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ATINER's Conference Paper Series
ARC2013-0735

Reviving the Design of Contemporary Masonry Vaults

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Email: info@atiner.gr URL: www.atiner.gr
URL Conference Papers Series: www.atiner.gr/papers.htm

Printed in Athens, Greece by the Athens Institute for Education and Research.

ISSN **2241-2891**
8/11/2013

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ATINER started to publish this conference papers series in 2012. It includes only the papers submitted for publication after they were presented at one of the conferences organized by our Institute every year. The papers published in the series have not been refereed and are published as they were submitted by the author. The series serves two purposes. First, we want to disseminate the information as fast as possible. Second, by doing so, the authors can receive comments useful to revise their papers before they are considered for publication in one of ATINER's books, following our standard procedures of a blind review.

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This paper should be cited as follows:

Rajabzadeh, S. and Sassone, M. (2013) **"Reviving the Design of Contemporary Masonry Vaults"** Athens: ATINER'S Conference Paper Series, No: ARC2013-0735.

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Abstract

This paper presents a cooperative experience in masonry brick shell construction through the workshop being held in *Politecnico di Torino*. Conjoining the collaboration between students in teaching method with masonry vaulting construction, we try to research on resuscitating of the contemporary masonry vaults in one hand and the restoration of the social meaning of masonry to the concept of construction in the other hand. Reviewing the brief background and characteristics of vaulting, construction and looking over the contemporary researches on it, this paper outlines the methods and disciplines of the workshop which tries to apply vault construction at present times regarding the current social and architectural requirements. This workshop is in place with supervision of second author and other three PhD students, Andrea Rosada, Tomas Mendez, Iasef MD Rian.

Keywords: Vaulting, Masonry, Brick Shell, Collaboration

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Historical Overview

The mud bricks and stones of the Jericho Site , a small village constructed in 8000-7000 BCE in Palestine, (Kleiner, 2009) is a strong evidence of masonry backward in the history of construction (figure 1a). False domes extracted from corbelled arches constructed by laying the flat pieces of lime stone in steps were the primary phase to cover the space in the Mediterranean areas (Escrig, 2006). This technique was developed well enough to provide a perfect dome at Mycenae, Greece (figure 1b&1c) at 1300–1250 BCE which was the largest dome for more than 1500 years until the construction of the Pantheon (Kleiner, 2009). Ancient architects and constructors developed the technique of stone and brick true arches which reached to its maximum presence in Roman architecture.

Roman concrete was an important breakthrough in construction of Vaults and true domes and the Pantheon was one of the most influential constructions in the history of architecture which was built with this material. It was a hemispherical dome 43.3 meters in diameter and of the same height as well (Escrig, 2006) (figure 2).

Pendentive domes in Byzantine era led the construction of another 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 square plan instead of circle one (Kleiner, 2009) (figure 3).

Apart from the occidental civilization, excavations showed the large construction of masonry vaults and domes in ancient oriental cultures. They were built in various usage as the Ishtar gate of Babylon constructed at 722 BC or even sewers in *Khorsabad* at Assyrian era (Escrig, 2006).

Moreover, masonry vault and domes were the common structure of Persian civilization after the first century AD in palaces and temples. Squinch, intermediary of dome over the square plan invented before Islam led to construction of complex geometry domes in Islamic period (Pirnia, 2001) (figure 4).

The concept of vaulting developed to variant complex vaults such as Rib vaults and Fan vaults, the process which continued until the advent of new materials era.

Masonry Vaults in Contemporary Architecture

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 (Curtis, 1996). New productions of eighteenth century reduce its role as structural and protective elements to infill and sub-divided materials (Beall, 2003).

After the second half of 19th century, except few architects, novelties have rarely been integrated to traditional methods of masonry construction. Antonio

Gaudi based on Catalan native architecture and parabolic arches and domes in his designs such as Palau Guell and Teresianes School created innovative structures from masonry material (Permanyer, 1997) (figure 5a). Also Rafael Guastavino and his son, immigrants from Spain, built about three thousands buildings in the US including some important historical landmark such as the Boston Public Library (figure 5b) and New York City's Grand Central Terminal (Davis,2012).

Louis Kahn because of his interests to masonry designed several buildings using brick and stonework. Fort Wayne performing art theater (McCarter, 2005), Indian Institute of Management Ahmedabad designed in 1966 with circular and semicircular brick arches in India and hotels and hospitals of National Assembly in Dacca (figure 5c) constructed by bearing brick walls and masonry arches (Diba,1989) are proper examples of his masonry vaults constructions.

In recent decades Alfonso Ramírez Ponce who has designed and constructed buildings and houses since 1969 until now represents his will in reviving of vaults and domes and traditional methods in contemporary architecture. Believing in regional material, techniques and even culture which influence on architecture and construction, and besides; emphasizing on 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 (Fantone, 2001) (figure 6).

Recent Research

Recently some architects and structural engineers have started researches and practical experiences on masonry vault construction for contemporary period.

Stone vault pavilion done with *Block Research Group* in calibration of MIT Masonry group started when the Philippe Block had internship at Escobedo a stone Factory, at 2008, designing and developing the unreinforced stone vault(figure 7) (personal website). The vault was designed using Thrust Network Analysis (TNA); a design procedure specialized for compression-only structure especially self-weight structures (Block, 2007).

Free-form Catalan thin-tile vault progressed in Block research group was an investigation for free form finding of timbrel vaulting (figure 10a). This project is the combination of high- tech design tools; Trust Network Analysis program, Rhino Vault, CNC Fabrication and low- tech material; cardboard box as a guide work system (figure 10b) and innovative form based on the Catalan traditional vaulting(Davis, 2011, Davis, 2012). The vault made of three layers of thin layer (15-25 mm), could resist the three-ton loads in the shape of stacked sand boxes which were applied over an area of 500mm * 500 mm the widest span and lowest rise point (Davis, 2012) (figure 10c).

Ramage, M., Ochsendorf, J.A., Rich, P as the member of Masonry research group in MIT, in 2007-2008 have designed and constructed the

Mapungubwe national park Center in South Africa (figure 8). They applied the Catalan vaulting method with stabilized earth tiles made by local workers. The use of steel reinforcing and formwork were minimized in this project (Ramage, 2010). The Center consists 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. They used two dimensional interactive thrust and network analysis system (Ramage, 2009).

Another innovative research on vaulting construction experience is the project developed by a team of researchers in Ethiopia focusing on the social implication of construction. The research aimed to find a way relied on vernacular construction, shortage of the bestowed material and resources and skilled labor by applying innovative techniques (Block, 2012). Stabilized soil tiles manufactured with local labors provided the blocks of vaults as the result of their construction research. For selecting a vaulting system the researchers compared three methods of vaulting, European style, Nubian/Mexican style and Catalan style. The European style was refused due to the required material and the expenses for the formwork. The other two styles are based on the funicular which is self-Wight supporting and resist only axial compression. As a result, timbrel method was used as the floor system and leaning bricks method was used for roof system (figure 9). 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 (Block, 2010).

A look at Masonry from Contemporary Architecture Point of View

Durability and long – term life of masonry are important property of masonry construction. Maintenance charges in addition to considering this quality, costs of masonry buildings are normally less than other types (Curtin, 2006).

In his book Pfiefer mentioned the relation between designer, manufacturer and material in masonry construction as one of the advantages of this method. He considers that when the designer select masonry as the construction material, he makes a significant step toward the final definition of the project and as the architects can feel its weight and from so they can design for it (Pfiefer, 2001). Minke declared his idea about the earth construction that is labor intensive and do-it yourself method (Minke, 200).

The reproduction of masonry technique regarding the current social and economic requirements, it seems to be a good solution for contemporary architecture. Masonry construction as its inherent nature is an interoperable material which can be preceded in collaborative method while new material and construction techniques, replace human resources by equipment and move the labors from construction sites to inside of the industrial factories.

According to Kahn, the natural shape formed by brick is arch. A vault as a load-bearing masonry can provide a roof, achieving high structural strength with minimal material (Ramage, 2009). The role of vaulting system in cooling and ventilation was one of the most important reasons to its worldwide construction. In hot and dry climate, as their greater height at the center, the collected light warm air can be discharged through the openings. In addition their surface in comparison with cubic room with the same volume is smaller and therefore absorbs and loses less heat (Minke, 2006).

The Computational Morphogenesis workshop at Politecnico di Torino

In most of the universities masonry construction is not part of design studies so students should just based on the personal experiences learn how to design a masonry building (Curtin, 2006). This consideration pushed to give a chance for students to experience brick vaults design and construction take it as the topic of the current edition of the *Computational Morphogenesis* workshop in the master course of architecture at *Politecnico di Torino*. This workshop is an interaction program of digital technology and design which tries to find the best solution for the architecture and structure through the computational tools. Via this course, the process of planning and design which are affected by the technological innovation integrates with traditional material. The program is held under the supervision of a professor and collaboration PhD students, who are involved teaching and helping students in different aspects of developing digital tools and their applying in project.

In 2012, the workshop was held by the theme of wood-lab, which tried to promote the role of poplar plywood in the field of technological research. *Mona Lisa Digital Design* workshop was intended to design a *Pop.for.Pav* pavilion for *MADEexpo 2012*. Been thought the proper softwares useful for design and optimization, students were organized in different competence groups which should develop their ideas. The two nominated groups, had the chance of editing and improving their design, and finally the winner's, constructed as the pavilion of *Politecnico* at the *MADEexpo 2012.*

This year, concentrating on masonry construction, it is decided to choose the theme of the workshop, masonry construction by the title of the *Brick shell*.

Objectives of the Brickshell Workshop

Not replicating the ancient forms, but contemporizing masonry construction in contemporary architecture and finding innovative shapes and methods, it is required to contract with digital technology. For training this combination and interaction it was decided to practice the traditional technology of brick vaults construction by applying digital design tools and form finding methods. Students were required to organize as the design group. Organizing the students in different design teams, spend so much energy and time separately on different concept which most of them never will be developed or constructed. In addition motivating the students whom designs would not be accepted as the final project to work in the winner's project and construct it will be a problem. Therefore it is decided to replace competition by association and cooperation instead of rivalry. It is intended to bring the interoperability in the process of learning, design and construction. Constructing a building for students by students makes each user a co-developer of the project and each developer will be dynamic member of decision making process.

The students were expected to design an innovative free form shell adopted with contemporary architecture. Not only reviving the masonry vaults in current architecture but also bracing the concept of workers as the craftsmen is the important object of this program.

This experience is the combination of creativity, innovation, software with simple material and techniques. Figure 11 is the diagram drawn *Computational Morphogenesis* shows the main concept of workshop.

Challenges and Limitation

Most of the challenges were occurred in the phase of the construction. It should guarantee the safety of students faced with dangers of material falling and mortar leaking. The process of constructing and the final result should be in agreement of building codes and safety standards.

Selecting vaulting technique, we should take into consideration some important features such as ease of block production, block laying, and guide work and formwork method, de-centering, form adaptability, error margins, construction rate and more important stability during construction.

Architectural Program

Finding a design program through the several meetings, it was agreed to design a meditation center. This building would be without any specific symbol of any religion and culture and it would provide an international meaning for meditation (Figure 12).

The design site should be in the direct relation to the university, accessible for students, not too calm and green landscape which fade the requirements of any building and complicated enough to challenge the students. For location of design, we decided to construct it inside the main campus of polytechnic near the Construction Laboratory. It provides the accessibility to proper tools and probable mechanical testing.

Applying the Concept of Open Source Software in Brickshell

In 1999, Eric S. Raymond, mentioned Bazaar as the good example of cooperative in creation of different ideas. Unlike the cathedrals which are constructed by the individual craftsman and are not unveiled before the full completion, the bazaars are releasing while forming from different schedules and methods driven of different notions therefore the result is released often and as the figuration. He used the Bazaar concept for developing open source software in which a logical stable system is emerged from the mass of different agendas and approaches and the users are supposed as the co-developers

(Raymond, 1999). In fact he simulated the bazaar as organism that its developing as the biological process is assumed as the morphogenesis expansion. Developing this idea in the process of the workshop, students are trained with the concept of open source and free software. Creating a form is intended to proceed through the generative algorithms both commercial base application such as Rhinoceros, Grasshopper, Generative Components and the user developing types like Rhinoscript and VBasic.

Process of Design

The schedule of this workshop was 15 teaching programs with 3 main trains and exercises, first introducing the masonry construction and contemporary experiences, the second explanation of the concept and meaning of participation in the creation and building process and finally introducing and teaching the useful softwares.

The design process was planned in the weekly meetings, with an initial teaching module and a further project development stage, in order to arrive to the final construction documents by the end of the semester. The initial teaching sessions provided a definition of the main aspects of the work:

1) The design and construction issues related to masonry vaults and domes; lessons were dedicated to introduction and overviews of basic informations about masonry construction, material, and history.
2) The interaction between architecture and geometry, mainly when geometry can be topologically complex or it can show non standard properties, as a fractal dimension, etc.
3) The use of parametric models in combination with computational and optimization procedures and structural FEM analysis, in order to perform an evolutionary design;
4) The analysis of the structural behavior of free form vaults and domes, in terms of deformations, strength, response etc.
5) The collaborative working environment, in terms of the sharing platform and protocols, and of the rules of interaction. Such five aspects of the design were presented and discussed, respectively, by Rajabzadeh, Iasef, Mendez, Sassone, and Rosada.

Since the participants were required to work in cooperation method, they were required to do two exercises. First one was a writing exercise. They created and developed a fairytale story with definite start and ending. All the students participated in crating the frame by writing a part and passing it to the other one until the whole structure was provided. Each step was published on the Facebook, which was editable by the other contributers the same as the open source Wikipedia page.

As the second exercise, students were wanted to modify and improve an assigned Grasshopper algorithm by reducing the complexity of its operations. Each of the students took the file and after editing it published on the webpage for later processes. Same as the writing exercise, this was a collaborative work, in which all the participants had a positive role. Both the exercises were meant to be training on cooperating and developing different ideas without losing the opportunity of proceeding their own. Moreover it helped the students to learn how to accept others' ideas and derive other possibilities and notion from them.

Starting to provide the sketches, all the ideas were published on the social web paged so others had the possibility to change or develop it. They developed their idea via Rhinoceros and Grasshopper softwares (Figure 13). The concept which developed to final design started from three ellipses with variable centers and controllable radius in sizes and directions. The resultant surface which was provided from application of Loft component and modified to desirable form, converted to mesh. The GSA tool analyzed the mesh and provided the optimal geometry for final structure. Through the optimized form, the area of the shape and the number of the bricks were calculated. The final design was the free-form vault with the dimensions of 6m in 5m and maximum of 2.5 m in height which consisted of about 1200bricks (Figure 14).

Two Experiences of Vault Construction

Between the processes of the design two short sub-workshops were organized in order to acquire the practical experiences of vaulting and understand all the construction problems and challenges. Both of the experiences were preceded by low-tech materials. The first workshop was a four hours process of single layer, single curvature catenary vaulting. A suspended chain was utilized for modeling the arc and the formwork was constructed by woods. A thick rope applied on the formwork eased the de-centering process. The extruded_bricks with gypsum mortar were used to lay the bricks in shiner state. After 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 (Figure 15).

The goal of the second exercise which took two complete days was construction the most challenging part of the final design. This experience helped to understand all possible failures and problems. Cardboards were utilized for the formwork construction. For projecting the formwork pattern on the cardboards, they were printed on the graph papers and transformed with the exact scale to the cardboard layers. Strip cardboards folded to U shapes, embedded and screwed between the layers provided their longitudinal stiffness and avoided the deformation. The mortar was made by mixing the sand, gypsum and water in the proportion of 1, 2 and 0.75 and the brick were laid in diagonal herringbone pattern to prevent the continuous joints between the bricks and provide a strong structural bond. As the role of the formwork in this method was guiding the margins and not supporting the weight of the vault, the de-centering process had not the danger of causing asymmetric load so it was removed by separating all the layers of the cardboard one by one. The final result was stable masonry free-from which provides a covered space with 2m in 5m with 2 m height dimensions (Figure 16).

Brickshell Construction

Experiencing the free-form vault construction, the final stage of the workshop started by participating of all students. The complexity of the designed geometry required the complex false-work design and construction. The designed final form was subtracted by the number of wood boxes which provided the platform of construction. A grid of the perpendicular planes with twenty centimeters distances which followed the geometry of the final design formed the formwork structure. The whole structure was divided to the thirty individual volumes in order to simplify its fabrication process (Figure 17). According to the position of each section, the planes of one of the directions were eliminated so as the amount of utilized cardboards, the false-work material, were reduced. By the means of a projector, the outline of each layer projected on the cardboard plane. The strips of cardboards in the comb form with twenty centimeters distance of each dental located all the layers precisely in their particular positions. The U-shape cardboards which were screwed and glued to layers provided the connection as well as the stiffness of the planes (Figure 18).

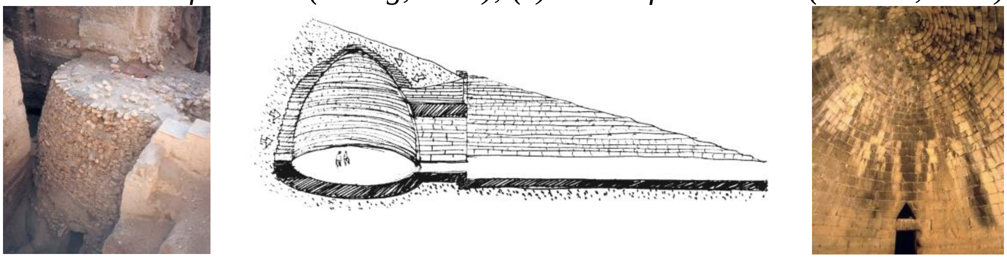
Due to the height and width of the form, accessibility to all part of the formwork was difficult thus the formwork assemblage was a step by step procedure which provided enough space for constructing and laying the bricks. in the first step the outer sections of the shell joined together and the bricks will cover them. Then, the central ring also will be completed and the other parts will be attached and be covered gradually. The figure 19 shows the fabrication process. The hollow bricks with dimensions of 4.5 x 15 x 30 cm and weighing approximately 1.60 kg are selected as the material and the mortar is mixture of the sand, gypsum and water. It is decided to arrange the bricks in herringbone pattern. It is planned to complete the fabrication process utile the middle of august.

Future Work

While the vaulting system is faded in contemporary construction, the *Brickshell* workshop is trying to demonstrate that digital technology and concept of cooperation construction can be a proper response to the social and architectural requirements. The stability test on the constructed vault can be the next step of this effort. It also has the capability of applying the other masonry material such as vernacular bricks or testing the stability of different brick patterns.

Figures with Captions

Figure 1. *(a) Remnants of Jericho (Kleiner, 2009); (b) Schematic detail from the Treasure of Atreom (Escrig, 2006); (c) Vault of the Tholos (Kleiner, 2009)*

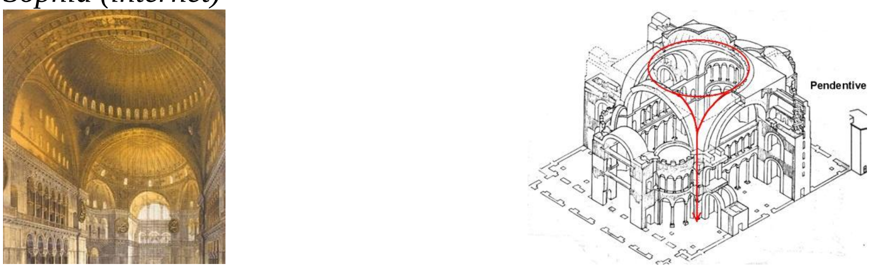


(a) (b) (c)

Figure 2. *(a) Scheme of the Pantheon of Agrippa (Escrig, 2006); (b) lateral section of Pantheon (Kleiner, 2009)*

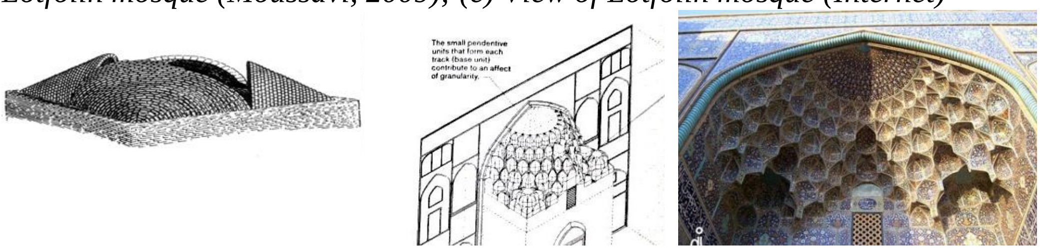
(a) (b)

Figure 3. (*a) Internal view of Hagia Sophia (internet); (b) Pendentive in Hagia Sophia (internet)*



(a) (b)

Figure 4. *(a) Scheme Squinch in Persian dome (Pirnia, 2001); (b) Geometry of Lotfollh mosque (Moussavi, 2009); (c) View of Lotfollh mosque (Internet)*

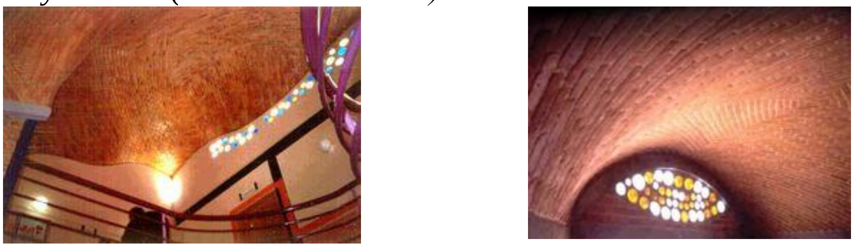


(a) (b) (c)

Figure 5. *(a) Casa Mila (Internet) ; (b) Boston Public Library (Internet); (c) National Assembly in Dacca (Internet)*

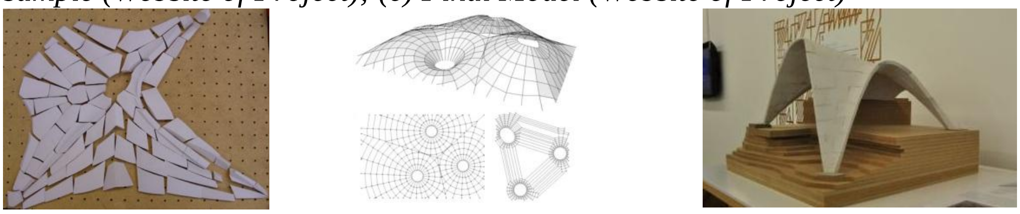
(a) (b) (c)

Figure 6. *(a) Hospital clinic in San Luis Potosi, (Architect's Website); (b) Hoyo House (Architect's Website)*



(a) (b)

Figure 7. *(a) Pre-assembly model (Website of Project); (b) Thrust network sample (Website of Project); (c) Final Model (Website of Project)*



(a) (b) (c)

Figure 8. *Mapungubwe national park Centre in South Africa (Website of Project)*

Figure 9. *Urban Dwelling Unit, Addis Ababa, Ethiopia (website of the SUDU of project)*

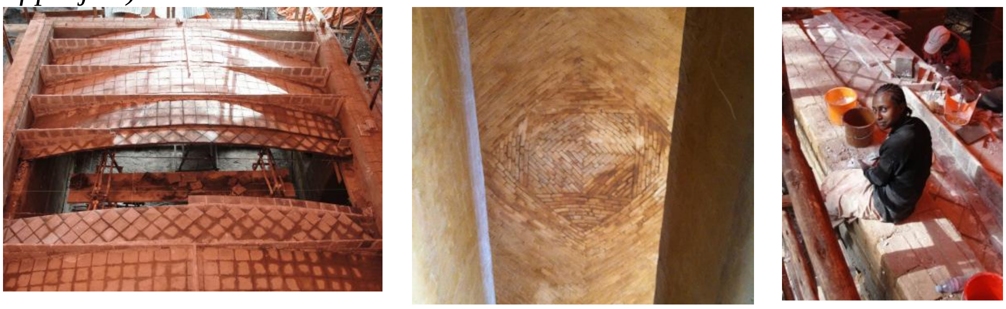


Figure 10. *(a) Free form vault (Davis, 2012); (b) Formwork of Free-form vault (Davis, 2012); (c) Structural test over the Free Form thin- tile vault (Davis, 2012)*

(a) (b) (c)

Figure 11. *Diagram of the main concept of the work shop (drawn Computational Morphogenesis)*

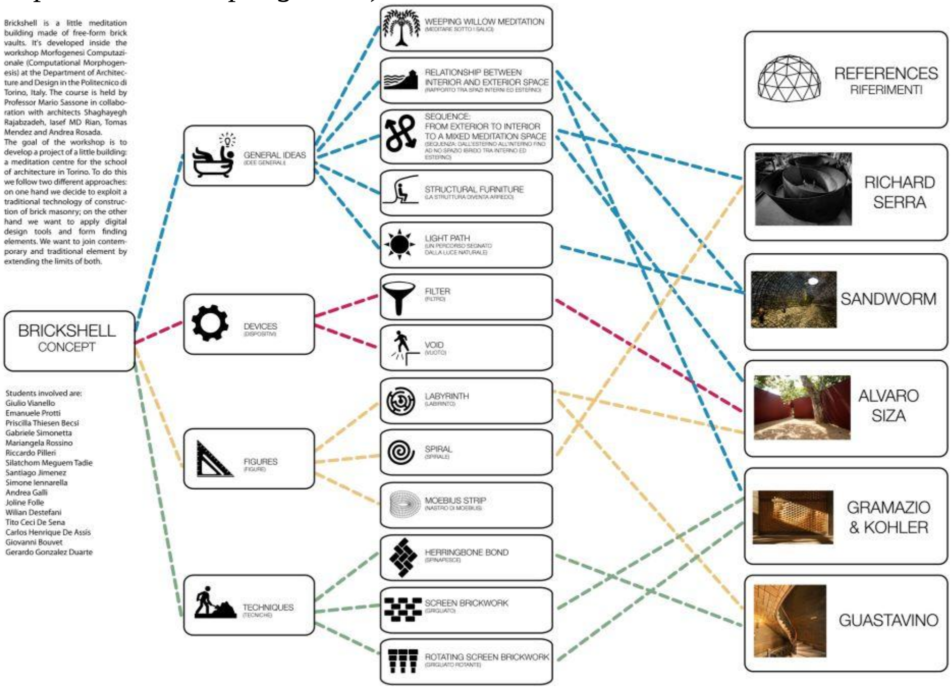


Figure 12. *First sketches of Meditation Center*

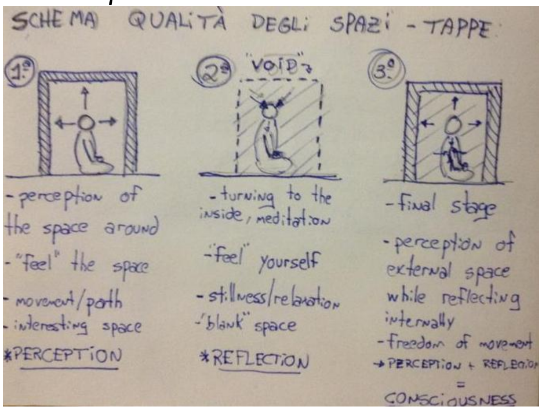


Figure 13. *The process of design developing*

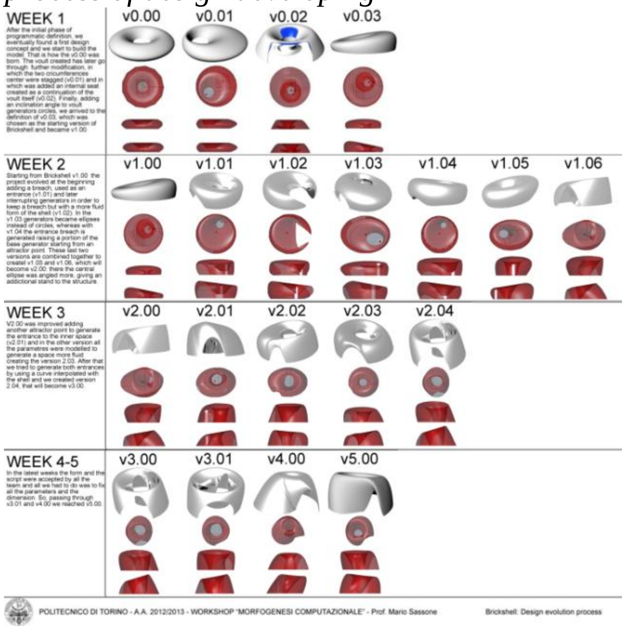


Figure 14. *Final Design*

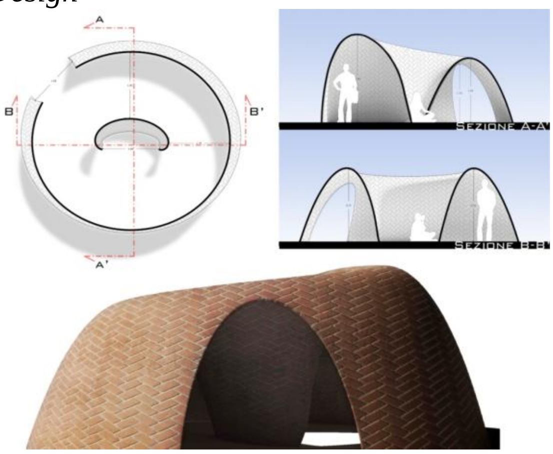


Figure 15. *The steps of catenary form construction*

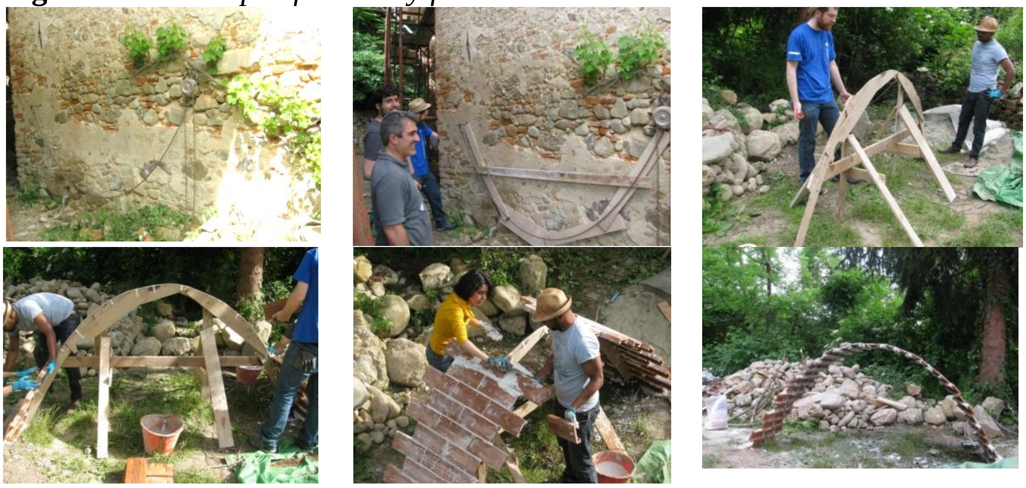


Figure 16. *The Process of Two Days Workshop*

Figure 17. *Sequential Steps of Formwork Construction*

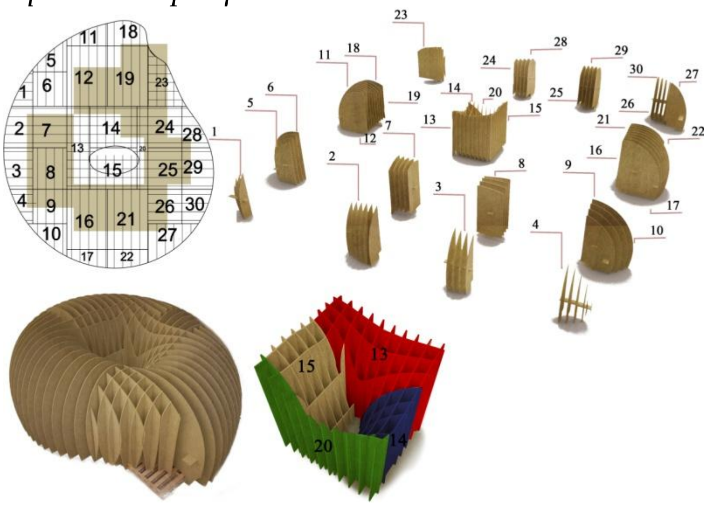
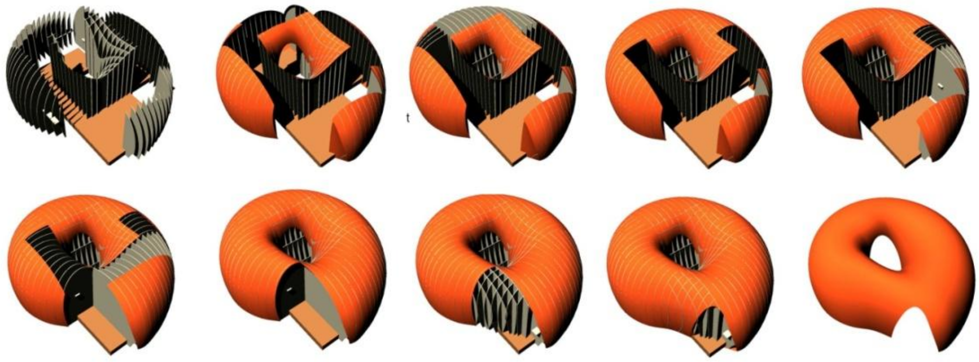


Figure 18. *The Process of Final Fabrication*

Figure 19. *Sequential Steps of Construction*



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