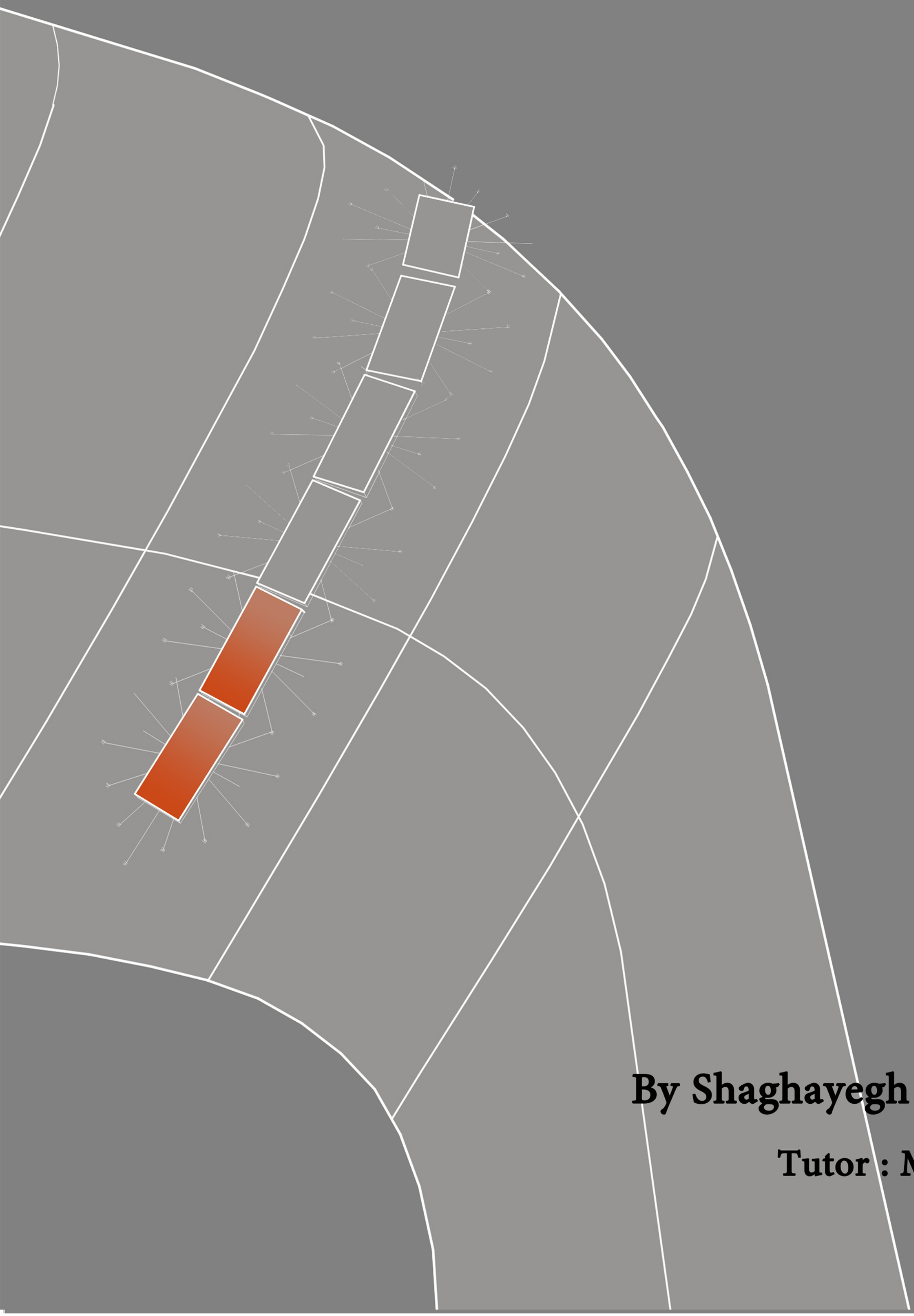
On the Computational Design

of Free-form **Masonry Vault**



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Abstract

For many years, shell structures have had an important role in architecture and engineering. After the industrial revolution and shifting from masonry construction to steel and concrete, the social, economical and environmental role in masonry construction has been underestimated. Targeting to use the digital tools, this thesis is proposing a method to re-design vaults and domes at present time, respecting the current architectural requirements. Reviewing the brief background of masonry construction and looking over the recent researches, two workshops have been processed in Politecnico di Torino. Both workshops were concentrated on designing and constructing free-form masonry shells by help of digital tools and computational methods. Regarding the results of these practical experiments, a tool has been created developed, which helps the masonry shell designers to model the brick patterning automatically on a curved surface. This research is exploiting the process of developing this method by means of digital tools. The bricklaying is simulated inside the 3D virtual environment by integrating the scripting language, Python, and commercial CAD software, Rhinoceros. Not ignoring the role of the designers in the decision-making procedures, this tool is implemented as an interactive method between the designers and the digital tools.

keyword: *Brickshell, Masonry vaulting, Computational morphogenesis, Brick pattern*

Contents

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Introduction

Masonry is one of the simplest construction techniques but at the same time one of the richest methods as it can take any role from a planar wall to complex curved surfaces. The history of masonry construction dated back to thousands of years ago when first examples of urban civilizations emerged. In arid areas where there was the lack of wood, masonry was the only solution of constructing a stable and long lasting structure. Masonry material is very strong in compression but behaves very weakly in tension. For centuries, the big challenge for architects was finding the geometries that could work totally under the compression loading. In the history of the architecture, they were trying to find a proper geometry which could work entirely in compression. Most of the historical buildings were spanned by dome and vault systems that only bear the compression forces. The form and the structural behavior of these systems are integrated with each other. For designing a vault or dome, the masons had to satisfy aesthetic issues as those of functionality and stability of the structure at the same time. Since the emerging of True vault from the false arch 4000 BCE, masonry structures were developed to more complex systems until the Industrial revolution era when it was started to transform from masonry construction to iron and concrete. In Contemporary architecture steelwork or reinforced concrete is the automatic choice of most of the architects. Nowadays, masonry buildings are mostly constructed in developing countries where it is frequently used as the separating walls or with reinforcement by iron.

Today we live at the time of Montage and industrial production dominancy.

Craftsmen of past days have become the workers who work in the industrial companies to produce prefabricated materials. A lot of energy and budget are cost to import materials from long distances to a construction site while masonry materials are able to be produced in local factories. Masonry materials strongly depend on the location of their derivatives. This property not only localizes the masonry buildings but also realizes the concept of zero km construction. The masonry has the capability of integration with local traditions both in form and technique. Masonry is labor intensive. To achieve a pleasing result, it requires the skills and meticulousness of craftsmen. It is the entrepreneur material since very simple types of tool such as a trowel and a shovel are required to build a complex structure. Masons aid each other, hand materials to construct even such a large building that a human mind can barely conceive. The vaults and domes technique is a type of construction, which can be done with cooperation method. It is a proper technique of social cooperation in construction of communal infrastructures like schools and health care facilities. These properties are able to make the masonry structures a good alternative for today 's requirements and problems.

Although there have been a lot of developments in other construction techniques, it seems that masonry structures are still designed and constructed with traditional tools and methods. CAD/CAE software have facilitated the design process and have increased the accuracy and speed of construction. Except some recent researches, there has been rarely attempting to develop the masonry method with the help of digital technology and computational methods. Especially the late researches mostly are useful inside the laboratories and are hardly applicable for usual constructors and designers. This study is an approach using innovative tools and methods for construction of masonry vaults. Specifically, it is developing new tools for assisting the construction of free-form brick surfaces, which are the new form of traditional brick vaults. After some primary studies on masonry construction also based on our group's practical experiences on masonry vaulting, it was come to conclusion that there is a big gap for an interactive design tool for modeling brick pattern on curved surfaces. Although a brick pattern on masonry structure is a part of a sequence of technical decisions that influences on strength, stability, constructability, aesthetic and economy of the structure, there are not adequate tools for designing the brick pattern on masonry structures. Especially the lack of a designing tool is more significant for curved surfaces as there are not any specific rules or standards for applying brick patterns on them. This study in detail tries to develop a tool for automating the modeling of the brick pattern on free-form surfaces.

This thesis is divided into four main parts. First part focuses on the state of art and literature reviews. Chapter one is *Problem Statement* and describes the motivation behind the research, hypothesis and tools and methods used to proceed this thesis. The morphology of vaulting and domes is studied in the second chapter. The classification of the vaults and domes based on geometry and structure is presented throughout this chapter. Furthermore, it is studied the role of secondary elements in a structural formation of domes and vaults. The third chapter reviews the historical development of masonry vaults. This chapter studies the significant examples of vaults and domes which their construction methods, geometries or materials were innovative at the time of construction. Masonry vaulting in the nineteenth and twentieth centuries is researched in the third section. The last section of this chapter studies the examples of masonry vaulting that are constructed as a part of contemporary architecture. The final chapter of the first part is specified to study about the research in masonry construction, specifically free-form masonry vaults. It covers the projects developed by digital tools and innovative methods. The outcome of this part would be the understanding series of methods, structural behaviors of forms, materials and innovative computational tools and software, which aid to design and construct a contemporary masonry vault.

Second part is allocated to the practical experiences of masonry free-form design and construction. These experiences were held as a part of the *Computational Morphogenesis Workshop.* First section of this part, chapter five, reviews the cooperative experience in designing, constructing and structural testing of a free-form surface through the Computational Morphogenesis workshop 2013. Not replicating the ancient forms, but contemporizing masonry construction for today's architecture and finding innovative methods were the objectives of this workshop. In this section, it is also described the load bearing test that was applied on the *Brickshell.* It reviews the utilized tools, methods and shows the result. The sixth chapter talks about the Computational Morphogenesis workshop 2014. The aim of the workshop was constructing a free-form vault by using *Catalan* method. It is mentioned the process of form-finding, designing the scaffolding and bricklaying. The methodology of this part is the combination of studying the other similar research and practical experience. The outcome of this part is supposed to clarify the procedure of the design and construction process of a free-form masonry vault.

During the construction process on workshop 2013, we faced some problems of bricklaying. It was required to produce a lot of non-standard bricks, which should have been cut without any stencil model. It decreased the speed of construction deciding on brick courses, especially when more than two bricklayers were working together. Based on these experiences the main objective of the thesis has been focused on developing a tool for modeling the brick pattern on free-form surfaces interactively and automatically. The third part of this thesis describes the process of developing above mentioned tool. The tool has been developed by means of programming software and commercial 3D computer graphics. Chapter seven reviews the brick pattern types and methods and researches about them. The geometry of bricklaying is explained in chapter eight. The developed tool is a plug-in for Rhinoceros software. Chapter nine and chapter ten, in more detail, describe the process of tool developing. They explain the logic of tool and review its commands.

Part four is specified to application of the developed tool on different examples. First results were applied on simple geometry-surfaces. They helped to know the weakness of the tool and requirements of the users. It was also applied on the Brickshell surface designed in the workshop 2013. By using this tool, the brick patterns on both layers of the surface were designed and modeled. It helped to derive the shapes of the non-standard bricks. By the help of this digital tool, the construction process was simplified, and the duration was decreased.

Part I

Introduction to search in masonry vault

Chapter 1

Problem Statement

1.1 Motivations and Objectives

Masonry is the most spreading technique in the world. Stone and soil are abundant and inexpensive. Through the centuries, there have been invented many techniques to construct durable and long-term life buildings using masonry materials. All around the world people are still using the masonry buildings that are hundred years old. Deeply rooted to the earth, it is the local method of construction. Short trip to *Monferrato* a small region in Piedmont, Italy, it is found small villages very close to each other but with different type of masonry material. Regarding geology at the buildings of one village is constructed of brick and sandstone and the buildings of another one are constructed of sandstone and blue marlstone. Masonry is the dominant material in traditional architecture of Iran but with a vast variety. Some parts are constructed of adobe, some parts with limestone and some parts with baked brick. Masonry is labor intensive and do-it-yourself method of construction. All these make the masonry construction a zero kilometer construction regarding the energy consumption and human sources. The reproduction of masonry technique regarding the current social and economic requirements, it seems to be a good solution for contemporary architecture. Masonry material such as brick and stone are strong in compression but weak in tension. Arches, vaults, and domes are geometries that can work entirely under the compression loading. There is a long time that digital technology, Computational tools, and CAD/CAE software are integrated to design and architecture, but masonry structures have been constructed approximately with the same traditional techniques. Recently some researchers have been developing some tools and innovative techniques. But still there is a big gap in adopting masonry shells (vaults and domes) to contemporary architecture. This thesis is investigating the methods and tools lead to constructing an innovative free-form masonry vault. Taking advantage of computational methods and digital technology, this thesis is trying to find a new method of developing traditional methods of masonry vaulting with todays requirements and conditions.

1.2 Hypothesis and Strategies

The aim of this research was finding an innovative method for adopting masonry vaulting to contemporary architecture by means of digital tool and CAD software. While it has been a lot of development and innovation for another method of construction, the masonry has rarely considered as a method which can be developed by new technology. Not replication historical forms and methods, this research supposed to find a new tool to improve the weakness of masonry construction. It was supposed that integration of masonry construction with computer- aided design tools optimize the method and make it proper for contemporary architecture. For vaulting, the geometric characteristics of the continuum of the components and specific pattern of bricklaying adapted to them (blocks, mortars, etc.) are part of a sequence of technical decision and it influences on strength, stability, constructability, aesthetic and economy of the structure. Spreading the construction of free-form vaults, it is important to design and model the brick patterns for them. One of the primary hypothesis was using the computer- aided design software to automate the brick pattern design process based on modularity, interaction, and recursion. laying the brick in the curved shape is one of the main reasons that increase the construction duration. It was supposed that developing a tool that semi-automatically model the brick pattern, would enable the bricklayer to know the material requirements and brick shape and position which decrees the construction time and so construction cost. In order to approach innovation in masonry vaulting, the first step was reviewing the history of masonry construction from design point of view. It was important to know what the challenge of the masons was and what the solution was. In addition reviewing traditional and historical buildings shows the further development that each designer achieved than previous ones. It helps to know the weaknesses of this method that should be solved. Historical methods of vaults and domes were researched based on their form, structural behavior and method of bricklaying. They were studied from early beginning to very recent studies in universities and laboratories. The real knowledge of the specific method of construction may be not achieved except making hands dirty to get practical experience. It was planned two workshops of brick vaulting while this research was being developed. First one was organized to precisely know the gaps in brick vaulting construction. Through that workshop, it was supposed to confirm the objective that the digital tool should be developed to achieved. The second workshop was planned to use the developed tool to construct a brick vault.

1.3 Methodology and Tools

The procedure of this research was based on the studying all the methods and possibilities, choosing the best solution considering the available facilities and requirements and achievement of the result based on the practical experiments and structural analysis in the laboratory. The historical review was studying the forms, structural behaviors, construction methods, scaffolding, and any other innovation that was applied by designers at the time. Two practical experiments of masonry construction were programmed as a part of *Computational Morphogenesis* workshop. The workshops have two phases, the design phase, and the fabrication phase. The design phase was developed by using 3D commercial software, Rhinoceros and Grasshopper that is a plug-in for Rhino and it is a tool for parametric design. The *GSA* software production of *Oasys* software company was used as a numerical structural analysis tool. The *Rhinovault* a form-finding tool for compression-only shells developed by Block research Group was used for finding optimized shape of the vault. The designs were constructed by using simple and cheap material. The scaffolding was installed by using second-hand cardboards. The bricks were provided by a brick company near to Turin, extruded brick for the first workshop and thin normal brick for the second workshop. The mortar was Gypsum in the training phase of construction and for the main construction it was the mixture of sand, gypsum, and water. The mortar of the second workshop was the mixture of sand, cement, and water. A load bearing test also applied to the shell that constructed at the first workshop. The test was preceded by using sensors (LVDT) that measure the displacement of each the points of vault during the loading. The loading was simple sand bags. Through the result of the first workshop, it was confirmed to develop a tool to automation of the brick pattern modeling on free-form surface. Scripting codes helps to do the repetitive tasks by a single action. This tool has been developed by means of programming (python scripting language) and Rhinoceros software.

Chapter 2

Morphology: geometry and structure

Masonry construction has been constructed all around the world since eight thousand years ago until now but more or less with same traditional methods. While it has been a lot of developments on other techniques, there has been a lack of attempts to adopt the masonry construction specially masonry vaulting with innovative tools and new methods. This part describes some important techniques of masonry construction aided to construct some of the architectural masterpieces.

2.1 The transformation form ‘false‘ arch to true arches

First attempts of constructing the permanent architecture in Mediterranean areas; started by piling up flat pieces of limestone in sloping form. This method of masonry units laying is known as the corbelling. False arch, false vault, and false dome are corbelled structures that were the origin of advanced radial joints [30]. Although the walls admit the sloping, the structure required to enclose by a wooden beam or big stones. The name *False* referred to this falsely lintel [41]. The false structures are safe if vertical joints positioned in such way to prevent overturning of any of the blocks and the blocks act in group [30]. This method developed to construct the round vault and domes. Back to 4000 and 5000 years BC in Mesopotamian region and lower Egypt it was discovered the first trace of true vault was a small barrel vault [30] and about 1350 BC in the Peloponnesus the corbelled technique was developed enough to construct the perfect domes of advanced courses. For many centuries, the *Treasure of Atreo* was the greatest dome ever constructed [41].

2.2 Vaults classification

A Masonry arch is a curved structure spanning element that works only in compression. Geometrically an arch is supposed as a two-dimensional element while vault and dome are three-dimensional structures. Transmitting from false arch to true vault and true dome opens the possibility of spanning the larger openings. Vaults and Domes are the techniques of spanning the space. These structures are compression only structures which are used as the solution for overcoming the limited tensile capacity of stone and soil [34]. Through the history, they have been invented many types of vaults and domes. The thickness and the geometry of vault have the direct influence on the structural behavior because of the thrust line being fit into the section of the vault. Thrust line indicates the path of compressive pressure force through the vault [34]. Disproportional loading along the vault might change the path of the thrust line and make the vault collapse. For instance, the path of pressure traveling along the steeper vaults are more vertically which makes the horizontal thrust smaller and decreases the requirements of reinforcement. This section is summarized introduction of some famous type of vaults and domes. Studying about these methods helps to know different design challenges of masonry construction and best solution for them.

Vault: Simple vaults are the result of extrusion the single arch, this kind of vault is called *barrel vault.* Early example of these curved structures is discovered in the Mesopotamian which date back to between the 4th and 5th millennium BCE [30]. According to arch that vault is driven from, there are the different type of the barrel vault such as semicircular barrel vault in Roman time, pointed barrel vault in Gothic time [90]. Barrel vault has a single degree of curvature. In the case of shaped as a simple geometry, it requires minimum guide work, two rigid arches at two ends of the vault, and a string between them. Barrel vault is more vulnerable to asymmetrical load. Comparing with double curvature vaults, to receive the horizontal thrust, it requires the less reinforcement edge support just in two sides [23]. The barrel vault because of the load speeding on its length is very limited to the openings only at two ends [64]. Overcoming this limitation, the *Groin vault* was innovated. The groin vault is composed of two barrel vaults. The diffusion of forces is along the principal axes of arch surfaces. If the cross vault is made of two pointed vaults they are also called ribbed vault and might be given thicker section in the place of intersection in order to stabilize the intersection. Forces are directed along the lines of these thicker parts called *ribs*. Cloister vault is also generated from two semicircular barrel vaults, but it is geometrically different from the Groin vault. The Cloister vault is supported on its four edge walls. Opposite to other vaults, it is completely closed because of surrounding with four lateral walls. But this kind of wall has been very commonly used in the different types of buildings (Figure 2.1) [30].

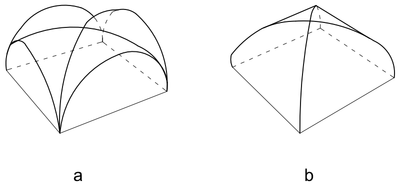


Figure 2.1: Geometry of Groin Vault and Cloister Vault

Entering ribbing or corrugation to architecture enabled the masons to construct more complex curvature across the more irregular plan. Different types of complex ribbed vault was the further development of Groin vault.

Curved rib vaults are developed by replacing the ribs with curves that the forces are distributed through them [64]. *Fan vault* is composed of equally curved ribs placed in equal distance in the radial pattern that provide curved shell or conoid [64]. The ribs in this method are always perpendicular to the vaulted surface [34]. Besides the classification of the vaults based on the geometry and load spreading, there are the other types of vault sorted based on the method of construction.

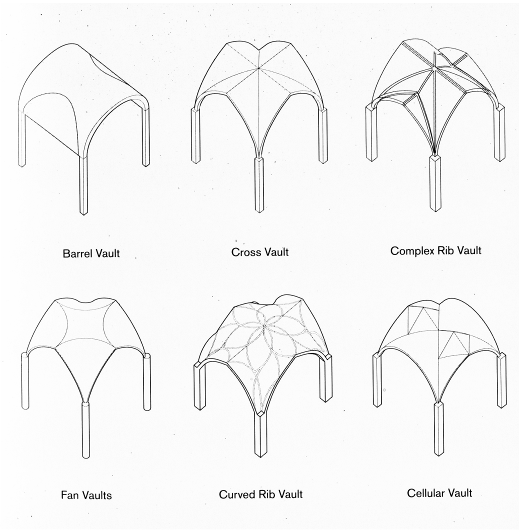


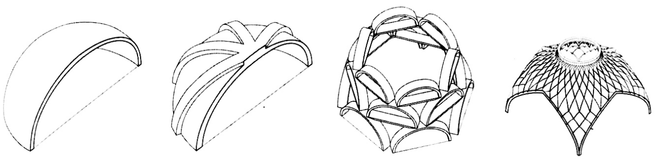
Figure 2.2: The classification of the vault base on form [64]

Timbrel vault, also known as *Thin-Tile vault*, *Catalan vault* or *Guastavino vault* is a Spanish historical masonry technique. This type of vault is a Mediterranean technique has been using since 15th century in Spain. Tiles laid flat to create the surface of the vault and tiles are stick together with their thin edges. These make the tile vaulting thinner than other vaulting methods. Typically the Timbrel vault concluded three layers of thin bricks. Bricks of the first layer are bonded with fast setting plaster to follow the geometry and prepare a layer for subsequent layers. Following layers are kept with conventional cement mortar [34]. The tiling pattern of each layer rotates 45 degrees to break continuous joints between the layers. Between

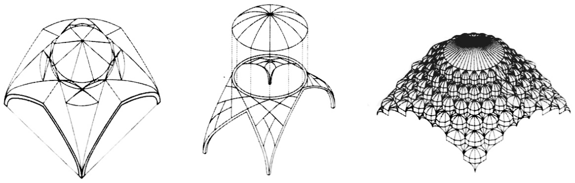
the 1870s and 1930s, Rafael Guastavino and his son through this method was successfully constructed hundreds of vaults over the buildings on the Eastern seaboard of the USA [66]. As Davis described in [34] and [23] *Nubian Vault* was originated form 1200BC. And was rediscovered by *Hassam Fathy* in 1980 who brought it to Mexico. Nubian vaulting mostly is constructed with the sun-dried earthen adobe. In both Nubian Vault, bricks are laid full bed, face to face and lean into the cross section of the vault. *Leaning Brick vault* is similar to Nubian vault in bricklaying method but different in geometrical aspects and construction sequence. Leaning vault is double curved vault, covering a square plan. It is constructed by being started from corners of the square, progressing continuously inward to create groins. The corners are shaped like squinch. The groin of the leaning brick vault has the cross-section with span at midpoint of it.
Undoubtedly there are other different methods of vaulting but introducing all types of masonry vaults are not the subject of this thesis.

Dome: According to Fletcher [44] *Dome* is a cupola or spherical convex roof, ordinarily circular on plan. It is an arch rotates around its vertical axis to form a hemispherical shape. Depends on being *Surface dome* or *Ribbed dome*, loads distribute in plane or along the ribs [64]. In surface dome, loads are transferred through any vertical intersection of the dome. It has good efficiency resisting the evenly distributed loads. Ribbed dome Consist of hemisphere and ribs which connect infill surface with each other. Loads are directed along the ribs and infill surfaces. Ribbed dome has a great efficiency resisting the asymmetrical loading. Other than these two type of domes, Moussavi in her book mentioned other types, *Stacked arch dome*, *Mugarnas dome*, *Yazdi-bandi dome*, *Kar-bandi dome* and *Kase-sazi dome.* She categorized these domes based on the load distribution and the degree of subdivisions of their surfaces. Except the Stacked arch dome, the others are mostly common in Iranian and Islamic architecture. Basically, the stacked arch dome is composed of the series of corbelled arches. The chains

of arches progress from the first line toward the apex. The arches form the nested arch, which direct the loads along them to the keystone of beneath arch. Muqarnas dome consists of squinches stacked together around a curve while pendentives fill the gap between them. This combination provides a flat surface for placing upper layer. Loads distribute along these subdivisions. In Yazdi- bandi loads are distributed along the diamond -shape elements interlocked each other to form the dome. Kar-bandi dome is a combination of cross vault and pendentives which distribute the loads. Kase- sazi dome consists of the number of shallow domes and set of pendentives [64].
This category is according what Moussavi mentioned in her book *Function of Form* and many famous structures are constructed by these methods. There are maybe other types that are not mentioned in this thesis.



Surface Dome Ribbed Dome Stacked Arch Dome Yazdi-Bandi Dome



Kar-Bandi Dome Kaseh-Sazi Dome Muqarnas Dome

Figure 2.3: The classification of the dome base on form [64]

2.3 secondary elements

Since emerge of vault and dome, different methods were invented by designers to overwhelm the structural or architectural problems of masonry elements such as arches, vaults, and domes. Some of these methods were achieved by setting up new elements to main elements. These new constructive devices in this thesis are known as the secondary elements.

Impost: Impost is a resting block on a column or wall serving a base for springer or the lowest voussoir of the arch i.e. it is the starting line of an arched opening or vault [90]. This element is structurally very important because for most types of arches mortar between the blocks are not capable of plastic deformation so the tensile stress imposed to Impost are very high [57]. This element usually was constructed with more emphasis on size. This element was a modification of similar element in Roman architecture and became common in Byzantine buildings [50]. *S. Apollinaire Nuovo*, constructed in 493-525 A.D., and *S. Apollinare* constructed in A.D. 538-549 are important three-aisled Basilican churches well known for their impost blocks [44]. According to Kurrer, [57] some recent test on historical bridges shows that Imposts were oversized for loading and increasing in size was unnecessary from the calculations point of views.

Corbel: Corbel seems that has borrowed the name from the corbelling arch which means laying the flat pieces of masonry units in steps to cover a half of the desired space [41]. As a structural secondary element corbel is a projecting stone or series of bricks *moulding* in step to support a weight [90]. If Corbels are constructed consequently to support a *parpet* or *cornice*, it is named corbel table. Corbel table is sometimes constructed in the arch module. In the sixteen century and following mostly in Scotland they were built many castles that the most characteristic features of them were round turrets carried by different types of corbels.

Squich: Squinch is a method of constructing dome over a square plan. It is formed in corbelled courses by bridging the corners of the square to form an octagonal base [55]. Some early examples are back to the first century in Iran. There are lots of examples in fire temples or palaces reaming from *Sassanian Empire* [71].

Pendentive: Pendentive is curved the triangle which transfers the weight from the great dome to the piers beneath, and makes it possible to place the dome on the square plan instead of circle one. This element is the characteristic feature of Byzantine architecture and enabled constructing of wider domes. It also made possible a union of centralized and longitudinal or basilican structures [55]. An extraordinary example of this technique is the dome of the Constantinople Cathedral, *Hagia Sophia*, from the sixth century. Squinch and Pendentive were dynamic solutions of setting a round dome on the square plan(Figure 2.4). They transfer the weight of the heavy dome to the pillars and moreover they allowed constructing dome without centering [90].

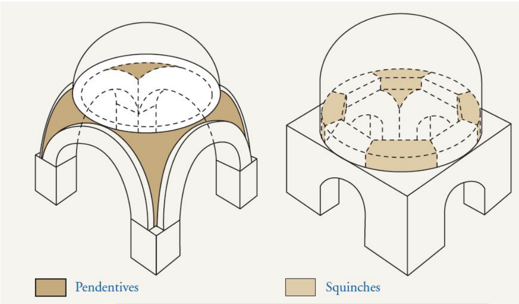


Figure 2.4: Geometry of Squinch and Pendentive [55]

Diaphragms Rib: Diaphragms walls or ribs are thin masonry walls of the vault that distribute point- load over the span of single curvature vault. This technique was used by *Guastavino* in some of his vaults constructed in United States [66].

It was also applied to the thin tile vaults in Low-Cost housing constructed by Block Group [23]. These methods and techniques were invented by masons to overcome the problems or make a big advancement in masonry construction. In next chapter, it is described some important examples using one or some of these techniques.

Chapter 3

Reviewing historical development of masonry vaults construction

One of the best references for learning about architecture is studying the historical structures. Historical overviews help to understand the changes in design and constructing across the ages and show the story of how overwhelming the design and structure issues [70]. There is a long history of the masonry shell construction. They should be studied to know that what the answers were to the structural and architectural problems. This part summarizes the evolution of masonry construction since beginning until recent examples.

3.1 Historical overview of domes and vaults construction

The mud bricks and stones of the Jericho, a small village constructed in 8000-7000 BCE in Palestine [55] is a strong evidence of masonry backward in the history of construction. It seems that because of the absence of permanent building material, the brick construction and arch and vaults started to improve in Babylonia. In Mesopotamia regions, Clay which was abundant material, first in the shape of sun dried flat square modules, then in the shape of kiln-burnt bricks and then in the shape of stone slabs from the mountains in Assyrian period was used in the construction [44]. Vaults are first invented by *Land Between Two Rivers*. First trace of baked brick vault was found at Ur constructed about 3500-3400 BC [70] False domes extracted from corbelled arches constructed by laying the flat pieces of limestone in steps were the primary phase to cover the space in the Mediterranean areas [41]. This technique was developed well enough to provide a perfect dome at Mycenae, Greece at 13001250 BCE which was the largest dome for more than 1500 years until the construction of the Pantheon [55]. Ancient architects and constructors developed the technique of stone and brick true arches which reached its maximum presence in Roman architecture. Roman concrete was an important breakthrough in construction of Vaults and true domes. It consisted of lime and lumps of tufa, peperino (kind of volcanic tuff), Brocken bricks, marble or pumice stone [44]. Thanks to Roman concrete *Pantheon* as the widest span covered without intermediate supports was constructed between 115 and 130 AD. The Pantheon was a perfectly circular drum covered with 43.3 m inner diameter and similar height hemisphere. The vault consisted of the curved lintel and superimposed three-dimensional arches which defuse the pressure to the walls. The ceiling composed of the hierarchy of hollows and cornices covered with concrete layer [70]. *Squinch* in *Sassanian Empire* facilitated construction domical vault over the square plans. *Palace of Ardashir* constructed AD 224 in Iran had three domes. The biggest one has 18 meter height. The building was constructed of local rocks [71]. Pendentive dome in *Byzantine era* led the constructing other remarkable masonry dome in *Hagia Sophia*. Pendentive transfers the weight from the great dome to the piers beneath and makes it possible to place the dome on the square plan instead of circle one [55]. The dome sits on the four transverse arches and pendentives transfer the domical dome to its rectangular base plan. The rigidity of horizontal thrusts is provided by two semi-domes in the northwestern and south-eastern sides which their forces were compensated with the shells of apse and four buttresses. The materials were brick and mortar obtained with the mixing of lime and crushed bricks [41]. The concept of vaulting started from Barrel vault back to between the 4th and 5th millennium BCE developed to variant complex vaults such as Rib vaults and Fan vaults, the process which continued until the advent of new materials era. Inventing Cross vault and in advanced Ribbed vault increased the complexity of vaulting in Gothic period [90]. The nave of Cathedral of *Holy Cross* in Germany Constructed between 1330-1552 is formed by the vaults which are subdivided by ribs to the small-scale rhomboid pattern [64]. The complexity of Ribbed vaulting of late 14th century and early 15th century led to an English type of vaulting named fan, palm or conoidal vaulting [44]. The fan vault of Kings College chapel in England completed by 1515 is the largest in the world. It spans 12.66 meters with a very thin thickness (10cm -15cm). Transverse arches divide the bays. Each bay is composed of four quarter fans and a central spandrel panel with a boss [21]. In fifteenth constructing of dome specially, the ribbed dome were rediscovered after the long time that had long been abandoned. *Cathedral of Santa Maria del Fiore* engineered by *Brunelleschi* and developed by *Michelangelo* is an outstanding example of this type of dome. Eight main ribs with circular with 36 meters radius and 8.8 meters width formed the dome and sixteen meridian elliptical ribs with 1.2 meter width formed their skeleton. Herringbone pattern was used as the brick arrangement [41]. The church of *Saint Lorenzo* in Turin designed by *Guardini* in 1668 is another example of ribbed dome. The loads are transferred through the sixteen star-shape bending ribs to the trumpet shells and then to the vertical columns which trumpet rest on them. The thrusts of the ribs are derived towards the vertical by means of a drum load that hides the curvature from the outside [41]. The chapel of *Sacra Sindone Chapel* in Turin constructed by Guardini in 1667 has a 15 m in diameter plan. The dome is a drum consists of six arches sit on the paired arches. From that level, six levels of superimposing arches started to ascend inward in a condition that each arch sits on the keystone of lower level. They end up with a circular cornice which implants a small dome made of a vegetal aspect mesh which imbeds the lantern [41]. *Kar-bandi* dome is an Islamic-Iranian architecture style for transforming load through the dome to the square pillars in plan. The entrance of *Masjed Noe* mosque in Iran constructed in 1750 is the combination of Kar-bandi base unit and two larger side arches. The dome directs the load along the surface to the compression ring to the top and through the pointed arch to the base. Pendentives fill the gap between compression ring and pointed arches [64].

These historical buildings are not reviewed just as records of events but to understand the changes in manufacturing and design across the ages. They are interpreted for being familiar with their influences on whole structural and architectural progression.

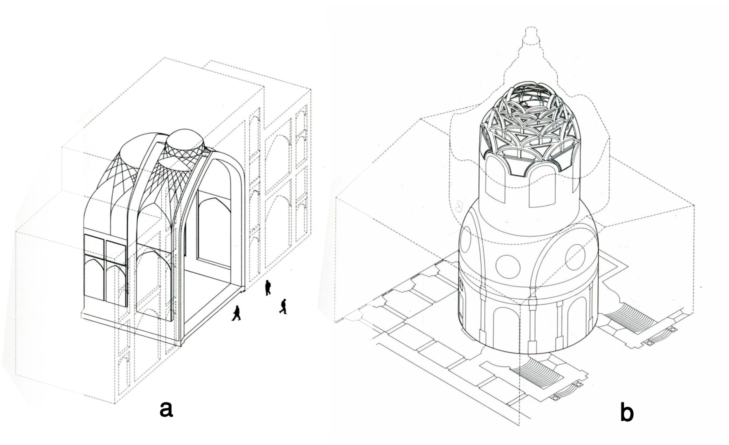


Figure 3.1: a)Kar-bandi dome in Masjed-noe(Iran), b)Stacked arch dome in Sacra Sindone Chapel (Italy) [64]

3.2 Masonry vaulting in nineteenth and twentieth centuries

The idea of progress in 19th century and industrial revolution motivated architectures to use new methods and new material and avoided past styles. This process highlighted the steel and concrete and faded the masonry from the construction industry [33]. New productions of the eighteenth century reduce its role as structural and protective elements to infill and sub-divided materials [16]. After the second half of 19th century, except few architects, it has been rarely novelties integrated to traditional methods of masonry construction.

Eladio Dieste innovated reinforced masonry (Ceramica Armada) is his brick construction [14]. In the cross- section of free-Standing and Gaussian system of Diesste, there was catenary shape [92]. *Eduardo Torroja* reinforced masonry with steel bars to resist tension [67].

Antonio Gaudi based on Catalan native architecture and parabolic arches and domes (non-circular shape) driven by form-finding methods in his designs. He used hanging cables; he added the corresponding weight to the cables. The cables under these loads adopt a specific shape. Through this method, he constructed many innovative structures such as the walls of *Parque Guell.* For designing vault, he used space hanging models as applied to the church of the *Colonia Guell* [69].

Rafael Guastavino and his son, immigrants from Spain to United States in 1889 brought the tradition of Catalan vaulting. During 70 years, their company constructed more than 1000 structures in US including some important historical landmark such as the Boston Public Library and New York Citys Grand Central Terminal by Catalan vaulting techniques [34]. This type of vault consists of three or four layers of thin bricks. in the first layer the bricks are bonded to each other by fast plaster that provides a layer for following brickwork. That period of time Tile vaulting was a revolutionary method for its economic profitability and speed in construction. Guastavino introduced this vault as a unified material (because of brick and mortar internal bonding together) and without any thrusts (because of their light weight, they provide fewer horizontal thrusts). Merging by the reinforcement method Guastavino(son) innovated in 19910 (he used steel bars between timbre vault) it was possible to construct the same comparable examples of vaults as the ancient time but lighter and short period [66].

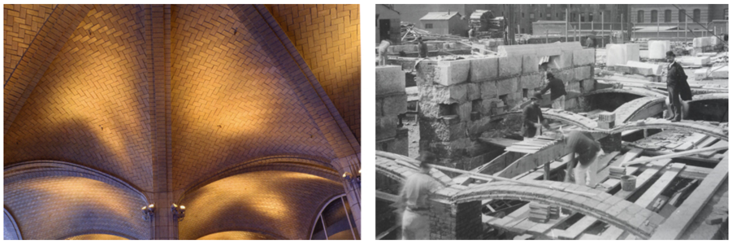


Figure 3.2: a) Tile arch supported by Ribs constructed by Guastavino b) Rafael Guastavino stranded on a newly built arch during the construction of the Boston Library, [66]

Louis Kahn was one of few architects who tried to give the brick back its structural character. At *Indian Institute* for management at *Ahmend Abad* the shear is absorbed through the segmental arches and at *Dhaka government* buildings circular walls cut open with spherical vaults [62] and [38].

3.3 Contemporary masonry vaulting systems

In recent decades *Alfonso Ramrez Ponce* who has designed and constructed buildings and houses since 1969 until now represents his will in reviving the traditional methods of vaults and domes constructing in contemporary architecture. Focusing on local material, techniques and even culture which influence on architecture and construction, also emphasizing the role of the artisan craftsmanship, he proposed traditional geometry in innovative shapes. His method concentrates on Mexican technique which is known as leaning bricks method [42]. He believes that culture is related to tradition and an architect should design and build with deep respect to particular societys culture. In addition, he believes that construction should be regional with admiration to environment and considering low energy consumption materials and high-efficiency structure [72]. In Mexico, he has constructed many vaults over different type of buildings such as hospital and house (Figure 3.3a).

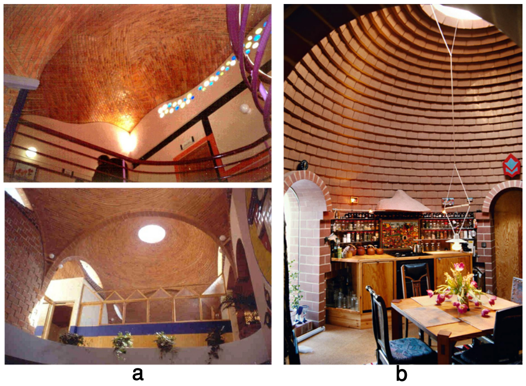


Figure 3.3: a) Hospital clinics Mexico designed and constructed by Ramrez Ponce [42], b) Residence cum office in Germany designed and constructed by Minke [63]

Gernot Minke is an architect that his main focus on Earth construction. He believes the earth is an abundant material that can be prepared with cheap and nonpolluting for constructing purposes. Using the natural material, he has constructed brick buildings included domes and vaults. Developing Nubian technique by adding rotational guide, the optimal geometry achieved without formwork by 20cm in thickness. He has constructed many buildings and house around the world with a dome over them including his own house in Germany(Figure 3.3b) [63].

There are definitely other architects around the world who are searching for new methods and innovative tools for adopting masonry shells to contemporary situation and requirements. But it seems that using steel and concrete are the first choice of the construction industry. Next chapter introduces recent research on masonry construction and more detailed brick vaulting.

Chapter 4

Recent developments: Innovative masonry construction

Masonry vaults are still being constructed all around the world however it is odd continuing construction of masonry structures with traditional installation and setting out methods without integration with computational methods, innovative tools and CAD/CAE software.

It might be considered that, lack of progress in vaulting techniques leads to fewer masonry vaults construction. Currently some researchers and architects are trying to apply computational methods and innovative tools to design complex geometry forms and optimize construction methods and structural behavior of masonry shells.

4.1 Virtual vision in architecture

The masonry vaults are still being built almost with the same laying out techniques, which were used 400 years ago. There is a little impact of digital technology in the construction field especially, masonry construction. Recently some researchers are trying to integrate augmented reality with the masonry construction. Removing the human errors, this method helps to build the complex shapes. The *Formation Studio* in Atlanta, America in 2010 experienced construction of the brick wall which was curved in all dimensions [8]. *Modelical* is an engineering and architecture company established based on the technology oriented methods [5] with the collaboration with *Bvedas Hispanas*. This company which is dedicated to designing and construction of innovative vaults structure [61], recently has developed a new method for free-form vaulting. The challenge was turning a virtual surface to the real surface without any physical reference and transferring the information to the bricklayer. The reference points linked to virtual environment and real environment must be very precise and accurate. The optical relationship between a camera and some predetermined objects was linked through the *Normal Vision* technique which is able to be installed on a mobile and undertaken by the computers. The system has been simplified the transferring the location of a point in reality to the virtual environment. Some marker series were printed on supporting plans. In further step, the camera distinguished the position of each marker series and the relationship between them could be obtained by using simple geometry patterns. The bricklayer took the camera with himself and moved it until it recognizing one of the markers. A conventional laser level determined the distance and position of a point where the brick should be placed [46]. This technique simplifies construction of the complex geometries surfaces without the formworks and the position of each brick can be found more accurately.

4.2 Vaults systems for low-cost construction

Sustainability ihas various delineations but in all of them, social, economic and environmental aspects are considered as the core of the notion. Accordance with the emerging concept, masonry vaulting seems to be a proper choice not only in areas with lack of trees and material but also in a country like UK. The *Pines Calyx Conference* building in UK is a good example of sustainable design and a sustainable merging of historic construction techniques with contemporary technologies and tools. The roof of building is a Catalan vault built in 2005 by the collaboration of MIT masonry group and English and Spanish masons [4]. It was constructed a shallow dome without any concrete and any requirements for formwork. The building has capacity of delivering a great weight of the vault and green roof above. The concept came from the idea of construction, by using local materials and low-intensity methods [4]. The techniques of constructing Catalan vaults are described in section 2.2. Based on this experience [4] the MIT masonry group constructed the *Mapungubwe National Park Center* in South Africa using Catalan vaulting method and locally made stabilized earth tiles made by local people. In this building the usage of reinforced steel and formwork were minimized . As the labor costs are low in relation to material costs in South Africa, the Catalan method seemed to be the appropriate vaulting style. The Centre is combined of ten free- form vaults with the rhythm of geological formation and earlier regional dwellings. For structural analysis, they used equilibrium method based on the graphic static to determine compression- only structure, by means of two-dimensional interactive thrust and network analysis system. Steel tension ties were used in reinforcement concrete buttresses resists the thrust across the longer span and barrel vault. Heymans theory was used to determine the thickness and degree of curvature. Since the vault becomes more stable with greater loads, they were covered with local stones. In addition, while tiles vaults provided the permanent shuttering for concrete floor system, as the part of the structure, they reduced the amount of the concrete. In the most cases, the light frameworks were used to visualize the shape of the vault [77]. As a result, it was saved large amounts of building materials and thus embodied energy. The building method was cheap; and because of Masonry's high thermal mass it is perfect for an energy-efficiency. Unskilled local workers were trained as masons as part of the project's Poverty Relief Program, and masonry construction is the part of the region culture now [9]. Tile vaulting with local material results better social, economic and environmental benefits when it is applied to the residential and dwelling buildings. Promoting the intermediate economics, finding a solution to the unemployment problems and lack of constructible land caused by population growth and urban migration, motivated *Block Research group* that by applying innovative techniques.These methods relies on vernacular construction, short use of material and resources also skilled labors [2]. The existing vernacular methods did not supply the needs for multi-story houses. Although it was cheap and affordable for poor, consuming limited natural resources and relied on imported material. For spanning a space, usually beams elements made of timber, steel or reinforced concrete , which work in bending, are used. These materials are mostly imported and would be considered expensive for Ethiopian and also would cause environmental impact on country. Therefore self-supporting roofs constructed with stone and soil are a good solutions for this area. The units of vaults were stabilized soil tiles that were manufactured by local labors [23]. For selecting a vaulting system for applying in Ethiopia, it was compared three methods of vaulting, European style, Nubian/Mexican style, and Catalan style. The European style is rejected because of cost and the amount of material which is required for the formwork. The other two styles are based on the funicular form, which is self-Wight supporting and resists only axial compression. The Catalan vaulting requires minimal centering and could be built with local materials. Nubian/Mexican style, back to 1200 Bc has been rediscovered by Hassan Fathy in 1980. Alfono Ramirez Ponce has combined this style with Central American vaulting and has named it Leaning Brick vault. This technique does not need centering. face bed brick are laid face to face to lean into the cross section of the vault. Usual cement mortar and even mud can be used and it has more tolerance for probable laying errors. The leaning vault has lower trust but steeper height, which could not be reasonable for floor system and require more infill material. In shallow vaults, it has more thrust force and it means that it needs more steel tension members to time back the vault. As a result, Timbrel method was used as the floor system and leaning bricks method was used for roof system [34] the method of their construction is explained in section 2.2. Avoiding the instability of vault caused by heavy symmetrical loading, stiffening diagram walls and stabilized fill on the top of the vault were applied while providing horizontal surface as the floor and distributing points load over a large area of the vault.

4.3 Nested Catenaries

The masonry arches are still interesting field for researchers to evaluate its spatial and structural potentials. Typically unreinforced masonry arches and vaults are strong in compression but weak in tension. They are also weak under non-uniform loads. These weaknesses make the masonry construction improper for seismic areas. *Performance-oriented Design* group is following a project dedicated to the structural and multi-functional capacity of masonry catenary arches and vaults by using nested organization system [51]. Catenary arch is a primary shape arch which acts in compression without tension [36]. Under the uniform loads this characteristic would optimizes the thickness of the structure. The catenary arch has weak bending under non-uniform vertical and horizontal loads. This research group tries to improve the bending resistance by modifying the geometry instead of increasing the thickness of the shell [6]. They use the form- finding method, computational modeling, Finite Element and comparative analysis in their research process. Testing the structural behavior of different shapes of shells constructed of similar material and under the similar loading was found out that the single transverse curvature resists horizontal and non-uniform loads much better than other tested shapes. It was implied that complex geometries have better structural resistance.The next stage was connecting one catenary shape to the other and evaluating the structural behavior that showed higher stability and stiffness compared to the single shell. Among the different combinations, it was indicated that common-plane combinations have a significant improvement in horizontal loading. Comparing the physical results with computational analysis, three full-scales nested catenaries were designed and constructed [92]. First prototype was an undulating wall formed from spatially organized nested catenary arches. The process was a combination of physical form-finding experiments with hanging chains, computational form-finding and associative modeling, and full-scale tests [6]. Removing the formwork, it was shown that the result was self-stable. The second phase of this research focused on the testing the effect of local shape of a catenary shell on the whole system of catenary nesting shell. The combination involved three shells, shell above which was a transition from concave to convex transverse with two base shells which were synclastic and anticlastic which were connected to each other. All the three shells had different shapes. The result of this phase was a thin masonry wall without reinforcement. Both of the two were constructed in the laboratory. The third phase was constructing a nesting catenaries shell in a seismic open area to evaluate. Chile is located in the seismic high activity area so it was an ideal place to test a structural behavior of a nesting catenaries shell in real seismic condition. The design consists of small interconnected sub-shells with two cavity walls that nested to the vault. In this project, the researches extended the influence of branching in creating tested spaces. All the catenary sub-shells were in the same form of synclastic surface curvature. Avoiding the production of a flat surface, the whole geometry was described in at least five transverse sections. In narrow-depth regions of the shell, the bricks had to be cut to the smaller size. The built structure has survived several earthquakes of between 6 and 7 Richter scale [92].

4.4 Form finding and optimization methods in masonry shell

In forms in which no bending occurs, the shape, and the forces have reciprocal relation [93]. masonry vaults are belonging to the form-active forms so understanding the relation of stability and form in structural behavior of masonry vaults opens up new possibilities for structural analysis and design for masonry shells [24]. Before the advent of computer, the form-fining methods were based on the physical models. Analyzing the thrust line was powerful graphical model for compression-only structures but just in 2-D cases. Adopting the advantage of graphical technique, Block and Ochsendorf proposed new method of from finding for compression only forms, named *Thrust-Network Analysis* [19] and [24]. The Graphic statics computes thrust lines and provides an appropriate visual representation of possible compression forces in the system and explores the range of equilibrium solutions limited by the minimum and maximum thrust [19]. This method provides the analyzing tool for complex geometries made by masonry and merges the structural and architectural design by using computational methods. It enables the user to control the equilibrium systems and to formulate an optimization problem. It starts with the discreet force networks visualizing all force paths in the vault, then the reciprocal diagrams to show the internal forces distribution. The relationship between these two determinate the shape of compression equilibrium over the vault. In the proposed method, the path loads can be defined throughout a surface as a three-dimensional network [19]. Thrust Network Analysis has been developed using Matlab, a programming language, and numerical computing environment and using RhinoScripting in Rhinoceros [24]. Based on this method, it is developed a Rhinoceros Plug-In named RhinoVAULT [83]. The development of this plug-in is supported by Block research group at ETH university [2]. This is a form-finding tool for free-form masonry vaults. The user by driving and controlling the diagrams of form and force which are bidirectional interdependent explores the structural form-finding process [84]. These are real-time modifying diagrams that enable the user to design novel and complex geometries. Using TNA method and RhinoVault, the developers of these tools, designed and constructed many thin-tile vaults [2]. Block research group with calibration of Masonry at MIT designed and developed the unreinforced stone vault. The vault was designed using Thrust Network Analysis [18]. *Free-form Catalan Thin-tile vault* was a project at ETH university. This project was the combination of high- tech design tools; Trust Network Analysis program, RhinoVault and CNC Fabrication, low- tech material; cardboard box as a guide work system and innovative shape based on the Catalan traditional vaulting [35], [36], [82].

4.5 Automated fabrication of masonry construction

Penalizing the brickwork and prefabrication in a plant environment, were the main motivation of merging robotic technology with masonry construction. This goal would set the brick construction with Flexible Manufacturing System [80]. In 1996, Carolina University succeeded to fabricate a brick wall by means of robot technology. They overwhelmed the challenge of gripping and handling the brick, controlling the brick by detecting the texture and color and brick placement by measuring the thickness of the mortar bed [80]. This integrated automation system in the construction field reduces construction time and effort [45]. Not only efficiency and cost but also the construction of the innovative building components with more aesthetic appearances are the main motivations for ETH university to establish a research group focused on the digital manufacturing [3]. They started by brick stacking that is the fundamental additive process [25]. Avoiding the load bearing issues the concentration was on the facing masonry [26]. One of the important differences of manual brick stacking and robotic method is its ability to place each brick in different position and angle with minimum error. Through an algorithm each brick is able to rotate in a different angle around its center point and could be placed in different positions. This type of arrangement enables construction of 3-D surfaces. This developed technique has enabled Gramazio Kohler Research group [3] to design and construct prefabricated brick faade for a winery building. The design is inspired from the grapes inside the basket close to the packing time. Falling of the grapes into the virtual baskets was digitally simulated. Angles, rotation and overlap of each brick was programmed to simulate this image in 3-dimensional design [3]. The facades were constructed by six-axis industry robot inside the laboratory, framed in the concrete lintel and and eventually were transformed to be installed.

Part II

Construction experiences: The Computational Morphogenesis Workshops

Computational Morphogenesis is an architectural master program in *Politecnico di Torino*. It is an interactive program for digital technology, computational tools and design which tries to link the break between architectural and structural design.It is aimed in this workshop to train students in both design innovation and on- site construction skills. Concerning the integration of innovative technology and traditional material, students are trained optimization techniques, digital tools, parametric applicants and basic programming codes to apply their knowledge in design and construction process. The participants of workshop consisted of master students, Ph.D. students as the coordinators and under the supervision of the professors.

Chapter 5

The BRICKSHELL Meditation Centre: A Collaborative Masonry Project

5.1 Concept, parameterization, cooperative design

5.1.1 Introduction

Concentrated on the role of poplar plywood in the field of technological research, in 2012 computational morphogenesis developed as the term of Mona Lisa Digital Design workshop intended to *Pop.for.Pav* pavilion for *MADE-expo 2012* [7].

In 2013, it was aimed to renew the use of masonry vaults regarding the requirements of contemporary architecture not merely by replacing ancient forms but in complex geometrical shape via generative algorithms and form-finding methods. Participants of the workshop were requested to use the digital skills and theoretical knowledge to design a free-form shape as a *Brickshell* which solves structural problems, as well as architectural problems. The Brickshell workshop training procedure included:

1. The definition of a specific architectural program, in order to concentrate the work on a real design problem.

2. A brief introduction of masonry vaults and their design issues, fabrication techniques, materials, historical and recent masonry construction potentiality in contemporary design.

3. The use of parametric design and digital tools as finite element modelers, simulators, structural optimization procedures, interactive design aids as the means of design activity. They were required mainly for designing of complex geometries and free-form shapes and analyzing their structural behavior.

4. The collaborative Open Source design approach, and the corresponding working environment, in terms of a two level sharing platform, its protocols and rules of interaction, in order to allow the participants to contribute to the project according to their own capacities, interests, and resources .

5. The organizing and designing the whole construction process, from the formwork to the laying of bricks and mortar, until the formwork removal.

Spreading the synergy as a foundation of the workshop, students were organized in a unique design group. Replacing the competition by association and cooperation instead of rivalry concentrates all energies and times of the members in the process of learning, design and construction of one project. Association of the students in the construction process revives the concept of workers as skill craftsmen and capacitates the memberships as a co-developer and dynamic member of the decision-making process.

5.1.2 Collaborative trainings

As the students were required to have active participation in the creation progression two exercises were planned to acquire the Cooperation as the important part of the workshop process. First training was developing a fairytale story started with specific beginning and finishing. The body of the story was developed by all the participants who added a part to the story and passed it to the other one. All reciprocates between the students were accomplished through a public Facebook page with possibility of saving all the versions. This exercise tried to simulate the policy of the open source Wikipedia page which all the contents are editable and expandable by the users without any owning consideration or authority just by agreement of the editors.

Second exercise was programmed to obtain the concept of optimization via a cooperation practice. In the training, students were asked to modify and improve an assigned Grasshopper algorithm by reducing the complexity without any disruption in its operations. Each student by turn edited the online file, specified the comment of edit and uploaded for accessing the next participants until all the participants accorded that the file reached its optimum status. This practice conceptualized to the students the simplifying a complicated duty to comprehensible steps and obtaining the best result with the least possessions.

These exercises were collaborative practice in which all the contributors had the opportunity of developing the different idea without losing proceeding of their own and qualified them to derive all possibilities and notions from one basic concept. The *Facebook* and *Worldchanging* webs were used for all activities and data exchanging in order to provide a network for the participants and as a platform for the other interested than the students to follow the workshop.

5.1.3 Architecture Program and Design Process

Distinguishing point of this workshop with some other similar experiences was the organizing an architecture program for design and defining a practical function for the building. Considering the facilities and resources of the workshop, a small meditation center for the *Politecnico di Torino* was specified as the outline of the design process. The concept of the building would be without any specific symbol of any religion or culture and would prompt a laic reflection of relaxing and self-consciousness. In order to start the first sketches, wide set of concepts and ideas were studied from the weeping willow tree, a common relaxing place in landscape architecture until the complex masonry texture constructed by robots. Different forms and techniques in similar masonry projects considered until the first sketches produced by the members.The picture below shows the concepts of the design.

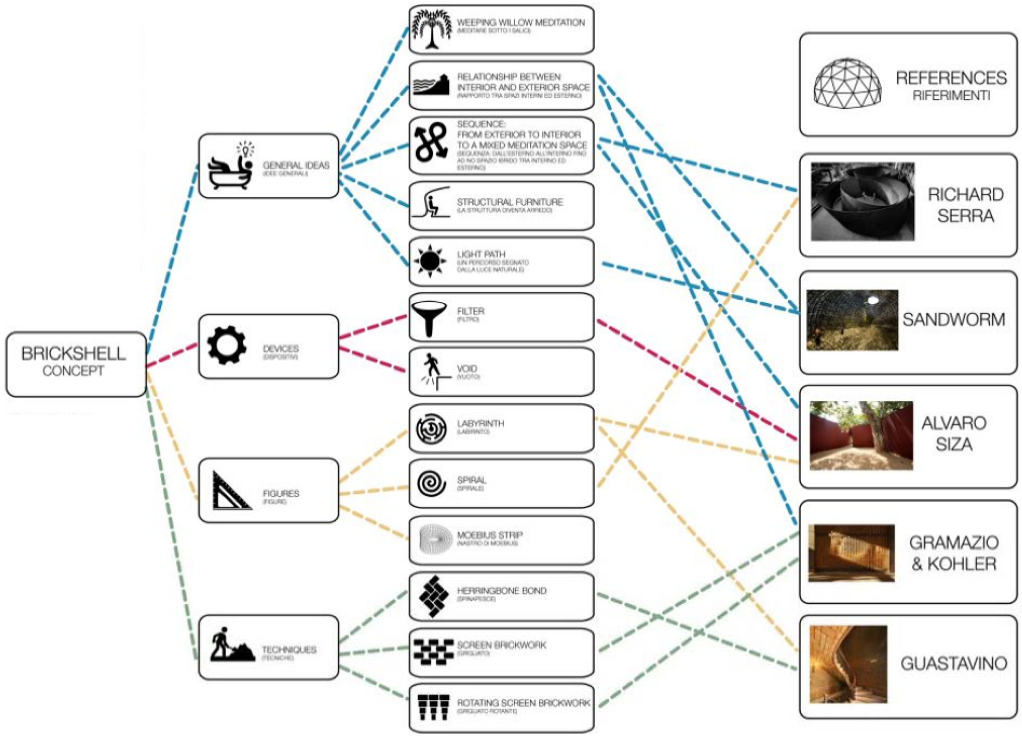


Figure 5.1: Diagram of the main concept of the workshop (Provided by Computational Morphogenesis)

Similar to the trainings, the ideas and sketches were discussed by all the students and the drafts were accessible in the public webpages. According to the group, the center supposed to provide the perception of the space around and it would be capable of keeping the continuity between external and internal spaces. The final design would consist of a covered space with an inner opening (Figure 5.2).

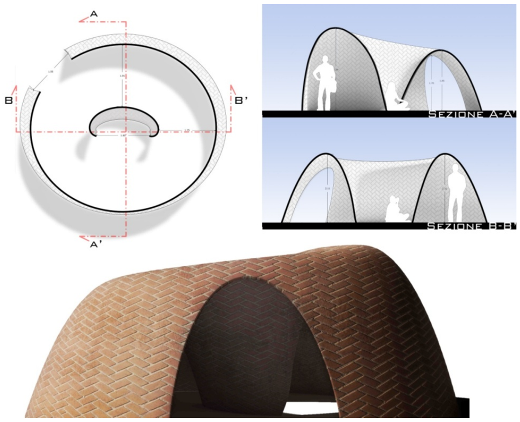


Figure 5.2: Final concept (Provided Computational Morphogenesis)

Parallel to sketches, modeling in Rhinoceros by means of Grasshopper software was started. Any edition in the design was shared with others. During five weeks, the final design was developed gradually (Figure 5.3).

5.2 Parameterization and structural optimization

Modeling the concept developed in grasshopper a parametric design tool. The concept finalized in design process started from three ellipses with variable coordinates of centers and changeable position and controllable radius in size and direction. The surface was created by applying*loft* component on them and refining desired modification. The result was a free-form vault with a decent curve in the middle, which provided a second opening toward

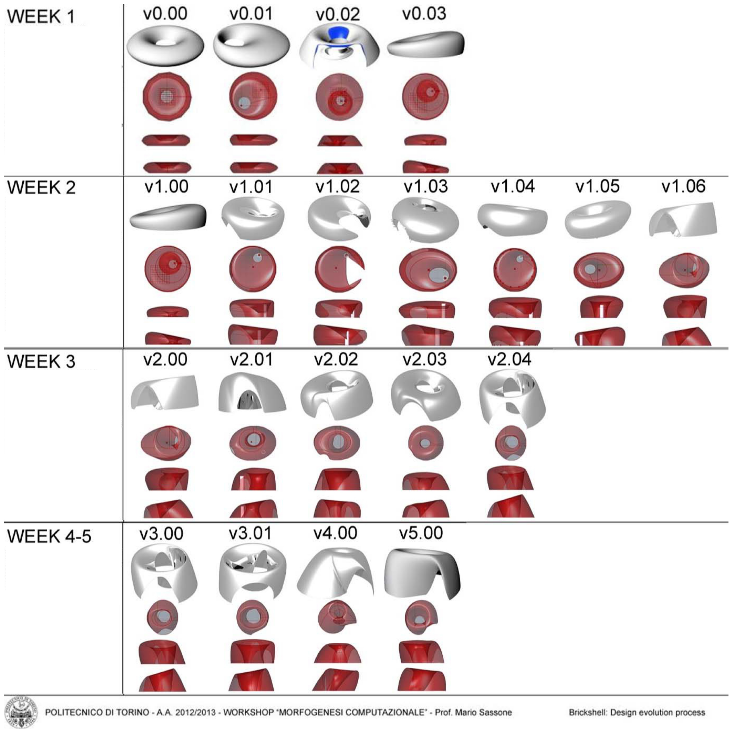


Figure 5.3: The process of design developing (drawn Computational Morphogenesis)

the sky. After the agreement on the shape, the proportion of it was manipulated to find the structurally optimized solution. The resultant shells were converted to mesh to be analyzable for GSA to obtain the nearby estimation of its structure behavior and displacement measurement. The *GSA suit* a production of *Oasys* is a software specified to the compression only. According to trial and error method, the structural behaviors of different proportions of the concept were evaluated. Among the different shapes, the structurally best solution was selected. The structurally optimized result is shown in figure 5.4 that students agreed on the fifth week.

This result was not fulfilled completely the designers. The curvature was sharp that impede the brick laying process. The height was high in proportion to the interior space of the shell. As in 2013, the focus of the workshop was on architectural program, the structurally optimized shape

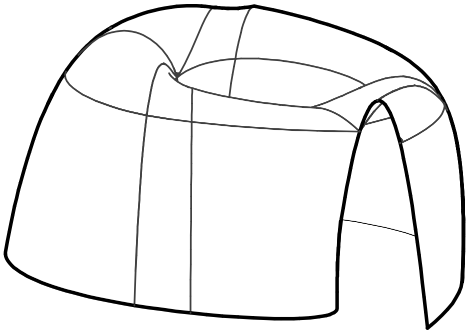


Figure 5.4: The structurally optimized version of Brickshell

was edited to find a shape that architecturally fulfilled the participants. This shape was the constructing version so it should be stable enough under self-weight (Figure 5.5). The structural behavior of it tested through the GSA to know the reaction of the shell under self-weight and loading. The process of this numeric test is explained in next section. The result showed that the designed shell would be a self-support vault with dimension of 6m in 5m and maximum of 2.5 m in height which consisted of approximately 1200 bricks.

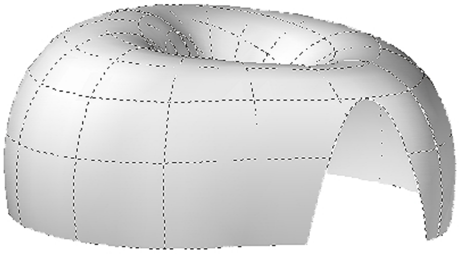


Figure 5.5: The final shape agreed to be constructed

5.2.1 Numerical Method Analysis

The *Oasys* is a structural analysis software which is the software house of *ArUp*. *Oasys* supports the entire design process from the concept phase to details and different construction types from tall building to deep foundations and enables the designers to overcome the seismic challenge and form- finding optimizations issues. The *GSA suit* a production of *Oasys* that is specified to the compression only structures was a tool which was selected to utilize in numerical testing process.

5.2.2 Transition

In order to link the resulting of design phase which had been produced via *Grasshopper* to *GSA* , It was required a mediator. A code scripted in *Python*, a programming language, connected these two software to each other. A component in *Grasshopper* , named *testSigmaTau* enables using both RhinoCommon and RhinoScript from within Grasshopper.

5.2.3 Input data

Transferred to the *GSA* the mesh surface converted to the shell surface which is a surface formed of triangular elements and the structure is supposed as a homogenous surface. Although there was distinctive difference between a masonry vaults of hollow bricks with a solid surface, the properties of the brick and the mortar which were utilized in the construction process were the input data for starting the analysis. The thickness of the brick that was 0.045 cm was considered as the thickness of the surface. For defining the elastic modulus of the brick, our reference was Nicola Canal who has tested the mechanical strength of horizontal hollow brick in the *Rbk* Laboratory of *Limana* [28]. According to the resultant of this research the *Young's modulus* was considered 4.06e+9 Pa. By achieving the *Young's modulus* and *Poisson's ratio* the *shear modulus* can be found.

$$G = \frac{E}{2(1+\nu)}$$

Where E is *Young's modulus* and ν*is* *Poisson's ratio*. The density of the material was considered based on the properties of brick and the mortar.

5.2.4 Output data

The primary analysis of the *Brickshell* was analyzing the 2D elements displacements under the gravity load. According to outputs of *GSA* the displacement range in x axis and Y axis are in the equal range but because the direction of gravity load and Z direction are parallel, Z direction displacement analyzed in different range. In X direction, the greatest displacement is in the entrance part of the vault where it is more than 90 μm. The white lines show the boundary of negative and positive displacement which means the 0 displacement. In addition, the great displacement happens in the internal opening part where the curve touches the ground where is more than 90μm (Figure 5.6).

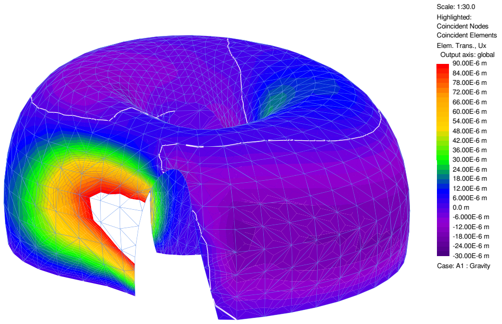


Figure 5.6: 2D displacement in X direction under gravity load

The displacement behavior of the shell in Y direction is similar to X direction. The greatest dislocation occurs in an entrance area but in the right side of it. Unlike the X displacement, there is not any out of range movement, more than 90μ m in the place of internal curve.

As the figure 5.8 illustrates evidently the maximum dislocation in Z axis occurs in the negative direction. Similar to other diagrams, the most changing is in the entrance area and upper part of the door displaces more than

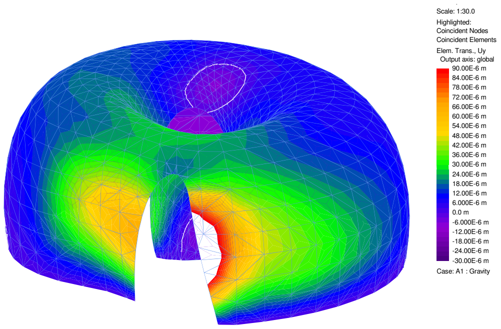


Figure 5.7: 2D displacement in Y direction under gravity load

other points. Totally the range of Z-axis displacement in Z axis is lower compared with two other axes.

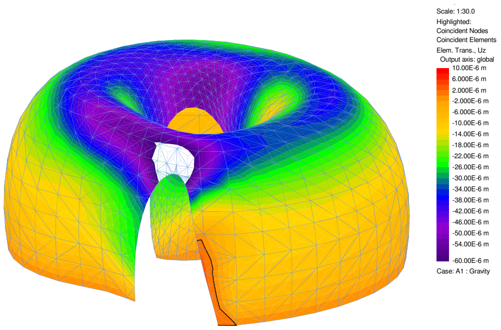


Figure 5.8: 2D displacement in Z direction under gravity load

Achieving better prediction of statically behavior of the vault under loading, 2D displacement analysis was repeated by applying 1000 N/m^2 on the vault. In *GSA* software, the elements of the upper part of the shell which was a ring that would be able to retain the sand bags, was selected to apply the dead loads. This amount of loads is close to the snow load that might be applied to the building in the region where the vault was constructed. According to the Italian Standard of manufacturing, the snow load is defined by this formula

$$q_s = \nu_i . q_{sk} . C_E . C_t$$

Where the q_s is the snow load on the roof, the ν_i is the roof slope factor, the q_{sk} shows the ground snow load, the C_E indicates the exposure factor and C_t is thermal factor. Being applied the load on the selected part; the 2D displacement analysis was repeated by considering the combination of both gravity and face loads. As the picture number 5.9indicates, the range of displacement in this condition is more than the previous one. In this condition, some parts of the shell move more than 300μm which is three times more than the displacement under gravity loading. Similar to the gravity loading, the greatest amount of dislocation occurs in the left side of the entrance.

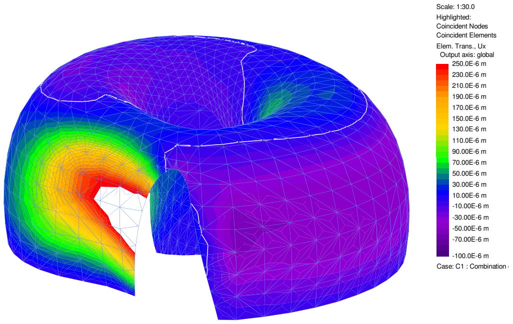


Figure 5.9: 2D displacement in X direction under custom load

The greatest amount of displacement in Y direction also occurs in the entrance part but in the right side. The maximum movement in negative direction is almost 100μm and in positive direction is almost 350μm but in this analysis it was defined to limit the range not more than 200 μm (Figure 5.10).

As it was expected, the negative Z direction had the most amount of movement in the negative direction. Similar to the previous status the range of displacement in Z axis is less than two other axes. According to the diagram of the 2D displacement in z axis (picture number 5.11) the most unstable part was the upper side of the entrance that displaced more than 150μm.

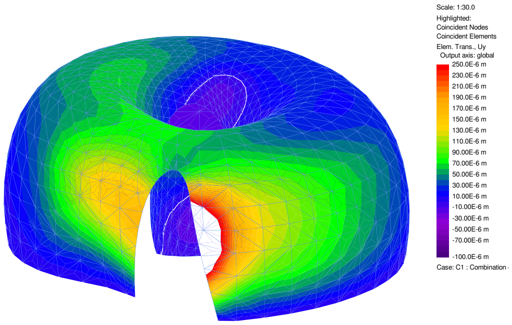


Figure 5.10: 2D displacement in Y direction under custom load

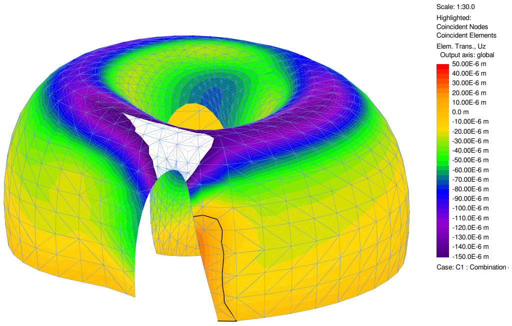


Figure 5.11: 2D displacement in Z direction under custom load

The load bearing analysis on the *Brickshell* demonstrated that the most amount of dislocation occurred in the entrance part. That could happen because of the big opening in the homogenous surface which disordered the load diffusion. In order to test the influence of the entrance on the structural behavior of the vault, the set of new analysis were repeated by considering restraints at the boundary nodes of the elements which shaped the entrance part. The result (figure 5.12) indicated that in X axis the critical displacement area was shifted from the entrance part to the left side. In addition, the edge of internal curve faced a displacement more than 40μm, the range that was defined for 2D displacement analysis in X axis.

In Y-axis as the picture number 5.13 illustrates, the right side of the entrance faced the biggest amount of displacement. The range of dislocation

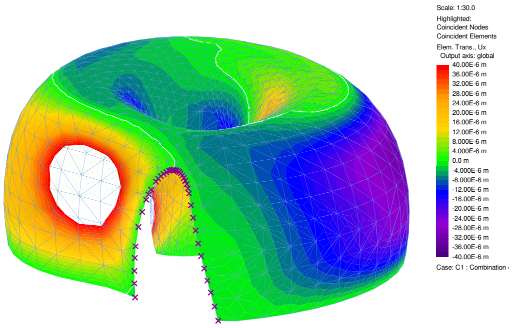


Figure 5.12: 2D displacement in X direction with restraints

was lower than 30μm in both negative and positive direction.

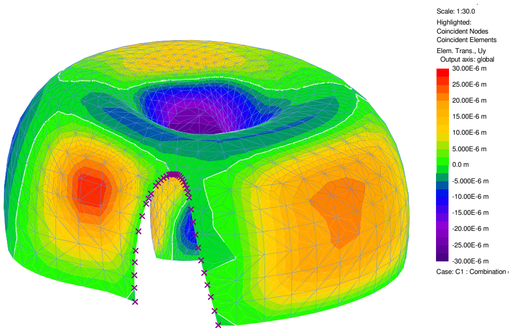


Figure 5.13: 2D displacement in Y direction with restraints

In Z axis, the area where the extra loading applied on faced, the greatest amount of displacement happened. Perceptibly the direction was negative (Figure 5.14).

By comparing both conditions, one the prime form of *Brickshell* and the other one made by adding restraints to the surface opening, Although it was evident that the range of displacement in second condition is less than the first type, the weakness of the structure occurred in both openings of the vault.

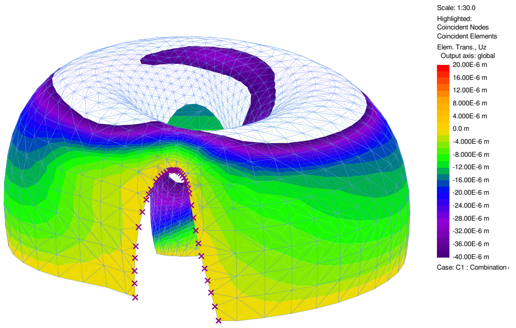


Figure 5.14: 2D displacement in Z direction with restraints

5.3 Final realization

5.3.1 Development of the construction technique

In order to have practical experience of masonry vaulting and finding out the limitation or requirements, two short time sub-workshops were organized with the aim of following all the steps that involved in the final construction. Both of the trainings were preceded by utilizing low-tech material and simple tools. First training was concentrated on construction the single curvature vault and second was double curvature vault. Through these trainings, it was required to touch the different structural behavior of single curvature vaults and double curvature vaults. The single curvature vaults adopt more risk against asymmetrical loads that a double curvature vault because in the first one the loads are able to be carried down in one direction [34]. The first training started by the intention of construction of the single layer single curvature surface which present a simple model of the catenary curve. A suspended chain used for projection of the curve final form. The inverting of a funicular shape, extracted from a hanging chain behaves in pure axial compression. This method is the earliest example of structural form finding published by Robert Hook. The idea is inverting the shape of that hanging chain which is in pure tension and without bending provides an arch that acts in pure compression [68].It is able to resist the weight load and design load [34]. The formwork (guideline) was constructed by secondhand woods. Before starting the brick laying, a thick rope extended on the formwork, therefore, the de-centering would be easier just by stretching the rope under the bricks that made a vacant space between bricks and formwork. The extruded brick produced in *Torino* with fast hardening gypsum mortar were used to lay the brick in shiner state.The catenary arch is strong in compression but weak in tension. This weakness is due to materials. This low mechanical resistance may lead to structural collapse [92]. Removing the formwork, there was an asymmetry in the load diffusion of final form which made the vault unstable. Putting a small stone on one side of the form provided the equilibrium of the structure. The outcome of this four hours training was acquiring with the concept of masonry material, mortars, stability and challenges of the non-industrial construction.

Figure 5.15: Construction of the catenary curve

The second construction experience was objected to build a part of the finalized design in order to obtain an estimation of whole fabrication duration and apply an experimental test on the structurally most challengeable part of it. This two days practice helped to understand all possible failures and problems. The materials and methods nearly were as the final fabrication. The secondhand Cardboards discarded from pickings were utilized as the formwork material and the mortar was made by mixing the sand, gypsum and water in the proportion of 1, 2 and 0.75. The formwork consisted of layers of cardboards embedded with 20cm distance from each other which attached to another strip cardboard. The projection of each layer was printed on graph paper in order to be easily reproduced in exact scale on the cardboard. Other strip cardboards folded into U shapes and screwed between the layers to provide their longitudinal stiffness and avoided the deformation. Diagonal herringbone pattern was selected both for this practice and final fabrication bricklaying. This pattern provides a strong structural bond and avoids continuous joints between the bricks. Due to the high adhesion power of mortar, the role of the formwork was as a guideline for placing the bricks rather than to support the weight of the blocks therefore de-centering process did not result from the danger of causing asymmetric load and easily were removed by detaching all the layers of the cardboards. The final result was a stable masonry free-form which provides an arch form space with 2m in 5m with 2 m height dimensions.

Figure 5.16: Second construction training

5.3.2 Brick Pattern

Laying the bricks in the variety of patterns, apart from the different appearances caused diversity in structural behavior and accordingly different role in masonry buildings. Each type of patterns has unique effects on quality of design and visual effects [70] driven by the orientation of the bricks and the course of their arrangement. Since the *Brickshell* was supposed to be a single layer, selecting a brick bond was a strategic decision which effects both either visual aspect of shell and structural behavior. In herringbone pattern, bricks interlock each other and because of the indivisibility of columns and rows of the brick it provides a strong structural bond and avoids continuous joints between the bricks. This property releases the masonry vaults and domes to be covered in two or three layers to reach the stability. The advantages of the herringbone pattern motivated the Computational Morphogenesis Workshop to apply this pattern to the free-form vault designed throughout the program. Before starting the construction process, it was already apparent that bricklaying in constructing of a free-form surface was not simple task. There would be required a lot of non-standard bricks which would be cut without any model and the brick layer would have to decide on brick courses during brick laying process. These obstacles would decrease the speed of construction. In order to solve this problem, it was generated the idea of developing tool for modeling the brick pattern automatically. Although this digital tool was not utilized for this workshop, the very first step of it started simultaneously with the construction process. This tool, named Brick Pattern is described in chapter 9.

5.3.3 Scaffolding

As it was supposed and second construction practicing also proved, scaffolding was the most challengeable and time-consuming part of the complex geometry masonry construction. Generally Material for formwork is one of the most significant hidden factor in the construction process [34] and for the free-form shapes, it should be added the complexity of form-work construction. It was decided to use cardboards for the false-work fabrication which are not expensive but easily can be cut to form the complex curvatures also it was important to consider the stiffness of the layers of cardboards in the long length cases. The complication of the shell necessitates having the guidelines in most part of the construction area. For projecting the shape of the building on the formwork, the structure was supposed as layers of cardboards adhere to each other and followed the curves in all directions. The model of the formwork was extracted from the grasshopper software by been divided into the grids of vertical planes with twenty centimeters distances from each other which followed the geometry of the final form. Provided the platform of the construction the model was subtracted with set of the boxes. The formwork structure was divided into the thirty individual models in order to simplify its fabrication process which regarding their placement, the planes of one direction were eliminated in order to reduce the spent material and time.

By means of the projector, the outline of each layer was projected on the cardboard and cut by the cutter. The strips of cardboards in the comb-form with twenty centimeters distance of each dental placed all the layers precisely in their particular positions. Avoiding the deformation and folding of the cardboards, the U shape cardboards which were screwed and glued to them provided the stiffness of the cardboards sheets also if it was required, foam boards attached to the sheets as the rib of the layer.

5.3.4 Final fabrication

Because of the dimensions of the shell, the whole part of it was not easily reachable for the participant to lay the bricks; therefore it was decided to construct the shell in step by step process. As The figure 5.19 shows the consequence of false work assembling, initially the exterior parts of the shell

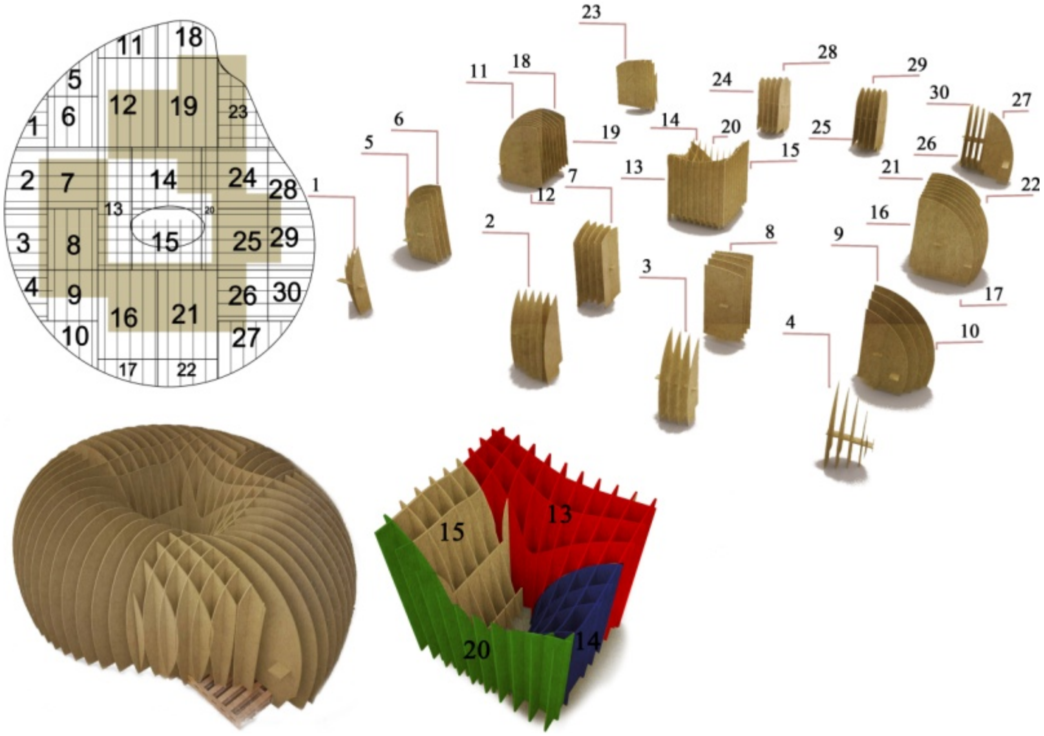


Figure 5.17: The process of formwork design

Figure 5.18: Construction of the formwork

were placed in their particular position, subsequently the bricks were laid following the shape, assembled the central sectors of formwork, the interior parts of the shell completed. Afterward, the middle parts were attached and covered gradually.

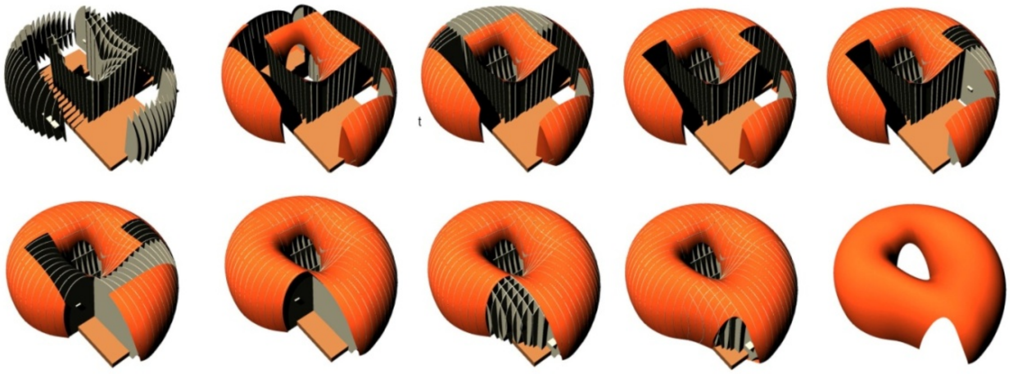


Figure 5.19: Sequential steps of formwork construction

The same as the second construction training, the hollow bricks with dimensions of 4.5 x 15 x 30 cm and weighing approximately 1.60 kg were selected as the material and the mortar was mixture of the sand, gypsum, and water. The brick arrangement was the herringbone pattern, progressing from bottom to top (Figure 5.20).

5.4 Structural test

The curved surfaces which are structurally continuous are the shell surfaces. Although masonry domes and vaults are composed of separate sub-units that are not necessarily cemented to each other, they are considered as shell structures since all part of the surface in the state of compression and transmit the compressive force throughout the surface [27]. The *Brickshell* was a shell surface and a compressive-only structure.The safety of the vaults is provided through the geometry of shape not the strength of the material.

Figure 5.20: Construction Process of Brickshell

If thrusts move the supports, the vault cracks [66]. If the vault is stable it is because of the accuracy of form. Being constructed in the experimental method, it was organized to experiment a load bearing test for the building. First step was to obtain an approximate prevision of structural behavior of the shell both under the gravity load and testing loads. The *GSA* software a three-dimensional static analysis tool was selected for processing the *FEM* technique for the surface. The part assigned to the gravity loading had been achieved before the fabrication phase in order to investigate the feasibility of designed shape. The advanced part was predicting the load bearing behavior of the masonry free-form shell before applying loads on constructed prototype. The aim of the experimental test was to evaluate the reaction of the complex curvature surface under the loading other than gravity such as the snow load. Due to this test, the displacement of the surface in the different direction, the shape deformation and the stability of the structure was analyzed. The numerical test is explained in section 5.2 The achievements of the numerical analysis indicated the weak and strength zones of the *Brickshell* and the place where would cause the risk of the collapsing because of the displacement. Analyzing the data obtained from the numerical testing, it was planned to investigate the structural behavior of the vault by applying loads on the upper part of it. It was decided that the loading be continued until the rupture of vault.

5.4.1 Tools and requirements

LVDT, the sensor measures the linear displacement of any points on a surface is selected for using in load bearing test of the Brickshell. This device works by voltages changes in three solenoidal coils which connect to the surface. Any displacement changes the voltages and shows the direction or amount of movement. The output, the sensor measures the linear displacement of any points on a surface is selected for using in load bearing test of the Brickshell. This device works by voltages changes in three solenoidal coils which connect to the surface. Any displacement changes the voltages and shows the direction or amount of movement. The output is the diagram show load-displacement. As this device is motion-sensitive, it should be stabilized in order to estimate the dislocation accurately. As the figure 5.21 shows, there are two methods for measuring a displacement of a point, to embed the sensors from the shell inside or from the shell outside. Because of the fragility of this device, it was decided to embed the sensors to the vault from the outside so, in probable collapsing time, the sensors would not be damaged.

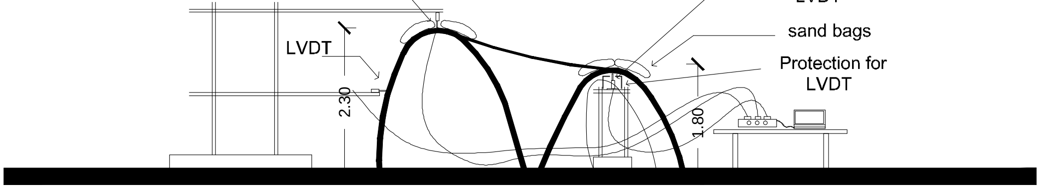


Figure 5.21: Diagram of load-bearing test

Regarding the curvature of the shape and the surface where the loads should be placed on, sand bags were selected as the loads. It was planned to fill the bags with 10 kg sand in each and the place them in the vault by means of the specific type of vehicle mounted with lifting platform which facilitate the loading.

5.4.2 Testing prosedure

The test was started by defining the location of the sensors. It was decided to embed ten sensors vault outside. Four sensors on the waistline of the shell, four on the top of the shell along the previous ones, one on the edge of the entrance and one on the internal curve. The figure number 5.22 defines the position of each sensor.

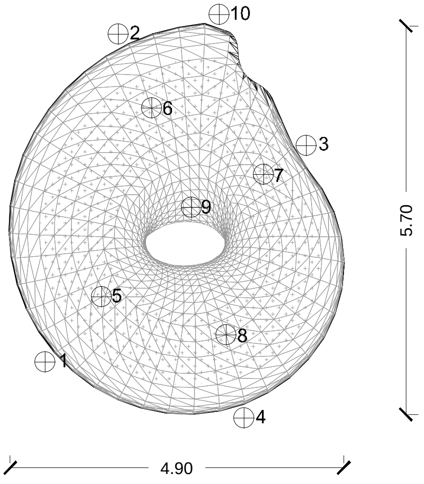


Figure 5.22: The positions of sensors on the shell

5.5 Test result and structural behavior

The test started by applying the loads on the vault while the computer was recorded all the displacements measured by LVDTs. the figure 5.23 illustrates the displacement of points recorded by each LVDT.

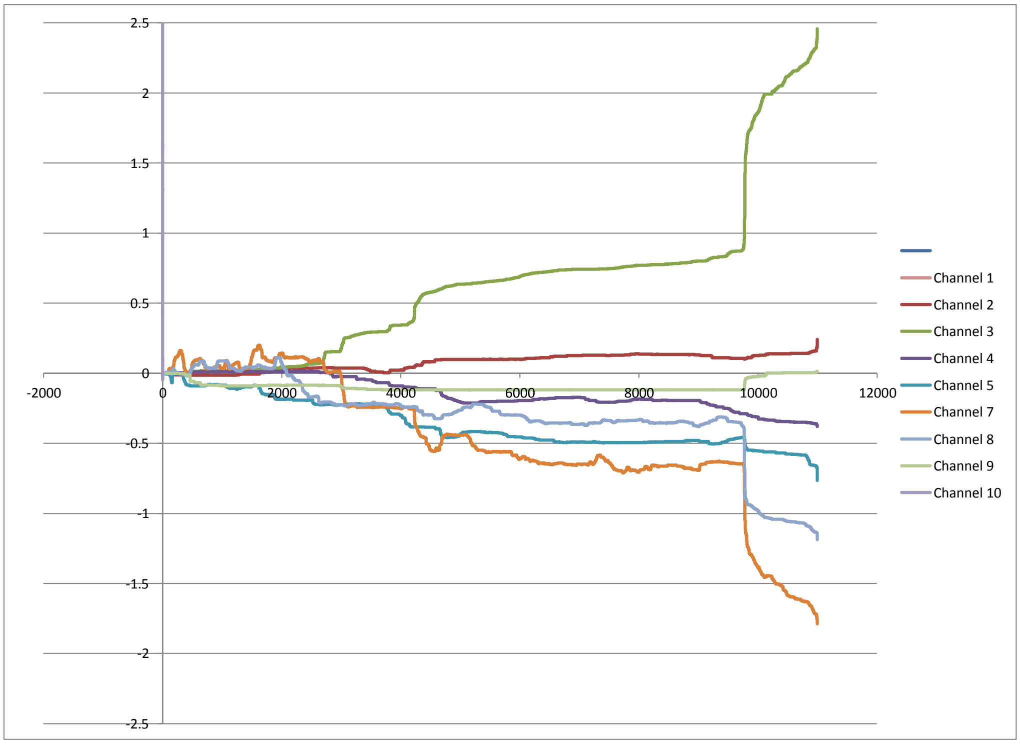


Figure 5.23: displacements diagrams of LVDTs

Describing more precisely, the figure 5.24 as an example indicates the diagrams of LVDT number 2 and 6, which vertical value indicates the displacements and horizontal value shows the test duration. According to the diagram, first sharp change in displacement values happened when the part shown in figure 5.24a has been loading for the first time. The values changed vividly in both points when it was loaded the area of LVDT 6 (figure 5.24a). This point is the top of the entrance of Brickshell, where the numerical analysis specified as a less-stable part of the vault. The movement of the number 6 was in the negative direction and the movement of the number 2 was in the positive direction (Figure 5.24b).

During the first turn, the vault was loaded with 500N/m2 loads. The

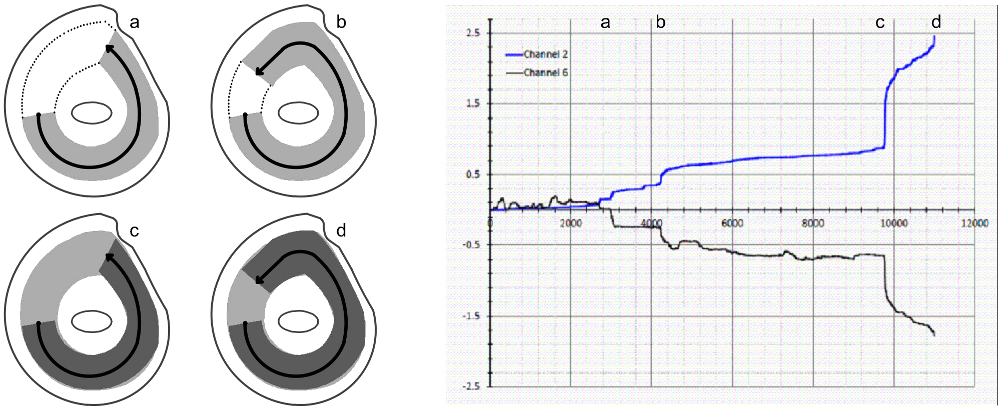


Figure 5.24: displacements diagrams of LVDT number 2 and 6

variations were changing slightly until whole vault was loaded with almost 50 sandbags and the top of the entrance has been loading for the second time (1000 N/m2 loads). At this moment, the changes of the values were dramatically when a crack happen in this point (figure 5.24c). When the 6 point was loaded with 1000 N/m2 loads, the vault fell down (figure 5.24d). The observations and video of vault shattering, indicated that the vault fell down because of the losing the equilibrium not weakness of the material. The figure 5.25 shows the process of load bearing test.

Figure 5.25: The process of Load bearing test

Chapter 6

Constructing a Free-form surface by Catalan Vaulting method

6.1 Concept, parameterization

6.1.1 Introduction

The Computational morphogenesis workshop 2014, concentrated on designing and constructing three shells with different materials. Brick, concrete, and wood were the selected material for this workshop and *Brickshell*, *Foldshell*, and *Fracshell* were selected as the theme of the workshop. All the students were asked to participate in the design and construction process of all of the shells so at the end of the workshop they would experience three different design methods, form finding, structural behavior, scaffolding and material requirements. The process of *Bricksll* is described in this thesis and the two other shells are skipped because of being out of the debate.

6.1.2 Architecture Program: designing a Catalan vault

The architecture program of the *Bricksll* was designing a free-form Catalan vault. Compared with other methods they are thinner and lesser weight so there is the fewer thrusts force [66] .This is a traditional method in Italy

Figure 6.1: Pervision of Brickshell, Fracshell, and Foldshell

which called *Volta in Foli* [66]. The Catalan vaults also known as the thin tile vault normally consist of small tiles stick together from their thin edges. This makes the tile vaulting thinner than other vaulting methods. Typically Catalan vault consists of three or four layers that bricks direction of each layer are 45 degrees rotated to the bricks direction of the prior layer. Saving time and material, it was decided to construct a Catalan vault with two layers.

Figure 6.2: Catalan Vaults a) United States, Guastavino b)South Africa, MIT research group c) Colombia, Block research group

6.1.3 First concepts

The design process started with training. The participants were asked to select a free-form vault constructed of brick, concrete or wood. They collected the documents and presented their design tools, material requirements, scaffolding techniques, optimization methods and construction process. It was required that all the students to get the overview of the workshop process.

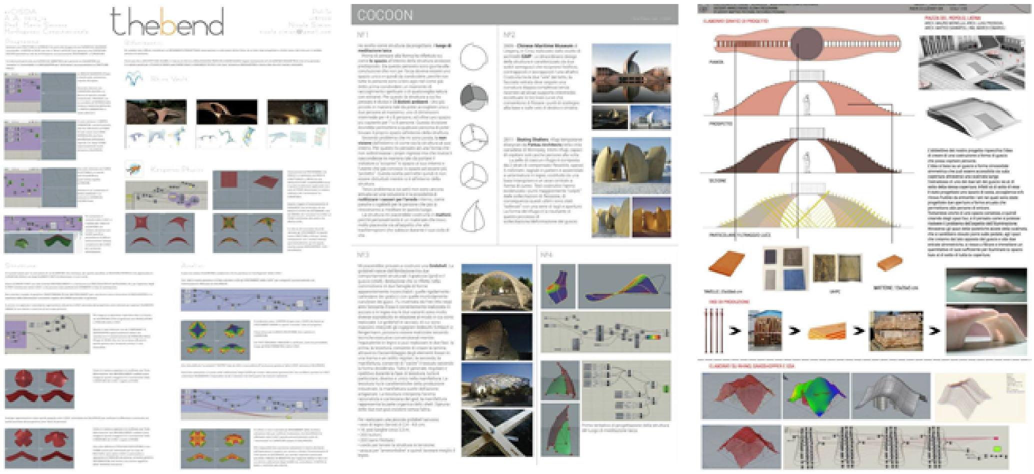


Figure 6.3: Case studies as small trainings of Workshop participants

6.2 Parameterization and Design Process

The contemporary architecture is deeply affected by Algorithmic Computational Geometry that help to create complex forms and free-form surfaces. Following the intentions of Computational Morphogenesis, explained in section 5.1.1 and tracking the contemporary architecture movement, , the design process was advanced by digital tools and innovative methods. As the design program, the goal of the workshop in 2014 was designing a free-form Catalan Vault by means of parametric design tools. The focus of the workshop 2013 was on the design and architectural form. As it was explained in the last section, because of losing the equilibrium of the shape, the shell collapses. In

2014, the main focus was on generating the form which would be structurally optimized. The final result of a design process is a combination of different parameters such as formal, functional, environmental issues [89]. Parametric modeling includes limited number of parameters that integrated each other to form a single design.

6.2.1 Design Tool

The Geometry of free-form surface is influenced by different parameters and it is not easily designable without CAD tools. Considering the influence of material properties on the final result, the logic of the material system is considered the whole process of innovative parametric tools [54]. NURBS curves and surfaces are the geometry description standards in CAD and Computer Graphics tools [48] NURBS surfaces, Non-Uniform Rational basis Spline surfaces are the logical extension of the Splines. The Spline is defined as the piecewise shape polynomial curve [47]. Through their control points (the parameters), the shapes are easily controlled over by users interactions. Rhinoceros is a 3-D computer graphics software based on the NURBS modeling. The software provided a platform for accurately modeling any shapes from simplest 2-D line to the most complex 3-D free-form surfaces tools [85]. Grasshopper, the plug-in of Rhinoceros (3D graphical software) provides a proper platform to advance the design process by means of Generative Algorithms and Parametric design methods. It is the real-time tools that by changing the parameters, the result would be updated accordingly.

6.2.2 Form-Finding method

The geometries in which the load is transferred through the axial or in-plane forces, the shape can be determined by the force and vice versa [93]. The shapes of these kinds of shapes are obtained optimally via the form- finding process. According to Block, form finding is the process of the manipulating the geometry of a structure to be funicular to the loading condition [93] , i.e. it is obtaining an optimum shape fits the equilibrium of the structure under the specified load [11]. The form finding methods typically answer the feasibility of a form under the specific load. The hanging chain assumes under its own weight, defining a catenary curve is a simple method of 2D form-finding tool. Inverting the curve, it creates the single curvature catenary vault by structurally optimized shape. The same method was adopted by Antoni Gaudi to obtain the most complex geometries in his buildings [69].

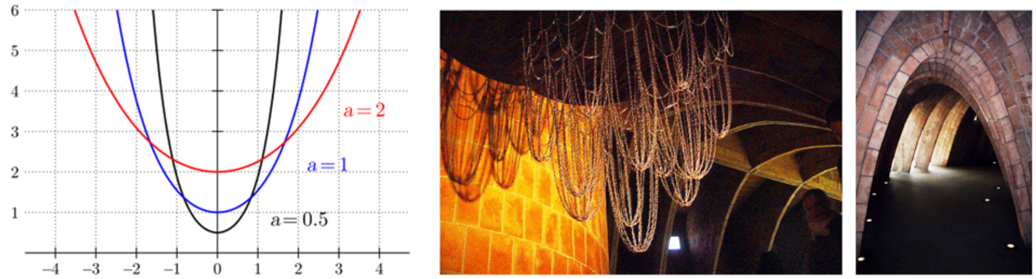
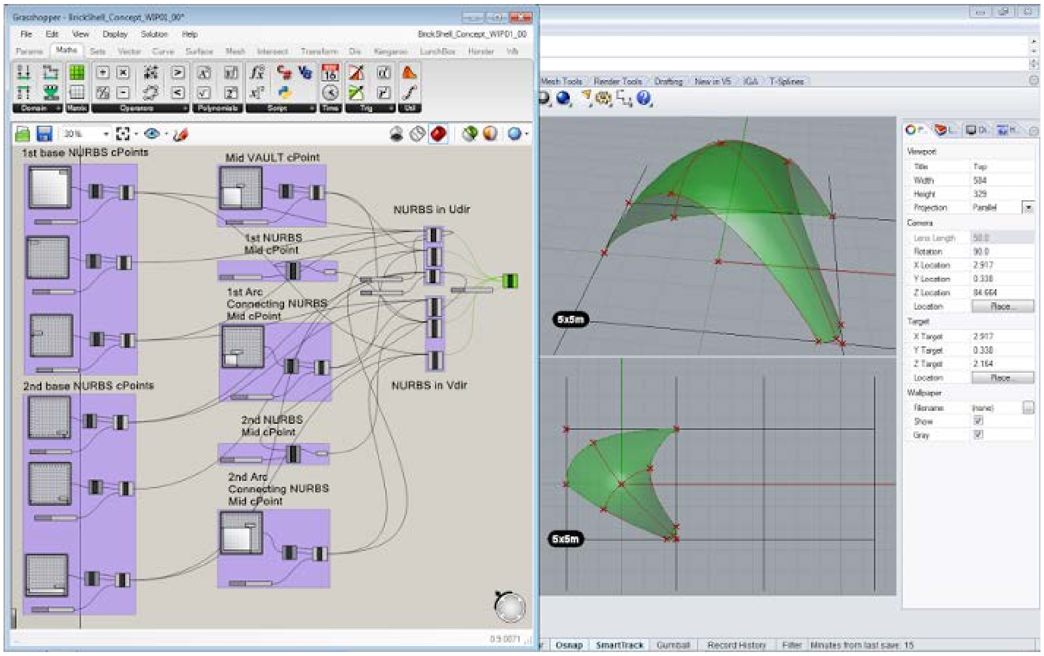


Figure 6.4: a) Catenaries for different values, b) Antoni Gaud's catenary model at Casa Mila, c) Catenary arches of Gaud's Casa Mila, Spain

A form -finding method generates the geometry and proposes an optiimzed form but it may require a desired starting shape [11]. By expanding the CAD tools, the computational methods for form-finding methods are developed and innovative tools such as Rhino vault developed by Block Research Group. The Rhinoceros Plug-In *RhinoVAULT* is a form-finding using Thrust-Network method to intuitively create and explore compression-only structures. This tool uses the bidirectional interdependency of form and forces represented in visual diagrams. These diagrams enable the user is able to drive and control the form-finding process [82], [2] and [83]. Similar to the previous workshop, the first concepts of form were generated by the students and parallel were converted to Rhino file. But in 2014, being focus on structural form, the architectural form was simple. It was decided to design a free-form vault generated from a rectangle. The varieties were the dimensions of each edge that attached to the platform and the height of long edges that shaped two arcs. Agreed on the concept, the form was manipulated in Rhino vault to find the structurally optimum result.



Viewport	
Title	Top
Width	584
Height	329
Projection	Parallel
Camera	
Lens Length	50.0
Rotation	90.0
X Location	2.917
Y Location	0.338
Z Location	84.664
Location	Place...
Target	
X Target	2.917
Y Target	0.338
Z Target	2.164
Location	Place...
Wallpaper	
Filename	(none)
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Figure 6.5: The designed Brickshell for Workshop 2014

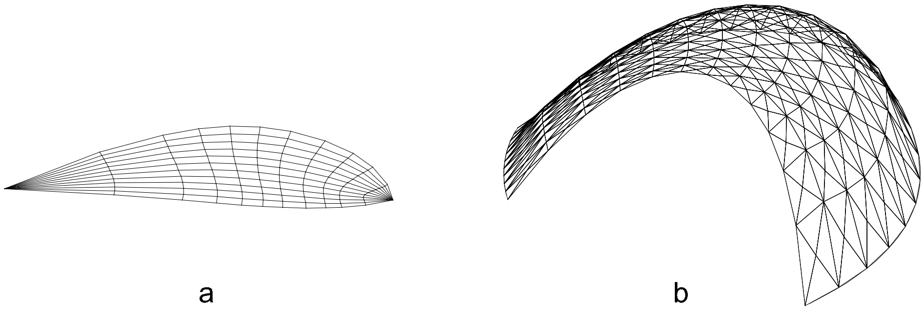


Figure 6.6: The structurally optimized shape for Workshop2014 driven from Rhinovault, a) TNA form finding method: force network in plan, b) Compression-only thrust network

6.3 Final realization

6.3.1 Development of the construction technique

Selecting a specific material is a first step of construction a free-form shape. The brick vault is a compression only surface while wooden grid shells only experience tension and reinforced concrete shell resists compression and tension simultaneously. Before starting the design process, students required being familiar with these different materials and the structural behavior of forms constructed of them. Therefore, a constructing training was organized for participants to experience constructing a small-scale surface out of brick, wood, and concrete.

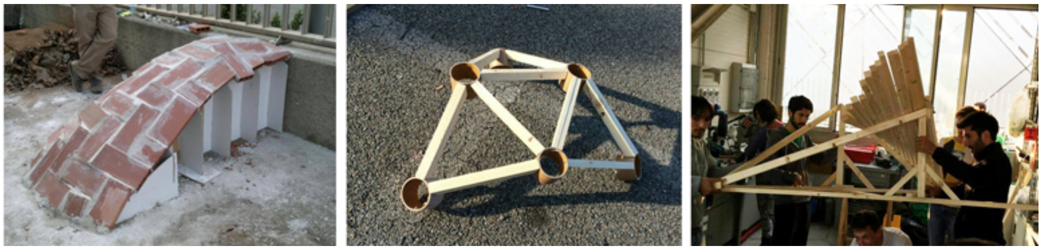


Figure 6.7: The construction trainings

The Brickshell training was constructing a shallow curve vault connected to the ground on one side and supported by the wall on the other side. The form was extracted from Grasshopper and The formwork was driven by the same method applied in Workshop2013. The herringbone pattern was selected as the brick pattern which is sufficient for one layer shallow vaults. The gypsum was selected as the mortar as it is the fast hardening mortar and typically is used for bonding of the first layer of Catalan vaulting.

6.3.2 Brick Patterning

During the construction process of the Morphogenesis Workshop 2013, it was required to pause the laying the bricks and cut the special shaped bricks

Figure 6.8: The training of brick vault construction

that they did not have cutting pattern. Despite time consuming, the cut bricks were not accurate and sometimes it was required to repeat the process more than once (Section 5.3.4). Predicting the material requirements (brick and mortar) and placement of each brick before starting the construction aid accelerating the construction time (Chapter 7) As it is described in chapter 9, the main part of this thesis is concentrated on a code which is scripted for automating the brick pattern simulation on a free-form vault. The prototype of the Catalan Vault constructed in the Workshop 2014, was the application to apply the description code that it was in the procedure at that moment. Comparing the construction process between the Workshop 2013 and the Workshop 2014 would provide a practical conclusion of the scripted code advantages. This code is an interactive tool that enables users to design their required pattern. Through this code, the designers are able to control the brick requirements and aesthetic issues at the same time i.e. it enables the designer to design a pattern that covers a surface with minimum brick requirements and minimum special shape brick in use. As it was described in the section 2.2, Catalan vault or Thin-Tile vaulting consisted of layers of thin bricks, laid in way that the tiling pattern of each layer rotates 45 degrees to break continuous joints between the layers. The Catalan vault prototype of the Workshop was planned to have two layers. Through the scripted code, participants of the workshop started to design the brick pattern on the each layer. In order to simulate the brick patterns on the free-form Catalan vault, the series of the codes, which are described in chapter 9 and 10 were applied. Since the aim of scripting these codes is not just automating the brick pattern modeling but providing an interactive design tool facilitating architectural tendencies. After some tries, it was decided that the first layer would be covered with array of bricks laid on the shiner position (bricks attach each other form the long narrow side and the board side is exposed). In this layer, small area of the top part (Inflection part) required to be covered with the special shaped bricks (the bricks which required to be cut). Through the code, the special shape bricks were enumerated so the bricks would be provided before earlier (Figure 11.9).

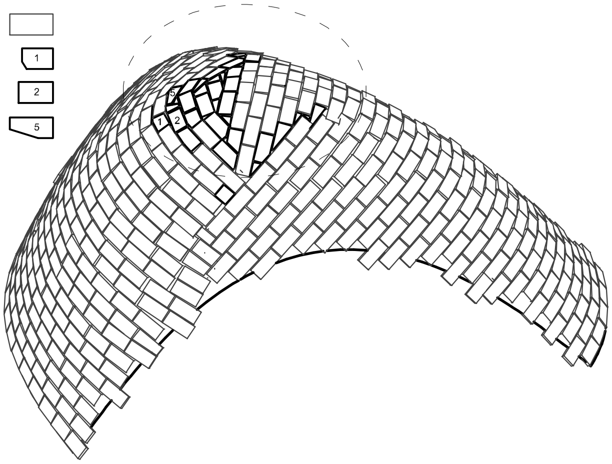


Figure 6.9: The brick pattern of the first layer (The Catalan Vault)

The bricks of the second layer should be arranged in a way that would be rotated 30-45 degree relevant to the layer below. In addition as it was the upper layer and so, viewable for public, it was required more consideration in visual aspects of patterning. After modeling some concepts, the final model was simulated through the scripted codes. Modeling this layer, it was not pure bricklaying but the pattern was deliberately designed. The edges of the surface were primarily covered. The arch-shaped edges were started to cover the ground so the special shape bricks were placed in the crown part. Besides, bricks followed three different courses that the interference areas required the special shape bricks (Figure 11.10).

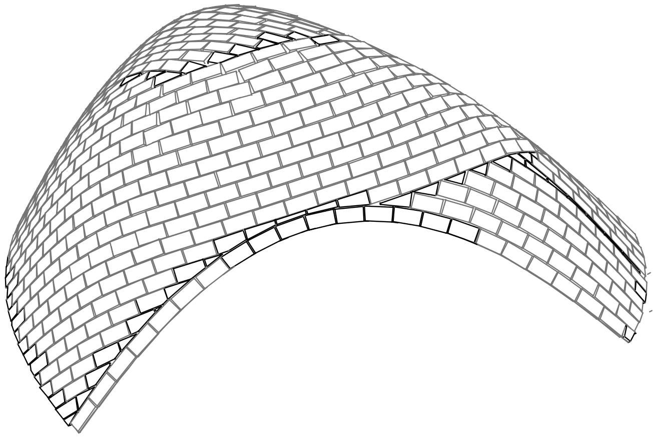


Figure 6.10: a) The brick pattern of the second layer (The Catalan Vault)

6.3.3 Scaffolding

The same as the Workshop 2013, it was decided that the scaffolding would be constructed of the low-cost materials. As the previous experience, the scaffolding was crossover layers of cardboard that followed the course of the curvature. Each layer of cardboard has twenty centimeter distance from the other layers.This method provides the more stiffness for scaffolding and more accuracy for curvature (Figure 6.11). The last experience in 2013 (section 5.3.3) showed that the scaffolding was the most challengeable part of the construction process. Projecting the outline of each layer to the cardboard and cutting them was a time and material consuming. In 2014, in order to reducing the duration of construction and cardboard using, the wooden boxes were used as the first levels of formworks.

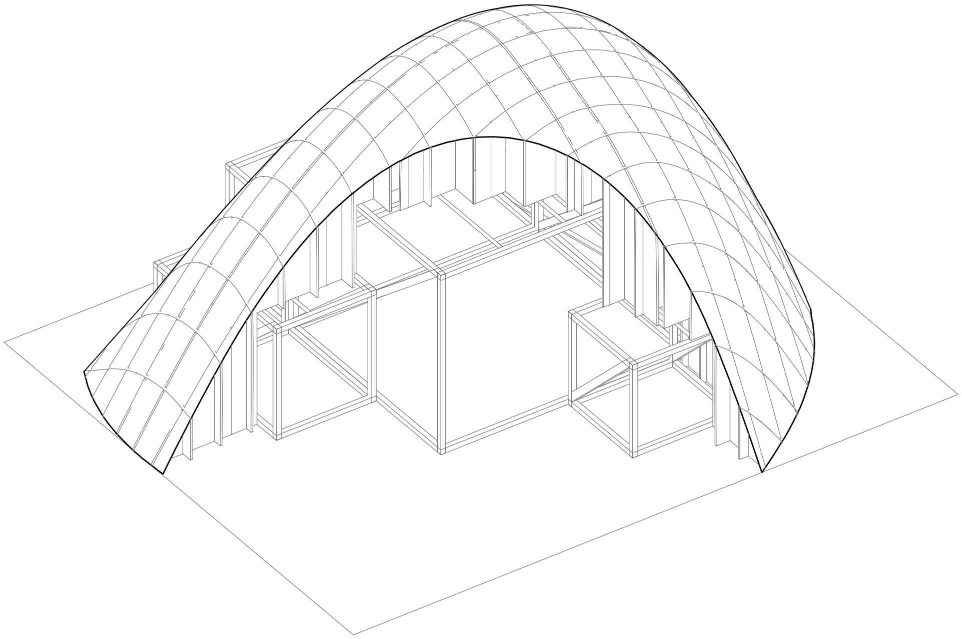


Figure 6.11: Cardboard scaffolding system

Through the *Grasshopper* software the scaffolding was divided into twenty-seven parts, each part consisted of intersection layers of cardboards and seven wooden boxes as the scaffolding platform.

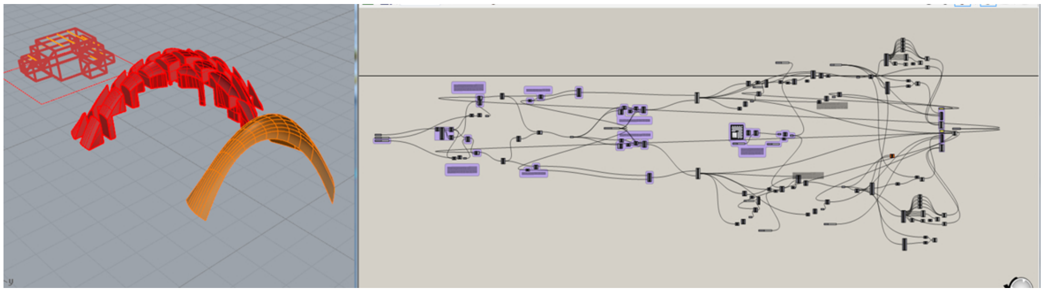


Figure 6.12: a) The process of Scaffolding design

The outline of each layer and the place of their intersection was printed on the cardboards and cut with the cutter. The layers stuck to each other by means of the seams that embedded in each layer. The width of the seam was equal to the thickness of cardboard. In necessary cases, the layers were screwed with each other to provide more stiffness for the scaffolding.

Figure 6.13: The process of the scaffolding construction

6.3.4 Final fabrication

Designing and modeling the brick patterns and installing the scaffolding, the construction process was fast and easy. The utilized bricks were 0.24, 0.115 and .025 dimensions. Bricks of the first layer attached to each other by means of gypsum mortar. Bricklaying process followed the brick patterning described in section 6.3.2. Bricklayers laid the started to lay the bricks from two edges connected to ground and the special bricks were at the top of the vault. The cutting models approximately match their digital types Second layer started to be covered exactly after finishing the first layer. Similar to digital modeling, at first, the edges of two arches were laid by bricks then according to the brick modeling generated by Brick Pattern tool (chapters 9 and 10), bricks were laid. The mortar was mixture of sand, cement, and water.

The modeling enabled that more than two or three bricklayers worked adjacent each other. This possibility increased the speed of construction thus the whole process of construction completed in three days. Figure 6.14 shows the construction process of each layer and figure 6.15 shows the completed vault integrated with two other Concrete and grid shell.


Figure 6.14: The process of constructing The Catalan Vault in workshop 2014


Figure 6.15: The final result of constructing The Catalan Vault in workshop 2014

Part III

Brick Patterning on free-form surfaces

Chapter 7

Brick Patterns

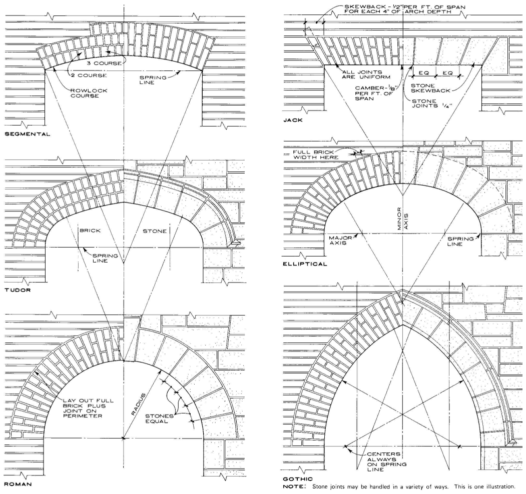
Masonry consists of masonry units (bricks, stones or concrete blocks) and mortar bond together to provide an architectural element. It is one of the most varied of techniques with the variety selection of colors, textures and patterns. Patterning means designing the repetition of a motif in a more or less systematic manner and fit together in a way that there is not gap between them or not overlapping each other but cover a plane or any other surface [49]. In masonry, the bond between units (patterning) is one of the most important means of design because not only it guarantees the stability of building (walls, arches or vaults) but also it creates its aesthetic performance [70]. Masonry units bonds or patterns can be traced in old civilizations, since Sumerians who laid plano-convex bricks flat to form their buildings, avoiding a successive vertical joint [37]. As a point of view of art, masonry patterning must have originated as soon as a man began to select the shape and colors to make the building more pleasing. Considering the different era or different culture, there are many kinds of masonry patterns. Masonry units are laid in various positions for aesthetic or structural reasons. According to [49] a plane tiling T is a countable family of closed sets

$$\left\{ T1, T2, ... \right.$$

which covers a plane without any gaps or overlapping. By the plane it means the familiar Euclidean elementary geometries. There are different types of *tiling* and each of the tiles can have different shapes. As a tiling, most of them are based on the mathematical relations that sometimes are complex [49].

7.1 Classification of masonry pattern

Being similar in concept, there is an important difference between bricks and stone. Bricks are molded to shape, but the stone is wrested from quarries, then cut and curved in a desired shape [40]. Based on this main difference, there are two methods of masonry unit laying to form the vault and domes. Bricks mostly are kept their self-format to form the shape of the surface while stones regularly are cut in customized dimensions and models to be adapted to the surface. Figure 7.1 illustrates the difference of brick and stone positioning system in different type of arches.



NOTE: Stone joints may be handled in a variety of ways. This is one illustration.

Figure 7.1: The difference of brick and stone positioning system in different type of arches, [40]

Stones are used in two distinct ways, *Rubble* is composed of un-square piece of stones and *Ashlar* is using stones that are manipulated in square pieces. Wide range of stones can be used in Rubble form, from rounded river-washed stones to broken pieces from a quarry. Ashlar may be made up of equal blocked or blocks with different dimensions [40]. Stones as a construction material of vaults or domes are mainly cut and curved in ways that form the curved surface. Picture 7.2 shows variety of stone positioning that where current in 16th century in Spain. For each type it can be found an example, type *a* was applied in the *Cathedral of Jean*. Type *b* was applied in *Cathedral El Escorial*. The *c* is the stone cutting type of *Saint Juan Bautista*. Type *d* is found in *Vanadelviras treatise*. Type *e* and *f* can be seen in *Our Lady of Consolacin* [41]. In comparison to other masonry materials, brick is special in two aspects, resistance and size. Traditionally most of the bricks aresized proper to human's hand. Hand- size bricks are less cracked than large size bricks [40]. This small unit size makes the brick work adaptable to any kind of geometries. Figure 7.3 shows the examples of different curved surfaces constructed by bricks.

In masonry construction, there is a classification based on how the brick is laid and its orientation related to the face of the wall. Figure 7.4 shows the different type of the brick orientation for constructing a wall. According to the figure, when brick is laid in a way that the long narrow side is exposed, it is *Stretcher*. *Header* is a brick laid flat when the biggest side is parallel to the face of the wall and the smallest side is revealed. If a brick laid vertically with the long narrow side of the brick exposed, it is called *Soldier*. When a brick is laid on the long narrow side and the widest face of the brick is exposed, it is *Shiner*. *Rowlock* is a brick laid on the narrow side while smallest side of the brick is reveals. *Sailor* is a brick laid vertically while the broad face of the brick is exposed.

Considering the cuboid as a regular brick shape, for walls, there are many kinds of bricklaying methods since bricks can be attached to each other with different sides, in more than one layer. The arrangement of the bricks for constructing a load-bearing wall is named brick bonding. The types of the bonds mostly are names according to their appearance in the face of the

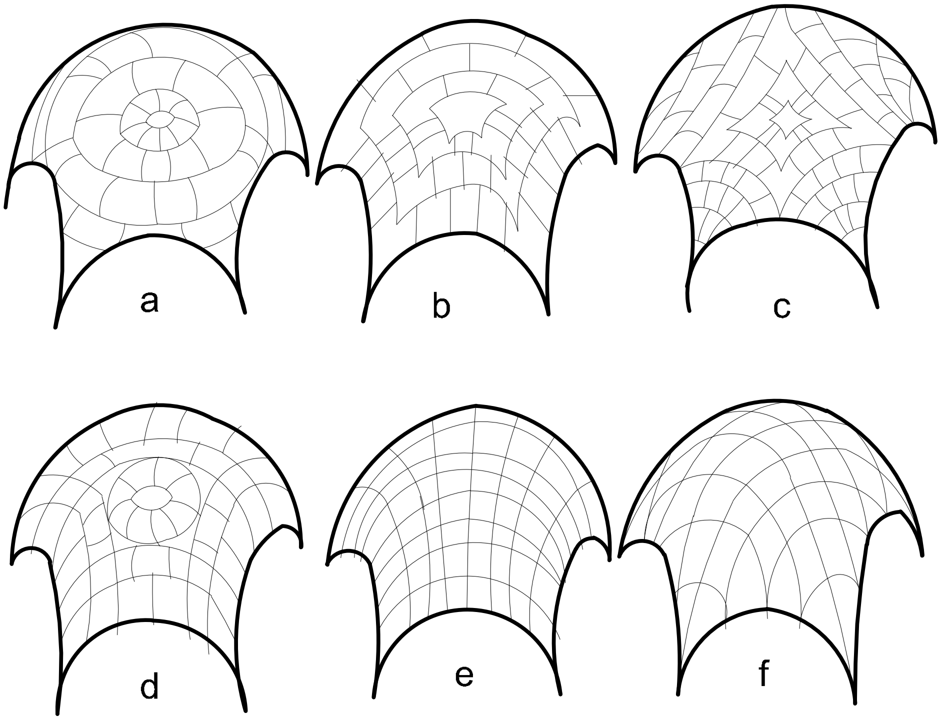


Figure 7.2: The methods of stone positioning in Spain of 16th century [41]

Figure 7.3: Curved surfaces constructed of bricks, a)The ambulatory roof at Bourges [40], b)The dome of Ziaiyeh School at Yazd (Autor) c)Muqarnas of Jameh Mosque and Isfahan(Autor)

wall. For instance *Header* bond is the type of bonding that the end side of the bricks is exposed in the face of the wall. *Running* bond is the type that each course of the brick is laid in stretcher and offset half stretcher from the course above [79] and *English* bond in walls are consist of one layer

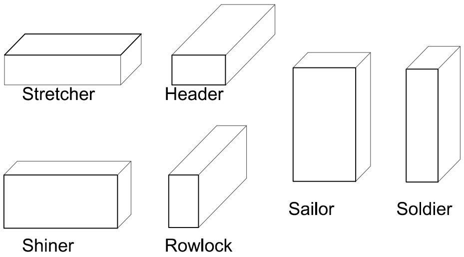


Figure 7.4: Orientations of masonry units in an element [56]

of stretchers and one layer of heeders [70]. Laying the bricks for paving or covering a surface, the variation of brick patterns are rather limited. If the bricks laid in a way that the largest side are parallel to the surface and each course offset half brick stretcher from the course beside. It is called running bond. The *Herringbone* is one brick shiner and the adjacent brick sailor. It means each brick is rotated 90 degrees related to the previous brick. The other pattern is *Basket Weave*, two bricks are placed side by side to make the square model, one brick placed the shiner (90-degree rotation) on the top of those. Another type of Basket wave consists of pairs of bricks are laid side by side that each pair is rotated 90 degrees and placed above the previous pair [79] (Figure 7.5).

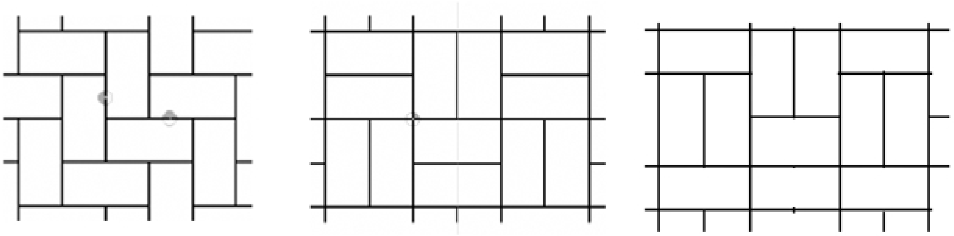


Figure 7.5: Brick Patterns a) Herringbone b) and c) Basket Weave [79]

Bricklaying as a manual work might seem simple and imprecise. It is worker-dependent task. The angles between the bricks or between the bricks and base surface are approximately controlled by the bricklayer. Nevertheless as an accurate geometrical task, it is complicated and requires accuracy and computational controls. In order to construct a brick wall, it is required to select the bonding type. All the bricks are stacked up parallel to the beneath course and the ground. The bricklayer should control the plumb of the wall and alignment of all the bricks with the horizontal line. Depends on the bonding, the bricks may be rotated on the horizontal plane. But laying a brick on a curved surface is different. The bricks should be rotated in 3D space to be aligned to the surface. Geometrically the rotation angle and axis is different for each brick because considering the local curvature of the surface, each brick is placed on a specific plane. The brick courses not only should follow the curvature but also the adjacent courses. The brick arrangements, such as the location of the bricks, the angle between them and the direction of the brick courses depend on the properties of the surface.

7.2 Laying a brick on a surface

Bricklaying process on any kind of surface means to divide it into small fractions composed of block and specific dimensions of the mortar. If a brick and the mortar around it are considered as the cuboid, it is intuitively clear that any flat plane is easily divisible to it. Laying the bricks on the surface other than flat can be considered as the converse procedure of mapping projection. It means to transform a plane to the curved surfaces in such a way that the angle between the objects should be aligned according to the geometry of the surface, but the size of bricks are always constant. For instance if plane of bricks is considered as the grid and we want to transform it to curved surface, the patterns and angles between components should follow the curvature of surface but the size of each component and the angles between the sides of them remain unaffected. The aim of this section is to define the differences between flat surfaces and curved surfaces, which have direct effects on the brick laying process.

7.2.1 Curved Surface

Different types of surfaces related to their geometrical properties such as *Gaussian curvature* and *Geodesic curves* produce different issues faced with brick lying. The radius of ρ is measured by $1/\rho$. If P is the point on a surface the measure of the combined curvature of sections of radii ρ_1 and ρ_2 is $1/\rho_1\rho_2$. The radii are signed to present their possible directions. One of the important issues, which affects the geometry of a surface, is the *Gaussian Curvature* which is the product of the sections k_1 and k_2 *principal curvatures.* The k_1 and k_2 are two curves define most positively curved k_1 and most negatively curved k_2 of the surface at the given point.

$$K = k_1 \times k_2$$

The cylinder is 0 the *Gaussian Curvature* because one of the sections of extreme curvature is a straight line. The cylinder is like plane R^2 as it can be made by joining the edges of a paper strip, which itself is the part of a plane [91]. Innately each point on a cylinder presents a corresponding point on a plane. Intuitively the cone is the flat base surfaces with 0 the *Gaussian Curvature.* The sphere is the positive constant the *Gaussian Curvature*, it means that if any normal plane cut the sphere at a specific point, curves have the radii of the curvature on the same side. The hyperbolic plane is the surface which curves are in the opposite way to sphere [91] so the *Gaussian Curvature*; is always negative and the surfaces with constant negative curvature is called pseudosphere. Since the sphere is not locally isometric to the plane and it is a self-contained structure, it is known as the first example of a non-Euclidean geometry [91]. The geodesics of the sphere are the arcs of the great circles [52]. Two poles of the sphere are the pair of points on the surface where infinite geodesics connect them. If a vector is perpendicular to every vector of a plane, it is called normal to the plane. In a surface normal vector is an orthogonal vector to the surface at a desired point in other word it is normal to the tangent plane of a selected point [88](Figure 7.6). Two planes are parallel if their normal vectors are parallel. The properties of the surface at a point influences the placement and orientation of each brick on a surface.

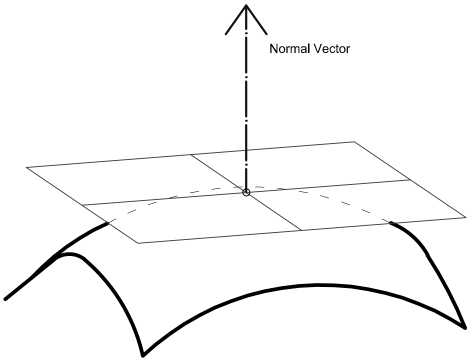


Figure 7.6: A normal to a surface at a point

7.2.2 Placing a brick on a surface

Practically, the process of bricklaying on a surface could be summarized to five steps. First of all the surface should be defined. In actual constructing, this surface is a hypothetical surface on a formwork or guide work which should be forms by laying the bricks side by side. A brick is picked from the stack of the bricks on the ground. Selecting a place on a hypothetical surface, the picked brick in transferred to the specified place. The brick should be laid on a surface in a position that the brick side be parallel to the surface, i.e. it aligned to the assumptive tangent plane of the surface. Lastly, the brick is rotated on the tangent plane to the desired direction.

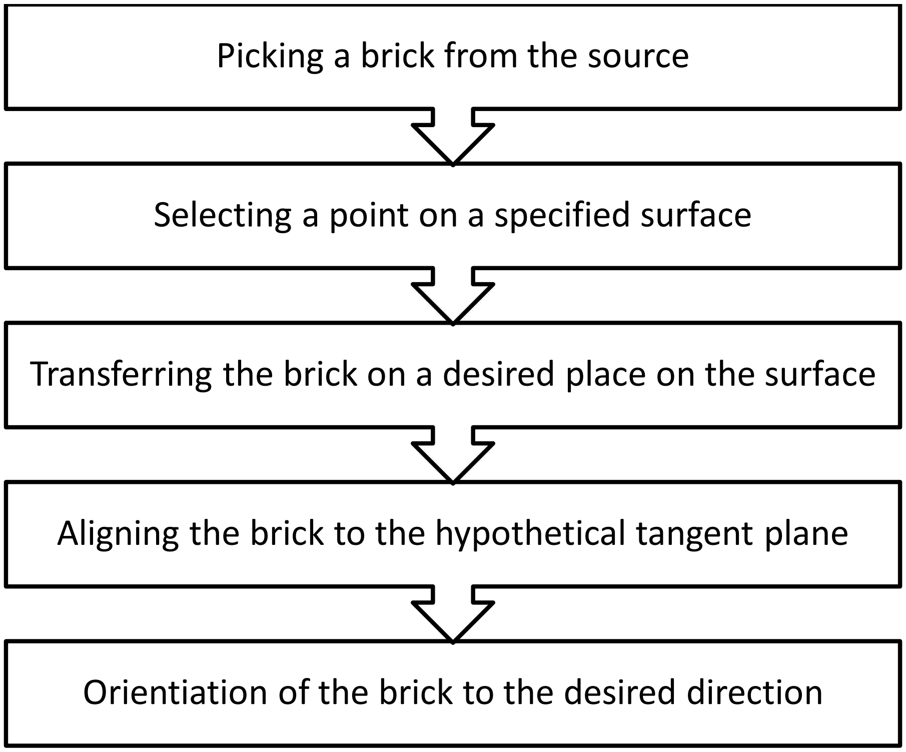


Figure 7.7: Diagram of laying a brick on a surface

Laying the bricks subsequently, one brick is positioned as described above; the subsequent brick is positioned according the prior brick. The mortar gap between bricks should be considered. The new brick is transferred from the origin to the new position. Then it is aligned to the tangent plane of the surface. Finally, it is oriented on the plane based on the direction of the adjacent brick. The type of the brick pattern, define the angle between the new brick and adjacent brick.

The brick courses in non-zero Gaussian curvatures are not always parallel. The line of the bricks might distance from each other so it is required some irregular shape of bricks to fill between courses or they might start overlap so courses it is required to cut the overlapped bricks. The brick courses ei-

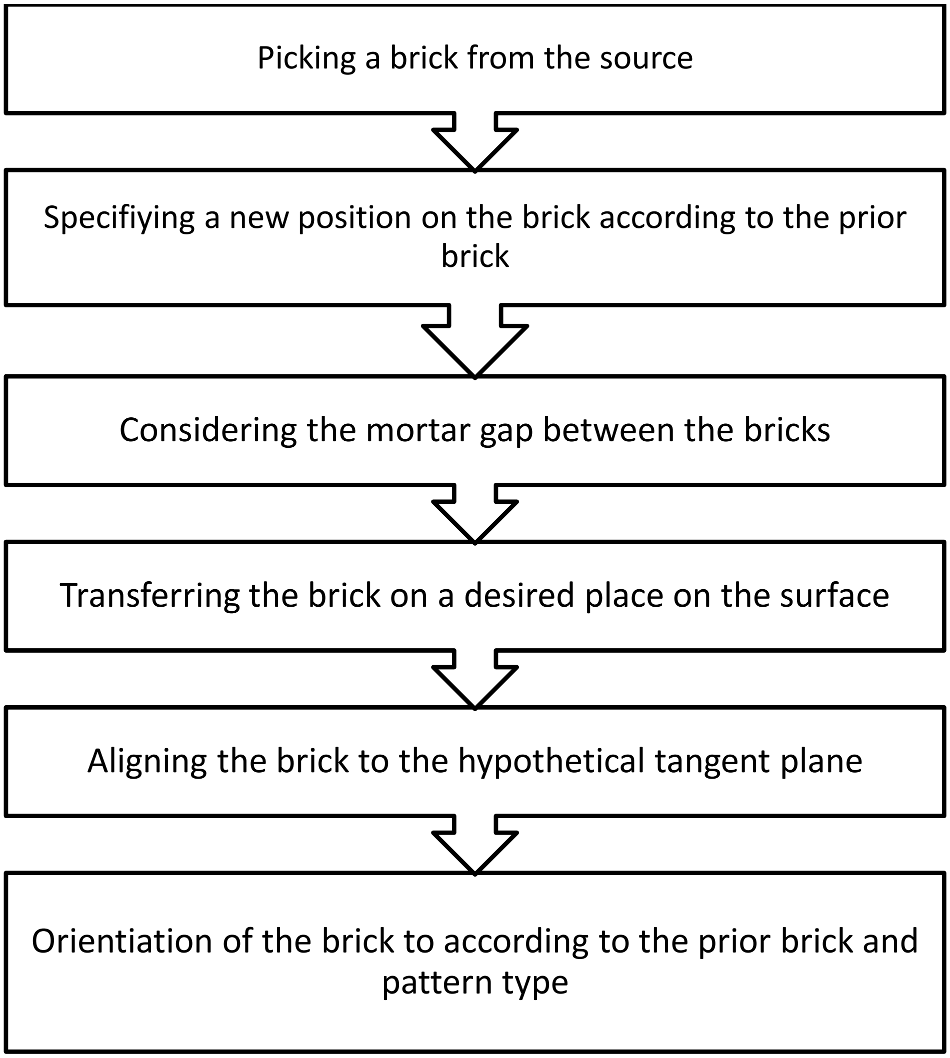


Figure 7.8: Diagram of laying a brick on a surface consequently

ther diverge or converge; the regular bricks should be cut and manipulated to special shapes to form the surface. These special shapes are driven from two bricks overlying each other, manipulating one of them to depart the redundant part. The first step is making a decision that which brick should be cut. The cut brick is selected based on minimizing the cutting process and wasted bricks. The cutting line is parallel to the edge of other brick. The mortar gap should be considered when the cutting model is extracted. Assuming a hypothetical plane for cutting the brick, it should be perpendicular to the brick. Although the bricklaying process seems very simple, it is a process which requires attention and considerable experience to provide a suitable result. In the case of curved surfaces, it is a delicate skill to follow the right shape of the curve. Especially when a number of bricklayers are working together side by side to produce an identical form, it is more difficult to control the coordination of them. Yet the speed in the process of masonry

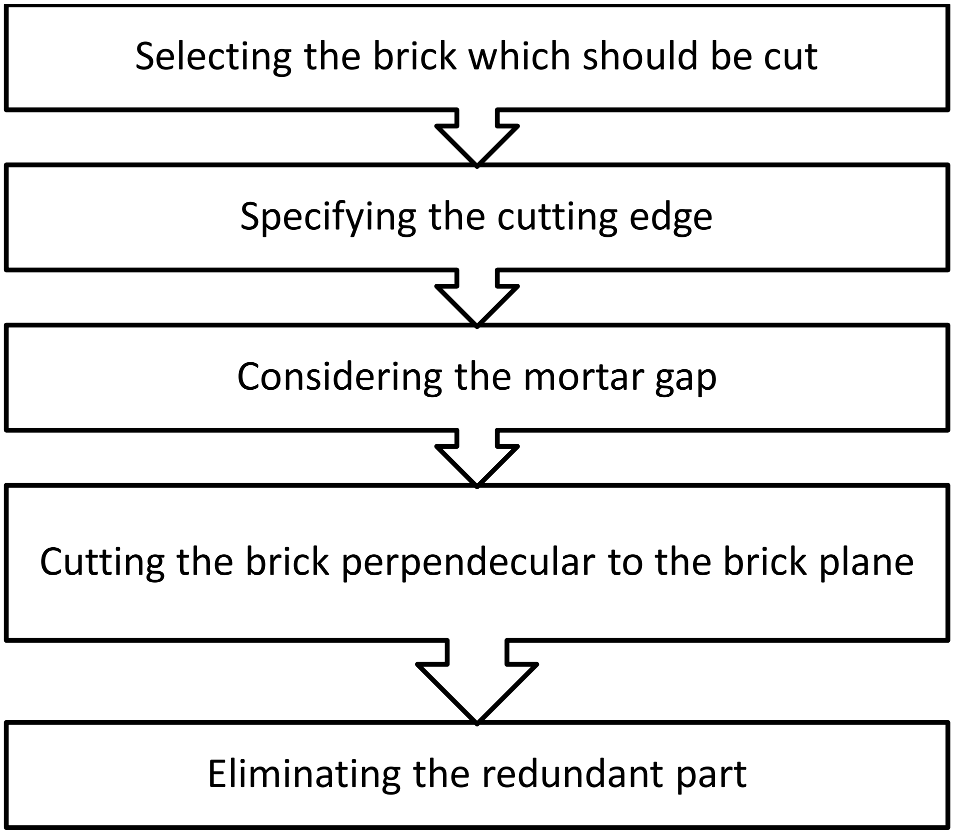


Figure 7.9: Diagram of extracting the special bricks pattern

construction is essential to the economy of masonry [40]. The bricks may be cut as needed. Most of the times, they should be cut very precisely for forming the right shape. Cutting of the bricks slows the process of the construction. In order to increase the construction process, it is very useful to exactly know the brick courses and the patterns of special bricks. Modeling the brick pattern on a surface before the starting construction process is one solution to improve the value of masonry construction.

7.3 Computational methods for brick pattern design

Despite the long history of masonry construction, presently there are limited tools for using in the process of brickwork design [13]. *BrickDesign*, RoB is software developed by the company *Keller AG Ziegeleien*. This tool enables the user to apply the patterns and images to the straight brick faade [31]. This software focuses on mapping an image on the straight walls and is not applicable to curved surfaces. The dimensions of the wall, brick dimensions, and the bonding system of the wall are controllable by the user. But it is limited when the user wants to apply different types of bonding on unique wall. At Georgia Institute of Technology, Afsari et al. [12] is developing an interactive and real-time tool to design patterns for brickwork. This tool is able to generate interactive arbitrary patterns and map it to the brick wall. But it is just applicable to the running bond and it is just limited to the straight walls. Moussavian and Gentry are working on digital tool for automated generation of brick vaults [65]. They presented a tool for modeling the brick pattern on three regular Persian vaults based on the existed construction techniques. In fact, their tool generated brick courses on the case studies according the bricklaying rules, which masons traditionally apply during the construction process. Although their research is one of the few bricklaying projects on the curved surface, it does not encompass all curved surface and it does not provide an aid tool for designers to generate their own concepts of brick patterns. Lachauer et al. [58] have applied technique to generate the tessellation of the funicular vaults. Their method is used for stereotomy of masonry units during fabrication. In this method, the tessellation is influenced by the general shape of the surface and it is not based on the standard masonry units. Considering the contemporary researches for finding innovative methods and tools for masonry design and construction, there is still a big gap in new methods and tools for masonry vaults. The form findings methods mostly ignore the aesthetic parts. The robotic tools or some other innovative methods for constructing of free-form surfaces do not cover the design phase or neglect the role of the designer. Accordingly there is a big gap of a tool that helps the vault designer to consider the both aesthetical and structural issues.

7.4 Research Problem

For many years, shell structures have an important role in architecture and engineering. As their form and structure behavior (Load transfer path) are not separated with each other, they always develop an interesting challenge for designers to design an innovative shapes with load bearing efficiency. Masonry construction is the continuum placement and bonding of individual components. Being laid in different position, pattern and forms and not always horizontally, sometimes obliquely, in meander frat, chevron or herringbone pattern [44] masonry construction has diversity in appearance and more important, different answers for structural issues. The nature of the shells is so that designing a shell, the designer should satisfy the aesthetic challenge, function and structural challenges at the same time [17]. For vaulting, the geometric characteristics of the continuum of the components and specific pattern of bricklaying adapted to them (blocks, mortars, etc.) are part of a sequence of technical decision and it influences on strength, stability, constructability, aesthetic and economy of the structure. While typically at the most of the structural analysis tools, the masonry surface is simplified as the homogeneous surface and geometry of components or their bonding systems are eliminated. These simplifications might cause some failures in prediction of structural behavior [29]. On the other hand, there are not any specific rules or standards for brick patterns on the vaults. It is more craftsmen intensive who usually decide for pattern courses, brick positions or boundary details during the construction process. This might not make any problem in simple geometries as the traditional vaults, but it might make errors for constructing free-form surfaces. This is more important when it takes into consideration that the visual aspects of facades rest on each brick position. Masonry units, bricks, for instance, are the principal material requirements for unreinforced shells and Quantity of units is considerable as a major material cost for them. Estimating the number of unit requirements by considering different unit dimensions with different prices might cause notable budgetary foresight in big projects. But it is not easy to estimate the exact quantity of unit requirements for constructing a curved surface and it is even more complicated to compare the costs providing different unit sizes. Considering the costs of construction, the masonry building is more optimized when the speed of construction is increased. The same as other type of buildings, 3D modeling of masonry shells with specific location of each unit accelerates the construction time, declines the human errors and enables the designer to evaluate the costs accurately while gives a precise overview of building visual impression. There is not an attributable tool for considering the material requirements and constructing duration. In usual CAD systems, designers are forced to model or place all the components by hand which it is time-consuming and tedious duty or even impossible in the case of free-form surfaces. During the construction of curved surfaces, it is unavoidable to use non-standard bricks which should be cut or curved. Because depends on the properties of surfaces (curvature), it is not possible to cover a surface with parallel courses with equal number of bricks. It is always required to manipulate some bricks to fill the gaps between the courses. Extracting the model of these non-standard or supposed special shapes is complicated, especially if not considered before brick laying process. In conclusion as a point of view, the thesis author, besides the form parameters, the unit dimension, pattern type and the arrangement of unit courses should be considered as the factors of a free-form masonry design. Although they have a big influence on the design and construction process, they are mostly neglected or devalued in contemporary researches. Considering the brick laying as transferring a brick from plan into three-dimensional space, it is not difficult to design and model the brick pattern on the simple geometries but for irregular geometry i.e. free-form surfaces require complementary tools. Next chapter is discussing about a new computational tool designed for modeling the brick pattern on a surface automatically.

Chapter 8

Geometries of bricklaying on a surface

The idea of this research is started from the Computational Morphogenesis Workshop 5.1.1. During the construction, because of the complexity of geometry and irregularity of form, selecting the courses for laying the brick was randomly. It caused some interruption in the construction process. In addition in order to follow the geometry, it was required for non-standard bricks to fill the gap between the standard bricks (Figure 8.1). Accordingly it imposed the bricklayers to stop working, extract the special bricks models, cutting the bricks and progress the brick laying. All of this caused stoppage in the construction process and was very time and energy consuming. The workshop experience indicated that the placement and bonding of each individual component which form a surface has strong effect on visual concinnity and the structural behavior of masonry shell on one hand and on the other hand on the time to build and even the economy of the whole project. This chapter describes the steps of the brick laying on a curved surface as a geometric point of view.

Figure 8.1: Brick laying problems in free-form vault construction

8.1 Laying a brick on a surface

8.1.1 Generating a brick

A regular brick is cuboid shape with three parameters, length, width, and height. Center of cuboid is a point where the space diagonals intersect. A cuboid is formed of 8 vertices, 12 edges, and 6 faces. If a cuboid is created in a Cartesian three-dimensional cordinate system and the center is pointed to the origin (0,0,0), the eight vertices are coordinated based on their directions. In the figure 8.2, a, b and c are respectively half of the length, width, and height. For instance, the cordinate of one of the vertices is (a, b, c) and the next one is (a, -b, c) and so on. By defining the cordinates of all 8 vertices, the cuboid is formed by lines that join adjacent points.

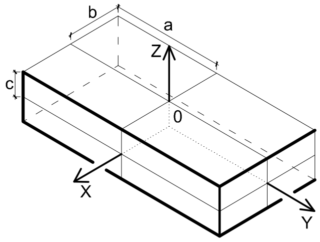


Figure 8.2: Geometry of a brick

8.1.2 Positioning a brick on a surface

Geometrically laying a brick on a surface means moving a brick from a place to a specific point on the surface and aligns it to the tangent plane at selected point. Precisely, it is the transmitting of all points of a cuboid from a 3D Cartesian cordinate system to any other three-dimensional Euclidean space. But in case of moving a cuboid (brick) which is parallel to the XY plane, from a Cartesian system to a new point on a surface, it would be sufficient to transmit a reference point from the first place to new position. All the attached vertices and lines will keep their distance and angle with the reference point. It means that transmitting an object requires a point in the original place and another point in destination or a transmitting vector. *Normal vector* is a vector perpendicular to a given object and on a surface it is the perpendicular vector to the tangent plane of a specific point [88]. In order to make a face of a brick tangent to a surface, the perpendicular axis of the brick should rotate in a way that becomes vertical to the surface. The perpendicular vector in a point of a surface is *Normal vector* of the surface in that point. As the Figure 8.3 indicates, rotating the brick in a way that the perpendicular axis of it is parallel to the Normal vector of the selected point, the brick is tangent to the surface. The angle between the normal vector and the vertical axis, defines the rotation angle. The axis of the rotation is a vector which is perpendicular to both of the vectors. This vector is the cross product of these two vectors that identifies the axis of rotation.

8.1.3 Displacing a brick on a surface

Displacing a brick on a surface means transferring all vertices of a cuboid from their first location to a new location in a way that the desired face is parallel to the tangent plane of the new position. But considering the placement of the cuboid on a non-plane surface and by considering that the cuboid must keep its original shape, it means transferring a reference point on a surface

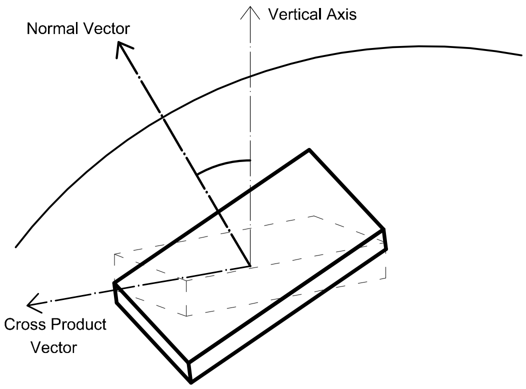


Figure 8.3: Aligning the brick to the tangent plane

to new position on the same surface and then rotate the object with an angle and around a vector that the vertical edges of the brick (cuboid) is parallel to the Normal vector of the new position on the surface. If it is considered that the brick is parallel to the tangent plane of first position so its vertical edges are parallel to Normal vector of the first point. Considering the center point of the cuboid (brick) as a reference point, the first Normal vector is unitized, displaced with 8 other vertices to the new place. The angle between the first Normal vector and the normal vector of the new position on the surface is the *Rotation Angle* and the *Cross Product* of these two vectors are *Rotation Vector*. By rotating all vertices and lines of cuboid Rotation Angle and around the Rotation Vector, the brick is parallel to the tangent plane of a new position and it is said that the brick is laid on a surface(Figure 8.4).

8.1.4 Rotating a brick on a surface

In aviation, Yaw rotation is a rotation around the yaw axis, Yaw axis is an axis drawn from the top to the bottom of the object and perpendicular to the other axis of the object. This term [12] can be used when a brick is rotated around the normal vector of the center point of the brick. As the brick is parallel to the tangent plane of the center point, this normal vector is parallel to the vertical edges. If the brick is intended to be rotated on

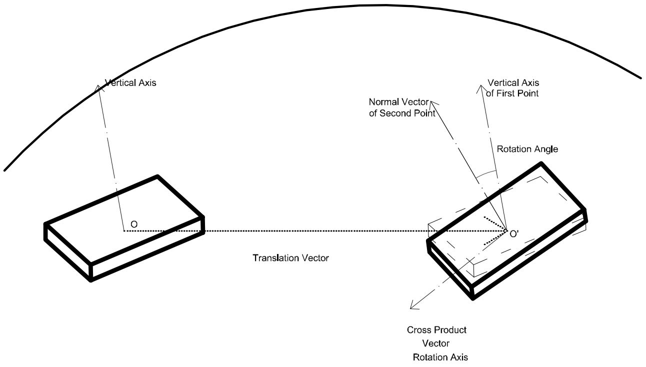


Figure 8.4: Displacing a brick from a point on the surface to the other point

the same plane that is laid, in this thesis, it is termed rotating a brick on a surface. Sometimes it is required to rotate the brick big angle for making the herringbone bond but sometimes small angle in order to follow the curvature of the surface.

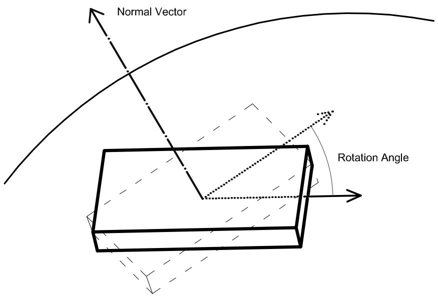


Figure 8.5: Rotating a brick on the tangent plane of a surface

8.2 Special Bricks

In brickwork, it is very common to use non-regular shape of bricks. Besides some standard cuttings models such as half closure or three-quarter closure, in most of the situations, mason should decide about the required shape during the construction. Especially during the constructing a curved surface, except the zero curvature surfaces, it is not possible to cover a surface of invariable parallel course of bricks. Depends on the surface properties, the courses close to each other, so bricks start to overlap or separate each other so some irregular bricks are required to fill the vacant lines. In both situations, indeed, there is always a brick meeting another one. The required shape can be extracted by slicing one of the bricks from the meeting points. The cutting plane should be perpendicular to the laying side of the brick. Since, on a surface, two bricks are not on a same plane, there is not a unique plane which is perpendicular to both of the bricks and cross the intersection points at the same time. As it is illustrated in the figure 8.6, the slicing plane should be defined based on the brick that should be kept complete. The side of this brick, which traverses the other brick defines the approximate place of the cutting plane. But this side is not perpendicular to the other brick which should be manipulated. The slicing plane should cross the remaining brick and be perpendicular to the manipulated brick. Between the two upper edge and lower edge, it is more precise if the plane crosses the midpoints of these two edges. If the vertical edges (parallel to the normal vector of its center point) of manipulated brick is copied to the midpoints of remaining brick, it is achieved a plane, perpendicular to the manipulated brick and crossing from the intersecting faces of both bricks. Considering the gap for putting the mortar, the slicing plane should be offset toward the manipulated brick. Deleting the redundant part, the reaming shape is the special brick. Laying the special brick on the plane, the cutting model is extracted.

8.3 Positing the bricks consecutively

8.3.1 The placement possibilities

Most of the prevalent brick patterns are based on the cuboid common bricks. These pattern arrangements are based on the relation between brick dimen-

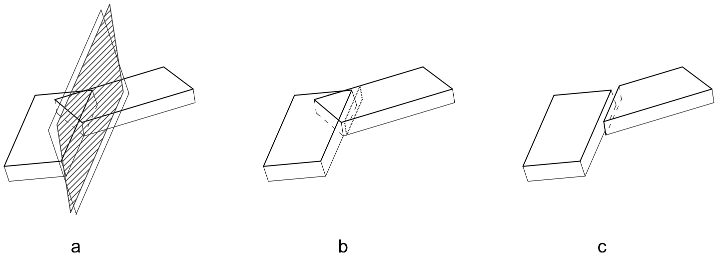


Figure 8.6: Splitting a brick overlaid by another brick

sions and the distance between two bricks. In order to lay the brick consecutively, each brick should follow the prior brick to define the point and angle of placing. The placement of each brick is considered regarding the previous ones. The Figure 8.7 shows all possibilities of brick location concerning the reference brick based on the regular patterns. For instance, if the pattern is *Herringbone* bond, the location of the following bricks would be point 2,4,6,8,10,12,14 or 16. It depends on the existing bricks on the surface.

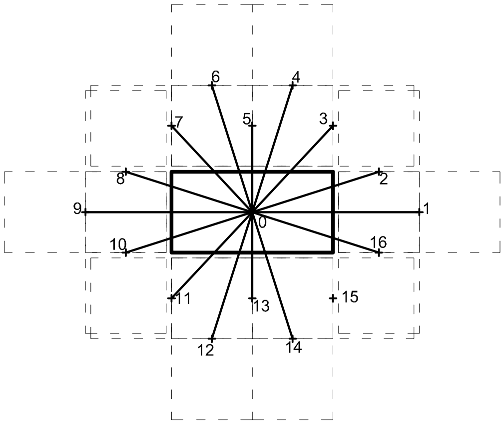


Figure 8.7: Possibilities of bricks placement

Assuming the center of the brick as a reference point for location of the brick, the placement of the following bricks on a flat plane are able to figure out by simple calculations. For instance in the cordinate system if the center point of first brick is supposed to an origin point (0,0), the placement of point 1 is equal to the length of the brick plus the gap between two bricks on the X cordinates (a+d,0)(Figure 8.8).

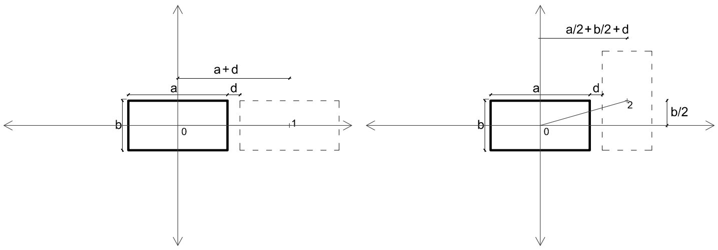


Figure 8.8: Locations of bricks based on the Origin in coordinate system

8.3.2 Orientation

Brick bonding or brick patterning means bricks laid sequentially, in the way that each brick is oriented according the adjacent bricks. In order to create a Stretcher bond, each brick after being laid on the surface should be parallelized with the previous brick. The direction of the brick is able to defined as an assumptive line intersects with the center point of the brick, laid in the tangent plane of the surface and parallel to the longer edge of it, named *Direction Line*. On a plane, the angle between directions of two bricks indicates the angle that new brick should be rotated to be parallel to the previous one. But on a curved surface, as these bricks are on two different tangent plane, these two Direction lines are skew lines i.e. two lines in 3D geometry that do not intersect and are not parallel. In order to find the angle between two bricks, it is enough to know the angle between the one of the Direction lines and the projection of the other on the plane of first one. Since new brick should rotate on its tangent plane, the projection of the first brick Direction Line should be defined on the tangent plane of new brick. The projection line can be defined by the intersection of the tangent plane and the other plane, which is perpendicular to the tangent plane and cross the copied Direction Line. The perpendicular plane is defined by knowing three points, center point as the origin point of plane, a point on the copied Direction Lined and a third point is obtained by copying the unitized normal vector of first brick to the center point of new brick. The intersection of the tangent plane of new brick and the perpendicular plane is a line crossing the center point. The angle between the intersection line and the Direction Line of new brick indicates rotation angle of the second brick to be oriented to the same direction of the previous brick. The new brick should be rotated on its plane or around the normal vector of its center point but as the normal vector direction is concerned by the properties of surface curvature; the rotation axis is the cross product of Direction Line and intersection lines (Figure 8.9).

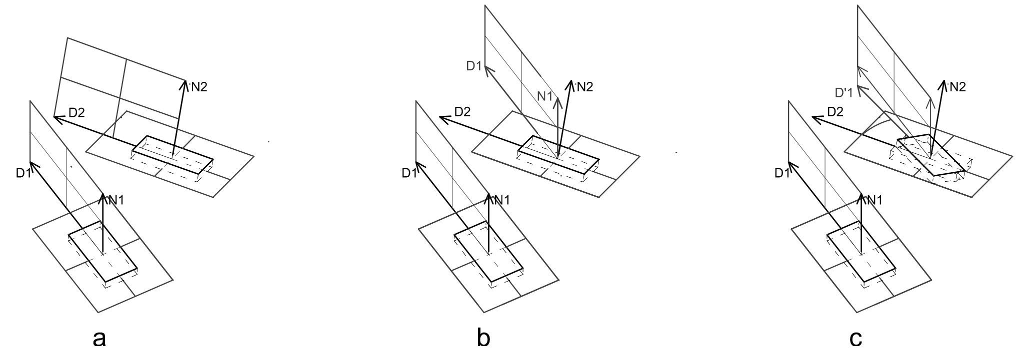


Figure 8.9: Arranging the brick with the direction of the previous one

These are the geometries which could be used when a brick layer starts to lay the bricks on a surface applied intuitively. Converted these rules as a series of commands inside software, the brick pattern is designable and manipulated through the digital tools. The next chapter is about the methods of transforming these geometric rules to software, i.e. a plug-in that is an interactive tool for designers helping them design and model the brick patterning on a curved surface.

Chapter 9

Digital Tool for designing brick pattern: First steps toward the Brick Pattern Plug -in

Today we live in the time of computer and digital technology. CAD and CAE software have proved their efficiency in architecture and engineering. They help the designers to create complex geometries, perform the computational analysis and do the repetitive tasks. Designing and manufacturing is not imaginable without computers. Integration between designing the masonry structures and digital tools could provide new opportunities for returning vaults and domes to contemporary architecture. A design of complex free-form vault requires designers to explore multiple alternatives. The integration between commercial CAD software with common scripting language helps the designers explore design possibilities in the early stage. The advantage of codes opens up the possibility of modeling system through digital means for providing structure. In the field of masonry vaulting, to operate the optimization process, it must be defined and codify the material and structural relationships of the individual elements to each other. This section concentrates on simulating the brick pattern on the free-form masonry shell by integration of scripting language, Python, with commercial CAD software, Rhinoceros. It is aimed to automate the modeling brick pattern that enables the designer to know the material requirements such as quantity of blocks and the shapes of unusual blocks, before the beginning of construction. This information reduces the construction time and material wastes. To achieve this goal, it was decided to develop a tool that stimulates the process of bricklaying on a curved surface of the real world in 3D software. The entire process should be automated to accelerate the modeling process. Not ignoring the role of the designer in the decision-making process for the brick pattern, it was defined to develop the tool as an interactive method of designer and the digital tools. This section describes the steps toward the coding the geometrical rules explained in the previous section in order to initialize a digital tool for designing brick patterns for free-form surfaces.

9.1 Implementation

9.1.1 Tools and implements

Programming is a powerful tool to automate tasks and geometric manipulations [86]. Joint with the graphical software and programming language provides a digital method to generate geometry and automate the repetitive tasks much faster and simpler than the normal methods. *Python* is a modern programming language and it is linked to the commercial 3D graphical software (*Rhinoceros*). Rhinoceros forms the shapes by utilizing (*NURBS* systems. NURBS , Non-Uniform Rational B-Splines, are mathematical representations of 3 D geometry. Any shapes such as simple 2 D lines, circle, arc, or curves and any complex 3 D organic free-form surfaces can be described accurately in this system [85]. Linking python to Rhinoceros, in addition to the python commands, all the command inside the Rhinoceros are available by means of programming scripts. Through these tools, the geometrical process of laying a brick on the surface is converted to the code scripted codes. It provides a new tool for designing brick patterns on a surface with the semi-automatic method. This section is describing the generation process of this new tool. Indeed, this new tool is a new plug-in for Rhinoceros that facilitate the designing and modeling the brick patterns on a curved surface. The tool is named *BrickPattern*.

9.1.2 Basic notions

In order to convert the geometrical method to a programming code comprehensively, some rules and terms are used in the programming process. The brick is considered as a cuboid in the Rhinoceros so the real meaning of term *Brick* in the generation process or inside the plug-in is a geometrical cuboid. The intersection of space diagonals center point is termed or *Reference Point*. It is used as applying any transmitting or rotation on the brick. The dimensions of the brick and the dimension of the mortar gap are the main parameters of different brick patterns. By formulating the relation between the types of patterns with the dimensions of bricks, the more of patterns are applicable to this tool. As it is indicated in section 8.3, the location of each brick is defined by the location of the previous one and for each one, there are several possibilities. The possible location of each new brick is defined by the *Reference Points*, which named *Guide Points*. The *Guide Lines* link the reference brick to other possible new locations. These lines are illustrated for better graphical expression. All the brick references or guidelines are created on a median plane of the brick that it is parallel to the stretcher side of the brick. This is the tangent plane to the surface and all the rotating or displacement are applied by referencing to it. Therefore, the brick laying is implemented on the surface that is half of brick thickness above the main surface. In order to have a reference direction for rotating a brick or finding the angle between two bricks, each brick is oriented based on a *Brick Direction*. It is a hypothetical segment started from the Reference Point of the brick laid on the tangent plane and parallel to the longest edges of the brick. In order to orient a brick, most of the times, the brick is oriented based on the direction of the brick already laid on the surface, the brick which is referenced to specify the direction of the other bricks is named*Reference Brick*. *Gizmo* in this tool, is a circle appears around the specified point to facilitate defining the orientation. As in this tool, the bricks are laid stretcher, i.e. the long narrow side of the brick is parallel to the tangent plane of the surface at the point, the *Vertical Axis* of the brick is parallel to the shortest edges of the brick. *Brick Line* means laying the bricks in a way that the center points of them form a line and *Brick Stain* means creating a group of bricks covering an area.

9.1.3 Frequent Functions

In the process of codifying, it is repeatedly required to script a set of codes that perform a single related action [39]. These set of codes can be blocked in an organization which is called *user-defined functions*. The functions are more useful when the related action is required more than once. In the process of developing the code, there were several duties blocked in the functions. Some of them are almost used in every sub-tool. These functions are defined in the format of pseudocode. In order to orient a brick according to other bricks or illustrated a Gizmo when the brick is supposed to rotate on the tangent plane, it is required to define a plane. The plane is created by means of three points and should be parallel to the tangent plane to the surface.

```
1. def (surface, point, parameters)
2. Evaluate the derivatives of the surface (Vector1 , Vector2)
3. Unitize the vector (Vector1, Vector2)
4. Create a plane form 3 points (point , Vector1, Vector2)
5. Return (plane)
```

When it is supposed to orient a brick according to the orientation of the Reference Brick, a Gizmo appears on the screen while indicates the direction of the Reference brick. The gizmo is supposed to place on the plane achieved from the last function. The main directions of gizmo are originated from the direction of the brick selected as the Reference Brick. The orientation of the brick is extracted from the Direction Line. The brick group that supposed to be the referenced brick is selected by the user. The segment which indicates the brick orientation, is separated (Direction Line). These are more functions that repeated in codes which are available in the appendix part.

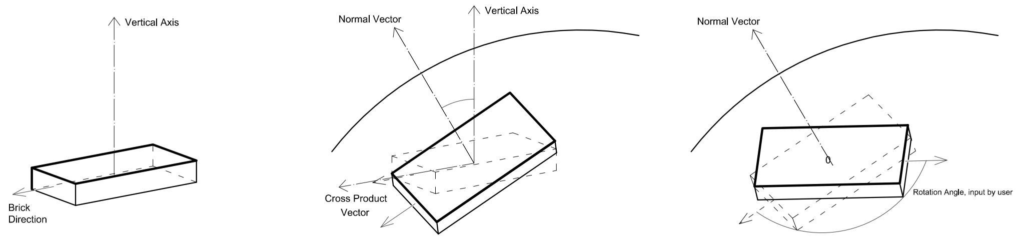
9.2 Main Parameters

The first step of bricklaying is selection of a surface that should be covered with bricks. In the real situation, this surface is a hypothetical surface approximately formed by the formwork. Inside the 3d graphical software, it is a surface with determined geometrical properties. The next step is selecting the dimensions of the brick which is going to be used during the brick laying. As these data are fixed during the whole process, it is time-reducing if they are input by the user once. The surface on which the bricks should be laid is selected by *GetObject* command which asks the user to select a surface by a click on at the desired point of a surface in Rhinoceros 3D environment. The dimensions of the bricks and the dimension of the gap for mortar are defined through the boxes display on the screen prompting the user to enter the numbers. This information is stored in a file that would be accessible by other commands of this tool.

9.3 Create a brick on a surface

The brick laying starts with laying the first brick on a surface. In this step, the code enables the user to put the brick one by one on the surface. Knowing the dimensions of the brick i.e. cuboid are created as the *Origin* is the center of it. Defining the coordinates of the vertices are described in 8.1.1. the position of each following brick considering the pattern type is indicated in picture 8.7 and 8.8 are illustrated by points (*Guide points* and for graphical demonstration (*Guide lines* are created as part of brick group. If the selected object is verified as the surface, the user is asked to select a point on the surface where indicates the brick location (center of the brick). By means of the command *SurfaceClosestPoint*, the user will be able to be certain that the selected point is placed on the surface and the U and V parameters of the point are defined. These parameters are utilized for defining the Normal Vector of the surface at the point. The reference brick accompanied the guide points and guidelines are moved from origin to the selected point. By means of *RotateObject*, the brick, and the other components are orientated the brick on the tangent plane of the surface at the selected point. The command *Angle* computes the angle between the normal vector and the vertical axis that defines the rotation angle and the cross product of these two vectors identifies the axis of rotation. Laying the brick on the surface, it is oriented according the properties of the surface. In order to align the brick to the desired direction aside from the center point, it is also required another point. These two points specify the line that indicates the direction of the brick. For specifying the second point, two options are provided for the user. In the first option, a circle is created around the center point as a *Gizmo* that the user is able to select any point on it. The circle is created on the tangent plane of the surface at the first selected point (the same plane that brick is laid) and the center of the circle is the center point (Figure 9.1).

The second option enables the user to select another brick as the reference brick. A gizmo circle is created around the center point with the main directions according to the direction of the selected brick. In order to create the lines showing the direction of the selected brick, the direction line of the selected brick is copied and aligned to the tangent plane of the first selected point. Specifying a point on Gizmo circle, a segment is created. The Center Point (a point selected by the user primarily) is the intersection point of



Creation of a brick

Displacing to surface and orienting to tangent plain

Rotating to desired direction

Figure 9.1: Laying a brick on a surface)

newly created segment and the Direction Line of the brick. The brick group that primarily oriented according to the properties of the curvature should be rotated on the tangent plane and referenced to the Center Point such way that the Direction Line overlays the created segment. Thus, the angle between these two lines is the rotation angle and the cross product of them is the rotation axis.

The process is described in the below Pseudocode.

```
1. Read the Dimensions and the ID of the surface from the Setting file
2. Compute the coordinates of the vertices and Guide Points
3. Create a box on the Origin based on the vertices
4. Create the Guide Pints and the Guide Lines
5. Make a group (box, Guide Lines, Guide Points)
6. Specify a point on the surface(Point)
7. Compute the Normal Vector of the point
8. Compute the Angle between the Normal Vector and Vertical axis (Rotation Angle)
9. Compute the Cross Product of the Normal Vector and Vertical axis(Rotation Axis)
10. def define the plane (surface,point, parameters)
```

11. Create a circle on the tangent plane of the point on defined plane(Gizmo)
12. Specify the second point that defines the brick direction(Brick Direction)
13. Move the group to the Point
14. Rotate the group *Rotation Angle* degree around the *Rotation Axis*
15. Orient the brick toward the Gizmo

9.4 Displace a brick on the surface

Displacing a brick on the surface means moving a brick from a point to the other point of the surface and orients it to the new tangent plane of the surface. The destination point is selected with user by specifying a point on the surface. The difference between two points indicates the transmitting vector. In order to lay the brick on the tangent plane of the new point, it should be rotated. The difference between the normal vectors of two points defines the rotation angle and the cross product of vectors specifies the rotation axis.

9.5 Rotate a brick on the surface

If it is supposed to change the direction of the brick, the brick should be rotated on the surface around the normal vector of the center point. Three methods are developed to rotate a brick; it would be rotated by defining the desired angle, by defining a second point and rotating according to the other brick. In the first method, the desired angle is input by the user and the *Direction Line* so the brick is rotated. In the second method, a circle around the brick is created that by selecting a point on it indicates the measure of rotation. In the third method, one brick as the reference point is selected. The direction of the selected brick defines the main direction of the gizmo.

This method provides the opportunity to the user to specify the desired point also rotate the brick according to any other brick.

9.6 Special Bricks

Except the flat planes, it is no possible to cover the curved surfaces just with one type of bricks. Using the bricks with special shapes is unavoidable in laying bricks on vaults and domes. Intersection of bricks in a brick course usually occurs when brick dimensions and mortar thickness are not compatible to the curvature of the course. Laying the brick on the curved surfaces, the bricks start to overlap each other. For extracting the model of the special bricks, the intersected parts of the bricks should be eliminated. One of the bricks is supposed to remain in complete shape and the other one is cut. Through the tool, the user is asked to specify the brick that supposed to stay without deformation and the brick that supposed to deform. The cutting place is one of the faces of the first brick, which intersect the other brick and is vertical to the tangent plane of the first one. Through this face, considering the gap for the mortar, it is created a vertical plane to the cut brick. The below Pseudocode clarifies the process more comprehensively.

```
1. Select the first brick (brick A)
2. Select the brick should be cut (brick B)
3. Extract the segment perpendicular to brick A(vertical line)
4. Select the side of the brick A that intersect the Brick B (selected side)
5. Find the middle of the curves of the selected side (midpoints)
6. Transmit the vertical Line to the midpoints (parallel segments)
7. Create a plane with parallel segments (cutting plane)
8. Offset the plane for mortar gap
```

9. Split the brick with cutting the plane
10. Delete redundant part
11. Return the remaining part (special brick)

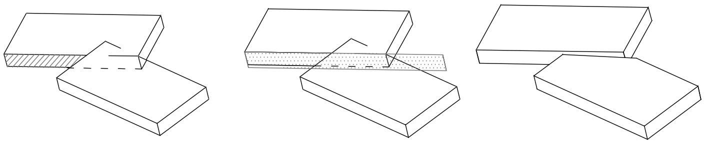


Figure 9.2: Extracting the model of special bricks)

This section is the implementation of geometrical rules of bricklaying on a curved surface to the scripted codes. Through these codified commands, the user or the designer is able to model and design any brick pattern on desired surface. Although most of the steps and rules are computed automatically, the user has to lay the brick one by one and the process is still time- consuming. In order to fulfill the designers requirements of brick pattern designing, it should be automated the consequence of bricklaying. Next chapter is talking about the *Auto Patterning*.

Chapter 10

Automated patterning:An interactive Brick Pattern Plug -in

Laying a brick on a surface one by one is so much time-consuming. In order to optimize the brick patterning code, it is required to automate the brick patterning on a surface. It is complicated to model the entire surface with bricks accurately in the totally automatic way. Moreover, emphasizing the role of architects and designers even in the patterning process, it is preferred to develop an interactive process for brick patterning. Model a line of bricks or stain of bricks on a surface is an interface method to automate the brick patterning.

10.1 Creating a course of bricks

A primary step toward the automating the modeling of the brick pattern, is laying the number of bricks sequence wise to make a line of bricks. Based on selecting the Center Point, this line can be formed in different axis and direction.

10.1.1 Automatic creation of the brick courses

The primary step is creating a line of bricks in the desired direction with a desired distance from each other. The first brick is located and oriented with the method described in section 9.3. In order to locate the next brick, as it is described in the section 8.3, considering the common kind of brick patterning, there are sixteen possibilities for locating a new brick following the prior one. The place of next brick is defined by the place of their center point. As the figure 8.7 indicates the possible position of center points are defined according to the center point of the prior brick. Selecting the proper point, the desired pattern of the brick in a line shape is modeled on this code. For locating the first brick (base brick), the user has the possibility of specifying the first center point and another brick as the reference brick, this enables user to continue the model in each place that the patterning had been stopped. By selecting each of the *Guide Points*, the type of the patterning would be changed. Laying the first brick, the user is requested to specify one of *Guide Points*. The selected point is the center point for the following bricks and automatically, the same guide point in the group of bricks is considered as the center point for the next brick. Each brickworks

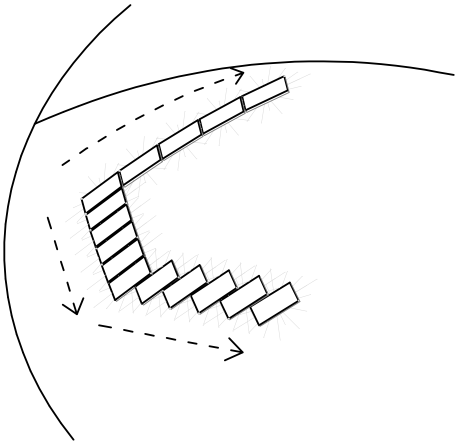


Figure 10.1: Line of bricks differed by specifying various guide points

as the reference brick for the following brick to specify the orientation of the brick. The bricks are parallelized with each other with the method described in section 9.1. The user defines the number of the bricks in the line right after the command is run. All the process leading to having a set of bricks arranged in a line shape is summarized in the diagram 10.2. All the following commands have similar logic.

10.1.2 Interactive creation of the brick courses

Laying the bricks on a line, although each brick is oriented according its former brick, they might be required to be rotated or to be moved. When the curvature becomes greater, the mortar gap between the bricks decreases so the brick should be shifted or be rotated for avoiding the overlapping. Controlling the orientation and location of each brick takes more time of bricklaying but provides the most accurate brick pattern with minimum overlapped bricks and so minimum bricks with special shapes. In order to enable the user to control the location and orientation of each brick while not obliged to lay the brick one by one the *Smart Line* code is scripted. The process of this application is approximately similar to the previous one but in this command, after laying each brick, the process is paused to ask the user whether any new orientation or displacement is required or not. The angle input by the user defines the rotation angle around the rotation angle which is a normal vector of the brick center point. Also, the code enables the user to displace each brick by specifying a new point on the guidelines. The brick is transferred to the new position and be aligned to the tangent plane of the surface.

10.2 Creating a stain of bricks

Developing the method of creating a line of bricks automatically, the plug-in is more optimized if it would be able to lay a set of bricks at the same time.

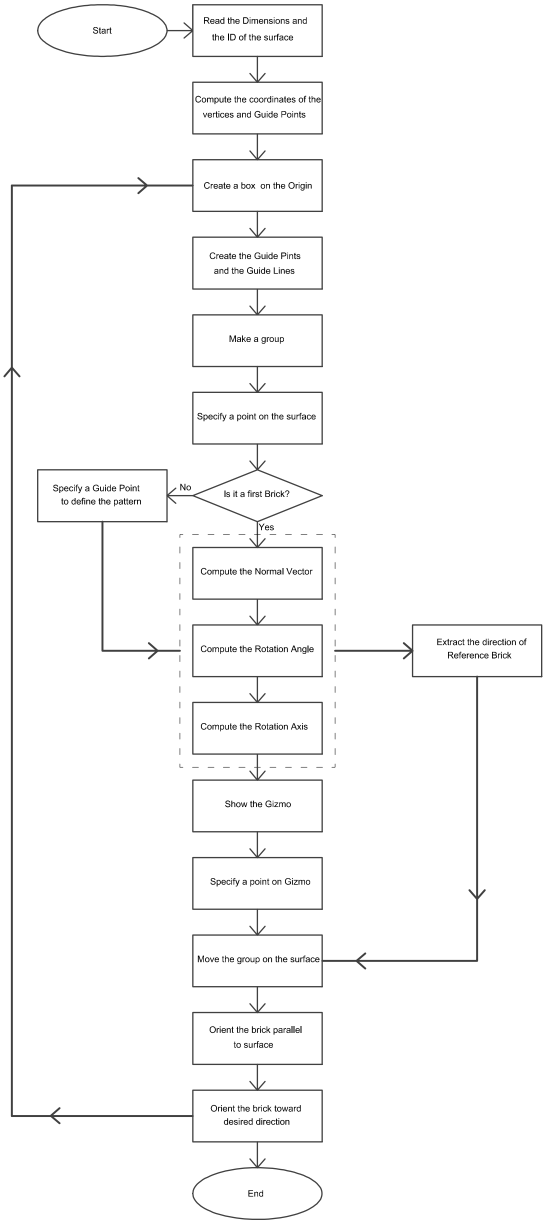


Figure 10.2: Diagram of creating a line of bricks

The modeling of a specific brick pattern on a surface, even on a small area is an advanced step toward the automation of the whole process.

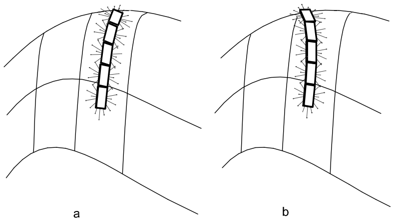


Figure 10.3: Line of bricks created by a) Smart Line b) Regular Line

10.2.1 Automatic creation of the Running Bond pattern

Running bond is one of the most widely used patterns in masonry construction. Not only for brick walls or paving but also for vaults and domes such *Catalan vaults*. Laying the bricks in the running bond means creating the course of bricks that the long wide side (stretcher) of them is exposed, in each course, the bricks are attached to each other from their width part and each course offset half stretcher brick from the adjacent course. If it is considered that the area would be covered with courses of the bricks, it should be defined the number of the rows and the number of the bricks in each row. These parameters are specified by user. The first brick is located on the surface with the method described in section 9.3. The glance to the figure 8.7, the possible location for following bricks is automatically defined. Each brick is oriented based on the direction of its pervious orientation. Just the user is required to specify the direction of the brick set on the surface.

10.2.2 Automatic creating the Herringbone pattern

Herringbone is mostly used as decorative patterns in masonry construction, but it is also widely used in shallow vaults. Herringbone on a plane is formed by placing one brick stretcher and the other one with 90-degree rotation to one side of the previous one making an 'L' shape, and this combination repeated continuously. There is not definite row or course of bricks vice versa, the bricks are waved to each other in a way that there is not any continues joints between them nevertheless the user is asked to enter the number of the *rows* i.e. the number of the bricks laid locally stretcher and the number of *columns* i.e. the number of the bricks laid with 90 degree rotation in accordance to the rows of bricks. In this arrangement, each brick after locating on the surface, is oriented on the same direction of the previous one, then will be rotated 90 degrees around the *Yaw* axis. By locating the first brick and determining the order of the bricks, a set of bricks are laid automatically in the herringbone pattern.

10.2.3 Interactive creating the stain of bricks

Moreover than the regular well-known brick patterns, there are other alternatives suggested by the designers. In the general pattern may refer to the different arrangement of the bricks so it is always possible to produce different pattern using the same bonding [12]. This possibility is considered for the designer to design its own specific type of pattern. Each brick can be located on the surface one by one and the user is able to move and rotate in desired direction. It is provided for the user to place each brick by specifying all the possible Center Points of previous ones. This sub -tool is merged of all previous sub-tools described in chapter 9.

10.3 Advancement

The commands described above do not fulfill all the necessity of a perfect interactive and at the same time automatic tool for designing brick pattern. The advancement of developing the code is to recognize the overlapping bricks automatically, trim the shapes and achieve the brick cutting patterns of each surface. This possibility enables the designer and constructor to estimate the brick requirements before fabrication. In addition, linking to the real-time software, such as grasshopper, it is decided to convert the code to the brick shells optimization tool which helps the designers to provide an optimized brick shell or pattern regarding the material requirements and construction time. Developing the code in order to enable the user to predict a precise evaluation of brick structure behavior, the reaction of mortar against the loads and probable displacement is the advancement step for this research. Although this tool is under developing, it has been applied to both simple geometries and free-form surfaces, which are explained in next part. Moreover, it is tested on a prototype, a Catalan vault that described on chapter 6.

Part IV

Applications

Chapter 11

Modeling the brick pattern on free-form surfaces

During the testing of the *Brick pattern* code on different surfaces, it was found out that Different types of surfaces related to their geometrical properties such as Gaussian curvature and Geodesic curves produce different issues faced with brick lying. Depends on the properties of the surface, different commands are useful to cover it. In this chapter scripted codes are applied on different surfaces and through the results it was driven the weakness of the codes and further advancement.

11.1 Bricklaying on simple geometries

11.1.1 Bricklaying on cylinder

The cylinder is 0 *Gaussian Curvature* as one of the sections of extreme curvature is a straight line. The cylinder is like the plane R2 as it can be made by joining the edges of the strip of a paper which itself is the part of a plane. Intuitively each point on a cylinder presents a corresponding point on a plane (figure 11.1). In order to cover a cylinder, the bricks should nearly cover the plane that the cylinder is made of. Ignoring the errors of cylinders with small radius, it requires clarifications at the edge where the pattern should enclose the surface.

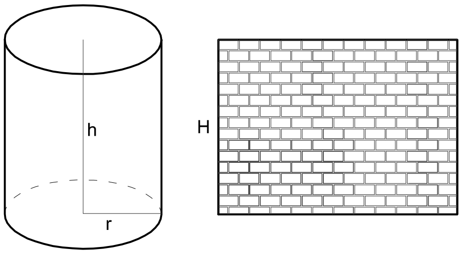


Figure 11.1: Projection of a cylinder on a plane

As it was expected to cover it, the bricklaying starts like a line on the surface, turns around the surface until meets the starting place. The requirement for special bricks may happen at this meeting point. If the dimensions of the cylinder are selected according the dimensions of bricks and mortar gap, the number of special bricks can be minimized. As a figure 11.1 illustrates applying different kind of bonds on a cylinder approximately same result is brought out and it can be automatically covered with *Line commands* and *Stain commands*. In herringbone and stretcher bond, the special shape bricks are required on the base line and at the edge where the pattern should enclose the surface.

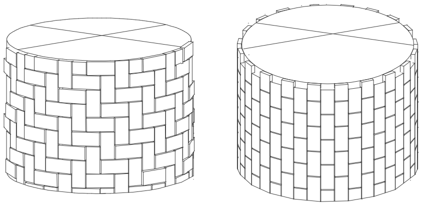


Figure 11.2: laying brick on cylinder by means of Brick Pattern plug-in

11.1.2 Bricklaying on cone

The cone is a geometrical shape that gradually decreased from a flat base to a point called the apex. It is also a 0 *Gaussian Curvature*. Each cone is made of a sector of flat circle that the height of it is the radius of the circle so laying brick on a cone is similar to cover a flat plane limited with a curve on one side and two intersected segments in two other sides (figure 11.3).

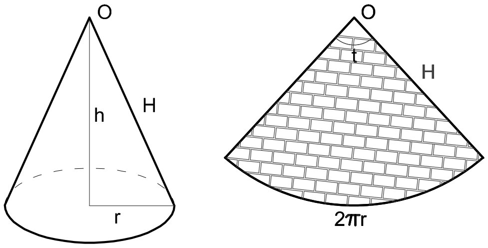


Figure 11.3: Projection of a cone on a plane

The challenges of bricklaying such an area are forming a curve and slant lines by straight rectangles. As the figure 11.4 shows, in 3Dimentional surface depends on the brick courses, special shaped bricks are required for different positions. If it is preferred to have parallel brick courses, the special shapes bricks are required two slant lines that overlap especially in the area close to the apex. If the preference is having the maximum number of brick course perpendicular to the base, plenty of special shaped bricks are required.

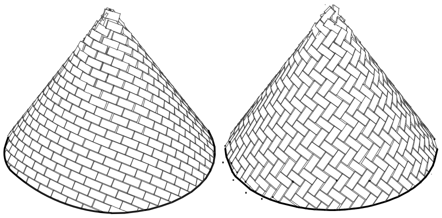


Figure 11.4: laying brick on cone by means of Brick Pattern plug-in

11.1.3 Bricklaying on sphere

The sphere is the *Gaussian Curvature* with positive constant, and it means that if any normal plane cuts the sphere at a specific point, the curves have the radii of the curvature on the same side. unlike cone and cylinder, a sphere cannot precisely flattened on a flat plane just very approximately with polyhedron with large number of sides by means if adjacent pointed ellipses (Figure 11.5).

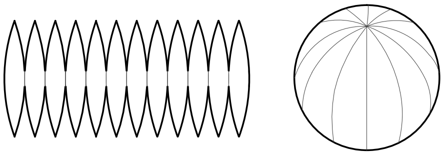


Figure 11.5: Projection of a sphere on a plane

If this plane is covered with rectangles, it is not possible to cover the curved corners with complete rectangles thus between all Euclidean geometries, sphere is most challengeable geometry to be laid by bricks. As the figure 11.5 illustrates, by testing the scripted Brick Pattern commands, it is approximately obtained similar results. In both automatic methods of brick laying; either herringbone pattern or stretcher pattern, after putting some number of bricks, they start to overlap. The size of overlapping increases by growing the distance from the starting point. If it is intended to apply the current scripted codes, the better result is obtained when the bricks are laid brick by brick or brick course by brick course. Experimentally, it is found out that best automatic method for covering a sphere with bricks is laying the bricks spirally. In this method first brick is laid similar to center of an area and following bricks are laid around it. Similar to previous methods the bricks start to overlap each other as they recede the first brick but with lower intensity. Most of the special shape bricks are required when these spirals overlap each other.

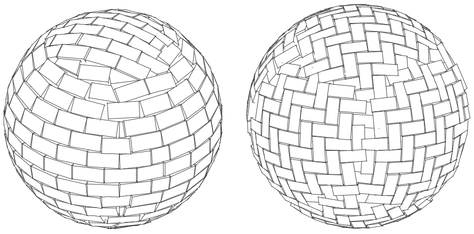


Figure 11.6: laying brick on sphere by means of Brick Pattern plug-in

11.2 Brick pattern on Brickshell (Computational Morphogenesis 2013)

As it is described in section 5.3.2, modeling the brick pattern on the designed shell had been started before the construction process but in very first steps. Finally the *Brickshell* was constructed without any model and by deciding on placement of each brick during the construction. The difficulties of brick patterning in the workshop decreased the construction duration. Finding an aid tool for increasing the speed of construction was the main motivation to develop the Brick Pattern plug-in. in order to understand the influence of the tool on the designing the brick pattern, the developed tool is applied on the Brickshell. The same brick dimensions utilized on Workshop 2013 are used in software. The modeling starts by setting 30cm, 15cm and .4.5cm as the dimensions of the bricks and desired surface as the bed for brick laying. During the modeling process, the area with shallow curves was modeled easily by Automatic Commands. The top part of the shell and the inner opening required more attention and laying the bricks one by one. The result shows that if the bricklaying in the construction process was followed by pre-designed model, the speed and accuracy were increased. In addition even on the parts with shallow curvature, using the pre-modeled version would help to have less special shape bricks and so, less wasted material.

During the construction, there were always more than one bricklayers who were working simultaneously. They had to decide on each brick placement that was influenced by the complexity of form while they were not skilled masons thus in constructed shape it was some misleading from the designed and form. These errors might cause big effects on structural behavior of the form. Following the bricks arrangements from a modeled plan would facilitate following accurately the form and achieve more trustful structure. By using the tool, The Brickshell also modeled by using stretcher bond to predict the brick arrangement for constructing by Catalan method.

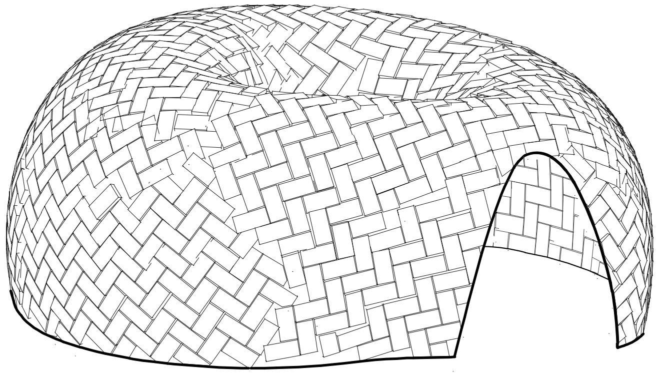


Figure 11.7: laying brick on Brickshell (Morphogenesis Workshop2013)

11.3 Brick pattern on Catalan vault (Computational Morphogenesis 2014)

The important aim of Computational Morphogenesis in 2014 was aside from constructing a Catalan was vault solving the defects and limitations of the previous workshop. Focusing on the structural behavior of the shell, in 2014, the form was achieved by using form-finding tools. By the help of *RhinoVault* , it was designed an optimized form. RhinoVault is a form-finding Plug-in designed by *Block Research Group* for compression-only vault [83]. It was supposed that most of the construction problems were rooted in brick patterning. Accordingly in order to increase the speed of construction, decrease the wasted material and to improve the aesthetic of the vault it was required to design and model the brick arrangement by means of CAD tools as it was spent minimum time in this modeling process. The advanced process of generating an automatic tool for modeling a brick pattern on free-form surface started at the same time as starting the form-finding process. Indeed most of the commands described in chapters 9 and 10 have been generated in response to requirements they have been faced during the process of modeling the brick patterns.

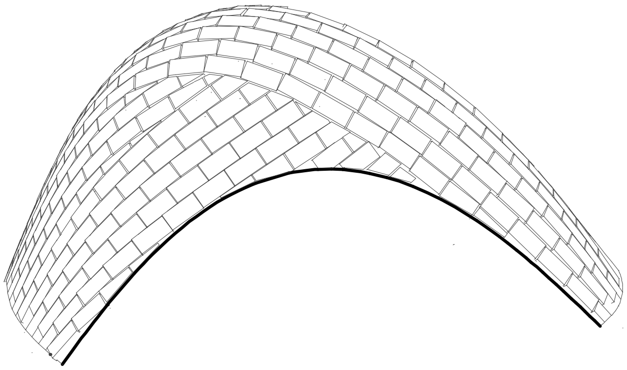


Figure 11.8: A concept of brick pattern for Catalan Vault (Morphogenesis Workshop2014)

The designed vault would be supposed to have two layers with different direction of brick arrangement. Frequently the stretcher bond is used in this type of vault. The designed surface which was modeled in the Rhino was similar to the formwork that the bricks of the first layer would lay on it. The bricks arranged through the scripted code are set from their mid-plane so the vault was offset out the half of the brick thickness. This new surface was the reference surface. The brick dimensions were the same as utilized in the workshop 24cm long, 11.5cm width and 2.5cm thickness. It was decided the first layer to be arranged by parallel brick courses. Two concepts were modeled by help of scripted commands. Not always the *Stretcher bond* command but with the combination different commands. One concept was started by laying a brick course perpendicular to the base lane and continuing by keeping the other courses parallel to it. Modeling this concept required more time because plenty of bricks should be rotated or displaced to not overlapping the adjacent bricks but stay approximately parallel to the neighboring course. Although the necessities for special shape bricks were limited to four edges of the surface, it was supposed that this concept would need precise controlling of displacement or rotation of each brick during the construction which is difficult for the manual work.

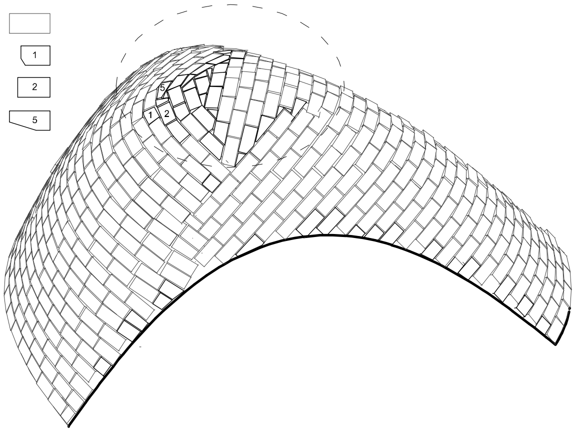


Figure 11.9: The brick pattern of the first layer of The Catalan Vault (Morphogenesis Workshop2014)

The other concept was having the course of bricks parallel with each other and baseline. Modeling this concept was faster and simpler. Bricks were laid from two baselines and each new course was parallel to its adjacent course and so to the baselines. The special brick shapes were required on top of the shell and where the two directions of brick courses started from two baselines reached each other. As this concept was closer to the real situation of the construction process, it was selected as the modeling of the brick laying on first layer. Second layer was the exposed layer so it required more attention on designing the brick pattern. It was also necessary that the brick courses of the second layer would be at different direction regard to the courses of the first layer. The first solution was utilizing the first concept for the second layer but focusing on the visual aspect motivated the designer to present a concept that would fulfill the aesthetic issue as the economic and the time of construction. figure 11.10 shows the proposed concept for the second layer. In this layer, primarily two side arches were modeled by bricks. Parallel brick courses started to form from both arches until they intersect each other. This intersection part placed the most of the special shape bricks. The design not only was very close to the real situation of the construction but also had a decorative role.

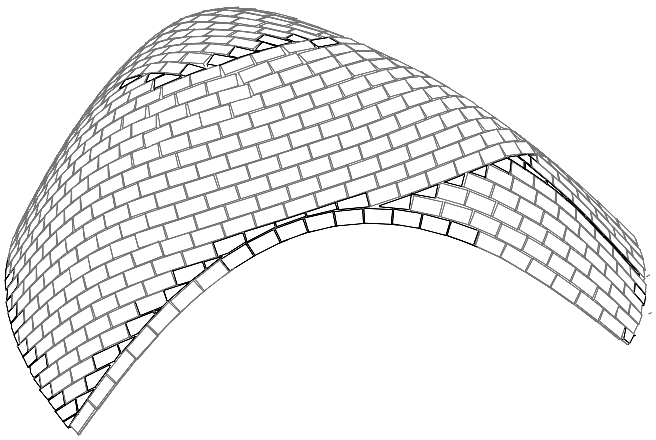


Figure 11.10: a) The brick pattern of the second layer of The Catalan Vault (Morphogenesis Workshop2014)

Both of the layers were constructed by following the modeled patterns. In order not to take a risk of wasting energy and material, it was preferred to manipulate the special shape bricks not before the fabrication time but during it. However as they were belong to the same area, they were cut simultaneously according to the pre-designed model and real conditions. The constructed layers were very similar to pre-modeled designs and the construction duration was short. Each layer was shaped by bricks in one and half day. Through these examples, it is found out the advanced requirements for this tool to make it both more interactive and more automatic. It is required to develop the code in a way that, it would be able to distinguish the edges of the surfaces. The overlapping errors would be approximately solved if the gap between the bricks is considered regarding to curvature of the surface. The process of modeling would be accelerated if the overlapping bricks are replaced automatically by special shapes. In addition, laying a course of bricks totally parallel to another course would facilitate the brick laying process and decrease the requirements of non-standard bricks. This tool is still under developing and further versions will be published subsequently.

Conclusion

This Ph.D. research proposes the use of CAD/CAE in early design phase of masonry free-form surfaces. Through this research, a digital tool has been developed which designs the brick pattern on a curved surface, semi-automatically. The proposed tool does not replace the designer, but it is an aid tool for doing the repetitive task of modeling the brick arrangement on complex surfaces. Through digital technology, this research proposes a tool to re-use and re-appreciation of traditional, poor and low-impact methods of masonry. Masonry materials depend on soil, which is abundant and inexpensive. Reconsidering these methods reduces the reliance on the imported material. The basic materials of masonry are mostly produced by small factories, from variety of local raw materials. It helps the local economic growth. It is a labor based method, which can help to solve the unemployment problems. In the two Computational Morphogenesis workshops (part two of the thesis) it was experienced the role of human resources in masonry constructions and more detailed in brick vaulting. The vaulting technique is a type of construction, which can be done with cooperation method. The concept of sustainability is closely integrated with context of construction. Aside the economic problems and resource constraint, the local human resources' role should be considered during the construction process. Throughout these workshops, a single concept was developed, and constructed. This technique brings in social cooperation in the construction. The concept of workshop 2013 was presented in 3rd annual international conference on architecture in Athens [74]. The process of workshop 2013 including description of load bearing test and an overview of the workshop 2014 was presented in *International Association for Shell and Spatial Structures* Symposium 2014, Brazil [75].

Masonry methods are craftsman intensive. They should decide on pattern courses, brick positions or boundary details during the construction process. Any aid tool should not ignore the role of human resources, but it should be as an interactive tool to facilitate the designers task. The cost of the masonry project is based on the price of material and construction duration. Based on our practical experience, during constructing a free-form surface (chapter five), it is a deliberate duty to decide for orientation of brick courses. There is a need for non-standard bricks that interrupt the bricklaying because of getting the cutting pattern and it is required to cut the bricks. Knowing the brick arrangements on the surface considerably accelerates the construction process. Modeling a brick pattern by means of usual CAD tools on a curved surface is whether impossible or a very time-consuming and tedious task. As it is described in part three, a tool is developed in Python programming language to help the designers for modeling the brick pattern on free-form surfaces and this tool is a plug-in for Rhinoceros software. This tool has been utilized in Computational Morphogenesis workshop 2014 [76]. The brick patterns of the two layers on a curved surface were modeled by this tool. The position of each brick, the exact number of required bricks, the shape and the place of non-standard bricks were apparent before starting the construction process. This information decreased significantly the construction duration. The brick pattern of Brickshell (designed in Computational Morphogenesis 2103) has been redesigned by using this tool. It helped to design new arrangement in which fewer special bricks are required and, as a result, less energy and material are consumed.

The brick pattern in masonry constructions plays role in both structure and decorative finish. The different patterns have various aesthetic effects. The plug-in helps to design a building without covering with the plaster. This tool is feasible on outside of laboratories; it is a free license downloadable by any user and applicable on any free-form surface. It enables the designer and constructor to estimate the brick requirements before fabrication. Linking to a real-time software, such as Ggrasshopper, it works as an optimization tool which helps the designers to provide an optimized brick shell regarding the material requirements and construction time.

The tool can be developed to be adopted by different surfaces. It can arrange the bricks by considering the forces directions. Connecting to structural analysis tools, it provides an advanced tool to obtain an optimized brick structure. Working with robotic technology, the tool provides an automatic method of designing and constructing free-form surfaces. Complex geometries arranged in complicated brick patterns can be easily constructed by merging this tool with robots. The human errors are completely omitted. The mortar between the brick courses is used precisely and the special-shape (non- standard) bricks are cut accurately.

In combination with augmented reality technology, it will be an advanced tool for architects, helping them to construct complex surfaces with bricks. The same as an automated method, the accuracy of constructing is considerably increased. The augmented reality is able to link the 3d graphical software to real-world environment. The location of each brick is easily transmitted from virtual space to physical space. Contrasting the automatic method, it is not negation of the role of craftsmen but an advanced tool facilitating construction of the complex-geometry vaults without scaffolding.

This tool is still under development. Its options are going to be expanded in order to facilitate further the brick pattern modeling on different surfaces. The interactive method and automatic method are developing simultaneously. It is planned to link the tool to real-time software in order to control the brick pattern by changing the shape. The other step would be developing a code for non-cuboid geometries. The tool is being developed to connect to the structural analysis software in order to know the effects of the brick pattern on structural behavior of the surfaces.

Masonry construction does not belong to a traditional method, but there are a lot of possibilities to adopt this method by contemporary design. Merging the digital technology with masonry construction returns this method to today's architecture.

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For many years, shell structures have had an important role in architecture and engineering. After the industrial revolution and shifting from masonry construction to steel and concrete, the social, economical and environmental role in masonry construction has been underestimated. Targeting to use the digital tools, this thesis is proposing a method to re-design vaults and domes at present time, respecting the current architectural requirements.

Reviewing the brief background of masonry construction and looking over the recent researches, two workshops have been processed in Politecnico di Torino. Both workshops were concentrated on designing and constructing free-from masonry shells by help of digital tools and computational methods. Regarding the results of these practical experiments, a tool has been created developed, which helps the masonry shell designers to model the brick patterning automatically on a curved surface. This research is exploiting the process of developing this method by means of digital tools. The bricklaying is simulated inside the 3D virtual environment by integrating the scripting language, Python, and commercial CAD software, Rhinoceros. Not ignoring the role of the designers in the decision-making procedures, this tool is implemented as an interactive method between the designers and the digital tools.

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