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# RE-GENERATION OF DOMES THROUGH DIGITAL TECHNOLOGIES: A CASE ON INTERLOCKING BRICK DOME

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**BY**
**Kardelen Betül KILINÇ**


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**IN**
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## ETHICAL STATEMENT

I hereby declare that in this thesis study I prepared in accordance with thesis writing rules of Gazi University Graduate School of Natural and Applied Sciences;

- All data, information and documents presented in this thesis have been obtained within the scope of academic rules and ethical conduct,
- All information, documents, assessments and results have been presented in accordance with scientific ethical conduct and moral rules,
- All material used in this thesis that are not original to this work have been fully cited and referenced,
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Kardelen Betül KILINÇ

07/06/2021

RE-GENERATION OF DOMES THROUGH DIGITAL TECHNOLOGIES: A CASE ON INTERLOCKING BRICK DOME

(M. Sc. Thesis)

Kardelen Betül KILINÇ

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## ABSTRACT

Domes are one of the oldest building systems. From prehistoric times to modern times, societies have been building domes with available materials for various purposes. However, the dome surface is a double curvature geometry, which challenges both the design and construction process. This thesis study presents a strategy to design and assemble an interlocking masonry technique to investigate the effects of parametric design and manufacturing tools on the design and installation process. In addition, this study proposes an alternative architectural tectonic for building a dome structure. Therefore, to investigate the effects of parametric design and manufacturing tools on masonry systems, a comparison between conventional dome masonry techniques and the interlocking brick dome has been completed and evaluated. For this reason, first, two different traditional masonry dome techniques were recreated on Grasshopper and manufactured by a CNC laser cut machine and installed. Second, regarding the conventional masonry methods, a new dome masonry technique has been developed and created with Rhinoceros 6 and Grasshopper and manufactured by a 3D printer and installed. The designed approach covers a 3-jointed interlocking masonry system, which is made by exploring a new topological brick geometry and a masonry brick configuration. Additionally, this system does not require an adhesive for the assembling process. In conclusion, an interlocking brick masonry dome has been generated to propose an alternative brick form, configuration, and installation method through digital design and manufacturing tools. This study is a step to understand the changing tectonics in architecture by digital design and manufacturing tools. It should be noted that this study only covers geometric exploration and installation. Further studies have to be done to have more complete results about the created method, the interlocking brick dome. For future studies, different materials and unit forms can be tested. Additionally, the structural behavior of the 3D printed dome can be investigated to examine its condition under stresses and loads.

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KUBBENİN SAYISAL TEKNOLOJİLERLE YENİDEN ÜRETİMİ: GEÇMELİ TUĞLA KUBBE ÖRNEĞİ

(Yüksek Lisans Tezi)

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# ÖZET

Kubbeler en eski yapı sistemlerinden biridir. Tarih öncesi çağlardan modern zamana kadar toplumlar çeşitli amaçlarla mevcut malzemeleri kullanarak kubbeler inşa edegelmişlerdir. Ancak kubbe yüzeyi, hem tasarım hem de yapım sürecini zorlayan çift eğrili bir geometriye sahiptir. Bu tez çalışması parametrik tasarım ve üretim araçlarının, tasarım ve kurulum süreci üzerindeki etkilerini araştırmak için bir strateji sunmaktadır. Buna ek olarak, kubbe yapısı inşa etmek için alternatif bir mimari tektonik önermektedir. Bu nedenle, parametrik tasarım ve üretim araçlarının yığma sistemler üzerindeki etkilerini araştırmak için geleneksel kubbe yığma teknikleri ile birbirine geçmeli tuğla kubbe arasında bir karşılaştırma yapılmış ve değerlendirilmiştir. Öncelikle, Grasshopper programı ile iki farklı geleneksel yığma kubbe tekniği yeniden oluşturulup, CNC lazer kesim makinesinde imal edilerek montajı yapılıştır. Sonrasında, Rhinoceros 6 ve Grasshopper programları kullanılarak yeni bir yığma kubbe tekniği geliştirilmiş ve 3 boyutlu yazıcı ile üretilmiştir. Bu tasarım yaklaşımı, yeni bir topolojik tuğla geometrisi ve konfigürasyonu geliştirilerek yapılan 3 eklemli ve birbirine geçen bir duvar sistemini kapsamaktadır. Ayrıca, bu sistemin montajı için yapıştırıcıya ihtiyaç duyulmamaktadır. Sonuç olarak, dijital tasarım ve üretim araçları kullanılarak tasarlanan birbirine geçmeli tuğla kubbe oluşturulmuş ve alternatif bir tuğla formu, konfigürasyonu ve montaj yöntemi önerilmiştir. Bu çalışma, değişen mimari tektoniğini dijital tasarım ve üretim araçlarıyla anlamak için bir adım olmuştur. Bu çalışmanın sadece geometrik bir yerleştirmeyi kapsadığını belirtmek gerekir. Oluşturulan yöntem olan birbirine geçmeli tuğla kubbe hakkında daha geçerli sonuçlar elde etmek için daha ileri çalışmalar yapılması gereklidir. Gelecekteki çalışmalar için farklı malzemeler ve formlar da test edilebilir. Ek olarak, 3 boyutlu yazıcılar ile imal edilen bir kubbenin yapısal davranışı, gerilmeler ve yükler altındaki durumunun da incelenmesi de gerekecektir.

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# SYMBOLS AND ABBREVIATION

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

| **Symbols** | **Definition** |
|---|---|
| **cm** | Centimeter |
| **m** | Meter |

| **Abbrevation** | **Definition** |
|---|---|
| **2D** | Two-dimensional |
| **3D** | Three-dimensional |
| **CNC** | Computer Numerical Control |
| **NU** | Non Uniform |
| **PLA** | Polylactic Acid |

# 1. INTRODUCTION

Domes are one of the oldest building systems. From prehistoric times to modern times, societies have been building domes with available materials for various purposes. Mainly, it has preferred in buildings where magnificence and greatness are desired to be emphasized. Dome surface is a double curvature geometry, which brings challenges both in the design and construction process.

This thesis study presents a strategy to design and assemble a 3-jointed interlocking masonry technique to investigate the effects of parametric design tools on the design and installation process and develop an alternative architectural tectonic to build a dome structure by using a 3-jointed interlocking system. The aimed system is based on a unit design that can be easily manufactured and assembled without requiring adhesive.

Four different hemispherical samples are created on Grasshopper and physically modeled on a 1/20 scale. First, the regular corbelled dome and brick masonry dome modeled on Grasshopper. This operation provided basic information about traditional architectural tectonics and helped to acknowledge the evolutionary process of design and construction methods. Later, the other two samples, interlocking brick dome structures, are modeled to propose a new brick configuration using Rhinoceros 6 and Grasshopper software. The proposal aimed to provide a new topological geometry to explore the potentials of digitally designed bricks and an alternative installation method without any adhesive for dome structures. Finally, the digitally modeled samples have been physically prototyped by using digital manufacturing tools. The corbel and the masonry dome prototype have been cut with CNC laser, and other interlocking pieces were 3D printed with PLA filament.

Throughout history, the construction of traditional structures has been based on flat, repetitive rectangular geometries. Today, digital technologies accelerate the change in architectural mechanisms, including form-finding algorithms and computational controlled machinery. By these methods, designing complex geometries, testing the design or structural failures on digital platforms, and producing intricate forms can become successfully applicable. However, there are still issues to overcome, especially in the installation process.

This thesis addressed this problem to explore the more straightforward method of assembling units by using an interlocking system to build a dome structure.

The study starts with a literature review of bricks, the historical background of domes, construction methods, and parametric approaches to establish comprehensive base information about crowns. It continues with explaining and illustrating the design process and production and installing the interlocking brick dome structure. The study's contribution shows the potential of using the interlocking brick system, parametrically designed, as a structural system. The thesis concludes with a discussion about the advantages and limitations of the result. Since this study is based on the development of geometric form, there is a need for further studies that require investigation of construction materials and applications and static balance tests at larger scales.

Background and problem definition

In this study, the validity of digital design and fabrication as a tool to discover an interlocking brick form and to determine dome geometry is examined. The following research questions are the main focus of the study:

How can we create a dome surface with a parametric design tool? And, what is the main differences between corbel dome, masonry dome, and interlocking brick dome while creating them on Grasshopper?

To answer these main questions, the following sub-questions were also investigated:

- How can a 3-joint interlocking system apply to a double curvature surface, a dome with an oculus, on Grasshopper?
- What are the assembling differences between the masonry brick dome and the interlocking brick dome?
- How can we integrate parametric design tools into a brick masonry system to create a double curvature surface?
- How can we topologically change the form of the regular brick into a 3-joint interlocking unit system?
- How can digital design and manufacturing technologies affect the future of masonry systems?

Research hypothesis

The research has been conducted to test the following hypothesizes:

- Parametric design and digital fabrication are remarkably changing the architectural paradigms and brick design and assemblage in particular.
- Computational design and digital fabrication applications in digital masonry architecture may provide easier assembling methods without the need for skilled labor.
- Algorithm-based designs can be articulated according to the target design area through rearranging parameters.
- Computational design and digital fabrication is the critical tool for the articulation of topologic brick geometries.
- Parametric design and fabrication evolve the tectonic of building dome structures and generate numerous altering opportunities to design dome surfaces.

The research hypothesizes have been tested through case studies and simulation research for a scaled prototype composed of a 3D printed unit's installation.

Research aim

The primary aims of this research can be listed as follows:

- Creating new topological geometries, patterns, and assemblage variations for exploring the potentials of digitally designed bricks.
- To study and develop alternative architectural installations out of the brick unit for dome surfaces.
- To characterize and analyze the differences between traditional and the current technological design and constructing methods.

Significance of the study

This study is important as it allows the development of interlocking brick form prototypically, with the help of programs such as Rhinoceros 6 and Grasshopper, to use in structures built to cover large openings such as domes. This study has explored a new brick geometry and simple assemblage to construct a dome structure by an interlocking joinery mechanism. Furthermore, this study has been planned to see the potentials to use digital design and fabrication technologies to fulfill this aim. Recently, digital design and technologies have been commonly used in building architectural design and construction. Therefore, it is vital to research the possibilities offered by these technologies that will contribute to the design, construction, and manufacturing fields.

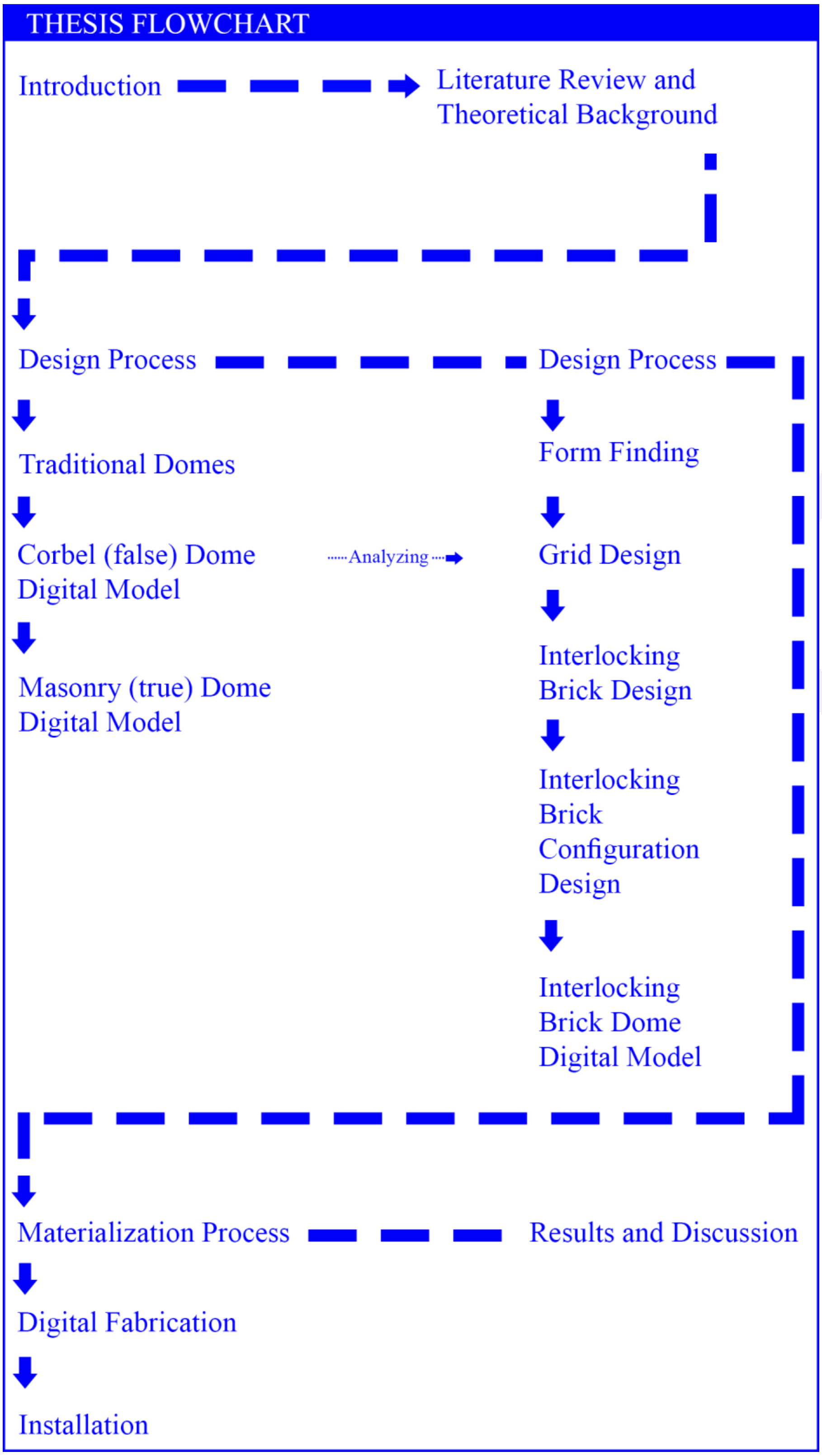
Limits of the study

This study is based on the exploration of the geometrical form and its design process. Even though the end product is a scaled CNC laser cut and 3D printed model, the evaluation and results do not include static equilibrium efficiency or material properties under specific weight loads of the created model. Future studies require further investigation of the mechanical behaviors of this study.

Methodology

For this research, a hemispherical dome surface has been selected to explore the contributions of the parametric design and manufacturing tools into masonry construction systems. First, two different conventional masonry dome types were created on Rhinoceros 6 and Grasshopper. Later, a 1/20 scaled modal was prototyped using a CNC laser cutting machine. By the lights of the information obtained from these experiments, a complex brick geometry and an interlocking brick configuration have been created and applied to the dome surface on Grasshopper. Finally, the 1/20 scaled physical modal has created via a 3D printer. The whole process of this study is divided into three parts as digital modeling, production, and installation. Experiences in each phase were noted and evaluated as a result of this research.  The flow chart of the thesis can be seen in Table 1.1.

Table 1.1. Thesis flowchart



# 2. LITERATURE REVIEW AND THEORETICAL BACKGROUND

This chapter aimed to unveil and discuss the conventional situation, terms, terminologies, definitions, and crucial information about the related subject. First, the definition of brick as a structural element, its historical background, production and assembly methods; later, the introduction of masonry domes, its historical background, its different types, construction methods, and historical masonry examples; lastly, current dome examples, which created with parametric design tools will examine and investigate to compose a theoretical background about domes for this study.

## 2.1. Brick: Basic Structural Element

Brick is man's oldest manufactured product used for thousands of years to build innumerable structures due to its durability. Brick is a simple object and has been a base unit of architecture for over 7000 year (Fiala, Mikolas, and Krejsova, 2019), embedded in the cultural consciousness of people as one of the fundamental symbols of architecture. No other material has such an extensive history, widespread application, and depth of association. Furthermore, the versatility possible through the simple geometry of brick allows for the creation of various forms and textures in architecture. In contemporary practice, digital tools in design have enabled methodologies for creating new forms in architecture. Especially, algorithmic software systems provide new opportunities for designers to create parametrically designed forms, such as the generation of new brick units. This research aims to find alternative brick form and installation patterns through a parametric design approach. In order to examine and understand brick, this section will describe its short history, types, and production and installation methods.

Masonry is a heterogeneous material that consists of units and joints. Units can be bricks, blocks, ashlars, adobes, irregular stones, and others. Joints are connecting each other with an adhesive material, usually mortar and its derivatives. Mortar can be clay, bitumen, chalk, lime- or cement-based, glue, or others (Lourenco, Milani, Tralli, and Zucchini, 2007). Masonry is not correctly a "material" in the strict sense of the word. It consists of the (generally man-made) assemblage of a primary component (the bricks) laid on each other or, more often, jointed by mortar. Bricks and mortar may have very variable mechanical properties. Therefore, the way the bricks are organized in the masonry volume may be very different and is subject to the skill and creativity of the designer and builder (Baratta, 2013).

### 2.1.1. A brief history of bricks

Brick masonry is one of the oldest manufactured building materials globally, which has been so prevalent in building throughout the history of the modern era. The first bricks were sun-dried mud bricks (see Figure 2.1) made by mixing clay or mud with straw or dung, and tar was used as a mortar to bind bricks (URL-1). The origin of the brick is the earth which is an abundant material in nature. Ancient people took the hint from nature. The soil around a water source hardened and cracked by the sun exposure, people learned from this to manufacture mud brick by themselves (A. F. B. Association, 1920: 5). The traditional manufacturing process starts with pressing the soft mud into wooden simple rectangular molds. Previously, the builders were submerging the molds into the water, and immediately after, they were pushing the mud into them. This method prevents the mud from sticking to the molds (Shakir and Mohammed, 2013). Many ancient brickwork remnants are well-burned and colored bricks that belong to cities of the Mesopotamian region. Brick craft had spread from the Euphrates to east Persia, India, and China and applied to west Egypt, Greece, and Rome (A. F. B. Association, 1920: 6). Bricks have been the building blocks of many of the world's great treasures, such as the pyramids of Giza, the Roman Colosseum. They have been used by the Ancient Egyptians, the Romans, the Greeks, the Mesopotamians, and almost every other civilization (URL-2). One of the earliest examples of the masonry unit found is in Egypt (2134 BC) in the Mortuary temples of Mentuhotep and Hatshepsut (Ambrose, Callam, Kunkel, and Wilson, 2009).

Figure 2.1. Shaped mud-bricks (URL-3).

Around 3500 B.C., firing bricks were found to be more resistant to the extreme weather conditions, and making them much more durable for use in permanent buildings where mud bricks would not have been sufficient. For this reason, fired bricks began to replace sun baking as a manufacturing method. The art of brickmaking spread to the world via the help of the Roman Empire and their mobile kilns. So producing of brick was no longer had to be made in warmer climates or during the summer (Fernandes, Lourenço, and Castro, 2010). By the time, brick manufacturing and masonry construction techniques have developed. Countries have had their traditional ways of pattern design and bricklaying methods (Massoud, 2018). In the early to mid-19th century, Richard VerValan invented the steam-powered brickmaking machine that has streamlined the manufacturing process, exponentially increased the production of bricks, and led to an industry boom. Before machinery production, workers should have to force clay into molds. However, automating this process with machines resulted in more uniformly square-shaped bricks (URL-2). Through the centuries, the methods for producing brick have continued to develop. Today, it is still in use as one of the most common structural elements. The timeline of brick evolution illustrated below (see Figure 2.2).

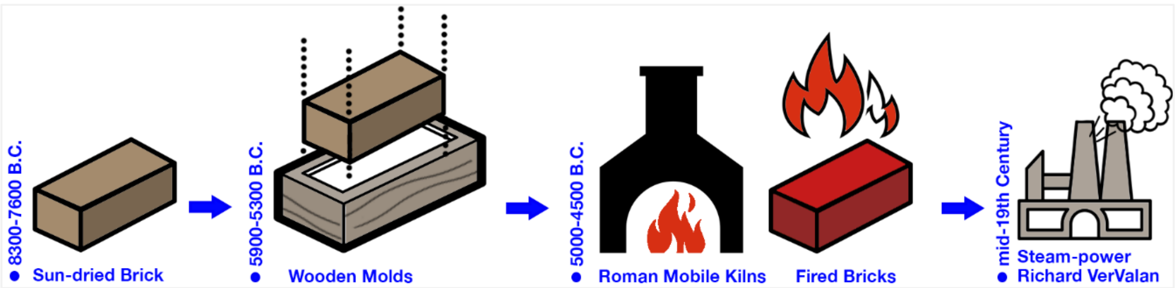



Figure 2.2. Evolution of brick types timeline, adapted from (Ganobjak and Carstensen, 2019), (Fiala, Mikolas, and Krejsova, 2019)

### 2.1.2. Types of bricks

Bricks are one of the most durable materials described as building units easily handled with one hand (see Figure 2.3). Traditionally, the term brick referred to a small unit of building material consisting primarily of clay. Clay is the naturally occurring raw material that consists mainly of silica and alumina (Hodge and Thorpe, 2006: 4-8).

Currently, the definition of brick has expanded to refer to any small rectangular building unit that is joined to other units via adhesive mortar and for larger building units that called blocks (URL-4).

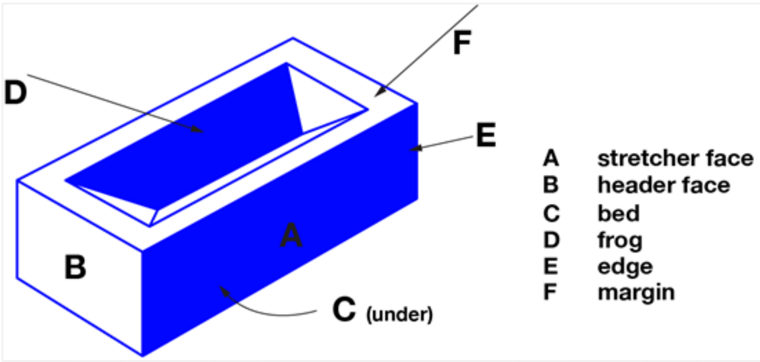



Figure 2.3. Parts of a Brick, adopted from (Bailey and Hancock, 1990: 78).

Bricks can be divided into groups according to their qualities, manufacturing methods, the purpose of use, shape, the orientation of using, and raw materials. The brick classification depends on the specific application that the brick will be used (URL-41). Whether composed of clay, sand, lime, or concrete, Bricks can be divided into four major types based on variety; facings bricks, commons, engineering bricks, and refractories. Facing bricks are used on the surface of the brick wall. These are high quality, which means they are made from good quality raw materials. They are manufactured in a wide range of colors and textured surfaces to be durable and attractive. Standard bricks are suitable for general building due to their stiffness and durability. They are mostly used for general purpose walling, which is most likely to be below ground level, externally rendered, or internally plastered, such as housing and garages, boundary walls, inspection chambers, depending on quality (Hodge and Thorpe, 2006: 9-19). Engineering bricks are hard and dense bricks that have low porosity and, therefore, low water absorption. For this reason, they have been used for bridges, sewers, powerhouses, and engine pits. Engineering bricks are produced for heavily loaded walls or are very exposed to the risk of frost damage. They were originally developed to use in tunnels and bridges (Bailey and Hancock, 1990: 77-79). Refractory bricks are, also known as firebricks, made from special clays which can resist very high temperatures. Refractories can be considered as two groups. The first one is very dense cream-colored solid bricks and produced for furnace linings, cement kilns, ships' boilers, and lining steel ladles transporting molten metal in steelworks. The second one is very lightweight bricks used to insulate chimney shafts to prevent heat leakage from flue gases, and this is the only brick that can float in water (Hodge and Thorpe, 2006: 15).

It should be considered that salts occur in some clay, and this causes efflorescence in brickwork. Rainwater dissolves the salts within bricks. In dry weather, the rainwater evaporates, leaving a dirty white scum on the face. So, brick raw materials have to be salt-free as possible they can (Bailey and Hancock, 1990: 80). Bricks can be divided into three types based on quality such as ordinary bricks, internal bricks, and special bricks. Ordinary and Special bricks are durable enough to be used in the exterior face of a building and resistant to harsh weather conditions like rain and frost. They must contain a limited soluble salt content to prevent the effects of challenging weather conditions. Internal bricks are being used for internal walls, not necessarily frost-resistant (Hodge and Thorpe, 2006: 11).

In modern construction practices, bricks are commonly classified according to their component materials and manufacturing methods. Clay is one of the primary brick materials. However, however, there are other common brick materials such as burnt clay bricks, sand-lime bricks, concrete bricks, and fly ash clay bricks. Burnt clay bricks are either molded, dry-pressed, or extruded, then dried and firing in kilns. Clay is an ancient building material typically found in many ancient structures. These bricks are solid blocks of hardened clay, usually have a reddish color. The main constituents of clay are silica and alumina. Also, they contain smaller proportions of iron oxide, magnesia, and lime. The mineral content of the clay determines its color. Clays rich in iron oxide would turn reddish or rich in lime with a white or yellow hue (URL-5). Sand-lime bricks, also called calcium silicate bricks, are made from a fine silica sand and lime mixture. This mixture is pressed into steel molds and then steam hardened. It is generally a white brick composed of lime and selected sands, cast in molds, and cured (URL-7). Different powder pigments can be added during the mixing stage of manufacture to obtain various brick colors (Hodge and Thorpe, 2006: 6-7).

Concrete bricks are poured into steel molds from a mixture of pressed fine aggregate and Portland cement. The natural hardening process of the cement determines the compressive strength of these bricks. The basic color of concrete bricks is grey, thanks to the Portland cement. Used as a substitute for clay sewer pipe, it does not have as much resistance to the corrosive action of certain acids (Hodge and Thorpe, 2006: 14-17). Fly ash clay bricks are produced with a mixture of clay and fly ash.  Fly ash contains a high volume of calcium oxide, so this type of brick is sometimes described as self-cementing, which expands when exposed to moisture. As a result, fly ash clay bricks are lighter in weight than clay or concrete brick (URL-5). Bricks can also be categorized according to their shape. There are five primary shapes of bricks; solid (a), frog (b), hollow (c), keyed (d), and perforated (e), (see Figure 2.4). Through the centuries the methods for producing brick have continued to developed, and today it is still in use as the most common structural element (Hodge and Thorpe, 2006: 9).

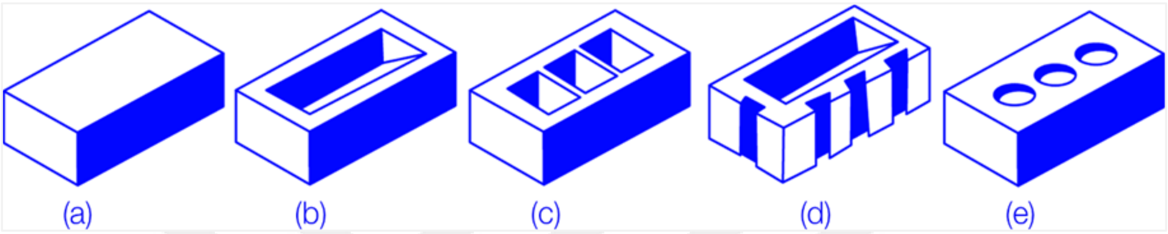



Figure 2.4. Types of bricks, adapted from (Hodge and Thorpe, 2006: 9).

Many buildings require decoratively shaped or molded bricks. In addition, there are other purpose-made bricks which are illustrated in Figure 2.5.

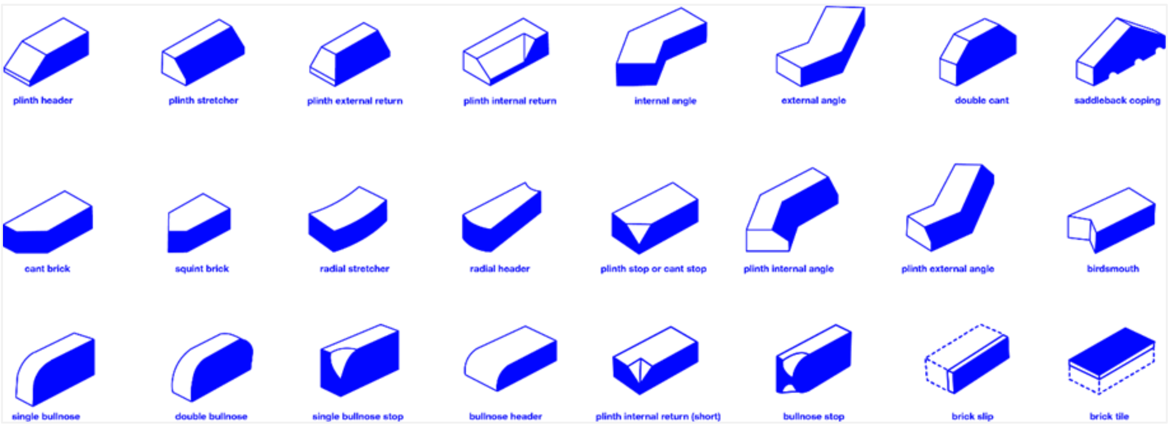



Figure 2.5. Types of purpose-made bricks, adapted from (Chudley and Greeno, 2005: 131).

### 2.1.3. Production and installation of bricks

Brick manufacturing principles have not changed over time. Technological improvements have made contemporary brick production more efficient and have increased the quality of the products. Vast knowledge about raw materials and their chemical features, better-controlled fire, improved kiln designs, and more advanced mechanization and automation have enhanced the brick industry. Clay is one of the most abundant natural mineral materials on earth. However, clay must have some specific characteristics for brick manufacturing—for instance, plasticity, which permits clay to be shaped or molded when mixed with water. In addition, plasticity balances wet and air-dried strength to continue its shape after forming. When subjected to appropriate temperatures, the clay particles must fuse (URL-42). The main components of clay are silica and alumina, in addition to which there are lesser proportions of iron oxide, magnesia, and lime. Metallic oxides act as fluxes promoting fusion of the particles at lower temperatures and influence the color of the fired brick (Bailey and Hancock, 1990: 80-83). Although the basic principles of manufacture are relatively uniform, individual manufacturing plants tailor their production to fit their particular raw materials and operation. Essentially, bricks are produced by mixing ground clay with water, forming the clay into the desired shape, and drying and firing. In ancient times, all molding was performed by hand. However, since the invention of brick-making machines during the latter part of the 19th century, most brick production has been machine-made.

The manufacturing process has six general phases: mining and storage of raw materials, preparing raw materials, forming the brick, drying, firing and cooling, de-hacking, and storing finished products. This manufacturing process is highly controlled, producing an excellent quality building material. As a result of the high temperatures achieved during production, brick masonry is a highly durable material that matures well and resists moisture and thermal damage, including fire. Bricks may be hand or machine molded; there are three main steps for forming brick. First, in the stiff-mud or extrusion process, a water ratio between 10 to 15% is mixed into the clay to produce plasticity. Second, the soft-mud or molded process is particularly suitable for fluidal clays to be extruded by the stiff-mud process. Clays are mixed to hold 20 to 30% water and then formed into a brick in molds. Finally, the dry-press is particularly suited to clays of very low plasticity. Clay is mixed with a minimal amount of water and then pressed into steel molds under pressure by compressed air rams (Brick Industry Association, 2009). In Figure 2.6, the stiff-mud process of brick, the manufacture has illustrated.

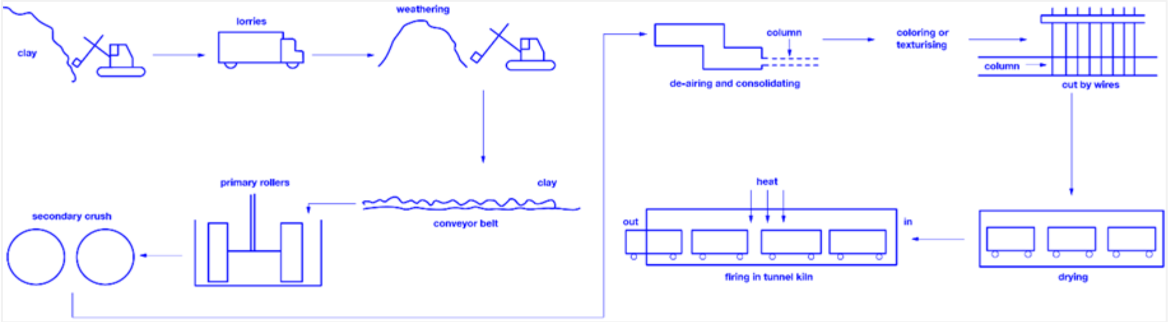



Figure 2.6. Brick production stiff-mud process, adapted from (Bailey and Hancock, 1990: 79).

The brick wall pattern is purposely arranged and is called a bond. Bricks must be lapped one over to the other in successive courses along the wall to maintain strength. There are practical methods such as using a half-brick lap or a quarter-brick lap, a half-bond, and a quarter-bond. The mortar joints and the bricks make an interlocking grid by making the collar joints moved in each course and keeping the bed joints running continuously. Both appearance and strength will be affected if the lap is larger or smaller than these. If bricks are placed that no lap occurs, that is called straight joint or stack bonding (see Figure 2.7) which the cross-joints or perpends are directly over each other. It can either appear on the face or inside the wall, and it must be avoided as much as possible. There are several bond methods use in general, as shown in Figure 2.7. Stretcher bond is used on the half-brick walls of a building and consists of stretchers, except where return angles, stopped ends, and cross walls occur. English bond has a firm bond, with no straight joints occurring in any part of the wall. This method creates monotony in appearance. Therefore it is mainly used on the walls where strength is more crucial than appearance. Flemish bond is used in brick walls of a decorative nature. Internal straight joints, quarter-brick in length, occur at 100 mm intervals along the middle of the wall. The header should be in the center of stretchers in courses above and below (Hodge and Thorpe, 2006: 46-48). The stack bond is created by courses of stretchers stacked directly above each other where joints vertically align. This bonding type is not for structural use, generally preferred for interior usage, or for non-load bearing walls (URL-6). Bond patterns vary according to specific construction techniques and desired appearance, but in general, bond patterns should be staggered to avoid weak lines along mortar joints. Stack bonds should be avoided for the same reason, as they can result in weakness along mortar joints (Dahmen and Ochsendorfs, 2012: 454-455).

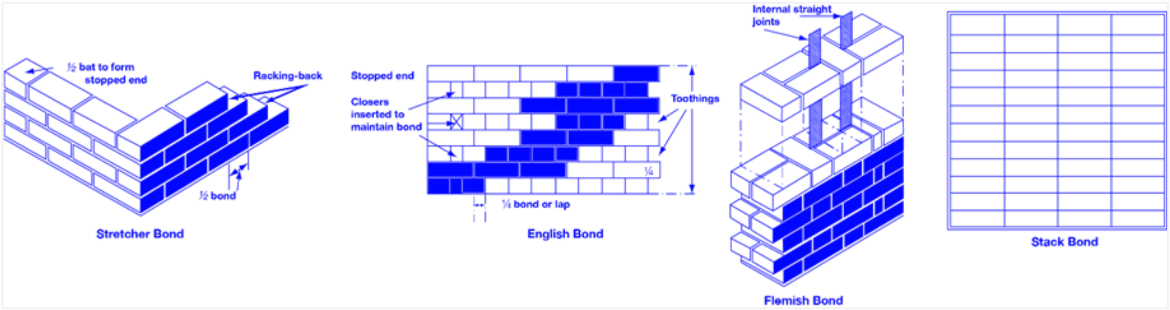



Figure 2.7. Bonding methods, adapted from (Hodge and Thorpe, 2006: 47-48, 96).

Mortar is an ideal material for bricks to rest upon each other firmly. Mortar is the bonding material to bind bricks, concrete blocks, stone, and many other masonry materials. Mortar must stick firmly to prevent the rain from penetrating the exposed joints. It is made from Portland cement, lime, sand, and water in varying ratios. Mortar is a gap-filling adhesive that evens out slight irregularities in size and shape between bricks. It also gives an even base and distributes the loads uniformly, which influences the compressive strength, durability, and resistance to rain penetration. Mortars are composed of a binder, aggregate, and water. They are divided into four main types: cement-sand, lime-sand, cement-lime-sand, and cement-sand and plasticizer (URL-8).

Although mortars are crucial to bond brick to each other, there is another way to bond them, which is directly associated with interlocking bricks. The interlocking bricks are different from conventional bricks. This is because the brick does not require mortar during bricklaying work, which makes building walls faster and requires less skilled labor (except for the first course of the layer) as the blocks are laid dry and lock into place. There are some advantages of using an interlocking brick system in construction. Compared to conventional masonry, the interlocking bricks save construction time and reduce the amount of mortar. It also contributes to a low cost of construction by reducing the cost of a wall achieved by building load-bearing walls with no timber formwork required (Asman et al., 2018), (T. B. D. Association, 2006: 16-18).

## 2.2. Masonry Domes

A dome is a structural system obtained by rotating an arch around its axis of symmetry on a circular base area. Dome covers long-span distances without any support elements beneath it (Heyman, 1997: 28-30), (Hung, 2009). A dome cross-section can differ according to its geometric form (Burden, 2002: 636). There are various types of domes in terms of geometry, explained in Section *2.2.2. Types of domes*, down below. Throughout history, domes have been one of the most preferred large-spanned structures due to the feature of enclosing a maximum amount of space with a minimum surface. The evolution of domes has been related to developing proper materials for construction (Saraç, 2005). For centuries, they have been constructed from a wide range of building materials such as mud, stone, brick, wood, concrete, metal, and plastic (URL-9).

Masonry structures have great importance for architecture since they have been building for thousands of years (Dugum, 2013). Builders have constructed multiple different structural elements by using masonry techniques (Dahmen and Ochsendorfs, 2012). Masonry domes are one of the most common structural elements that have been constructed for ages for diverse purposes. They have an important place in traditional architecture and engineering heritage. They have been used in many historic structures such as temples, churches, palaces, and mosques (Öztürk, Bayraktar, Hökelekli, and Ashour, 2019). In order to understand masonry domes better, this section explores the historical background, geometric types, and construction methods of the domes, as well as some important historical examples.

### 2.2.1. Historical background domes

Societies from prehistoric times to modern times have been building domes with available materials of the period. The first dome that has ever been built is unknown. However, there are prehistoric remnants of mammoth bones considered the discovery of the first dome (URL-10). Prehistoric domes varied according to the regions where people lived; materials differed from bones to ice, loam to wood, and mud to bricks (URL-11). The etymological root of the word *dome* comes from the roof or house in the middle and the Late Latin period. Domes have significant importance that indicates civic, religious, or communal places regarding the meaning of the dome (Makowski, 1984: 10-12).

Throughout history, constructions have been strongly related to the materials that are accessible. In the early periods, stone was the only material for people to use. Neolithic civilizations discovered the corbelling technique and used it for building dwellings (Melaragno, 1991: 13-18). The earliest rock-cut dome examples have been found in many civilizations, including the Egyptian, Aegean, Greek, Etruscan, Persian, and Roman. These domes are used as tombs and have significant importance in the starting evolution of the domes. Later, brick-making techniques developed, and it took the place of stone masonry gradually. Then, a primitive type of concrete invented by the Romans and started to use extensively. During the middle ages, timber was also an optional material for roofing, and dome construction shifted to predominantly timber, where it easy to find. In the 19th century, iron and its derivatives started to be used due to its high strength and relatively lightweight features. Later, a new material, steel, was invented with high strength in tension and compression and thinner in thickness. This discovery allowed builders to construct a more significant spanned new type of dome structure. Afterward, a combination of concrete and steel materials led construction methods to evolve to reach different types of shell domes.

Domes are one of the oldest three-dimensional structural building systems. The earliest finding of a dome was found on an Assyrian relief that shows a group of buildings covered with circular domes. The primitive domes were commonly based on a circular floor plan. In the past, domes developed to become symbols for religious places. Tombs, tabernacles, baptisteries, churches, and mosques were where domes were commonly preferred as a roof element. Many famous domes in antiquity, such as the Pantheon in Rome, built around 120 A.D. Other outstanding domes are Hagia Sophia in Istanbul, Les Invalides in Paris, and St. Paul's Cathedral in London, see Figure 2.8. (Makowski, 1984: 28-33).


Figure 2.8. Pantheon (a) (URL-12), Hagia Sophia (b) (URL-13), Les Invelides (c) (URL-14), St. Paul’s Cathedral (d) (URL-15).

Domes were also used in various utilitarian forms in early history. Granaries, storage buildings, ovens, kilns, cisterns, and ice houses were in domical structures in most parts of the world. Paintings have found in the tombs of Ramses III (12th Century B.C.) was illustrating dome-shaped silos and ovens. Dome-shaped kilns were used in China as interconnecting dome structures at their bases along a hillside. In Iran, sun-dried brick masonry domes were used as ice houses. Mainly in the Middle East, masonry domes were used to cover cisterns for water storage (Melaragno, 1991: 14-15).

Domes are convex roofs that are categorized according to their base and profile shapes through the center of the dome. For instance, a hemispherical dome has a circular base and a semicircular section. This is a distinct type for Renaissance Architecture and Baroque, Neo-Renaissance and Neoclassical period domes (Shalunts, Haxhimusa, and Sablatnig, 2012). Domical roofs over churches, baptisteries, and tombs were significant elements in Byzantine architecture. Byzantine domes were built over square bases and became circular through pendentives, contrary to Roman domes, which were built over circular or polygonal structures. In addition, byzantine domes were generally built over high drums to exposed domes directly to view. Byzantine construction was commonly based on brick, with thick mortar application. The mortar was consist of lime, sand mixed with crushed bricks, and tile and pottery fragments. Interior surfaces were generally covered with marble plates, mosaics, or frescoes.

The historical development of the domes split into two currents with the advent of Islamic architecture. The western tradition that progressed along its original direction throughout Europe; and an eastern adjustment of western models used by the new Islamic culture searching out its symbolic expression (Melaragno, 1991: 41-42). In the Seljuk period, by the end of the 11th century, Islamic architecture first produced simple mosques that showed architectural improvements, such as domes to cover large spans. Structures like caravanserais and mosques with minarets were emerged in Islamic architecture (Köseoğlu, 2011). The use of the Muslim dome spread throughout Asia and North Africa after expanding the Islamic faith. Although the basic underlying concept was the same, several specific Islamic dome types characterize the many local influences on the dome structure. For example, Egyptian and Persian domes are more pointed than others. Turkish domes are mostly hemispherical; Indian ones are usually covered with marble sheeting. Persian domes are generally covered with polychrome ceramic tiles, as well as Iraq.

In the Ottoman period, Mimar Sinan (1489 -1587) significantly contributed to Islamic Dome architecture. The magnificent mosques of Mimar Sinan fully exalted the symbolic value of the Ottoman dome. The source of inspiration for Mimar Sinan's dome architecture was undoubtedly the Hagia Sophia in Istanbul. His first masterpiece was the Sehzade Mosque in Istanbul, a composition of four domes crowning the mosque's central dome. Unlike the melon shape typical of common mosques, these domes had a fully spherical profile. Selimiye Mosque in Edirne is crowned with a 31,3 m diameter dome supported by an octagonal base vertically and eight buttress towers laterally connected to the dome by pillar arches. Sinan used pendentives and squinches as transition elements to connect polygonal supports with a circular dome base. At the same time, he counteracted horizontal thrust with buttresses and pillar towers in various designs. The products of Ottoman architecture are rich in detailing and grandiosity of expression, primarily via their domes. Today, domes of the Islamic tradition in vernacular architecture are still building by local masons throughout North Africa and the Middle East. These masons use practical guidelines passed down from father to son or master to apprentice to build domes (Melaragno, 1991: 36-38).
Domes have been the preferred structures for large unobstructed areas (Saraç, 2005). Domes have been in use as a form of covering for various utilizations such as concert halls, stadiums, and water reservoirs. These days, domes are already an accepted form of enclosing element for dance halls, skating rings, and warehouses. An American architect, Richard Buckminster Fuller, invented a new dome type called a geodesic dome. This invention brought the attention of architects and engineers to this efficient dome structure. The large spans that can be covered with braced domes always sparked the imagination of architects. Several large exhibition buildings were covered by the different types of a dome in the past (Makowski, 1984: 68-74).

### 2.2.2. Types of domes

Throughout history, various types of domes have been built to cover structures. Geometric evolution of the domes strongly related to the available technology of the time, as well as the need for large-span spaces and architecturally visual impact of them. There are many different types of domes that have been built since ancient times. This study will cover the most common types to explain domes better. These are corbelled or beehive dome, braced dome, compound dome, geodesic dome, hemispherical dome, onion dome, oval dome, parabolic dome, sail dome, saucer dome, and umbrella dome (URL-9) explained as follows;

Corbel dome

Corbelling is one of the oldest masonry dome techniques used before developing the true dome construction method for roofing spaces (Lazar, Kadane, Chen, Cavanagh, and Litton, 2004). Corbelled domes, also knowns as beehive domes, and have a similar concept with the false arches. Both of the construction techniques are based on horizontal dry brick or stone layers slightly cantilevering or corbelling on top of each other towards the midpoint of the dome, see Figure 2.9 (Fraddosio, Lepore, and Piccioni, 2019). The construction method for this type of dome does not require center supports. The horizontal joints reduce the load-carrying capacity of the dome (Melaragno, 1991: 20-21). This technique primarily for narrow distances, maximum 2 to 3 meters, with a slight slope. Archeologists have found some examples of corbelled domes spanning 8 to 14 meters in Mycenae, Greece (Lazar et al., 2004). To achieve a larger span, the center of gravity has to move outward by putting more weight on the outside extension of the stones, as in the example of Treasury of Atreus, see Figure 2.10 (URL-16). Corbelled dome conceived as false-dome from an architectural point of view since it is the 3D extension of the false-arch concept. This type of dome is considered a composition of independent strings of false arches that transfer forces between sequential strings of stones or bricks through a vertical axis (Fraddosio et al., 2019). This methodology is known as Corbelling Theory that explains the structural behavior of the domes (Snijders, 2020). Corbelling method has significant importance that illustrates the starting point of the evolution of the other dome types and vaults constructing techniques (Melaragno, 1991:20-21).

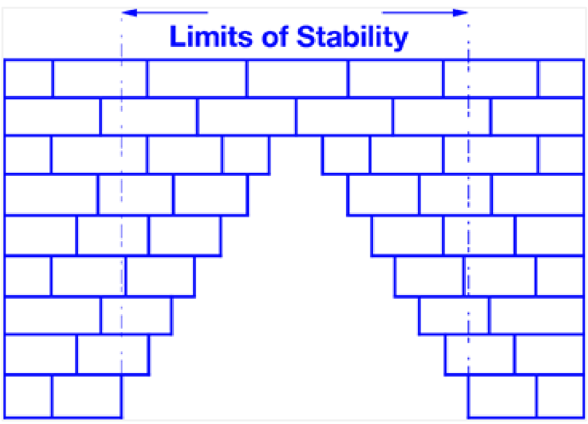



Figure 2.9. Corbelling technique section illustration (URL-17).

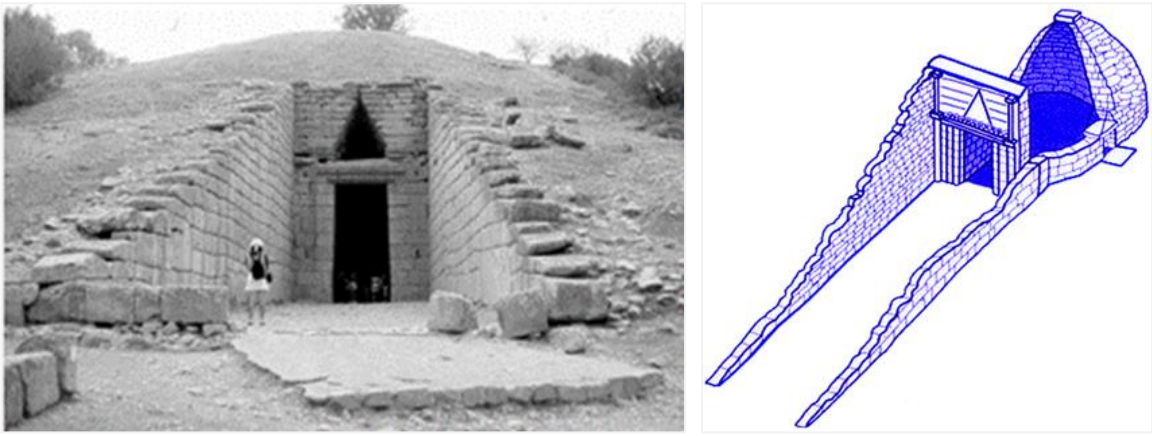


Figure 2.10. Tresaury of Atreus; the entrance (left) (Como, 2006), the axonometric illustration (right) (URL-18).

<u>Onion dome</u>

The onion dome, also known as a bulbous dome, is an onion shape structure that tapers smoothly to a point. Onion domes are usually associated with Russian Orthodox churches, church towers, and Islamic Mosques. They are mostly found in eastern architecture; in Russia, Turkey, Middle East, and India. This type of dome became popular in the late 15th century in Northern Europe, inspired by Islamic Architecture by the finials of the minarets in Syria and Egypt (Born, 1944). However, some resources claim that according to the analysis of historians about Russian art and architecture, the onion dome typology existed in the 13th century in Russia before the Islamic architecture examples that belong 15th century (Block, 2010: 74-77).

This type of dome is bulge outs beyond the diameter of the drum that it is set upon, and mostly the height exceeds with a pointed top that creates an ogee profile that larger than a hemisphere and resembles an onion which is named after, see Figure 2.11 (Born, 1944). Onion domes mostly have a circular or polygonal base. European architecture examples are typically wooden, whereas Islamic architecture examples are mostly made of masonry with thick and large buttresses. The Saint Basil's Cathedral in Moscow and the Taj Mahal in India is some of the most famous examples of this type, see Figure 2.12 (Shalunts et al., 2012).

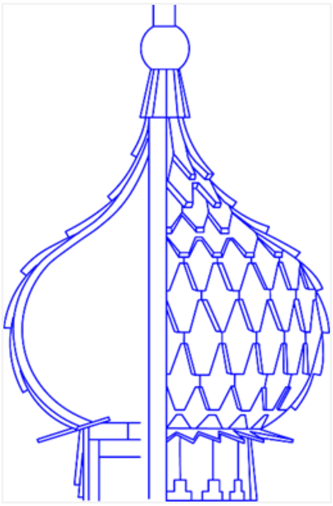


Figure 2.11. Onion dome profile, adapted from (URL-19).

Figure 2.12. The Saint Basil's Cathedral (Left) (URL-20), Taj Mahal (Right) (URL-21).

Oval dome

An oval dome is a type of dome with an oval plan or section or both in some cases. This type of dome resembles an egg shape. This geometry was started used by the ancient builders to enclosing spaces simply and economically. First, the oval shape is defined by circular arcs with common tangents at the points of change of curvature. Then, it reached a more proper form with two axes of symmetry. The oval enclosures were first covered by the masonry corbelling method in about 4000 B.C.  An oval dome has more complex geometry than the usual circular dome with a central vertical axis of symmetry. The most common ways to generate a dome surface are rotation and translation. When it comes to the oval dome surface, the relationship between the two axes of the plan, height, span, and profile, must have taken into consideration as well (Huerta, 2007). The largest oval dome has built Sanctuary of Vicoforte by Francesco Gallo, see Figure 2.13 (Aoki, Chiorino, and Roccati, 2003).

Figure 2.13. Sanctuary of Vicoforte; entrance (left) (URL-22), top view (Right) (URL-23).

Saucer dome

A saucer dome, also called a segmental dome, is a low-pitched shallow dome that geometrically has a circular base, segmental section, and less than a semicircle profile. These domes are strong since their structure helps to reduce the tension portion of the dome. Usually, the largest domes built and most of the non-masonry mosque domes in India, Pakistan, Iran, and Afghanistan are saucer domes (Uçak, 2012). This type of dome has popularity dates back to the 18$^{th}$ century. These domes are usually ornamented with plaster-work internally. Vienna Islamic Center can be an example of this type; see Figure 2.14 (Shalunts et al., 2012).

Figure 2.14. The saucer dome of Vienna Islamic Center (URL-24).

Umbrella dome

Umbrella dome, also named pumpkin, melon, scalloped, or parachute dome, is a type of dome divided by ribs radially arrayed from the center of the dome to the base. The construction material between ribs arches from one another transfers the force downward. The central dome of St. Peter's Basilica, (see Figure 2.15), uses this method by allowing a ring of windows to be placed between the ribs at the dome base (Uçak, 2012).

Figure 2.15. St. Peter's Basilica; exterior (left) (URL-25), the central dome of St. Peter's Basilica, adapted from (right) (Mainstone, 1999).

Rotational domes: paraboloid dome and hemispherical dome

Rotational domes are surfaces generated by rotating a meridian curve around a vertical axis. Various forms can be obtained by rotating a circular arch; a parabola makes paraboloid, a semicircle makes hemispherical dome surface (see Figure 2.16). Since their horizontal sections are all circles, these are often called rotational domes. The primary stress in a paraboloid dome is compression, both radially and circumferentially. These domes are stiffer than hemispheric domes due to increasing curvature (Arun, 2006). In ancient times, paraboloid domes were widely in use before the advent of composite structures. Hemispherical domes were mostly preferred during Renaissance (Uçak, 2012).

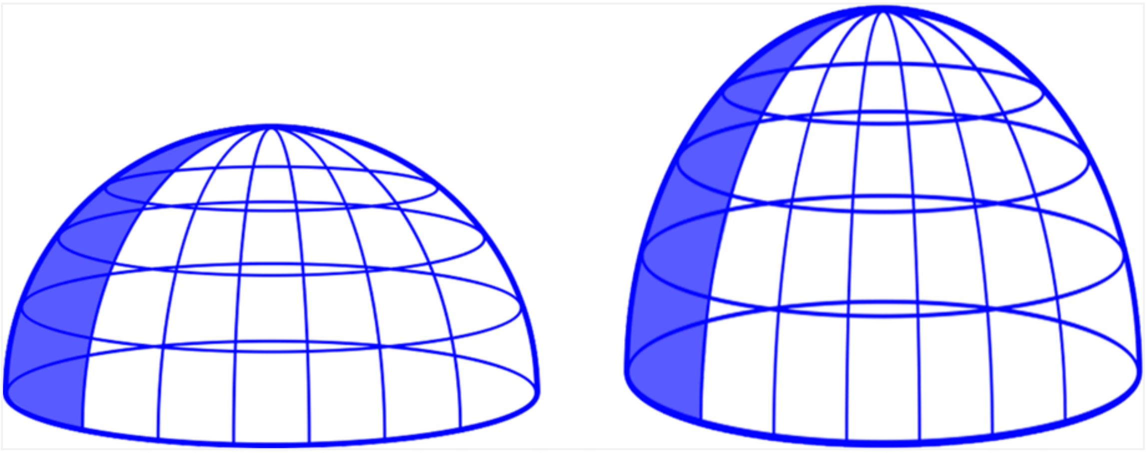


Figure 2.16. Hemispherical dome (Left), paraboloid dome (Right), adapted from (Arun, 2006).

<u>Sail dome</u>

Sail dome is also known as pendentive dome or Byzantine dome. This type of domes can be considered as pendentives that touch each other to form a circular base or a drum and continues the curve to form the dome itself (see Figure 2.17). Thus, the dome looks like a rectangular sail got down at each corner and generated the dome (Uçak, 2012).

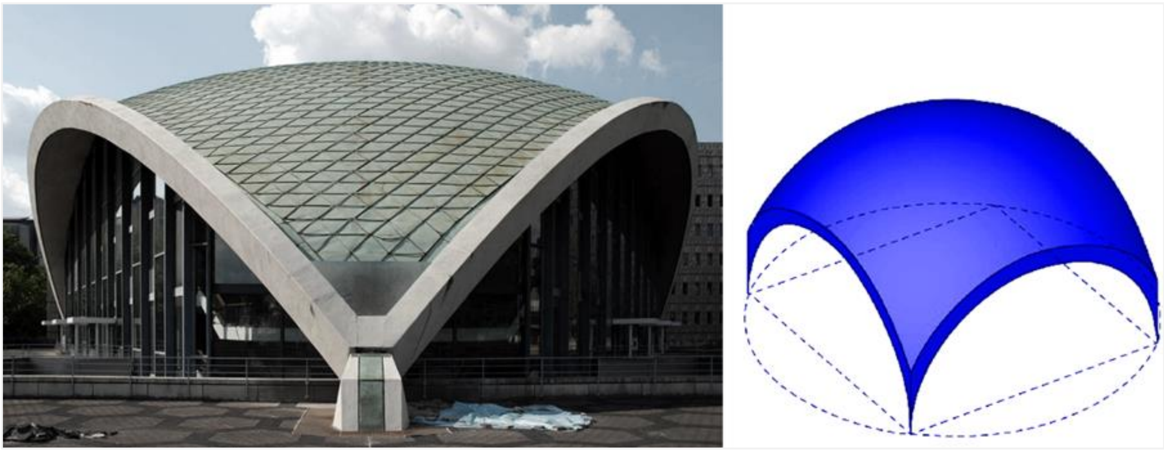


Figure 2.17. Dortmund Opera House (left) (URL-26), Sail Dome Illustration (right), adapted from (Arun, 2006).

<u>Compound dome</u>

Compound domes, also called pendentive domes, support a smaller dome above them, as in the example of Hagia Sophia (see Figure 2.18), or in many Renaissance domes). Since the arches or the dome-base structure supports the upper dome, the pendentive construction does not require a column and beam. Instead, this type of dome has a sphere form with the space underneath it, a rectangular or circular plan shape (Hassan, Mazloomi, & Omer, 2010). Thus, compound domes differentiate from simple domes, where the pendentives are part of the identical sphere as the actual dome (Denison and Glancey, 2018:34).

Figure 2.18. Hagia Sophia; interior view (left) (URL-27), pendentive illustration, adapted from (URL-28).

Polygonal dome

Polygonal domes, also called domical vaults, are the dome type that has a polygonal horizontal cross-section. The most famous example is the dome of Santa Maria del Fiore by Filippo Brunelleschi. Polygonal domes have a complex design created by the rotation of a quarter-circle (see Figure 2.19) around a vertical axis. Each masonry ring must be completed perfectly to build the dome without the use of a supporting structure. Brunelleschi used this method. The brick arrangement in the Santa Maria del Fiore dome is called herringbone, which illustrates a spiral profile (Uçak, 2012).

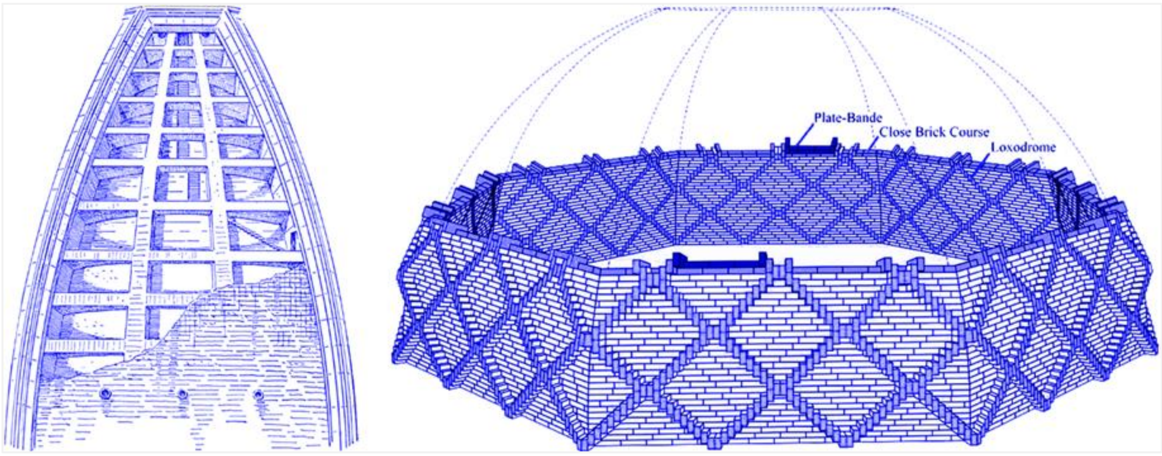



Figure 2.19. The quarter-circle of the Santa Maria del Fiore dome (Left) (URL-29), Herring-bone brick arrangement (Right) (URL-30).

Braced domes

Braced domes are practical, lightweight large-span applications constructed by the connection of single-layer slender members. Superdome structure in New Orleans is one of the most famous examples of this type of dome (see Figure 2.20). Braced domes are used for large spaces such as public halls, worship places, and other large spanned buildings (El-Sheikh, 2000). Steel, glass fiber, plastic, and aluminum are the common materials for braced domes. However, aluminum is the most preferred material since its lightweight and corrosion-resistant features. Braced domes can be classified according to the changing configurations of the connecting members. These are ribbed domes, Schwedler domes, lamella domes, two-, three-way, and four-way grid domes, and geodesic domes, see Figure 2.21 (Saraç, 2005). In this section, only ribbed and geodesic domes will be explained.

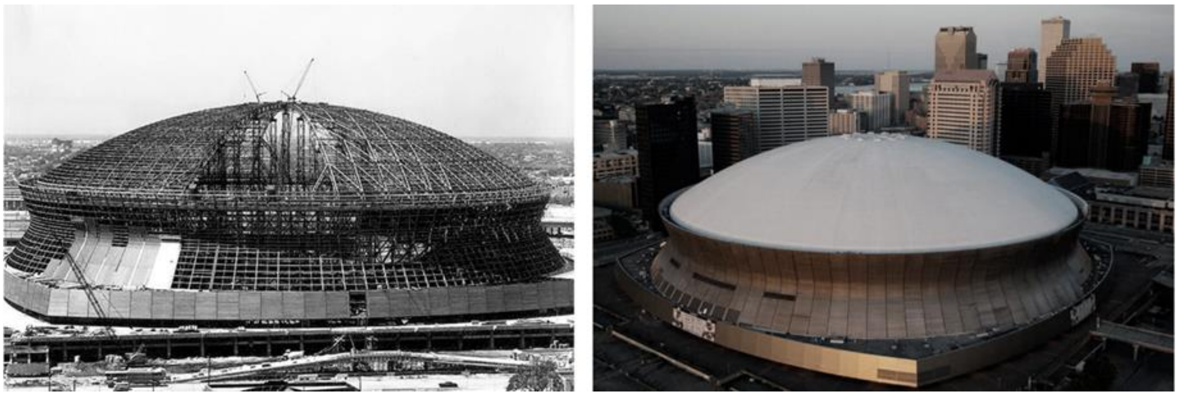


Figure 2.20. New Orleans Super Dome construction (left) (URL-31), Super Dome (Right) (URL-32).

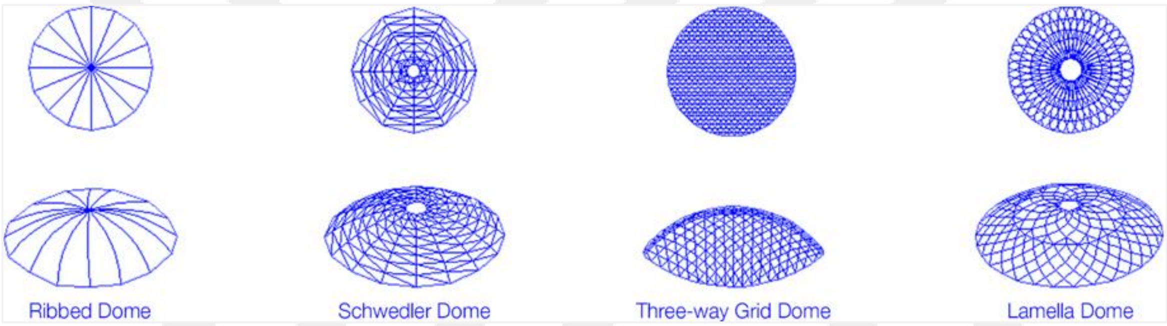



Figure 2.21. Types of braced domes, adapted from (URL-33).

Ribbed domes consist of intersecting rotating ribs (arches) and rings (horizontal element) to produce a star-like pattern. This star pattern is associated with the heavens in almost every architectural culture. Ribbed domes connect compression and tension rings. This type of dome requires a rigid joint system to be structurally stable. The entrance roof of Al-Hakam II of Cordoba-Mosque-Cathedral is a famous example of this type of dome, see Figure 2.22 (Sakkal, 1995).

Figure 2.22. The ribbed dome of Al-Hakam II (Cordoba Mosque-Cathedral) (URL-34).

The geodesic dome was invented by Richard Buckminster Fuller to create an economic structure and to enclose a maximum area with minimum material usage. Geodesic domes are composed of mapping polyhedron faces on a dome surface. They are light and robust skeleton structures. Geodesic domes commonly based on a connecting triangle since it is the most durable geometric shape. Aluminum is the most common material for this type of dome. This type of dome can also construct as a double-layer structure connecting two surfaces with bracing elements. Montreal Biosphere in Canada by R. Buckminster Fuller is a well-known example of a geodesic dome, see Figure 2.23 (Denison and Glancey, 2018:34).

Figure 2.23. Montreal Biosphere Dome by R. Buckminster Fuller (URL-35).

### 2.2.3. Construction methods of masonry domes

In prehistoric times, the primary aim of building a dome was to create a shelter to live underneath, to afford the bare minimum need for protecting and living for people. However, with the advent of civilization, the meaning of the dome and its building purposes has changed into obtaining grandiose spaces for sophisticated users such as religious buildings, palaces, or public buildings (Melaragno, 1991: 32-35). Nevertheless, the purpose of constructing a dome has always been to create large-spanned openings, as maximum as possible. That is why builders perpetually tried to overcome this problem with different techniques, which continuously evolved masonry dome construction methods (Cowan, 1977).

Masonry domes have gone through several methods over the centuries due to human knowledge and technological development. Architects first approached the design of such structures through proportion and geometrical construction rules that were mainly obtained by experience. Later, geometric variations are developed to increase the height and slope of the dome (Cavalagli and Gusella, 2015).

Figure 2.24. Three methods of the dome construction, adapted from (Ghasempourabadi, Mahmoudabadi Arani, Bahar, and Mahdavinejad, 2012).

Masonry domes have been built by three main methods, as shown in Figure 2.24, that each of them different in load-bearing capacities. The first method is called corbelling; bricks are horizontally oriented, and the upper row of brick cantilevers through the dome center, see Figure 2.25 (Ghasempourabadi et al., 2012). Corbelling is the most primitive and basic method for masonry. Projecting brick courses inwards have to be done correctly regarding the length of the brick unit. Distancing up to half of the length of the masonry unit can technically work. However, the units would tip and fall over the edge. Therefore, to reduce the tensile stress and ease the builder's installation phase, it is better not to cantilever a unit more than its height. For the stability of the structure, each brick course can be back weighted with masonry or earth, as in the example of Treasury of Atreus in Mycenae, Greece that explained in the section above (Allen and Zalewski, 2009: 216-228). The building process of the corbelled dome allows a self-supporting construction phase. The brick courses have to lay with care and a certain firmness as much as possible. The selected material type is an important parameter to create the firmness that combines the individual brick rings. It enables the structure to behave as one homogenous body (Rovero and Tonietti, 2012).

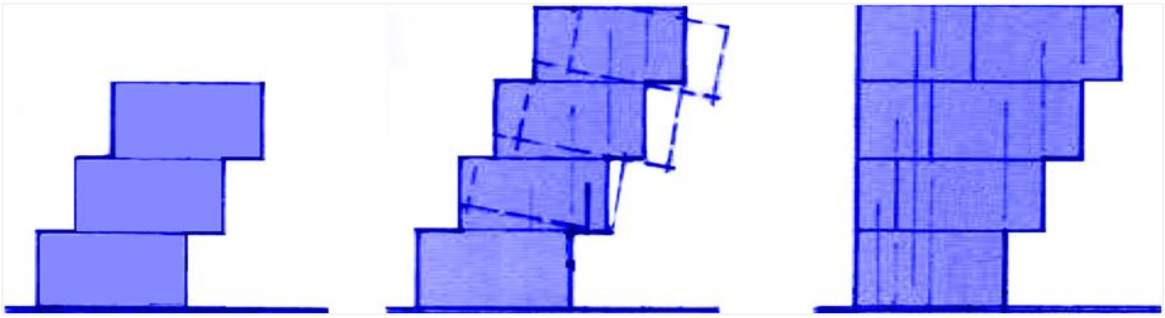


Figure 2.25. Corbelling technique, adapted from (Allen and Zalewski, 2009: 216).

The second method is masonry domes, also called a true dome. In this method, the direction of the bricks always follows the surface curvature of the dome (Ghasempourabadi et al., 2012). Masonry domes are created by masonry elements such as stones and bricks, which are pressure-operated. The loads are transmitted to the supports by compressive stress through the meridians. As a result of the static analyses carried out at the beginning of the 19th century, the horizontal tensile and compressive stresses on the dome's surface (along the parallels) and the regions of the vertical compressive stresses (along the meridians) were determined. According to that, the compression stress in the upper 1/3 and the tensile stress in the lower 2/3 emerges on the dome's surface. Due to the low tensile strength of the masonry materials, lateral supports are required to prevent the dome from exploding on the bottom (Savaşır, 2016). In conventional examples, domes are generally placed directly on the bearing walls. By this technique, the vertical loads are transferred through walls or pillars to the foundation. Suppose the supporting elements of the dome structure or the dome itself have architectural elements like windows or doors on them. In that case, the span between these elements is generally required to cover by arches to better balance and distribute the upper loads. The joints between the arches and the dome have to be inclined. The supporting system elements, the walls, and the piers, must have enough width to keep the emerging forces within their thickness (De Matteis, Cacace, and Rouhi, 2019).

Domes generally provide a covering for square or polygonal planned spaces. Therefore, transition elements adjust from the square to the circular, elliptical, or polygonal base of the dome. The dome construction starts by positioning the transition elements on weight-bearing supporting elements. These transition elements have many different forms, and each of them requires various mounting and installation methods. These elements are pendentives, tromp, and Turkish triangles (Drioueche-Djaalali and Chabbi-Chemrouk, 2017). A pendentive allows a dome to sit on a square or polygonal structure. It has a concave profile and converts the angle into a curve as it extends from the angled joint of the two walls (Denison and Glancey, 2018: 34). The geometrical design of the pendentives, which depends on the form of the cover rather than the structure, can take two forms; as a spherical triangle with the same diameter as the dome's diameter (Figure 2.26 (a)) or a spherical triangle with a spherical triangle circle diameter drawn outside to cover the square base (Figure 2.26 (b)). In the first case, the dome with the pendentive is a continuous surface. This form of cover is also called a sail vault. In the second case, the surface is separated from the pendentives. In a way, it becomes the pat of structural support elements (Kuban, 2016:47). The stability of the brick dome construction was ensured without centering by building ring by ring. One of the most crucial innovations in Byzantine time was the superimposition of a dome over a rectangular plan through transitioning elements (Reyhan, 2011).

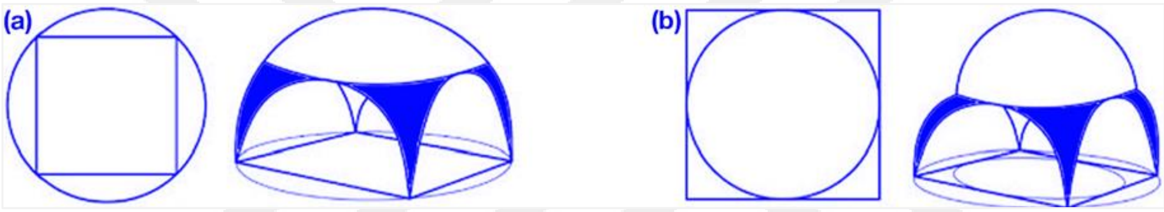



Figure 2.26. Dome transition element; pendentive, adapted from (Hasol, 1993: 388).

Tromp is a vault system constructed beside the central dome on a rectangular plan, see Figure 2.27 (a). It is mostly preferred in smaller spaces where height is more than the span distance. This transition element is also used decoratively, especially in the mosque architecture. Finally, the Turkish triangle is a transition element that is used both as structurally and decoratively, see Figure 2.27 (b). This element is used to connect the non-circular dome drum with its rectangular base (Kuban, 2016: 47-48).

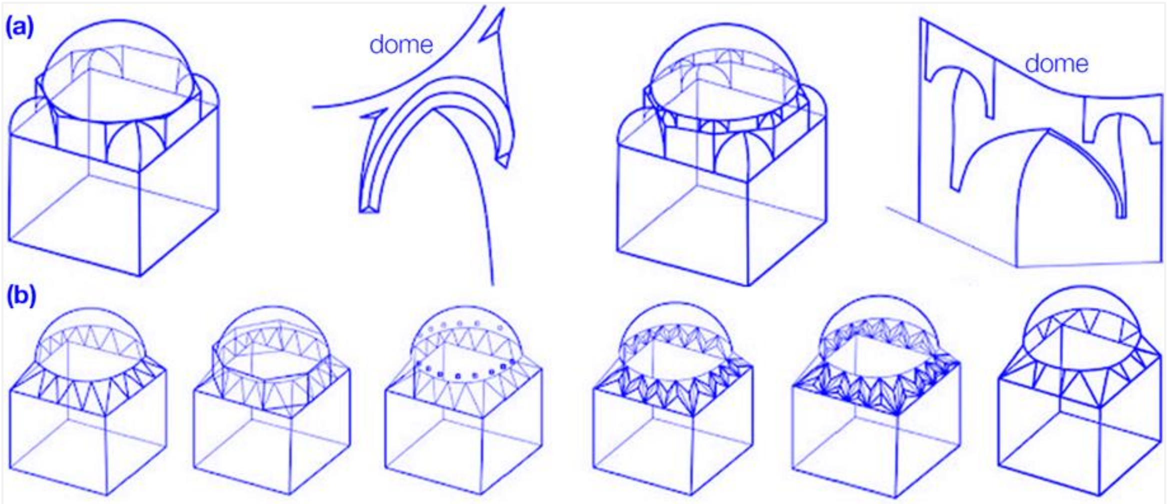



Figure 2.27. Dome transition elements; types of tromp (a), types of Turkish triangle (b), adapted from (Turan and Yaldiz, 2018).

Construction techniques of masonry domes were improved by increasing the quality of bricks, especially during production phases, and with various types and mortar usage. In addition, the invention of the Roman concrete also had an impact on changing construction techniques (Köseoğlu, 2011). The advent of Roman concrete provided relatively more straightforward construction of structural elements, especially for double curvature surfaces. Pantheon is the most important example that this material had used. The dome of Pantheon created on a set of horizontal and vertical ribs using bricks and Roman concrete. The builders poured the Roman concrete into the molds in the construction site and covered the distance between brick ribs. The bricks were placed as successive individual cyclic ribbons so that the joints of the successive layers formed a spherical dome (Penelis and Penelis, 2020:33).

In the third method, ribs are used as divider skeleton of the dome surface, and later the bricks are put between them to cover the dome (Ghasempourabadi et al., 2012). Two different elements create ribbed domes. The first one is a rib, and the other one is the filling materials that form the dome slice between the ribs. Filling materials transfer their weight and loads to the ribs. Therefore, the transferring loads are carried out to the bottom of the dome. Florence Cathedral is an excellent example of this method of construction. Construction of this dome is completed without center support to hold the structure the construction. Instead, two dome surfaces are created and held together by brick arches, and interlocking rings of stone and wood keep the dome from expanding outward (Beatini, Royer-Carfagni, and Tasora, 2019).

### 2.2.4. Historical examples of domes

This section covers three historically significant masonry dome examples to understand the masonry dome structures. These examples are selected according to the masonry construction techniques covered in the previous section.

Urfa Harran beehive domes

Harran is an ancient city in Turkey's southeast, which is known for interesting vernacular architecture. Harran beehive dome houses, which primary building material is mud brick. They are not seen in other parts of Anatolia; however, they are seen in Southern Italy, Cyprus, and Libya's Kufra and Fezzan regions. However, it is unknown how this distinctive beehive-shaped building style came to be. Some stone reliefs of Assyrians who controlled the area between 2500 and 600 BC show figures that resemble Harran homes. Additionally, the excavations in Mesopotamia, where many civilizations have flourished, show that conical domed building forms with a square frontcourt or room were used as early as the 7th century BC. It was difficult to find timber that could be used in buildings in Harran, a region with low rainfall and a dry climate. For this reason, people had to build their houses from materials such as adobe and stone. Harran houses were heat and cold-resistant structures and were built quickly like tents following the nomadic lifestyle.
Figure 2.28 (a) shows conical domes constructed on the ground like tents in a 19th-century picture of Harran. By the 20th century, all conical domes had been placed on cubic bases with a square plan, as seen in Figure 2.28. (b). At the end of the 20th century, rectangular rooms with earthen roofs were added to these (Bekleyen et al., 1998).

Figure 2.28. Urfa Harran Domes; in 19th century (Left) (Bekleyen et al., 1998), in 20th Century (Right) (Baran, 2006).

Today, a conical dome covers the square rooms of most homes. Each room, which serves as a living room, kitchen, cellar, or barn, has a dome. Interior doors or arches connect these rooms. Some rooms open to the courtyard with a small door. The kitchen also has a bathroom. New rooms can be added to the house as the family expands. Therefore, Harran houses are specific examples of the expandable house concept. Rooms are placed in one, two, or three rows on one side of the courtyard in the spatial arrangement of their houses. The rows are generally positioned on the east-west axis. The domes shade the solar radiation from the west, and cool spaces are obtained. Each conical dome has vents on the sides and a single hole at the top that acts as both a chimney and a vent. Small windows were opened on the sidewalls of the cubic plinth, facing both the courtyard and the street.

In summer, the hot air inside the building rises and is expelled from the upper hole. Thus, with continuous natural ventilation, cooler places are obtained compared to the extreme heat of summer. Due to the domed and cubic forms of the buildings, they have relatively lower exterior surface-to-volume ratios. Thus, with closed holes and windows, the building loses very little heat in winter. In addition, adobe walls with a thickness of 60-70 cm provide good thermal insulation. The conical dome is formed by sliding mud bricks or bricks inward in each row. These are burnt bricks, either sun-dried or collected from ancient remains. The thickness of the dome wall is approximately 30 cm. The tops of the domes were left open as chimneys, and the diameters and heights of the domes vary. They are 3-5 m high from the base and are usually plastered with mud from the outside in June every year. The stone protrusions on the sides of the domes were left to be used as scaffolding during plastering. Since all bricks are handmade, their sizes may vary. On average, brick dimensions are 24x24x4,5cm. Generally, a stone was used between the upper corners of the pedestal walls and the dome. Some of the bricks were obtained from the remains of old buildings. Some Harran homes even have stone carvings of ancient civilizations on their walls. For bonding stones and bricks, only mud mortar was utilized. Sand and lime were never used, and straw was only added to the mud during the processing phase (Bekleyen et al., 1998).

The Pantheon

The Pantheon is one of the most important architectural monuments of time from antiquity to the present. It was completed in Emperor Hadrian period in Rome in AD (120-125). It is a structure originally built as a temple for all the Ancient Roman gods. This monumental building, which has always been used throughout history, is the best-preserved Roman structure. Although the design of the present-day building is usually attributed to Trajan's architect Apollodorus of Damascus, it is more likely to belong to Emperor Hadrian or his architects (Marder & Jones, 2015: 49-54).

The dome of the Pantheon is the most important of those constructed before scientific engineering and architecture. The dome was perfectly designed and built using materials such as Roman concrete and all the known and time-empirical techniques of vault statics. A vertical cylinder containing a sphere constitutes its volumetric composition, (see Figure 2.29 (a)). The cylinder is one-third of its height above the sphere's equator. The hemispherical dome was created using only half of the sphere's surface area. Although the extension of the cylindrical body above the equator of the sphere minimizes the external dominance of the dome, it is mainly for structural reasons. Structurally, the weight and mass of the elongated portion of the cylinder act as a tension ring to counteract the horizontal thrust under the dome. Although the visually enlarged cylinder hides part of the dome, the inner surface of the dome is the essential indicator of magnificence, (see Figure 2.29 (b)). A theoretical sphere that could be placed in the cylindrical body of the Pantheon would be 43,5 m in diameter. At the same time, the diameter of this sphere is the diameter of a cylinder equal to its diameter at the base of the dome and the height of the top of the dome from the ground. Among the materials used for the Pantheon are tuff and pozzolan, which are known for their lightness and are abundant in the region between Rome and Naples. Particularly important in the Pantheon dome is relieving the horizontal pressure at the base of the dome. This lightening was accomplished by removing some of the materials within the thickness of the dome and forming the crates. The oculus, a central opening at the top, measures 2,7 m in diameter, were architectural elements that also contributed to the weight reduction of the dome. Oculus is also the only effective lighting source (Melaragno, 1991:29-30).

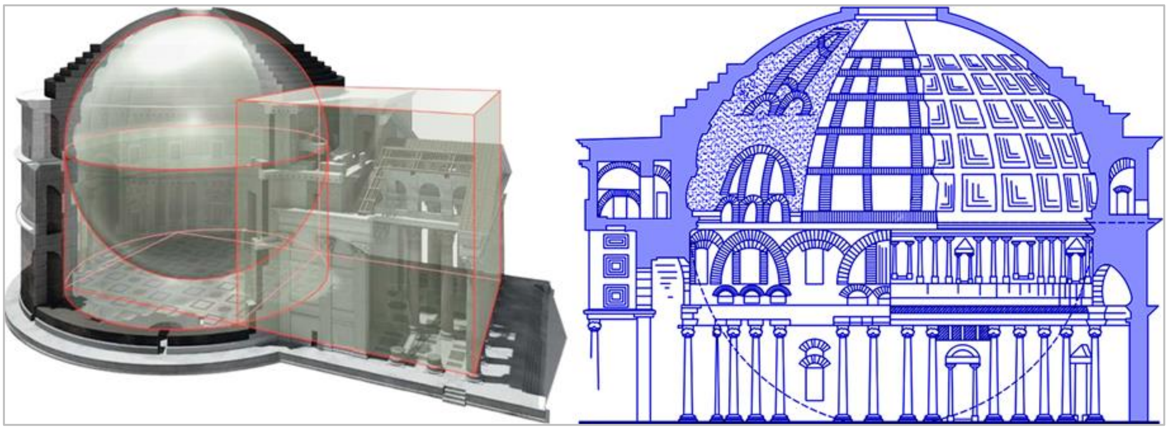


Figure 2.29. Volumetric composition of Pantheon (Left) (Marder and Jones, 2015: 175), Section of the structure that shows its construction (Right), adapted from (Ortega-Andrade, 1995).

The dome sits on eight vaults rising from the base. The walls under these vaults act as a vertical buttress around the dome. In addition, it is necessary to support the high walls of the building. The fact that the walls are placed under the dome is one of the factors that ensure the tectonic quality of the building. The walls provide articulated spaces and niches as well as absorbing the dome's horizontal forces. It can be said that during the design of the Pantheon, the structural guidelines regarding the span of the masonry domes and the height of the masonry walls were not followed (Hurol, 2015: 87-88).

Hagia Sophia

Hagia Sophia is the monumental cathedral in the old city center of Istanbul (see Figure 2.30). The word Aya in the name of Hagia Sophia means holy or saint. The word Sofia comes from the Ancient Greek word sophos, meaning wisdom. Therefore, the name Hagia Sophia means holy wisdom or divine wisdom and is considered one of the three attributes of God in Orthodoxy. This basilica planned patriarchal structure was built by the architects Anthemius of Tralles and Isidorus of Miletus under the Byzantine Emperor Justinian I period (A.D. 532 - 537). First, the original church was built by Constantine in 335 and rebuilt by Theodosius II in 415. It was converted into a mosque by Fatih Sultan Mehmed after the conquest of Istanbul by the Ottomans in 1453 (URL-36). The dome dominates the entire space with its 32,5 m diameter and 51 m height above the floor level at the crown. The dome at the center of the church covers a square floor area, from the corners of which four large pillars extend vertically. Each pillar has a cross-section of 7,5 m by 18 m. Four semicircular arches, on top of them, connect the pillars to constitute supports for the dome. These create four pendentives 18 m high that make a transition from the square floor plan to the circular base of the dome. The height of the dome from its base to its top is 15 m. The dome is hemispherical, as observed from the inside, since its diameter is 32,5 m. On the outside, a ring has 40 windows encircles the base of the dome.

The dome of Hagia Sophia was built of brick masonry laid in courses that progressively inclined beds do not radiate from the center of the dome but had a lower slope. The thickness of 70 cm is achieved with square bricks in the lower part of the dome. Each brick is 70 by 70 cm and 5 cm thick, laid down with mortar joints of around the same thickness. The dome's upper portion, which is 61 cm thick, comprises square bricks measuring 61 by 61 cm and having a depth of 5 cm. They form a wall 61 cm thick when the bricks are laid down flat. These numbers for dome thickness contrast extraordinarily with the thickness of the Roman domes that predated St. Sophia, highlighting the increased efficiency of Byzantine building technology (Melaragno, 1991:36-38).

Figure 2.30. Exterior of the Hagia Sophia (South) (Schibille, 2016:49).

### 2.3. Parametrically Designed Dome Examples

In this section, domes that are built through parametric design tools will be examined, disregarding the type of the dome structure. The spread of digital design and manufacturing tools allows architects and engineers to create innovative designs.

Arbor Arena

Arbor Arena is a geodesic dome pavilion constructed in Brazil. The design is based on parametric design methods through computational algorithms. The design has been inspired by a tree as representative of life. The dome pavilion is composed of woodwork triangular panels supported by steel frames, see Figure 2.31 (URL-40). The dome pavilion was designed by dividing the hemispherical dome surface into triangles. An opening on top is placed to allow light to the interior.

Figure 2.31. Arbor Arena exterior view (Left), Interior view (Right) (URL-37).

Project Egg

Project Egg is a pavilion composed of 4760 uniquely formed stones, which are 3D printed by the Studio Michiel van der Kley. The pavilion has an egg-like shape has double curvature surface, see Figure 2.32. The surface is divided into segments, and each unit is printed individually. The material is PLA, which is a type of re-usable plastic (URL-38).

Figure 2.32. Project EGG exterior view (Left), interior view (Right) (URL-38).

<u>Louvre Abu Dhabi</u>

Louvre Abu Dhabi (see Figure 2.33) was built on the artificial island of Saadiyat, with its most innovative, challenging, and parametrically designed project in recent times. This building, a joint product of traditional design and modern construction techniques, makes its visitors experience the changing relationship among the sun, sea, dome, and buildings.

Figure 2.33. Louvre Museum in Abu Dhabi; exterior (left), the roof (right) (URL-39).

The museum's architecture includes multiple display pavilions connected by an open-air circulation system and surrounded by water. The organization of the pavilions resembles a local Arabian urban morphology. A large and circular dome covers these pavilions and pools. The dome is constructed with steel space-frames and wrapped on two sides with over 8700 aluminum façade units named Arabian stars (see Figure 2.33). The cladding of the dome’s space frame consists of eight layers. All of the layers consist of stars organized in a bidirectional grid. The diameter of the dome is 165 meters and is 26 meters high, with a structural depth of 5 meters—the four columns, arranged in a square, support the dome. The pattern of the dome’s cover is not water-tight. However, it adjust the sunlight into a beam of light that is brighter on the roofs and darker on the circulation areas and pools. Thus, the dome creates an intriguing play of light and shadow and a comfortable outdoor environment. In summary, parametric design has been used to create, develop, and test the light-modulated geometry of the elements to generate data for the digital fabrication and assembly of the pavements of this museum, which was awarded with many awards (URL-39).

# 3. CASE STUDY: THE INTERLOCKING BRICK DOME

Despite the long history of brick and masonry in the built environment, the possibilities for application in design are often limited. Digital technologies can therefore help develop proper masonry methods to meet contemporary design requirements and integrate new geometric possibilities (Afsari, Swarts, and Gentry, 2014). Furthermore, with the advent of digital architectural design and production tools, it is viable to regenerate one of architecture’s most traditional material systems - brick masonry. Historically, architects and builders utilized brick specials to achieve more complex geometries within brick architecture due to 3D printing technology, which has become increasingly advanced and has made its way into architecture (Lange and Holohan, 2019).

There are specific parameters to create a geometry with parametric design tools. In this study, Rhinoceros 6 and Grasshopper software had been used to generate the parametric codes to obtain the interlocking dome structure. In order to substantiate examine the hypothesis of this study, this section will first cover the design process of the corbel, masonry, and interlocking dome structure starting from the dome surface to the result; later will continue with the production and installation section.

<u>The surface: hemispherical dome surface</u>

A *dome* is a surface that has curvature in two directions. To create a dome surface on Grasshopper, first, the changing parameters have to be determined. The center point of the base geometry, a vertical axis in the Z direction from the center point, and an arc on the XZ plane are the dome's parameters. Dimension of these parameters is inputted as well. This study is based on a hemispherical dome surface with an opening on top called *an oculus*. Oculus will be created in the following steps of the design. The determined radius for the studied dome is 1,5 meters. Since it is a hemispherical dome, the height is also 1,5 meters.

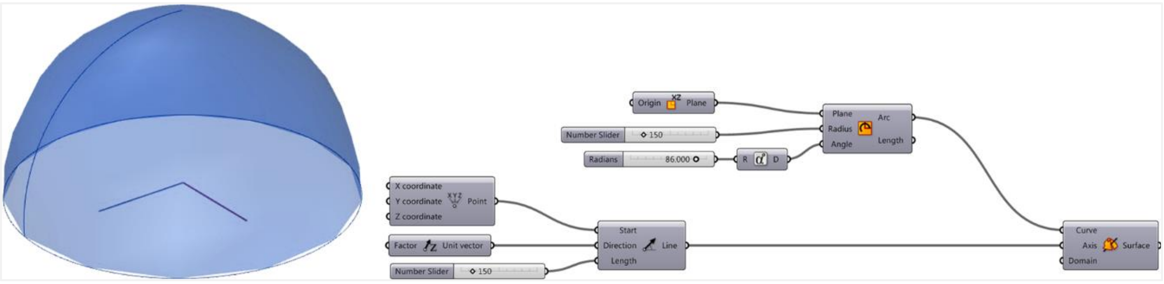



Figure 3.1. The hemispherical dome surface and the Grasshopper code for to construct dome surface.

The code above shows that there are two main parameters to create the dome surface. The first one is the vertical axis, and the second one is the arc that rotates around the axis. The result is the perfect hemispherical dome surface, see Figure 3.1. Before modeling the masonry dome, the other structural element has to be created, a brick. The determined brick is solid, and its dimensions are 20x10x5cm—this brick type is called *Standard* (Brick Industry Association, 2009).

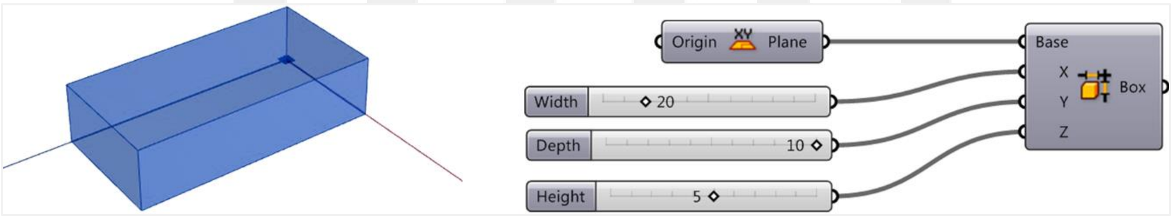



Figure 3.2. The *Standard* brick and the Grasshopper code for to construct the brick.

The brick has three defining parameters (see Figure 3.2): length, width, and depth. The box component was created on an XY plane regarding the dimensions of the brick. This brick will be the main geometry for the following sections to construct traditional masonry techniques on Grasshopper.

Modelling traditional masonry techniques on Grasshopper

Main constructing masonry dome techniques have explained in the previous sections above. Before designing the interlocking brick dome, the traditional masonry methods have modeled on Grasshopper to understand the geometry behind the structure. In addition, one of the aims of this study is to compare conventional masonry techniques with contemporary design methods regarding the calculation and design process.

*Corbelling* is a false dome method based on piling bricks horizontally cantilevering on top of each other through the center point. This exact configuration is created on Grasshopper by including the scripts for the dome surface and the brick illustrated above. First, the surface is divided into contour lines and dispatched into two clusters. Next, horizontal frames are placed on contour lines for bricks to later orient on the XY plane. Since the corbelling technique is convenient for using the exact size of bricks, the script below is written accordingly (see Figure 3.3).

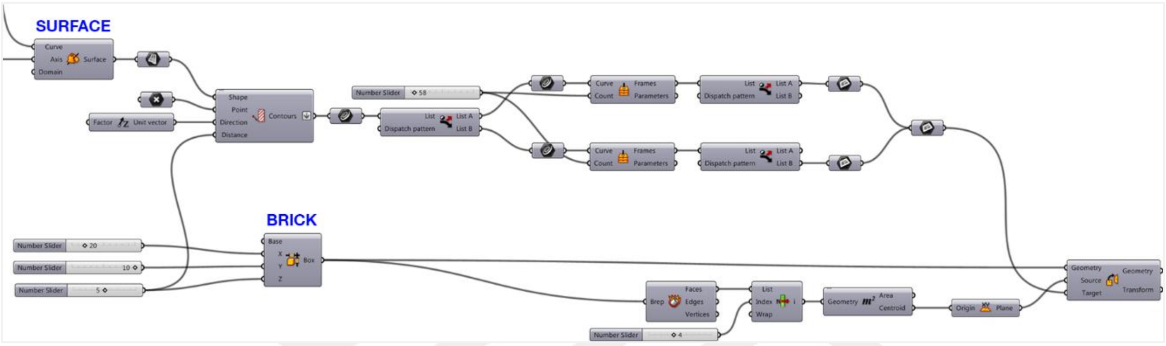



Figure 3.3. Corbel dome Grasshopper script.

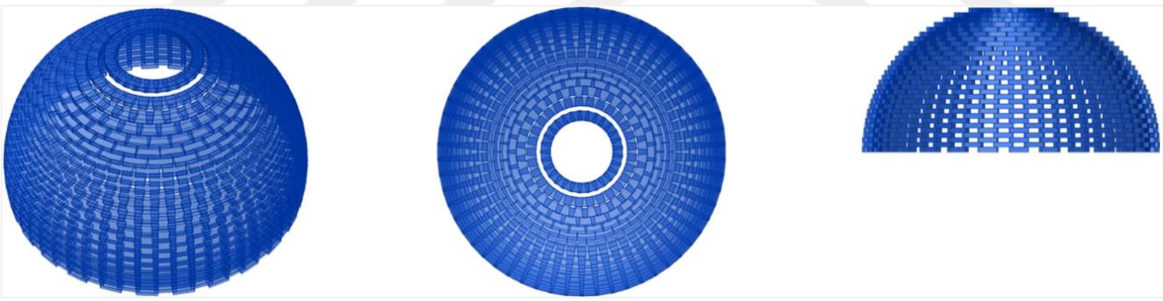


Figure 3.4. Corbel dome Grasshopper model; front, top, side (Left to Right).

As shown in Figure 3.4, the modeled dome is not correctly working to obtain a successful corbel dome. The brick corbelling pattern is distorted where the compression ring starts with horizontally intersecting bricks and vertically corbelling the bricks on top of the dome. The diameter of the dome (3m), size of the bricks are the main factors of this result. In order to avoid that, an oculus has opened on top of the dome by reducing the arc component's angle. As a result, the oculus level is 130cm above the ground. By changing only one parameter, the corbelling technique was appropriately completed, see Figure 3.5.

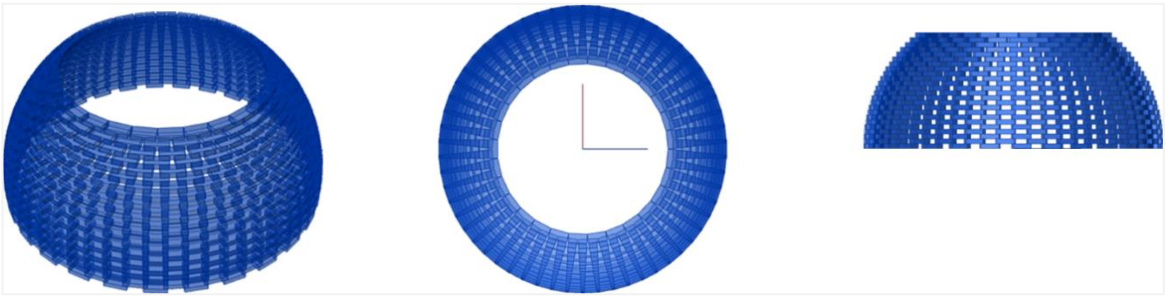


Figure 3.5. Corbel dome with and oculus (Left), cantilevering bricks on top of each other (Middle), piling bricks on XY plane (Right)

Domes are double curvature surfaces that optimize the distribution of material and forces that are carried axially. Brick masonry domes are one of the most common types to encounter in conventional architecture. This technique differentiates from the corbelling method by the orientation of the bricks. However, the same code for corbel cannot be used by articulating a brick's position (see Figure 3.6 and Figure 3.7). In the masonry technique, bricks stand vertically and follow the tangent of the dome surface (see Figure 3.8). To obtain that, the first element that has to be considered is the dome surface itself. Dividing the surface regarding the brick size would give the required solution.

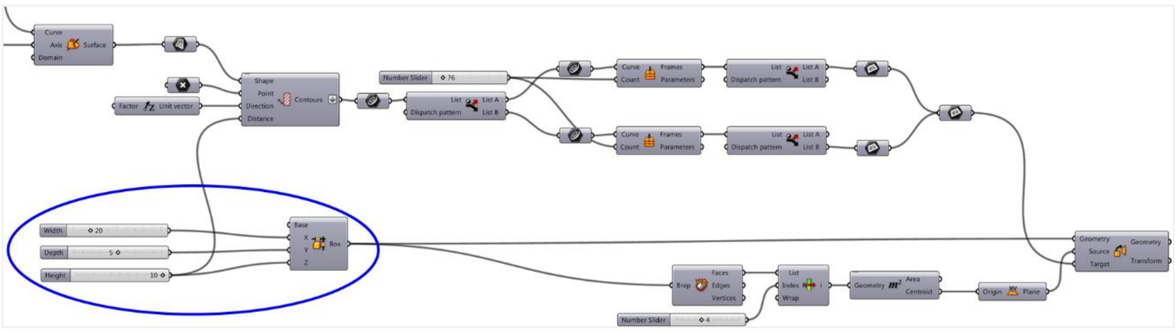



Figure 3.6. Vertical brick orientation; code failure for true dome.

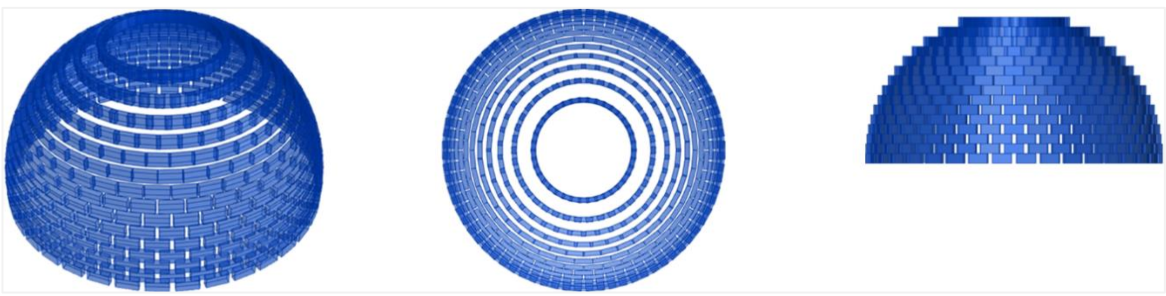


Figure 3.7. Vertical brick orientation; code failure for true dome model

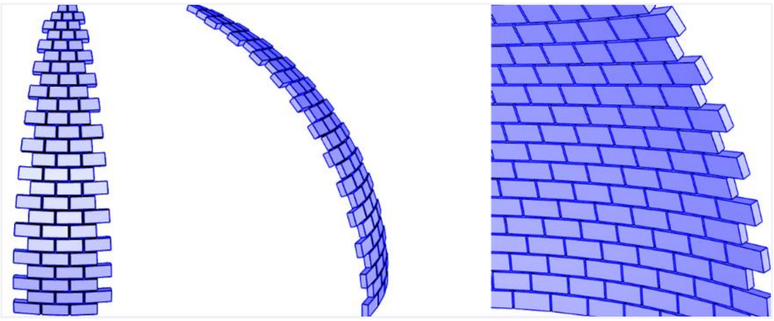


Figure 3.8. Brick configuration along the dome surface.

The largest brick size locates on the bottom ring can provide necessary information for U and V counts. The radius of this dome is 150 cm, and the height 10 cm, and the width 20 cm of the brick. V count stands for the Z direction, so the V count has to be 15. Calculation of U count based on the base geometry of the dome. Dividing the base circle into the width of the unit brick gives the result for the number of points. Point number gives the number of the segments, which is the input for the U count, see Figure 3.9.

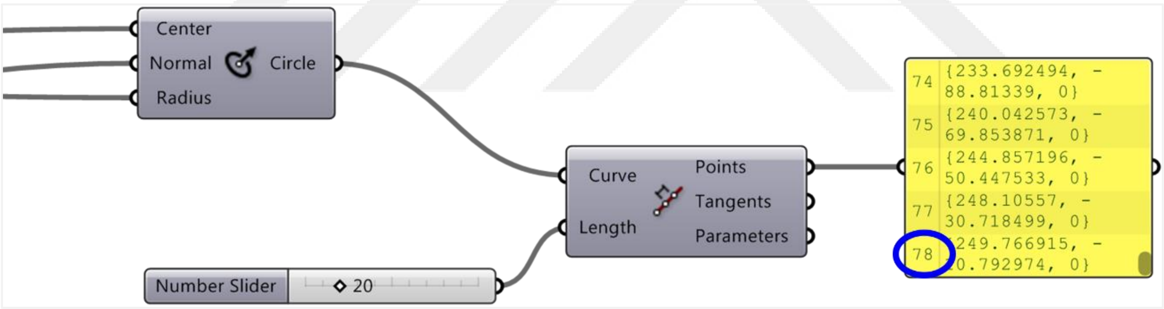



Figure 3.9. Calculation of the U count.

In the script in Figure 3.10, the surface is divided into rectangular areas representing the unit brick geometry profile. This division could have done by using contour lines, dividing them into a certain number of points, and connecting them along the surface. However, digital platforms are in use to make modeling easier. That is why the Parakeet plug-in has been used to divide the surface, which completes the exact steps within itself. The brick joints have 1 cm distancing from each other for the mortar application. The brick masonry dome is illustrated in Figure 3.11.

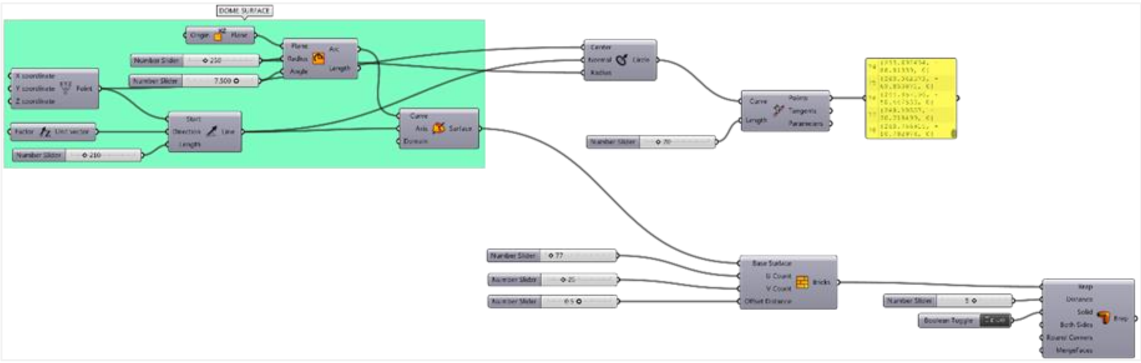


Figure 3.10. Brick masonry dome Grasshopper script.

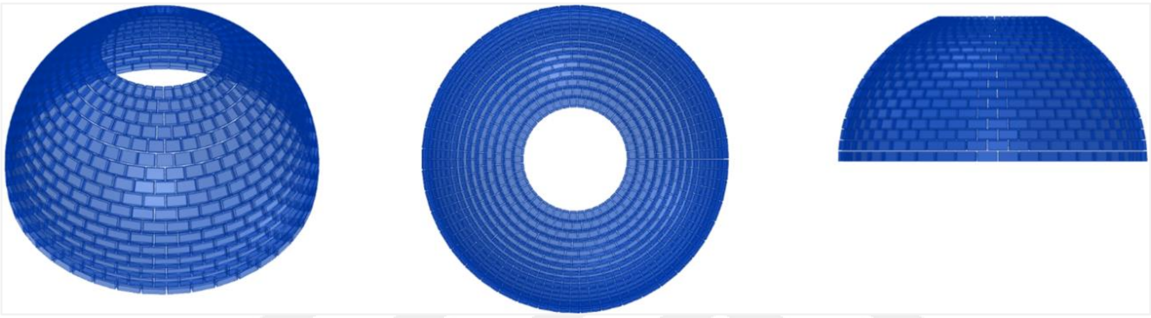


Figure 3.11. Model of brick masonry dome.

Many masonry bricklaying methods have been used throughout history. This study covered the most known examples, which are modeled above on Grasshopper. The process of constructing these techniques on Grasshopper contributed to developing the design process of the interlocking brick dome, seeing the evolution, and interpreting the possible future construction techniques of the domes.

Design process: interlocking brick dome design

Most of the brick types are rectangular and generally require adhesives to bonding. Therefore, especially to achieve large spans for dome structures, an adhesive is an indispensable element. The related examples have been observed in conventional masonry methods covered in the previous section of this study.

One of the aims of this study is to design a masonry method that can form a dome without the need for mortar or its derivatives. An interlocking system that resembles previous masonry techniques has developed to accomplish this purpose. However, there are specific difficulties to overcome since the dome surface has double curvature. That is why the interlocking system had to be 3-jointed to prevent the structure from collapsing.

The first step is to form a finding that interlocks each other. The design process starts by investigating interlocking grid patterns and continues by deforming the rectangular brick form.

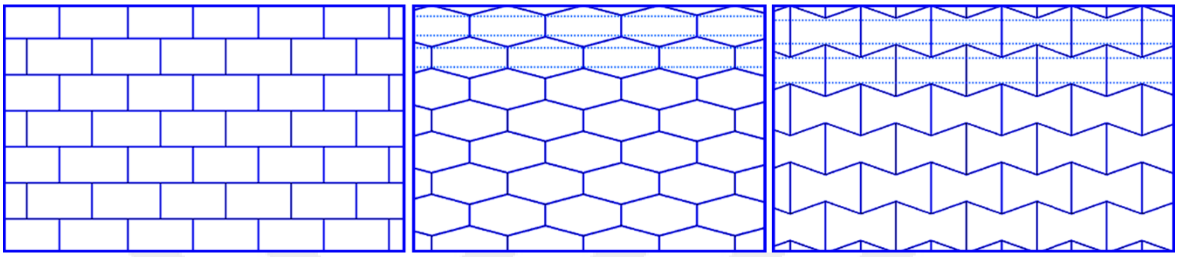


Figure 3.12. Deforming rectangular grids into interlocking forms.

The grid examples are shown in Figure 3.12 interlock with each other in 2D. Turning these grids into brick units that dry bonds might have worked for a flat, low-rise surface. However, in the case of a dome surface piling, those bricks without mortar cannot work structurally (see Figure 3.13). For this reason, there should be another detail on the brick that holds them together both meridional and latitudinal directions.

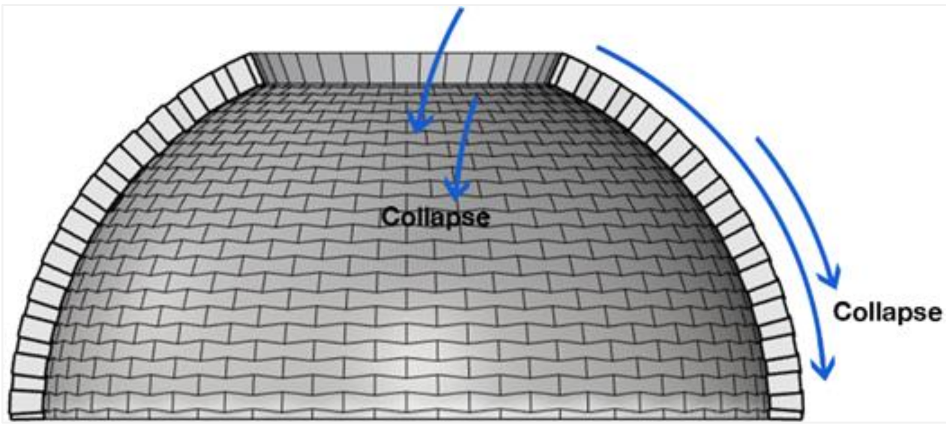



Figure 3.13. Grid to brick unit for dome surface.

The designed unit is based on the determined brick geometry. The units are obtained by morphing the rectangular form by pushing the brick joints inwards (see Figure 3.14 (b)). Morphing the geometry creates an interconnection between adjacent units in the horizontal direction. The following steps are shown in Figure 3.14 (c), (d), and (e). To increase the effectiveness and to balance the compression forces of the geometry, another articulation has been done by stretching the back of the form vertically (see Figure 3.14 (f)). This process has been completed on Rhinoceros to be precise about the dimensions and the design ratio of the brick. The designed brick form generates a new configuration of integration. Each unit's depth decreases as they reach the top of the dome (see Figure 3.15). This is beneficial to lower the weight load of the units on top of the structure, which is an essential factor for a dome structure.

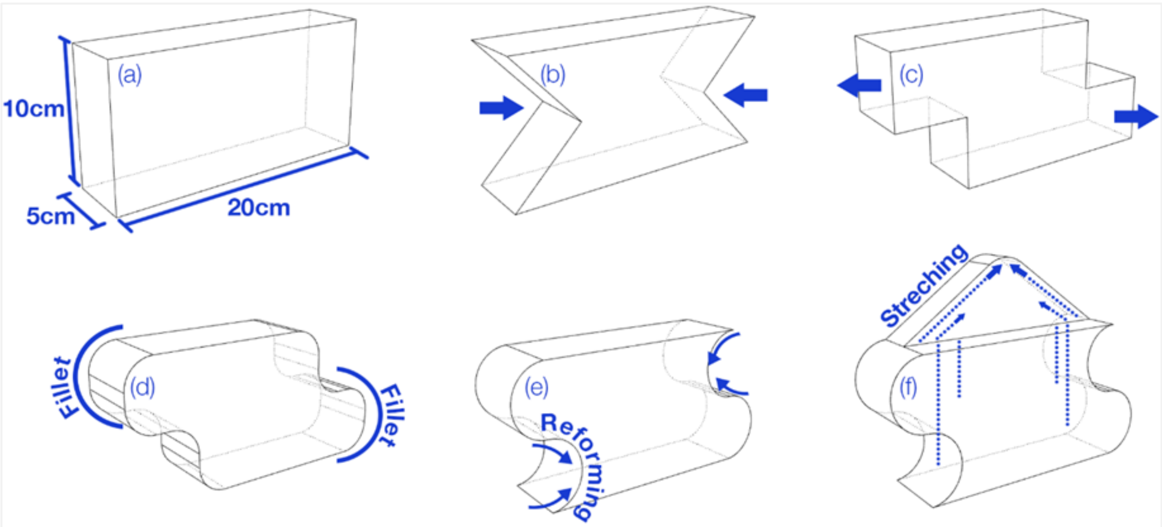



Figure 3.14. Phases of the unit brick design.

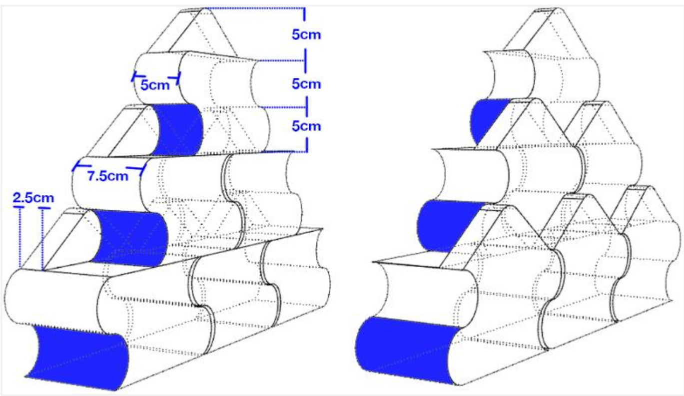



Figure 3.15. Goal configuration of the created units and illustration of the decreasing depth through the top.

The code is generated with a box morphing method to bond the brick units in the intended configuration (see Figure 3.16). The box morph component has three parameters, which are geometry, reference, and the target. The geometry is the brick unit that has been assigned to Grasshopper. The reference parameter requires a box containing the geometry and morphs it into the box positioned on the surface. So, this can be easily provided by the bounding box tool. Lastly, the target is the twisted box that recognizes the dome surface within the component. A domain needs to be set to divide the dome surface properly, regarding the U and V calculations above in this section. In addition, the Scale NU component has been used to define the spacing between the brick units.

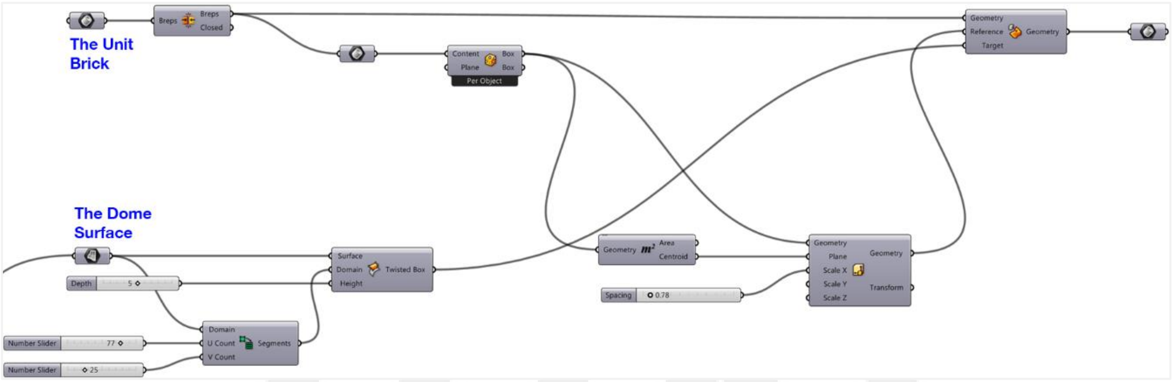



Figure 3.16. Generating dome surface with the designed brick by using box morph component on Grasshopper.

The baked products of the script above are not efficient for the desired configuration, overlapping brick bottoms on top of each other. As in Figure 3.17, the surface has divided into box cells. However, these box cells follow each other along the surface. In that case, the configuration of bricks in Figure 3.15 is not possible to obtain.

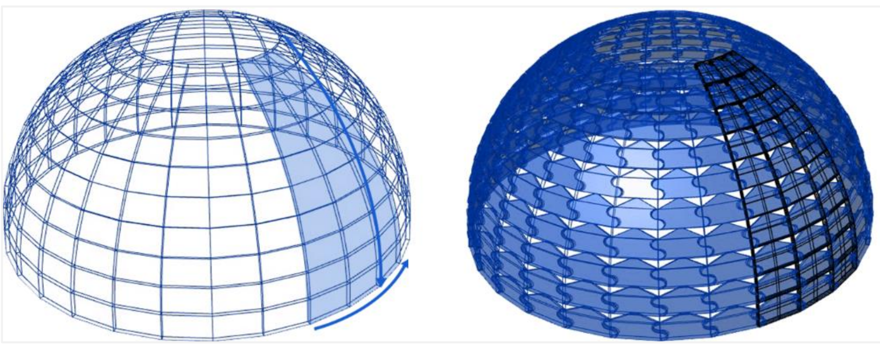


Figure 3.17. Dividing the surface into box cells (Left), and mapping the geometry inside of them (Right) with box morphing component.

Figure 3.18 illustrates the sequencing failure of the bricks as a result of the code above in Figure 3.16. Each brick is supposed to sit to a 5 cm lower margin to complete the vertical interlocking system. That is why the script needs to be recalculated to accomplish this aim.

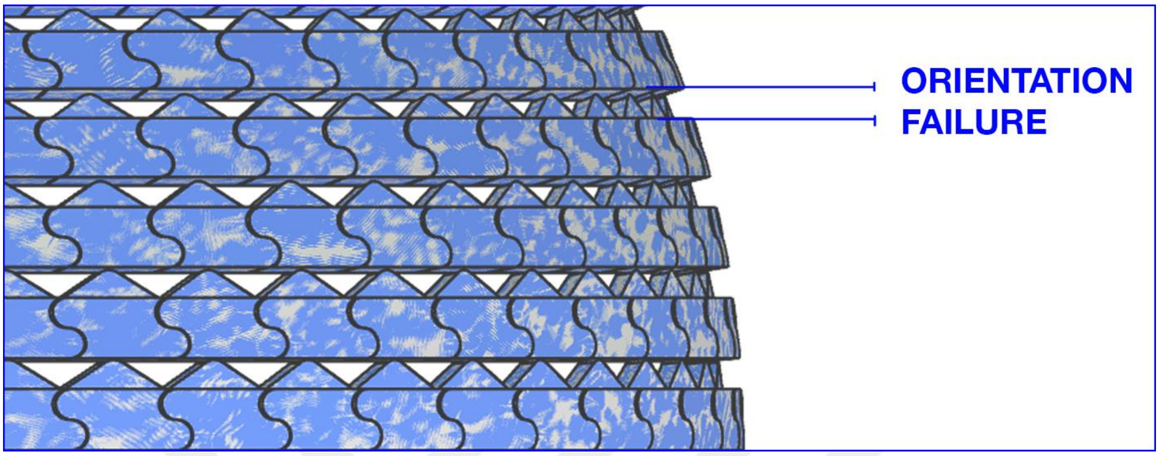



Figure 3.18. Orientation failure of the bricks.

Since the bricks' depth is supposed to decrease as they reach the top, the correlation between vertical brick joints can be thought of as dome surfaces increasing in diameter that envelops the dome surface beneath it, as illustrated in Figure 3.19. The amount of increase in diameter is as much as the backing of the interlocking brick depth, which is 2.5 cm. Box morphing works as dividing the dome surface into meridians and latitudes by generating box cells from divided surface pieces. This way helps the code to calculate for a smaller area, making it easier to assign any geometry to any surface. However, this only works along the surface. So, it is not possible to dislocate the box cells into another orientation. For this reason, to achieve the intended alignment on Grasshopper, the dome surface approached as a combination of latitudinal ribbons. By dividing each latitudinal ribbon into cells with determined dimensions, the designed brick can be assigned to those box cells. It can be assumed as each horizontal set of bricks have a dome surface of increasing diameter, which eventually allows bricks to interlock both in the horizontal and vertical direction.

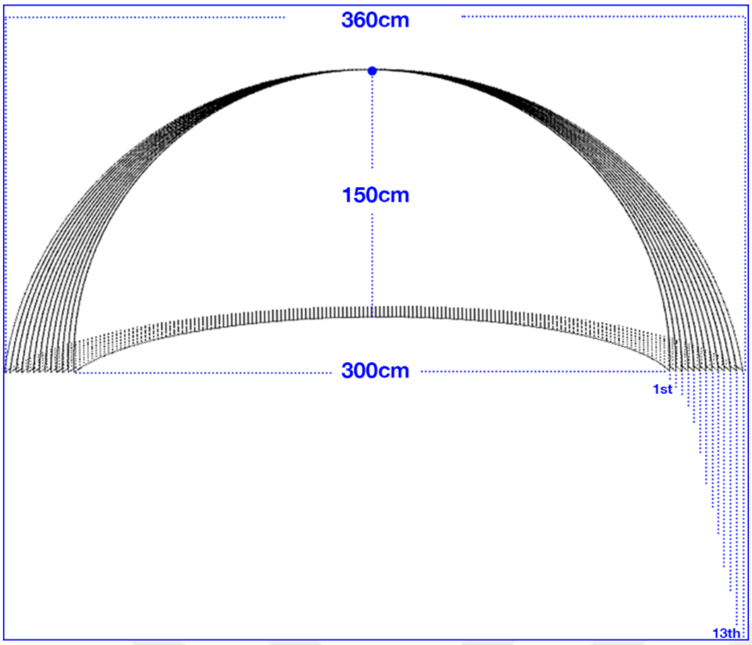



Figure 3.19. Dome surfaces enveloping each other.

The hemispherical dome surface has a diameter of 300 cm. As previously stated, the dome has an opening on the top, which stands 130 cm above ground level. The script for the interlock unit has 13 steps for each interlocking brick ring. Since the height of the designed brick is 10 cm, 130 cm vertical length can be completed with 13 steps. Each brick ring has an identical interlocking brick form. However, as the surface reaches the top, the brick sizes change according to the surface division dimensions. This change is provided by the script, as shown in Figure 3.20. The script starts with the dome surface and the designed interlocking brick geometry. As mentioned before, the box morphing component has been used to divide the dome surface into box cells and for the brick geometry assigned into those cells. This method has already worked with horizontal interlocking. However, to obtain the vertical configuration along the dome meridian curve, a specific series of box cells is indicated for each step individually. It is essential to state that the box morphing component orients the bricks into the box cells and morphs the brick's geometry according to the surface curvature (see Figure 3.21). For this reason, the unit brick design has been completed in Rhinoceros as the primary geometry since the Grasshopper script reforms the geometry measurements.

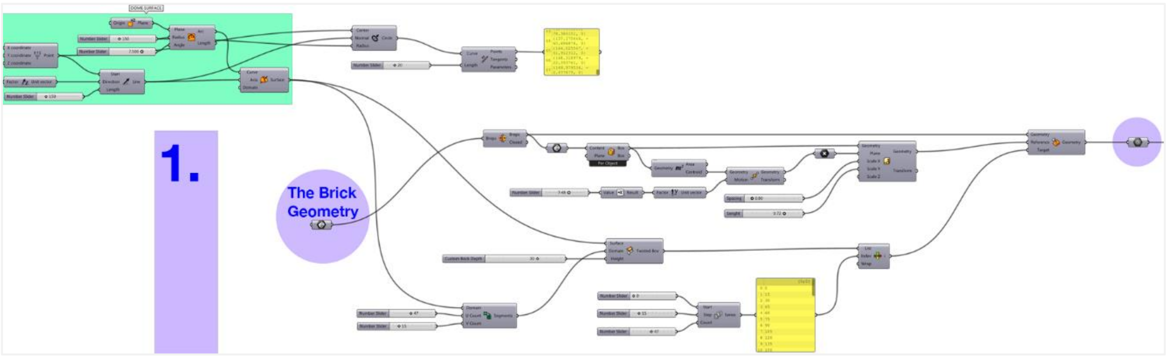



Figure 3.20. The first segment of the Grasshopper script.

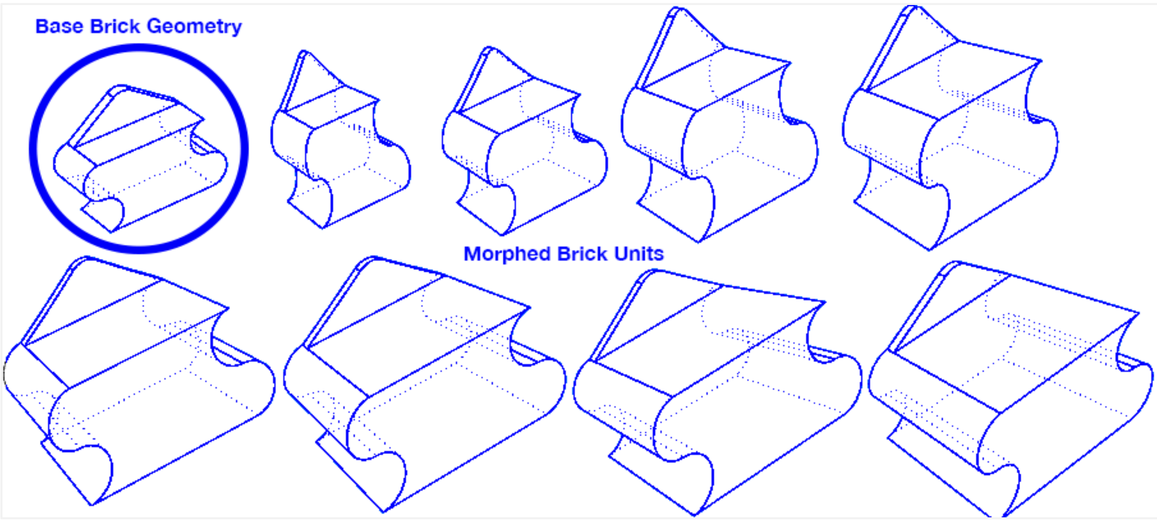



Figure 3.21. Morphed geometries by Grasshopper script.

There are three parameters to be decided; start, step and count, see Figure 3.22. Determining the step spacing and the count amount are based on dividing domain inputs, U and V count. Series component addresses the brick geometry to the determined box cells on the surface.

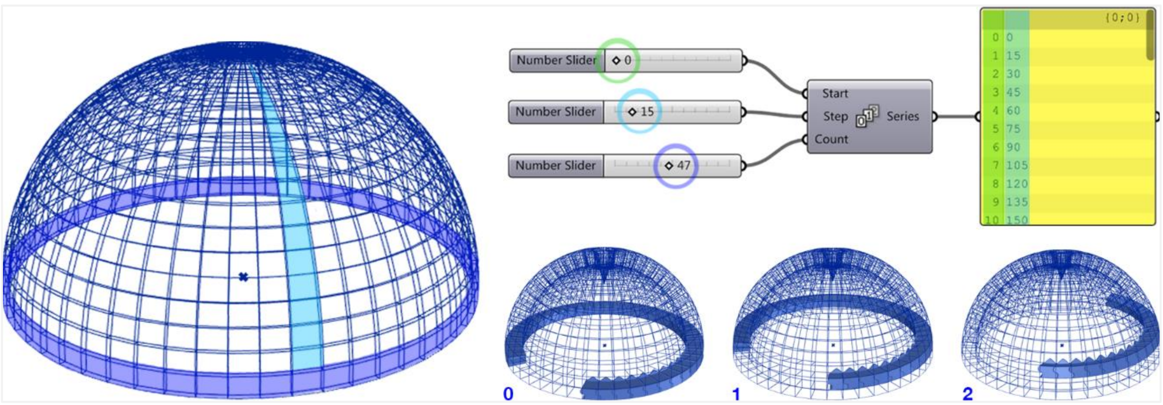



Figure 3.22. Illustration of series component working logic.

Series component is the critical factor to construct the desired interlocking dome structure. The diameter of each latitudinal ring expands gradually from 2.5 cm to the top. This method provides to maintain the hemispherical meridian curve with multiple dome surfaces that superpose, see Figure 3.23.

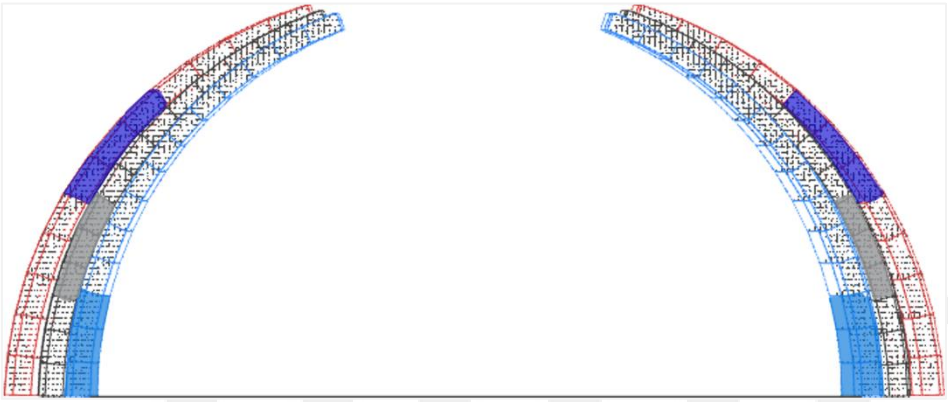


Figure 3.23. Overlapping dome layers.

The end product of the script provides the desired brick configuration, see Figure 3.24. Each brick unit sits on top of the brick underneath. The size of the units decreases gradually and the overall geometry morphing by the code to supply the hemispherical curvature of the dome. However, the installation experiment resulted in the structural collapse of the dome, which the following section will explore in detail. In addition, it is observed that the interlocking brick design is not sufficient to carry the brick above the weight load.

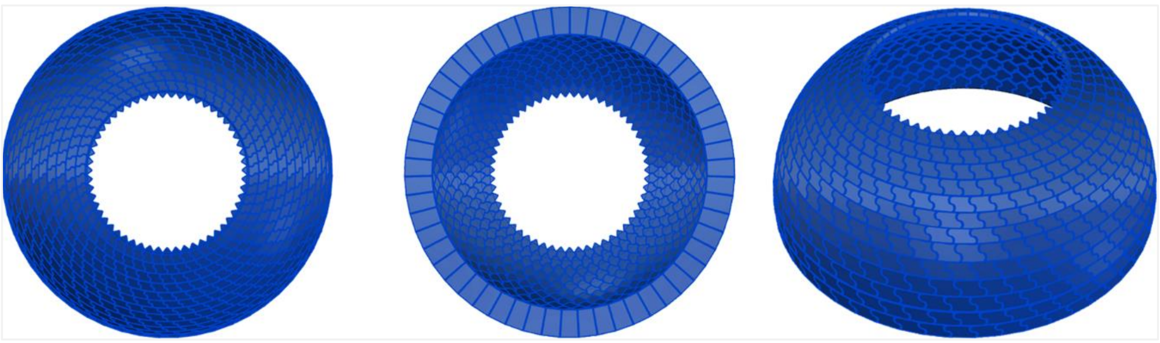


Figure 3.24. End product of the script; top view, bottom view, perspective (from left to right).

Despite the decreasing weight of the interlocking bricks along with the dome, collapsing has been observed. This structural weakness is majorly caused by the interlocking system detail not effectual enough for this specific case. As shown in Figure 3.25, the problem starts where dome curvature starts to increase. The dome structure is vulnerable to balance the gravity and the weight of the interlocking brick unit itself. The backing of the interlocking brick unit is not strong enough to carry the weight load against gravity.

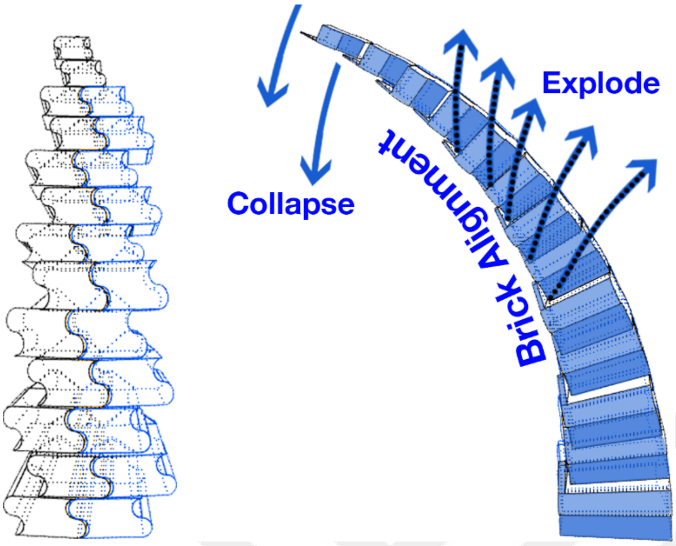



Figure 3.25. Alignments of the Interlocking Bricks; front view (Left), section (Right).

Consequently, since the problem is caused by the design of the brick, not the sequencing, a design re-articulation is needed for the interlocking brick system. The change in design contains an extra stretch of the form of the unit brick. What is needed for the design is a better joinery system that can work on behalf of an adhesive application. A superior joinery system can be obtained by the spacing between the elongated backing and the main body, see Figure 3.26.

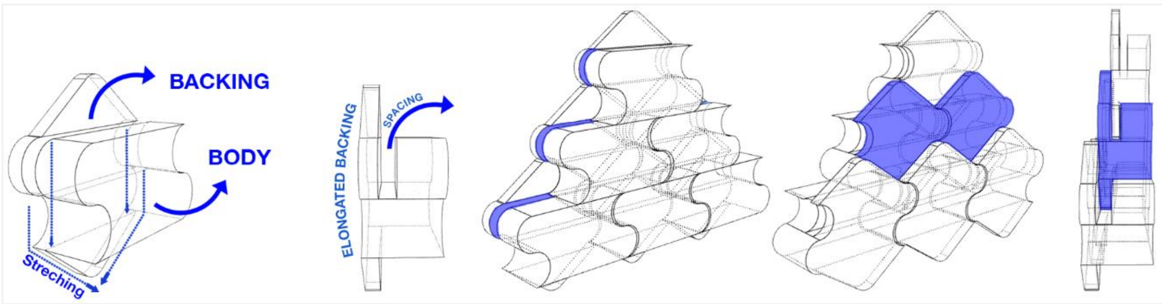



Figure 3.26. Illustration of changes in design and sequence of the bricks.

By this geometric change, the structure can carry the bricks' weight load while generating the dome curvature properly. To reach this improvement, the only change that has done is the form of the brick design. The same Grasshopper script was used to construct the dome structure, see in Figure 3.27 and Figure 3.28.

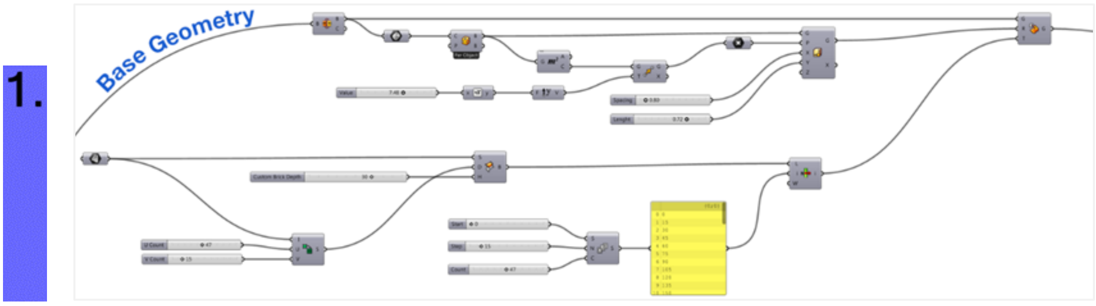



Figure 3.27. The interlocking brick dome Grasshopper script

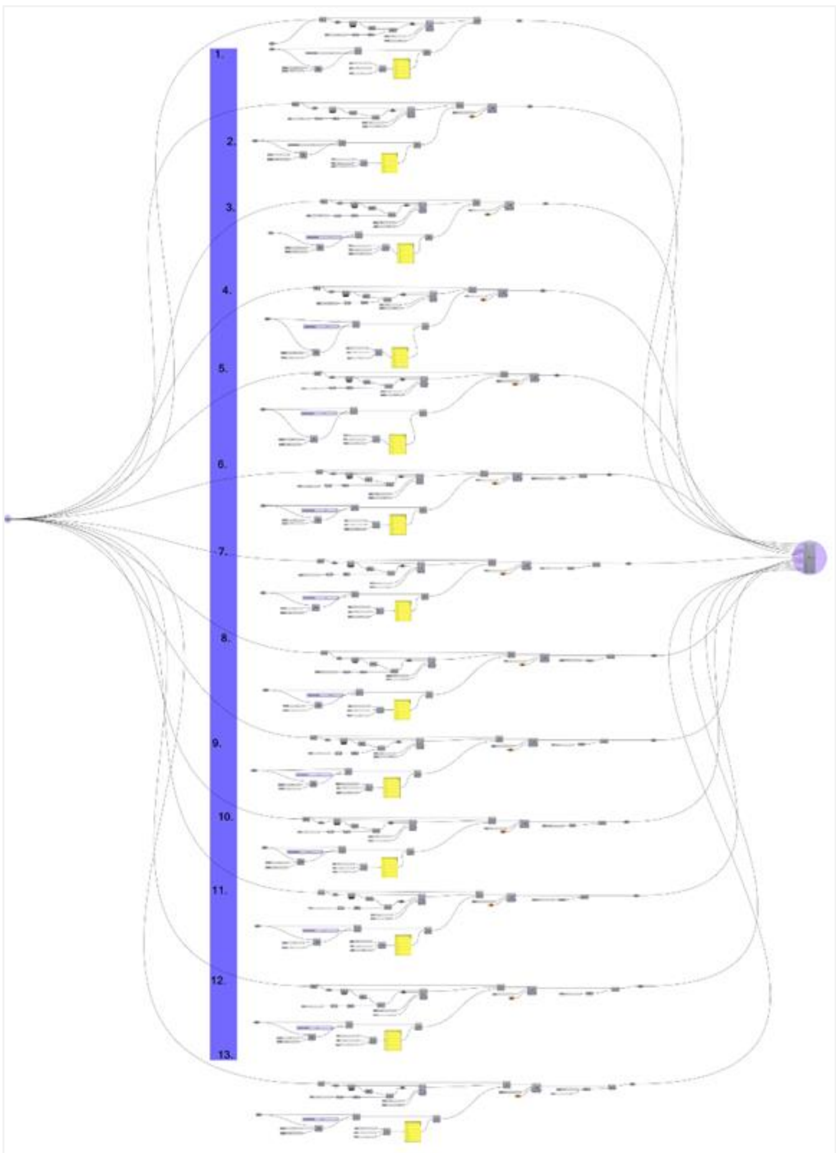


Figure 3.28. The complete Grasshopper script for the dome structure.

The result of the Grasshopper model with redesigned interlocking brick is also looking quite similar to the previous one, see Figure 3.29. That is because the only change in the design is the elongation of the backing and the spacing detail of the brick. The part that has extended stays inside of the other brick's spacing area; see Figure 3.30. For this reason, there is no difference in appearance. However, by redesigning the brick unit, the static balance has obtained, and the structure prevented from collapsing. The joinery system creates a ring that balances the tension on the surface of the dome. In the previous design, bricks tended to explode outwards and collapse from the top. With the rearranged method, bricks sit on the spacing area, which is lower in height than the body of the brick. This detail prevents the other brick on top from moving outward. By this, it can be observed that the full integration of the brick into each other holds them together against the forces and keeps them structurally stand.

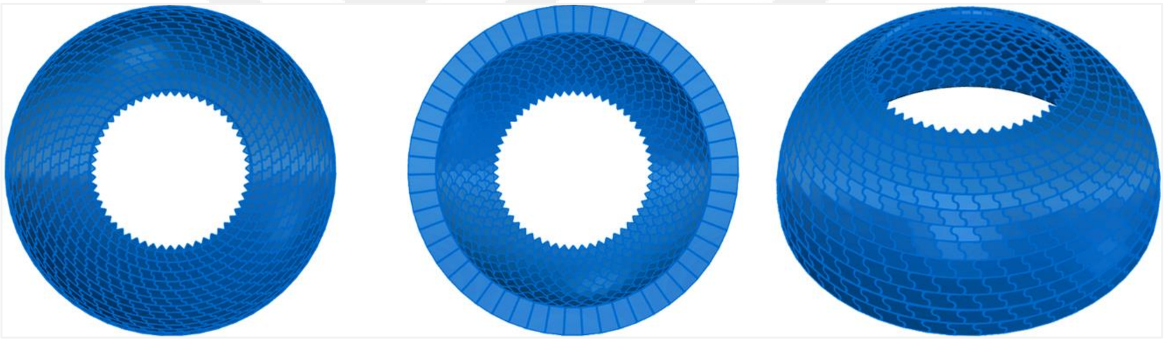


Figure 3.29. End product of the script; top view, bottom view, perspective (from left to right).

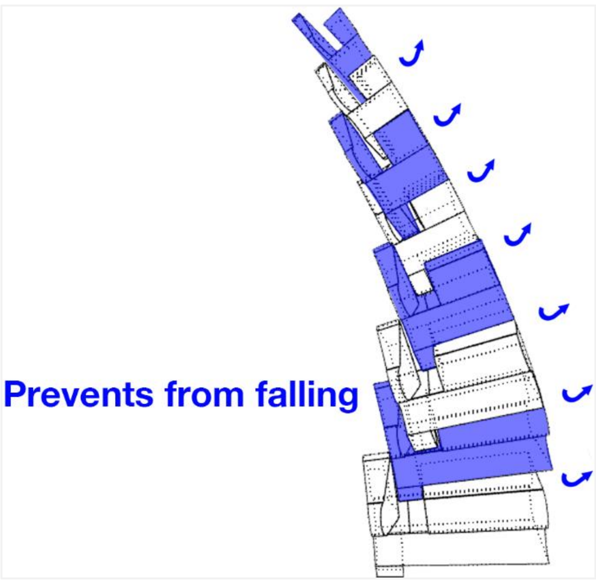



Figure 3.30. Alignments of the interlocking bricks.

This design contains specific features from both corbelling and true masonry dome techniques. Each brick is carried by the backing of the other brick underneath, which resembles the corbelling method since bricks are cantilevering through the center. However, the backing detail prevents the pieces from collapse. It keeps them on the tangent alignment of the dome surface, which resembles the true masonry dome technique. Even though this code is worked effectively, the study has to move further to be more precise in the interlocking brick unit's design and generate the dome surface successfully.

Production process

Digital manufacturing technologies allow the production of complex geometric forms and a variety of shapes with different materials. This new technology provides designers to achieve precisely manufactured models without mistakes or material wastes. Therefore, these technologies are getting spread and preferred more (García-Alvarado, 2013). However, digital manufacturing requires a process of preparation for the machine to produce. There are lots of different types of machinery that work differently. That is why it is a crucial step to prepare the generated digital model for production.

This section includes the production and installation process of the generated dome models on Grasshopper and Rhinoceros 6. In this study, four different dome models have been evaluated. These are; corbel dome, masonry dome (true dome), interlocking brick dome -1 (failed), and interlocking brick dome - 2 (re-arranged). Corbel dome and masonry dome (true dome) are considered to build a comparison between traditional and digital methods of designing and to explore the assembling differences. The production process starts with preparing the digital model according to the machine's features to manufacture, such as size and the type of technology in use, because the digital model has to be prepared according to the capabilities of the machinery.

First, the corbel dome model was created on Grasshopper. After the parametric design process, the model was baked and imported to the Rhinoceros 3D modeling platform. From this point, the digital model is no longer parametrically able to change. The manufacturing process starts with arranging pieces according to their kind and enumerating them on Rhinoceros. Giving numbers to them helps during the installation. CNC laser cut machine has decided for the corbel dome physical modal manufacturing. The CNC laser cutting process is illustrated on Figure 3.31.

Figure 3.31. The corbel dome modal brick manufacturing process with CNC laser cutting.

Since the bricks of the corbelled dome need to be horizontally placed, additional placemarks are assigned on the bricks for the CNC laser machine to scratch (see Figure 3.32). Due to the corbel dome bricks have a simple and rectangular form, CNC laser cutting is a fast and inexpensive method for production. Hardboard is used as a material for the physical model. For a CNC laser cutting machine to cut the pieces, 3D solids need to be converted into 2D lines. Thereby, the machine can follow the lines and cuts them with a laser ray. After the CNC laser cutting process, the pieces are arranged from bottom to top (see Figure 3.32).

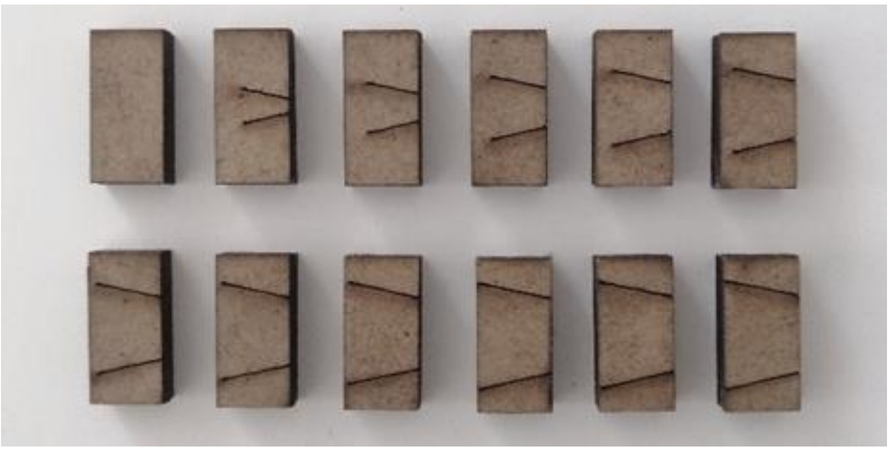


Figure 3.32. The corbel dome modal bricks and CNC laser scratched place marks on top.

The installation process starts with classifying bricks for each sequence. There are 12 ribbons, which contain 15 pieces of brick for this scaled physical model. The modal has a 1/20 ratio; that is why the diameter of the physical modal is 15 cm long. The steps of the installation illustrated in Figure 3.33. In each step, the placemarks are used as a guide to reaching the exact same physical modal with the Grasshopper modal. This way, the distances between bricks are kept precisely. The bonding material is determined as silicone, which dries fast and able to remove in case of any incorrectly bonding quickly. Installation starts from the bottom course of bricks to the top by following the placemarks that are scratch via the CNC laser cut machine. Traditionally, corbel dome bricks have no such placemarks to guide the builder to reach the perfect double curvature surface. Therefore, it is an advantage to arrange a path to follow during manufacturing regarding the installation process. As indicated in the previous section, the corbel dome modal has a large oculus to prevent the intersection of the bricks on top due to constant brick dimensions. As a result, the physical modal can be completed as same as the Grasshopper modal due to the precise cutting measurements of brick units and placemarks via CNC laser cutting.

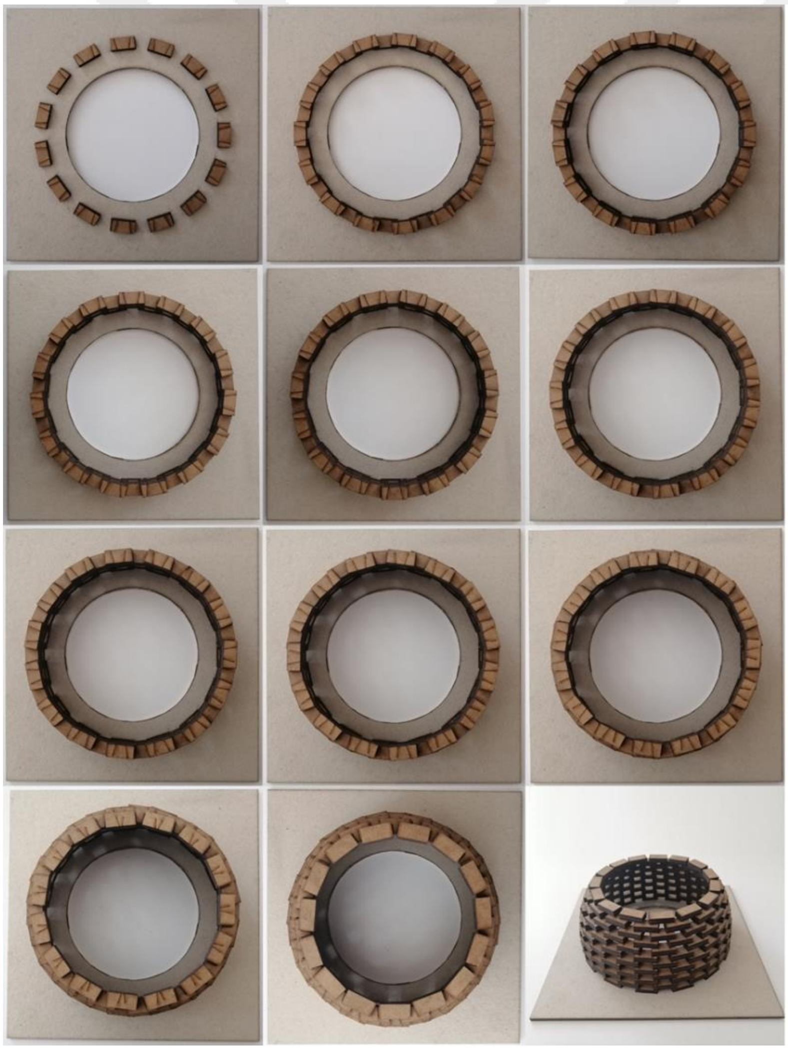


Figure 3.33. Installation phases of the corbel dome scaled model.

Second, the masonry dome model was created on Grasshopper. The preparation process for manufacturing the physical masonry dome follows the same steps with corbel dome modeling. The determined digital manufacturing tool is again a CNC laser cut machine due to the simple rectangular geometry desired to obtain. First, the Grasshopper modal has been imported to the Rhinoceros, and the 3D bricks are converted into 2D lines. Then, each brick is enumerated and arranged according to its kind and size. There are 8 ribbons, which contain 15 pieces of brick for this scaled physical model. Hardboard is used as a material. Since the brick orientation of the true masonry dome is vertical that follows dome curvature, no placemarks were scratch as a guide to installation. Behalf of that, guide ribs are cut with the exact dimensions and curve with the dome surface. After the cutting process, the pieces are first aligned according to their sizes (see Figure 3.34 (1)).

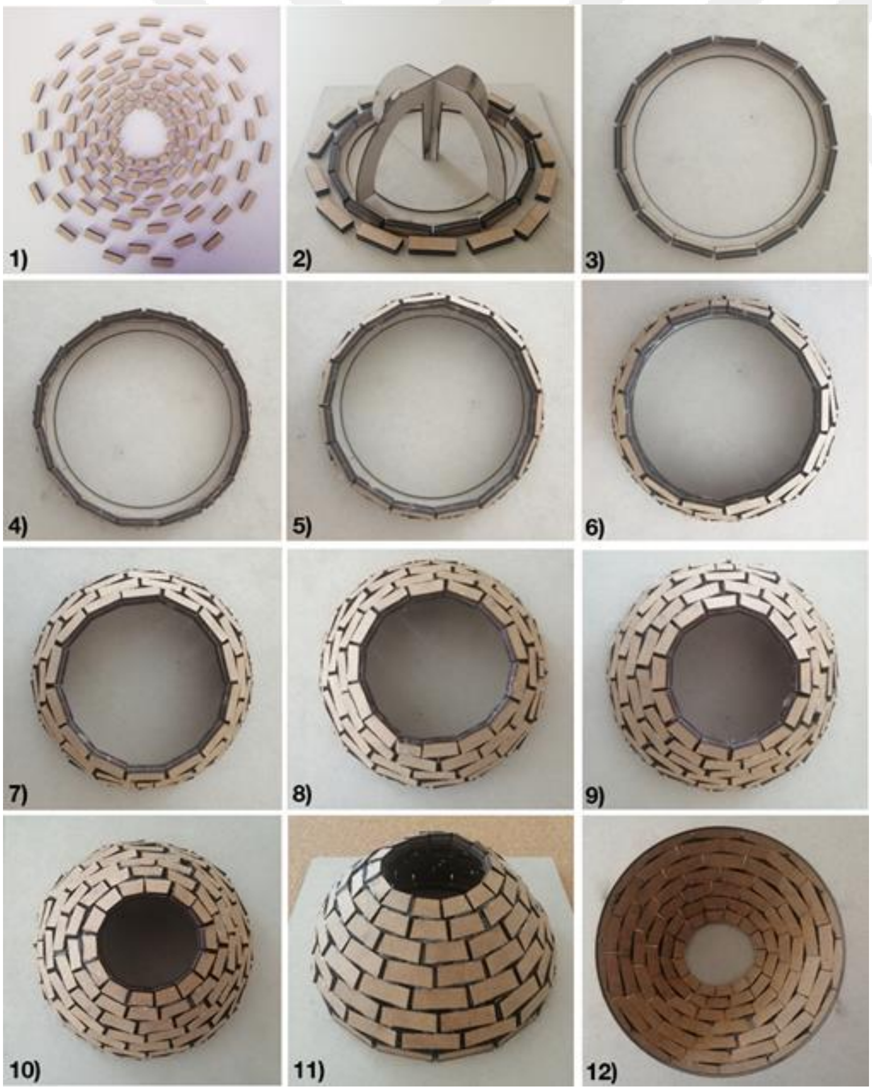



Figure 3.34. Installation phases of the masonry dome scaled model.

Masonry domes are challenging to build without a guideline underneath during construction. As in Figure 3.34 (2), a base platform and ribs are used to achieve the correct form of a masonry dome structure. In the previous section, it is asserted that the digital models of the domes have a diameter of 300 cm. Physical models are scaled to a 1/20 ratio, therefore the diameter of the 15 cm long. The phases of the installation illustrated in Figure 3.35. In each phase, ribs are used to provide the hemispherical curvature of the dome. Silicone adhesive is used as a bonding material for the same reasons as in the case of corbel dome. Even though the model pieces are precisely correct, the installed modal does not seem perfect and flawless. The form of the model is not smoothly curved, and the spacing between bricks is changed in some places, which are enough criteria for a dome construction to fail. This is because the masonry works demand skilled labor that construction has to be done by experienced builders. Especially double curvature surfaces like domes require detailed knowledge and hand skill to construct.

Third, the interlocking brick dome has been created on Grasshopper. The modal was created via a 3D printer (see Figure 3.35) since it has a complex geometry. The production process for 3D printing more complex than the CNC laser cut. Before the production, the digital model converted into *Standard Tessellation Language* or *Standard Triangle Language* (STL.) file format. Later, the model needs to be controlled on software such as Solid Works to arrange the orientation of the pieces for printing. Also, the thickness of the filament, the sensitivity, and the pace of the machine have to be arranged according to the product to print. Finally, the physical modal is scaled to a 1/20 ratio, and its diameter is 15 cm. In the previous section, the properties of the interlocking brick dome and its details are both explained and illustrated. First, the modal file is prepared as following the steps mentioned above. The duration of the printing takes time. Each piece was printed approximately within 10 minutes. There are 160 pieces that have 8 different variations. The time duration is related to the machine properties as well as the complexity of the geometry. However, as shown in Figure 3.36, the end products were perfectly smooth and fitting to the dimensions that are supposed to.

Figure 3.35. 3D Printing; Production process.

Figure 3.36. 3D printed interlocking bricks.

The installation process started with arranging the printed pieces according to their type and size (see Figure 3.36). For this modal, there are 8 ribbons that each ribbon contains 20 bricks. This modal is generated to be able to assemble without the need for adhesive. Until the third ribbon, the modal was steady. However, the structure started to collapse during the installation of the fourth ribbon (see Figure 3.37 (4)). This is because of the weak interlocking joints that are not sufficient to carry the brick's weight load on top of it. For to complete the installation process, silicon adhesive was used partially to be able to see the overall structure and the geometry. In this first attempt, the modeled dome collapsed because of the geometric failure of the interlocking unit brick design. This information is obtained by making a physical model.

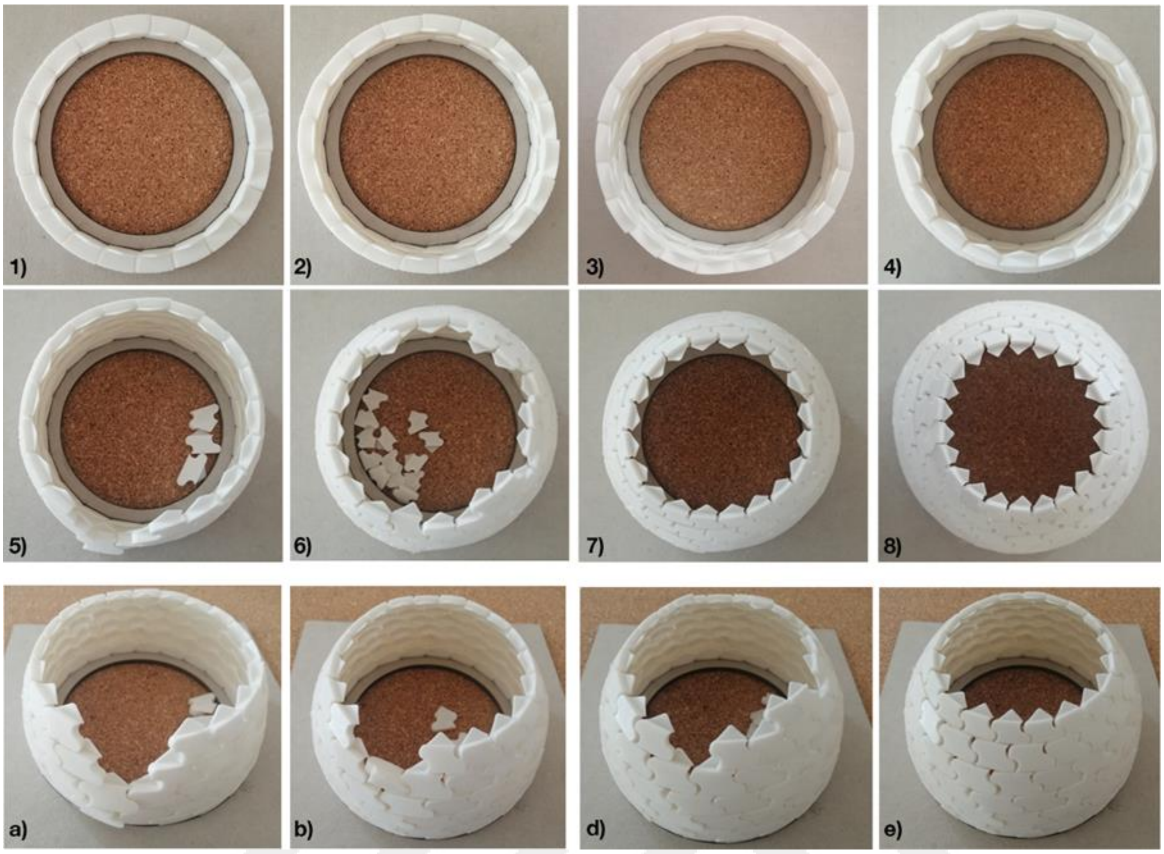



Figure 3.37. First attempt; Phases of interlocking brick dome installation.

In the second attempt, the brick geometry was articulated and redesigned. The 3-joinery system has been developed to prevent the structure from collapsing. The same 3D printing preparation process was applied for the second interlocking brick dome as well. In this attempt, not a full-dome but only a meridional segment of the dome has been printed. The reason is to obtain a quicker result and to avoid the possible second failure. After the printing process, the pieces were removed from the extra structural pieces they printed together. As illustrated before, this interlocking brick has a spacing between its backing and body. Therefore, in the preparation process, a supportive structure must be assigned to that spacing for the printing. Otherwise, the desired shape cannot be achieved. Before the installation, the supports were removed from the body of the brick. The installation process for this modal was easy since it is not required adhesive or support to stand, see Figure 3.38.

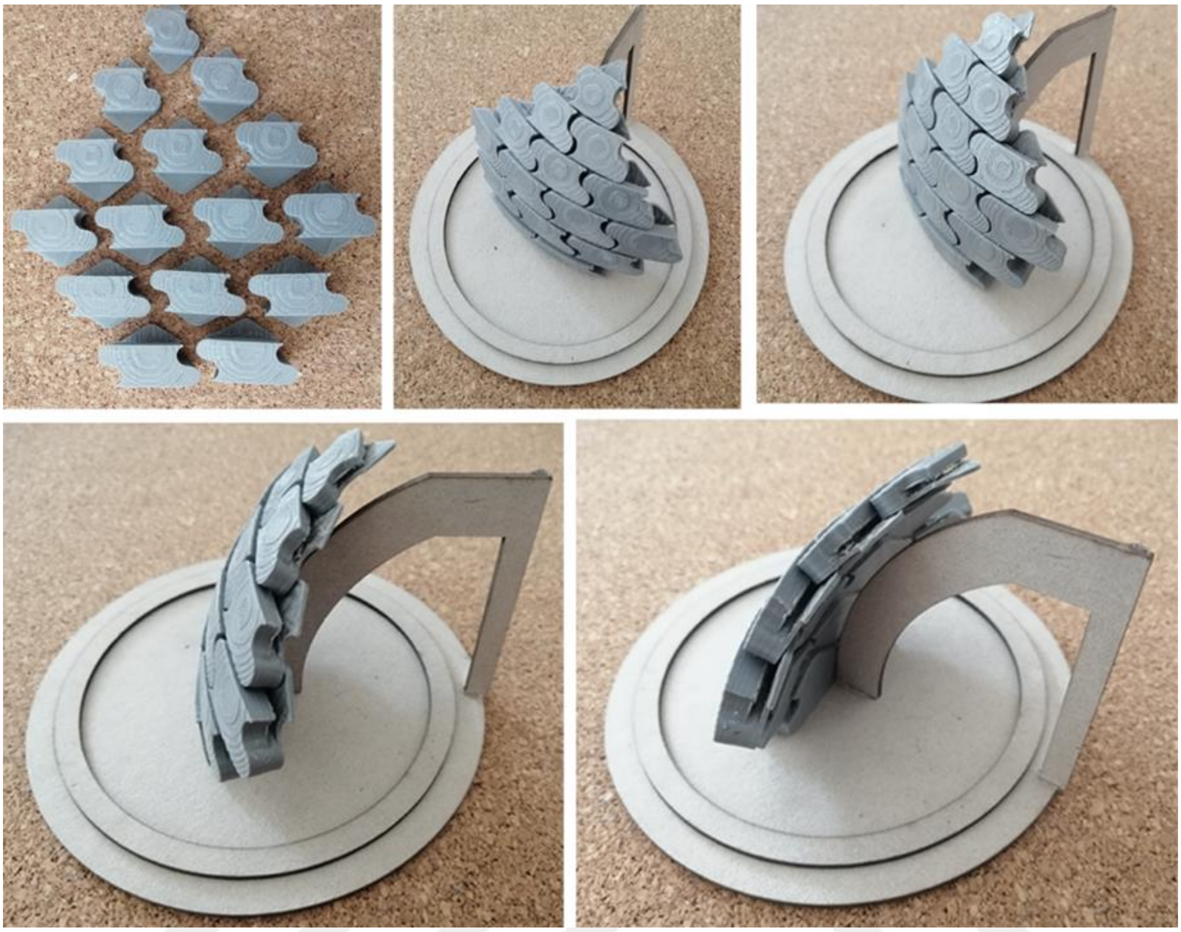


Figure 3.38. Second attempt; 3D printed interlocking bricks and their configuration.

# 4. RESULTS AND DISCUSSION

In this paper, the limits of parametric design tools have been investigated through constructing a dome structure by a 3-jointed interlocking brick system. First, the traditional dome construction methods, corbel and masonry domes, explored and modeled on Grasshopper. Since the conventional constructing methods are majorly based on the repetition of rectangular forms, the same logic has applied to the Grasshopper script. Even though these techniques are old and have primitive technology today, it is fascinating to see the calculation behind these methods. Parametric designing majorly based on mathematical calculations. Hence, script creators have to able to understand both the problem and the solution mathematically. By this notion, even today, it is straightforward to see the deep and intelligent calculation behind the traditional techniques that are discovered thousands of years ago. A conventional masonry system re-interpreted, and a new system has designed to understand better and embrace this intelligence. As traditional constructing methods, the corbelled dome and masonry dome are modeled on Grasshopper individually, then produced and installed physically. The exact size of bricks has been used as a base unit to build them. Later, the interlocking brick dome is created in Grasshopper by generating a unique script specifically for the designed interlocking brick configuration. The base information for creating an interlocking brick dome is obtained from both the literature review of this study and the traditional modals generated on Grasshopper. This study proposes exploring possibilities of brick masonry techniques by using digital design and manufacturing tools through a hemispherical dome structure.

The method to create the corbelled dome on Grasshopper is based on the division of the dome surface into contour lines and arranging the horizontal frames where the bricks are horizontally assigned to place. The changing parameter for this script is the spacing between the bricks rather than the bricks' size. The spacing between bricks is getting decreased along to the top, so avoiding the intersection of the bricks corbel dome has the largest oculus among the other generated models. The CNC laser cut machine has used for the manufacturing process. This method is swift and inexpensive, especially for small-scale physical models. The total of the scaled model is composed of 180 pieces of bricks. It took less than 1 hour to laser cut all of the pieces. Thanks to the base sheet and the placemarks, the installation process took less than 1 hour, which is a fast result for 180 pieces of a dome modal. This is an advantageous result of the digital manufacturing tools that allow builders to assemble pieces easier with the determined guiding during the design process. However, it should be noted that the selected tool and the modal itself must adequately match the modal’s features. In the corbel dome case, the horizontal course of the bricks allowed such guiding opportunity during installation. As a result, the scaled corbel dome modal has been generated physically with matching properties with its digital modal. The installation experience can be evaluated on a scale from 1 to 10 as 5. Even though digital production helps the builder, bricklaying methods still require an effort to assemble them correctly by considering the adhesive amount.

The same script with the corbelled dome has tried; however, it did not work out. Therefore, a whole new code is arranged for this method. The design process of the masonry dome on Grasshopper is based on the division of the surface into meridians and latitudes according to the specified brick dimensions. Dividing the surface is done by a component, which creates the stretcher bricklaying method along the dome surface. This method shifts the brick joints for each course. Otherwise, brick joints align vertically, and this can result in the collapse of the structure. The division of the base surface along the curvatures causes the segments to get smaller as they reach the top. Extrusion of these segments gives the desired masonry dome modal. The changing parameter for this modal is the width of the unit bricks. The vertical yet along the dome tangent orientation of the bricks requires a decrease in width to complete the hemispherical surface. For the Grasshopper modal, this process is done by diving the surface. However, in the traditional method, the builders do this by breaking the unit brick according to the curvature of the brick course. It can be observed that digital design and manufacturing tools help designers pre-calculate the dimensions that eliminate the need for a manual calculation. Like the corbelled dome, the CNC laser cut machine has been used for the manufacturing process of the masonry dome due to its features of being cheap and fast. The total modal comprises 120 pieces of bricks, and it took less than 1 hour to laser cut all of the pieces. The installation process took 2 hours, which is more than the corbel dome assembling duration. This is because of the brick orientation of the masonry dome, which is not allowed to scratch a placemark as a guide. Instead of that, a base sheet and supporting ribs are created to maintain the correct curvature of the hemispherical dome. In each brick course, these ribs are used. Despite the supporting elements, it was not easy to maintain the dome curve and calculate the adhesive amount properly. This is because traditional brick masonry techniques require skilled labor, a builder that has experience. Therefore, the modal that is completed has a distorted hemispherical form. As a result, the scaled masonry dome modal has been generated physically without matching properties with its digital modal. The installation experience can be evaluated on a scale from 1 to 10 as 7. Even though digital manufacturing accelerates production, assembling is an essential factor that affects the form of the whole structure.

The design of the interlocking brick system has been inspired by the combination of the corbel and the true dome masonry techniques by eliminating the need for adhesive. The design of this brick geometry allows horizontal piling and follows the tangent of the dome surface. This system has been created on Grasshopper by arranging the brick configuration based on decreasing in-depth as they reach the top of the dome. In the first attempt at the interlocking brick dome, the design failure of the 3-joinery interlocking system ended up in the collapse of the whole structure. This is caused by the insufficient joinery system that could not balance the gravity, compression, and tension forces of the dome surface without the use of mortar. Therefore, the interlocking brick configuration design was revised and developed. The part called *backing* has been extended, and a new detail called *spacing* has been added.

The sequence of the bricks has to follow the order of interlocking backing of a brick with the spacing of the brick underneath it. This connection prevents the structure from exploding and collapsing without mortar or its derivatives. The Grasshopper script for this design is based on the division of the dome surface into box cells with box morphing components, creating a series as determined and assigning the units into them. Both of the interlocking dome bricks have 3D printed because of their complex geometry. The white PLA filament has been used as a material. For the first attempt of the interlocking brick dome, there are 8 different brick types and 160 pieces in total. The production process took 26 hours, 10 minutes for each piece on average. This duration is longer than the CNC laser cut modals. However, the complexity of the geometry and the capacity of the 3D printer have to be taken into consideration. During the installation of the first interlocking dome, as mentioned before, the dome has started to collapse after the fourth course of bricks without the mortar. So, the design mistake has observed during the assembling. After revising the interlocking brick design and the configuration, the second interlocking brick pieces are manufactured via a 3D printer. This time only the slice of the dome has been printed to save time and to test the design if it is working properly or not. Material is selected as grey PLA filament. A total of 15 pieces are printed in 3 hours, 12 minutes for each piece on average. Since the redesigned bricks have more detail than the previous one, it took more time to produce each brick. However, the installation process is completed without the need for any guide or adhesive. The 3D printed pieces are interlocked easily, and the overall dome form emerges by itself during interlocking. Since the Grasshopper script morphed and articulated the base brick according to the surface that assigned no effort to maintain the hemispherical form, it was already embodied during the design process. Even though the 3D printing process takes more time than the production of previous examples, the precise calculation of the complex pieces and assembling the modal perfectly without supporting guides are advantageous features of this manufacturing method. However, it should be noted that considering the modals that are physically modeled for this study, 3D printing is a much more expensive method than the CNC laser cutting machine.  As a result, the scaled interlocking dome models have been generated physically with perfectly matching properties with their digital modal. Therefore, the installation experience can be evaluated on a scale from 1 to 10 as 2 for the first attempt and as 1 for the second attempt.

Table 4.1. The design process of the domes in Rhinoceros 6 and Grasshopper.

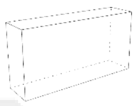
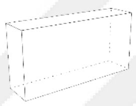
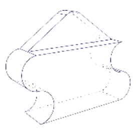
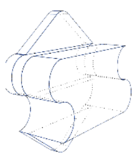
| DESIGN PROCESS | Types of Domes | Base Unit | Unit Change Along the Dome Surface | Unit Orientation | Geometry Classification | Method of the Grasshopper Script |
|---|---|---|---|---|---|---|
| | Corbel (False) Dome | Brick 20x10x5  | Constant | Horizontal | Simple rectangular form | Dividing the dome surface into contour lines, arranging horizontal frames and assigning the unit brick into them |
| | Masonry (True) Dome | Brick 20x10x5  | Decreasing in width | Vertical and follows tangent curve | Simple rectangular form | Dividing the dome surface into meridians and latitudes, and extruding the divided pieces |
| | Interlocking Brick Dome - 1 | Interlocking Brick  | Morphed | Vertical and follows tangent curve | Complex Geometry | Dividing the surface into box cells with box morphing component, creating a series as desired and assigning the units into them. |
| | Interlocking Brick Dome - 2 | Interlocking Brick  | Morphed | Vertical and follows tangent curve | Complex Geometry | Dividing the surface into box cells with box morphing component, creating a series as desired and assigning the units into them. |

Table 4.2. The production process of the physical dome modals.

| | Types of Domes | Selected Digital Manufacturing Tool | Physical Modal Material | Duration of the Production | Financial Expenses |
|---|---|---|---|---|---|
| PRODUCTION PROCESS | Corbel (False) Dome | CNC Laser cut machine | Hardboard | < 1h (180 pieces) | x unit money |
| | Masonry (True) Dome | CNC Laser cut machine | Hardboard | < 1h (120 pieces) | x unit money |
| | Interlocking Brick Dome - 1 | 3D Printer | PLA Filament (white) | 26h (160 pieces) | 26x unit money |
| | Interlocking Brick Dome - 2 | 3D Printer | PLA Filament (grey) | 3h (15 pieces) | 3x unit money |

Table 4.3. The Installation Process of the Physical Dome Modals.

| | Types of Domes | Used Adhesive | Installation Duration | Installation Guides | Installation Experience from 1 (easy) | Form of the Physical Dome Modal |
|---|---|---|---|---|---|---|
| INSTALLATION PROCESS | Corbel (False) Dome | Silicon | < 1h | A base sheet and the CNC Laser scratched placemarks | 5 | Matches with the digital modal |
| | Masonry (True) Dome | Silicon | 2h | A base sheet and supporting ribs | 7 | Does not matches with the digital modal (Form failure – deformed) |
| | Interlocking Brick Dome - 1 | No adhesive (Collapsed – attempt failure) | < 1h | A base sheet | 2 | Matches with the digital modal |
| | Interlocking Brick Dome - 2 | No adhesive used | < 1h | No guide needed | 1 | Matches with the digital modal |

This study shows that digital technologies allow designers to reach complex geometries and configurations. These tools enable designers to explore the limits of geometric forms from basic to complex for architectural use. Digital design and manufacturing create and produce solid masonry systems that can be applied to domical surfaces. The provided opportunities evolve the architectural tectonics. In this study, a hemispherical double curvature surface has been studied. The results of this study mainly are as follows;

For this study, first, the conventional masonry dome constructing techniques have been recreated on Grasshopper. This algorithm-based program acknowledges the mathematical calculations behind the traditional methods by its various components, which designers need to combine regarding the structure. Since creating a combination of components can be done in numerous ways, digital design tools allow the designers to model a structure with many different compositions, creating variety in design methods. Second, a new brick geometry has been created on Rhinoceros 6. Digital modeling programs provide a platform for designers that they can change the form of geometry repeatedly. In this study, a base brick form and a configuration have designed and later assigned to the Grasshopper to map the design on a domical surface. Rhinoceros 6 and Grasshopper work together. However, the work methods of these programs differ. Rhinoceros 6 has provided a solid design, while Grasshopper provided changing design possibilities with altering parameters.

The working principle of algorithm-based programs is a crucial instrument to obtain various topological geometries. The created script has morphed the base brick geometry and the configuration according to the determined hemispherical dome surface. This shows that not only the designer’s decisions but also the algorithm has a contribution to the resulting structure. Third, the Grasshopper models produce by using digital manufacturing tools. For the traditional masonry dome models, the CNC laser cut machine and the interlocking brick dome the 3D printer used. Digital manufacturing provides a fast and precise production process. CNC laser cut machine has been selected for simple rectangular geometries, while 3D printers are used for complex geometries. It is crucial to indicate that each machine uses different methods. That is why designers have to arrange digital models according to the features of the digital manufacturing tools they have chosen. The comparison between the CNC laser cut machine, and the 3D printer has shown in Table 3. However, the comparison is specifically related to this study. Different digital manufacturing machines have to be compared to have more comprehensive information about their differences and features. Lastly, digitally manufactured pieces have been assembled. The precise dimensions and guide marks on the surface of the pieces have provided relatively easy installation for the corbelled dome than the masonry dome. The interlocking brick dome has been easily installed since its complex form of bricks has been manufactured via a 3D printer with exact dimensions in the digital model. The related comparison has shown in Table 4.

In conclusion, an interlocking brick masonry dome has been generated in this study to propose an alternative brick form, configuration, and installation method through digital design and manufacturing tools. This model has compared with the conventional masonry dome models to evaluate the differences, and to take the limits of the masonry dome techniques further. This study is a step to understand the changing tectonics in architecture by digital design and manufacturing tools. It should be noted that this study only covers geometric exploration and installation. Further studies have to be done to have more complete results about the created method, the interlocking brick dome. For future studies, different materials and unit forms can be tested. Additionally, the structural behavior of the 3D printed dome can be investigated to examine its condition under stress and load.

## REFERENCES

Allen, E., and Zalewski, W. (2009). *Form and forces: designing efficient, expressive structures*. (2nd ed.). United State of America: John Wiley and Sons, 215-232.

Ambrose, M., Callam, B., Kunkel, J., and Wilson, L. (2009, April). *How to make a digi-brick.* Paper presented at the Proceedings of the 14th International Conference on Computer Aided Architectural Design Research,Yunlin,Taiwan.

Aoki, T., Chiorino, M. A., and Roccati, R. (2003, January) *Structural characteristics of the elliptical masonry dome of the Sanctuary of Vicoforte.* Paper presented at the Proceedings of the First International Congress on Construction History, S. Huerta, ed. Madrid: Instituto Juan de Herrera, Madrid.

Asman, N., Bolong, N., Mirasa, A. K., Saad, I., Asrah, H., and Han, L. (2018, April) *Life cycle assessment of interlocking bricks system construction-a review*. Paper presented at the Joint Seminar on Science, Engineering and Technology, South Korea.

Association, A. F. B. (1920). *A manual of face brick construction*. (1st ed.). USA: American Face Brick Association, 5-15.

Association, T. B. D. (2006). *BDA guide to successful brickwork.* (3rd ed.). United Kingdom: Routledge, 13-30.

Bailey, H., and Hancock, D. (1990). *Brickwork 1 and associated studies*. (2nd ed.) London: Macmillan Education UK, 76-91.

Baran, M. (2006). Halk mimarisinin halkbilimi bağlamında değerlendirilmesine Harran evleri örneği. *Milli Folklor,* 72, 141.

Baratta, A. (2013). On the structural assessment of masonry vaults and domes. *International Journal of Mechanics,* 7(3), 201-209.

Beatini, V., Royer-Carfagni, G., and Tasora, A. (2019). A non-smooth-contact-dynamics analysis of Brunelleschi's cupola: an octagonal vault or a circular dome?. *Meccanica*, 54(3), 525-547.

Bekleyen, A., Gönül, I., Gönül, H., Sarigül, H., Ilter, T., Dalkiliç, N., and Yildirim, M. (1998). Vernacular domed houses of Harran, Turkey. *Habitat International,* 22(4), 477-485.

Block, E. (2010). *Garlic other alliums*. (1st ed.). Cambridge: Royal Society of Chemistry, 74-78.

Born, W. (1944). The Introduction of the bulbous dome into gothic architecture and its subsequent development. *Speculum,* 19(2), 208-221.

Burden, E. (2002). *Illustrated dictionary of architecture*. (3rd ed.). USA: McGraw-Hill Companies Incorporated, 72-73.

Cavalagli, N., and Gusella, V. (2015). Structural investigation of 18th-century ogival masonry domes: from Carlo Fontana to Bernardo Vittone. *International Journal of Architectural Heritage,* 9(3), 265-276.

Chudley, R., and Greeno, R. (2005). *Construction technology*. (4th ed.). Malaysia: Pearson Education, 122-131.

Como, M. T. (2006, March) *Analysis of the statics of the Mycenaean Tholoi.* Paper presented at the Proceedings of the second international congress on construction history, United Kingdom.

Cowan, H. J. (1977). A history of masonry and concrete domes in building construction. *Building and Environment*, 12(1), 1-24.

Dahmen, J., and Ochsendorfs, J. (2012). Earth masonry structures: arches, vaults and domes. In M. R. Hall, R. Lindsay, and M. Krayenhoff (Eds.), *Modern Earth Buildings*. UK: Woodhead Publishing, pp. 427-460.

De Matteis, G., Cacace, D., and Rouhi, J. (2019, April) *Masonry vaults: architectural evolution, structural behaviour and collapse mechanisms.* Paper presented at the Proceedings of the 7th International Conference Structural Engineering World Congress, Istanbul.

Denison, E., and Glancey, J. (2018). *30-second architecture: the 50 most signicant principles and styles in architecture*. UK: Ivy Press, 56-92.

Drioueche-Djaalali, N.-K., and Chabbi-Chemrouk, N. (2017). Traditional construction techniques of domes in the Kasbah of Algiers (1500-1800). *Construction History,* 32(2), 1-18.

Dugum, H. H. F. F. (2013). *Structural Assessment of The Guastavino masonry dome of the Cathedral of Saint John the divine*. Master thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts, 13-28.

El-Sheikh, A. (2000). Configurations of braced domes. *Advances in structural engineering,* 3(3), 231-244.

Fernandes, F. M., Lourenço, P. B., and Castro, F. (2010). Ancient clay bricks: manufacture and properties. In R. P. Maria Bostenaru-Dan, Akos Török (Eds.), *Materials, technologies and practice in historic heritage structures*. (1st ed.). USA: Springer Science and Business Media, pp. 29-48.

Fiala, J., Mikolas, M., and Krejsova, K. (2019, March) *Full brick, history and future.* Paper presented at the IOP Conference Series: Earth and Environmental Science, Prague, Czech Republic.

Fraddosio, A., Lepore, N., and Piccioni, M. D. (2019). Further refinement of the corbelling theory for the equilibrium analysis of corbelled domes. *Curved and Layered Structures*, 6(1), 30-40.

Ganobjak, M., and Carstensen, J. V. (2019, November) *Topology-optimized insulating facebrick with aerogel filling.* Paper presented at the Journal of Physics: Conference Series, Switzerland.

García-Alvarado, R. (2013, July) *Design and visualisation strategies in parametric building components.* Paper presented at the ARCC Conference Repository, North Carolina, USA.

Ghasempourabadi, M., Mahmoudabadi Arani, V., Bahar, O., and Mahdavinejad, M. (2012). Assessment of behavior of two-shelled domes in Iranian traditional architecture: the Charbaq School, Isfahan, Iran. *Transactions on Ecology and the Environment,* 155, 1223-1233.

Hasol, D. (1993). *Mimarlık sözlüğü*. (1st ed.). Istanbul: Yapı-Endüstri Merkezi, 389-394.

Hassan, A. S., Mazloomi, M., and Omer, S. (2010). Sectional analysis of pendentive dome mosques during Ottoman Era. *Canadian Social Science,* 6(5), 124-136.

Heyman, J. (1997). *The stone skeleton: structural engineering of masonry architecture*. (1st ed.). UK: Cambridge University Press, 1-47.

Hodge, J. C., and Thorpe, M. (2006). *Brickwork for apprentices*. (4th ed.). UK: Elsevier Ltd., 4-31.

Huerta, S. (2007). Oval domes: history, geometry and mechanics. *Nexus Network Journal*, 9(2), 211-248.

Hung, C. W. (2009). *A comparative study of structural material for dome construction.* Master thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts, 15-33.

Hurol, Y. (2015). *The tectonics of structural systems: an architectural approach*. (1st ed.). New York: Routledge, 53-80.

Kereshmeh Afsari, Matthew E. Swarts, T. Russell Gentry (2014). Integrated generative technique for interactive design of brickworks, *Journal of Information Technology in Construction (ITcon)*, 19, 225-247.

Köseoğlu, G. Ç. (2011). *Investigation of a damaged historical mosque with finite element analysis.* Master thesis, Middle East Technical University, Ankara, 4-43.

Kuban, D. (2016). *Mimarlık kavramları: tarihsel perspektif içinde mimarlığın kuramsal sözlüğüne giriş*. (13th ed.). Istanbul: Yem Yayın, 30-58.

Lange, C., and Holohan, D. (2019, April) *Ceramic information pavilion-rethinking structural brick specials through an indexical 3D printing method.* Paper presented at the Intelligent and Informed - Proceedings of the 24th CAADRIA Conference, Hong Kong.

Lazar, N. A., Kadane, J. B., Chen, F., Cavanagh, W. G., and Litton, C. D. (2004). Corbelled domes in two and three dimensions: The Treasury of Atreus. *International statistical review,* 72(2), 239-255.

Lourenco, P. B., Milani, G., Tralli, A., and Zucchini, A. (2007). Analysis of masonry structures: review of and recent trends in homogenization techniques. *Canadian Journal of Civil Engineering,* 34(11), 1443-1457.

Lourenço, P., Roca, P., and Modena, C. (2006). Behaviour of masonry vaults and domes: geometrical considerations. *Structural Analvsis of Historical Constructions, 2*, 1031-1040.

Mainstone, R. J. (1999). The dome of St Peter's: structural aspects of its design and construction, and inquiries into its stability. *AA Files*, 21-39.

Makowski, Z.S. (1984). *Analysis, design, and construction of braced domes*. (1st ed.). New York: Nichols Publishing Company, 32-138.

Marder, T. A., and Jones, M. W. (2015). *The Pantheon: from antiquity to the present*. (1st ed.). USA: Cambridge University Press, 21-59.

Massoud, P. M. (2018) The Versatility of using bricks to produce generative monolithic surfaces using different construction methods. *International Journal of Current Engineering and Technology,* 8, 6.

Melaragno, M. (1991). *An introduction to shell structures*. (1st ed.). New York: Springer Science and Business Media, 13-55.

Ortega-Andrade, F. (1995). La construcción etrusca (II). *Revista de Edificación,* 11-20.

Öztürk, Ş., Bayraktar, A., Hökelekli, E., and Ashour, A. (2019). Nonlinear structural performance of a historical brick masonry inverted dome. *International Journal of Architectural Heritage,* 14(8), 20.

Penelis, G. G., and Penelis, G. G. (2020). *Structural restoration of masonry monuments: arches, domes and walls*. (1st ed.). USA: CRC Press, 32-44.

Reyhan, K. (2011). *Architectural characteristics and construction techniques of domes in a group of ottoman baths*. PhD thesis, Izmir Institute of Technology, İzmir, 9-126.

Rovero, L., and Tonietti, U. (2012). Structural behaviour of earthen corbelled domes in the Aleppo's region. *Materials and structures*, 45(1), 171-184.

Sakkal, M. (1995). Geometry of ribbed domes in Spain and North Africa. *Journal for the History of Arabic Science*, 11, 53-73.

Saraç, Y. (2005). *Optimum design of pin-jointed 3-d dome structures using global-optimization techniques*. Master thesis, Middle East Technical University, Ankara, 8-24.

Savaşır, K. (2016, June) *Kubbelerin yapım sistemlerinin yük aktarım prensiplerine göre İrdelenmesi.* Paper presented at the 8. Ulusal Çatı ve Cephe Sempozyumu, Mimar Sinan Fine Arts University, Istanbul.

Schibille, N. (2016). *Hagia Sophia and the Byzantine aesthetic experience*. (1st ed.). United Kingdom: Ashgate Publishing Company, 49-70.

Shakir, A. A., and Mohammed, A. 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 (IJAAS)*, 2(3), 145-156.

Shalunts, G., Haxhimusa, Y., and Sablatnig, R. (2012, July). *Architectural style classification of domes.* Paper presented at the 8th International Symposium on Visual Computing, Crete, Greece.

Snijders, M. (2020). *Corbelled Dome Design Using HCEB.* Bachelor thesis, Delft University of Technology, Delft, 3-19.

Turan, Ş. N., ve Yaldiz, E. (2018). XIII. Yüzyıl Konya mahalle mescitlerinde kullanılan kubbeye geçiş elemanları. *Türk İslam Medeniyeti Akademik Araştırmalar Dergisi,* 13(26), 163-187.

Uçak, Ş. (2012). *Tarihi yığma kubbelerin dinamik davranışlarının operasyonal modal analiz yöntemiyle belirlenmesi.* Master thesis, Karadeniz Technical University, Trabzon, 2-11.

Internet: (URL-1). Retrieved from https://science.jrank.org/pages/1022/Brick-History.html, Access Date: 27.03.2021

Internet: (URL-2). Retrieved from https://sullivanengineeringllc.com/2018/02/28/history-brick-masonry/, Access Date: 25.03.2021

Internet: (URL-3). Retrieved from https://www.bbc.com/news/business-47643925, Access Date: 08.05.2021

Internet: (URL-4). Retrieved from https://ceramics.org/ceramic-tech-today/construction/the-many-types-of-bricks, Access Date: 03.04.2021

Internet: (URL-5). Retrieved from https://www.thebalancesmb.com/bricks-types-uses-and-advantages-844819, Access Date: 05.04.2021

Internet: (URL-6). Retrieved from https://www.archtoolbox.com/materials-systems/masonry/brickbonds.html, Access Date: 04.04.2021

Internet: (URL-7). Retrieved from https://www.britannica.com/technology/brick-building-material, Access Date: 06.01.2020

Internet: (URL-8). Retrieved from https://www.thebalancesmb.com/mixing-mortar-tips-mix-like-a-pro-844820, Access Date: 02.04.2021

Internet: (URL-9). Youssef, Maged. Power of domes in architecture. Retrieved from https://www.researchgate.net/publication/342513215_POWER_OF_DOMES_IN_ARCHITECTURE, Access Date: 04.05.2021

Internet: (URL-10). Retrieved from https://donsmaps.com/mammothcamp.html, Access Date: 08.05.2021

Internet: (URL-11). Retrieved from https://www.re-thinkingthefuture.com/architectural-styles/a2615-evolution-of-domes-in-architecture/, Access Date: 08.05.2021

Internet: (URL-12). Retrieved from https://romeonsegway.com/10-facts-about-the-pantheon/, Access Date: 06.05.2021

Internet: (URL-13). Retrieved from https://goc-stthomas.com/metropolitan-evangelos-statement-3/, Access Date: 04.06.2021

Internet: (URL-14). Retrieved from https://tr.pinterest.com/pin/567523990549602157/, Access Date: 04.06.2021

Internet: (URL-15). Retrieved from https://www.hisour.com/st-pauls-cathedral-london-united-kingdom-5690/, Access Date: 05.06.2021

Internet: (URL-16). Retrieved from https://thestonetrust.org/master-class-masterclass-theory-of-corbelling/, Access Date: 25.05.2021

Internet: (URL-17). Retrieved from http://www.earth-auroville.com/avd_construction_en.php), Access Date: 04.06.2021

Internet: (URL-18). Retrieved from http://kenney-mencher.com/pic_old/aegean/aegean_helladic.htm, Access Date: 05.04.2021

Internet: (URL-19). Retrieved from https://tr.pinterest.com/pin/663577944936127 17/, Access Date: 06.06.2021

Internet: (URL-20). Retrieved from https://www.britannica.com/topic/Saint-Basil-the-Blessed, Access Date: 04.06.2021

Internet: (URL-21). Retrieved from https://www.britannica.com/topic/Taj-Mahal, Access Date: 04.06.2021

Internet: (URL-22). Retrieved from https://www.wanderingitaly.com/blog/article/1186/sanctuary-of-vicoforte, Access Date: 04.06.2021

Internet: (URL-23). Retrieved from https://www.cittaecattedrali.it/en/bces/375-santuario-basilica-della-nativita-di-maria-regina-montis-regalis, Access Date: 04.06.2021

Internet: (URL-24). Retrieved from https://mrandmrshalal.com/muslim-friendly-destinations-for-summer-2018/, Access Date: 04.06.2021

Internet: (URL-25). Retrieved from https://www.segwayfunrome.com/st-peters-basilica/, Access Date: 06.06.2021

Internet: (URL-26). Retrieved from http://architectuul.com/architecture/opera-house-dortmund, Access Date: 06.05.2021

Internet: (URL-27). Retrieved from https://www.pallasweb.com/deesis/dome-of-hagia-sophia.html, Access Date: 03.06.2021

Internet: (URL-28). Ramli, Muhammet. Multiple domes and semidomes construction: lessons from Hagia Sophia. Retrieved from https://awa.auckland.ac.nz/index.php?p=architecture-planning&textid=1498, Access Date: 03.06.2021.

Internet: (URL-29). Retrieved from https://archive.org/details/characterofrenai00mooriala/page/17/mode/1up?view=theater, Access Date: 12.05.2021

Internet: (URL-30). Retrieved from https://www.princeton.edu/news/2020/05/21/double-helix-masonry-researchers-uncover-secret-italian-renaissance-domes, Access Date: 12.04.2021

Internet: (URL-31). Retrieved from https://tr.pinterest.com/pin/327919035075789317/, Access Date: 12.05.2021

Internet: (URL-32). Retrieved from https://www.thoughtco.com/how-strong-louisiana-superdome-roof-177712, Access Date: 12.05.2021

Internet: (URL-33). Retrieved from http://fgg-web.fgg.uni-lj.si/~/pmoze/esdep/master/wg14/l0500.htm, Access Date: 15.05.2021

Internet: (URL-34). Retrieved from http://www.arquitecturapopular.es/arquitectura-historica/religiosa/estructura-haram-mezquita-cordoba.htm, Access Date: 16.05.2021

Internet: (URL-35). Retrieved from https://www.archdaily.com/572135/ad-classics-montreal-biosphere-buckminster-fuller?ad_medium=gallery, Access Date: 20.05.2021

Internet: URL-36. Retrieved from https://www.worldhistory.org/Hagia_Sophia/, Access Date: 04.06.2021

Internet: (URL-37). Retrieved from https://parametric-architecture.com/arbor-arena-by-selvagen/, Access Date: 22.04.2021

Internet: (URL-38). Retrieved from https://parametric-architecture.com/project-egg-by-michiel-van-der-kley/, Access Date: 04.06.2021

Internet: (URL-39). Retrieved from https://www.archdaily.com/883157/louvre-abu-dhabi-atelier-jean-nouvel, Access Date: 19.05.2021

Internet: (URL-40). Retrieved from https://www.designboom.com/architecture/parametric-dome-shaped-arena-selvagen-structure-tree-11-19-2018/, Access Date: 20.04.2021

Internet: (URL-41). Brick Industry Association. (2007, December). *Manufacturing of brick*. Retrieved from: https://www.gobrick.com/home, Access Date: 05.01.2021

Internet: (URL-42). Brick Industry Association. (2009, February). *Specifications for and Classification of Brick.* Retrieved from: https://www.gobrick.com/home, Access Date: 05.01.2021

*GAZİ GELECEKTİR...*