dieste (left) (Jonas *et al.*, 2014: 513-522) Sicli SA Factory shell, Heinz Isler (right) (Chilton and Chuang, 2017:763-785)

Dieste has achieved structurally important methodologies with the forms it has created and has provided great benefits to architecture with the integration it has created between the material it uses and the form. Due to the frequent availability of brick material in Uruguay, this material was frequently used by Dieste and importance was given to the form-material-structure relationship of the buildings. By using the possibilities of the period, Dieste both developed the role of brick material in the building and demonstrated its advantages in use in the building through the structures it created. Thus, the role and importance of the material in the design has been revealed. Matias Imbern (2012: 315-321), an important figure in

design and technology, stated that Eladio Dieste has the features of being more cost-effective solutions for their structures and included the following statements for ceramic structures in his review: “For some scenarios, structural surfaces built with ceramic components, ceramic elements It has proven to be more affordable than concrete shells, taking advantage of its lower weight and cost, reduced need for reinforcement, and the unmatched quality of the finish” (Imbern, 2012: 315-321).

In the past, especially since the 20th century, the use of brick by some builders has shown the unique tectonic effects of brick and has led to the realization of the potential of brick on today's projects (Pedreschi, 2008: 12-19). However, despite being a frequently encountered material in the built environment, surprisingly, it was not widely accepted as a structurally applicable element in the practice of contemporary architecture until recent years (Rosenwasser, Hamada, Luo, and Sabin, 2018: 203-218). Today, this shortcoming has attracted attention, and although it is not enough, the role of brick material in design is tried to be explored with many research.

In the present century, the approach of architects and engineers to the relationship between form, force and mass has changed significantly (Pedreschi, 2008 :12-19). The strong tectonic effects created by the form-material-structure relationship are experienced digitally today. Thus, the search for original form and new structure has begun in today's architecture. Brick, on the other hand, acts as a mediator between the architect and the building in this quest with the unique tectonic tradition it has created as a material that has been used in buildings for years. In line with these developments, in this section, the Atlantida Church, which was built by Eladio Dieste between 1958-1960 and successfully benefited from the potential of brick through form, was revisited to evaluate the changes created by digital tools on the brick material.

3.1. Resistance Through Form

Eladio Dieste is a structural engineer who started his career in Uruguay in 1942. For nearly half a century, Dieste has designed outstanding architectural structures for communities and industries that are both inexpensive and of high aesthetic quality. Avoiding the costly steel or reinforced concrete structural systems characteristic of many twentieth-century buildings, Dieste considered the conditions of the region and opted for fired brick, a material that is

both attractive and easily produced locally. Dieste's approach incorporates traditional, even medieval, techniques in part because it made use of low-tech vaults that provide stability through form. However, his method is revolutionary in that its vaults are very thin in cross-section and extremely light, thanks to the complex double curves and the use of reinforcing rods between the mortar and the hollow bricks. Dieste's approach is important for architectural structures as it provides great efficiency and low cost (Bach, 1993: 38-45).

20th century steel, concrete, etc. when it came with new materials, the form was shaped with these materials and turned into flatter surfaces. According to Dieste, although working with planes creates an easier process during the construction phase, planar geometries do not always create the optimal form (Figure 3.2). Although the planar skeleton is easy to analyze, it also has some disadvantages. In the middle of the 20th century, with the increasing need for large-span space, master architects turned to produce more complex structures, and considering the effect of its form in this period, structural experiments were carried out with a system on building performance, literally exploratory, through three-dimensional physical model experiments (Hu and Li, 2014). Dieste has shown that the form creates structural and spatial benefits through the forms it creates, and it still makes a name for itself with its structures.

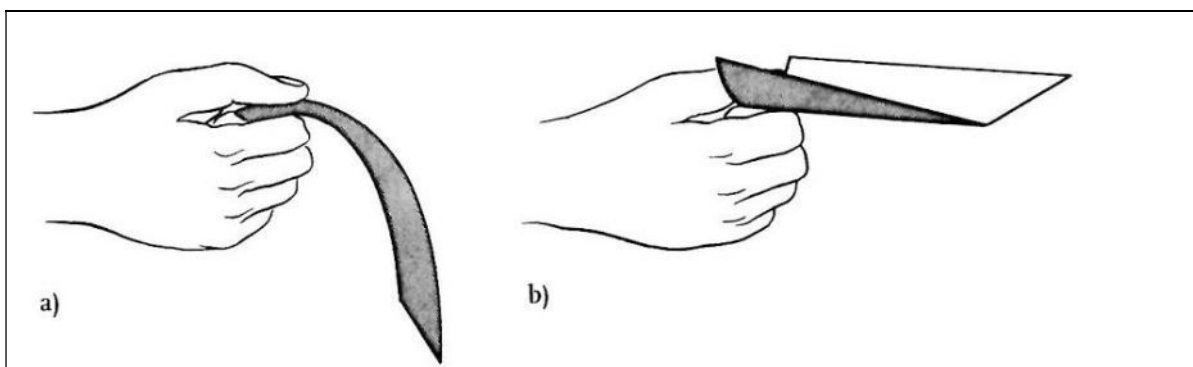


Figure 3.2. Basic “resistance through form” illustration, (Elliott, 2019: 21-138)

Acting on the principle of “resistance through form”, Dieste stopped making use of the technology and materials of that time and created new structures and methodologies with surfaces such as brick and Gaussian shells, self-supporting shells, ruled surfaces, folded plates (Figure 3.3). Thus, in these structures, the inertia required to prevent buckling of a thin structure is provided by the curves formed by the surface. For example, complex

bicurved forms called Gaussian vaults use form to resist buckling and resist through form (Anderson, Dieste, and Hochuli, 2004: 144).


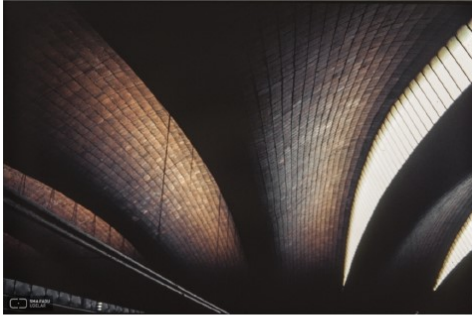


Important Structures of Dieste	Year	Image Sample	Structural Type
Christo Obrero Church	1960		Ruled Surfaces, Continuous Gaussian Vaults
Fabrica TEM	1962		Non-Continuous Gaussian Vaults
Dieste Residence	1968		Barrel Vaults
San Pedro Durazno Church	1971		Folded Planes

Figure 3.3. Important Structures of Eladio Dieste, (Image samples: URL-20)





Important Structures of Dieste	Year	Image Sample	Structural Type
Salto Bus Terminal	1974		Self-Supporting Vaults
CADYL Silo	1978		Continuous Gaussian Vaults
Dan Basco School Gym	1984		Non-Continuous Gaussian Vaults
Montevideo Shopping Center	1985		Ruled Surfaces, Barrel Vaults, Non-Continuous Gaussian Vaults

Figure 3.3. (Continuation) Important Structures of Eladio Dieste, (Image samples: URL-20)

According to Bach (1993), the creative building product in architecture and engineering is “the essence of functionality or utilitarian purposes, a durable function and a structural type, economy and construction process, and the harmonious consideration of the aesthetic qualities of the shape and dimensions of the structure” (pp. 38-45). According to Dieste,

architecture is also construction and art (Anderson *et al.*, 2004: 144). The structures created by Dieste with form awareness have the most appropriate and rational form solutions, because the obtained form provides a significant benefit in minimizing the required amount of material and in terms of structural calculations. Thus, it set an example for the formation of buildings that are both structurally and aesthetically successful because, according to Dieste, a solid architecture cannot be realized without the rational and economical use of building materials (Pedreschi, 2008: 12-19). Dieste's structures successfully demonstrate all these features. The challenge for Dieste was to create a structure language that was contemporary and modern, but not dependent on the technology of the developed world, more suited to Uruguay's conditions. It achieved this by reinventing a new structural language with brick.

Brick is a lightweight building material often used in Uruguay and is built faster than concrete. Thanks to the forms developed by Dieste, brick has turned into a material with new possibilities (Figure 3.4). These forms use brick as sparingly as possible, making maximum use of structural performance to a rather surprising effect. In these structures, the form provides structural and aesthetic benefits. With this perspective, Dieste has developed design procedures in order to obtain more stable structures with lower buckling rates, unlike the typically constructed vaults (Pedreschi, 2008: 12-19).

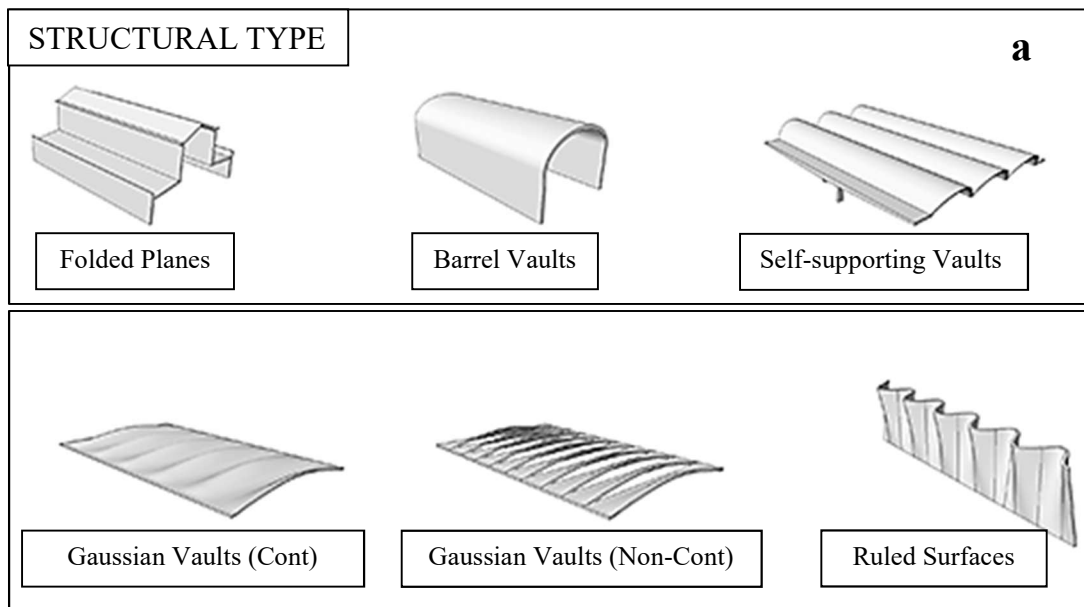


Figure 3.4. Structural types of Eladio Dieste's structures (a) (URL-21) Gaussian Vault from Eladio Dieste (b) (Pedreschi, 2008: 12-19) Gaussian vault development (c) (Pedreschi and Theodossopoulos, 2010: 779-787)

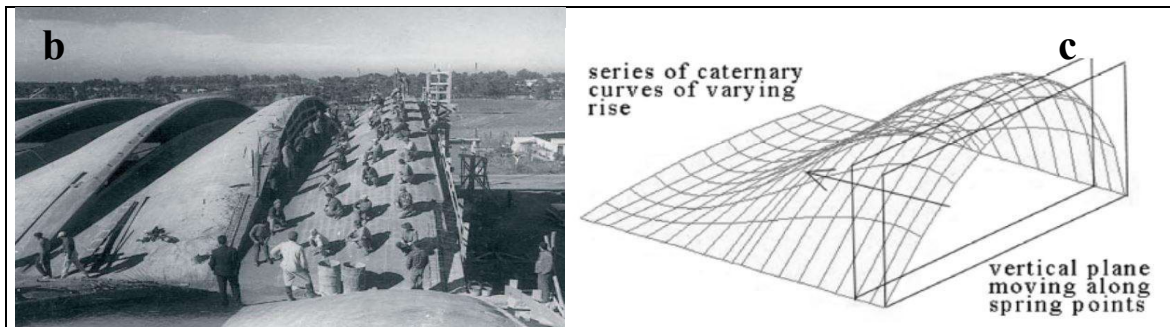


Figure 3.4. (Continuation) Structural types of Eladio Dieste's structures (a) (URL-21) Gaussian Vault from Eladio Dieste (b) (Pedreschi, 2008: 12-19) Gaussian vault development (c) (Pedreschi and Theodossopoulos, 2010: 779-787)

Eladio Dieste has developed an innovative construction method for large span roof structures. Double-curve geometries, known as Gaussian vaults, are mainly based on the catenary resulting in axial compression forces (Pedreschi and Theodossopoulos, 2007: 3-11). Experience in the construction of reinforced concrete vaults has led him to experiment with brickwork in the construction of laminate surfaces. Relying on solid theory and mathematical computation and applied to construction and design, Dieste focused his exploration on the relationship of brick material and form as the moderator of structure. With this material-form relationship, Dieste built vaults with a thickness of only one brick layer, unlike traditional wall vaults. In this way, unlike typical vaults, it has succeeded in creating vaults with a lower buckling rate and more statically efficient. Dieste has developed design procedures to create more efficient structures using the curved surface of the vaults to resist buckling (Pedreschi and Theodossopoulos, 2007: 3-11). The methodology that developed by Dieste exemplified at Figure 3.5.

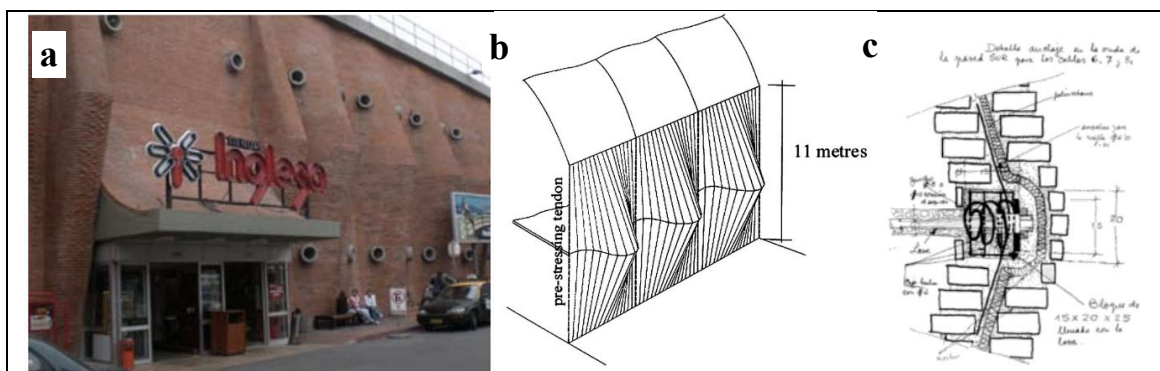


Figure 3.5. Montevideo Shopping Mall wall (a) (Lee and Garlock, 2010: 1562-1568) pre-tension cable placement (b) (Pedreschi, 2001: 111) and detail (c) (Pedreschi, 2001: 111)

Dieste's works fit those purposes and he exhibits the potential of brick material. Architects and engineers were responsible for the development of many structural forms and innovative uses of materials, which attracted attention with their architectural qualities as well as efficient and resourceful materials and construction technology in a short time in line with the ongoing trends in architecture. By evaluating the properties of brick material in its buildings, Dieste revealed the relationship of both material and form with the principle of resistance through form and became the pioneer of important developments in architecture with these structures. In Atlantida Church, this relationship can be seen clearly. "The structural system Dieste used for both walls and roof employs surface form, akin to a folded or bent piece of paper, allowing the building to perform as an efficient structural shell through its shape" (Elliott,2019: 21-138). He created the pre-tension cables applied in concrete and brick structures in the 20th century, with the belief that brick is a more advantageous and local material, as well as being influenced by the structures of Guastavino. The integration of important methodologies from the masters and today's developing technology again pushed the boundaries of architects and engineers, and the material began to be reanalyzed. To pre-tension the construction system, steel tendons connect the ends of each vault, adding rigidity to the structure. There are lessons to be learned from this architectural endeavour that could help us address the challenges that our society and, more specifically, the construction industry, faces today.

With the arrival of the computer age after the 1990s, a new structure calculation method and analysis tools emerged (Hu and Li, 2014). The ability to process and manipulate sophisticated forms provided by today's computational technologies has led architects and engineers to question the value of the form-material-structure relationship and to question the possibilities of constructing non-standard forms. With the help of computational technologies, the geometric constraints imposed by traditional techniques have been overcome and the gap between design and production has been minimized. Thus, it has been seen that it is possible to reform not only the design strategies, but also the entire architectural perception and boundaries (Saridal, 2007: 2-6). The buildings created by Dieste with the principle of "resistance through form" are also an important milestone for architects and engineers today, and have been the subject of many research today and have been chosen as the case study of the thesis.

3.2. Revisiting Wall of Atlantida Church

Digital design methods have begun to play a major role in the architectural discourse, enabling architects to parametrically reinterpret existing building types, providing the needs of the building with form, material and structural integrity, and meeting complex needs without sacrificing structural performance. At the same time, while traditional tectonics is the accumulation of thousands of years of experience and understanding of artisans, digital simulation technologies have made it possible to reveal the knowledge inherent in traditional architectures that can be simulated in digital environment. Thus, innovative design methods have emerged by transferring existing building methods to digital (Yuan and Chai, 2019: 265-282).

Despite the benefits of complex geometries in the building, architects and engineers generally use these geometries as; they avoided due to the difficulties of representation, production difficulties and economic difficulties. The construction/construction processes of these complex geometries bring some challenges and require the involvement of the structural engineer as shown below (Figure 3.6). Digital design provides an ease for complex structure creation through the structural analysis. According to Yuan and Chai (2019) “Through the comprehensive analysis of form and performance, the qualitative knowledge can be transformed into quantitative calculation, and the tacit knowledge can be transformed into explicit knowledge” (p. 267).

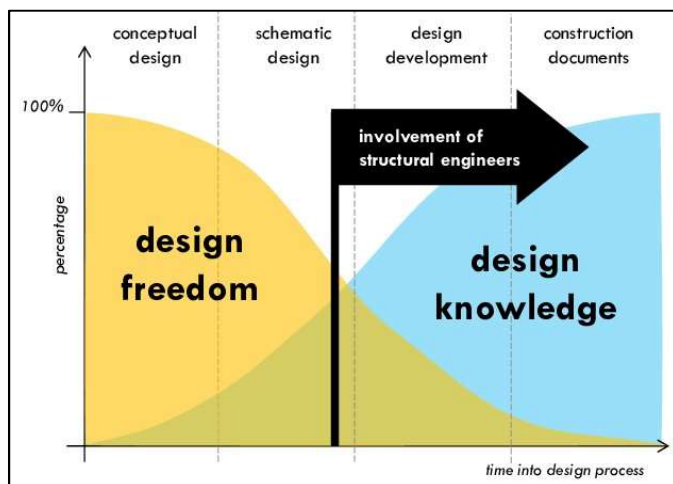


Figure 3.6. Relation between design freedom and design knowledge (Mueller and Ochsendorf, 2013: 46)

Today, the benefits of complex geometries in the building have been the subject of many studies, in line with what the digital environment has made possible in architecture. In addition to the geometric complexity, material is an important issue in designing structure. These issues are also important area for the 20th century both architects and engineers for creating economically and structurally effective structures.

In Dieste's work, the double-curved forms and pre-tension cables are one of the most easily recognizable elements of his architecture. Its structural solutions, including free-standing vaults, gaussian or double-curved vaults, canonical surfaces, and folded planes, are all based on the ingenious use of reinforced ceramics (URL-21). In these works the form is concerned with the vertical or horizontal manipulation of brick surfaces, avoiding linearity wherever possible. For example, in the Atlantiada Church, one of Dieste's best-known works, one can see the use of double-curved walls combined with gaussian vaults, a more suitable surface and form application, using masonry techniques (Figure 3.7). Planar forms were used in the building only to create lighting. In this sense, the Church of Atlantiada is the most successful example of Dieste's principle of resistance through form.

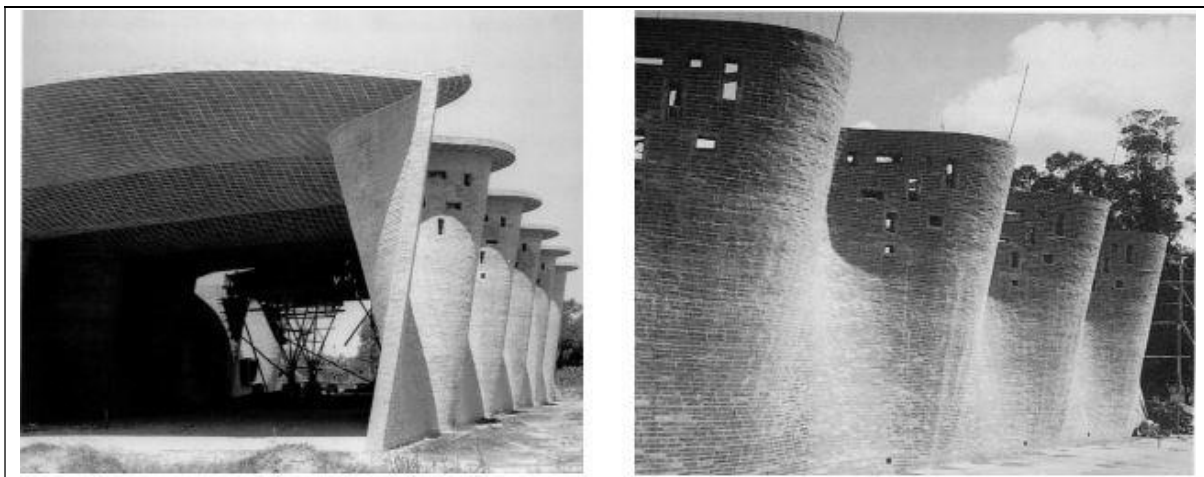


Figure 3.7. Atlantiada Church, Eladio Dieste (Estevez Cimadevila and Vázquez Rodríguez, 2004:13-21)

The Atlantiada Church is an example of public architecture designed by Eladio Dieste between 1958 and 1960. The church is an example of a new, rational and economical form of construction suitable for Uruguay, as it has an architectural language appropriate to the context of its environment and was built using cheap, domestic materials (Wadell, 2016). The first known sketches of the Atlantiada Church were created in 1954 by Dieste and his

team (Figure 3.8). It was conceived as a continuous vault 10 meters high and took its final shape over time (Figure 3.9) (Elliott, 2019: 21- 138).

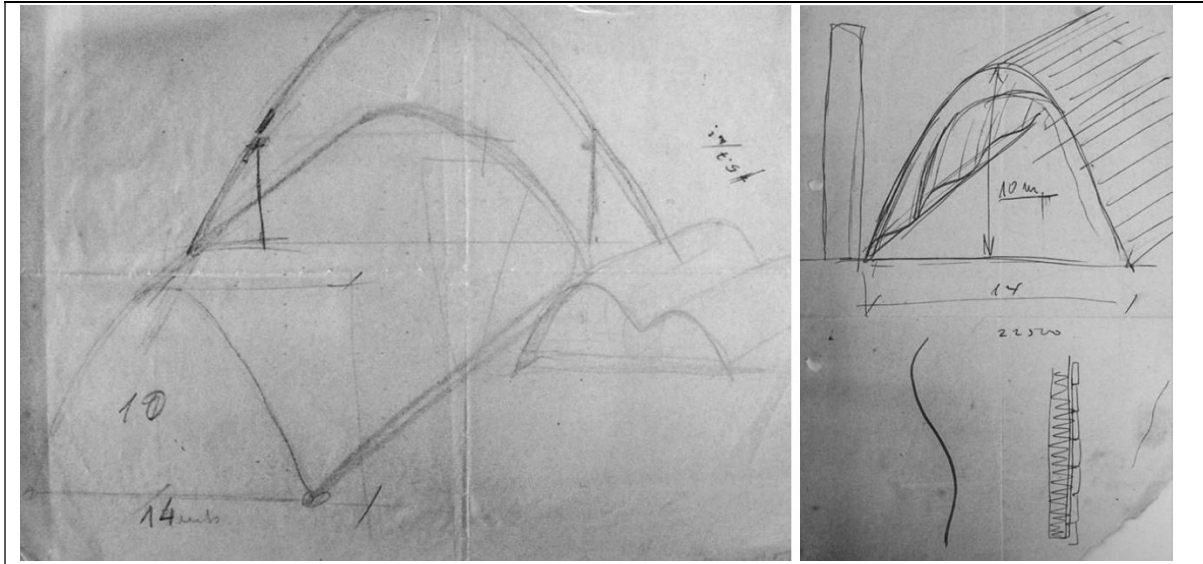


Figure 3.8. First known sketches of Atlantida Church by Eladio Dieste (Elliott, 2019: 21- 138)

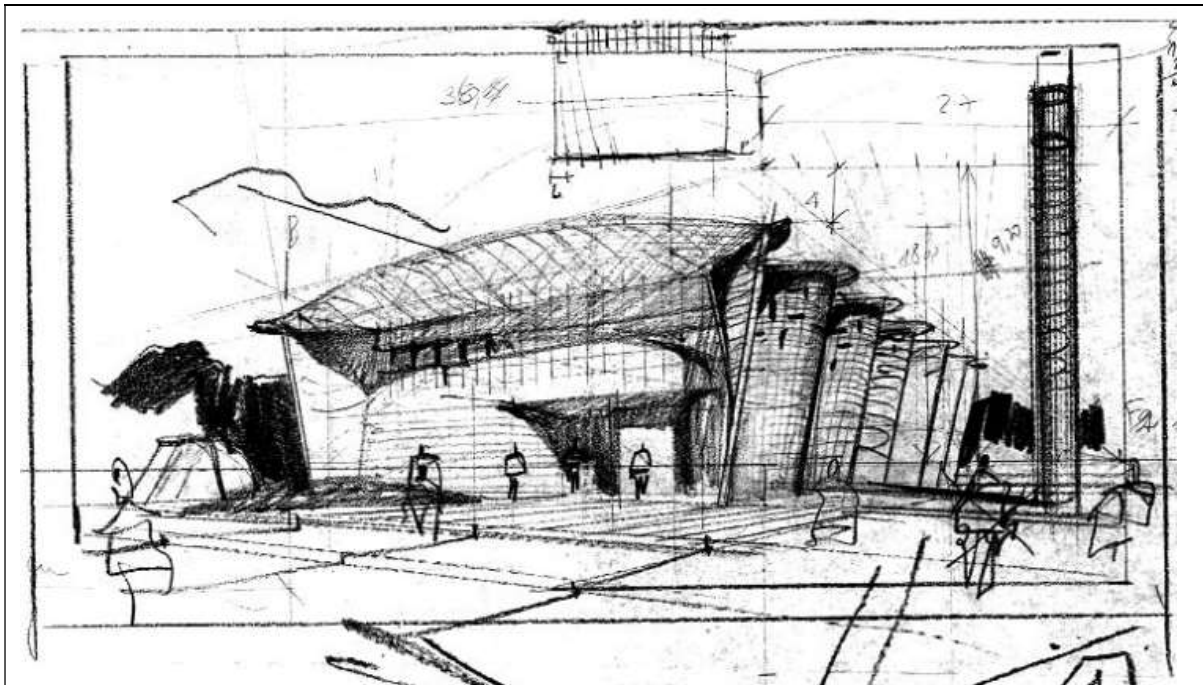


Figure 3.9. Last sketch version of Atlantida Church (URL-22)

All the surfaces of the church are made of brick material. Like the other structures of Dieste, this structure is an important structure that shows how brick and masonry construction can

be used in the building and how the potential of the material can be utilized. The form of the building was settled before the construction details and the roof subsequently underwent significant changes for constructability. The walls and surfaces of the church are covered with a thin, folded brick laminate designed by Dieste, and it is so thin that no one has ever achieved this effect with traditional materials. At that time, Dieste showed his creativity and skill with the use of materials that contrasted the structures of master architects who formed the contemporary architectural language with their reinforced concrete structures such as Candela and Le Corbusier.

When looked at the building features, the idea of “Resistance Through Form” can be easily seen in the Atlantida Church structure, as in the other structures of Dieste (Elliott, 2019: 21-138). The geometry of structurally undulating walls is based on a simple principle to enhance their structural performance. By this principle, a series of conoid wall surfaces were formed by joining a straight profile at ground level and a curved profile at the top using vertical lines (Figure 3.10).

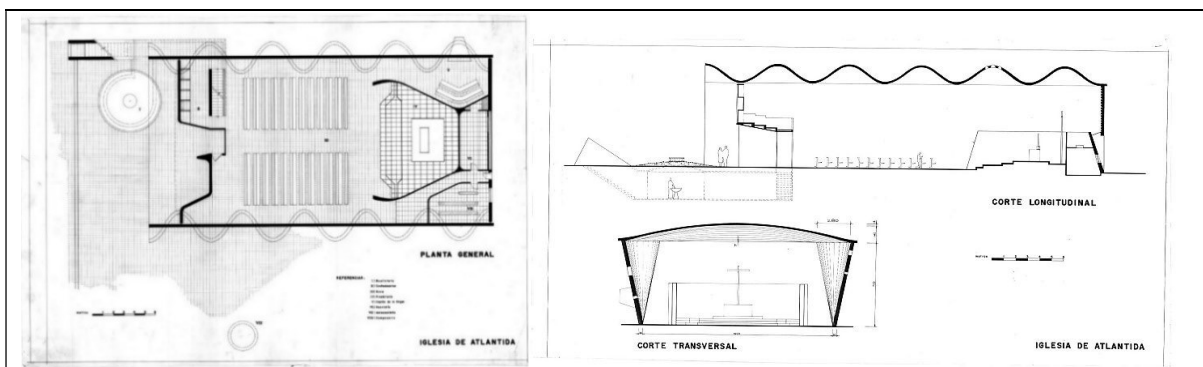


Figure 3.10. Plan and section of Atlantida Church (Elliott, 2019: 21-138)

The conoid surface, which was formed from the curves designed during the construction process, was solved by the frame method and thus the position of the bricks could be determined (Figure 3.11). The roof, on the other hand, is a vault that he designed using a catenary line in the form of 3 curved lines, which acts efficiently in compression and creates a surface that resists deflection by using the minimum amount of material (URL-21). Dieste's method of construction can be seen as a clear advance in sustainable architecture due to its effectiveness in using the material (Elliott, 2019: 21-138).



Figure 3.11. Construction of Atlantida Church (Elliott, 2019: 21-138)

In the years when the church was built, architects/engineers used the graphic method to provide a direct correspondence between the forces in a building and the geometry of the building itself. This, in turn, has become a design tool that allows rapid development and refinement of form, either to control forces or to manipulate the geometry of the structure (Pedreschi, 2008: 12-19). Unlike many of his international contemporaries, such as Felix Candela or Frei Otto, Dieste derived its structures and forms solely through non-graphical calculations. Regardless of the scale or scope, prominent masters such as Dieste and Antoni Gaudí are known for not applying form-finding methods (Garcia Fritz and Garcia Lammers, 2016).

Dieste's use of potential of the brick material is another reason that makes his structures special. Technologies, on the other hand, carried the material further in these representations and led to the evolution of the material. The fact that the brick material is suitable for digital production and the way Dieste uses bricks in its buildings is important in terms of discovering the future potential with brick material. With the abandonment of the use of brick as a building material in contemporary architecture, its use has been found mostly in non-bearing building elements. This is due to the difficulties of designing bricks and the existence of some disadvantages of the brick rather than the fact that the brick material does not have a static value. However, Dieste has developed this material efficiently with the formal possibilities it has created. Through his tremendous work, he has demonstrated the immense possibilities of creating astonishing spaces where constructive rationality is combined in a spatial richness of the highest architectural quality (Hu and Li, 2014).

With the development of digital tools day by day, the relationship between architecture and structure has developed and complex geometries that provide structural benefits have become today's research topic in architectural discourse and practice. Especially the tectonically strong structures created in the 20th century have been successful examples for today. At this point, Eladio Dieste's buildings set an important precedent, especially for brick structures. Today, double curved surfaces with brick material developed by Dieste became an important structure in line with these benefits. However, the difficulties created by the workforce have been the biggest obstacle to the spread of these structures. Today's technology, on the other hand, has made it possible to construct complex geometries through the facilities it has created today, and when these geometries are re-evaluated in the digital environment, representation forms and constraints can be removed. For this reason, in this part of the thesis, the Atlantida Church, which is an important structure of Dieste, was created digitally through the Rhino program (Figure 3.13), and the wall form of the church was evaluated through digital tools.

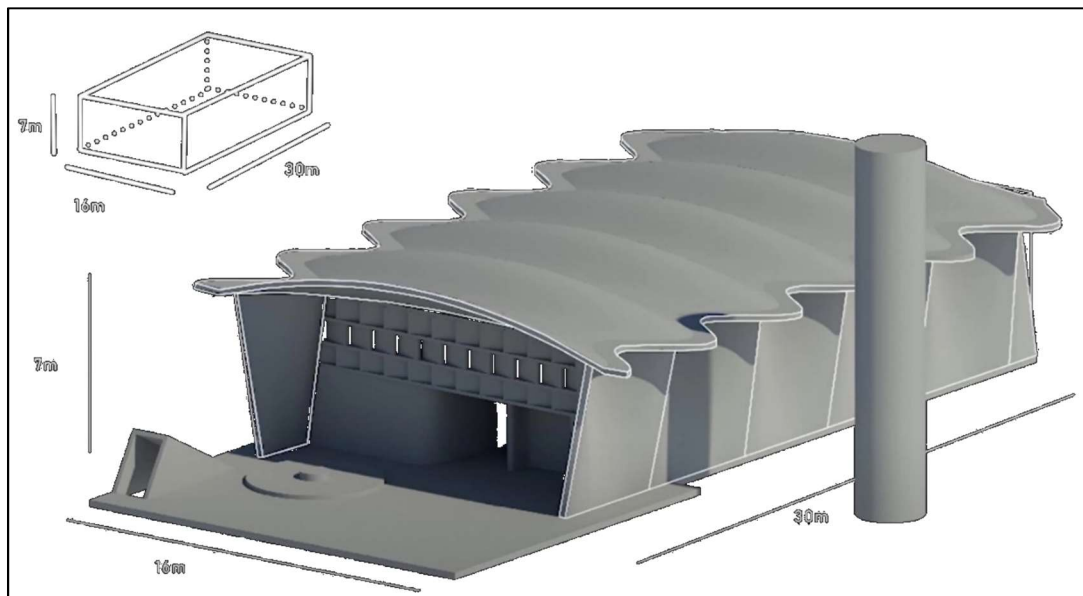


Figure 3.12. Atlantida Church dimensions (URL-23)

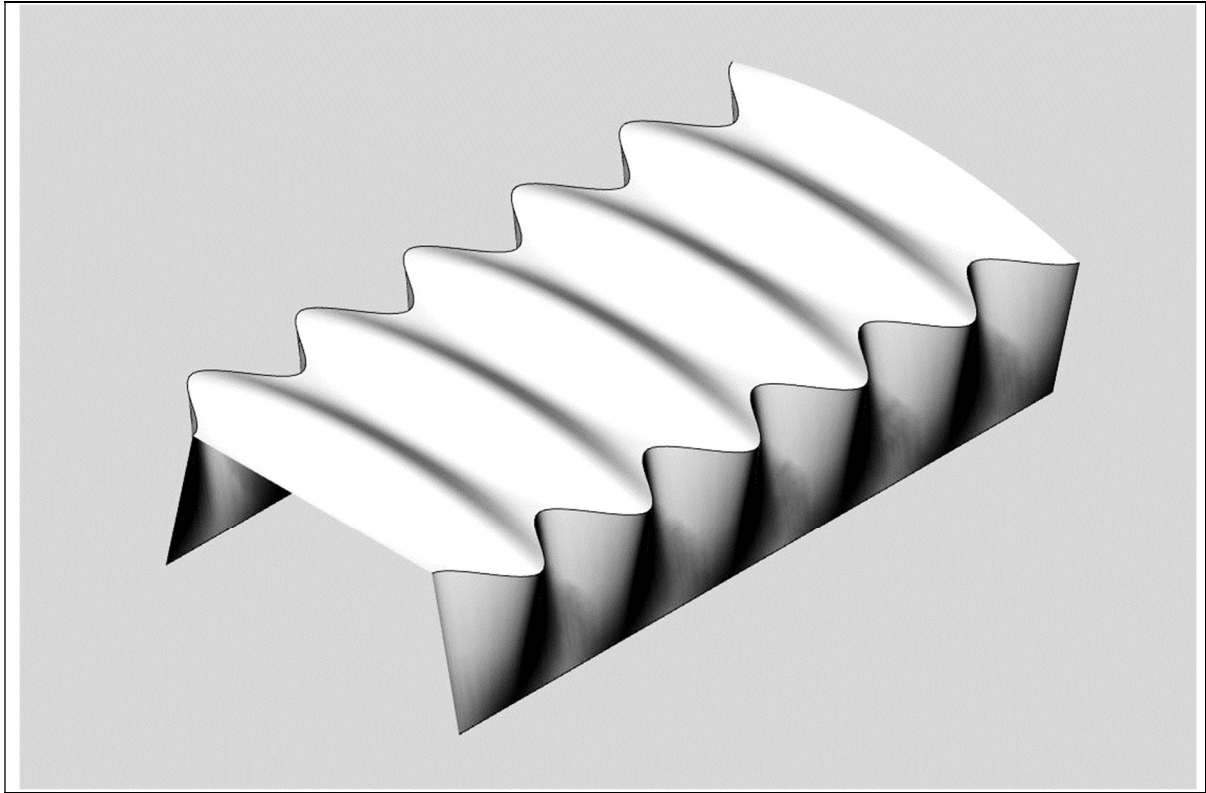
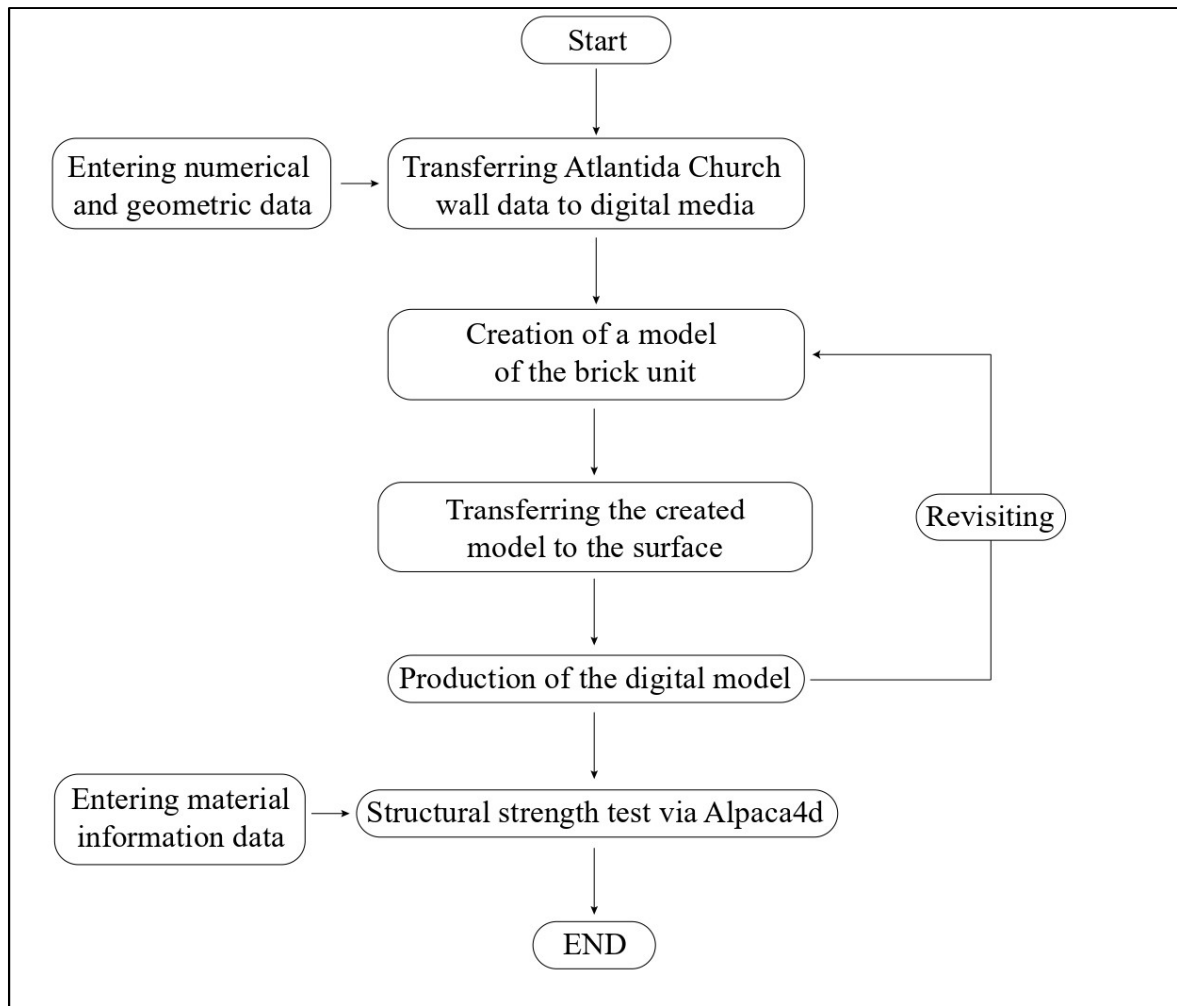


Figure 3.13. Digital representation of Atlantida Church via Rhinoceros, (Author)

At first, the geometry obtained from grasshopper transferred into SAP2000 to see static behavior with adding steel tendons and comparison made. Then, original brick unit was replaced by digital brick units. Thus, self-interlocking brick units created in the virtual environment of Rhinoceros. How this parametric process is designed is shown in the table below (Table 3.1). These units and their structural behavior integrated into the structure by use of the Starfish and Alpaca4d plug-ins in the digital environment.

Table 3.1. Parametric workflow of Atlantida Church wall via Grasshopper



As can be seen in today's brick examples, transforming the brick unit into a new unit with the digital methods have a potential to providing a lighter and more robust structure to the structure emerges as an important research topic in brick applications. The situation observed in some examples, as in other building materials and tectonics, the existing methods and brick laying methods used in the brick material design process have begun to be reviewed and developed with the opportunities offered by digital means (Eldemir Kara, 2021:329-344).

In this study, the unique wall surface geometry of the Atlantida Church is digitally modeled with Rhino Grasshopper to be re-evaluated with today's digital tools. First, geometry was transferred into SAP2000 and then, reinforcement cables were added to the wall surface, inspired by the methodologies that Dieste applied in his buildings, and the structural behaviors were evaluated with SAP2000. Thus, the effect of tendons on the brick wall, which

is indicated by FEA, was observed to understand the effectiveness of their methods and the brick relationship. Thus, the structural behavior of the wall was calculated clearly with SAP2000 and the structural behavior was revised by adding steel beams. Then, it was discussed what else can be done with the rhino grasshopper with today's technology and architecture. In the light of the fact that the role and potential of the material can be re-evaluated with today's tools, the relationship -form-structure-material- has been evaluated.

3.2.1. Reproduction of wall through digi-bricks

Dieste argued that the brick material has advantages over the concrete material, and in order to improve the benefit provided by the brick material in the building, the principle of resistance through form was used, and moreover, prestressing cables were often used. Thanks to the methodologies it has developed, Dieste has created important structures both in terms of architecture and engineering, with the structures created in the context of space and economic conditions. Although these methodologies are a proven method to improve the potential of the brick, its efficiency has been re-examined with today's technology and the question of how the brick material can be improved today has been questioned. For this, the structure was tried to be improved by using digital tools through the wall of the Atlantida Church (Figure 3.14). The original version of wall was tried to be obtained by transferring the brick unit to the wall surface by designing it in digital environment (Figure 3.15).

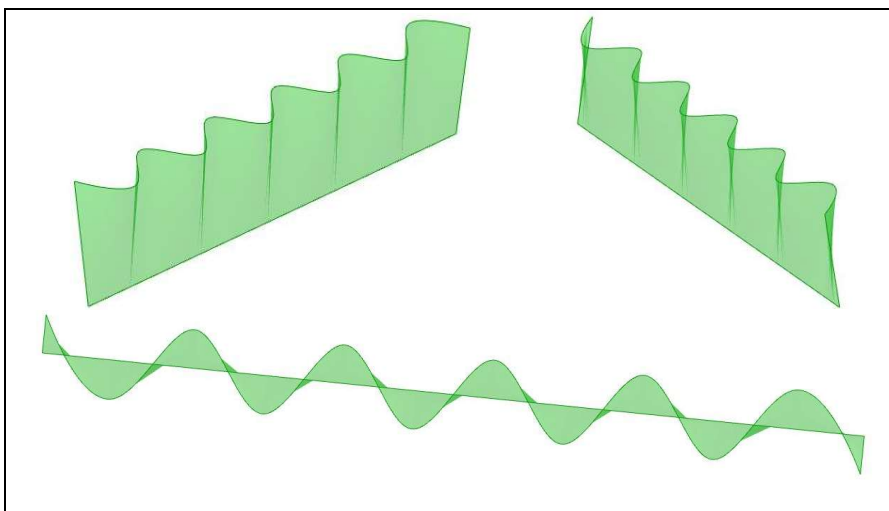


Figure 3.14. Digital representation of Atlantida Church wall via Rhinoceros, Grasshopper (Author)

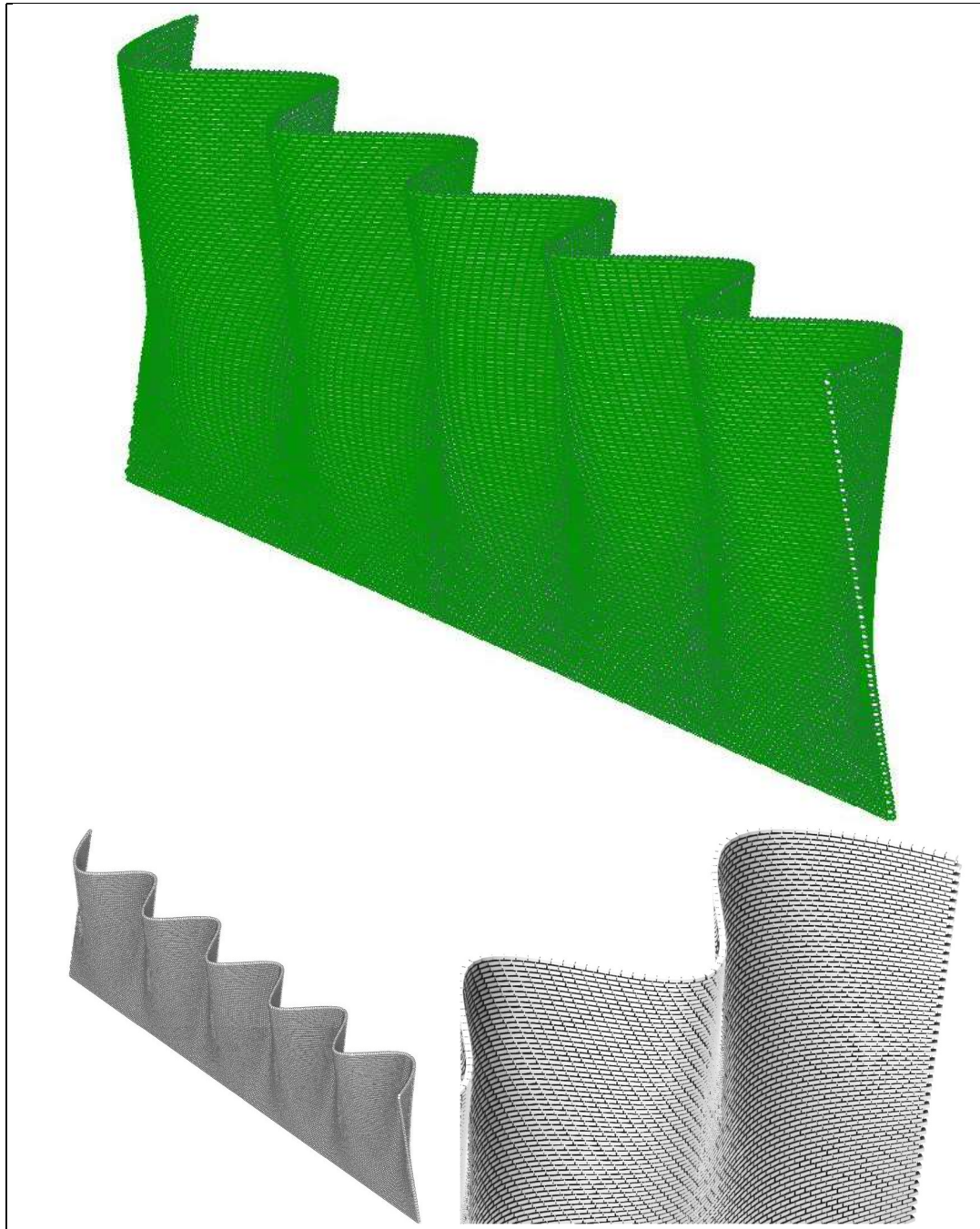
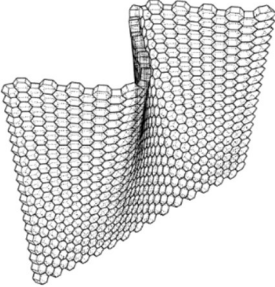
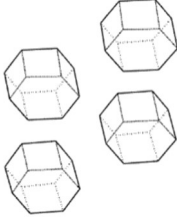
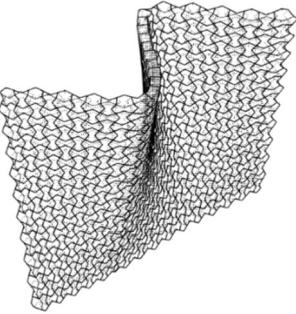
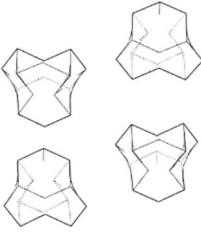
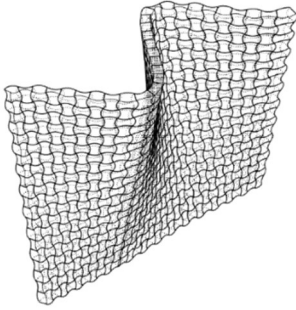
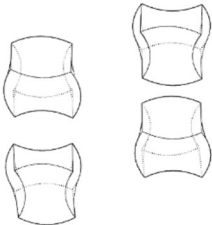
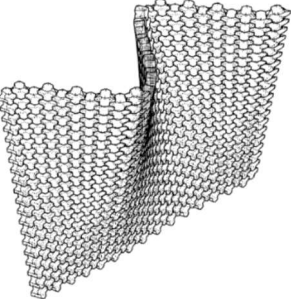
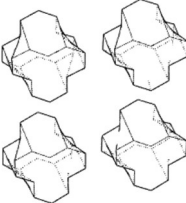
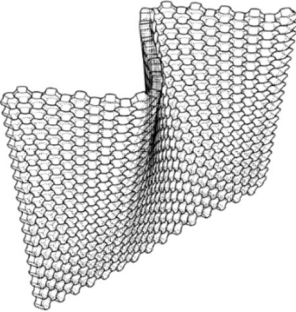
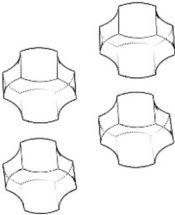


Figure 3.15. Atlantida Church wall via Rhinoceros, Grasshopper (Author)

With the benefits of the Grasshopper in the laying process of brick material have been tested and the formation of self-interlocking systems has been achieved in digital environment. The double curved brick wall surface of the Church of Atlantida was developed in an experimental way by reconsidering using digital tools and simulation technologies. The digital units, in which the original unit of the church wall was replaced, were created in starfish as a topologically interlocked blocks and then mapped to the target surface. In this way, a new brick laying systems was created on the wall.

The digital wall is created with additional attachment of the grasshopper, Starfish. In this section, with the component of grasshopper, church wall revisited with different units. Thus, new units were transferred to the church wall created and made ready for static analysis and manufacturing. In this study, brick laying systems based on Atlantida Church wall form has been discussed with 5 different representations. These are given in the Table 3.2 below.

Table 3.2. Information table for revisited models of brick wall

No	Typology	Model	Units
1	Hexagonal Grid Tiling		
2	Square Grid with Sharp Blocks		
3	Square Grid with Curved Blocks		
4	Hexagonal Grid with Sharp Blocks		
5	Hexagonal Grid with Curved Blocks		

With the flexible modeling environment offered by Grasshopper, regular tiling typologies were created on the wall in 3D according to the working logic of the component. Thus, the relationship with the material was taken into account in the process of creating the complex form. Furthermore, its structural behavior can be tested through grasshopper component called, Alpaca4d. The workflow of the program is shown below (Figure 3.16).

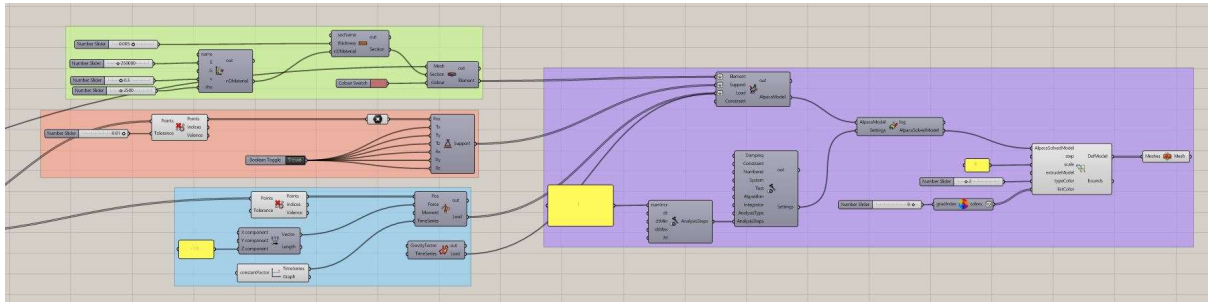


Figure 3.16. The workflow of the Alpaca4d, Grasshopper (Author)

According to previous works, church wall has fixed supports and those supports added into the system, gravity and dead load added as a loads and wall added as a mesh element through the grasshopper plug-ins (Figure 3.17). All those information was aggregated by system builder component of Alpaca4d and finally deformed model obtained. In the analyzes made with Alpaca4d, there is no use of any reinforcement element to strengthen the wall.

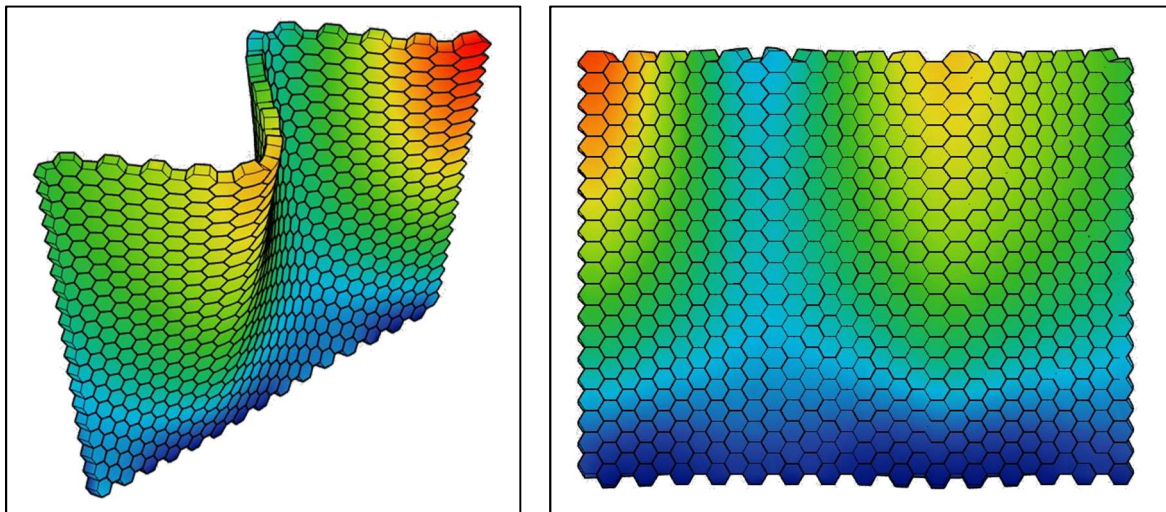


Figure 3.17. Structural analysis of wall through Alpaca4d, Grasshopper (Author)

Compared with the other structural calculation method, the advantages of “Alpaca4d” lie in its dynamic and interactive interface, but more explanation through diagrams is required for

the analysis result to be reasonable for applications, and the formation of the program is still in progress.

Emerging technologies added significant value to complex forms and paved the way for re-engineering of design (Oxman and Oxman, 2010: 14-23). Grasshopper program, as a program that can be used in the construction of the relationship between architecture and structural engineering, constitutes the design engineering relationship today. Today, digital programs used while creating buildings create a holistic design approach and strengthen the relationship between architecture and engineering. Thus, the formation of tectonically successful structures is facilitated.

3.2.2. Structural analysis of the revisited wall

Finite element analysis is a mathematical method that allows precise examination of tensile stress, compressive stress and displacements occurring in structures with complex geometry. “Analysis of historical masonry structures is mostly performed using finite element analysis. The analysis begins by generating a finite element model of the entire structure or structural element” (Ünay, 1997: 26-27). With the emergence of FEA methods in the 1970s, structural engineers began to benefit from this method and adapted to the use of computational tools. However, many of these programs cannot be directly applied in the design or synthesis of a new structural solution (Mueller and Ochsendorf, 2013: 46-56).

An element or a component may be subject to different types of forces/moments or a complex combination thereof. These forces and moments, or combinations of them, cause different types of stresses in the members at different points. Depending on the material of the element and the stress generated, the element may fail due to the excess of different types of stress. Therefore, it is necessary to have knowledge of the breaking mechanism of different types of materials so that the structure can be properly designed to prevent this stress from being exceeded at the critical point. In masonry structures, brick shows more brittle character. Within the scope of the study, a structural analysis was obtained by considering the wall of the Atlantida church modeled in SAP2000, in the digital environment, the brick unit dimensions, the unit element material information, the support type of the wall and the vertical loads affecting the system.

SAP2000 software and with the help of alpaca4d component grasshopper help to understand structural behavior of brick in complex form through the finite element analysis. In this case, firstly, the prototype brick wall analyzed with some altered load cases and then, the wall of the Atlantida Church was analyzed using finite element analysis as a structural element and revisited with adding additional steel tendons. When the structural behavior of brick wall revisited with steel tendon is examined with the SAP2000 program, the working principle under different load situations and combinations is given below through the prototype model (Figure 3.18). Definitions and load cases are given below at Table 3.3.

Table 3.3. Definition of analytical model for prototype model

<p>Definition of Analytical Model: Number of joints (nodes): 45 Number of SHELL elements: 32 Number of tendons: 3 Number frame element: 4</p> <p>SHELL element: (Brick with mortar) Element thickness 400 mm (40 cm) Modulus of elasticity (E): 2340000 kN/m² (2340 MPa) Specific weight of brick with mortar: 17.54 kN/m³</p> <p>TENDONS: (Steel cables) Diameter $\varphi=1$ mm Modulus of elasticity (E): 200 000 000 kN/m² (200 000 MPa) Specific weight of steel: 76.97 kN/m³ (STL-01)</p> <p>FRAME ELEMENT: (A weightless steel plate at the top of the wall) Cross-section : 2 mm x 400 mm square section Modulus of elasticity (E): 200 000 000 kN/m² (200 000 MPa) Specific weight of steel : 0 (STL-02)</p>
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Table 3.4. Definition of load cases for prototype model

<p>LOAD CASES: Four independent loads cases and three loading combinations are applied. DL: (Dead load analysis) Self weight of the brick wall is applied in vertical direction (negative global z axis) HRZ-X: Horizontal loads in positive global x axis. %40 total mass (weight) of the brick wall is considered as gravity loads in positive global x direction. HRZ-Y: Horizontal loads in positive global y axis. %40 total mass (weight) of the brick wall is considered as gravity loads in positive global y direction. TND: Tendons 30 KN of axial tensile forces are applied to three tendons. COMB 1: DL++TND COMB 2: DL+HRZ-X+TND COMB 3: DL+HRZ-X+TND</p>

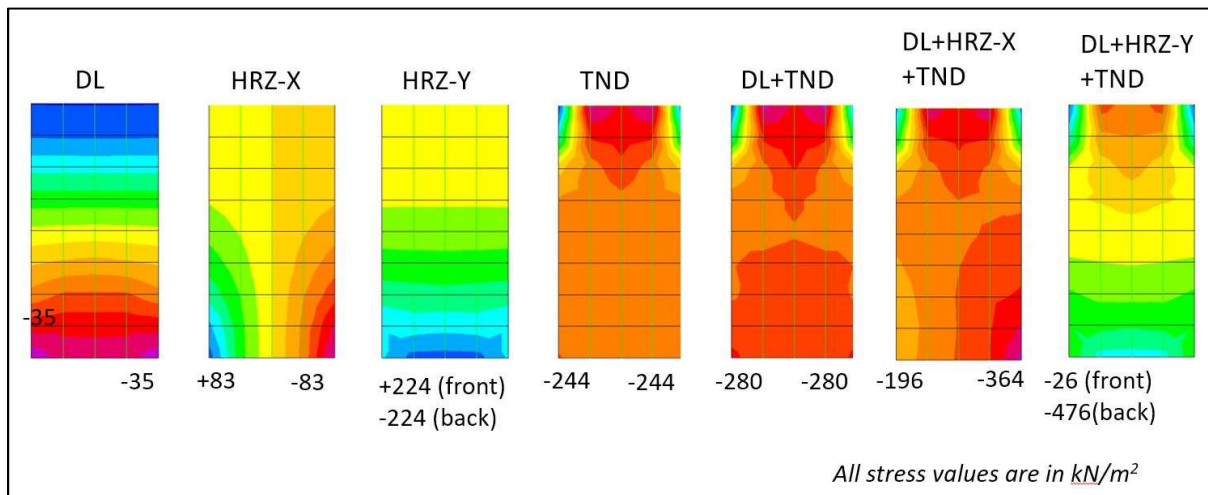


Figure 3.18. The variation of stresses in the vertical direction (S22) according to DL, HRZ-X, HRZ-Y and TND loads cases, and DL+TND, DL+HRZ-X+TND and DL+HRZ-Y+TND loading combinations respectively

A prototype finite element model is prepared for a part of brick wall to observe the variation of stresses due to the application of tendon forces. A prototype is an early sample, model, or release of a product built to test a concept or process. The seven figures in Figure 3.19 above obtained from prototype model and show the variation of stresses in the vertical direction (S22) according to DL, HRZ-X, HRZ-Y and TND loads cases, and DL+TND, DL+HRZ-X+TND and DL+HRZ-Y+TND loading combinations respectively. The variation of S22 stresses at the lowermost level of the brick wall according to these seven loading conditions and load combinations can be easily seen. The conversion of tensile stresses to compressive

stresses by means of tendons can be calculated by simple mathematical operations based on the load combination. This analysis example with simple and explanatory finite element model may guide similar or comparable analysis of structures with more complex geometry.

In order to understand the static behavior of the wall clearly, the material properties obtained from previous studies and the geometric properties of the wall were transferred to the digital environment with the SAP2000 and the structure was tested through finite element analysis. The geometry created in the rhinoceros was transferred to the SAP2000 program (Figure 3.19) and maximum and minimum principles stress are shown below (Figure 3.20). Then, the load cases tried on the prototype wall were applied to the selected wall for case study.

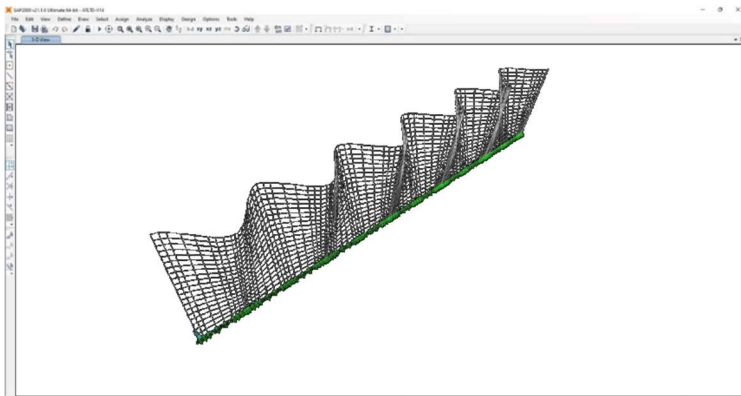


Figure 3.19. SAP2000 model of the wall (Author)

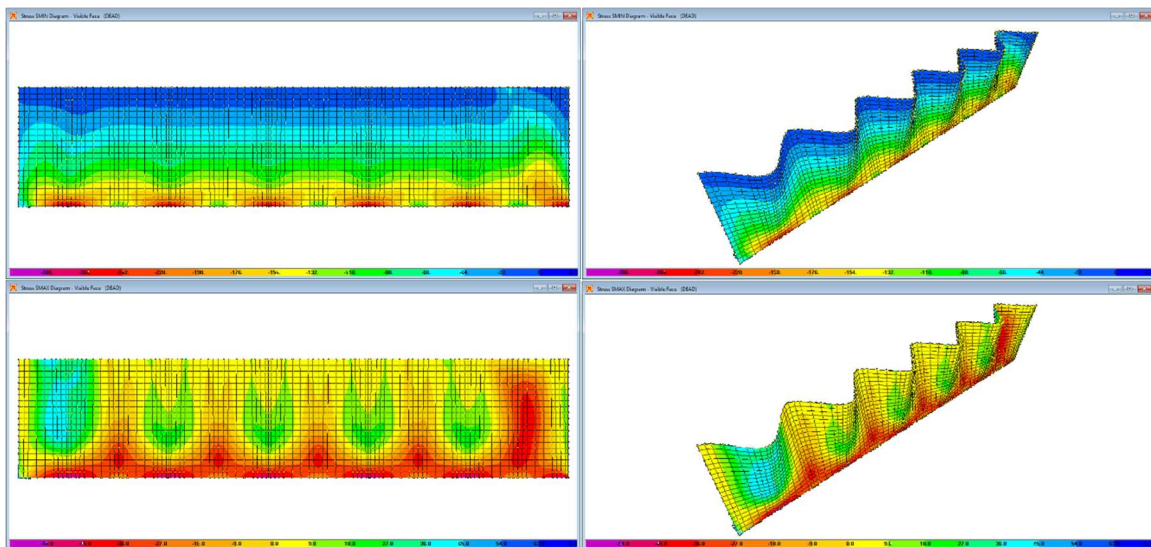


Figure 3.20. Variation of maximum principles stresses of wall (above), and variation of minimum principles stresses of wall (below) via SAP2000

Four analyses with altered load cases through SAP2000 software, it was observed how the tendons reduce the tensile stresses in the wall. The figure below shows the variation of stresses resulting from the under the dead load application of tendon forces in an Atlantida church brick wall (Figure 3.21). In the load case analysis, dead load analysis is shown in Figure 3.21 a. In this load case, self-weight of the brick wall is applied in vertical direction. In the tendon load case analysis, 30 KN of axial tensile forces are applied to three tendons. In this load case, located in figure 3.21 b, a more optimal structural behaviour is observed compared to the dead load analysis. The conversion of tensile stresses to compressive stresses by means of tendons can be calculated by simple mathematical operations based on the load combination. The structural behaviour of these two load cases combination is seen at figure 3.21 c. The application of steel tendons and supports placed at figure 3.22. Definitions and load cases are given below at Table 3.4.

Table 3.5. Definition of analytical model for church wall model

<p>Definition of Analytical Model:</p> <p>Number of joints (nodes): 588</p> <p>Number of SHELL elements: 540</p> <p>Number of tendons: 3</p> <p>Number frame element: 28</p> <p>SHELL element: (Brick with mortar)</p> <p>Element thickness 400 mm (40 cm)</p> <p>Modulus of elasticity (E): 2340000 kN/m^2 (2340 MPa)</p> <p>Specific weight of brick with mortar: 17.54 kN/m^3</p> <p>TENDONS: (Steel cables)</p> <p>Diameter $\phi=1 \text{ mm}$</p> <p>Modulus of elasticity (E): $200\,000\,000 \text{ kN/m}^2$ (200 000 MPa)</p> <p>Specific weight of steel: 76.97 kN/m^3 (STL-01)</p> <p>FRAME ELEMENT: (A weightless steel plate at the top of the wall)</p> <p>Cross-section : 2 mm x 400 mm square section</p> <p>Modulus of elasticity (E): $200\,000\,000 \text{ kN/m}^2$ (200 000 MPa)</p> <p>Specific weight of steel : 0 (STL-02)</p>

Table 3.6. Definition of analytical model and load cases for church wall model

LOAD CASES:

Four independent loads cases and three loading combinations are applied.

DL: (Dead load analysis)

Self weight of the brick wall is applied in vertical direction (negative global z axis)

HRZ-X: Horizontal loads in positive global x axis.

%40 total mass (weight) of the brick wall is considered as gravity loads in positive global x direction.

HRZ-Y: Horizontal loads in positive global y axis.

%40 total mass (weight) of the brick wall is considered as gravity loads in positive global y direction.

TND: Tendons

30 KN of axial tensile forces are applied to three tendons.

COMB 1: DL++TND

COMB 2: DL+HRZ-X+TND

COMB 3: DL+HRZ-X+TND

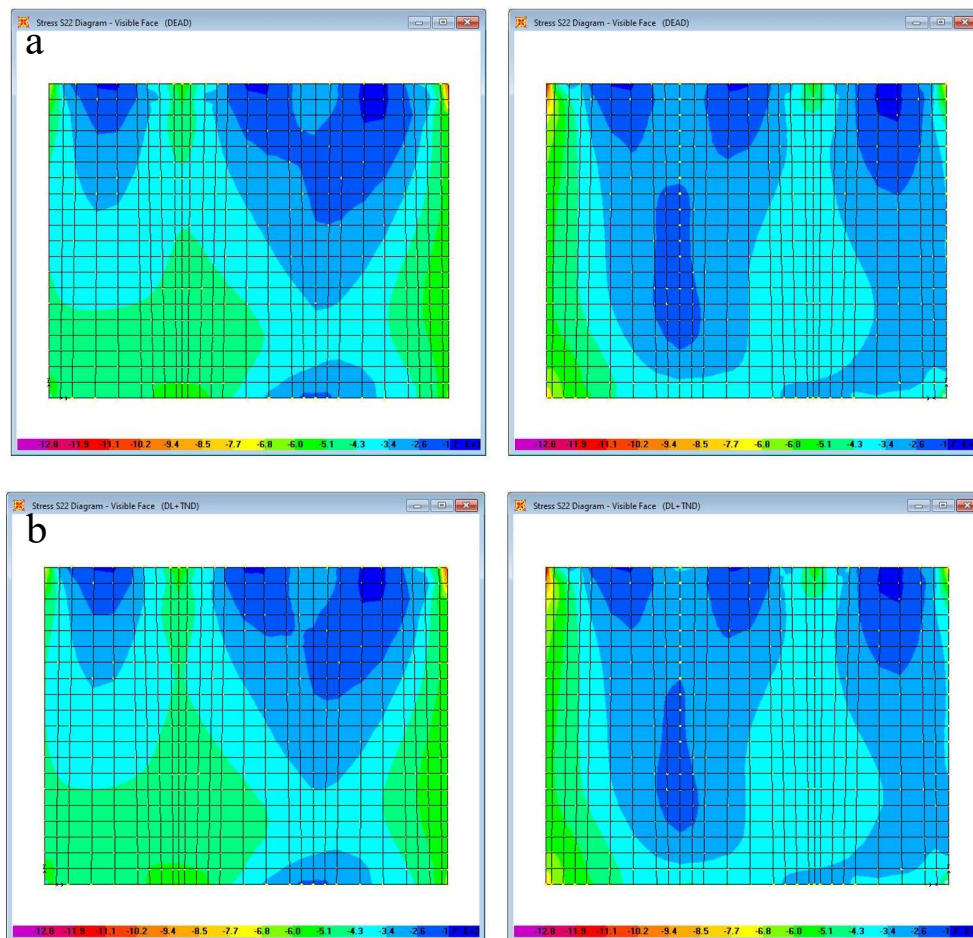


Figure 3.21. Load case analysis 1 (dead load analysis of wall)(a) load case analysis 2 (tendon analysis of wall) (b) loading combination (dead load and steel tendon combination analysis of wall) (c) via SAP2000 (Author)

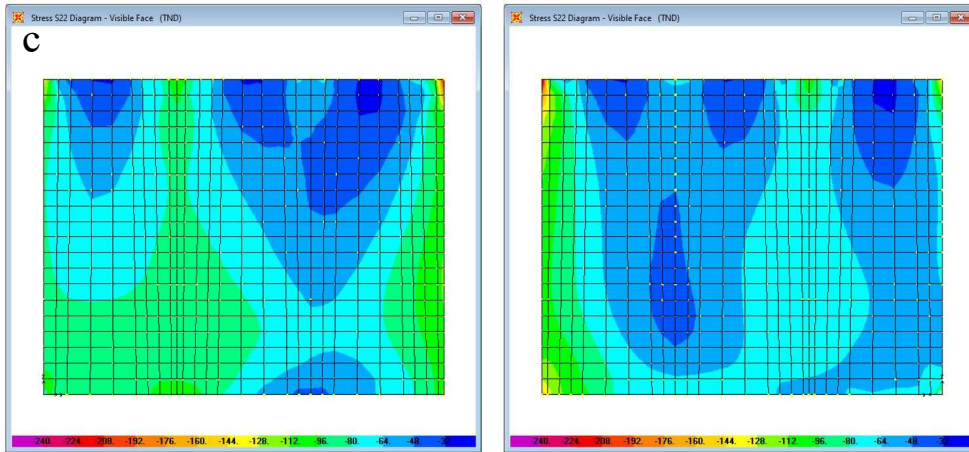


Figure 3.21. (Continuation) Load case analysis 1 (dead load analysis of wall)(a) load case analysis 2 (tendon analysis of wall) (b) loading combination (dead load and steel tendon combination analysis of wall) (c) via SAP2000 (Author)

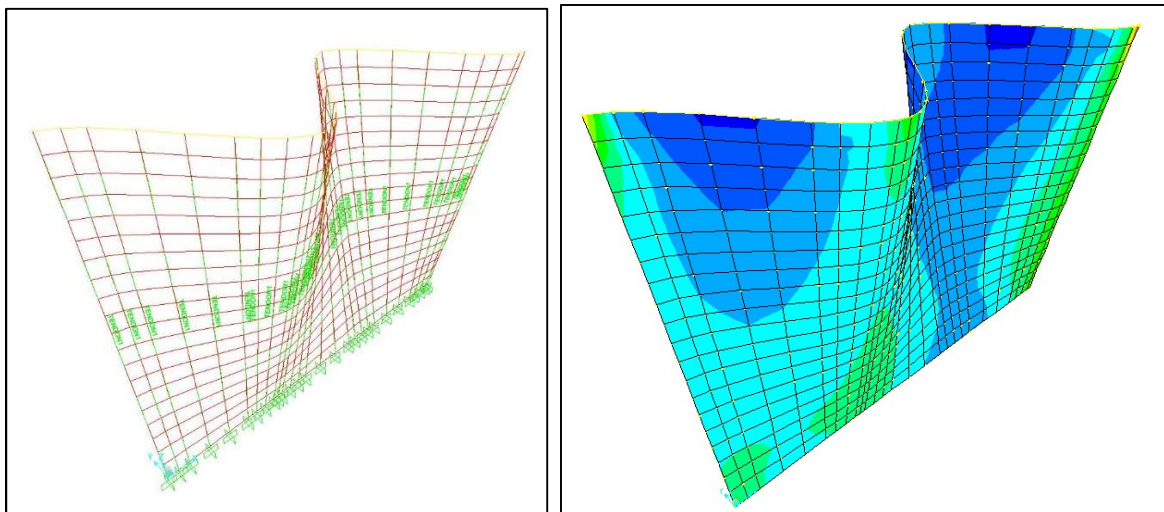


Figure 3.22. Application of steel tendons in church wall via SAP2000 (Author)

Since the brick material is resistant to compression but weak to tension, the tensile strength has been increased by making use of 1 mm diameter steel tendons, and it has been strengthened with steel tendons in the parts where the tensile force is high and the tensile zones have been converted into compression. As observed in figure 3.21, the structural behavior of the church of Atlantida is more optimal with the combination of dead load and tendon load.

After seeing the effect of tendons on dead load analysis, HRZ-X (Figure 3.23) and HRZ-Y (Figure 3.24) load cases were created to see the structural behavior under lateral loads. In

these load cases, while they constitute 40% of the total mass (weight) of the brick wall, they are considered as positive global x- and y-direction gravitational loads.

Tensile stresses due to the HRZ-X and HRZ-Y load cases are eliminated in the stress variations shown in all loading combinations. With the all load case analysis and combination of those analysis, it was observed how the tendons reduce the tensile stresses in the wall. It can be said that this is due to the steel tendons.

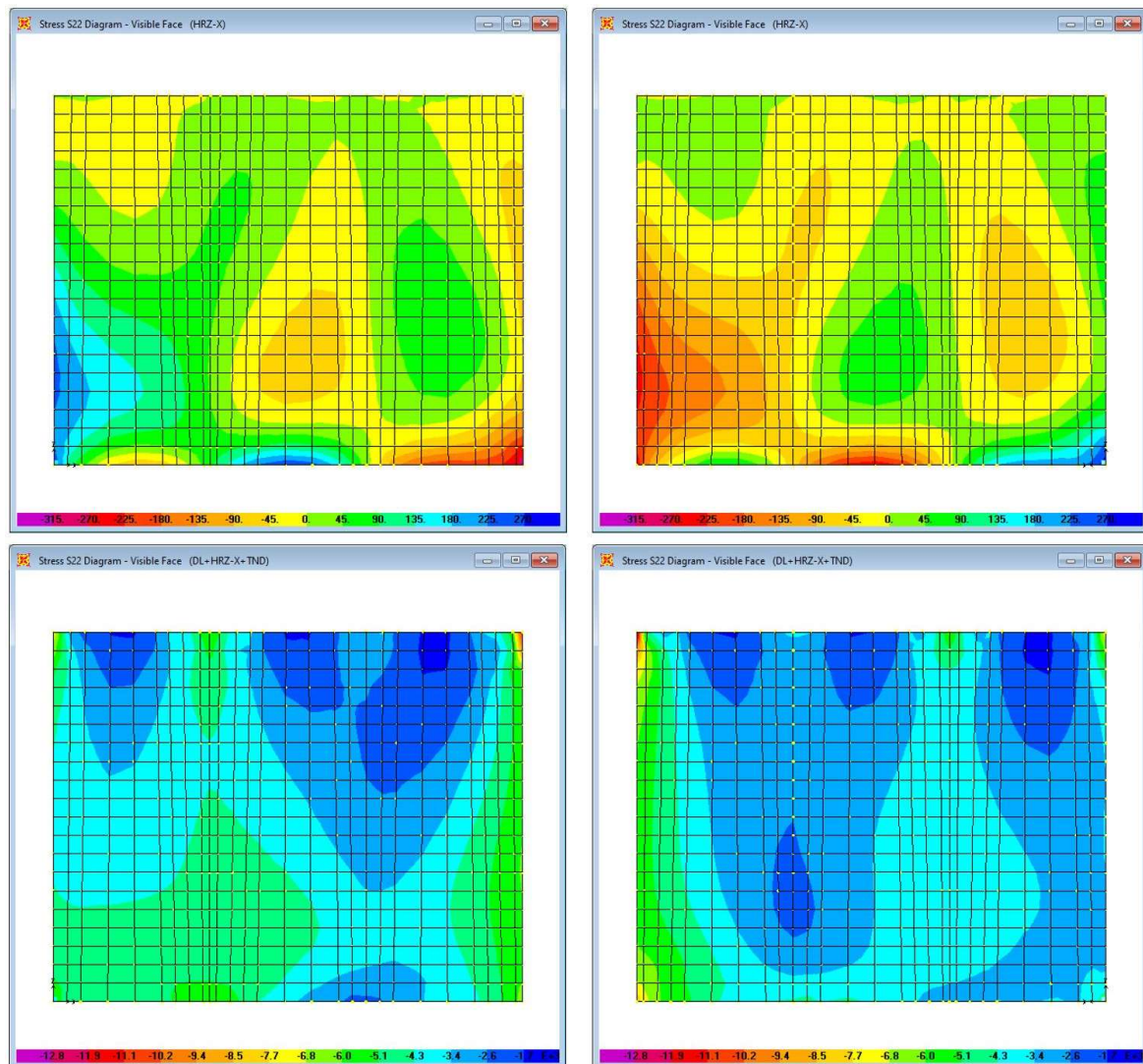


Figure 3.23. Load case HRZ-X (above) loading combination (dead load, HRZ-X and tendon combination analysis of wall) (below) via SAP2000 (Author)

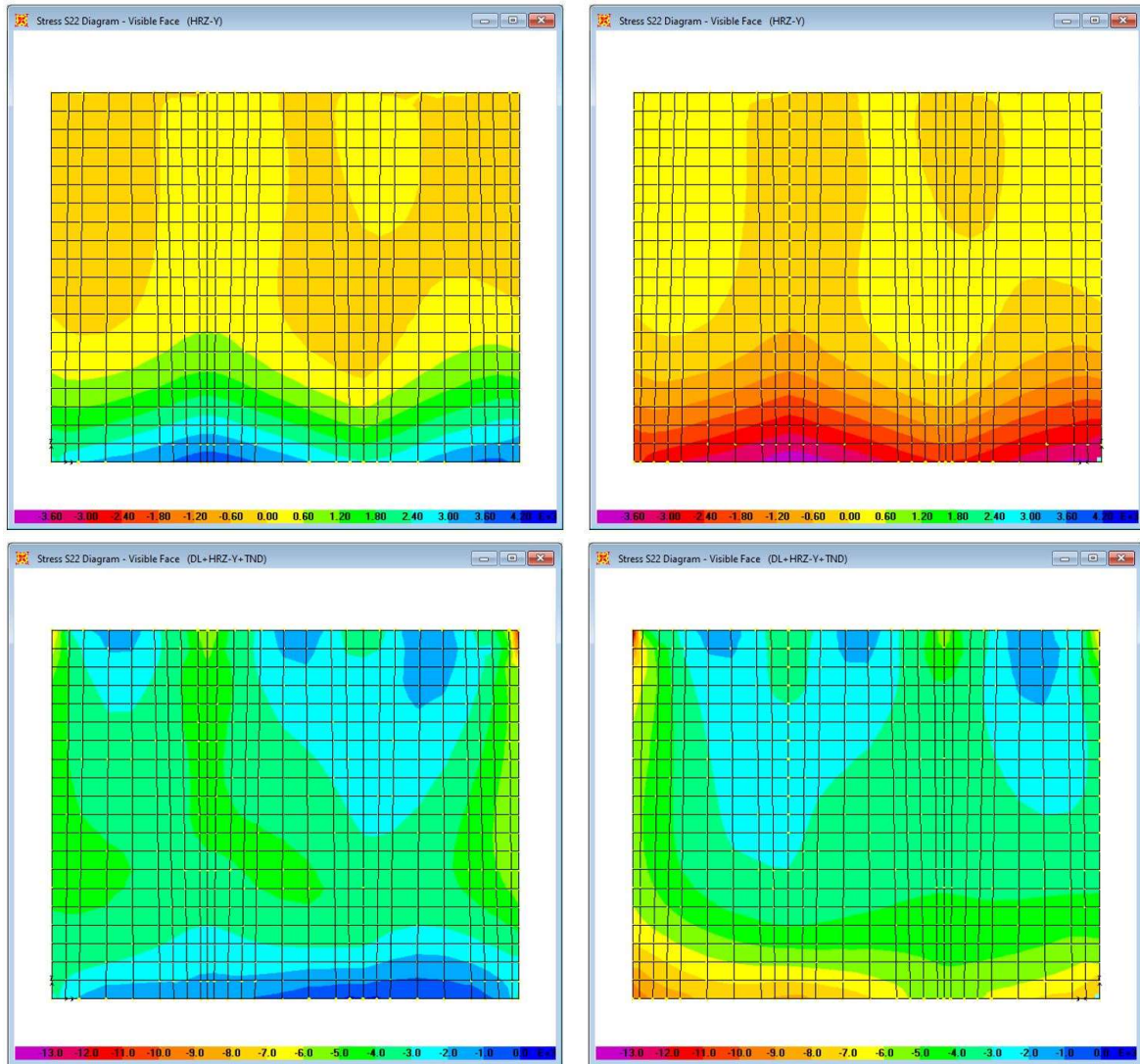


Figure 3.24. Load case HRZ-Y(above) loading combination (dead load, HRZ-Y and tendon combination analysis of wall) via SAP2000 (Author)

The results of the analyzes obtained from SAP2000 were evaluated at the results and discussion part of the thesis with the discussions and tables, and thus how recent computational technologies and brick integration affects the future of the brick through digitally exploration of complex forms with created revisited walls was understood through this approach.

4. DISCUSSION

In this thesis, the question of how computer technologies, which have been under the influence of the discipline of architecture in recent years, support the creation and research of complex forms derived from brick material and the process of producing new masonry for architectural design has been investigated in general through the thesis. For this reason, the brick wall revisited through steel tendons and its structural behavior was tested by SAP2000 program, and it was evaluated comparatively. Then, for creating strong form-structure-material relationship with new methodologies tested through grasshopper. Form formation, new brick unit generations and structural analysis of the Atlantida Church were made simultaneously with digital tools.

In the process of the thesis, first of all, the use of brick material throughout the history of architecture and the potentials of using brick units in the formation of architectural components and the purpose of using the brick unit in complex forms/structures were questioned. Brick, which has been frequently used in the creation of complex forms throughout history, has left its place to new materials after the industrial revolution, but especially in the 20th century, brick has shown the power of its tectonic effect with its structural uses. However, due to the difficulty of physically creating this tectonic effect, the brick material could not structurally overtake other materials.

Master builders such as Nervi, Torroja, Aalto, Candela and Dieste contributed both structurally and architecturally to the construction processes. They have revealed the structural art with the methodologies they have developed. Dieste paved the way for brick structures, and thanks to the developing technologies, the benefits of brick material to the structure began to be reconsidered by making use of these methodologies. Dieste's use of pre-tensioned cables in brick structures has affected the structural behavior of the material, thereby expanding the boundaries of brick design. While developing these methodologies, Dieste reached its structures at the experimental level during the construction process, within the conditions of the 20th century.

Today, the advantageous aspects of brick material such as its raw material and its size have brought the material back to the agenda with the technological development of production

processes. Technological developments in the discipline of architecture have created the concept of digital tectonic, and this has allowed building materials, forms and structures to create a more optimal structure both in the design phase and in the production phase. In line with the characteristics of the brick material, as can be understood from today's examples, the integration of digital technologies with brick architecture has increased the benefit it provides to the architectural structure and the brick has turned into a contemporary building material. Thus, the advances created by technological developments in buildings created using brick materials have started to create future scenarios in the history of architecture for the use of brick materials.

In line with these developments, in this study, In this part of the thesis, the form, material experience and structural behavior analysis created by grasshopper are tested simultaneously (Figure 4.1). When evaluated from an architectural point of view, brick has increased its potential with technology and expanded its usage area, like Dieste did it own time zone. As a result, new generation methods give us different unit possibilities (Figure 4.2) and it can create holistic relationship between elements. However, its analysis goes beyond the scope of architecture and this thesis.

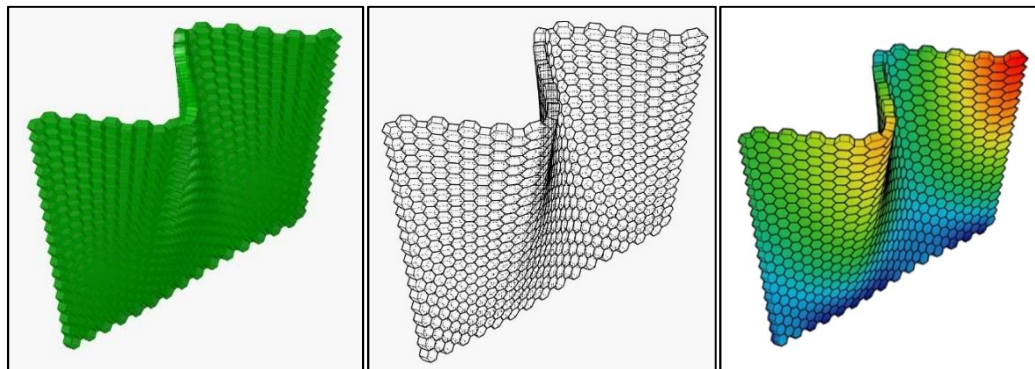


Figure 4.1. Design process and analysis through same interface Grasshopper (Author)

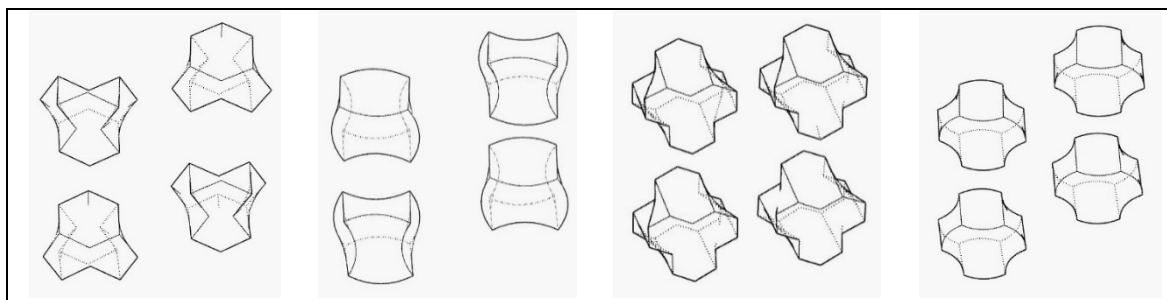


Figure 4.2. Digi-brick units with topological interlocking system, via Starfish (Author)

The most important finding of the study is that the methodologies of the masters can be understood by means of digital tools, in this thesis example, Dieste's methodologies and FE techniques and the structural effect of his techniques on the structure are reviewed. As Dieste's work has proven, the structural stresses of the tensile zones of brick material can be alleviated by reinforcement elements such as tendons. While the methods developed by Dieste give ideas to the designer today, it also proves that today, the structural potential of the brick material can be developed through both form and material in an intensely interacted relation. After the studies showing that the brick can be considered as a contemporary material, the structural strength of the material can be improved with different masonry units. Architectural solutions can be produced in this way, but testing the structural efficiency of these units is the subject of an advanced study. For this reason, within the scope of this thesis, the wall structure is considered as a single surface and the behavior analyzes are presented in figure 4.3. and figure 4.4.

This finite element analysis, inspired by the Atlantida Church, shows the variation of stresses resulting from the application of tendon forces in an ondulated brick wall. Following figures show the variation of stresses in consecutive analysis altering loads cases and loading combinations respectively. The variation of S22 stresses at the lowermost level of the brick wall according to these load conditions and loading combinations can be easily seen. The conversion of tensile stresses to compressive stresses by means of tendons can be calculated by simple mathematical operations based on the load combination. Tensile stresses due to the HRZ-X and HRZ-Y load cases are eliminated in the stress variations shown in all loading combinations. It can be said that this is due to the tendons.

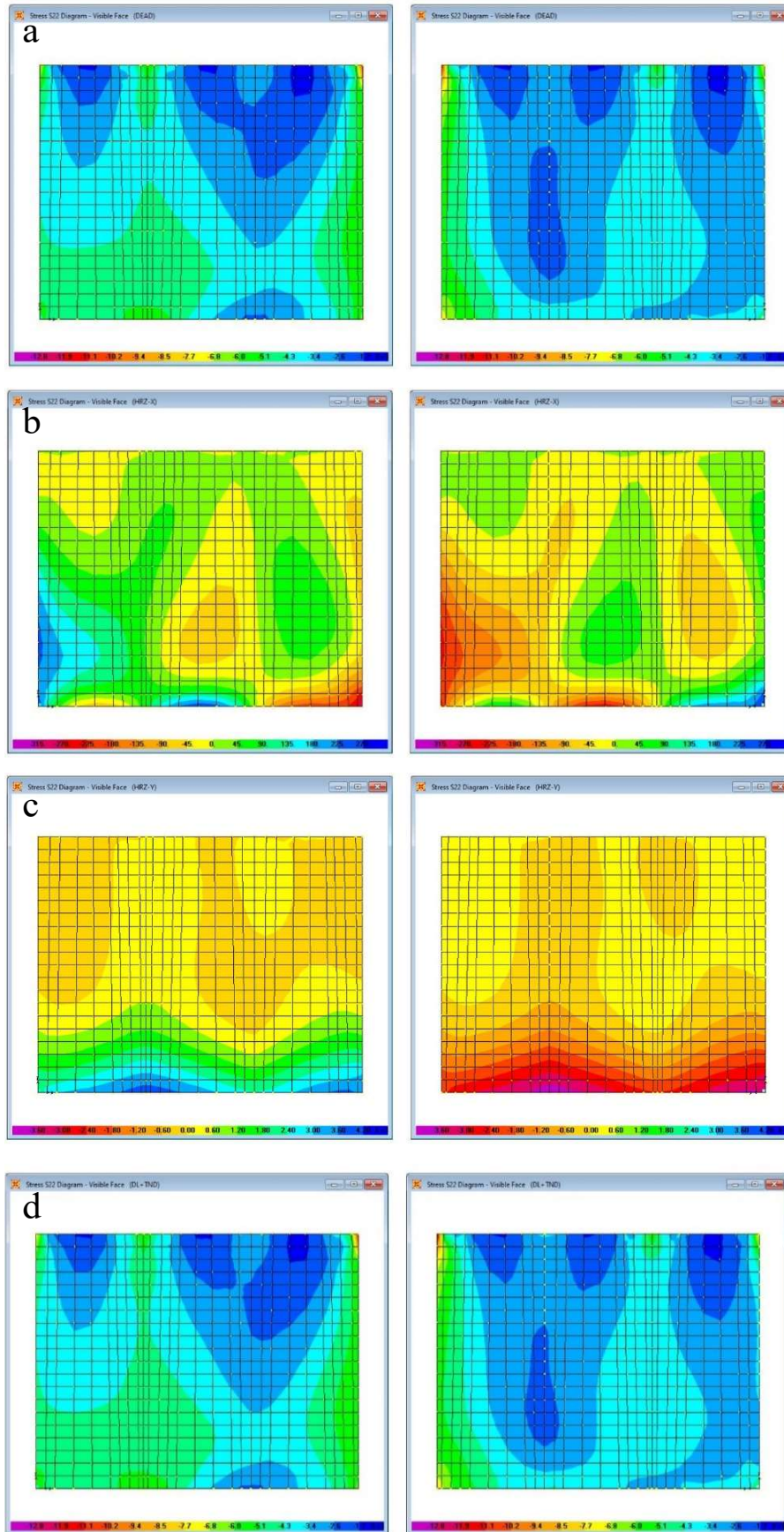


Figure 4.3. The variation of stresses in the vertical direction (S22) according to DL (a), HRZ-X(b), HRZ-Y(c) and TND(d) loads cases respectively via SAP2000

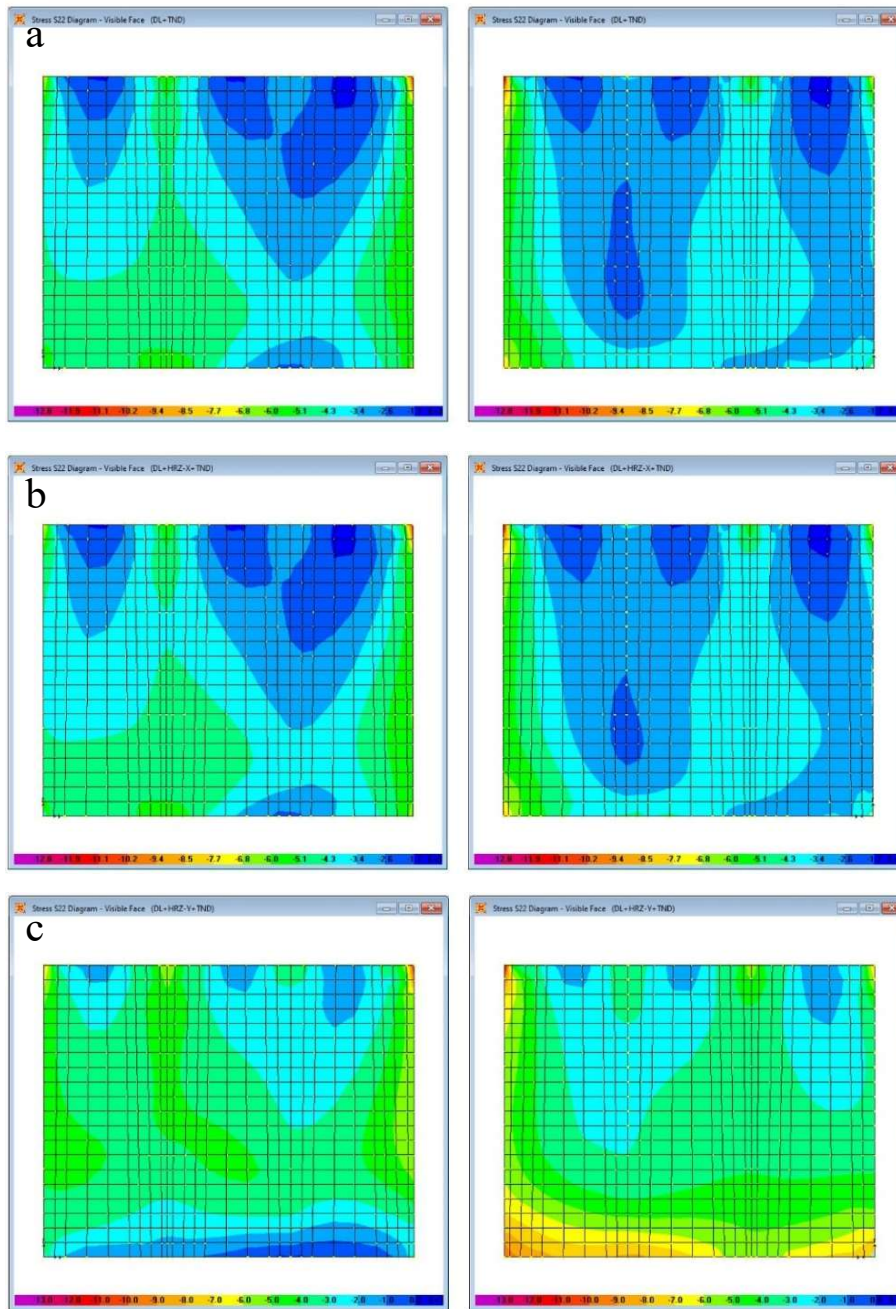
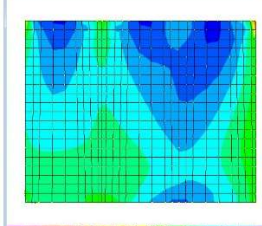
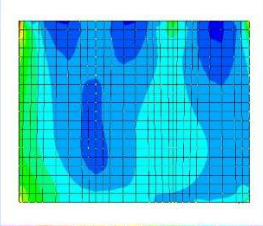
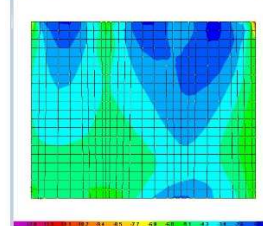
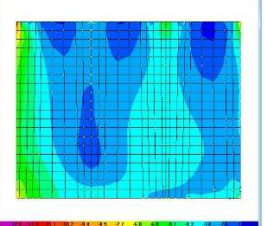
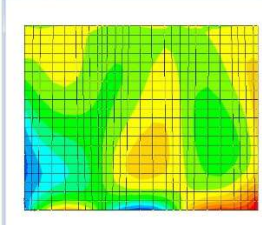
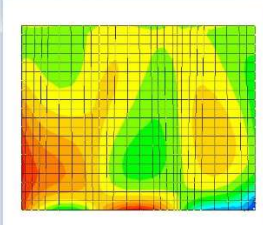
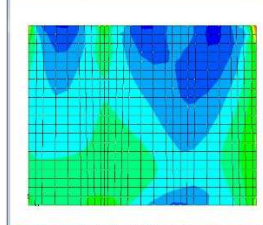
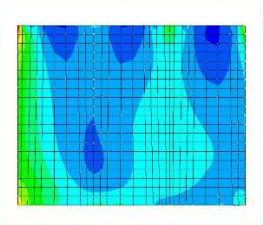
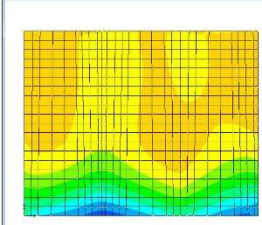
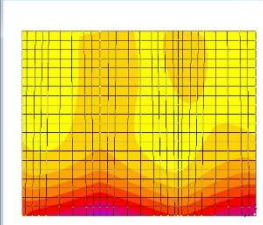
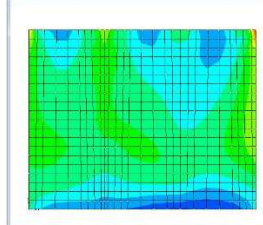
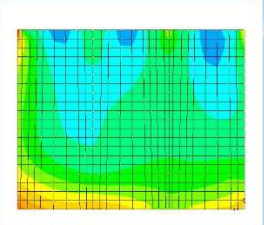


Figure 4.4. The variation of stresses in the vertical direction (S22) according to DL+TND(a), DL+HRZ-X+TND(b) and DL+HRZ-Y+TND(c) loading combinations respectively via SAP2000

After four successive analysis with altered load cases in figure 4.1, it was observed how the tendons reduce the tensile stresses in the wall within the figure 4.2. This analysis may guide similar or comparable analysis of structures with more complex geometry. The comparison between load cases and load combinations is given in Table 4.1 to clearly see the tendon effect on wall.

Table 4.1. Comparison of load cases and load combinations

Load cases DL, HRZ-X, HRZ-Y respectively	Load cases DL, HRZ-X, HRZ-Y respectively	Loading combinations DL+TND, DL+HRZ-X+TND and DL+HRZ-Y+TND respectively	Loading combinations DL+TND, DL+HRZ-X+TND and DL+HRZ-Y+TND respectively
			
			
			

As a result, the paradigm shift that has taken place in the last 30 years has also changed the approach to structure. The effect of digital tools in architecture has contributed to the relationship between form-material-structure and has created a digital tectonic concept. This relationship, which started to gain value in general since the 20th century, has allowed the formation of stronger structures in terms of tectonics, the construction technique that makes it possible to re-evaluate traditional structures digitally with the effect of digital tectonics today. Thanks to the tectonic tradition of the brick material, today's manufacturing technologies and analyzes performed in the digital environment, its behavior can be understood and the missing aspects can be easily improved with new methods. In this study, the tectonic effect provided by digital tools was evaluated by comparisons and the regenerations made on the wall of Eladio Dieste's Atlantida Church building, and it was concluded that brick material is an advantageous material that can be re-evaluated within the framework of contemporary and sustainable architecture.

5. CONCLUSION AND FUTURE REMARKS

As a result, in the study, the transfer of the wall to the digital environment was realized with the help of digital design tools, the transferred wall was revised with new brick units and it was observed that the analysis could be done on the same interface. First of all, questions such as how different brick units can be formed, how they can be transferred to the surface and how they can be analyzed are answered. Thanks to the opportunities provided by digital tools, the analyzes of these units can be made within the same interface. Form-structure-material relationship, which has been further developed thanks to digital tools, can create tectonically successful structures. With these models created throughout the thesis, it is aimed to create an exemplary model for the future scenarios created by technological developments in buildings with brick units. By these ways, brick material can make comeback as a contemporary material in architecture with the new methodologies. The analysis of these units is beyond the scope of architecture and this thesis. Later, the structure of Dieste has been analyzed as an example to the question of what purpose and how the brick unit has been used in complex forms/structures throughout history. With all these reproductions and structural analyzes, the question of how digital technologies and brick architecture benefit from each other has been tried to be answered.

The application of Dieste's methods was expressed in digital environment and the validity of Dieste's technique was tried to be determined again with today's technology. As a result of all the determinations made, how the double curvature surface geometries can be developed with brick material can be developed with both structural and formal arrangements is answered. According to the results, the architectural importance and actuality of Dieste's "resistance through form" manifesto were determined with digital tools. With these answers, the main question of the thesis, "How recent computational technologies supports creation and exploration of complex forms derived from a single brick unit and process of generating novel masonry work for architectural design" has been answered.

The case study and literature review show that the situations and features of the structure can be experienced again with the help of digital tools, and a better holistic relationship can be established by experiencing the existing structure. While the ordinary state of the structure can be developed with new structural strategies with the SAP2000 program, new approaches

can be envisaged in the form-material-structure relationship for complex projects in line with 3d modeling programs such as grasshopper that supplies an interface that works simultaneously. Thus, rethinking and utilizing the complex form masonry works created in the past through computational design and manufacturing technologies has prompted new design approaches for brickwork. Thanks to the form created by Dieste in 1952, the brick material proved its potential and its methodology for today's architecture set a precedent.

In this thesis, with the help of grasshopper the masonry works can be improve in morphological way. However, changing the form of the brick units was considered only as a formal decision, not as a factor affecting the structural status of the building. The resulting surface is the same surface and there is no structural difference. Thus, the analyses continued with the normal brick unit in analysis phase in sap2000. with the analysis obtained from sap2000. Then, comparison table was created to see tendon's effect. Especially in the horizontal direction, the effect of the tendon is seen more clearly and it is understood how these tendons change the tensile stresses to compression. As a result, because of its properties, the brick only forms against compressive strength. this is an important design criteria for brick structures. That's why, the structures created by Dieste with a unique methodology set an important precedent for creating complex forms with bricks. With the digital tools and knowledge that can acquires from important precedents, today, how the double curvature surface geometries with brick material can be developed with both structural and formal/morphological arrangements is answered. Finally, the hypothesis that "Revisiting Eladio Dieste's complex masonry works through computational design and manufacturing technologies can stir up new design approaches for brickwork" has been validated by established models.

As can be seen from the walls of the Atlantida Church, the structural behavior provided by the complex geometries provided more resistance in the building, but forming the wall in the conditions of that time prevented the creation of such a shell form. Today, these difficulties have begun to be overcome thanks to the convenience provided by digital technologies in the formation of forms. Through this thesis, it was observed that the form-structure-material relationship, which was further developed by digital tools, strengthened the structure tectonically and increased the value of the brick material and it can be developed by methodologies that used in this thesis. It has been understood that the potential of the brick and its strong tectonic effects can be increased through form, and it is a

contemporary material suitable for digital production by achieving optimal structural behavior through the modifications created during the design phase of the brick wall.

The system, which was developed as a model that tests the effectiveness of computational design tools as an effective tool in strengthening interdisciplinary interaction, was asked to create a sample model for researchers. This model is an effective model for making early design decisions and is expected to be useful as a productive design model that can support the planning of necessary workflows for material / form / structure / part-whole relationship and digital-physical manufacturing tools. The double curvature surface geometry of the Atlantida Church wall has been observed by setting an example for complex surface geometry modeling, thanks to the model created, which has the potential to be tested structurally and be effective in design decisions at the early design stage.

Consequently, with the development of digital technologies, a highly interactive environment has emerged between architects and structural engineers, and this has created an environment for the use of complex forms challenging orthodox structural engineering methods for structural purposes, and thus new approaches have emerged in building formation. Finally, the hypothesis that “Revisiting Eladio Dieste's complex masonry works through computational design and manufacturing technologies can stir up new design approaches for brickwork” has been validated by established models. The relationship between form-material and structure has been further developed thanks to these technologies, and the inclusion of technologies in the design processes has made it possible to form tectonically successful structures. Thus, a new relationship developed between formal models and concretization processes and a new relationship that improves communication between architects and engineers.. Further studies should be carried out to obtain further results about the brick with the established method. In this respect, analysis can guide similar or comparable analysis of structures with more complex geometry. For future studies, mortar properties can be included in the examination and the geometry of the units can be developed more successfully with coding methods such as python. In addition, the process can be supplemented with 3D fabrication processes to better examine the structural behavior of the wall, its state under stress and load.

REFERENCES

- Abdelwahab, S., and Elghazi, Y. (2016). *A generative performance-based design for low-cost brickwork screens 2*. Paper presented at the Proceedings of the Building Simulation and Optimization Conference (BSO16). Newcastle University, UK. 1102-1103.
- Afsari, K., Swarts, M., and Gentry, R. (2014). Integrated generative technique for interactive design of brickworks. *Journal of Information Technology in Construction (ITcon)*, 19, 225-247.
- Ambrose, M., Callam, B., Kunkel, J., and Wilson, L. (2009). *How to make a digi-brick*. Paper presented at the Proceedings of the 14th International Conference on Computer Aided Architectural Design Research in Asia, Hong Kong, China. 5-12.
- Anderson, S., Dieste, E., and Hochuli, S. (2004). *Eladio Dieste: innovation in structural art*. New York: Princeton Architectural Press, 144.
- Andreani, S., and Bechthold, M. (2014). *RJ evolving brick: geometry and performance innovation in ceramic building systems through design robotics*. Paper presented at the Conference: Fabricate: Negotiating Design and Making 2014, Zürich, Switzerland. 797-806.
- Attaran, M. (2017). The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing. *Business Horizons*, 60(5), 677-688.
- Bach, C. (1993). Making bricks soar. *Américas*, 45(2), 38-45.
- Baliński, G., and Januszkiewicz, K. (2016). Digital tectonic design as a new approach to architectural design methodology. *Procedia engineering*, 161(4), 1504-1508.
- Bechthold, M. (2004). *Surface Structures: digital design and fabrication*. Paper presented at the: Proceedings of the 23rd Annual Conference of the Association for Computer Aided Design in Architecture and the 2004 Conference of the AIA Technology in Architectural Practice Knowledge Community, Ontario, Canada. 88-89.
- Beesley, P., and Seeböhm, T. (2000). *Digital tectonic design*. Paper presented at the State of the Art versus State of Practice in Computing for the Design and Planning Process, 18th eCAADe Conference Proceedings / ISBN 0-9523687-6-5, Weimar, Germany. 287-290.
- Block, P., Van Mele, T., Rippmann, M., Ranaudo, F., Calvo Barentin, C. J., and Paulson, N. (2020). Redefining structural art: strategies, necessities and opportunities. *The Structural Engineer*, 98(1), 66-72.
- Bonwetsch, T., Gramazio, F., and Kohler, M. (2007). *Digitally fabricating non-standardised brick walls*. Paper presented at the ManuBuild, 1st International Conference, Rotterdam, Netherland. 1-5.

- Brick Industry Association. (2006). Manufacturing of brick. *Technical notes on brick construction*, 9(1), 1-7.
- Castellon, J. (2012). Cellular Ceramics: Reinforced Brick Construction in the Digital Age. *Interceram*, 61(5), 277-282.
- Chilton, J., and Chuang, C.-C. (2017). Rooted in Nature: Aesthetics, Geometry and Structure in the Shells of Heinz Isler. *Nexus Network Journal*, 19(3), 763-785.
- Collier, C. J. (2016). *Code to matter - Integrating Industrial Robotic Arms: Reconciling the Rapid Advancement of Digital Potentials with a Tangible Physical Existence*. Master of Science, University of Washington, Ann Arbor. 1-2.
- Cruz, PJ, Knaack, U., Figueiredo, B., and Witte, D. d. (2017). *Ceramic 3D printing—The future of brick architecture*. Paper presented at the Proceedings of IASS Annual Symposia. Wroclaw, Poland. 1-2.
- Dalkılıç, N., and Nabikoğlu, A. (2017). Traditional manufacturing of clay brick used in the historical buildings of Diyarbakir (Turkey). *Frontiers of Architectural Research*, 6(3), 346-359.
- Ding, LR (2016). *Structural fantasy of a brick wall: Groningen Earthquake Memorial and Museum*. Master of Science, TU Delft, Delft. 9-11.
- Dunn, N. (2012). *Digital fabrication in architecture*. London: Laurence King Publishing. 6-14.
- Eldemir, Kara, C. Evolution of Brick Architecture Through Digital Tools and Technologies. *Gazi University Journal of Science Part B: Art Humanities Design and Planning*, 9(4), 329-344.
- Elliott, J. R. (2019). *Eladio Dieste's Modern Religious Architecture: Innovation through Form, Program, and Artistic Inspiration at the Churches of Cristo Obrero and San Pedro*. Master of Science. University of Oregon, Oregon, USA. 21-138.
- Estevez Cimadevila, J., and Vázquez Rodríguez, J. (2004). Spatial truss of hollow bars made of laminated timber supported by walls of reinforced masonry. *Journal of the International Association for Shell and Spatial Structures*, 45(1), 13-21.
- Fiala, J., Mikolas, M., and Krejsova, K. (2019). *Full brick, history and future*. Paper presented at the IOP Conference Series: Earth and Environmental Science, 221 012139, World Multidisciplinary Earth Sciences Symposium (WMESS 2018), Prague, Czech Republic. 1-4.
- Flöry, S., and Pottmann, H. (2010). *Ruled surfaces for rationalization and design in architecture*. Paper presented at the ACADIA 10: Life in:formation, On Responsive Information and Variations in Architecture, 21-24 October, 2010, New York, USA, 103-109.

- Fure, A. (2011). *Digital materiallurgy: on the productive force of deep codes and vital matter*. Paper presented at ACADIA 11: Integration through Computation: Proceedings of the 31st Annual Conference of the Association for Computer Aided Design in Architecture, Banff, Alberta. 90-97.
- Ganobjak, M., and Carstensen, J. (2019). Topology-optimized insulating facebrick with aerogel filling. Paper presented at the *Journal of Physics: Conference Series*, 1343, 012195. doi:10.1088/1742-6596/1343/1/012195
- Garritzmann, U. (2018). *Tectonic Expressions in Brick Architecture*. Paper presented at the CA2RE: Conference for Artistic and Architectural (Doctoral) Research. Ljubljana, Slovenia. 72-73.
- Grobman, Y.J. (2008). *Building the digital world—architectural design methods based on the use of digital tools—performance based form generation and optimization*. Doctor of Philosophy, Technion—Israel Institute of Technology, Haifa. 21-26.
- Grobman, Y.J. (2013). *Cellular building envelopes*. Paper presented at International Conference on Research into Design, ICoRD'13, Indian Institute of Technology Madras, Chennai. 951-963.
- Helm, V., Ercan, S., Gramazio, F., and Kohler, M. (2012). *In-situ robotic construction: Extending the digital fabrication chain in architecture*. Paper presented at the Synthetic Digital Ecologies: Proceedings of the 32nd Annual Conference of the Association for Computer Aided Design in Architecture, San Francisco, USA. 169-172.
- Imbern, M. (2012). *A digital approach to ceramic structural surfaces*. Paper presented at the ACADIA 12: Synthetic Digital Ecologies Proceedings of the 32nd Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA), San Francisco, USA. 315-321.
- Imbern, M. (2014). *(Re) Thinking the brick: Digital tectonic masonry systems*. Paper presented at the Rethinking Comprehensive Design: Speculative Counterculture, Proceedings of the 19th International Conference on Computer-Aided Architectural Design Research in Asia CAADRIA 2014, Kyoto, Japan. 211–220.
- Jonas, K., Penn, A., and Shepherd, P. (2014). *Designing with discrete geometry*. Paper presented at the Rethinking Comprehensive Design: Speculative Counterculture—Proceedings of the 19th International Conference on Computer-Aided Architectural Design Research in Asia, CAADRIA 2014, Kyoto, Japan. 513-522.
- Kalkatechi, M. (2016). *The design and analysis of a multi-performance 3D printed construction unit: An algorithm to upgrade the structural environmental and assembly performance in masonry units construction*. Doctor of Philosophy, Illinois Institute of Technology, Ann Arbor. 45.
- Kharazmi, M., and Topoi, EC (2016). *A study on geometric constructions on brickwork decorations in Iranian architecture*. The Proceedings of Bridges 2016: Mathematics, Music, Art, Architecture, Education, Culture, 301-308.

- Kline, E. (2017). *Ceramic Architecture: Showcasing a Forgotten Architectural Medium Through Recycled Rubble*. Master of Science, University of Cincinnati, Ohio. 23-35.
- Kolarevic, B. (2000). *Digital morphogenesis and computational architectures*. Construindo n (o) espaço digital, PROURB, Universidade Federal do Rio de Janeiro, Rio de Janeiro. 98-103.
- Kolarevic, B. (2001). *Digital fabrication: manufacturing architecture in the information age*. Paper presented at the Proceedings of the Twenty First Annual Conference of the Association for Computer-Aided Design in Architecture / ISBN 1-880250-10-1] New York, USA. 268-278.
- Kolarevic, B., and Klinger, K. (2013). *Manufacturing material effects: rethinking design and making in architecture*, London: Routledge, 6-20.
- Kroger, S. A. (2005). *Architecture Built to Last: The Timelessness of Brick*. Doctor of Philosophy, University of Cincinnati, Ohio. 1-24.
- Lange, C., and Holohan, D. (2019). *CeramicINformation pavilion-Rethinking structural brick specials through an indexical 3D printing method*. Paper presented at the Intelligent and informed, Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2019, Hong Kong, China. 103-111.
- Lee, J., and Garlock, M. E. M. (2010). *Eladio Dieste and Félix Candela: a comparative analysis*. Paper presented at the: Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2009, Valencia Evolution and Trends in Design, Analysis and Construction of Shell and Spatial Structures, Valencia, Italy. 1562-1568.
- Little, T. S. (2006). *Materials Matter: Exploring Unconventional Applications of Brick in Architecture*. Doctor of Philosophy, University of Cincinnati, Ohio. 6-28.
- López-Almansa, F., Sarrablo, V., Lourenço, PB, Barros, JA, Roca, P., Da Porto, F., and Modena, C. (2010). Reinforced brick masonry light vaults: Semi-prefabrication, construction, testing and numerical modeling. *Construction and Building Materials*, 24(10), 1799-1814.
- López, D., Domenech, M., and Palumbo, M. (2014). “Brick-Topia”, The Thin-Tile Vaulted Pavilion. *Case Studies in Structural Engineering*, 2(C). 33-40.
- Lynch, G., Roundtree, S., and Architects, S. (2009). *Bricks-A guide to the repair of historic brickwork*. Dublin: Government Publications Sales Office. 4-12.
- F. Madeo and M. A. Schnabel. (2014). *Integrating the Tectonics in Architecture Design*. Paper presented at the Architectural Research through to Practice: 48th International Conference of the Architectural Science Association 2014. Italy: The Architectural Science Association and Genova University Press. 433–442.

- Marin, P., Liveneau, P., and Blanchi, Y. (2012). *Digital Materiality: Conception, fabrication, perception*. Scaleless Seamless, Performing a less fragmented architecture and education. Münster: Charis Ltd, 137-150.
- Massoud, P.M. (2018). The Versatility of using Bricks to Produce Generative Monolithic Surfaces using different Construction methods. Paper presented at the *International Journal of Current Engineering and Technology*, 8(5), 1277-1282
- Menges, A. (2016). Computational material culture. *Architectural Design*, 86(2), 76-83.
- Mousavian, E., and Casapulla, C. (2020). Structurally informed design of interlocking block assemblages using limit analysis. *Journal of Computational Design and Engineering*, 7(4), 448-468.
- Mueller, C., and Ochsendorf, J. (2013). *From analysis to design: A new computational strategy for structural creativity*. Paper presented at the Proceedings of the 2nd International Workshop on Design in Civil and Environmental Engineering, Worcester, Massachusetts. 46-56.
- Nilsson, F. (2007). *New technology, new tectonics?-on architectural and structural expressions with digital tools*. Tectonics-Making Meaning. Conference Proceedings, Eindhoven University, Netherlands. 1-7.
- Oliveira, R., and Sousa, J. P. (2016). *Building traditions with digital research-reviewing the brick architecture of Raúl Hestnes Ferreira through robotic fabrication*. Paper presented at the Herneoja, Aulikki; Toni Österlund and Piia Markkanen (Eds.), Complexity and Simplicity - Proceedings of the 34th eCAADe Conference, 1. University of Oulu, Oulu, Finland, 123-131.
- Oswald, S. (2013). *Brick: A Story of Construction*. Master of Science, University of Waterloo, Ontario. 8-26.
- Oxman, R. (2012). Informed tectonics in material-based design. *Design Studies*, 33(5), 427-455.
- Oxman, R., and Oxman, R. (2010). New structuralism: design, engineering and architectural technologies. *Architectural Design*, 4(80), 14-23.
- Paoletti, I. (2017). Mass customization with additive manufacturing: new perspectives for multi performative building components in architecture. *Procedia engineering*, 180, 1150-1159.
- Parigi, D. (2014). *Performance Aided Design: tradition and development of tectonic design process*. Paper presented at the Proceedings of IASS Annual Symposia : Shells, Membranes and Spatial Structures: Footprints – General 6: Conceptual Design, 1-8.
- Pedreschi, R. (2001). *Eladio Dieste: The Engineer's contribution to contemporary architecture*. London: Thomas Telford Ltd. 111.

- Pedreschi, R., and Theodossopoulos, D. (2007). *The double-curvature masonry vaults of Eladio Dieste*. Proceedings of the Institution of Civil Engineers-Structures and Buildings, 160(1), 3-11.
- Pedreschi, R. (2008). Form, force and structure: a brief history. *Architectural Design*, 78(2), 12-19.
- Pedreschi, R., and Theodossopoulos, D. (2010). *Eladio Dieste; 'resistance through form'*. Structures and Architecture, London: Taylor and Francis, 779-787.
- Peters, B. (2013). *Building bytes: 3D-printed bricks*. ACADIA 13: Adaptive Architecture Paper presented at the Proceedings of the 33rd Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA) ISBN 978-1-926724-22-5 Cambridge, UK. 433-434.
- Radivojević, A., and Kurtović-Folić, N. (2006). Evolution of bricks and brick masonry in the early history of its use in the region of today's Serbia. *Journal of materials in civil engineering*, 18(5), 692-699.
- Rahman, K. (2019). Can robots do more than just laying bricks? *The Future of Robotic Fabrication in Architecture* (PDF Document) Retrieved from: Can robots do more than just laying bricks? the future of robotic fabrication in architecture (researchgate.net)
- Rosenwasser, D., Hamada, S., Luo, D., and Sabin, JE (2018). PolyBrick 3.0: live signatures through DNA hydrogels and digital ceramics. *International Journal of Rapid Manufacturing*, 7(2-3), 203-218.
- Saridal, C. (2007). *A Research on Architectural Design Techniques and Manufacturing Processes in the Digital Age*. Doctor of Philosophy, Istanbul Technical University, Istanbul. 2-6.
- Shakir, A., and Mohammed, A. (2013). Manufacturing of Bricks in the Past, in the Present and in the Future: A state of the Art Review. *International Journal of Advances in Applied Sciences*, 2(3), 145-156.
- Sousa, JP (2017). Robotic Technologies for Non-Standard Design and Construction in Architecture. *Nexus Network Journal*, 19(1), 73-83.
- Sousa, JP, de Azambuja Varela, P., and Martins, P. (2015). *Between manual and robotic approaches to brick construction in architecture*. Martens, B, Wurzer, G, Grasl T, Lorenz, WE and Schaffranek, R (eds.), Real Time - Proceedings of the 33rd eCAADe Conference, Vol 2, Vienna University of Technology, Vienna, Austria. 361-370.
- Söffker, GH, and Deplazes, A. (2005). *Constructing architecture: materials, processes, structures*. Berlin: Springer Science and Business Media, 27-30.
- Sunguroglu, D. (2008). Complex brick assemblies. *Architectural Design*, 78(2), 64-73.

- Terzi, N. (2009). *Mimarlıkta hesaplamalı teknolojiler ve geometri*. Master of Science, Yıldız Technical University, Istanbul. 1-8.
- Ünay, A. İ. (1997). *A method for the evaluation of the ultimate safety of historical masonry structures*. Doctor of Philosophy, The Middle East Technical University, Ankara. 26-27.
- Varela, B., Paio, A., and Rato, V. (2013). *Digital tectonic: Rethinking building with earth in architecture*. Paper presented at: International Conference on Vernacular Architecture, Vila Nova de Cerveira, Portugal.
- Vazquez, E., Diarte, J., and Gursoy, B. (2018). *Bridging parametric design and craftsmanship: Materializing the digital parametric wall with low-tech masonry construction techniques*. Proceedings of the 23rd International Conference of the Association for Computer-Aided Architectural Design Research in Asia, Beijing, China. 3-8.
- Willmann, J., Augugliaro, F., Cadalbert, T., D'Andrea, R., Gramazio, F., and Kohler, M. (2012). Aerial robotic construction towards a new field of architectural research. *International Journal of Architectural Computing*, 10(3), 439-459.
- Wu, C., and Roe, S. (2006). What a Brick Wants to Become: A Design-Research Project. *AA Files*, 53(1), London: Architectural Association School of Architecture. 8-13.
- Xu, W., Luo, D., and Gao, Y. (2019). *Automatic brick masonry system and its application in on-site construction*. M. Haeusler, M. A. Schnabel, T. Fukuda (eds.), Intelligent and Informed - Proceedings of the 24th CAADRIA Conference - Volume 1, Victoria University of Wellington, Wellington, New Zealand, 83-92.
- Yenice, Y., and Park, D. (2019). *V-INCA-Designing a smart geometric configuration for dry masonry wall*. Sousa, JP, Xavier, JP and Castro Henriques, G (eds.), Architecture in the Age of the 4th Industrial Revolution - Proceedings of the 37th eCAADe and 23rd SIGraDi Conference, Vol. 2. University of Porto, Porto, Portugal. 515-520.
- Yuan, P.F., Chai, H. (2019). *Reinterpretation of Traditional Wood Structures with Digital Design and Fabrication Technologies*. Paper presented at: Bianconi, F., Filippucci, M. (eds) Digital Wood Design. Lecture Notes in Civil Engineering, Vol. 24. Springer, Cham, 265-282.
- Yuan, P.F., Zhang, M., and Han, L. (2013). *Low-tech digital fabrication: traditional brick as material in digital practice*. Paper presented at the International Conference on Computer-Aided Architectural Design Futures, 139-148.
- Zandavali, BA; Jimenez Garcia, M; (2019) *Automated Brick Pattern Generator for Robotic Assembly using Machine Learning and Images*. Paper presented at Proceedings of 37 eCAADe and XXIII SIGraDi Joint Conference, "Architecture in the Age of the 4Th Industrial Revolution", 217-226. Editora Blucher: São Paulo, Brazil.

- Internet: (URL-1). *Red Brick Country Auditorium / Huazhong University of Science and Technology + ADAP Architects*. 16.04.2018. Web: https://www.archdaily.com/892573/red-brick-country-auditorium-huazhong-university-of-science-and-technology-plus-adap-architects?ad_medium=gallery, Access Date: 28.08.2021
- Internet: (URL-2). *Tudor Chimneys*. 19.07.2017. Web: <https://www.geograph.org.uk/photo/5257706>, Access Date: 25.09.2021
- Internet: (URL-3). *The Great Mosque (or Masjid-e Jameh) of Isfahan*. 08.08.2015. Web: <https://smarthistory.org/the-great-mosque-or-masjid-e-jameh-of-isfahan/>, Access Date: 08.10.2021
- Internet: (URL-4). *Basilique Palladienne*. 27.10.2007. Web: https://fr.wikipedia.org/wiki/Basilique_palladienne, Access Date: 08.10.2021
- Internet: (URL-5). *History of Brick Masonry*. 01.01.2021. Web: <https://sullivanengineeringllc.com/2018/02/28/history-brick-masonry/> Access Date: 10.10.2021
- Internet: (URL-6). German, S. (August,2015). *Ziggurat of Ur*. Smarthistory. Web: <https://smarthistory.org/ziggurat-of-ur/>, Access Date: 10.10.2021
- Internet: (URL-7). *Manufacturing of Bricks for Masonry Construction*, Web: <https://theconstructor.org/building/manufacturing-of-bricks-methods-and-process/11972/>, Access Date: 26.08.2021
- Internet: (URL-8). *Hagia Sophia*, 01.01.2009. Web: <https://www.hagiasophia.com/>, Access Date: 26.08.2021
- Internet: (URL-9). *Climate Change, Cultural Heritage and Energy Efficient Monuments*, Web: <http://www.co2olbricks.de/index.php?id=178>, Access Date: 01.09.2021
- Internet: (URL-10). *Guastavino Tile Vaults*, Web: <https://structurae.net/en/structures/buildings/guastavino-tile-vaults> , Access Date: 23.10.2021
- Internet: (URL-11). *9 Dazzling Tiled Archways Devised by Rafael Guastavino*, 08.06.2016. Web: <https://www.architecturaldigest.com/gallery/guastavino-tile-arches>, Access Date: 23.10.2021
- Internet: (URL-12). *Why Louis Kahn Would Often Talk to Bricks*, Web: <https://ca.phaidon.com/agenda/architecture/articles/2019/january/16/why-louis-kahn-would-often-talk-to-bricks/>, Access Date: 08.05.2021
- Internet: (URL-13). *Alia Bengana: Terres*, 02.06.2016, Web: https://www.domusweb.it/en/architecture/2016/05/31/alia_bengana_terres.html, Access Date: 06.05.2021

- Internet: (URL-14). Cabeza, Lainez, J.M. (December, 2008). *Eladio Dieste and the Evolution from Brickwork to Architectural Form*, Web: <http://www.arquitecturatropical.org/EDITORIAL/documents/DIESTE%20J%20M%20CABEZAS.pdf>, Access Date: 04.06.2021
- Internet: (URL-15). *Wall Relief No. 1*, Web: <https://www.sculptureinternationalrotterdam.nl/en/collection/wall-relief-no-1-en/>, Access Date: 04.06.2021
- Internet: (URL-16). *Winery Gantenbein / Gramazio and Kohler + Bearth and Deplazes Architekten*. 09.08.2012. Web: <https://www.archdaily.com/260612/winery-gantenbein-gramazio-kohler-bearth-deplazes-architekten>, Access Date: 05.06.2021
- Internet: (URL-17). *V-Brick Wall*, Web: <https://www.aclab-idegui.org/v-brick-wall>, Access Date: 25.05.2021
- Internet: (URL-18). *5 Robots Revolutionizing Architecture's Future*. 28.02.2013. Web: https://www.archdaily.com/336849/5-robots-revolutionizing-architectures-future?ad_medium=gallery, Access Date: 04.06.2021
- Internet: (URL-19). *Robots in Architecture*. 15.07.2013. Web: <https://www.roboticstomorrow.com/article/2013/07/robots-in-architecture/180/>, Access Date: 05.04.2021
- Internet: (URL-20). *Eladio Dieste*, Web: <https://www.fadu.edu.uy/eladio-dieste/sin-categoria/>, Access Date: 04.06.2021
- Internet: (URL-21). *Material tour de force: The work of Eladio Dieste*. 27.07.2012. Web: <https://archleague.org/article/material-tour-de-force-the-work-of-eladio-dieste/>, Access Date: 04.06.2021
- Internet: (URL-22). *Clásicos de Arquitectura: Iglesia del Cristo Obrero / Eladio Dieste*. 19.07.2011. Web: <https://www.plataformaarquitectura.cl/cl/02-98249/clasicos-de-arquitectura-iglesia-del-cristo-obrero-eladio-dieste/>, Access Date: 04.06.2021
- Internet: (URL-23). *Iglesia del Cristo Obrero*. 11.07.2020. Web: <https://www.youtube.com/watch?v=f-JfpcBW8wwandt=1s>, Access Date: 04.06.2021



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