AR3B011 EARTHY

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CONTENTS

1 INTRODUCTION

A year after the war erupted in Syrian the Al'Zaatari refugee camp was opened in Jordan. As of May 2020, 8 years later, the camp has a total of 76,878 refugees which is 5 times more than when it started. The camp has slowly transform from a temporary settlement to a semi-permanent city. Al'Zaatari is becoming the fourth largest city in Jordan but the living situation in this so called city are below average. More than the half of the population are children (under 18 years old). Of the remaining adults only one third have a working permit so most households rely on the limited aid provided.

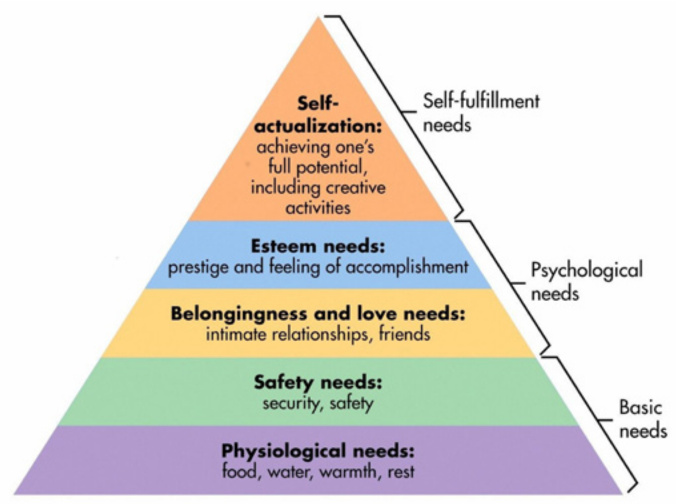


Figure 2 - Maslow's Theory I Source: see bibliography

Figure 1 - Al'Zaatari camp I Source: see bibliography

Figure 3 - Craftsmanship I Source: see bibliography

1.1 PROBLEM STATEMENT

Al'Zaatari was build in haste and as a temporary place in times of emergency. This means that in principle only the basics needs where taken into account. When looking at the Maslows's hierarchy of needs in figure 2 the basic needs would incorporate physiological and safety needs. Now that the camp is slowly transforming to a permanent city it is time to start improving on the psychological needs for the refugees.

As of now the camp is very generic lacking a sense of identity. When Syrian left their home country a part of their culture was left there as well. Craftsmanship is a bit part of their culture. As can be seen in figure 3 these skills are normally passed down from generation to generation but unfortunately with the crisis this knowledge chain got broken and so these talents got lost.

1.2 DESIGN PROBLEMS

There are four design problems we found being most important and interesting to address. These will be explained further below.

<u>Lack of traditional Syrian craftsmanship:</u> The war has caused a loss of artisans especially in the specialized arts and crafts of Syria. These arts can get lost over time therefore there is a need to preserve them.

<u>Negligence of vernacular architecture:</u> Due to the modernization of building materials traditional materials and techniques have been overlooked. Although it takes more time, skill and maintenance, these methods have proved to be more sustainable and perform better in harsh climates.

<u>Lack of communal spaces for cultural celebration:</u> The existing camp falls short of space for cultural events and communal gatherings.

<u>Economic poverty:</u> Due to lack of skills, the majority of refugees do not have work permits leading to economic poverty. Development of a skill set would foster job opportunities and reduce economic poverty over time.

1.3 DESIGN VISION

Our vision is to create a Bayt Alturath which means "House of Heritage", in Arabic. This conveys the type of center that we envisioned to provide to the refugees at Al'Zaatari. Not only is this building meant to revive and teach traditional Syrian crafts and skills, but it also will be a place for the community to come together. In this way, the residents would be able to reclaim their identity and dignity while learning skills to make them economically self sufficient.

Empowering the refugees in an exciting way led us to choose this building typology. The literal building is meant to look like a Syrian structure, while its creation and use are meant to foster people to come together, learn and make.

Figure 4 - Syrian architecture I Source: see bibliography

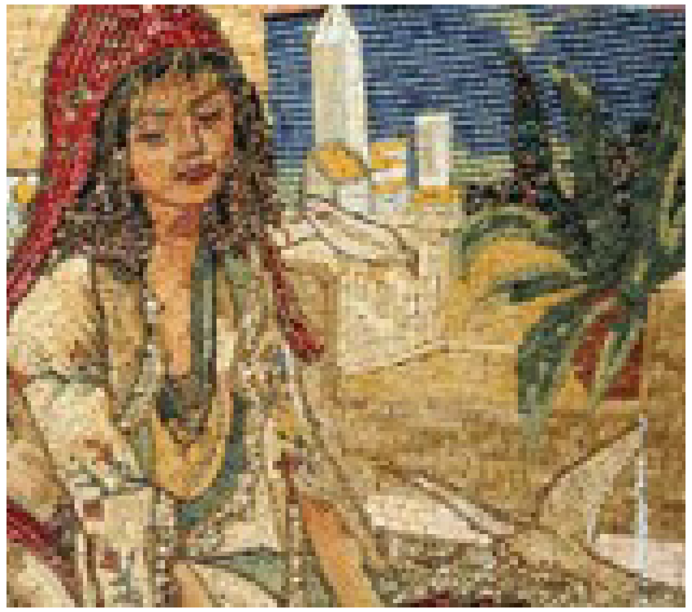


Figure 5 - Syrian crafts I Source: see bibliography

1.4 DESIGN GOALS

To make this vision come true we set four design goals that should be met at the end of the design process.

Reviving the Vernacular Syrian architecture

Reviving traditional Syrian arts and crafts

Creating jobs for the refugees and giving them the means to start their own business

Providing more communal spaces in the camp

Figure 6 - Goal symbolsI Source: see bibliography

1.5 METHODOLOGY

This flowchart shows an overview most relevant to the ways that our research into traditional Syrian crafts merged with that of the urban context to influence our layout and final form. Developing the layout based on unique spaces also led to many typologies of vaults and domes, which resulted in our final form which was then simplified or modified as per the construction and structural aspects leading us to our final building form.

With each new phase a new way of looking at the design was approached. This resulted in many changes that brought the design to the next level. Slowly through our process the once vague idea transformed to a ready to build design.

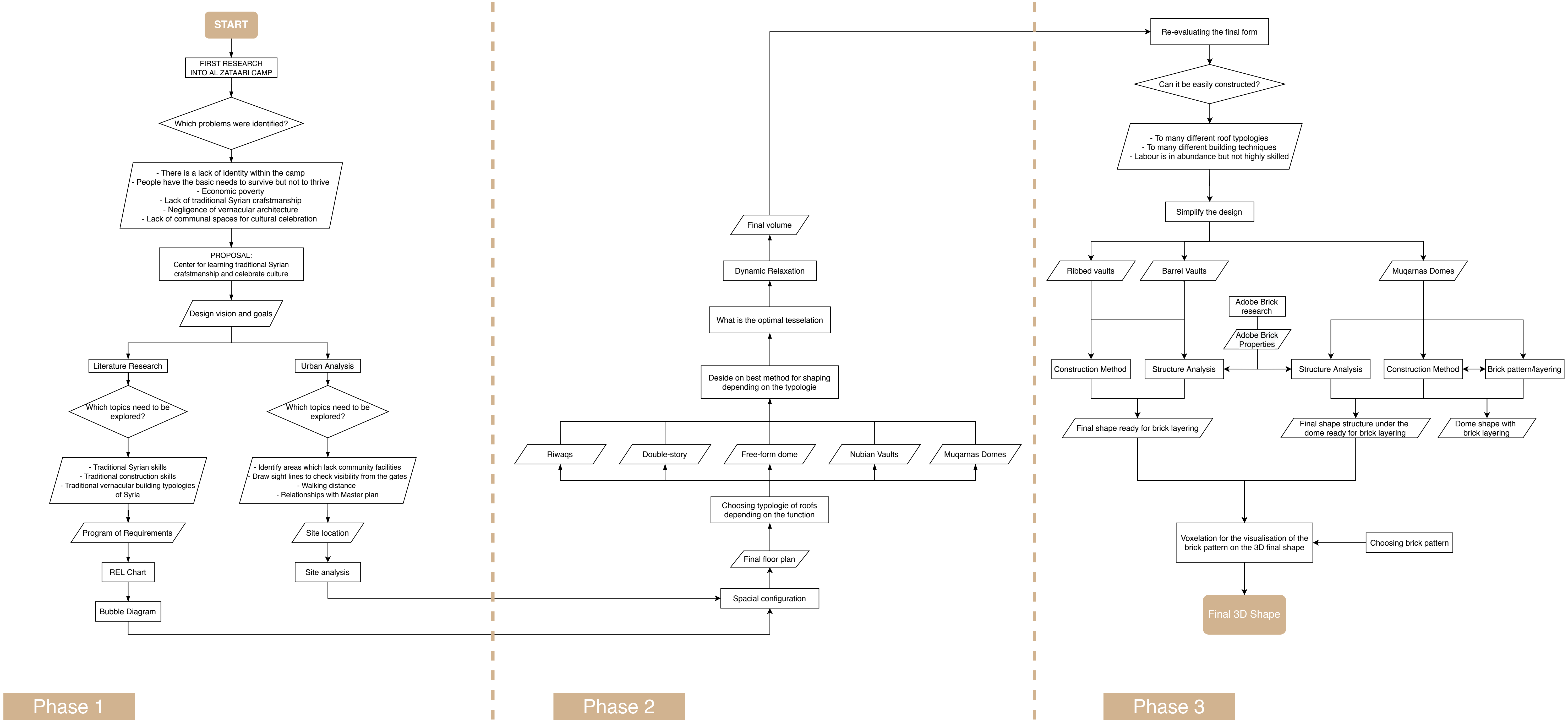


Figure 7 - Complete Flowchart I Source: authors

1.5.1 PHASE 1

After having a general idea about what the current situation in Zaatari is and what are the design problems and goals that we are going to undertake two research branches where explored. The urban analysis focused more on where would be a good place to realise our design. At the same time the literature was focusing on two things, traditional Syrian architecture and traditional Syrian crafts. From the literature study a program of requirements followed. The outputs of these two branches where then analysed resulting in the input that will form the basis of our configuration in phase 2.

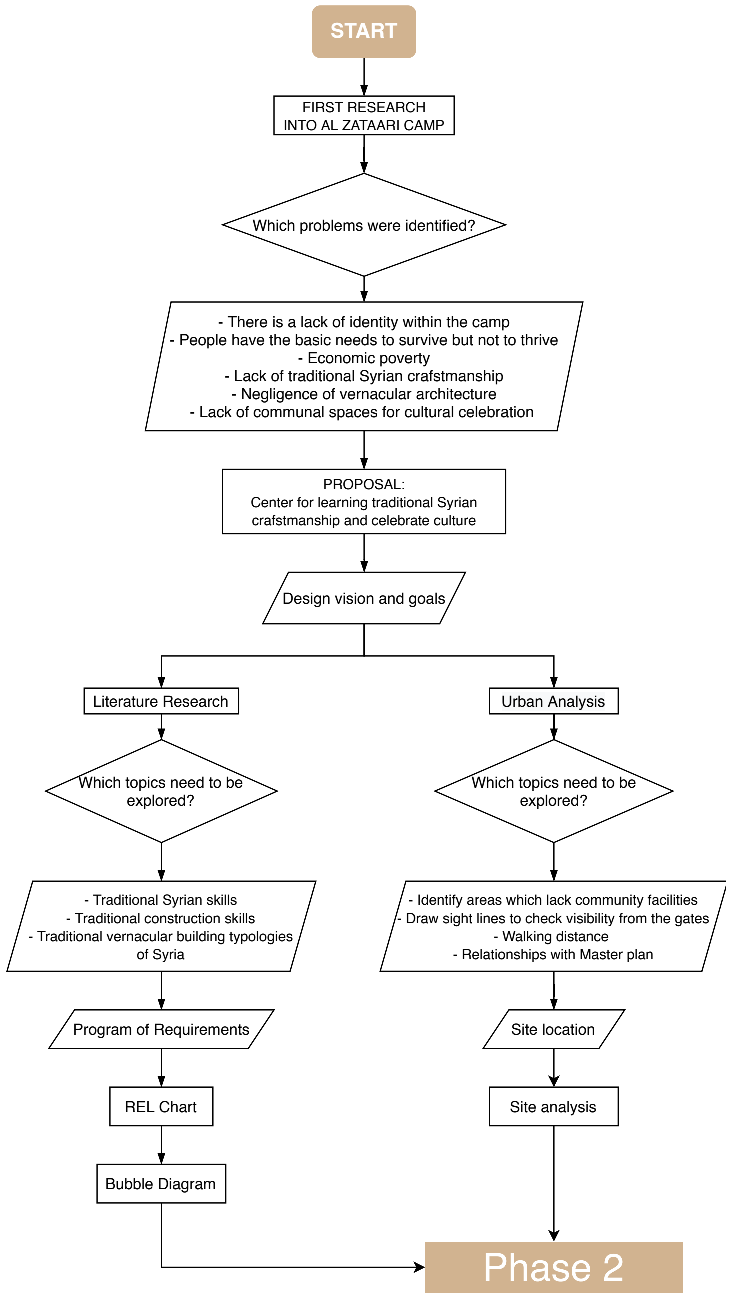


Figure 8 - Flowchart Phase 1 I Source: authors

1.5.2 PHASE 2

With the input from phase 1 the spacial configuration was finalized and translated into floor plans. These than resulted in many different roof typologies. For each typology a choice was made in the type of approach that would best suit it. The shapes would be tessellated and dynamically relaxed to approximate the wanted shape. When satisfied with the result it would then be passed on to the next phase, phase 3.

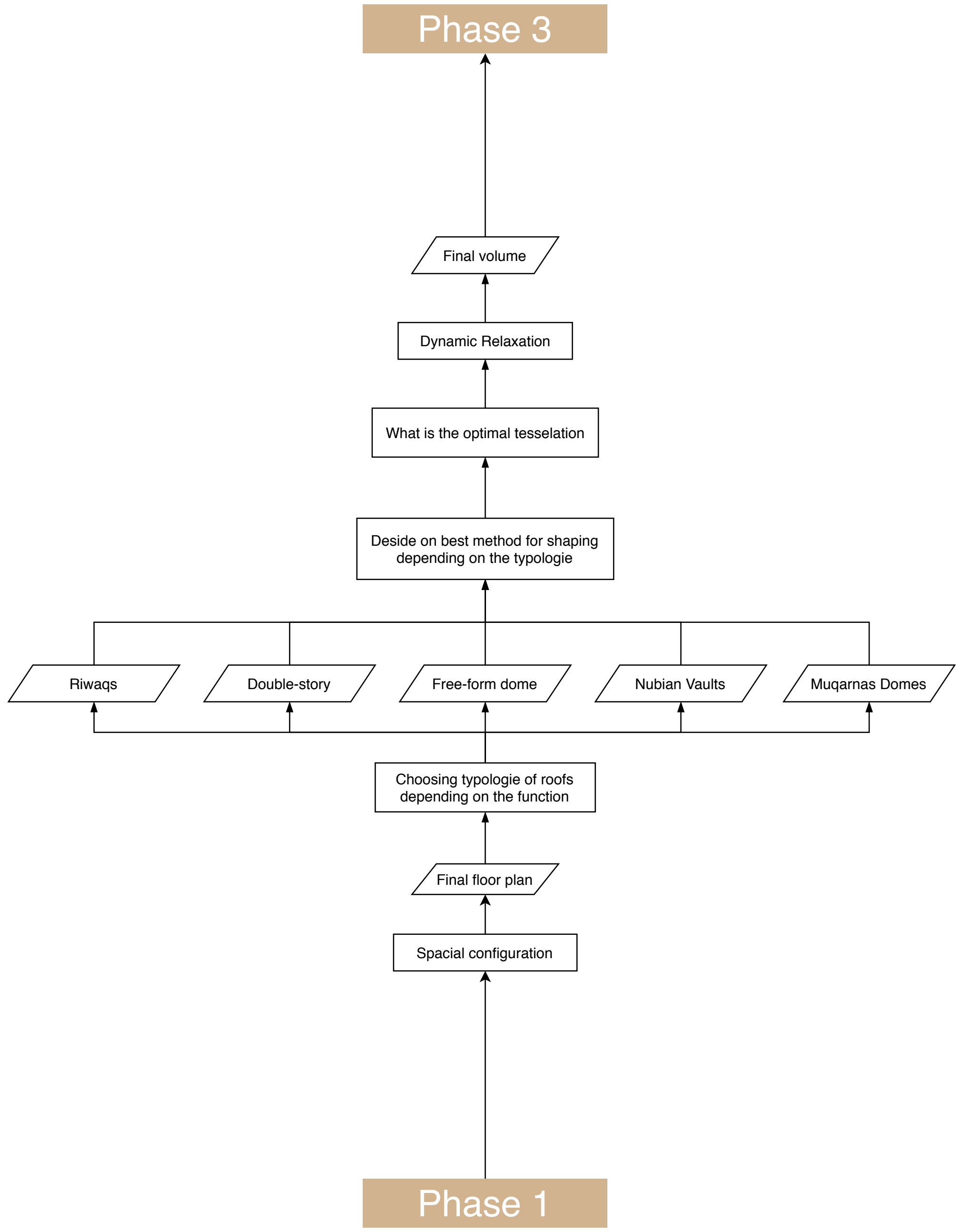


Figure 9 - Flowchart Phase 2 I Source: authors

1.5.3 PHASE 3

With the new phase came a new perspective of our design and so a re-evaluation was done. The many different types of roof typologies would make it to complex to build so we simplified. Within this simplification it was important to find a correct balance. The design needs to be striking enough to be called a heritage centre but not too difficult to construct. With this into consideration the design got groin vaults for most of the one story spaces, barrel vaults for the riqwas and the double story spaces and for the arched entrances and the multipurpose hall the domed muqarnas where kept.

After choosing a brick type the structural analysis took place together with the construction method. During this process the design was changed in some areas to make it structurally feasible.

The final design was then turned into actual bricks with an grasshopper script. This would then be the final shape of the whole building.

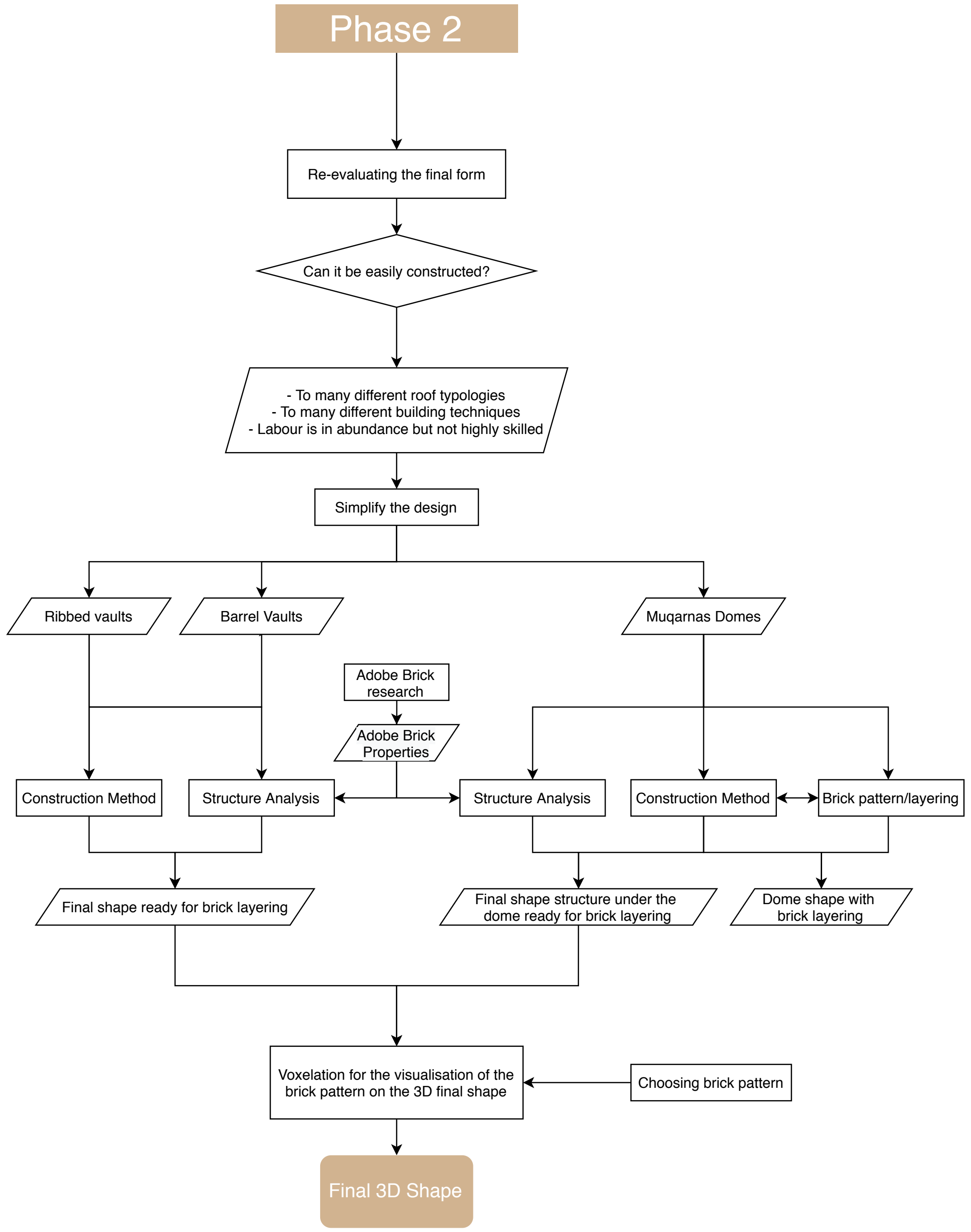


Figure 10 - Flowchart Phase 3 | Source: authors

2 RESEARCH & ANALYSIS

In this chapter the initial research done will be looked into and explained. This includes urban analysis, vernacular architecture, muqarnas architecture and traditional crafts.

2.1 URBAN ANALYSIS

A first look into the location of al the existing community buildings lead us to two districts where there was a lack of these type of building as can be seen in figure 11.

There will be only one heritage center of this scale, and its location was chosen largely based on visibility from the entrance gates (figure 12). The building is an icon of vernacular Syrian architecture to the residents of the camp as well as to passersby.

To maximize the impact and make a statement, this building is located at the intersection of three secondary roads (figure 13). This position allows for the formation of a square with the focal points which is visible from the major roads.

Furthermore, a grand entry point helps to convey the idea of a heritage centre upon entry of the camp.

Figure 11 - Centres within the camp l Source: authors

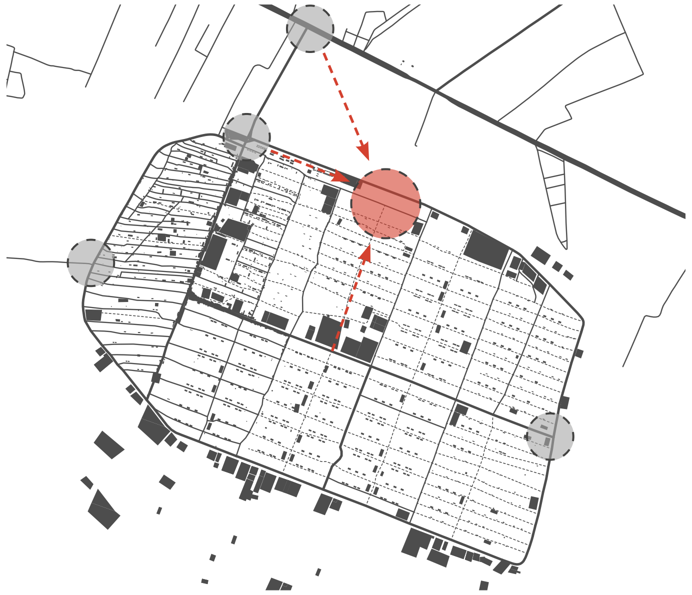


Figure 12 - Site Location l Source: authors

Figure 13 - Site Location l Source: authors

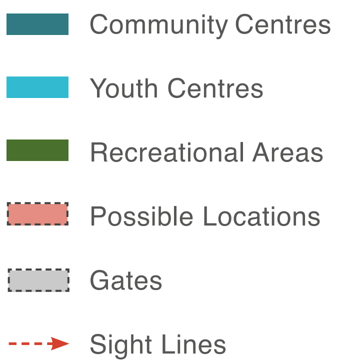


Figure 14 - Legend figure 5-7 l Source: authors

2.2 VERNACULAR ARCHITECTURE

Research on vernacular Syrian architecture was also done to understand the spatial configuration. There where three spaces that where interesting to apply for our building.

The first one is like a verandah, it is called the Riwaq and it is found in traditional houses. This space is a covered gallery where several rooms are aligned along. This serves as a transitional space between indoor and outdoor areas. Another purpose is when it is hot it provides shading for the room alongside it whilst still letting in daylight. When the rain season comes it will also serve as a cover while walking from room to room. An example can be seen in figure 15.

Another unique space is called the Liwan (figure 16) which acts like a transition space to connect the street (public area) to the house (private are).

The last common typology found was the courtyard which prevails in most medium to large houses. This space is a multi-purpose area that because of its enclosure can be categorised as private. It also has a very important role in thermal comfort. With a courtyard there is protection of the hot dusty wind and at the same time it still provides shade (figure 17) and a good air circulation because al the big opening are facing towards the courtyard.

These three spatial features of vernacular architecture were taken into account in designing.

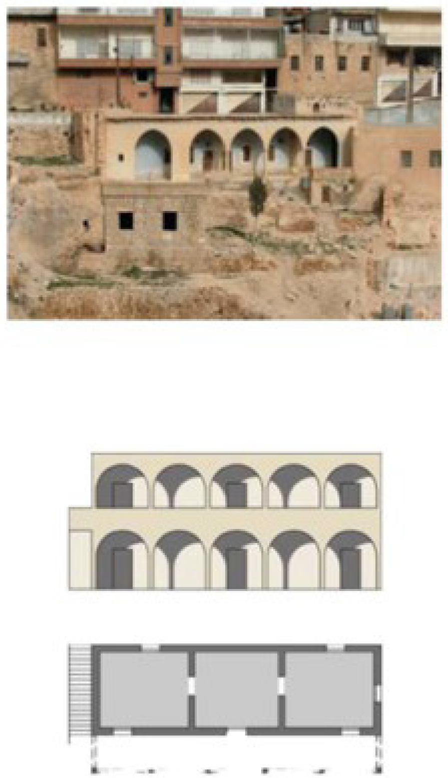


Figure 15 - Riwaq

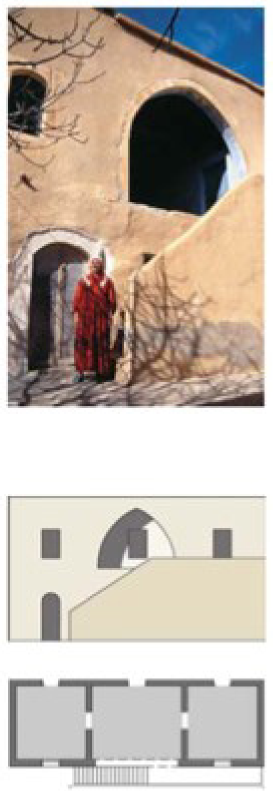


Figure 16 - Liwan

Figure 17 - Courtyard

Source: see bibliography

2.3 MUQARNAS ARCHITECTURE

An element we seemed to see repeated everywhere in the Syrian architecture where the muqarnas.

The muqarnas seen on those examples are mostly ornamental as can be seen in figure 19 and 20. That is how they have been used the most but they originated as a structural element as can be seen in figure 18.

As a structure it is a simple way of approximating the shape of a dome. In this type of structure it is easy way of also creating some openings to let the hot air flow away and thus cooling the inside.

This type off element could be used in our building as an eye catching architectural element. Also it can be used as an example to highlight vernacular architecture in the region.

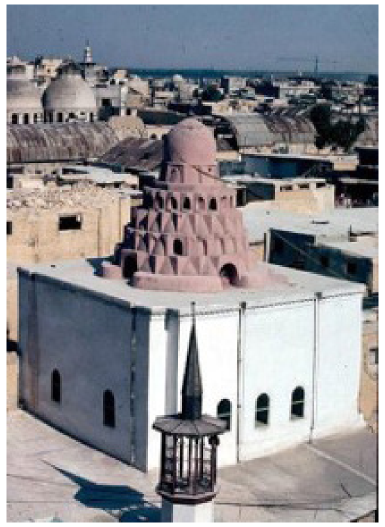


Figure 18 - Muqarnas as a dome

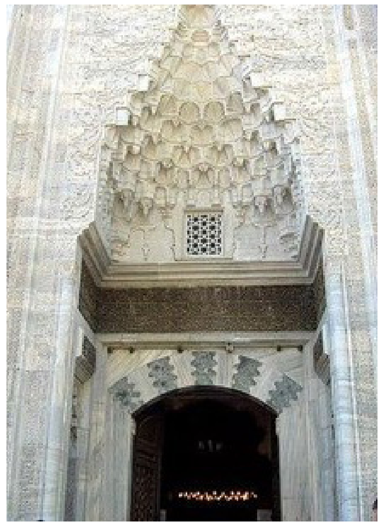


Figure 19 - Muqarnas on the wall

Figure 20 - Muqarnas on a column

Source: see bibliography

2.4 TRADITIONAL CRAFTS

From the research we found crafts that fitted into five main categories. These where textile work, wood work, ceramic work, glass work and metal work. It was decided that glass work and metal work would not be implemented in the heritage centre because it required quite a few special tools and machines. This can however be introduced in the future when there is more room in the budget for that.

Textile work

Within this category the following workshops will available: al aghabani, brocade and oriental rugs.

Wood work

The following workshops fall within this category: mother of pearl marquetry, al ajami and oud (musical instruments).

Ceramic Work

The workshops given within this category will be: pottery, al qishani and mosai.

For the workshop rooms there where a few things to take into consideration. A very obious one is storage for materials and products. Some rooms need to be nicely lit and quiet because the craft requires patience and accuracy. Other rooms need to be big enough to have multiple hand looms. Also outside areas are important to sun dry the pottery.

Figure 21 - Al Aghabani

Figure 22 - Brocade

Figure 23 - Oriental rugs

Source: see bibliography

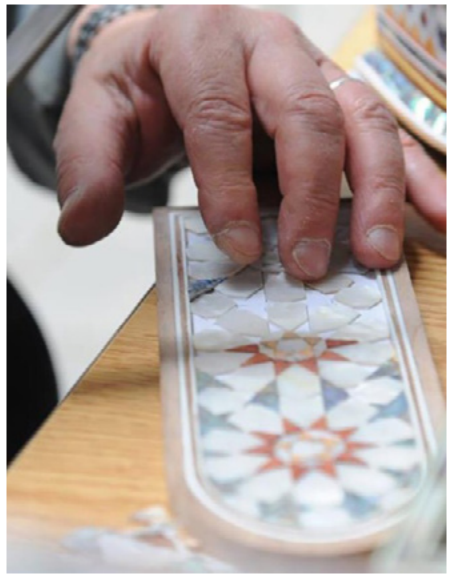


Figure 24 - Mother Pearl Marquetry

Figure 25 - Al Ajami

Figure 26 - Oud (Music Instruments)

Source: see bibliography

Figure 27 - Pottery

Figure 28 - Al Gishani

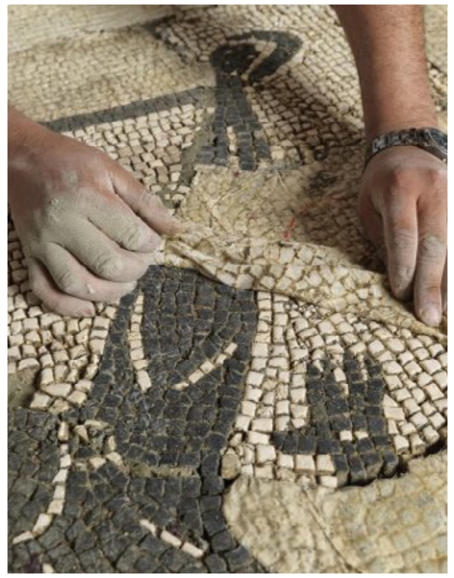


Figure 29 - Mosai

Source: see bibliography

3 CONFIGURING

Within this chapter the configuring of the floor plan will be done. This includes the program of requirements, the REL chart and the bubble diagram, site analysis, layout methodology followed by the final floor plans and sections.

3.1 PROGRAM OF REQUIREMENTS

With the knowledge required from the research into traditional crafts and vernacular architecture a program of requirements could be put together.

This program was divided into five categories depending on the type of function of each area. The first category is the communal spaces which includes the multi-purpose hall, library, exhibition room, shops and child-care. The public square and courtyards are part of the second category which are transitional or gathering spaces. Next we have two categories that are needed in every type of public building. They are the admin and services spaces including office, meeting rooms, storages, toilet and kitchenette. Lastly the learning spaces where al the workshops will be held.

The areas of these spaces are based on the capacity and square metres needed per person. The full program of requirements can be found in the appendix.

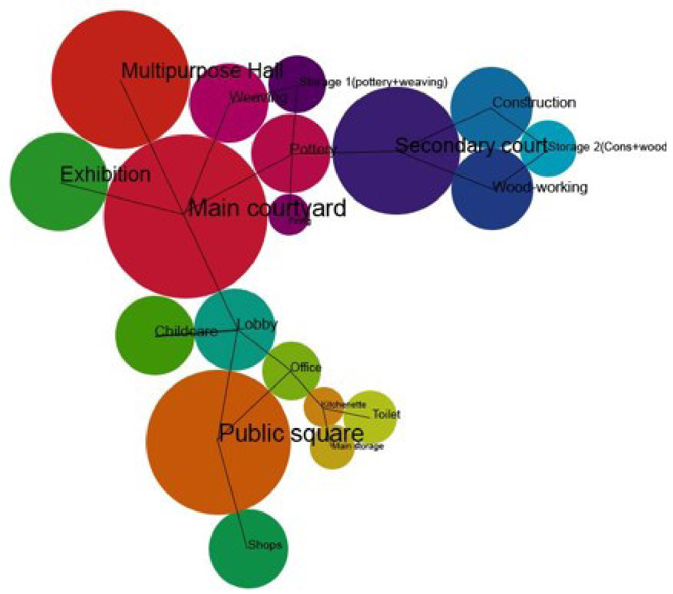


Figure 31 - Bubble Diagram I Source: authors

3.2 REL CHART & BUBBLE DIAGRAM

To get a better understanding of our program of requirements a better look into the relationship between spaces was taken. This was done by creating an REL chart which can be seen in figure 32.

With the information gathered on which connections where strong or weak the next step could be made to creating the bubble diagram seen on the left. This was done using the syntactic tool that showed the adjacencies. The diagram helped us understand the proportions for our different courtyards and also visualizing the general flow from the public square to main courtyard to the secondary courtyard and the respective adjacencies.

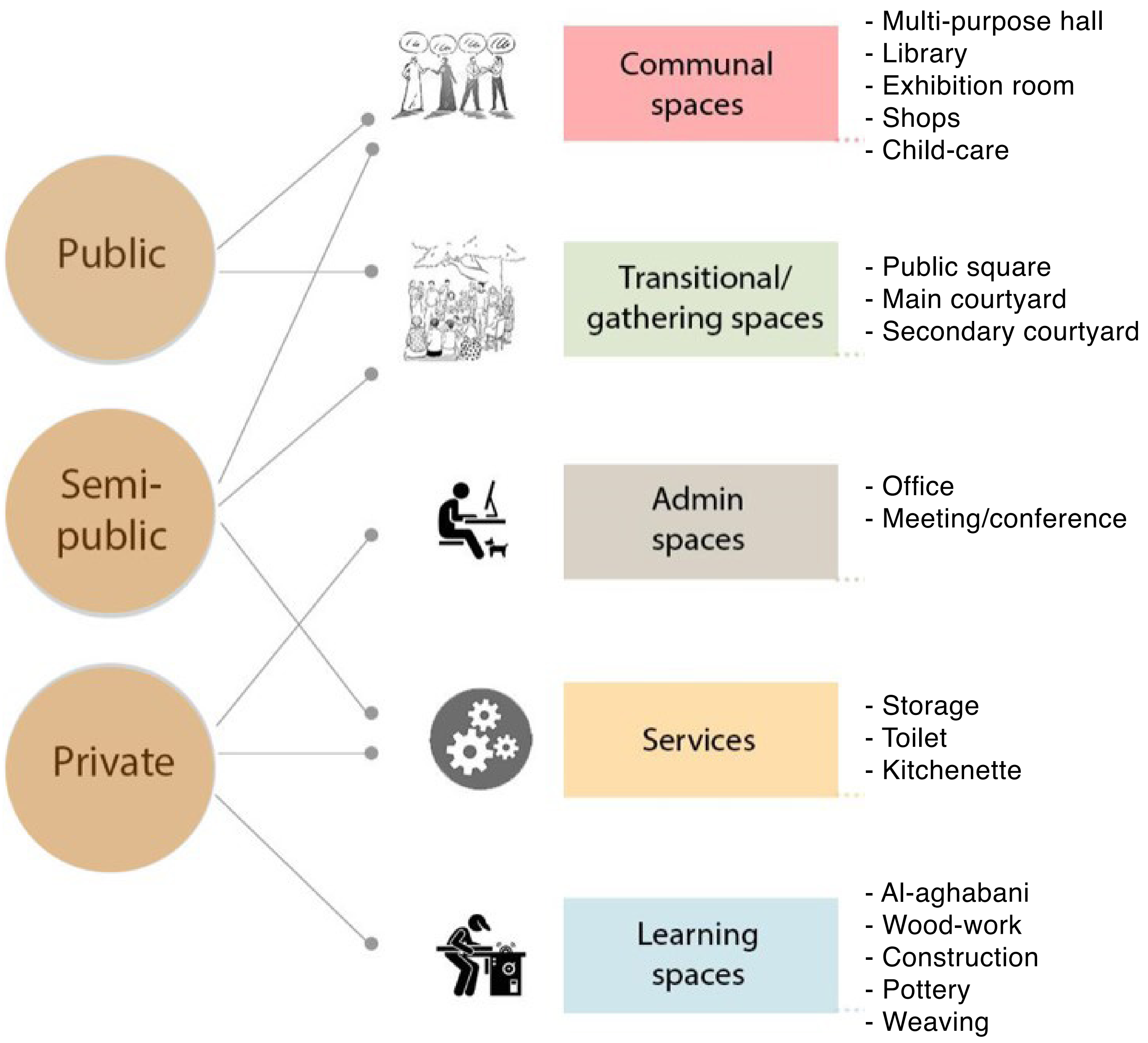


Figure 30 - Program of Requirements I Source: authors

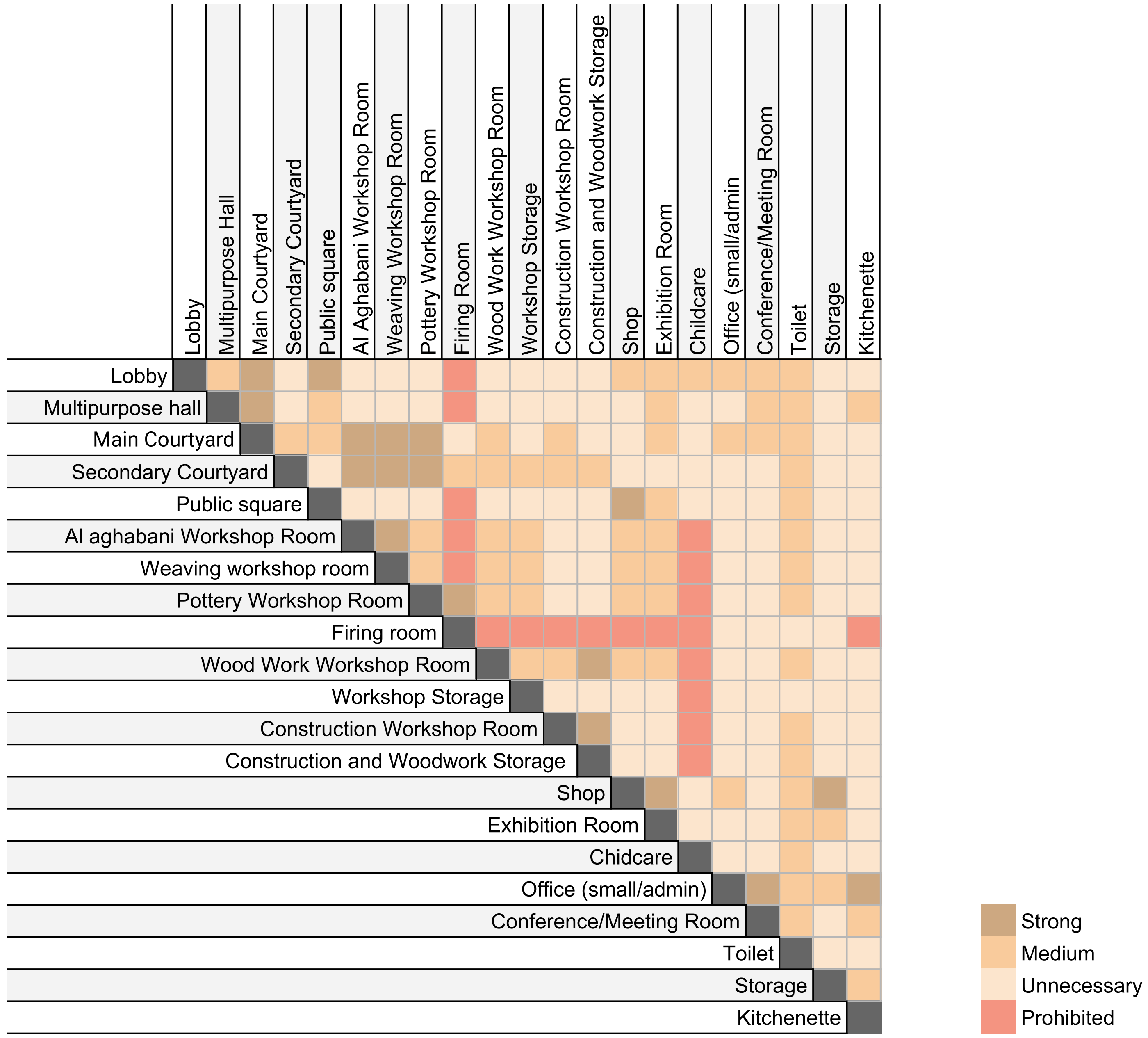


Figure 32 - REL Chart I Source: authors

3.3 SITE ANALYSIS

Having an understanding of the adjacencies, we moved on to the site analysis. Here we established different elements that would help us translate the bubble diagram to a floor plan.

On of the elements that played a role since the design goals was the access and visibility. This meant that the building should be visible form the three roads it sits on but also from afar. For this we needed to make no part of the building at least two story high.

The other important part was to locate the nodes and its connectivity. This helps to identify the main circulation and the hierarchy of the spaces. As can be seen in figure 33 there will be an entry node that connects to the three roads. This one is then connected to the primary node which will then branch out to secondary nodes. So to get to the secondary nodes you need to pass through the primary node.

With the knowledge of the vernacular types of architecture the decision was made to take the nodes as central open spaces for gatherings and to interconnect al the rooms.

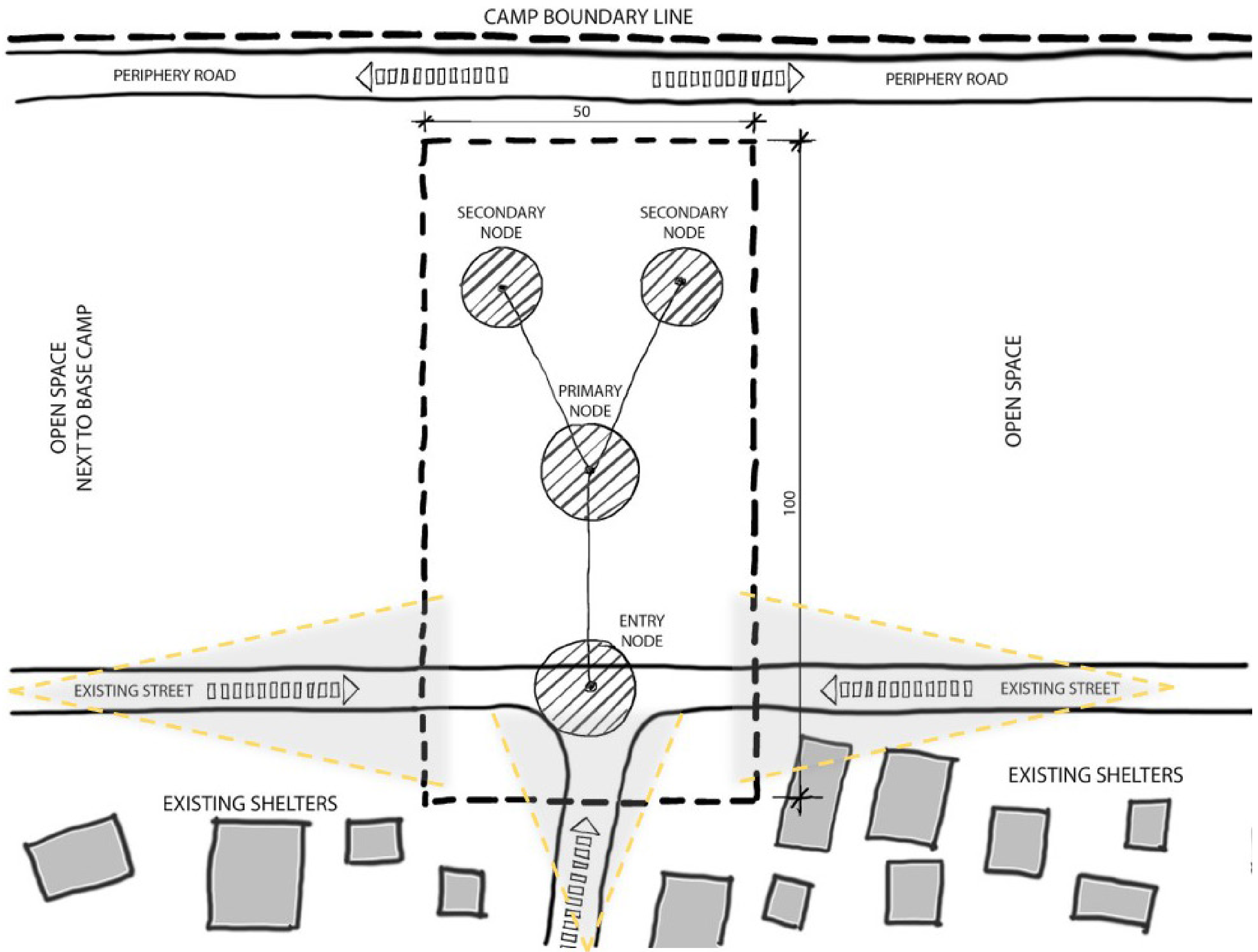


Figure 33 - Site access and visibility & Site nodes and connectivity I Source: authors

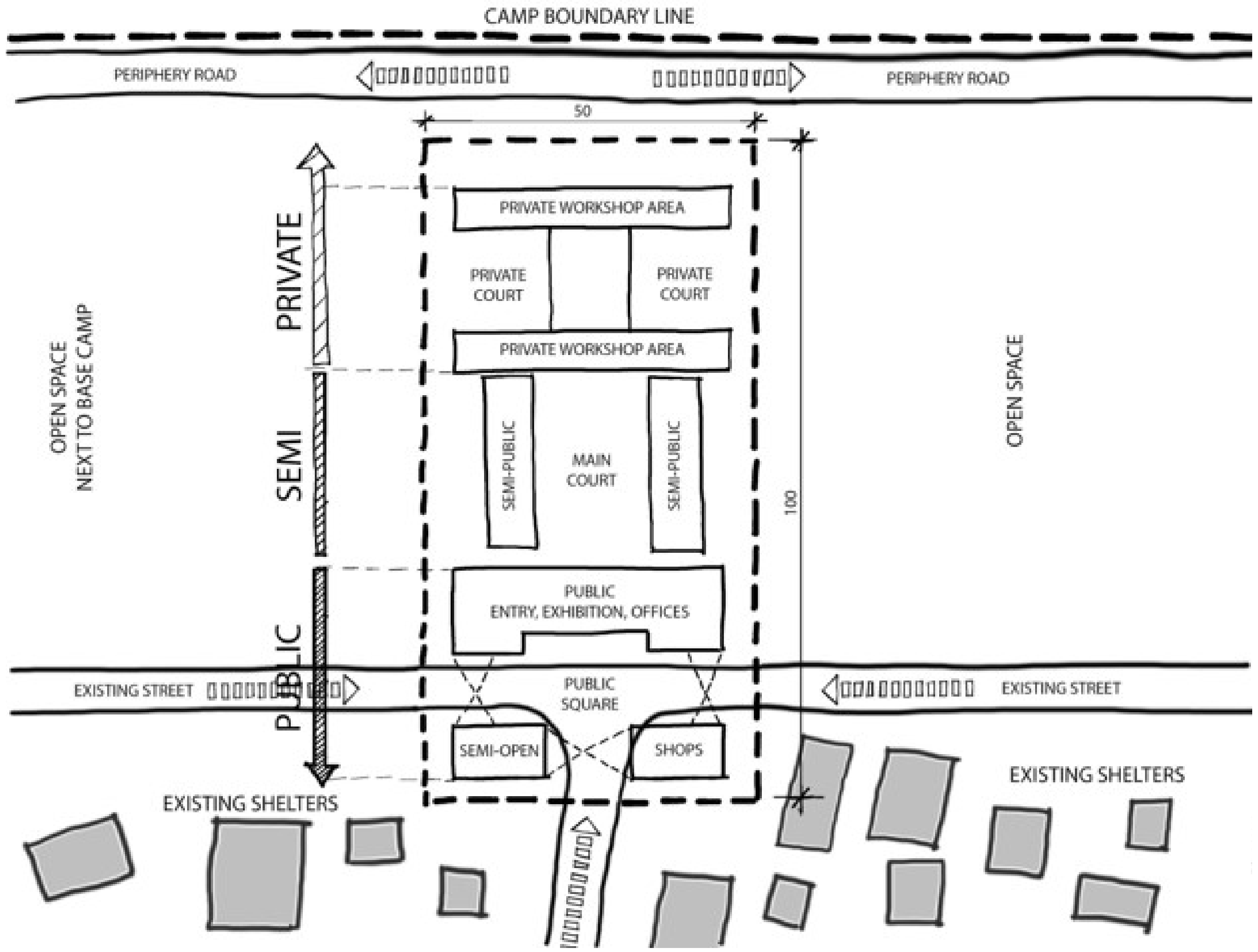


Figure 34 - Site zoning and climate I Source: authors

The insight gathered from the initial analysis led to a manually drawn concept floor plan as the first iteration. Within this floor plan a greater attention was paid to the site zoning in terms of privacy and to the climate.

At the entry node, which is the public square in figure 34, the level of privacy is very low to non existent. This gets more and more private the further you get in the building. So the primary node or main courtyard can be considered a semi-private space whilst the secondary nodes are a privates space, available only for the people that are going to learn there. This transition also comes with a increasing level of security so that it can be a safe place where everyone can be comfortable.

In terms of climate it was important to self shade and self protect from the hot and dry summers. The analysis resulted in moving the higher massing towards the south and to add trees and water elements in the courtyards.

With this basic layout we had an idea of how to evaluate the resultant floor plans produced in the grasshopper model. This will be explained further in the next part.

3.4 LAYOUT METHODOLOGY

With al the information collected the layout configuration could be started. To begin al the line work needed to be implemented. This includes the basic site boundary as well as roads. Together with this the shops were decided to be placed right alongside the public square and remain static for floor plan optimization. These would make the script more compact and result in more accurate layouts.

The inputs for the kangaroo solver where already there but needed to be translated into grasshopper. These inputs include preferred orientations, adjacencies, and strong as well as weak connections between different connections. This was achieved by creating magnetic attraction or repulsions in between spaces which could be stronger or weaker. Lastly the area size input was determined by using a grid of 1.2m, based on brick dimension.

Playing with the magnetic strength between the different functions as well the attraction strength to the courtyards, the solver tried to resolve the layout.

And it gave us different options (figure 36) for the configuration layout. The options helped to loosen up the floorplan from a rectilinear grid to a more offseted one to prompt future expansion on the site for accommodating more workshop spaces.

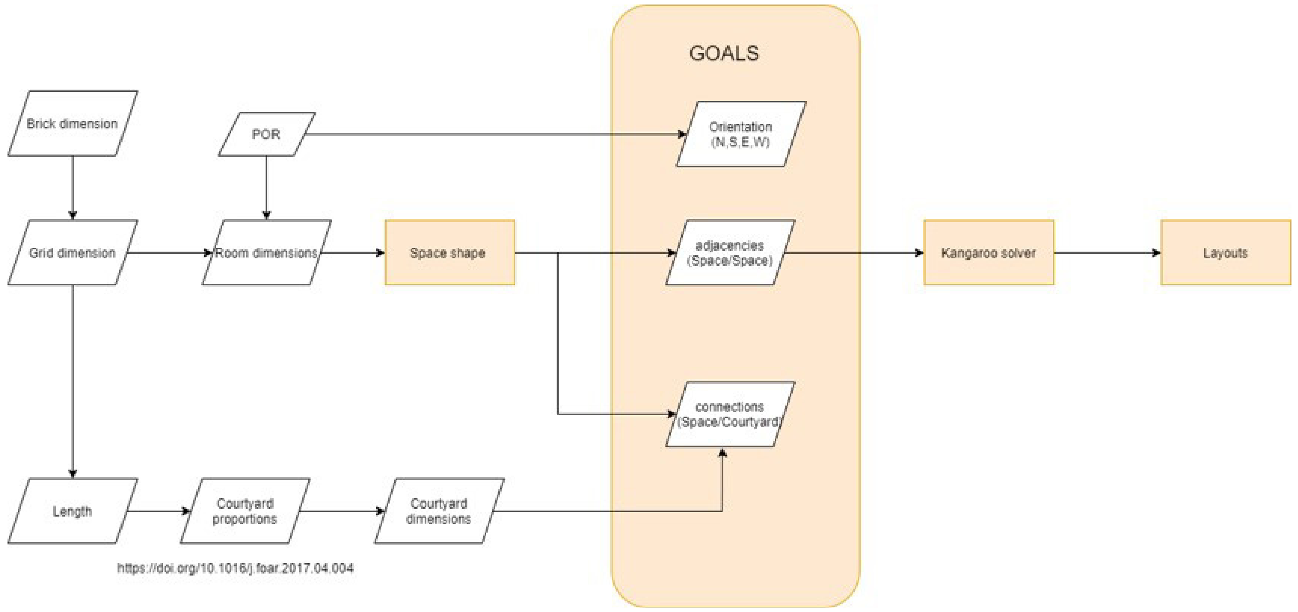


Figure 35 - Flowchart of the configuration I Source: authors

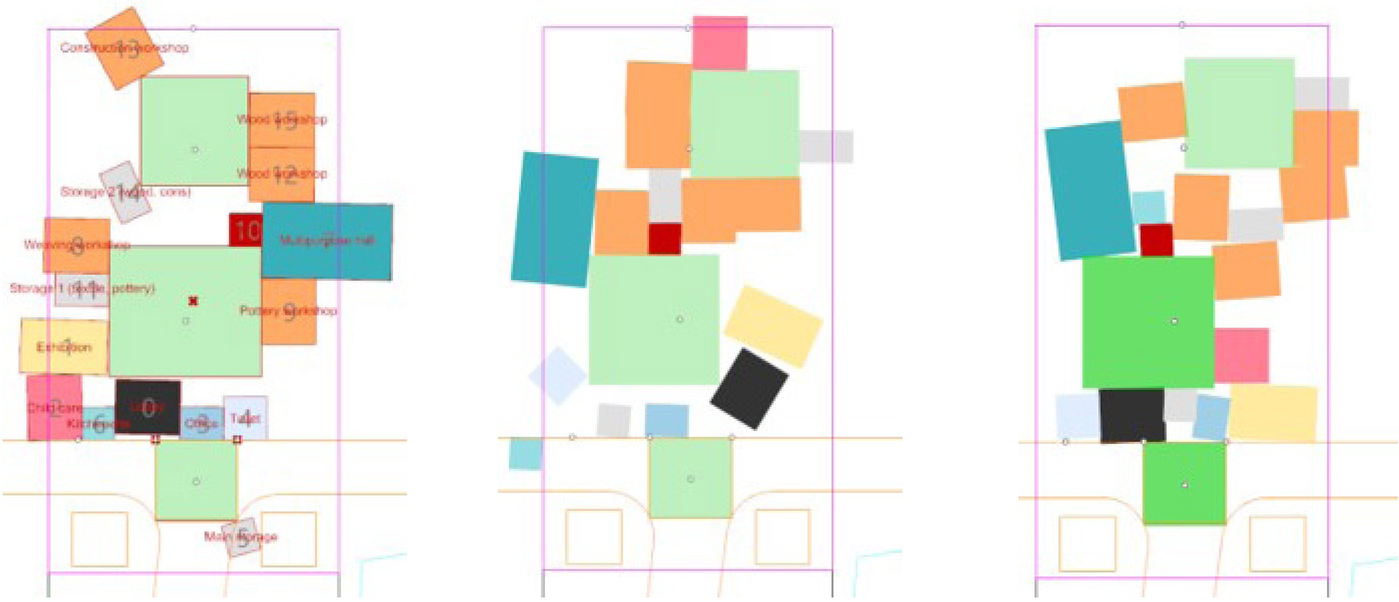


Figure 36 - Different options of configuration I Source: authors

Figure 37 - Chosen configuration option I Source: authors

The grasshopper script was perfected until the strengths of the magnets was correct and the resulting adjacencies would not be contradicting our initial goals established beforehand.

When that was achieved there still where a few options to choose from. The decision to which was the best one was determined on the basis of the basic layout and the design goals.

The final layout which closely resembled our intentions and visions for the building was taken forward and then post-processed to make the final floor plan.

3.5 PLANS

The final floor plan accounts for a tartan grid which creates regular modules for the Riwaq arches and for all the workshop spaces. The layout has a flow of spaces from the public square to the main courtyard which also flows to the secondary courtyard.

The public square is the major communal junction with shops and the building entrance around it. The three gateways serve as the main entrances to this court without compromising the traffic flow and the design showcases the majestic character of the building.

The main courtyard is semi-public, acting as a spillover space for multifunctional rooms and exhibition spaces, whereas the secondary courtyard is for outdoor learning and serves as a working space for prototyping, sun drying and other workshops.

The building also has a first floor, which is located towards the south to provide some shading on the courtyard. This location was also chosen because the spaces on the ground floor have a much smaller span which can ideally support a top floor. The top floor houses the quieter spaces such as the library, conference and the Al aghabani weaving workshop.

1. Public square
2. Shops
3. Entrance lobby
4. Main courtyard
5. Multipurpose hall
6. Office
7. Kitchen
8. Store
9. Toilets
10. Child-care
11. Exhibition
12. Weaving
13. Store (for 12 & 14)
14. Pottery
15. Firing
16. Secondary courtyard
17. Construction
18. Woodwork
19. Store (for 17 & 18)
20. Prototyping
21. Future expansion

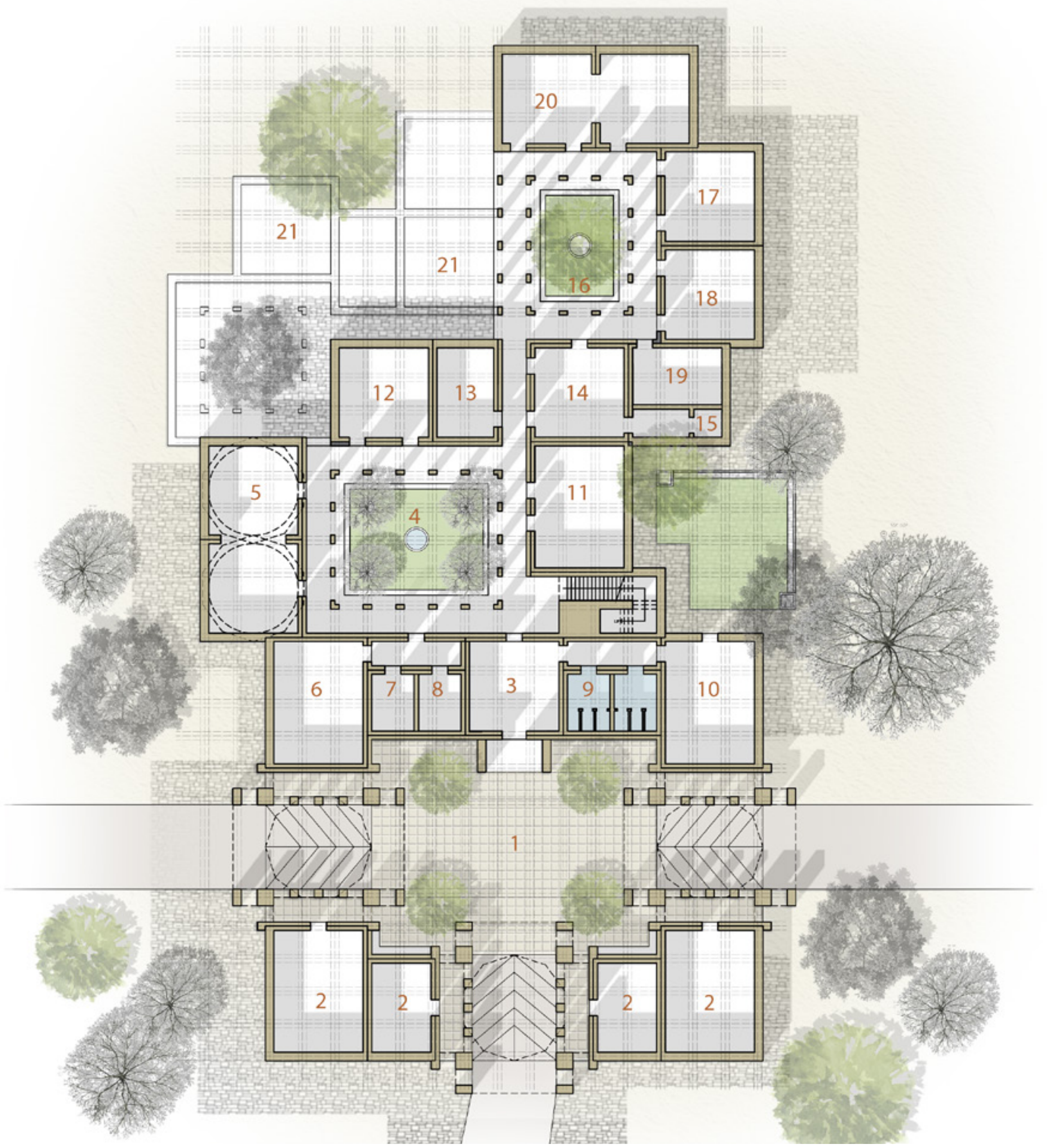


Figure 38 - Floor plan: 1st floor I Source: authors

1. Al aghabani
2. Conference
3. Library

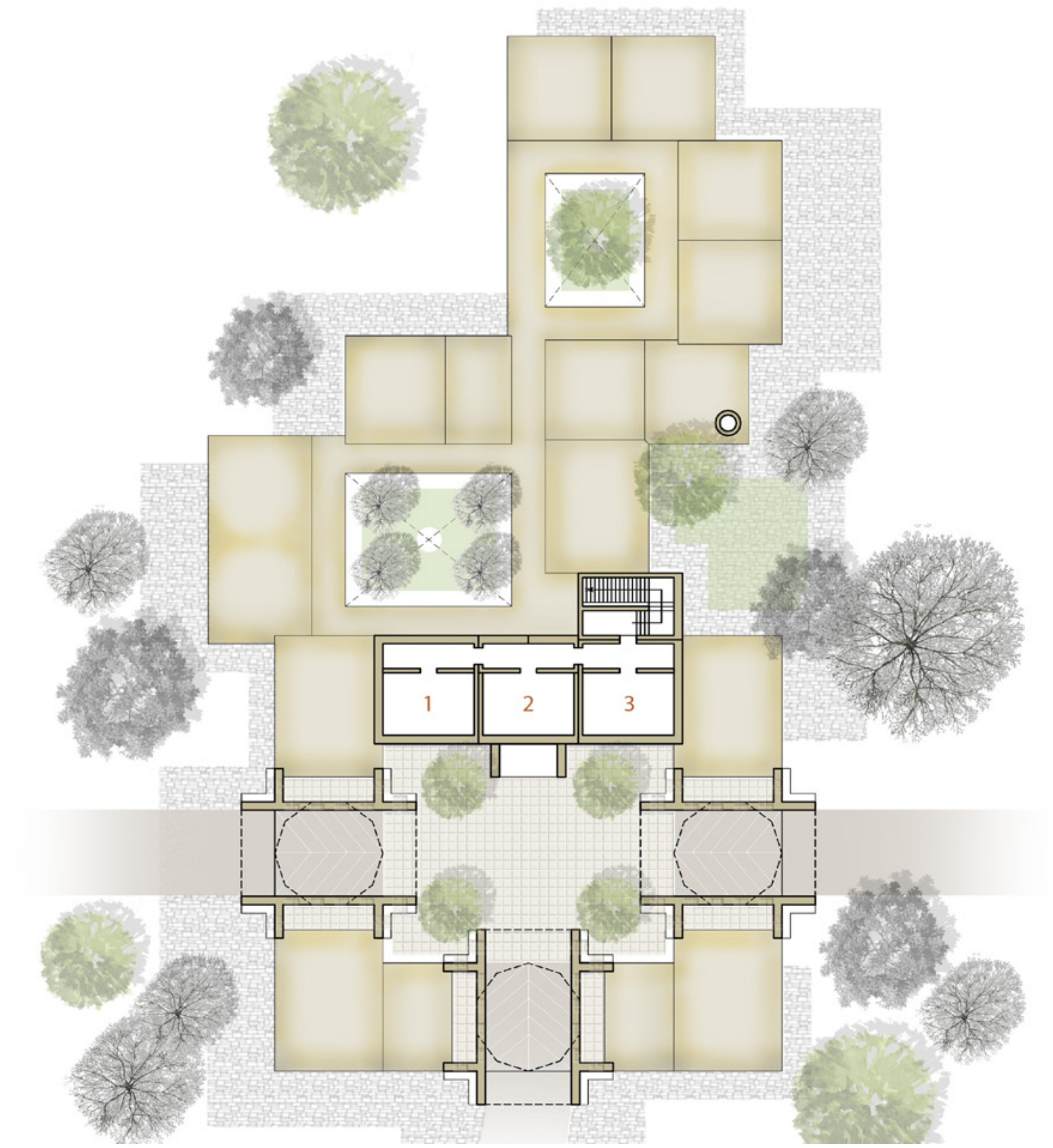


Figure 39 - Floor plan: 2nd floor I Source: authors

3.6 SECTIONS

Section A is through double story structure showing the two levels with the majestic Muqarna domes on the back. Section B is through the public square and the main courtyard showing the built-open relationship.

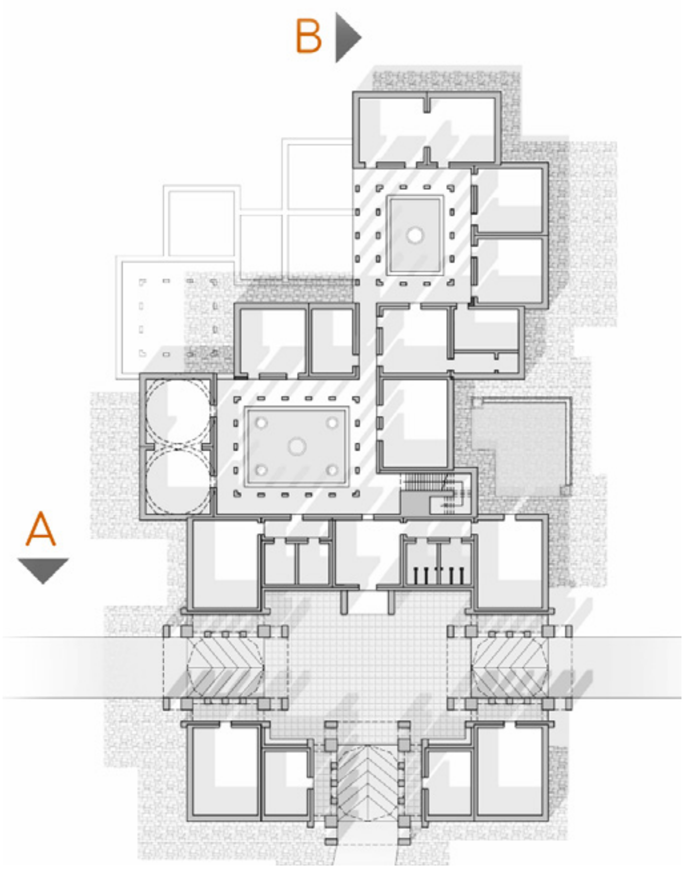


Figure 40 - Floor plan sections I Source: authors

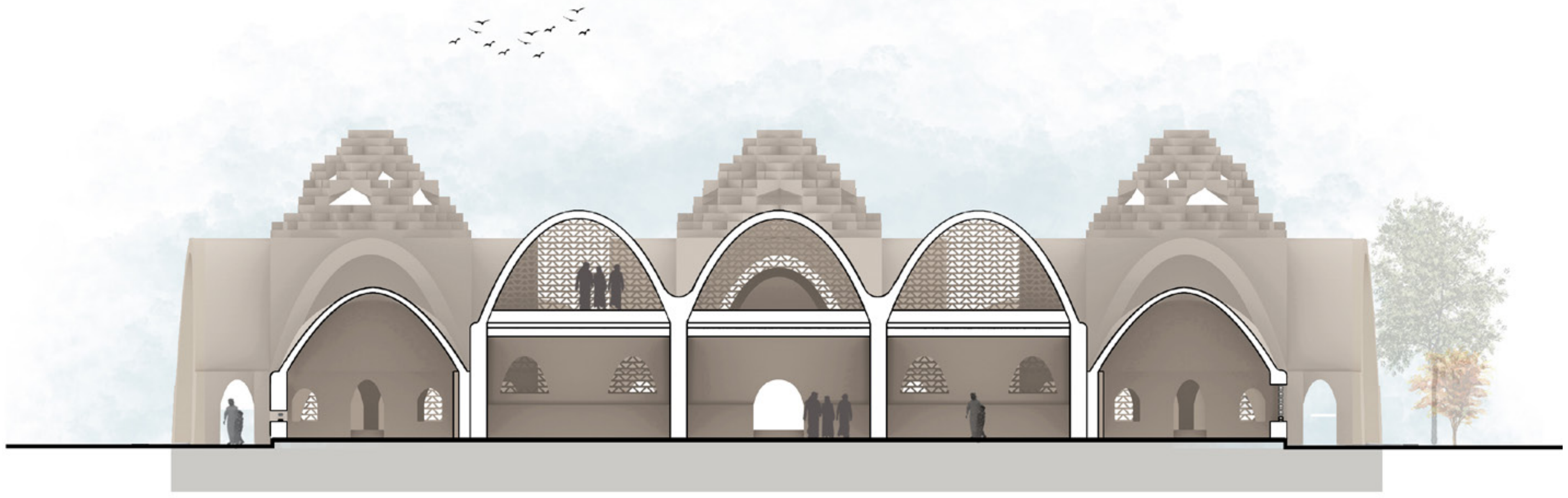


Figure 42 - Section A-A I Source: authors

Figure 41 - Section B-B I Source: authors

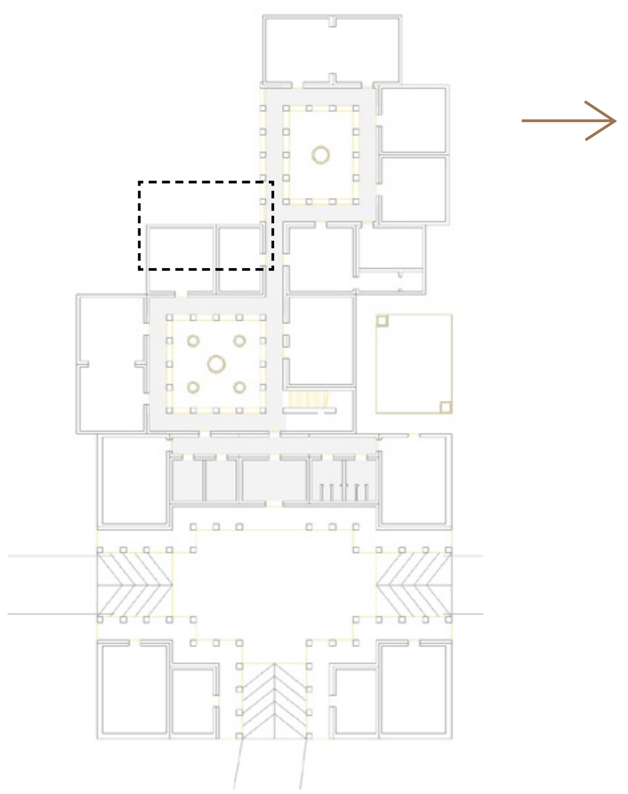
4 SHAPING & STRUCTURING

In this chapter the shape and structure of the building will be in the spotlight. It will be explained how the process towards the final shape developed and how the structuring was of influence.

4.1 METHODOLOGY

Being a Heritage centre, it is essential to provide a strong architectural form to the building showcasing the majestic character of the traditional architecture of Syria. The shaping and structuring process for the entire building is driven with this aim to celebrate the heritage. The first step is to decide on the different roof typologies for different building parts. Having done so, each typology is then developed by exploring various meshing techniques for giving shape to the floor layout. The different meshes generated are then dynamically relaxed using the kangaroo solver to obtain the desired form for the different roof typologies. The next step is to simplify and adapt the generated forms based on structural analysis and feasibility of construction. A series of exploration has been done based on the stresses and deflection values to ultimately obtain a safe, stable and secure building form. For the structural analysis, Karamba 3d FEA has been used.

Shaping



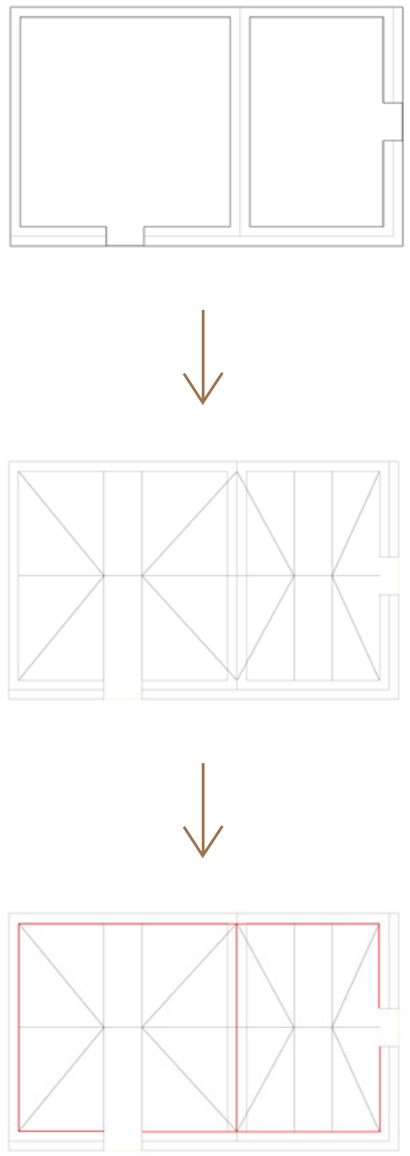


Figure 43 - Process overview for shaping. I Source: authors

Structuring

For the structuring process, it is essential to first define the material properties which would provide the material inputs and limit values. The flowchart shows the process undertaken to do the structural analysis for the different parts of the complex.

MATERIAL INPUTS

The adobe bricks for constructing the different parts of the building is composed of a mixture of clay, sand and straw to increase the strength of the brick. Further elaboration about the material properties is provided in chapter 05. This section gives an overview of the material inputs and limit values which is incorporated for the structural analysis.

Safety factor-

A safety factor of 2.5 is used as the complex has buildings with one than one floor height.

Shear Modulus-

Adobe has a poisson ration of 0.35 (R, Illampas 2011). Therefore,

Shear modulus G = E/(2(1+v))

= 150/(2(1+0.35))

=55.55

= 60 N/mm2

Specific weight-

As per ABC of making adobe bricks, dry brick has a weight of 4 x 8 x 16. In specific weight it is 14.8kN/m3. Therefore an approximation of 15 is used for the calculation.

Material input values	
Young’s modulus (N/mm2)	150
Compressive strength (N/mm2)	3.67
Safety factor for stress	2.5
Safety factor for live load	1.5
Safety factor for dead load	1.2
Allowable compressive strength (N/mm2)	1.5
Allowable tensile strength (N/mm2)	0.15
Shear modulus (N/mm2)	60
Specific weight (kN/m3)	15

Figure 44 - Table for material inputs. I Source: authors

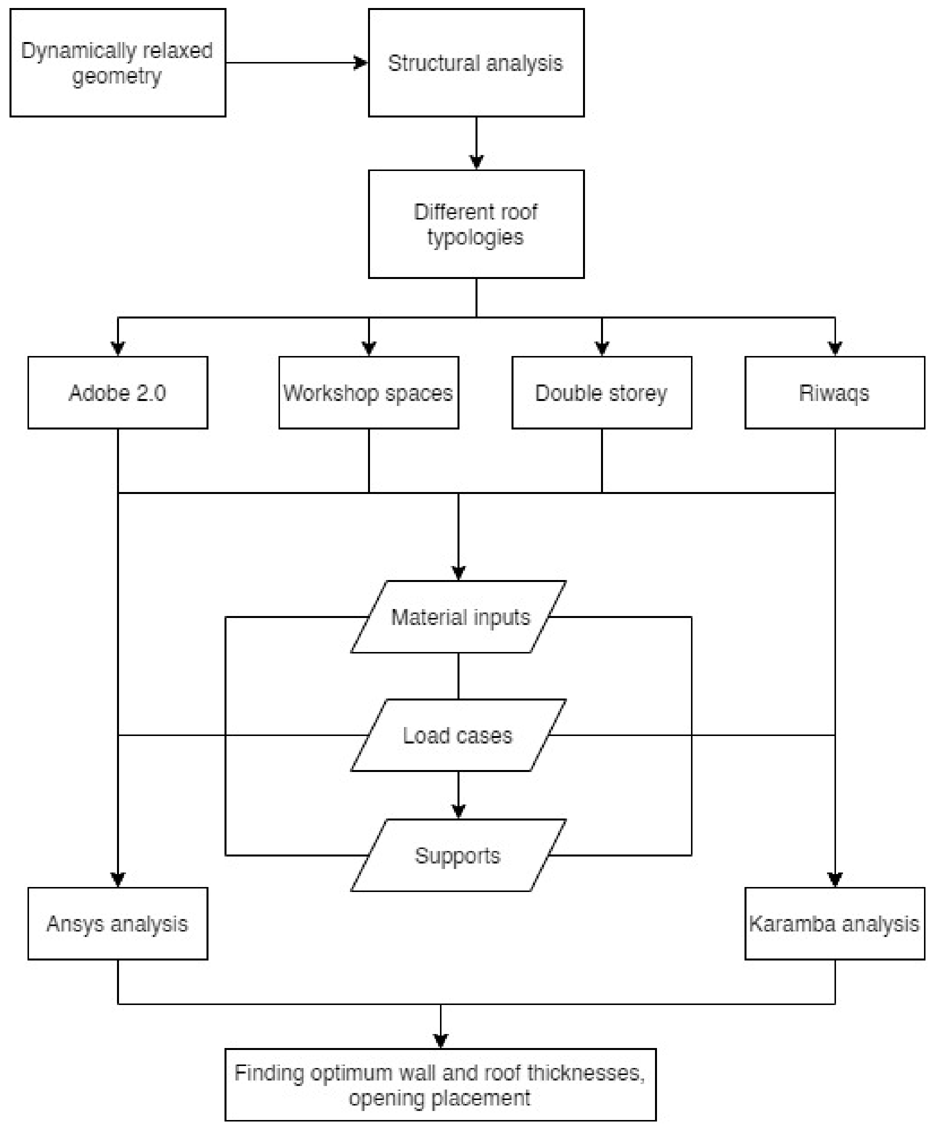


Figure 45 - Structural analysis flowchart I Source: authors

4.2 ROOF TYPOLOGIES

With the aim to provide a strong architectural identity to the entire complex, different roof typologies have been explored for different functions. Moreover, since the loading conditions for the different parts vary, it is more efficient to have different roof forms based on the structural aspects as listed below:

1. Ribbed vaults for Workshops, shops and exhibition
2. Nubian vaults for double storey
3. Nubian and cross vaults for Riwaqs
4. Muqarnas domes for the gateways and the multi-purpose hall.

The spectacle piece of the muqarnas domes (yellow in the figure below) was placed on the entrance arches and on the multi purpose hall. These spaces are expected to see many different people each day and so leave an impression behind of traditional Syrian architecture.

The free form vaults can be seen in blue in figure 43 and are applied in al the one floor hight spaces. Whilst the riwaqs (green) will have cross vaults. This has to do with the easy repetition of these elements.

For the double story building the nubian vaults will be applied for the ground floor and first floor level due to its ease to structurally be stacked.

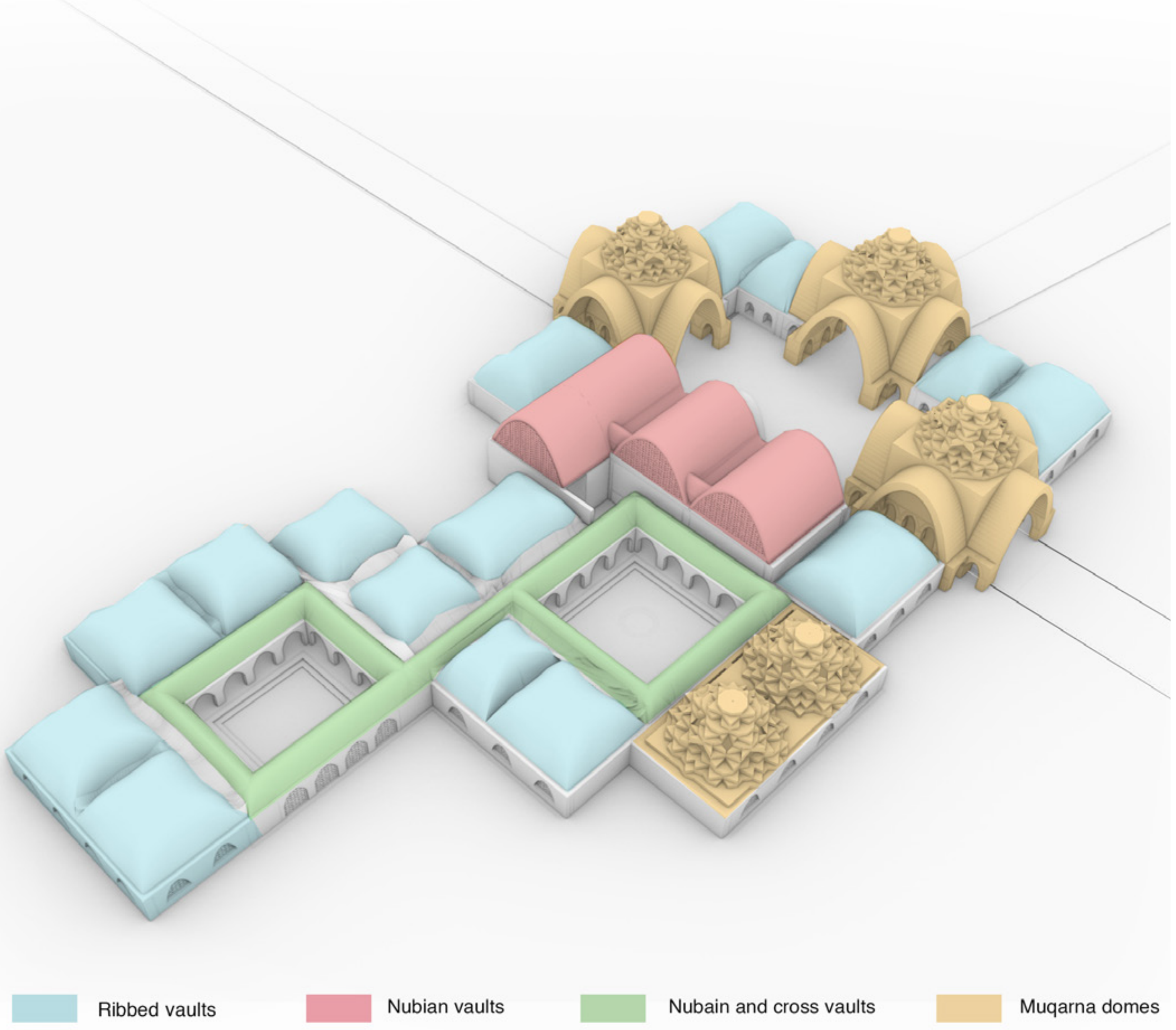


Figure 46 - Different roof typologies I Source: authors

4.2.1 RIBBED VAULTS

The most repeatable roof module for the entire campus is the Ribbed vault roof form. A ribbed vault composed of a framework of arched ribs, can cover wide spaces and thus is greatly suitable for the most used module of our project.

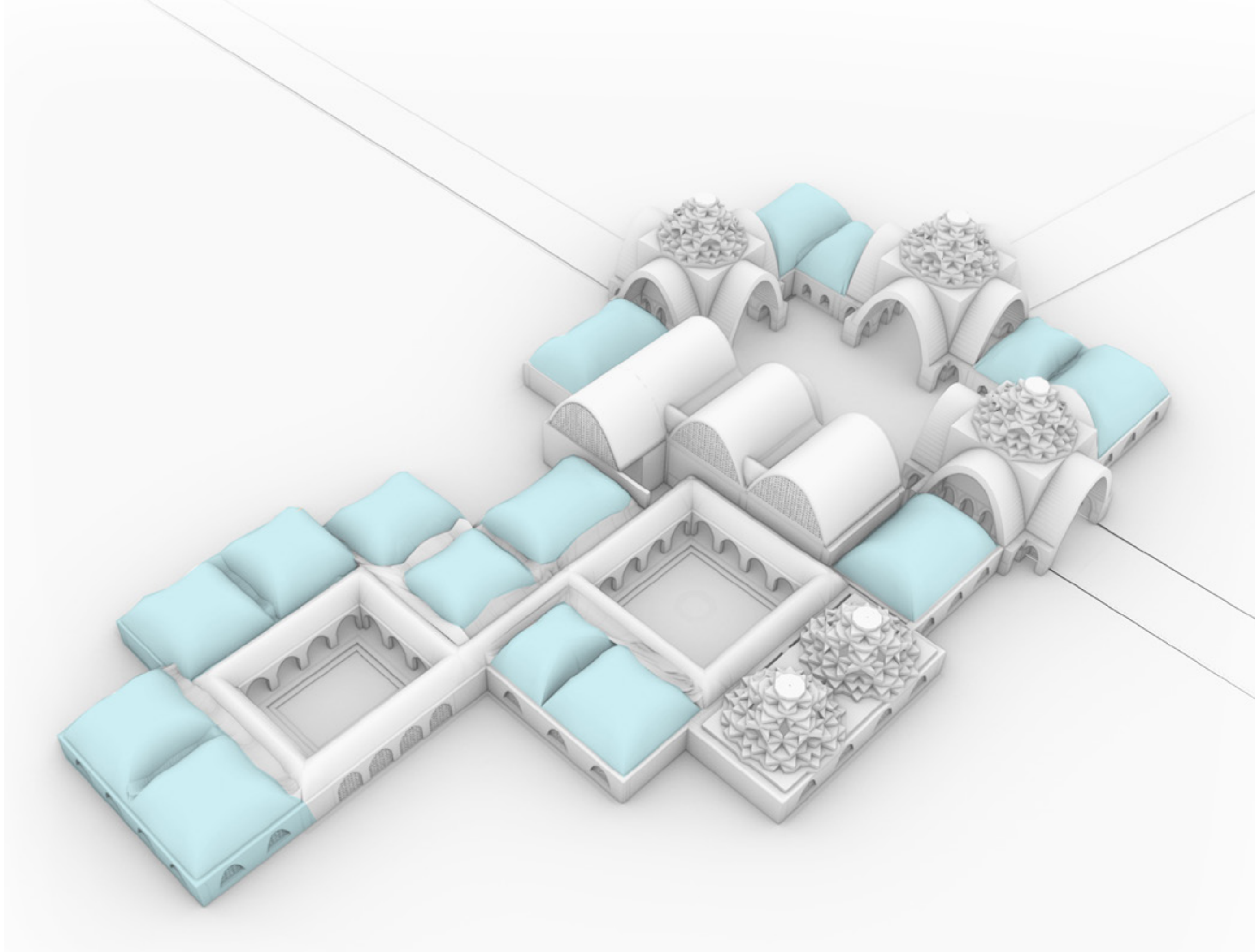
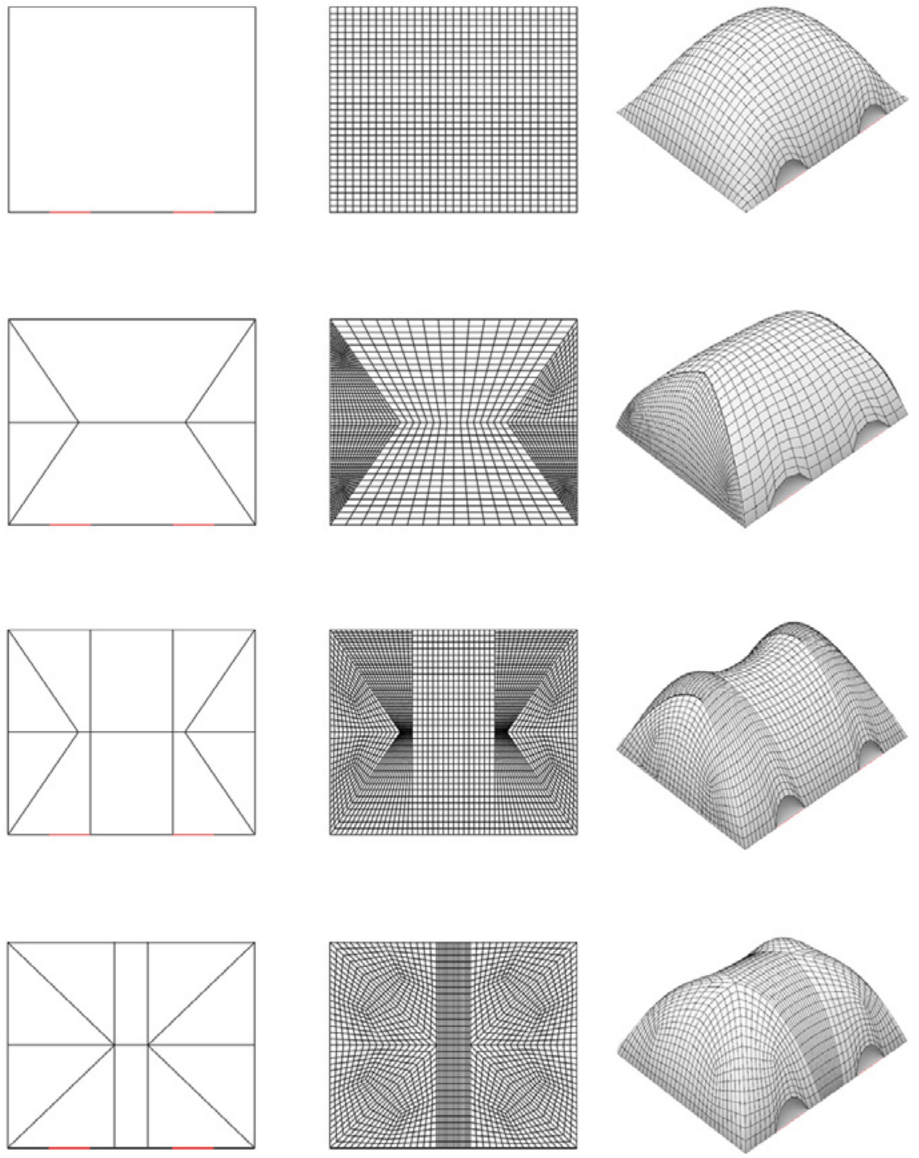


Figure 47 - Ribbed vault roof typology I Source: authors

Forming

For the form-finding process, various tessellation patterns have been explored initially for one of the workshop modules. In the beginning of the process, it was decided to have a 1.5m base wall and then the roof form above it. Thus the tessellation patterns also took openings into account and the anchor points are selected accordingly. The strength of the anchor points and the load values were adjusted several times to achieve a roof form with a clear height of 3m. A step by step tessellation process was carried out to achieve a satisfactory form which is show in the next figure. On achieving a roof form through dynamic relaxation for one of the modules, the tessellation was then applied for more spaces to see the architectural impact of the form as a part of the overall design. The dynamically relaxed form would need to be simplified later for the ease of constructability and structural performance. Hence, the tessellation patterns were explored such that the form becomes more compact and would be easier for further simplification.



Square mesh for checking the heights and the form. The form bends towards the inside from the four corners.

Addition of central ridge and the diagonal lines to avoid the bending of the form inside from the four corners.

Addition of two ridges aligned with the door openings to increase the opening height. However it formed two bumpy surfaces at the top.

Making the form more compact by moving the ridge lines closer. The form generated shows potential for inside space utility and has a proportionate openings as well as height.

Figure 48 - Tessellation exploration I Source: authors

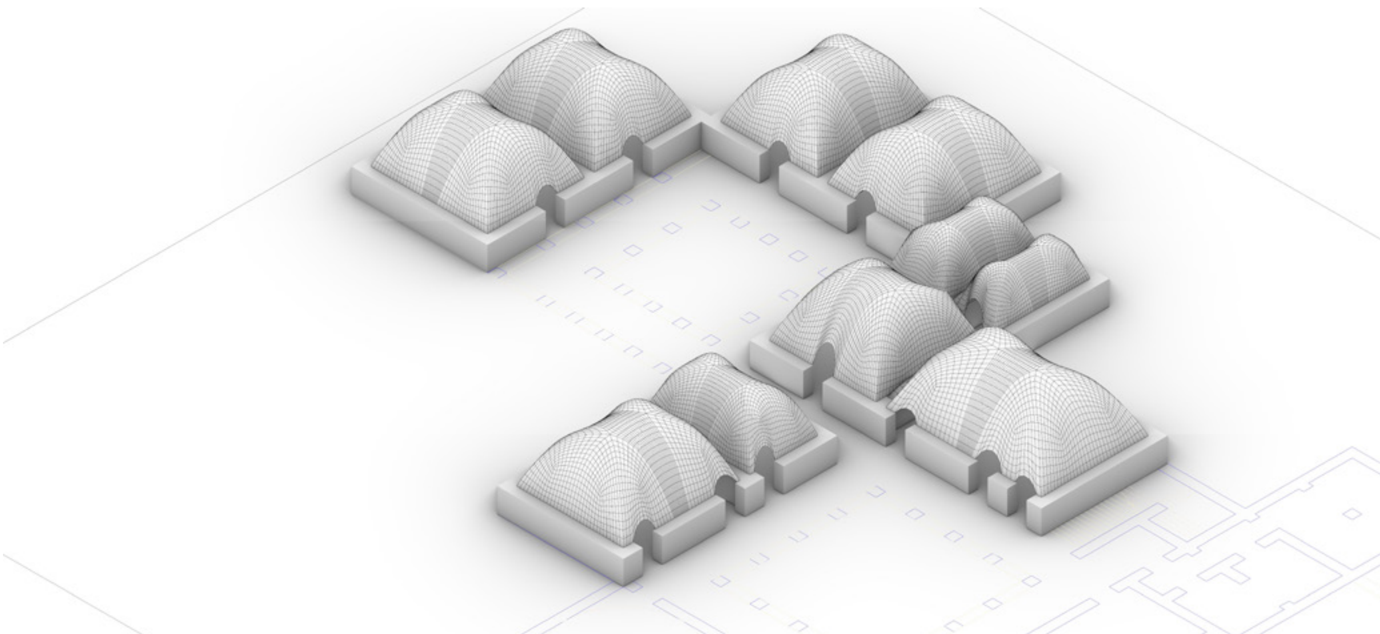
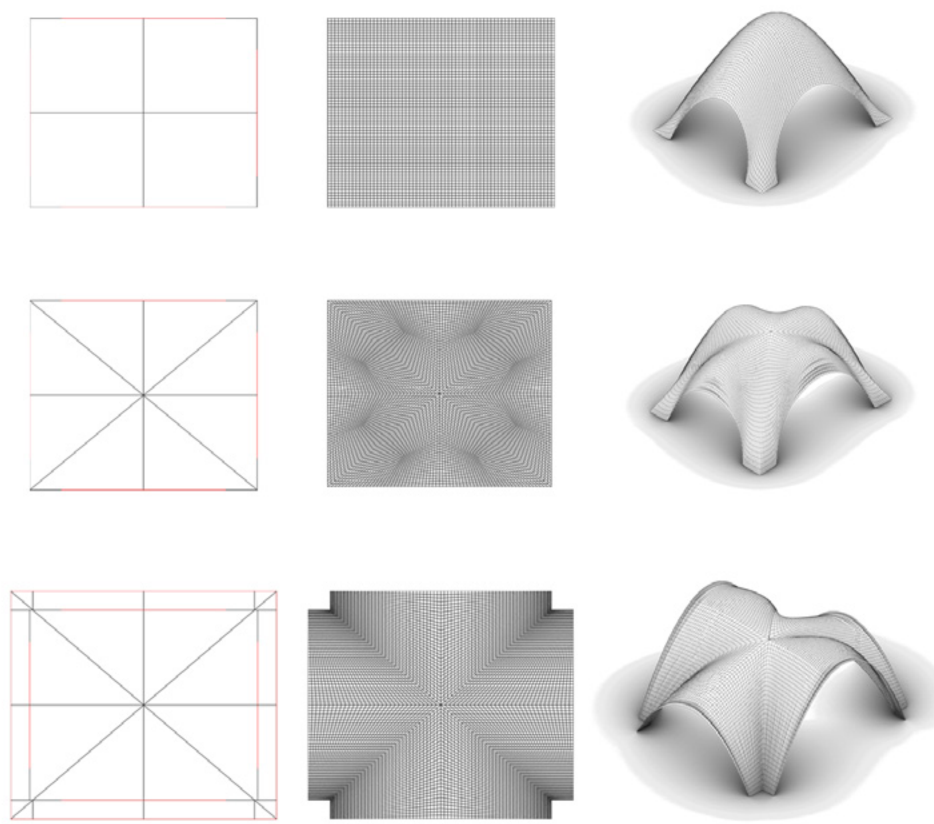


Figure 49 - Dynamically relaxed meshes for ribbed vault typology I Source: authors

While the initial exploration resulted in a form which was aesthetically pleasing and showed good potential for further development, a second exploration process was undertaken to tessellate groin vaults for the roof forms of these spaces. Groin vaults are another ribbed vault typology widely used in the Islamic architecture. After the dynamic relaxation process, groin vault roof form was generated, after which both the roof typologies were compared based on their architectural characteristic as well as potential structural aspects. The Groin vault typology would imply the load transfer to the four corners of the room resulting in very thick corner columns. The initial ribbed vault typology would however distribute loads on the perimeter of the walls resulting in even wall thickness. Moreover, since the construction would be carried out by the people of the camp who might not be skilled to build the form with precision, the first roof typology would be easier to construct. Based on these aspects, it was decided to provide the initial ribbed vault typology for these spaces.



Square mesh for checking the heights and the form. The anchor points are provided at the four corners of the layout. The perpendicular intersection in the tessellation pulls the roof form higher from the centre.

Addition of the diagonal lines lowers the roof height and provides a slight resemblance to the groin vaults.

Cutting the corners of the geometry resulted in the final groin vault roof form.

Figure 50 - Tessellation exploration I Source: authors

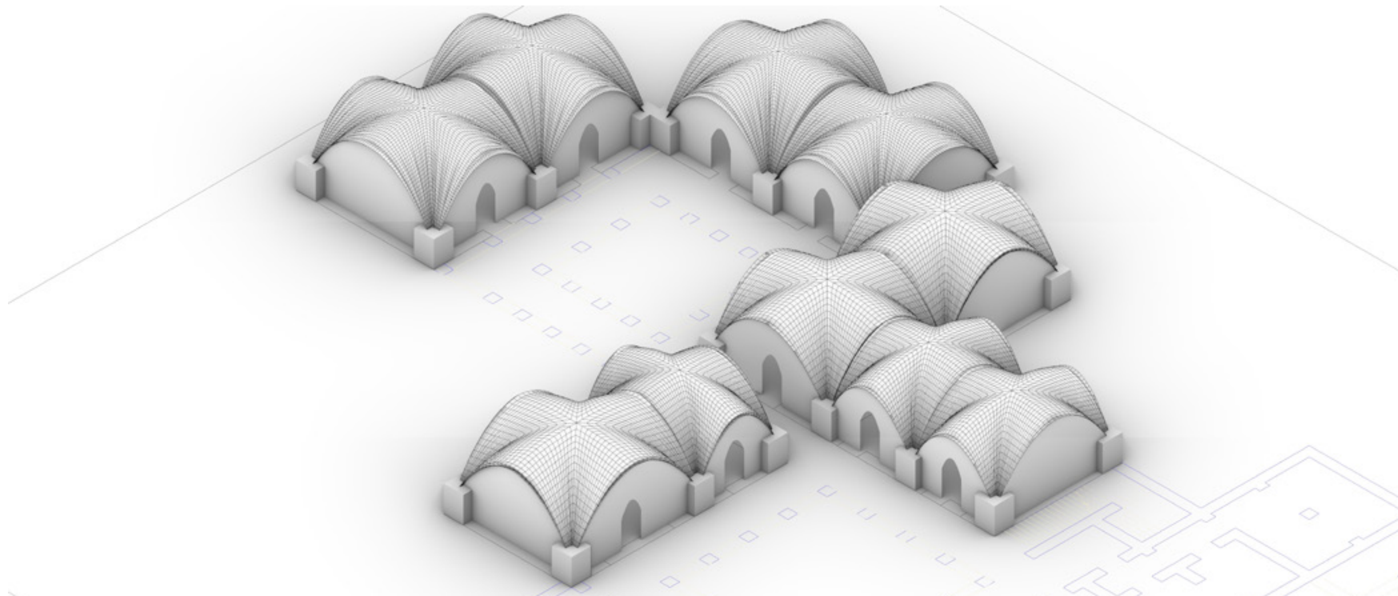


Figure 51 - Dynamically relaxed meshes for groin vault typology I Source: authors

All the spaces are then tessellated and dynamically relaxed to get the final ribbed vault geometries. The walls are decided to be changed from 1.5m to 2.4m so that the connection with Riwaqs is simplified thereby maintaining ease of construction aspects. The final roof forms thus do not have openings cut into them. As shown in the figure above, the dynamically relaxed meshes can be further simplified to have ribs based on the aspects of constructability which is elaborated in chapter 5. For further development, the rooms that have a common interior wall are tessellated and dynamically relaxed together to analyse them together for their structural performance.

Figure 52 - Overview of the ribbed vaults after dynamic relaxation. I Source: authors

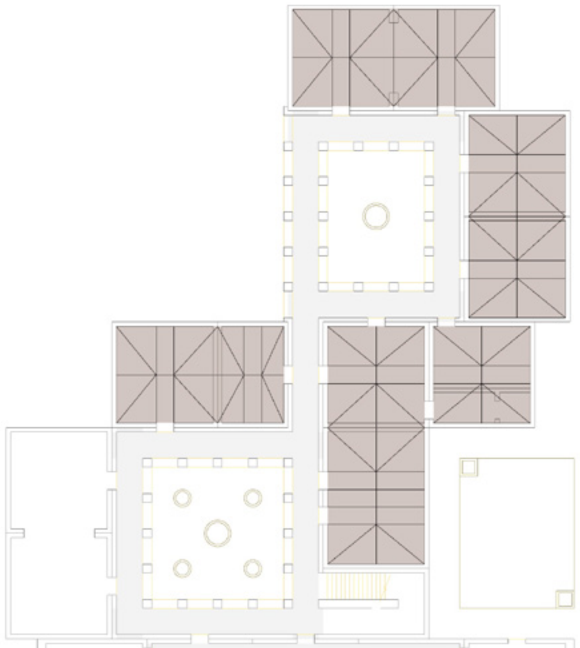


Figure 53 - Tessellation layout I Source: authors

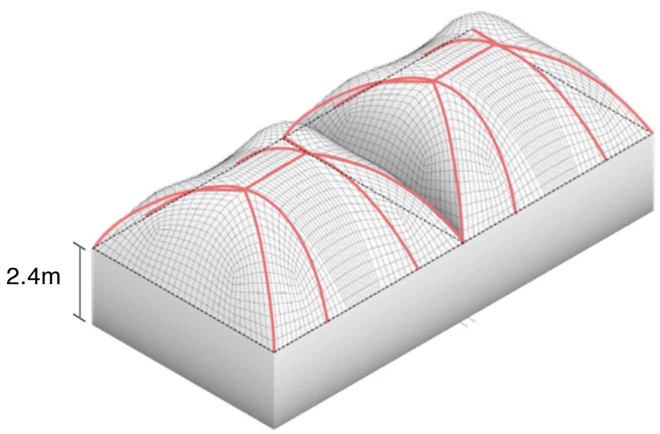


Figure 54 - Ribs highlighted in the roof I Source: authors

Structuring

The final geometries found as a result of the forming process, ware then tested in Karamba 3d for the structural performance and validation. The structural scheme adopted for the analysis is show in the figure and the structural inputs provided are:

Load:
For the load cases, self-weight, filling load and sand load were considered for analysis. The wind load calculated as 0.06 KN/m2 is almost negligible and is thus not considered for calculation. The final load cases after incorporating safety factor of 1.2 are described below:
Filling load of 1.2 kN/m2 applied as mesh loads in karamba with an orientation which is local to the mesh as it affects every point in the mesh system.
Sand load of 1.2 KN/m2 applied as mesh loads with a global direction on karamba.
Self-weight

Supports:
Fixed supports are provided from all directions.

Design values:
Allowable compressive stress- 1.5 MPa
Allowable tensile stress- 0.15 MPa
Allowable deflection- span/400- 6600/400- 16.5 mm

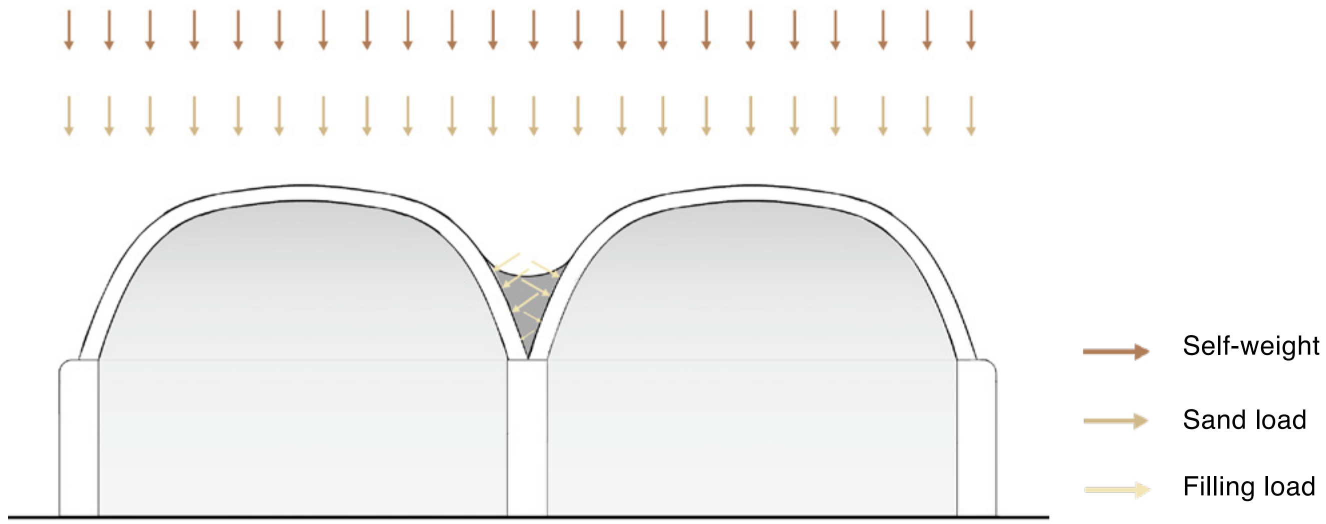


Figure 55 - Input for Structural analysis I Source: authors

VALIDATION OF COMPUTATIONAL MODEL

The computational model done for one of the roof modules was verified with hand calculation so that the results are reliable. With the inputs mentioned earlier, the dynamically relaxed mesh was analysed in Karamba.

Hand calculation-
Specific weight = 15 KN/m3
Young's modulus = 80 MPa
Surface area of the mesh= 68.055 m2
Shell thickness= 0.3m
Reaction force= 68.055 x 0.3 x 15 = 306.25 KN
Reaction force calculated in Karamba model= 306.21 KN
Hence, the model gives reliable results.

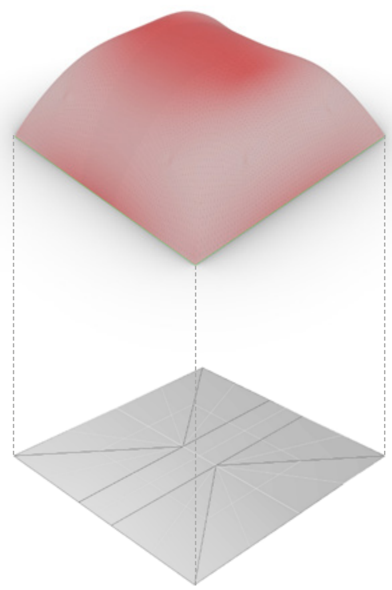


Figure 56 - Karamba analysis for one roof I Source: authors

STRUCTURAL ANALYSIS PROCESS

The ribbed vaults roof are provided over the spaces with three different room dimensions as shown in the figure. Hence, we have three different modules with different spans. As the rooms share the common interior wall, it is important to analyse those geometries together. Therefore as highlighted in the figure, the following modules are analysed for structural performance on Karamba:

- Workshop- store
- Workshop-workshop
- Workshop- exhibition

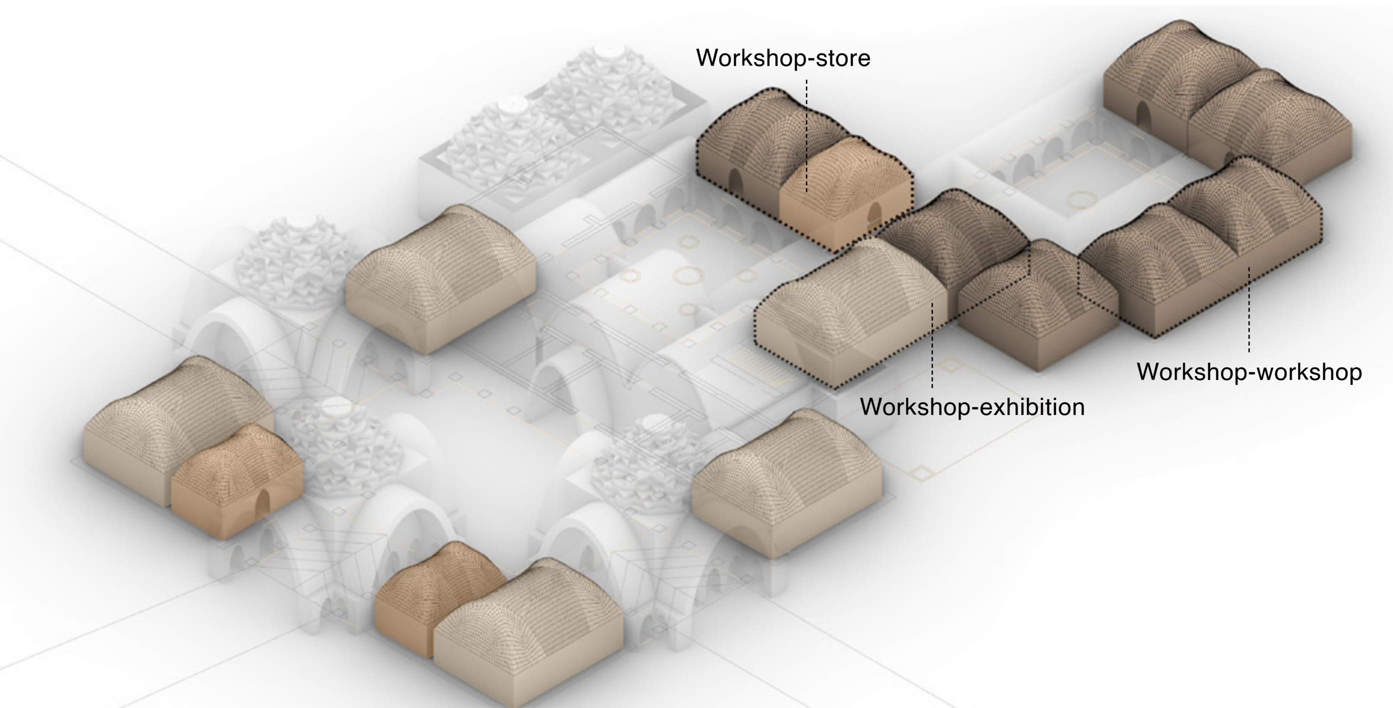


Figure 57 - Classification of the roofs based on spans I Source: authors

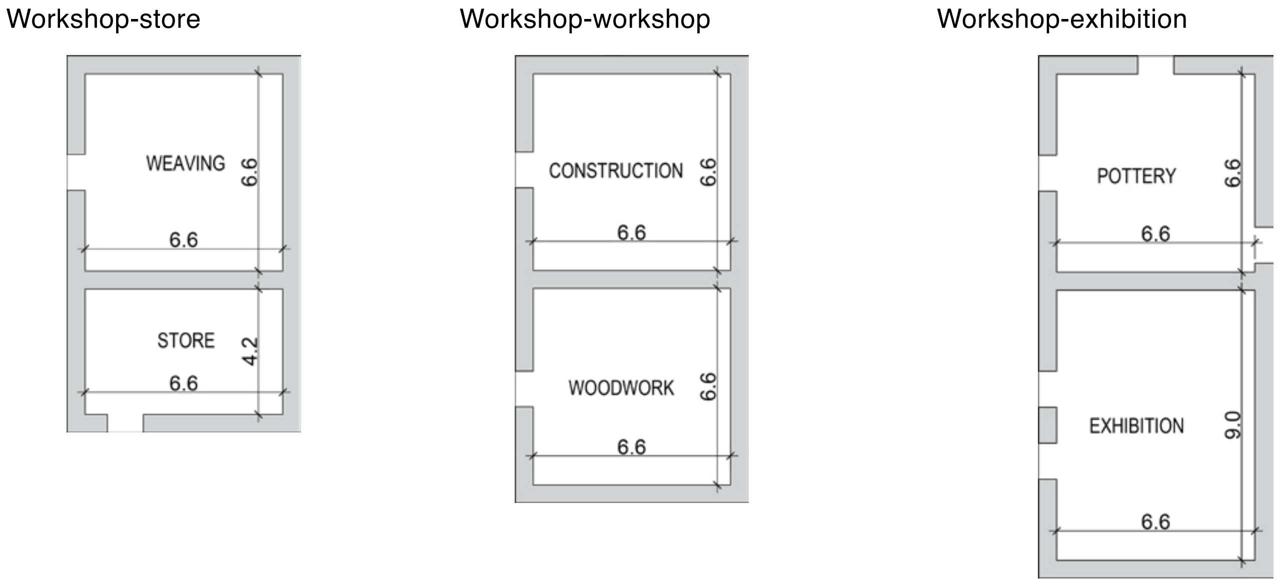


Figure 58 - Dimensions of the different room configurations. I Source: authors

WORKSHOP-STORE MODULE

The analysis was first carried out for the workshop-store module after applying the load and support conditions as described earlier. The finite element analysis showed that the structure was stable with a wall thickness of 0.6m and roof thickness of 0.3m. The steps taken to perform the analysis is described below.

Step 01: The walls of height 2.4m and with door openings of height 2.1m are added below the dynamically relaxed mesh. The wall surfaces are tessellated in accordance with the roof mesh. The walls and roof of 0.3 m thickness are then analysed. The analysis showed peak tensile stresses of 0.283 MPa near the door openings which are higher than allowable values. This is due to the fact that due to denser mesh at the centre, higher load transfer occurs at the top of door openings.

Step 02: The door openings are shifted to the sides and the analysis is performed again. The peak tensile stresses reduced from 0.283 MPa to 0.243 MPa and it can be seen that the opening closer to the shared interior wall has less tensile stress values as the wall is in compression at that region.

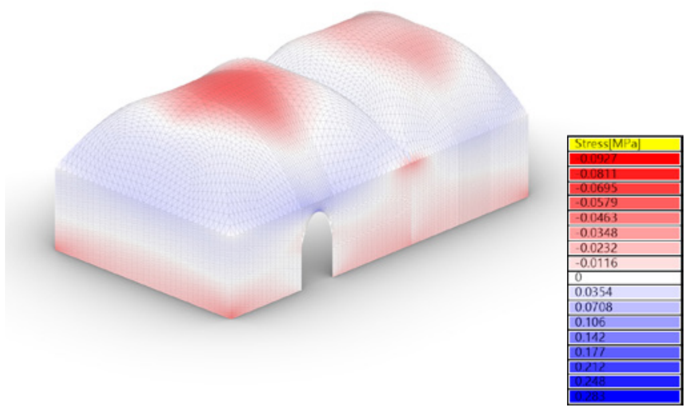


Figure 59 - Principle stress values for step 01I Source: authors

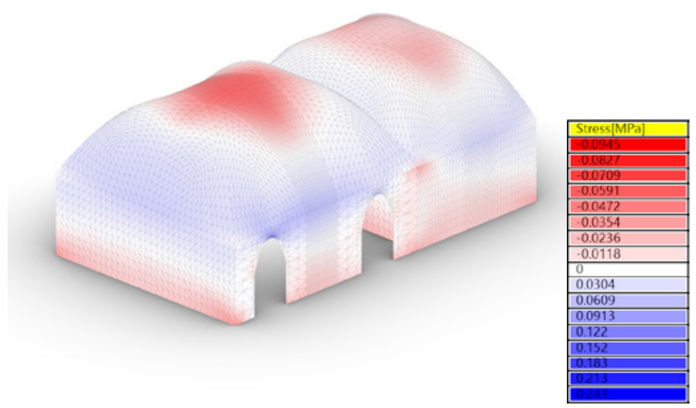


Figure 60 - Principle stress values for step 02I Source: authors

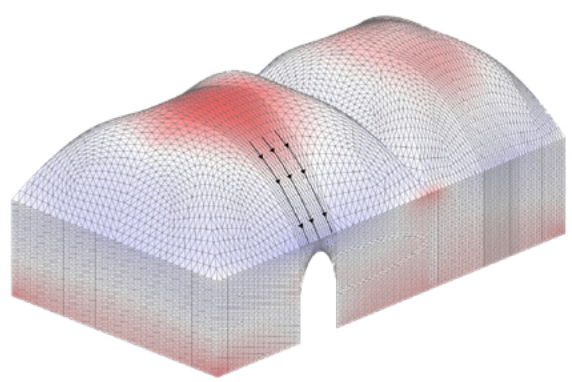


Figure 61 - Load transfer at the centre. I Source: authors

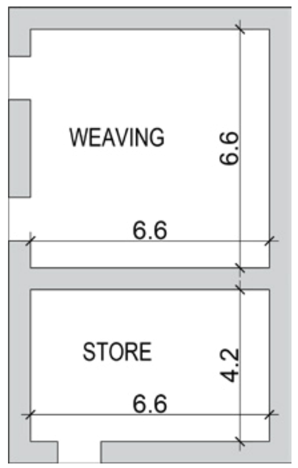


Figure 62 - Changing door placement. I Source: authors

Step 03: The geometry is then analysed with different wall and roof thickness combinations to achieve the safe and stable structure. The higher tensile stresses values at the junction of the roof and wall is due to a slight outward thrust of the roof which is resolved by having thicker walls so that the force transfer vertically and the tensile stresses are under the allowable range. The structure is stable with a wall thickness of 0.6m and roof thickness of 0.3m. The maximum displacement value is 5.71mm which is under the allowable range (6600/400= 16.5mm). The highest tensile stress is 0.13 MPa at the top of the door openings (denser mesh) and at the junction of the roof and the wall.

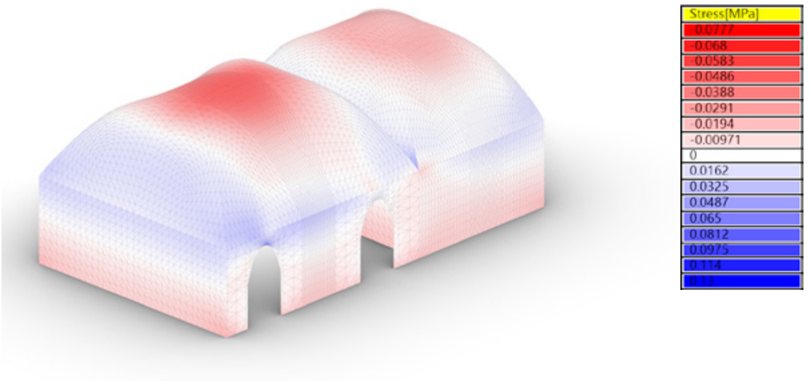


Figure 63 - Principal stress 1 values. I Source: authors

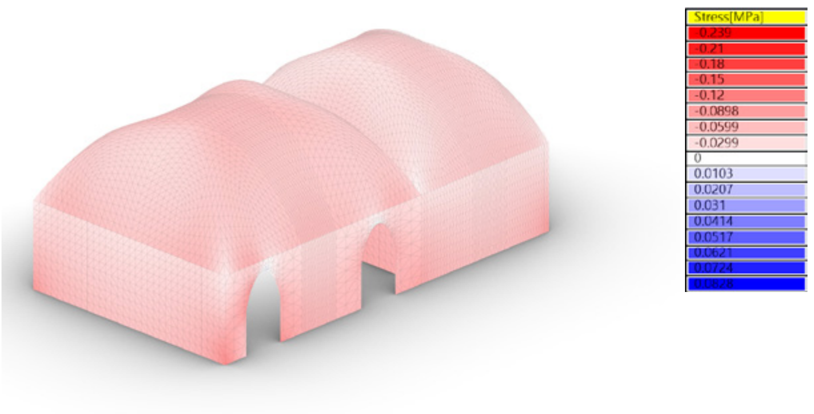


Figure 64 - Principal stress 2 values. I Source: authors

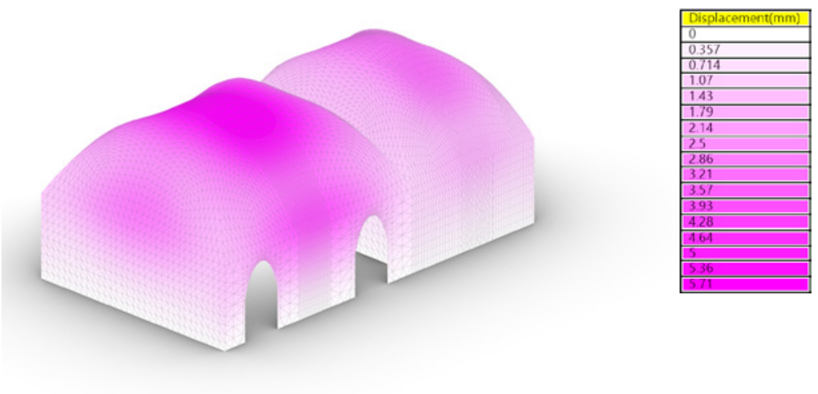


Figure 65 - Deflection values. I Source: authors

Workshop-store module					
Type	Units	Step- 01 0.3m walls and roof	Step- 02 0.3 walls and roof with changing doors	Step- 03 a 0.45m walls and 0.3m roof	Step- 03 b 0.6m walls and 0.3m roof
Max displacement	mm	7.9	8.1	6.6	5.71
Peak compressive stress 1	MPa	0.0927	0.0945	0.0836	0.077
Peak tensile stress 1	MPa	0.283	0.243	0.169	0.13
Peak compressive stress 2	MPa	0.316	0.31	0.252	0.239
Peak tensile stress 2	MPa	0.129	0.133	0.107	0.0828

Figure 66 - Results for the different steps. I Source: authors

WORKSHOP-WORKSHOP MODULE

This module type has same span for both the rooms and thus the force exerted towards outside is also same. This case is thus simpler than the previous one. Based on the previous conclusion regarding the opening placement, the doors are shifted at the two sides for both the rooms and the analysis is then performed after applying the load cases, material inputs and support points as described earlier. The finite element analysis showed that the structure was stable with a wall thickness of 0.6m and roof thickness of 0.3m. The peak tensile stress of 0.134 MPa is again observed at the top of the door opening towards the outer end which is under the allowable limits. The maximum displacement value is only 5.68mm.

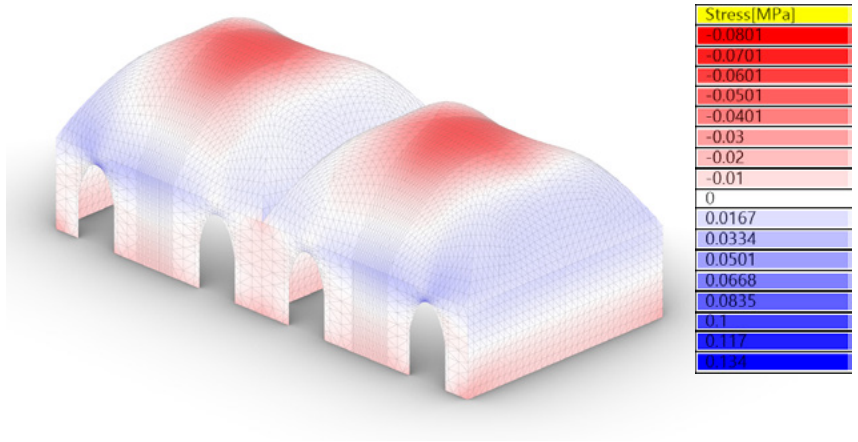


Figure 67 - Principal stress 1 values. I Source: authors

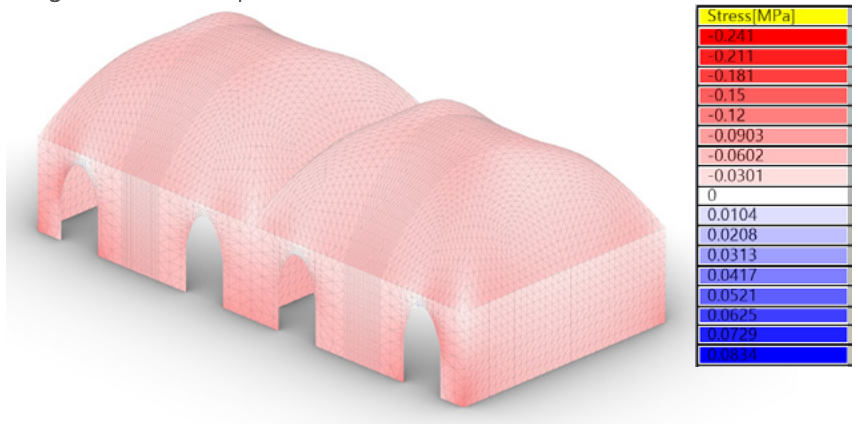


Figure 68 - Principal stress 2 values. I Source: authors

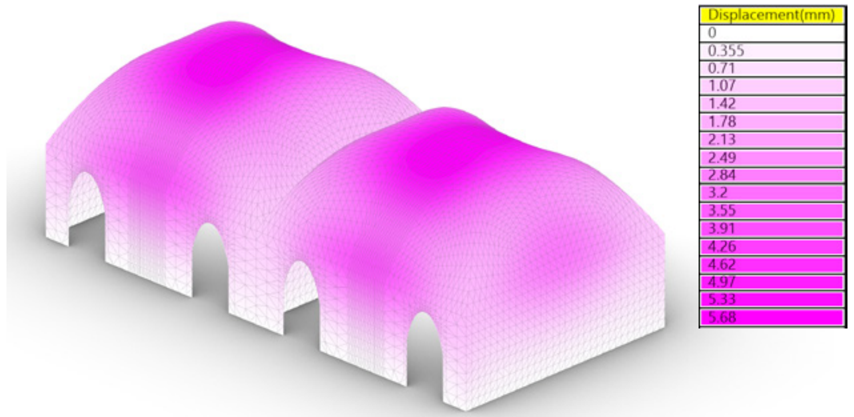


Figure 69 - Deflection values. I Source: authors

Workshop-workshop module				
Values	Units	Step01- 0.3m walls and roof	Step02- 0.45m walls and 0.3m roof	Step03- 0.6m walls and 0.3m roof
Max displacement	mm	8.1	6.58	5.68
Peak compressive stress 1	MPa	0.0963	0.0871	0.0801
Peak tensile stress 1	MPa	0.249	0.174	0.134
Peak compressive stress 2	MPa	0.322	0.254	0.241
Peak tensile stress 2	MPa	0.133	0.107	0.0834

Figure 70 - Results for the different steps. I Source: authors

W O R K S H O P - E X H I B I T I O N
MODULE

This module type has higher span for exhibition and lower span for the workshop. Thus the force exerted towards outside is higher for the exhibition. This suggests a need of thicker wall to keep the structure stable. The finite element analysis showed that the structure was stable with a wall thickness of 0.6m and roof thickness of 0.3m.

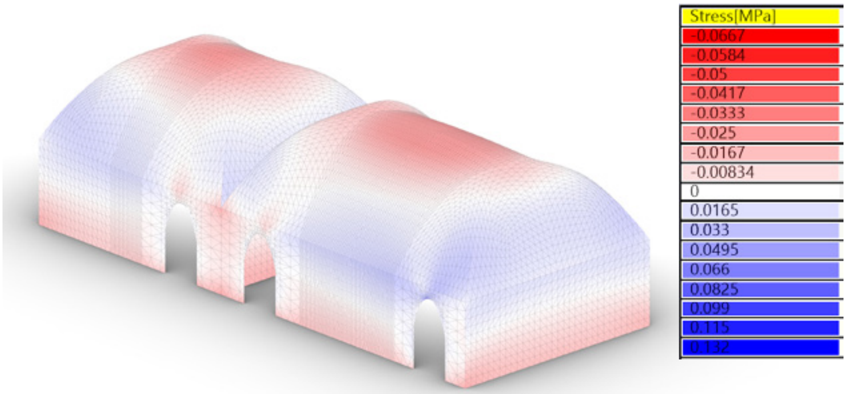


Figure 71 - Principal stress 1 values. I Source: authors

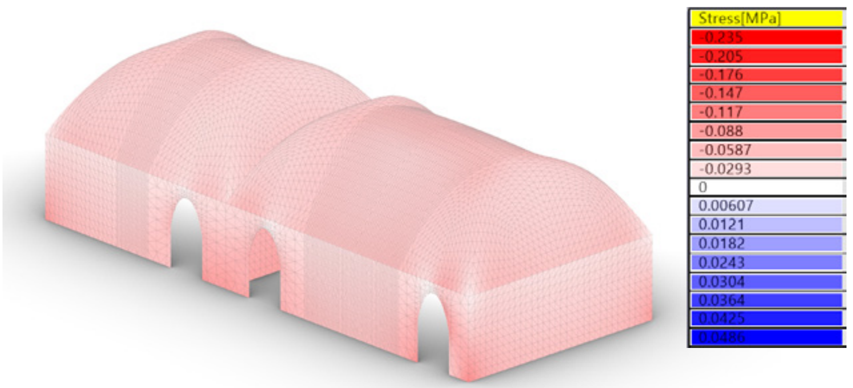


Figure 72 - Principal stress 2 values. I Source: authors

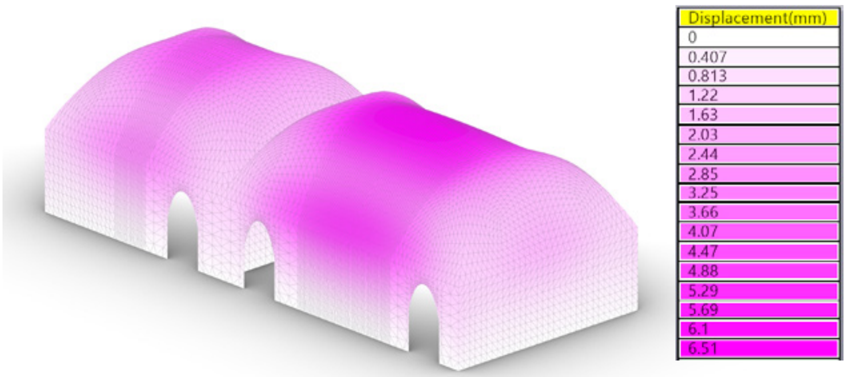


Figure 73 - Deflection values. I Source: authors

Workshop-exhibition module				
Values	Units	Step01- 0.3m walls and roof	Step02- 0.45m walls and 0.3m roof	Step03- 0.6m walls and 0.3m roof
Max displacement	mm	9.69	7.81	6.51
Peak compressive stress 1	MPa	0.0822	0.075	0.0667
Peak tensile stress 1	MPa	0.245	0.165	0.132
Peak compressive stress 2	MPa	0.312	0.257	0.235
Peak tensile stress 2	MPa	0.106	0.0738	0.0486

Figure 74 - Results for the different steps. I Source: authors

4.2.2 NUBIAN VAULT DOUBLE STOREY

The double storey building houses the main entrance, offices, toilets, childcare and kitchen on the ground floor while the library, conference centre and al aghabani workshop are located on the top floor. The unit is characterized by two different modules, the one on the ground floor and the one on the first floor. The rooms in this section of the building were decided to be roofed under two sided vaults.

4.2.2.1 Ground floor

Figure 76 - Ground floor vault I Source: Own authors

Forming

For the form-finding process, the tessellation is kept very simple. A 2.4m base is used as a consideration with the first variation of the roof form placed above it. The first step in order to define the form of this roof is to determine the direction in which the vault will span. The decision for this is made based on both architectural as well as structural purposes. The wider the span, the thicker the walls as the force exerted is larger. This is shown in the image.

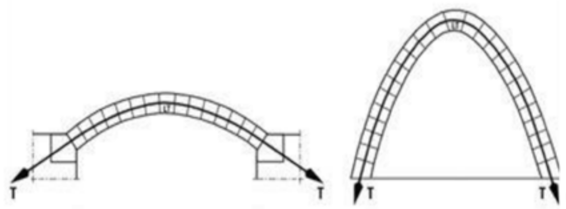


Figure 75 - Nubian vault typology I Source: authors

The mesh surfaces of the different shaped rooms were first generated and these were then imported into grasshopper. In order to provide a straightforward geometry of a vault, the tessellation was that of a regular grid. Anchors were provided along the longer side of the room and appropriate loads were applied before the dynamic relaxation. The load value was adjusted in order to accommodate for A clear height of at least 3.6 meter at the highest point in order to ensure reasonable head space.

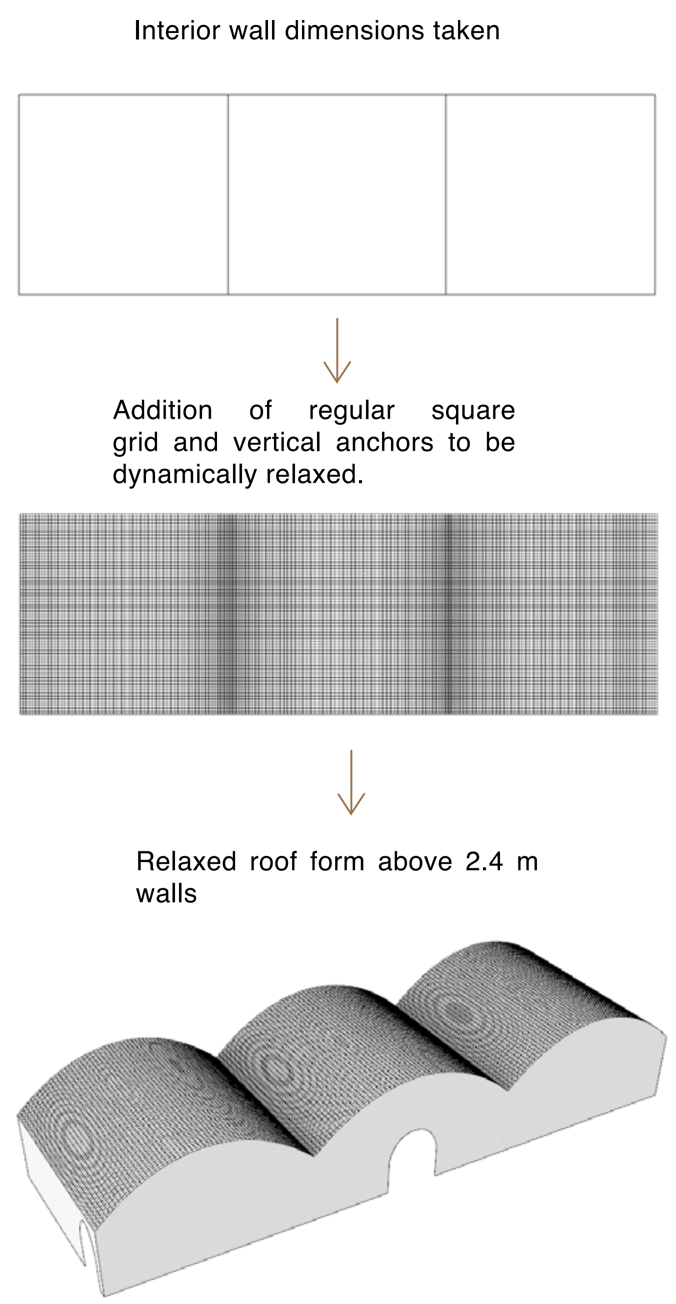


Figure 77 - Catenary nubian vault tessellation explanation I Source: authors

Structuring

In order to validate the structures generated from the forming process, the relaxed geometry was tested in Karamba 3d for the structural performance and validation. The structural scheme adopted for the analysis is show in the figure and the structural inputs provided are:

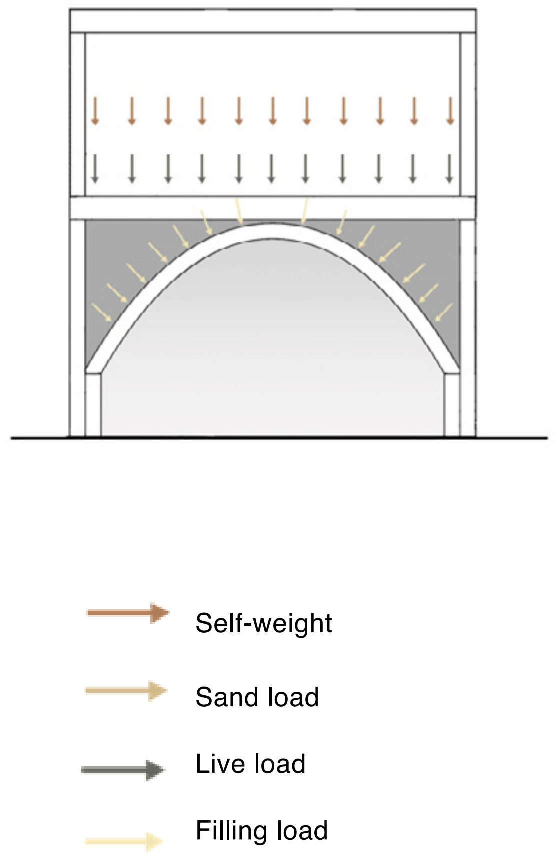


Figure 78 - Ground floor vault load cases I Source: Own authors

Load:

For the load cases, self-weight, filling load sand load and live load were considered for analysis. Where the live load of the first floor was considered as 4kN/m2 (Malakatas, 2008) The slab load with a thickness of 0.45m is used. This is calculated as
0.450 x 1 x 1500 = 675 kg which is equivalent to 6.62 kN. The value taken is 6.62kN/m2 .

Sand load is taken at 1kN/m2. These are applied as mesh loads with a global direction on karamba.
The filling load is taken as 1kN/m2. (Malakatas, 2008). These were applied as mesh loads in karamba with an orientation which is local to the mesh as it affects every point in the mesh system. A safety value of 1.5 was applied for the live loads, and a safety factor of 1.2 was applied for the dead loads.

Design Values:

Allowable compressive Stress – 1.5MPa
Allowable Tensile Stress – 1/10 Compressive Stress – 0.15 MPa
Allowable Deflection – Span/400 – L/400 - 6600/400 – 16.5mm
Young's Modulus - 150 MPa

First configuration

The initial configuration shows high tensile stresses even with increased wall thicknesses and even when buttresses were included. This is as a result of the thrust experienced along the other side of the structure. The tensile stresses of 0.946 is above the allowable stress of 0.15 therefore it is not suitable.

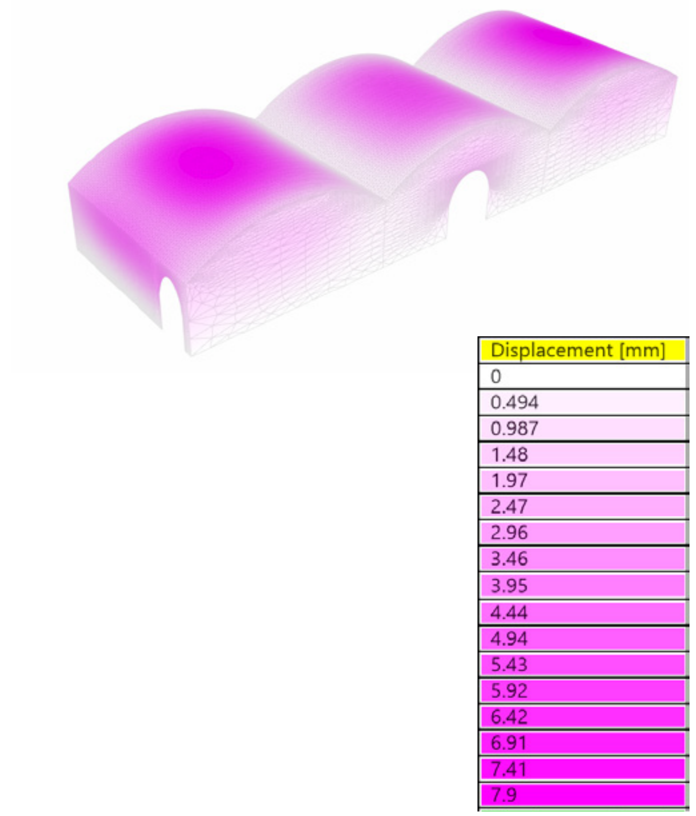


Figure 81 - Deflection values. I Source: authors

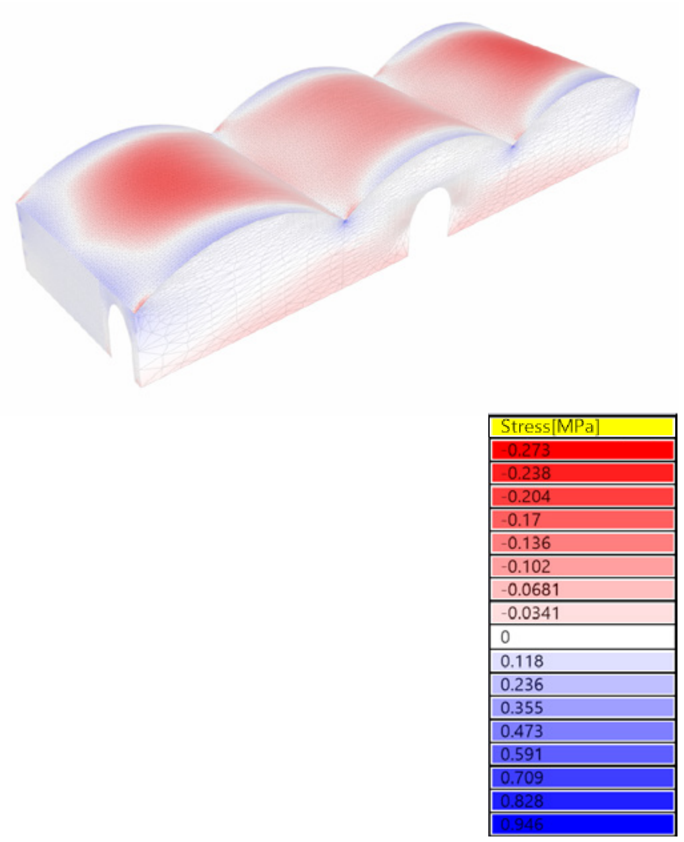


Figure 79 - Principal stress 1 values. I Source: authors

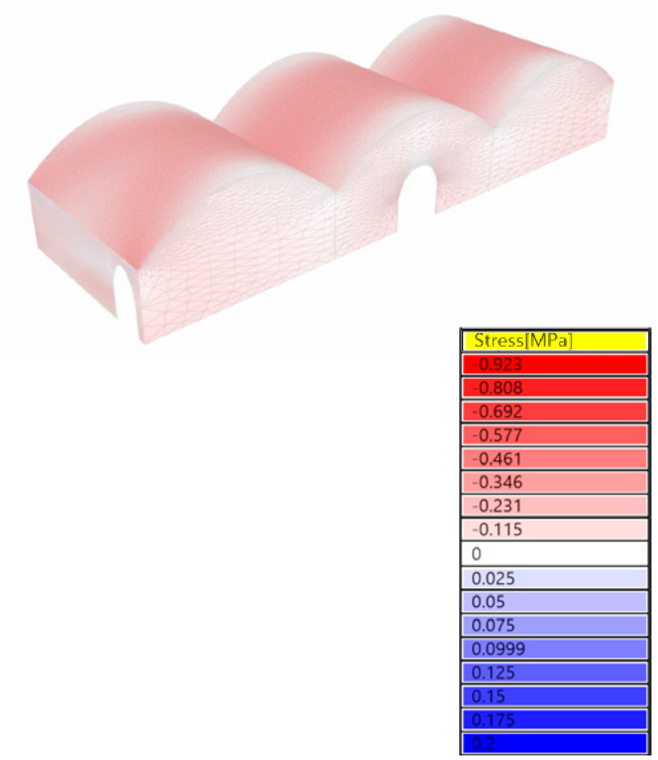


Figure 80 - Principal stress 2 values. I Source: authors

Second configuration

In order to keep the design relatively the same in terms of spatial quality, the barrels are turned along the other direction and a shorter wall of 1.2m is used. This form is tesselated and relaxed in the method described earlier. In this configuration, the walls in the middle become load bearing and the entire length is divided into three modules of the same proportions. One module is first used for analysis.

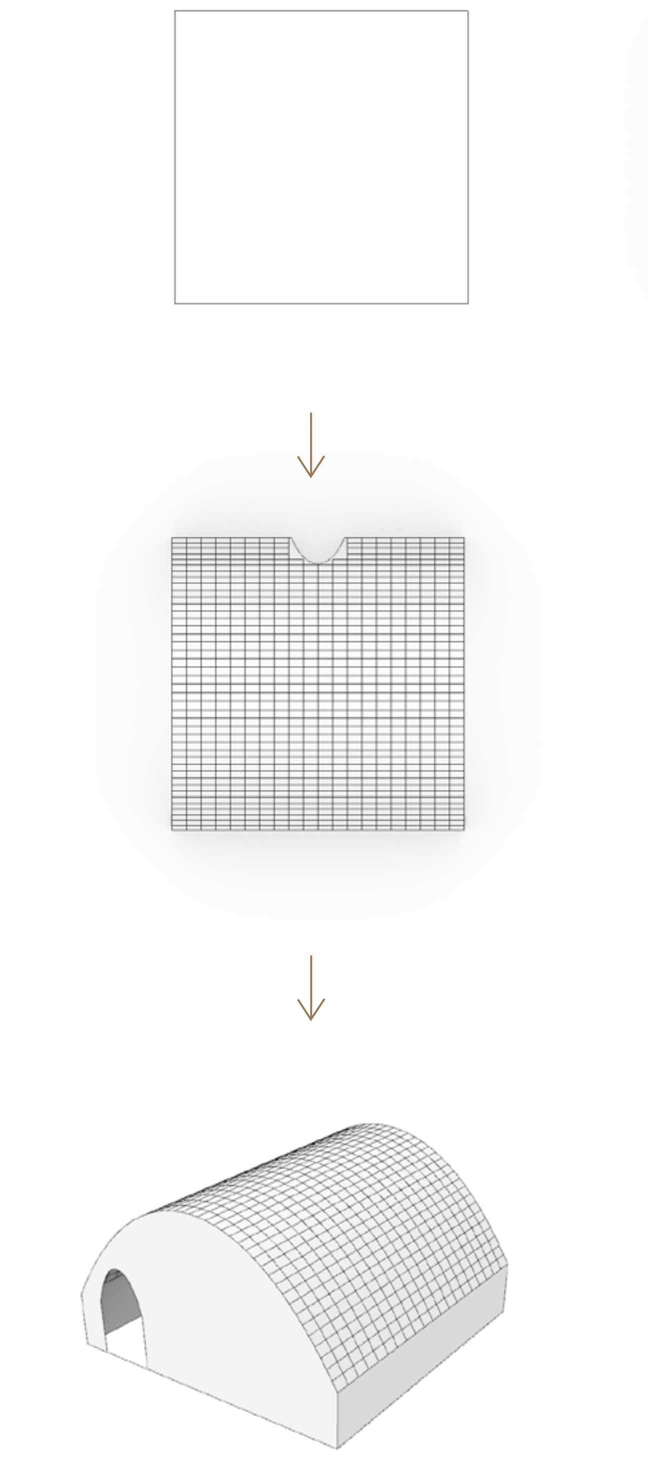


Figure 82 - Second variation of catenary nubian vault tessellation I Source: authors

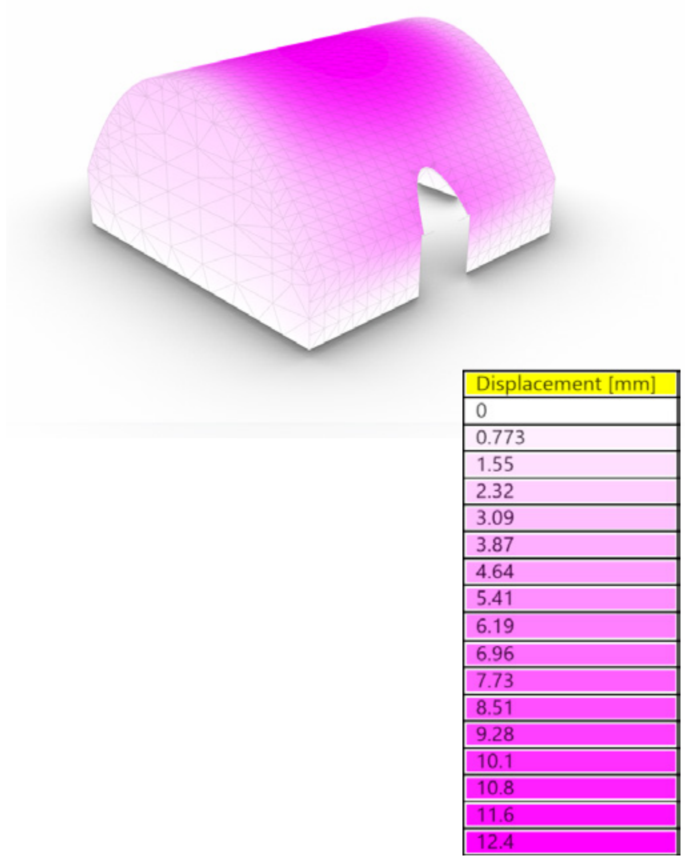


Figure 83 - Deflection values. I Source: authors

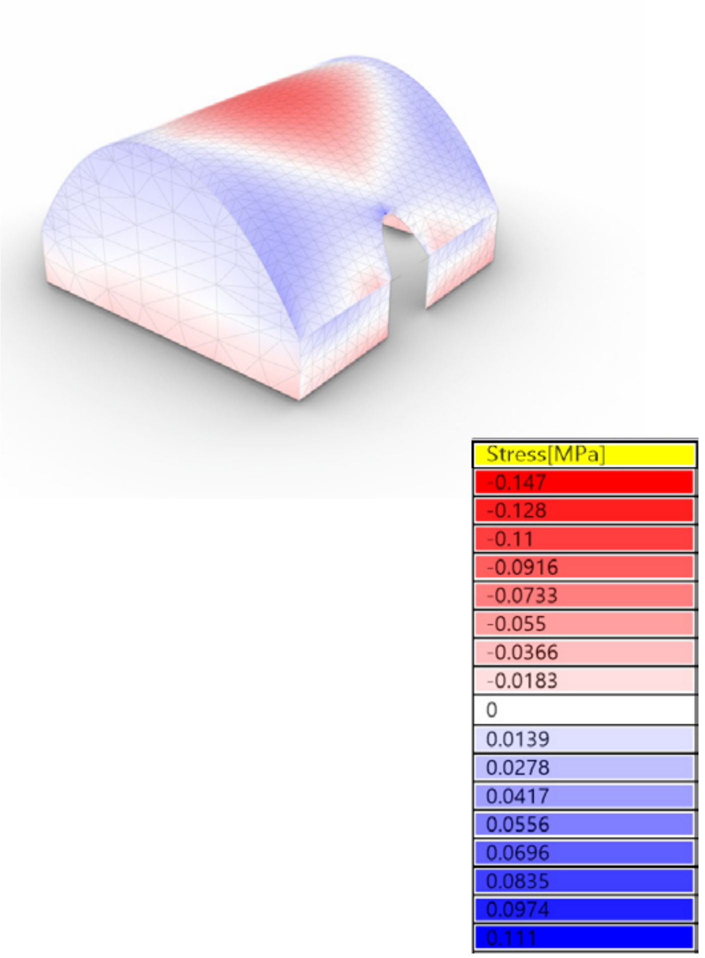


Figure 84 - Principal stress 1 values. I Source: authors

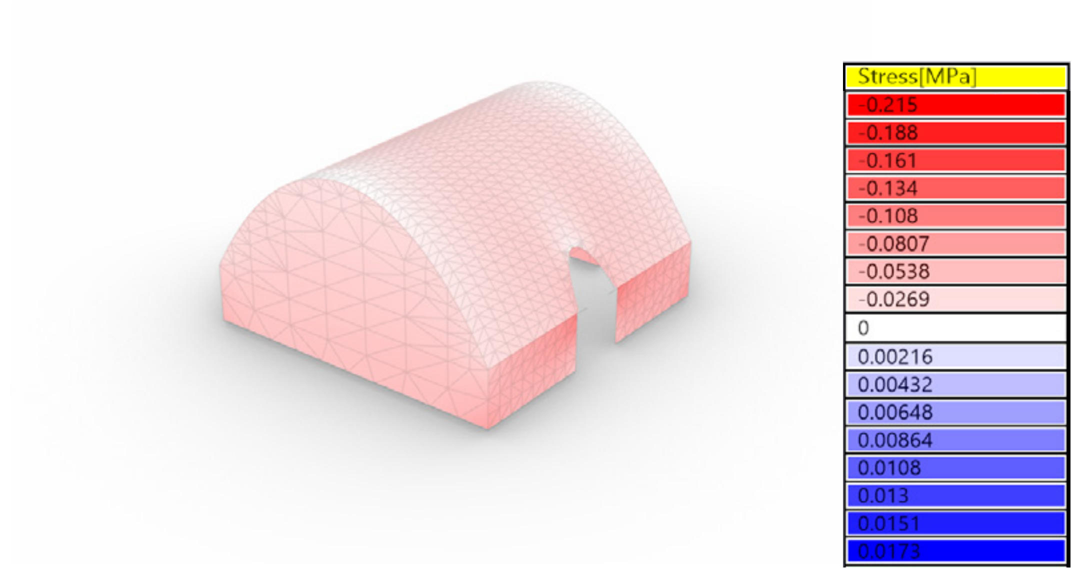


Figure 85 - Principal stress 2 values. I Source: authors

Ground floor module second trial						
Type	Units	Step- 01 0.15m walls and roof	Step- 02 0.3m walls and roof	Step- 03 0.45m walls and roof	Step- 04 0.45m walls 0.3m and roof	Step- 05 0.60m walls 0.30m roof
Max displacement	mm	48.10	18.50	11.60	14.60	4.05
Peak compressive stress 1	MPa	1.150	0.461	0.152	0.174	0.147
Peak tensile stress 1	MPa	0.373	0.203	0.199	0.145	0.111
Peak compressive stress 2	MPa	2.060	0.992	0.674	0.889	0.215
Peak tensile stress 2	MPa	0.012	0.018	0.001	0.017	0.017

Figure 86 - Results for the different steps. I Source: authors

The results show that the structure is stable with a wall thickness of 0.6m or 0.45m and a roof thickness of 0.3m. The peak tensile and compressive stresses of 0.111 and 0.147MPa are below the allowable tensile stresses therefore it is suitable.
In order to ensure that the entire module is stable, the three modules are analysed.
These are placed side by side with separating walls on the inside as shown in the image.

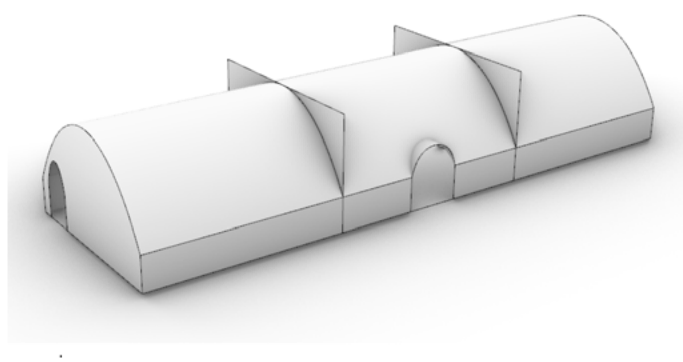


Figure 87 - Second configuration I Source: authors

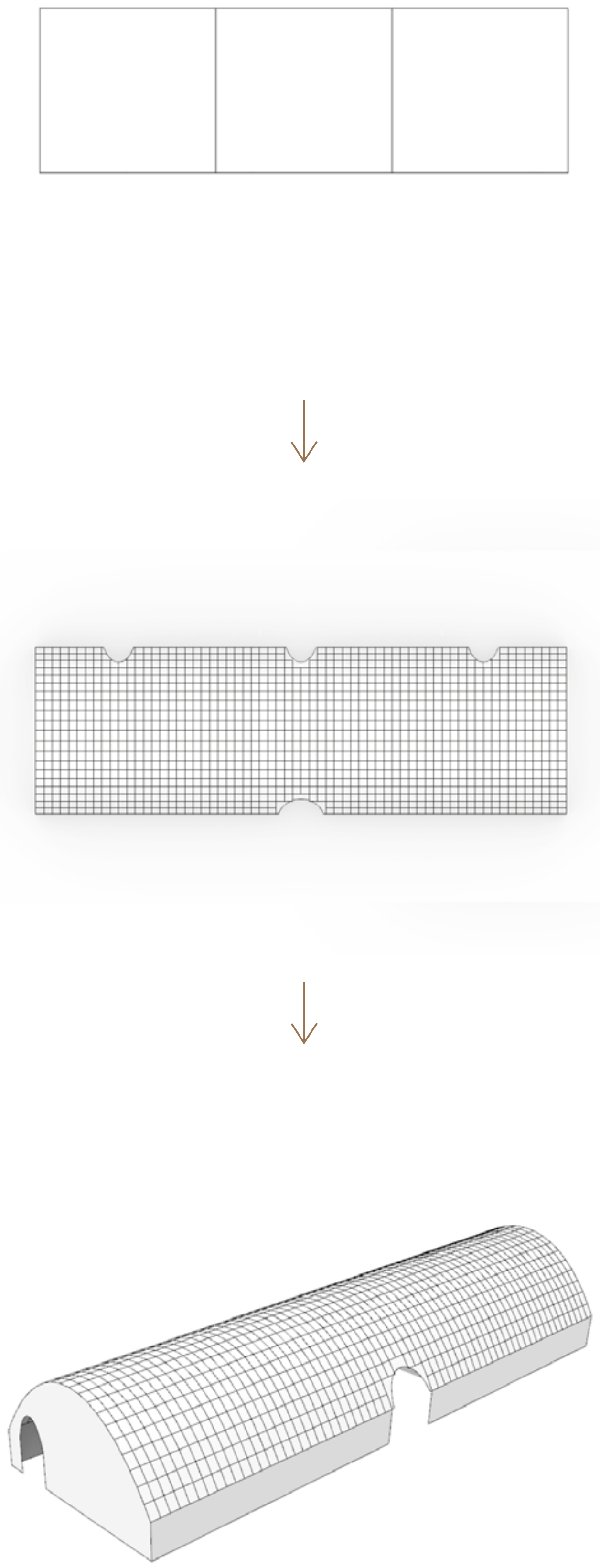


Figure 88 - Third variation of catenary nubian vault tessellation I Source: authors

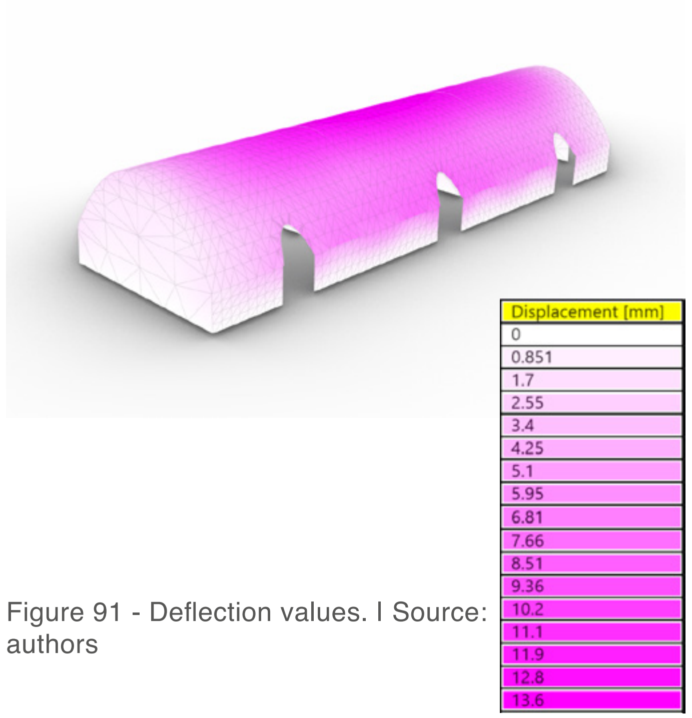


Figure 91 - Deflection values. I Source: authors

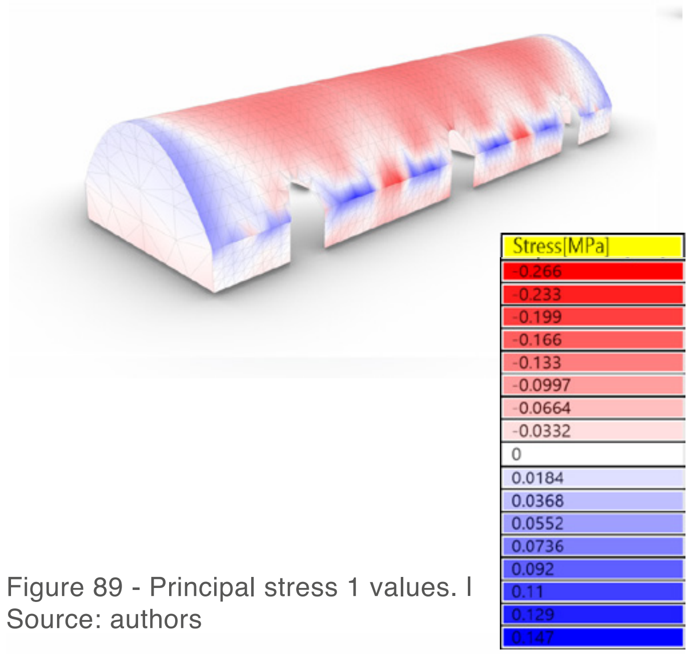


Figure 89 - Principal stress 1 values. I Source: authors

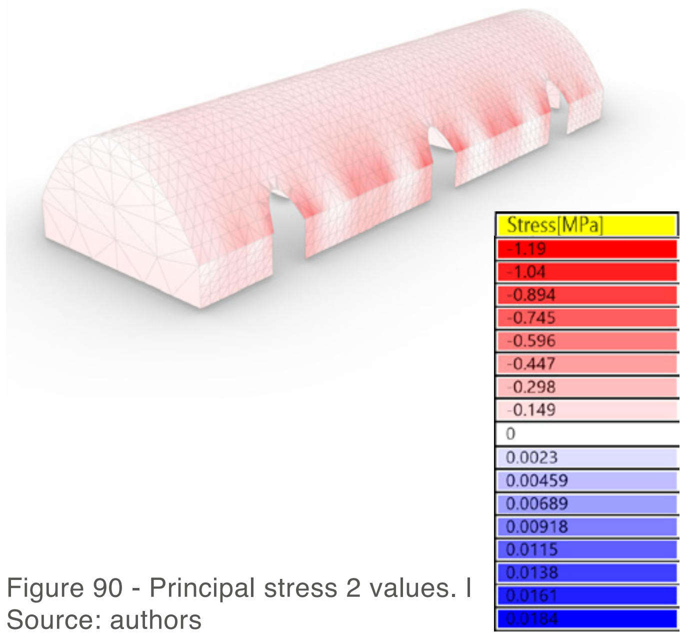


Figure 90 - Principal stress 2 values. I Source: authors

Ground floor module final configuration						
Type	Units	Step- 01 0.15m walls and roof	Step- 02 0.3m walls and roof	Step- 03 0.45m walls and roof	Step- 04 0.45m walls 0.3m and roof	Step- 05 0.60m walls 0.3m roof
Max displacement	mm	324.00	71.00	31.00	43.50	13.60
Peak compressive stress 1	MPa	0.464	0.865	0.223	0.257	0.266
Peak tensile stress 1	MPa	1.780	1.470	0.224	0.218	0.147
Peak compressive stress 2	MPa	2.250	2.080	0.86	0.980	1.190
Peak tensile stress 2	MPa	0.364	0.023	0.026	0.079	0.018

Figure 93 - Results for the different steps. I Source: authors

This configuration shows that the interior walls have to be at least 0.6m for it to be structurally stable. This gives peak compressive tensile stress of 0.147MPa and a peak compressive stress of 0.266MPa and a 13.60mm displacement which are below the allowable values. Therefore the final configuration is 0.6m thick walls and 0.3m roof is used for the final ground floor structure.

4.2.2.2 First floor

Forming

For the form-finding process, the tessellation is kept very simple similar to the ground floor. However in this case, the nubian vault starts from the floor. This is because there is a looser constraint on the height as compared to the ground floor. Furthermore, nubian catenary vaults are theoretically already structurally stable when they begin from the ground, have similar widths and are not too shallow in height.

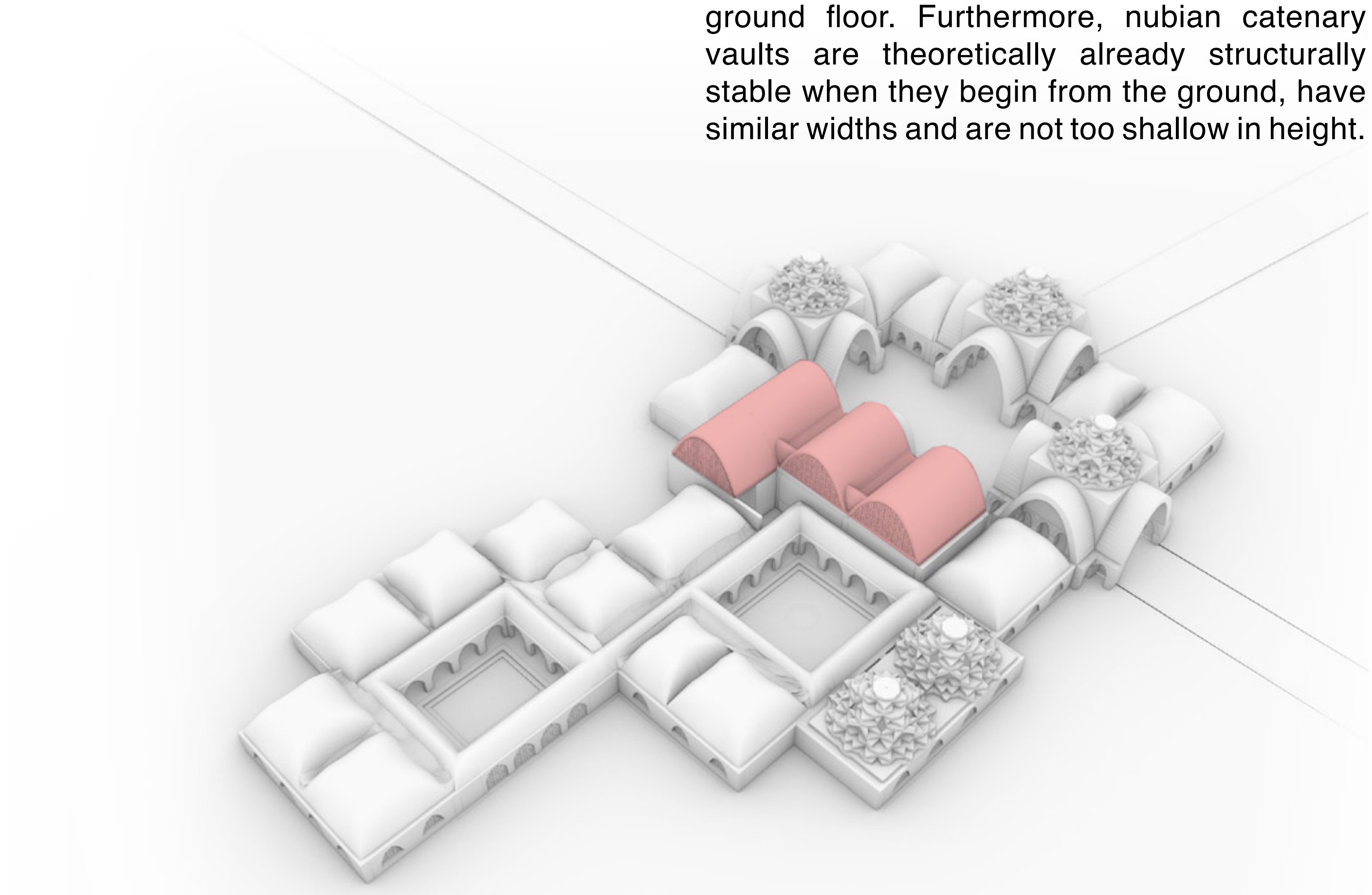


Figure 92 - First floor vault I Source: Own authors

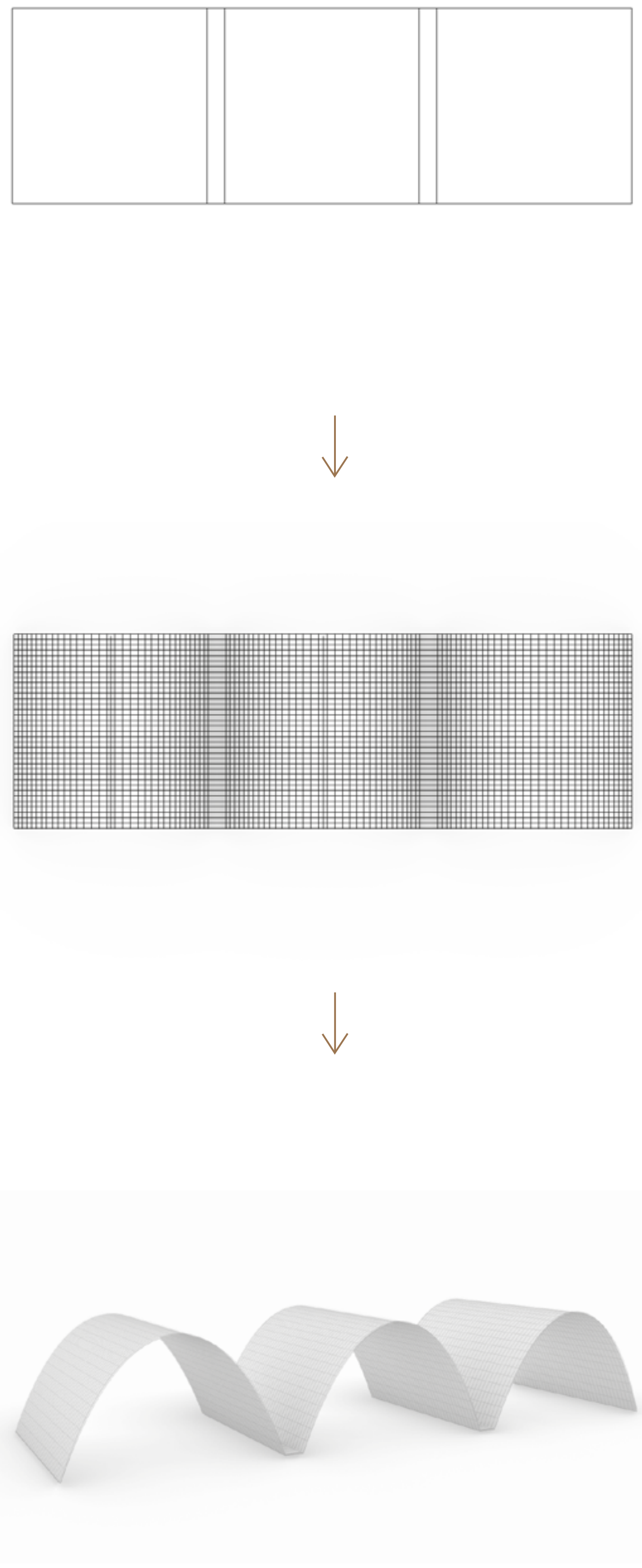


Figure 95 - First floor catenary nubian vault tessellation I Source: authors

Structuring

In order to validate the structures generated from the forming process, the relaxed geometry was tested in Karamba 3d for the structural performance and validation. The structural scheme adopted for the analysis is show in the figure below.

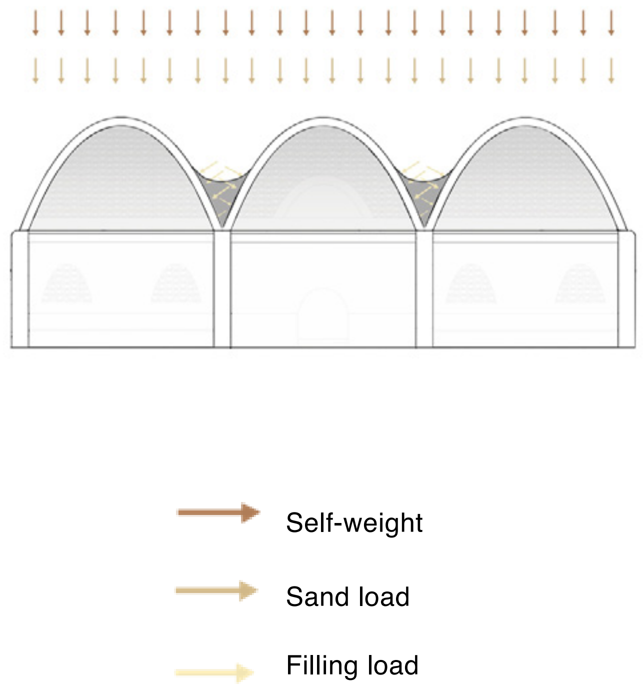


Figure 94 - First floor vault load cases I Source: Own authors

Load:

For the load cases, Sand load of 1kN and filling load of 2kN was taken. These were applied as mesh loads in Karamba software. A safety factor of 0.2 was applied as all the loads are dead loads. The wind load is neglected in this case as it is negligible. However it will be taken into account for the tallest structure, the gateways.

Design values

Allowable compressive Stress – 1.5MPa
Allowable Tensile Stress – 1/10 Compressive Stress – 0.15 MPa
Allowable Deflection – Span/400 – L/400 - 6600/400 – 16.5mm
Young's Modulus - 150 MPa

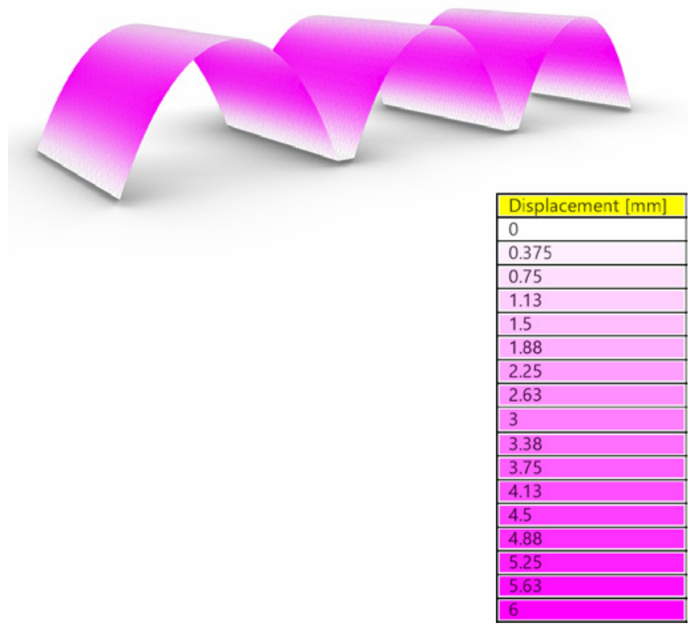


Figure 98 - Deflection values. I Source: authors

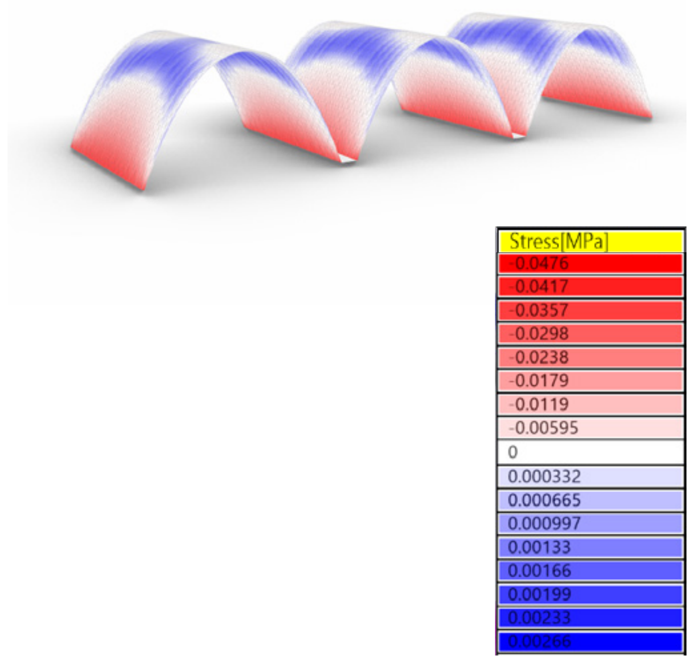


Figure 96 - Principal stress 1 values. I Source: authors

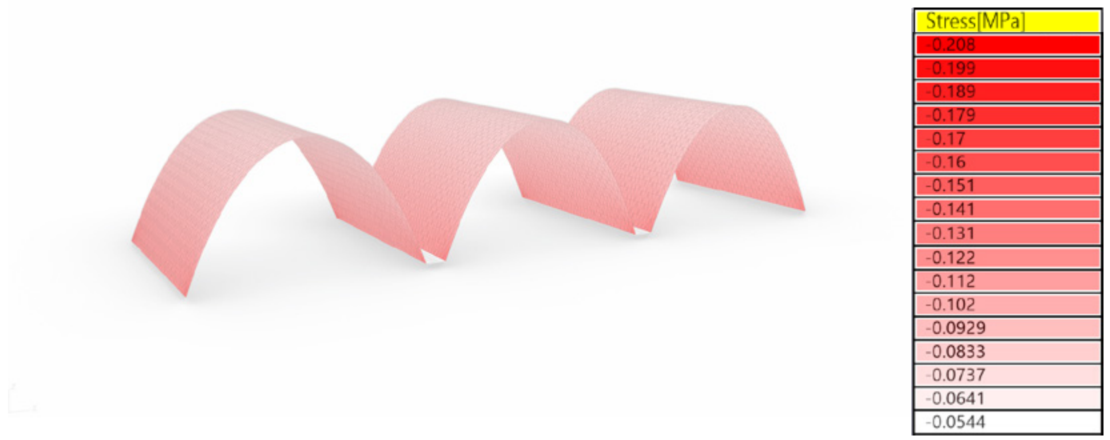


Figure 97 - Principal stress 2 values. I Source: authors

First floor module configuration				
Type	Units	Step- 0.15m	Step- 02 0.3m	Step- 03 0.45m
Max displacement	mm	32.70	6.000	
Peak compressive stress 1	MPa	0.031	0.048	3.1
Peak tensile stress 1	MPa	0.108	0.003	0.029
Peak compressive stress 2	MPa	0.375	0.208	0.002
Peak tensile stress 2	MPa	0.009	0.054	0.14

Figure 99 - Results for the different steps. I Source: authors

The results show that a minimum of 0.3m roof is suitable enough to ensure the stability of the structure. The displacement of 6mm, peak copressive stress of 0.0048MPa and peak tensile stress of 0.003 are much below the allowable values therefore it is very suitable.

4.2.3 NUBIAN VAULT RIWAQ

The riwaq runs the entire length of the courtyard.

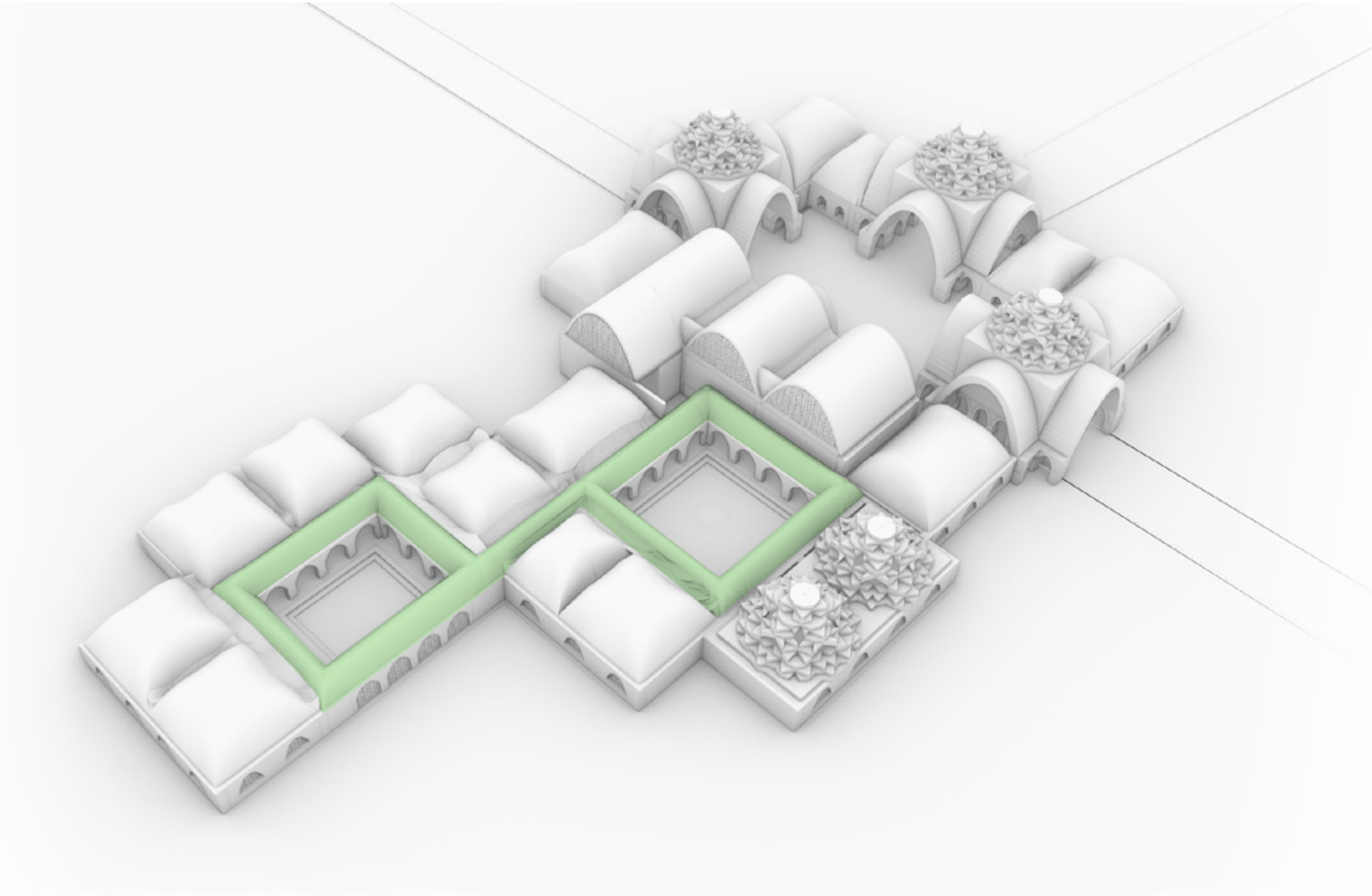


Figure 100 - Riwak vaults I Source: Own authors

Forming

From the initial planning, the pathways covered by the riwaks are meant to be modular as an equal spacing of 1.8m is given on the plan. Therefore it is important to develop a system which is modular and also adaptable. Different configurations were explored in the first tessellation process. A simple square grid tessellation is employed in the formation of the riwak vaults as this spans a long space. It is important to keep the structure simple in order to achieve the modular concept efficiently.

The second configration explored used the columns as anchor points. These are shown in the images below. While these configurations are aesthetically pleasing, It becomed difficult to construct them efficiently as the shapes are not standardized. This led to a third configuration

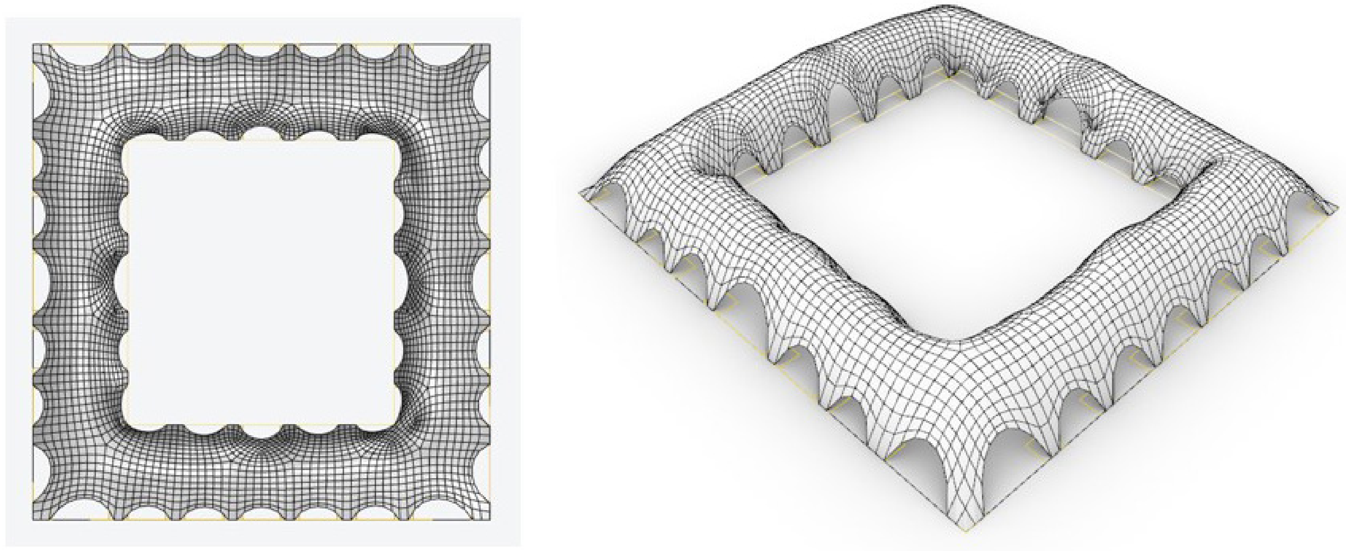


Figure 101 - Riwak with lines as anchor points I Source: Own authors

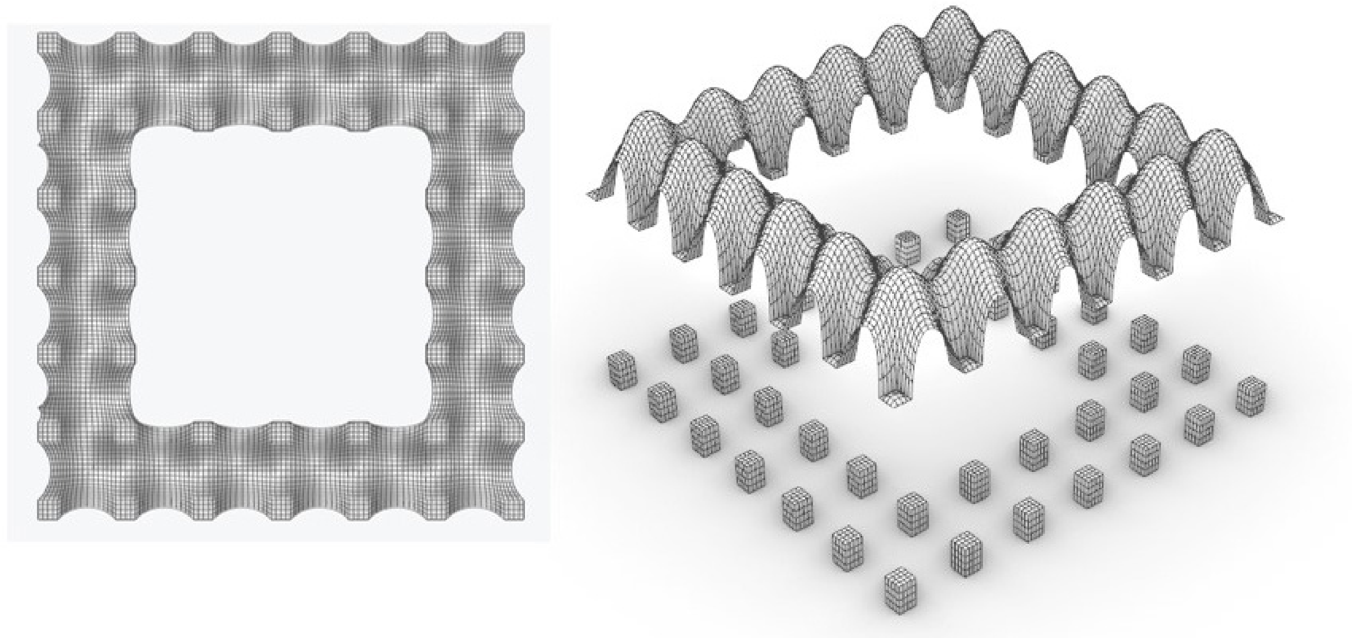


Figure 102 - Riwak with column boundaries as anchor points I Source: Own authors

In order to create a simpler form, a different approach to the tessellation is explored. The ribbed vaults are placed on a 2.4m base, therefore it is logical to also have the riwaq roofs on walls of the same height. A simple nubian vault is formed with anchor points along the edges of the corridor space. The edges and intersections of the vaults are tessellated to form cross vaults.

The same method mentioned in the groin vault section is applied to these critical points. This ensures that the edges and intersection points are standardized and the rest of the roof is a catenary vault

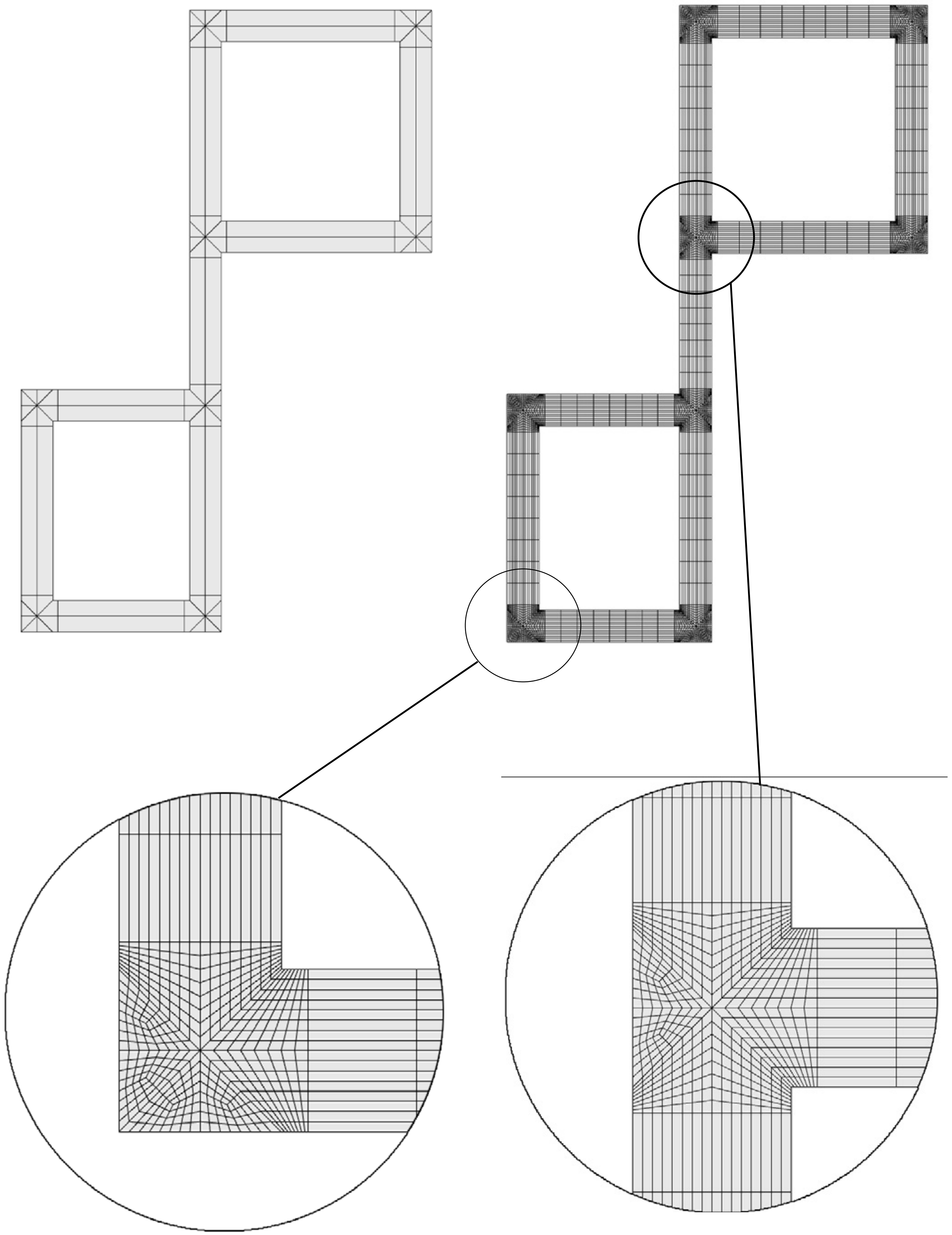


Figure 103 - Riwak tessellation pattern I Source: Own authors

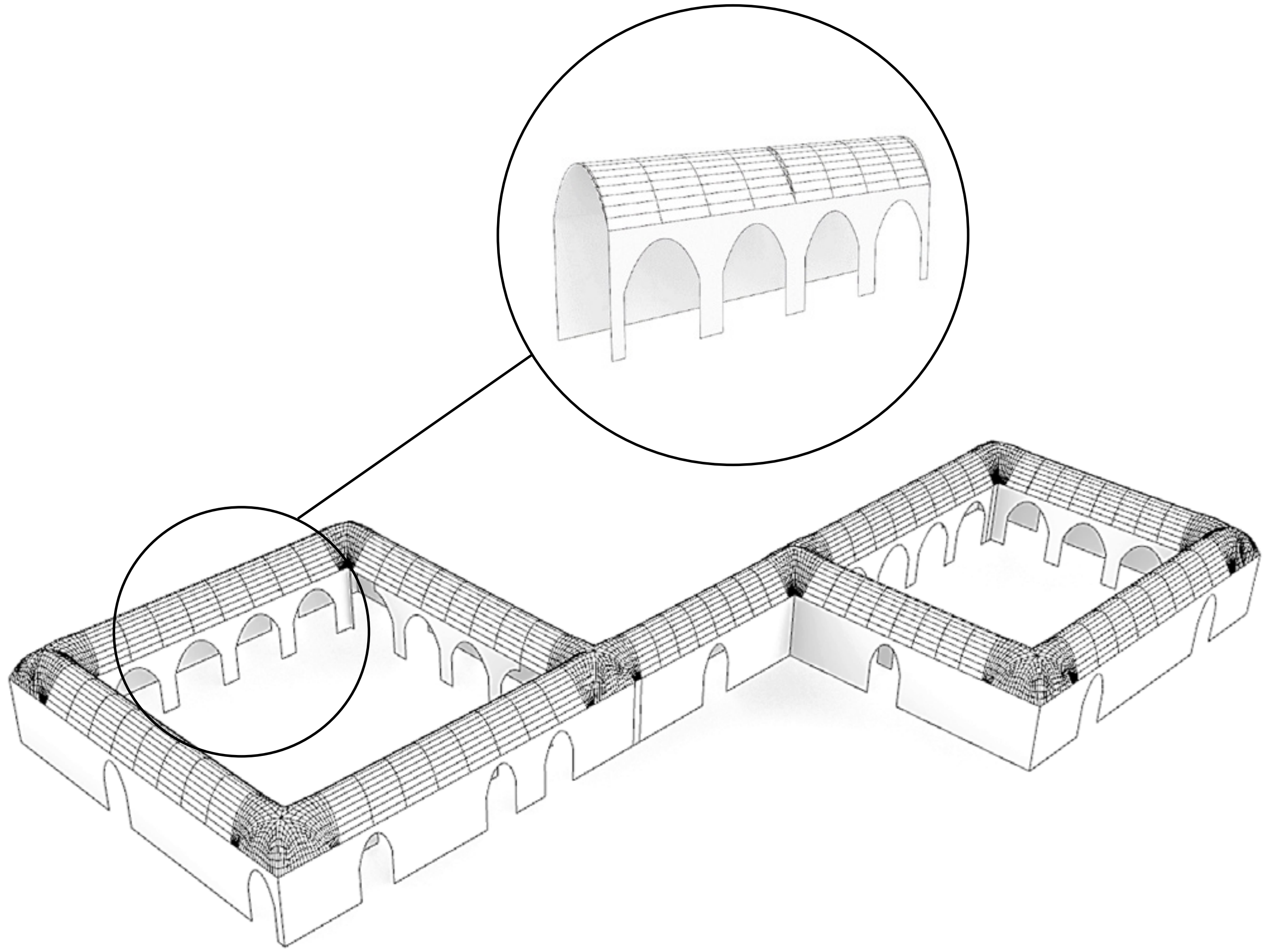


Figure 105 - Riwak configuration and chosen area for structural analysis I Source: Own authors

Structuring

In order to validate the structures generated from the forming process, the relaxed geometry was tested in Karamba 3d for the structural performance and validation. One portion of the riwak is chosen for structural analysis due to time constraints. This approximation is considered suitable for the entire structure.

Loads

Sand load 2kN was taken and filling load of 1kN was taken. These were applied as mesh loads in karamba.

Design values

Allowable compressive Stress – 1.5N/mm2
Allowable Tensile Stress – 1/10 Compressive Stress – 0.15 N/mm2
Allowable Deflection – Span/400 – L/400 - 1800/400 – 4.5mm
Young's Modulus - 150 MPa

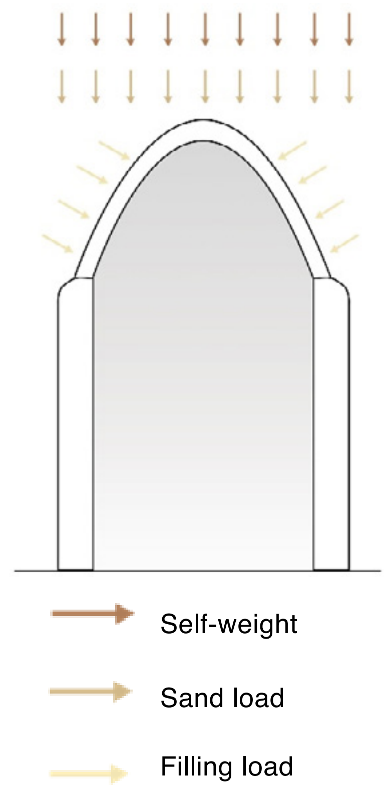


Figure 104 - First floor vault load cases I Source: Own authors

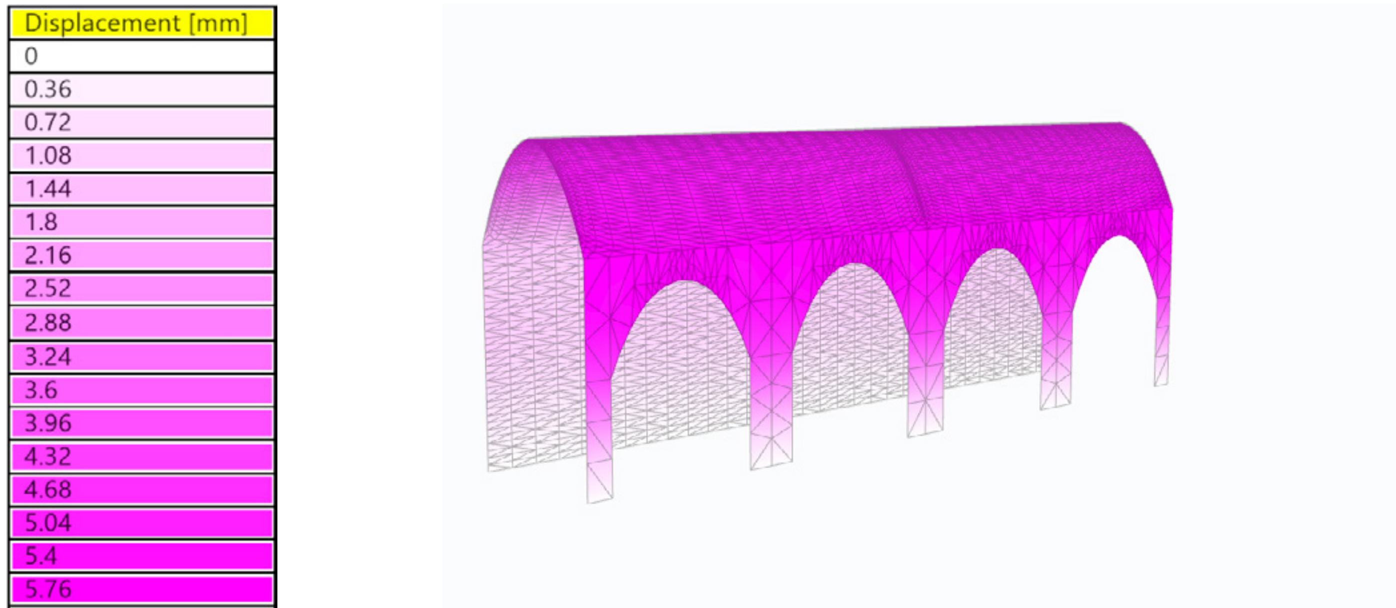


Figure 108 - Deflection values. I Source: authors

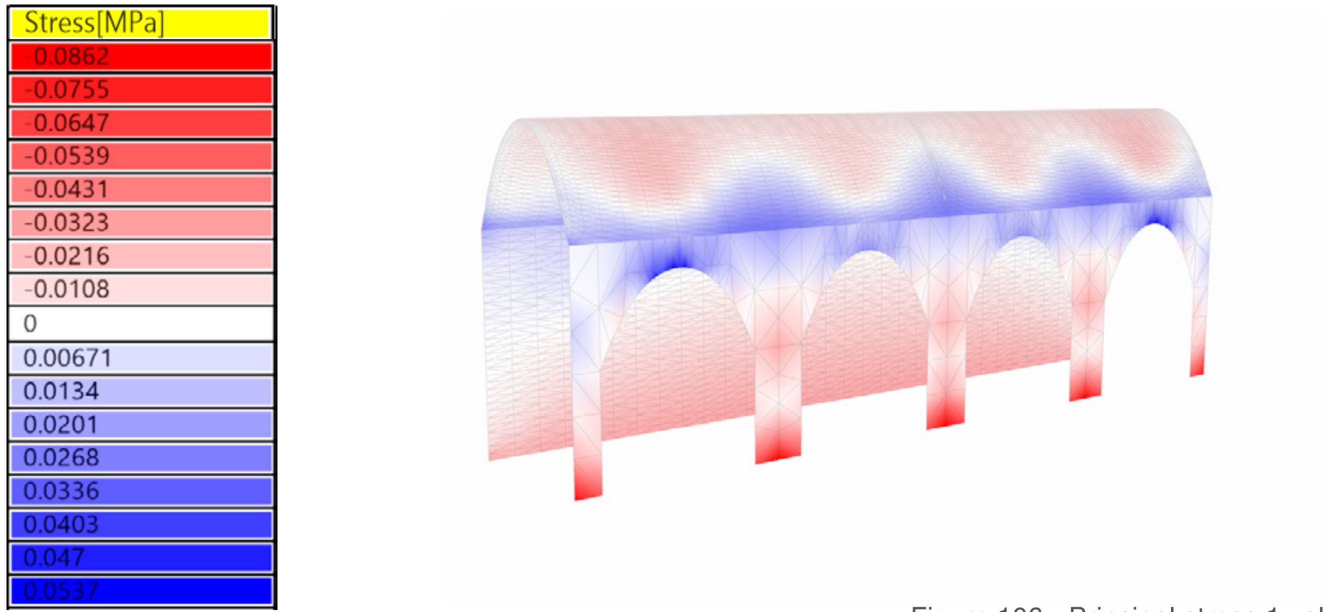


Figure 106 - Principal stress 1 values. I Source: authors

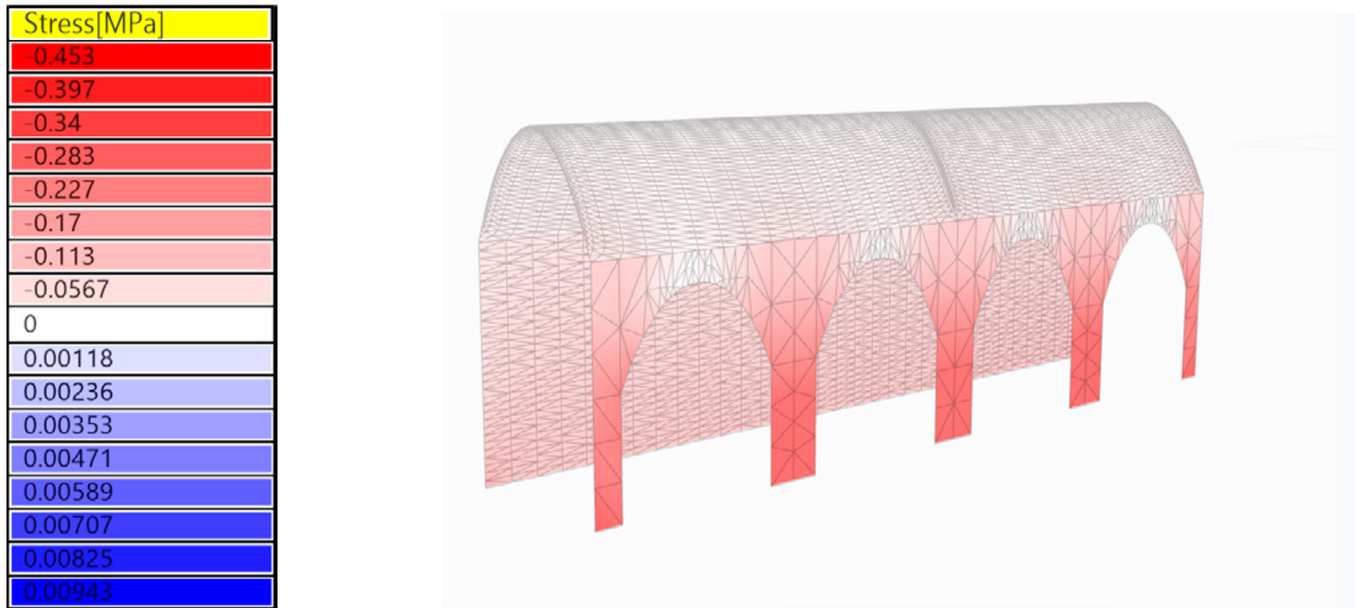


Figure 107 - Principal stress 2 values. I Source: authors

Riwak module configuration					
Type	Units	Step- 0.15m	Step- 02 0.3m	Step- 03 0.3m walls, 0.15 roof	Step- 02 0.45m
Max displacement	mm	32.20	6.50	5.760	3.242
Peak compressive stress 1	MPa	0.173	0.111	0.086	0.036
Peak tensile stress 1	MPa	0.137	0.065	0.054	0.068
Peak compressive stress 2	MPa	0.715	0.472	0.453	0.273
Peak tensile stress 2	MPa	0.050	0.014	0.017	0.001

Figure 109 - Results for the different steps. I Source: authors

The riwak module shows a thickness of 0.3m complies with the stresses however the displacement 0f 5.76mm is above the allowable of 4.5mm. In order to conform with the grid available as it is important to have enough space for the corridor, therefore, although 0.45m produces an accceptable displacement limit of 3.24mm, 0.3m for the wall thickness and 0.15m for the roof is reserved. It is important to note that safety factors have been added to the loads and a medium compressive strength value is used for the brick, however in reality it would be stronger as it is a mixture of adobe and starch. Furthermore, as this is only a section of the riwak, there is a possibility that the entire riwak is stable as the forces are transferred over more area.

4.2.4 MUQARNAS DOME

The muqarnas domes can be found on the arched entrances or on the multi-purpose hall as can be seen in figure 63. At almost eleven meters high the arched passage way are the most interesting to explore structurally.

For this roof typology we took a different approach. Because the structure was a bit more complex we choose to model it in 3D instead of relaxing it dynamically. To do this we used Ansys to model and analyse it. This was handy however there was a need for simplification in terms of the form created.

The final structural form as can be seen in figure 62 on the left was approximated by using a dome as an abstraction of the muqarnas dome seen on the right.

In this way the structure focus a bit more on optimizing the structure supporting the muqarnas dome so that in the mean time the forming of the actual muqarnas can take place. How that process went will be explained right after the structural analysis.

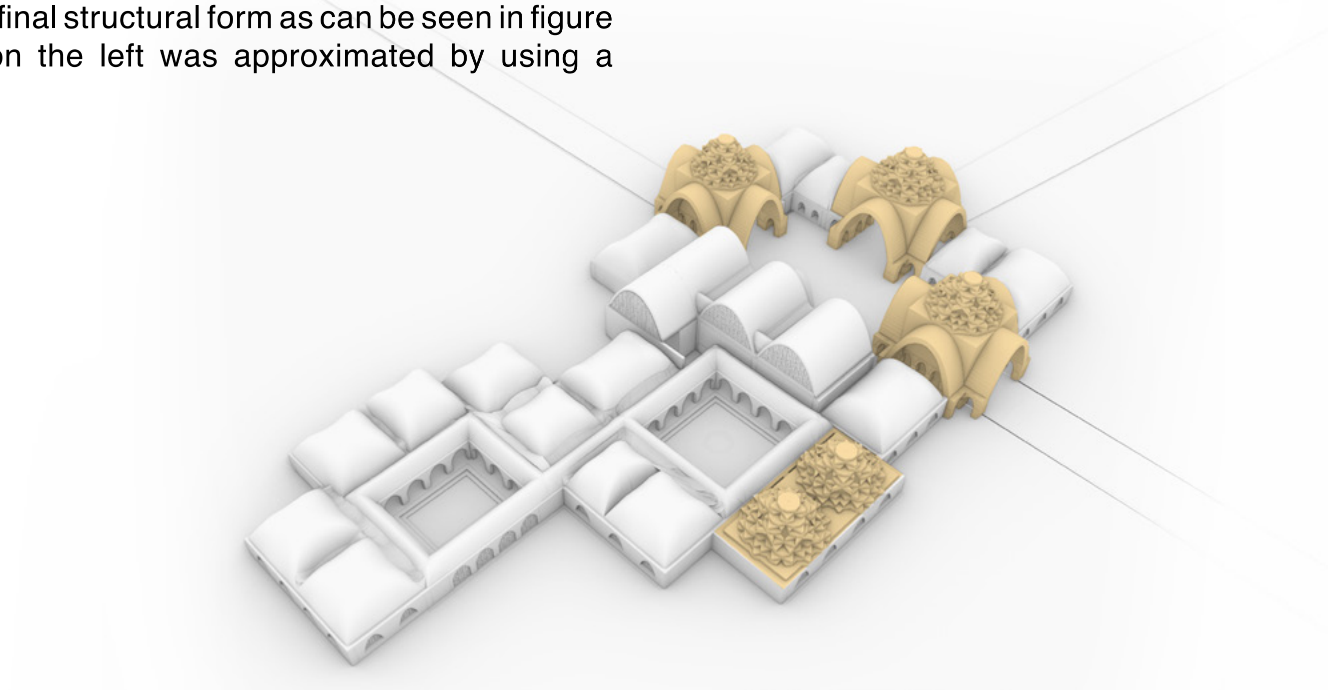


Figure 111 - Muqarnas domes locations I Source: authors

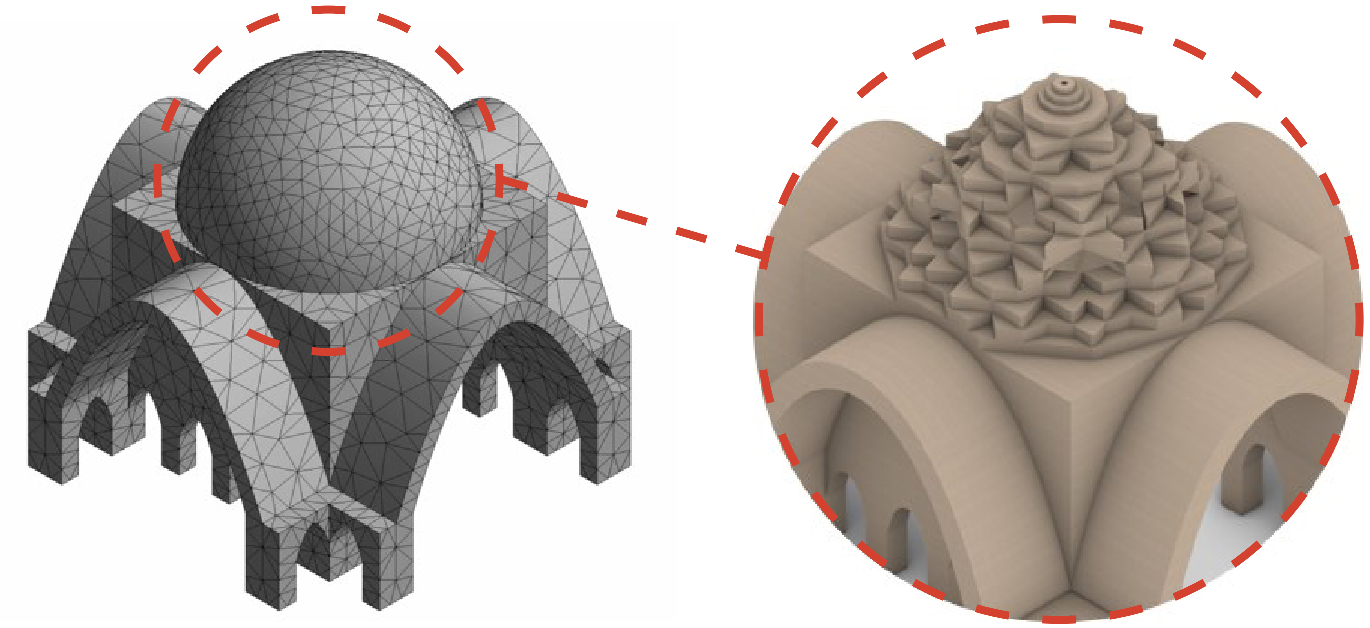


Figure 110 - Muqarnas dome structural approach I Source: authors

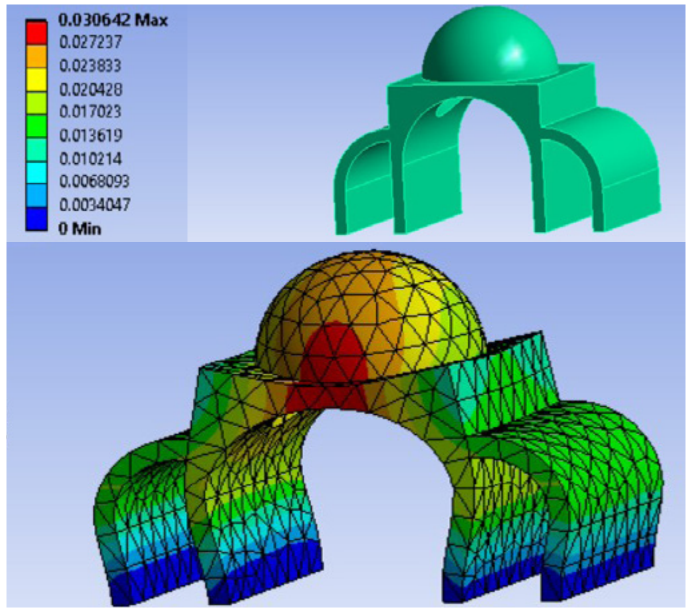
Structural Analysis Input

When starting at the structural analysis the architectural model was used which was not based on any structural principles. This of course resulted in undesirable values as can be seen in figure 64 (in this analysis and in figure 65 only the self-weight was applied).

Before being able to know what to improve it was important to get a better understanding of these types of structures. To achieve this a small research was done into similar examples. This proved harder than initially was expected because it was not very common to see domes on arched passage ways. Nevertheless some comparable examples where found. These showed thicker columns and/or tension rings, which improved the results but it still was not structurally feasible.

An other idea that came up during the process was creating a sort of cross vault where the dome would rest on. This was analysed and gave great results but it was not yet optimized. That is when the comparison between round and catenary curves gave us the solution as the catenary curves gave satisfactory results. For a more extensive look into the in-between steps see the appendix.

The loads applied include self-weight of the construction, sand load of the finish, live load of the maintenance occurring once a year and wind load pushing and pulling.



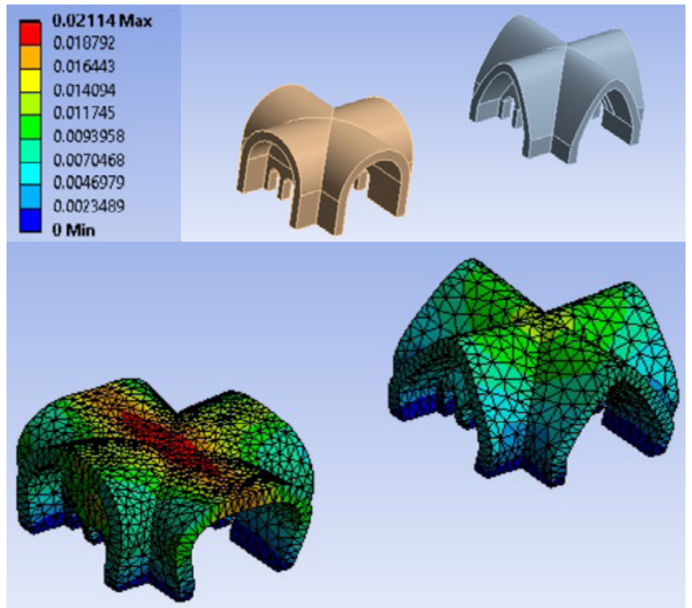
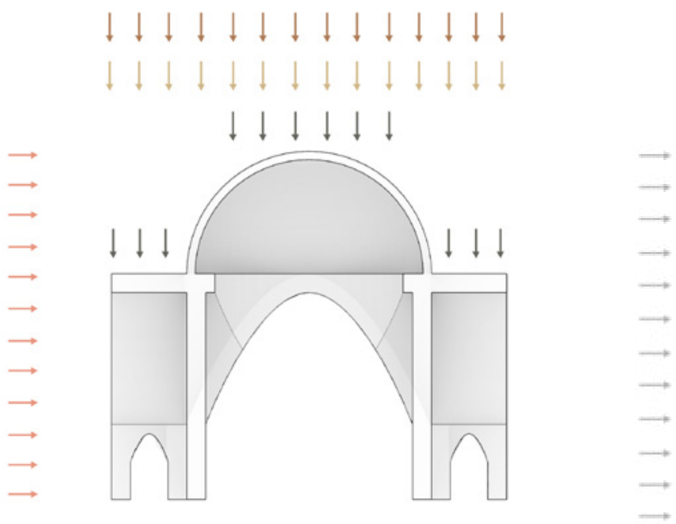
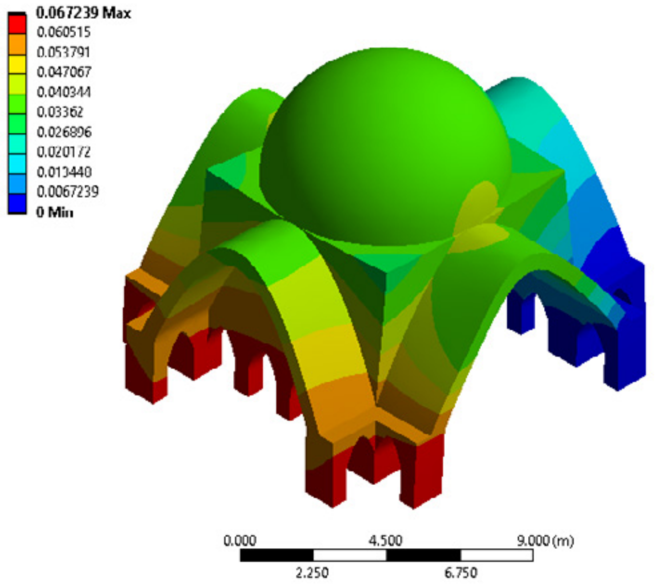


Figure 112 - First model displacement (in meters) Figure 113 - Catenary vs round curve (in meters)
Source: authors



Allowable Design Values
Compressive stress – 1.5 N/mm² - 1.5e6 Pa
Tensile Stress – 0.15 N/mm² - 0.15e6 Pa
Deflection – Span/400 – 6600/400 - 16.5 mm

Figure 114 - Input structure analysis I Source: authors



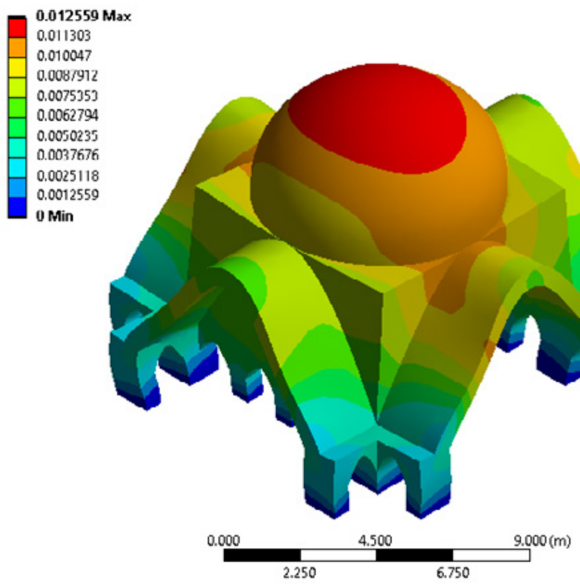
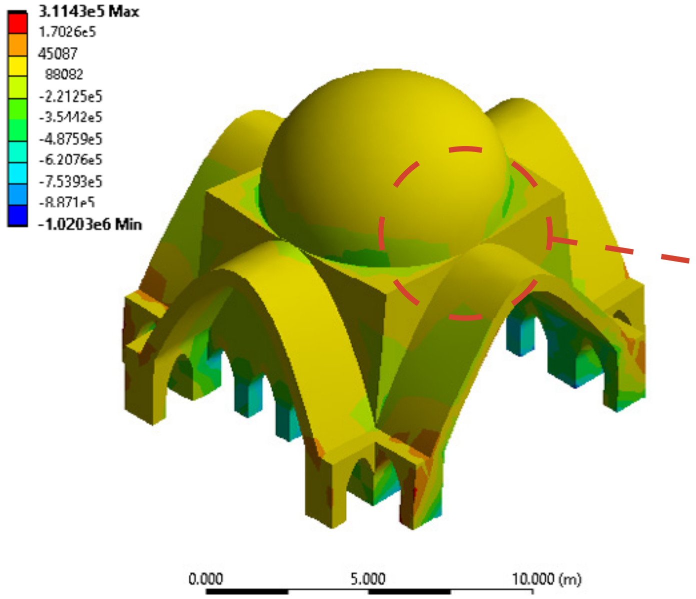


Figure 115 - Deformation displacement (in meters) Figure 116 - Deformation fixed support (in meters)
Source: authors



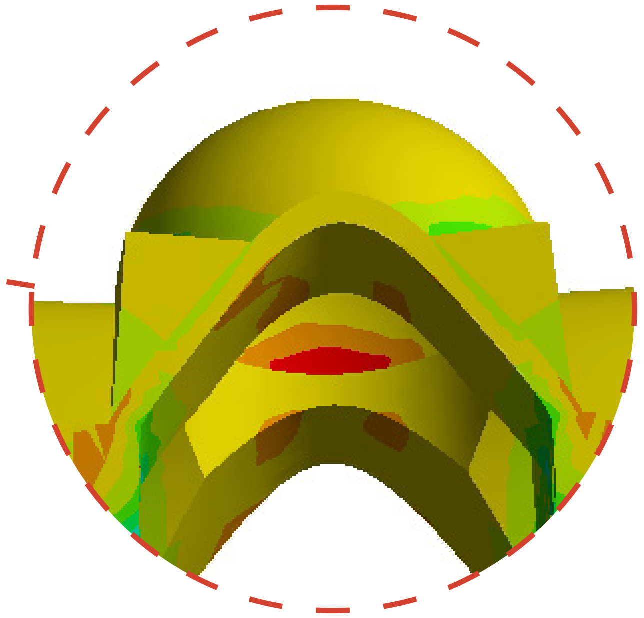


Figure 117 - Stress (in Pa) I Source: authors Figure 118 - Problem area (in Pa) I Source: authors

Structural Analysis Results
As mentioned before there was a long process to optimize the structure until this point. But with this shape it can be said with almost certainty that the structure is safe.

In figure 67 the deformation can be seen when the model was analysed with one side being a fixed support and one being a displacement support. This gives a value of maximum 67.2mm which is way above the allowable of 16.5mm. On figure 68 on the other hand the value is of 12.6mm this occurs because it has only fixed supports. When taking into account that a structure is never completely free on one side or completely fixed to the ground on both we can expect the value ranging somewhere in between. Because of this we assume that in terms of deformation it is safe.

As is already known about adobe bricks they can handle compression stresses quite well but not tension stresses. This can clearly be seen as the maximum compressive stress (blue areas in figure 69) is 0.5 Pa below the allowable value whilst the maximum tensile stress is two times the allowable. This can be a problem however because the areas where the tensile stress is above allowable are compact (figure 70) this can be resolved. From previous studies it was found that adobe bricks can have higher strength values making the allowable tensile stress higher. These could be used in this area to resolve the issue.

Figure 119 - View of the North shabistan dome

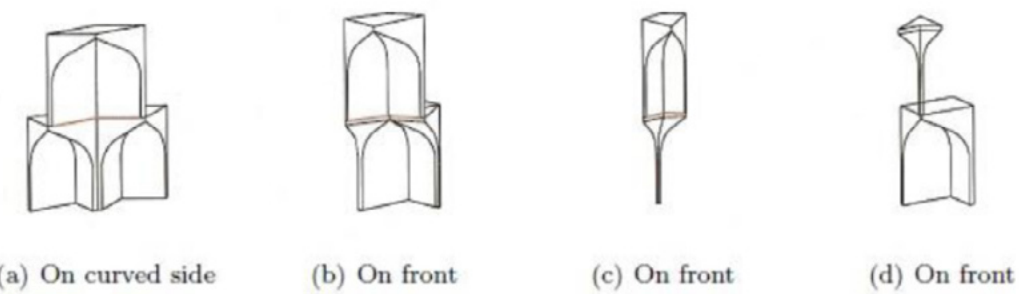


Figure 120 - Traditional muqarnas stacking

Computational Approach

During in-depth research it was discovered that the traditional construction of Muqarnas is superficial. The building construction does not rely upon the muqarnas for structural support, instead the blocks are superficial. The muqarnas blocks were made of wood or stucco, then essentially "glued" to the building via stucco, or nails. [Yaghan 2007]

Two main design goals established criteria by which to evaluate different methods for creating the muqarnas. The first was to limit the number of distinct modules to a maximum of 20, and the other was to obtain the maximum amount of variation using these modules. This variation should result in an interesting pattern that has a similar aesthetic to the original muqarnas. Throughout the process constructability was also kept in mind. Some options, while promising, required too much effort or skill to put together. One particular method required each horizontal ring to be in compression so that each block holds the other in place, meaning that up until its complete construction the entire ring is unstable. Elements such as this instability forced the option to be deemed not feasible.

Approach Options

Radial Approach
In an effort to create structural muqarnas, more often referred to as “genuine” muqarnas, one resource led to a radial method of creating blocks. [Yaghan 2007] The approach by Dr.Yaghan was then simplified into blocks which could form a perfect dome. Figure 73 shows the radial slicing in both plan and section, which leads to a basic block as shown in the same figure. The next step would be to carve or add to the inner face of this block in order to make a pattern, however at this step it was already realized that due to the varying radii as slices are made along the dome, this method would result in far too many modules. This method of interdependent blocks did play a role in the later evaluation since the wedge form in either plan or section can aid in constructability since the blocks then stay in place during construction better.

Stacking Approach
The stacking method developed from studying the Vaulted dome of “Masjed-e Jameh mosque” (Friday mosque) of Isfahan, Iran. The simplicity of the forms, which were structural, made this example a promising precedent (figure 71). This scale of dome uses regular blocks to create the form, however it is not entirely in compression, presenting an issue were it to be made from adobe. The traditional blocks can be seen in figure 72, whereas the manual study of the dome with its 2D pattern results can be seen in figures 74-76 demonstrating how each block sits over top of a gap, meaning that this design is non-structural.

Pattern Generation
During research focused on pattern-making, it was suggested that the Penrose Pattern be explored. [Penrose 2014] This pattern, invented in the 1970s by Sir Roger Penrose, has 5-fold symmetry and never repeats. However, the entire pattern consists of two types of triangles. The concept of achieving a non-repeating pattern with, theoretically, two modules met the previously-established criteria for the design and therefore led to more in-depth analysis.
During this analysis, the pattern was extruded with different methods which led to an initial block design where the blocks were superficial. In spite of this, the aesthetic achieved by extruding the pattern was precisely the variation desired in the design goals. The overall technique then played an integral part in the final technique used for the creation of the dome.

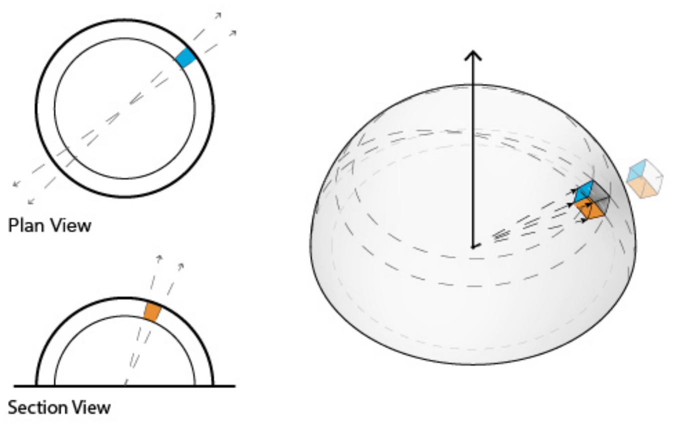


Figure 121 - Diagram of the radial approach.

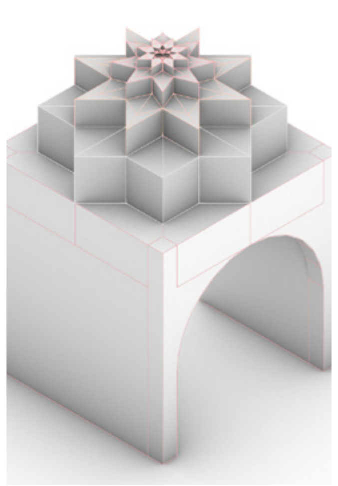
Chosen Method

Due to the successful patterning of the penrose method, more time was invested to develop a structural approach to making the dome from this pattern. The final method utilizes a logic of pairing triangles to then stack their way up to the top of the dome. In the process, the pieces do have wedged sides in plan, therefore the knowledge gleaned from researching the other methods led to a logic which addresses the strengths and weaknesses of either method.

Process

Piece One: the Pattern
The initial step in making the muqarnas dome is to dynamically create the Penrose Pattern. In the creation fo the triangles for the pattern, the triangles have a color, along with A, B, and C, where A, B, an C are the three corners of the triangle. The process begins with a series of acute triangles, which are then subdivided according to the golden ratio:

$$\frac{1+\sqrt{5}}{2}$$



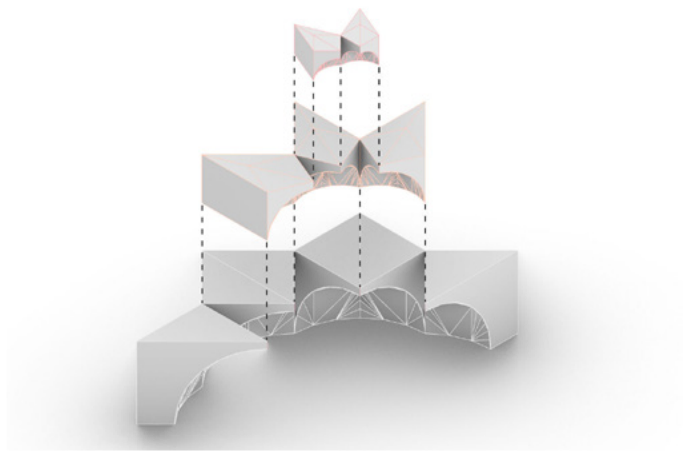


Figure 122 - (top, left) Stacking Approach, 3D view
Figure 123 - (top, right) Stacking Approach, 3D plan
Figure 124 - (above) Stacking Approach, 3D diagram

The python script which creates the pattern, based off of the script written by Josh Preshing [Preshing 2011], stores these triangles as complex numbers. These numbers contain this information:

$$(color, A, B, C)$$

The color relates to which type of triangle it is, where red is the acute triangle and blue is the obtuse triangle. The triangles can be seen in figure 77 where A B and C have both imaginary and real values. The imaginary value contains the x coordinate, while the real value contains the y coordinate. In this way the triangles are stored:

$$(color^{red}_{blue}, A^{real}_{imag}, B^{real}_{imag}, C^{real}_{imag})$$

The piece of code for the pattern has inputs for the diameter, number of subdivisions, and the number of sides to the polygon. For the creation of the dome, the number of subdivisions is set to 5, the diameter is 6.6 meters, and the number of sides is 10. The script runs and stores the triangles in the complex numbers in the first part of the script, then performs the following loop for the triangles:

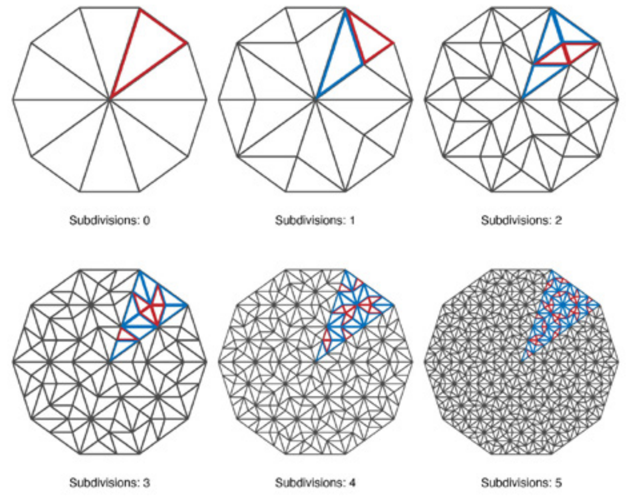


Figure 125 - Penrose Pattern Subdivision

```
for color, A, B, C in triangles:
    Apt = rg.Point3d(-A.imag, A.real, 0)
    Bpt = rg.Point3d(-B.imag, B.real, 0)
    Cpt = rg.Point3d(-C.imag, C.real, 0)

    #calculate the center point of the triangle
    Dy = ((A.real+B.real+C.real)/3)
    Dx = -((A.imag+B.imag+C.imag)/3)
    Dpt = rg.Point3d(Dx, Dy, 0)
    distToCenter = origin.DistanceTo(Dpt)

    Dsin = Dy / distToCenter
    Dcos = Dx / distToCenter
    DSa = math.asin(Dsin)
    DCa = math.acos(Dcos)

    singleTri = rg.Polyline([Apt,Bpt,Cpt,Apt])
    redTri.append(singleTri)
    tri.append(singleTri)
    tri_info.append([distToCenter, DSa, DCa])
```

For each triangle a polyline connecting the three corners of the triangle is created. The centroid of the triangle is also found using to following equation [Page 2011]:

$$O_x = \frac{A_x + B_x + C_x}{3} \qquad O_x = \frac{A_y + B_y + C_y}{3}$$

With this centroid, the distance to the center of the pattern along with the arcsin and arcos values are calculated. This information is appended to a value and then these are passed on to the next block of code in the script which performs the sorting.

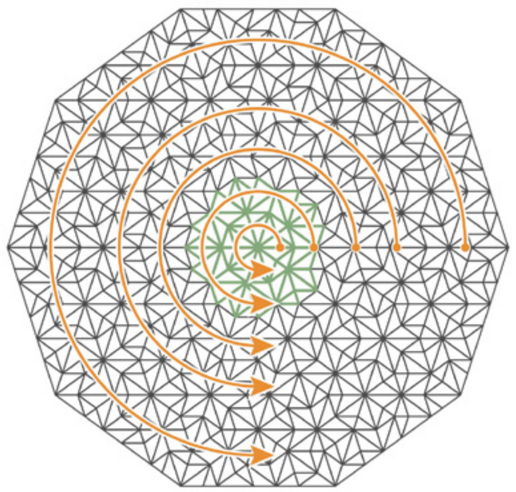


Figure 126 - Sorting triangles individually.

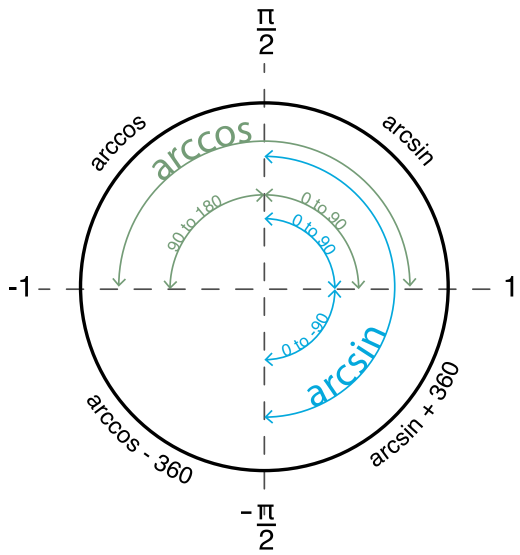


Figure 127 - Diagram of radial sorting method.

Piece Two: the Sorting Hat

The values of the distances along with the arcsin and arccos are fed an algorithm in order to give priority to the sorting method. In this script distance has a higher value than angle *(dw>aw)* , which then allows the script to sort the individual polyline triangles from the inside to the outside as well as counterclockwise from the horizontal seam on the right (figure 78).

```
aw = 1
dw = 100000000000

order_values = []
degs = []
dists = []
for ti in tri_info:
    sdeg = math.degrees(ti[1])
    cdeg = math.degrees(ti[2])
    if 90 >= sdeg >= 0 and 90>=cdeg>=0:
        deg = sdeg
    elif 90 >= sdeg >= 0 and 180>=cdeg>=90:
        deg = cdeg
    elif 0 >= sdeg >= -90 and 180>=cdeg>=90:
        deg = 360 - cdeg
    elif 0 >= sdeg >= -90 and 90>=cdeg>=0:
        deg = 360 + sdeg

    order_value = aw * deg + dw * ti[0]
    order_values.append(order_value)
    degs.append(deg)
    dists.append(ti[0])
```

For the organization portion, the script uses the information appended to tri_info in the previous piece of code in order to use the arcsin and arccos values to locate the points within a circle. These values are converted to degrees, and then ranges are defined in order to determine where in the circle the triangle is located.

To elaborate, arcsin has a domain of π/2 to -π/2 while arccos has a domain of -1 to 1. arcsin, associated with the y value, and arccos, associated with the x value, then cover the entirety of the circle by evaluating them together. Referring to figure 79 can help to visualize the sorting code.

The next piece of the code performs an argsort written in python and based on the numpy function. Relevant values are then sorted via this method:

```
order = argsort(order_values)
tri_sortd = [tri[id] for id in order]
```

Piece Three: the Rings

The distances are used and sorted with a tolerance of .0001 in order to use ids and log which triangle is in which ring. This number is later used as a definition of where the blocks are located in the entire dome. The end result of the script is shown diagrammatically in figure 80.

Piece Four: Pairs

The method we developed manually is to select a pair of adjacent triangles, and define an angled piece and a flat piece. The flat piece serves as the base of the module which connects it to the next module. This next module utilizes the triangle form which was just used to create a flat piece, however in this adjacent module that triangle is used to create

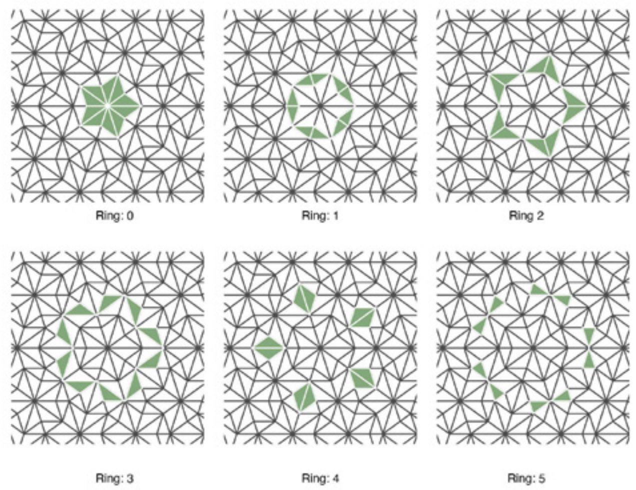


Figure 128 - Grouping the triangles into rings

an angled piece, and the next triangle (not yet used) becomes a flat piece. This process is repeated in order to ensure that each block is stacked in some way upon another block.

The pairs of the triangles are manually defined for the script. This same pattern becomes the main element for the next part of the script.

```
tris_leveled = []
this_level = []

for i, t in enumerate(tris):
    this_level.append(t)
    if levels[i] != levels[(i+1)%len(tris)]:
        tris_leveled.append(this_level)
        this_level = []

order = [[0,1], [1,2], [2,3],[3,5],[5,7],
[7,10],[10,12],[12,13],[13,17],[17,20],
[20,25],[25,26],[4,6],[6,9],[9,11],[11,14],
[14,16],[16,21],[21,24],[18,22],[22,28],
[19,23],[23,27],[27,31], [15,20],[14,15]]
all_pairs = []

for o in order:
    first_pairs = tris_leveled[o[0]]
    second_pairs = tris_leveled[o[1]]
    this_pairs = zip(first_pairs, second_pairs)
    all_pairs.append(this_pairs)
```

The first section of the script, **for** i,t in enumerate(tris) loops through the rings in order to produce tris_leveled which has an overall length equal to the number of rings, however within tris_leveled[0] will be the enumerated polyline triangles. The second section **for** o in order takes each pair in the pattern, then identifies those triangles in the tris_leveled. The next step is to take the first and second triangles, then to zip them together so that a triangle with **index 0 of level 0** is paired with the triangle of **index 0 of level 1**, and so on. The basic logic of this script can be seen in the figures on the right hand page. Where figure 81 shows just one of the 'strings' beginning at the base of the dome and working its way up. Figure 82 shows the adjacent 'strings' as well for context.

In Piece Six: the Modules, the diagrams of the 3D construction of the blocks shows how this method translates into literal blocks.

Piece Five: Adjustments

In observing the pattern, there are multiple starts at the base of the dome, which result in different lengths of triangle pairs. There is the segment of pairs which will stack up to the very top of the dome, however there is also a segment of pairs which stops approximately 3 rings from the top. This translates to:

$$z = 3 * bH$$

Therefore the ring pattern is adjusted to account for the different starting and stopping points. Prescribing the pattern and thereafter using the values to displace the modules.

```
for i in range(len(all_pairs)):
    if 0<= i <= 11:
        for j in range(len(all_pairs[i])):
            x = (i)
            adj_levels.append(x)
    elif 12<= i <= 15:
        i = i-9
        for j in range(len(all_pairs[i])):
            x =(i)
            adj_levels.append(x)
    elif ...
```

The above code shows a portion of the loop which manually adjusts the i, this was done by grouping the pairs by their i value and then adjusting the i for that group.

Piece Six: the Modules

Each module, as explained before, consists of an angled and a flat piece. A for loop iterates through the list of pairs to perform basic extrusions on the triangles based on whether they are the angle or the flat piece.

Angled Piece

Regardless, the first step of the process is to find the vertices of the triangles. These vertices

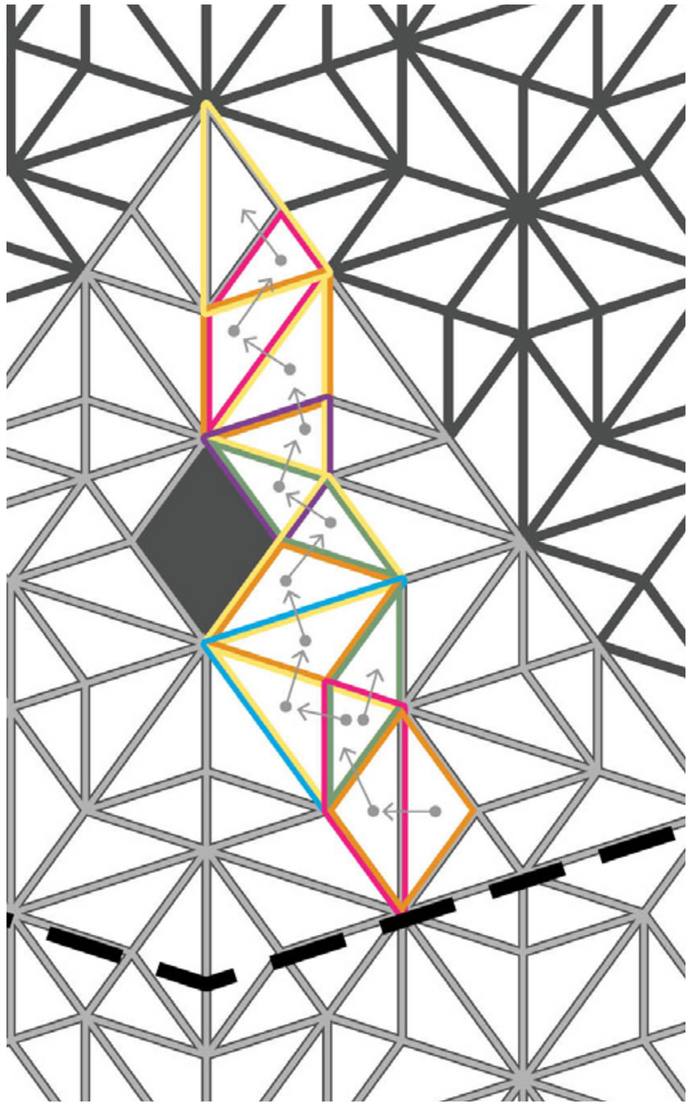


Figure 129 - Process of finding the ‘strings’

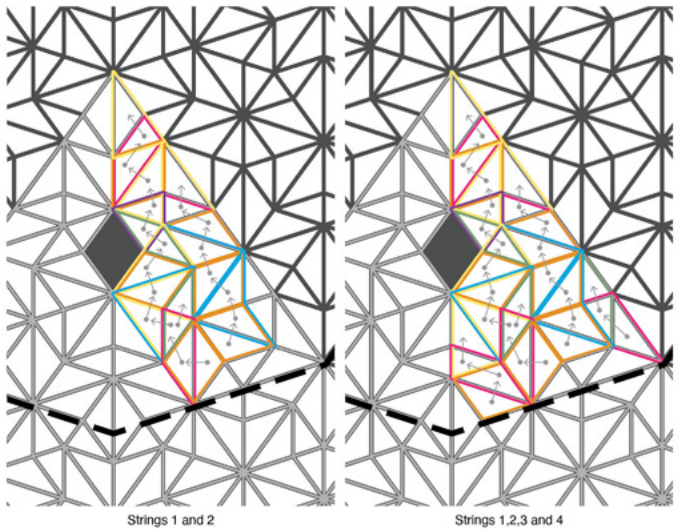


Figure 130 - Process with context

are then sorted in order to find which corner is closest to the origin, which is the center of the pattern. The function **def** getCorners(curve) is given the polyline for the angled face, and will then **return** cornerPoints[0],cornerPoints[1], minPoint

Another function, called **def** duplicatePoints(corner_one,corner_two)is given the output of **def** getCorners to then displace them vertically by *(bH)*. This results in the last two corners needed to construct a polyline rectangle. Within the for loop which loops over the pairs of triangles, the line angle_ext = rs.ExtrudeCurvePoint(rectangle,facet_points[2]) is performed so that the rectangular polyline is extruded toward the point with the minimum distance to the origin. This concludes the process for creating the angled portion of the module, as can be seen in the top sequence of figures 84.

Flat Piece
A similar, even more simple approach is used to construct the flat pieces of the modules. For this a function called **def** getOneCorner(curve) is essentially identical to **def** getCorners, the only main difference being that for the flat piece an arbitrary curve is used in order to use the ExtrudeCurveStraight function which requires the curve_id along with a start point and an end point. Therefore the arbitrary corner is retrieved from getOneCorner, then duplicatePoint makes a copy of the point displaced by *(bH)*. This results in all the geometries required to extrude the flat piece of the module, the only step left being to cap the geometries.

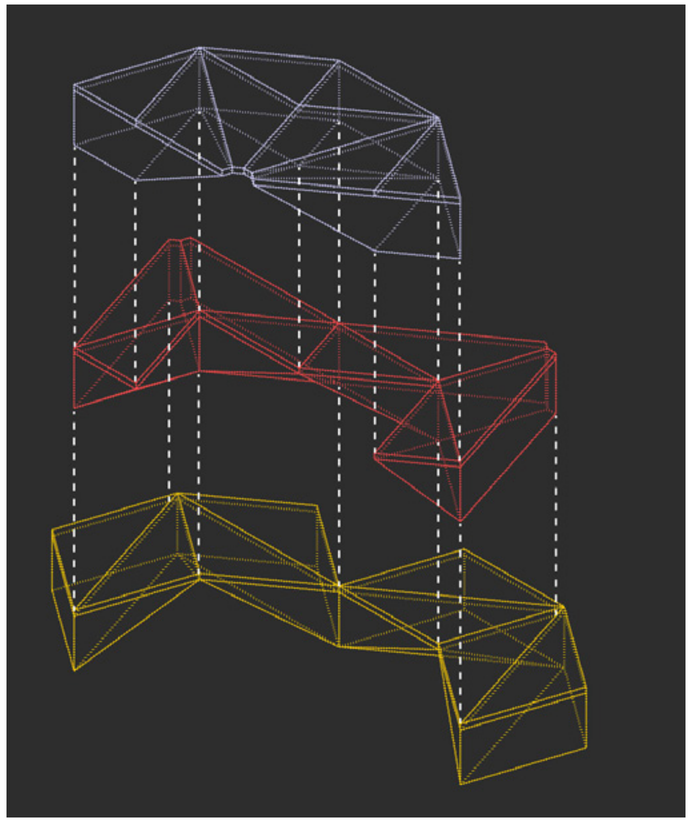


Figure 131 - 3D view of the modules

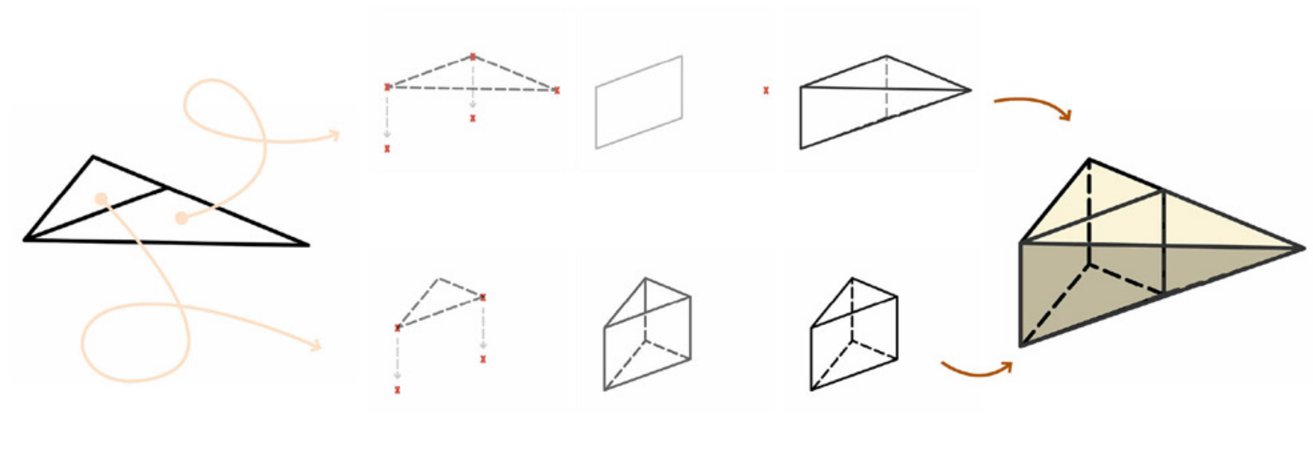


Figure 132 - Diagram of 3D Module

Displacement of the Modules
The displacement of the modules is performed in the negative z-direction, do to how the pattern is consistently iterated through in this order in each part of the script.

```
new_modules = []
for i in range(len(modules)):
    h = -(levels[i]*bH)
    new_angle = rs.MoveObject(angle_piece[i],[0,0,
        h])
    new_modules.append(new_angle)
    new_flat = rs.MoveObject(flat_piece[i],[0,0,h
        ])
    new_modules.append(new_flat)
```

For clarity, the flat and angled pieces are moved separately, however by the same distance. The adjusted levels list is used in order to define the height they blocks are located at, and all geometries are moved accordingly. The method of stacking can be seen in figures 83 and 85 in order to also understand how the 2D plan translates to a 3D form.

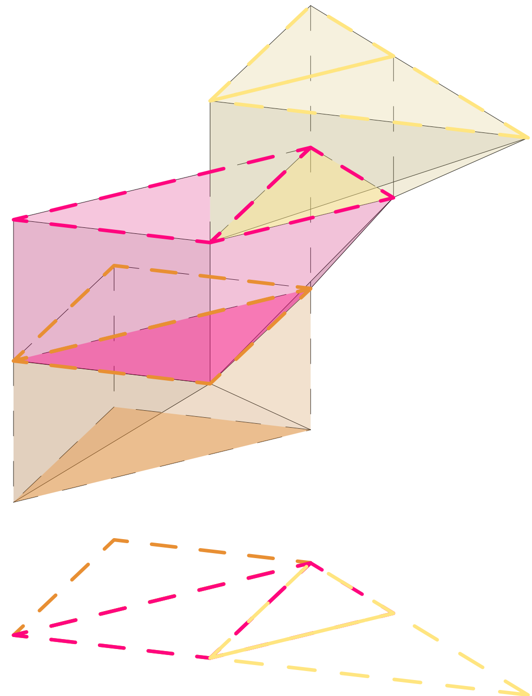


Figure 133 - 3D Modules with ‘string’ plan shown

5 CONSTRUCTION

The whole construction process should be carried out by the refugees in the camp with locally available materials. Therefore the process needs to be easy to understand and easy to apply on site for skilled as well as unskilled labour. The proposal accomodates for interested refugees to pick up these skills in the construction workshop, where one would be taught so that the acquired skill can be used for future structures in the camp.

5.1 ADOBE BRICK

For making the adobe bricks locally available ingredients i.e clay, fine sand and coarse sand are used in a proportion of 3:3:4 respectively. To this 10% water is added to create a homogeneous mixture. 10% of dry straw is added to improve the strength of the material. The ingredients are mixed using bare hands and feet and casted into a wooden mould shaped according to the desired brick shape. It is hand pressed manually after which the mould is removed and the bricks are allowed to dry for 28 days. The mortar is also prepared with the same basic composition with higher percentage of water as required to make a sticky paste. The figure below shows the brick making process.

For the special Muqarna bricks, 10% gypsum powder is added as a stabilizing agent, which according to research improves the strength of the bricks further (Turkmen and Ekinci et al., 2017). This is done because the special bricks have some acute corners which would require more strength. However, for validation further physical tests have to be carried out. Another option to increase it’s strength would be to use a hydraulic press for these special bricks and bake them separately.

Figure 134 - Brick making process I Source: authors

5.2 BRICK TYPES

The bricks are classified into two basic types and 14 special modules for the Muqarna domes.

In the basic type, as shown in figure no. 136 alongside, Type A follows a typical brick dimension ratio of 1:2:4 and is used for all walls and roofs except the Muqarna domes. A size of 29 x 14 x 6.5 cm brick is used and a 10 mm gap for the mud mortar is taken into account in the size. An English bond bricklaying pattern is implemented for all walls for easier understanding for masons. Type B queen closer of size 29 x 6.5 x 6.5 cm is used to fill the gaps in this bricklaying pattern. Wall thicknesses of 30 and 60 cm are used in the design as shown in figure no. 135. For the arches and vaults, the same bricks are used and the acute angles are adjusted within the mortar.

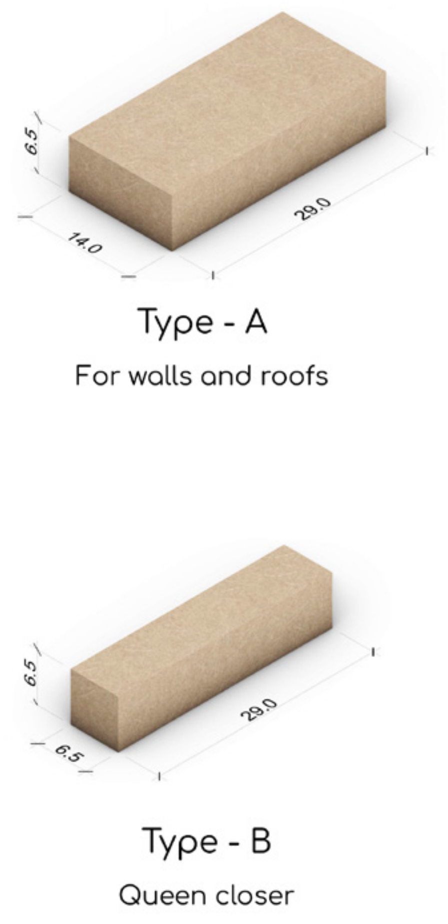


Figure 136 - Basic brick types I Source: authors

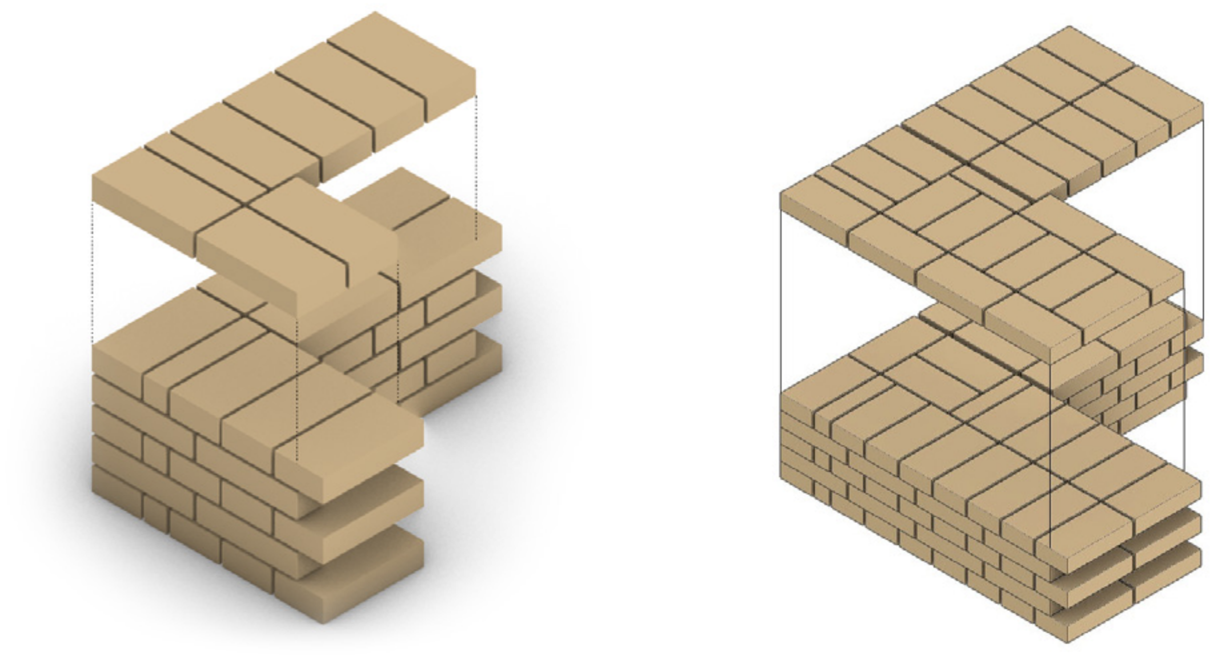


Figure 135 - English bond brick laying pattern I Source: authors

For the Muqarna domes, 14 types of modules have been generated according to the penrose pattern explained earlier. These repeatable modules can be scaled according to the size of the penrose pattern generated and the size of the dome to be built. A brick module comprises of two adjacent triangles in the pattern, where the base of one triangle is slanted to a point, while the other triangular base remains flat as shown in the image alongside. With this logic, 14 types of modules have been generated that can be stacked on top of each other to create a corbelled dome.

The acute corners that are less than 72 degrees are chamfered creating a blunt corner face to avoid sharp angles. This is done for ease of constructing these modules and to ensure the corners do not chip off during the construction process.

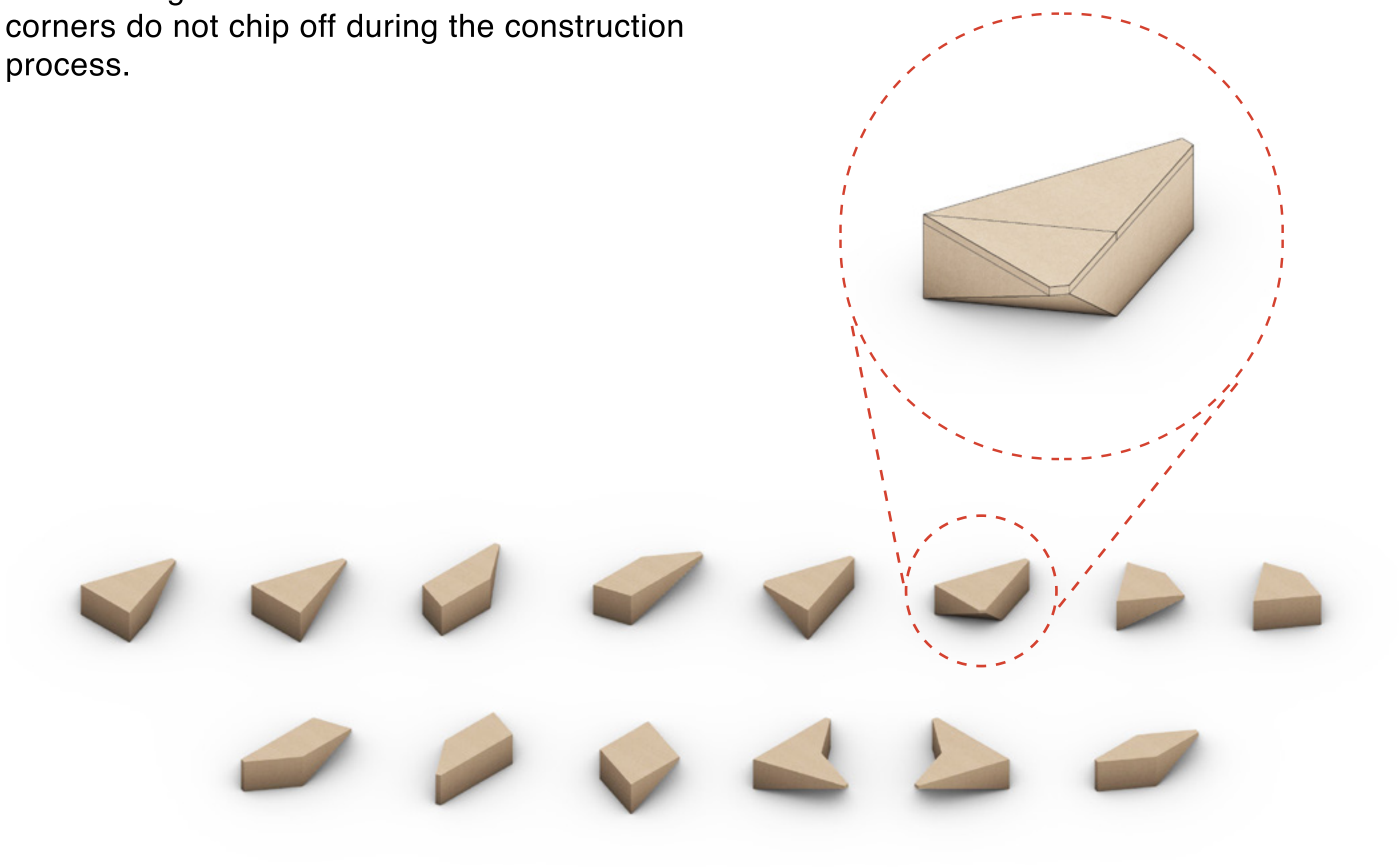


Figure 137 - 14 brick modules for the Muqarna I Source: authors

5.3 CONSTRUCTION TOOLS

Since resources are scarce in the camp, innovative solutions with available materials needs to be considered for construction. Basic construction tools such as shovel, bucket, trowel, rope, measuring tape, hammer etc. have been taken into account which can easily be found in any developing countries.

Apart from the basic tools used for building construction, some waste materials generated from the camp are used to build a formwork system for the project. According to a discussion paper 'Trash Talk' by Oxfam organization in 2017, the most common recyclable materials found in the camp are cardboard, plastic, metal etc. as shown in the figure alongside.

Since cardboard constitutes 48% of the recyclable waste material generated from the camp, it has been used as the primary material for the proposed formwork system. Along with this used plastic bags and scrap wood is also used which can be found in the camp. Other materials such as scissors, adhesive tape and glue are used to make the formwork. A metal chain is used to determine the catenary curve.

Figure 139 - Basic construction tools I Source: authors

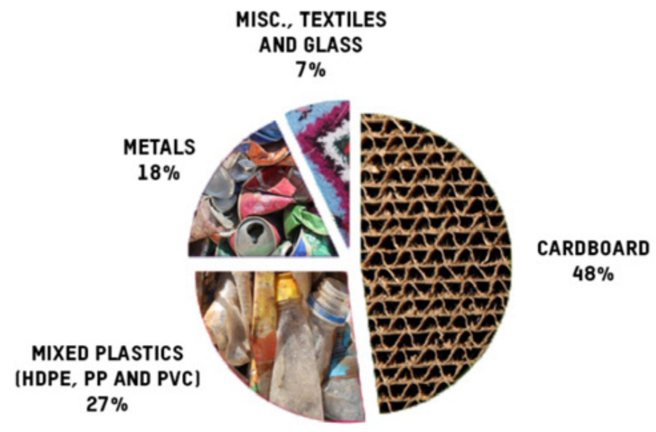


Figure 140 - Recyclable materials I Source: Oxfam

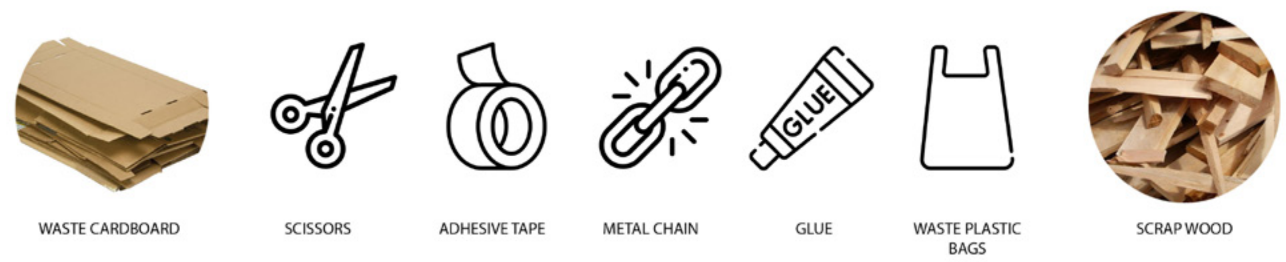


Figure 138 - Formwork materials and tools I Source: authors

5.4 FORMWORK

The waste cardboard is cut to the desired shape and size using scissors to form grid boxes similar to grid dividers used in the packaging industry as shown in figure 142. An overall width of 350 mm is maintained which is slightly wider than the arched ribs of 300 mm that would be constructed on site. The dimensions of the grid would be estimated practically on site depending on the thickness and quality of the cardboard available. The top and bottom surface would be sealed off with another peice of cardboard with the help of glue or adhesive tape.

The desired catenary curve would be drawn on the wall after which the cardboard box would be bent to achieve the desired catenary shape as illustrated in figure 143. This concept gives a strong and stable frame that has also been used in making cardboard beds that has the structural capability of supporting several people as shown in the figure 141. The cardboard frame is covered with used plastic bags at the top face before it is used to keep it safe from the wet mortar. After its use in the construction process, it can be cut or joined together to be used as shelving units or other furniture items in the camp.

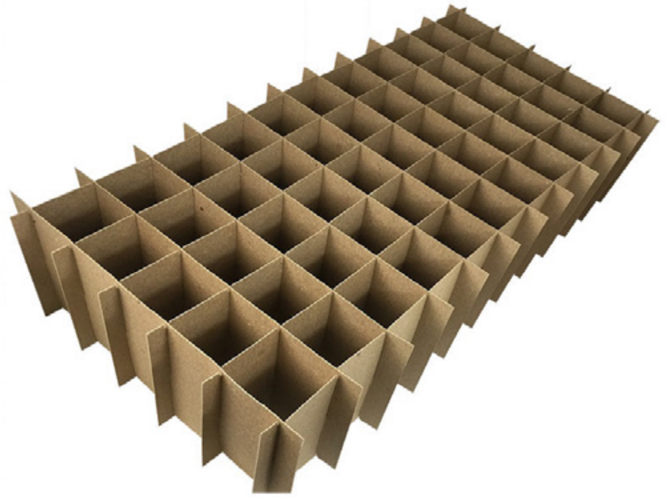


Figure 142 - Cardboard divider I Source: cactuscontainer

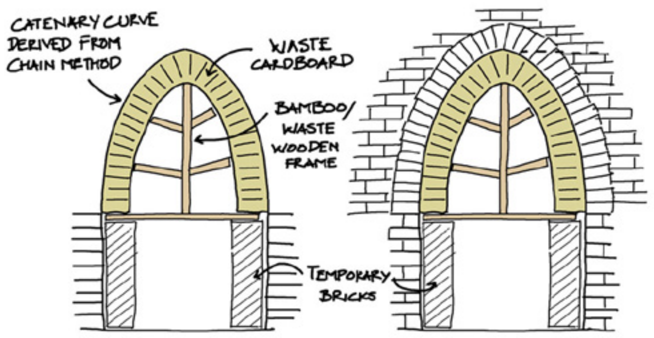


Figure 143 - Cardboard divider I Source: author

Figure 141 - Cardboard bed I Source: lushome.com

5.5 BUILDING PROCESS

Three of the roof typologies will be explained in terms of construction. The roof that will not be illustrated is the riwaq considering it has, for most parts, similar construction principles as the nubian vault used in the double story building. Another element being briefly looked at are the type of openings used.

5.5.1 RIBBED VAULTS

This roof typology is used in workshops, stores and exhibition hall. The following steps illustrate the construction sequence of these roofs.

Step 1 - 2. Position of the walls are marked and foundation trenches are dug upto the required depth. Locally available stones or burned bricks are filled in the trench and then the site is levelled manually.

Step 3. Walls are erected with arched door openings using an English bond brick laying pattern.

Step 4. The walls are finished upto a height of 2.4 m from the ground.

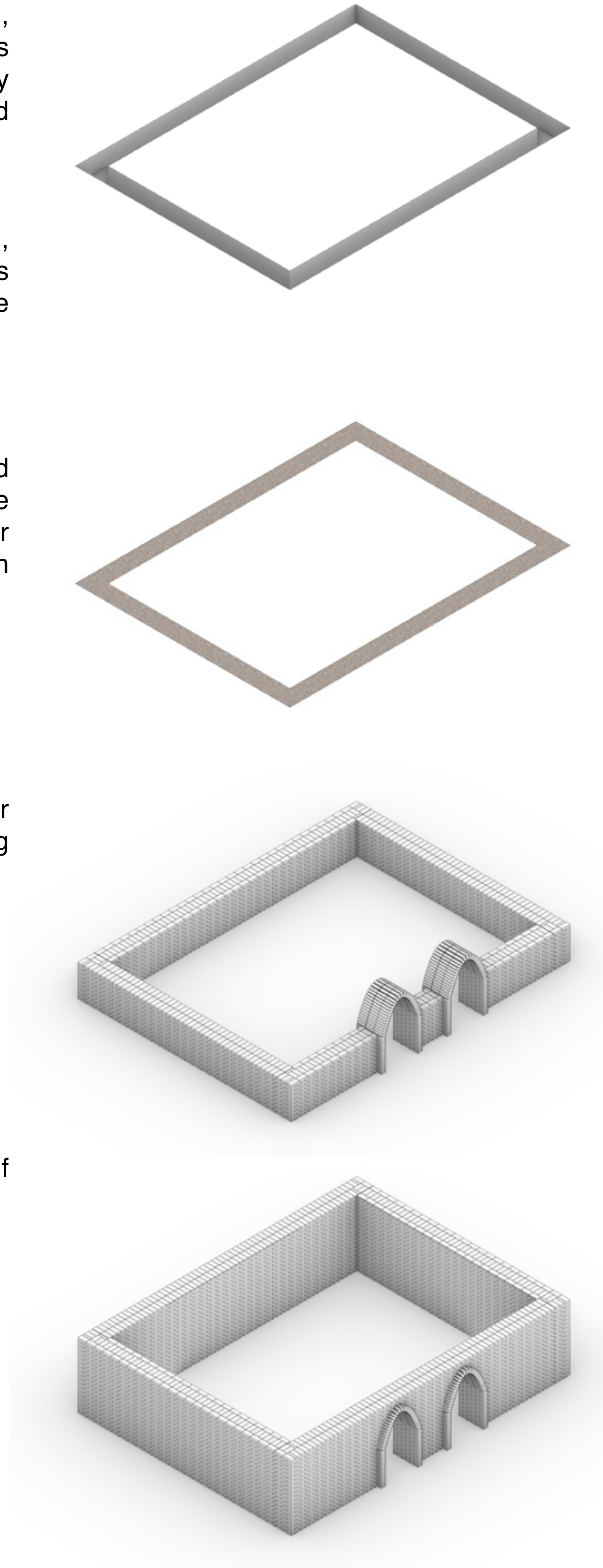


Figure 144 - Ribbed vaults, Step 1 to 4 I Source: authors

Step 5. Used cardboard is stuck on the wall using adhesive tape and using the metal chain, a catenary curve is drawn over the cardboard.

Step 6. Cardboard grid boxes are made along the catenary curve and covered with used plastic bags as explained earlier in the formwork concept.

Step 7. Cardboard ribbed arches are hoisted in position with the help of wooden supports made from scrap wood on both sides of the structure.This formwork is used over again for all the ribbed and Nubian vaults since the dimensions are all the same.

Step 8. Bricks are laid along the carboard formwork to form ribbed arches.

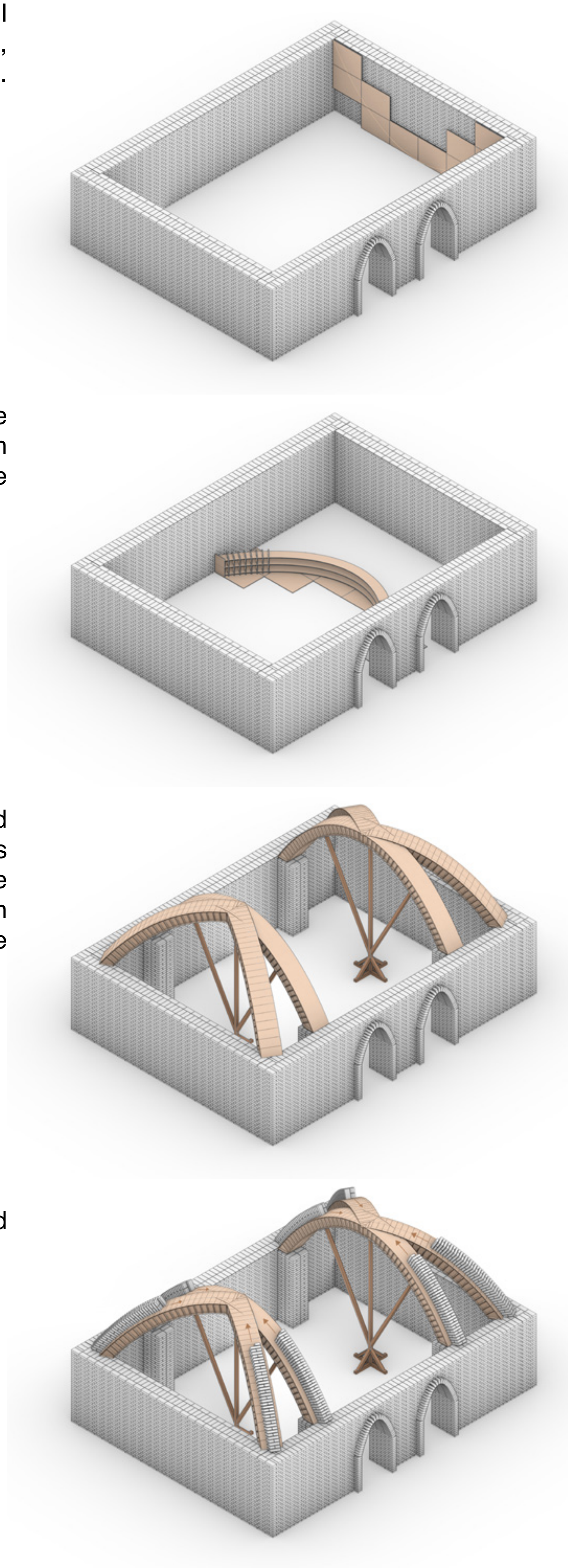


Figure 145 - Ribbed vaults, Step 5 to 8 I Source: authors

Step 9. Intermediate vault is formed between the parallel ribbed arches. This is done simlutaneously on both sides to meet in the middle.

Step 10. Rest of the roof is formed along the curved ribs.

Step 11. The roof is closed and completed from both the sides.

Step 12. Mud-plaster is applied on the roof and walls. Lime is mixed with mud plaster for water resistance.

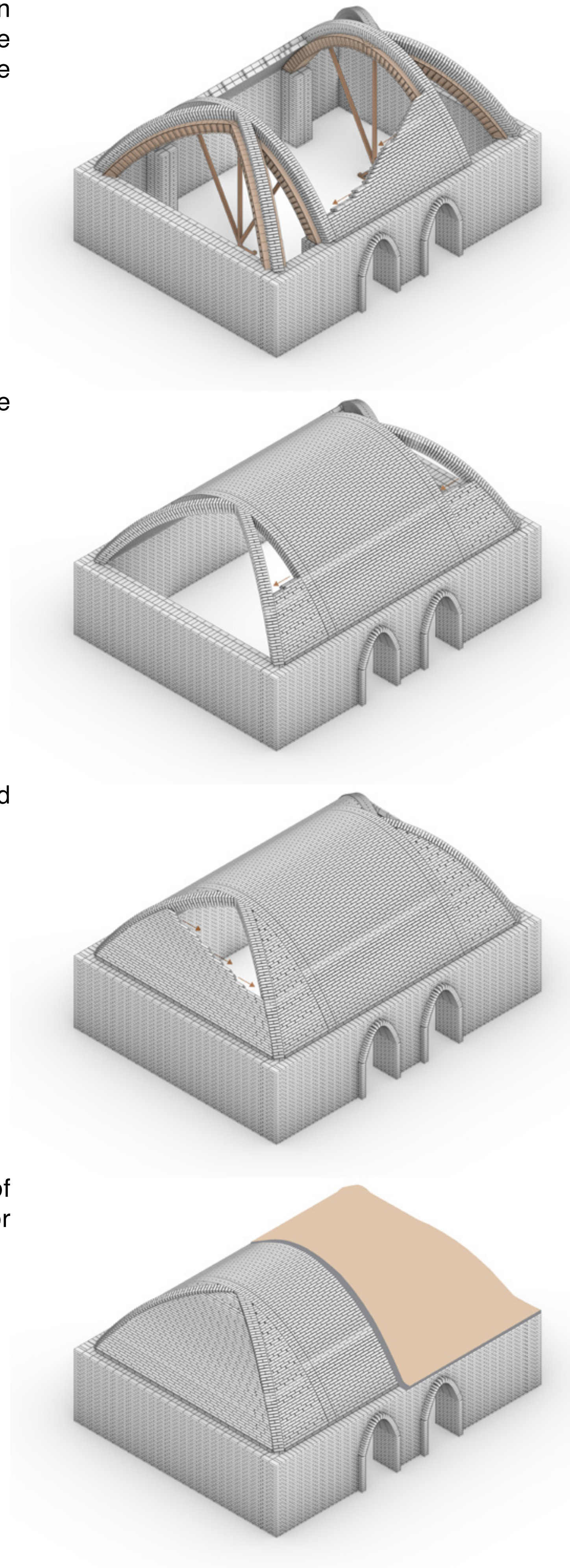


Figure 146 - Ribbed vaults, Step 9 to 12 I Source: authors

5.5.2 DOUBLE STORY

For the double storey nubian vaults, the first steps for this part of the building are the same as the steps of the ribbed vault. This includes laying the foundation and levelling the site. The next steps is to construct the walls with the English bond al the way up to the first floor level. When this is done the same fromwork as the ribbed vault can be used to get the correct arch which is then constructed. To get the first floor on top of the previous vault the difference needs to be filled with sand an then levelled. When the floor is constructed the next vaults can be build using once more the same formwork. The last walls are constructed and then the building is finished with mud plaster against weather conditions.

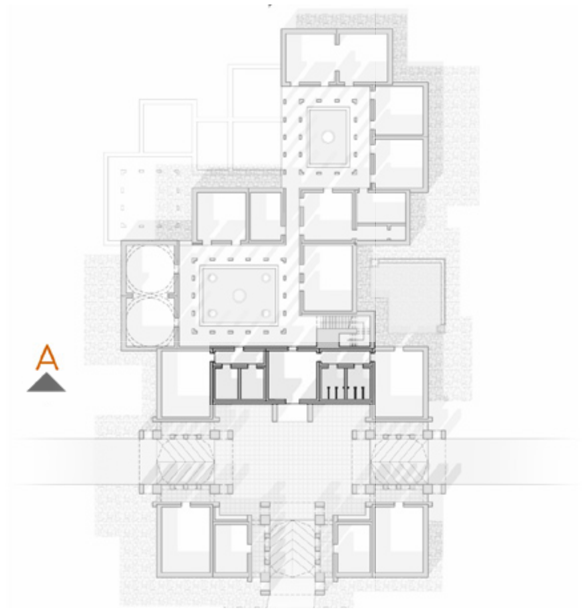


Figure 147 - Section placement I Source: authors

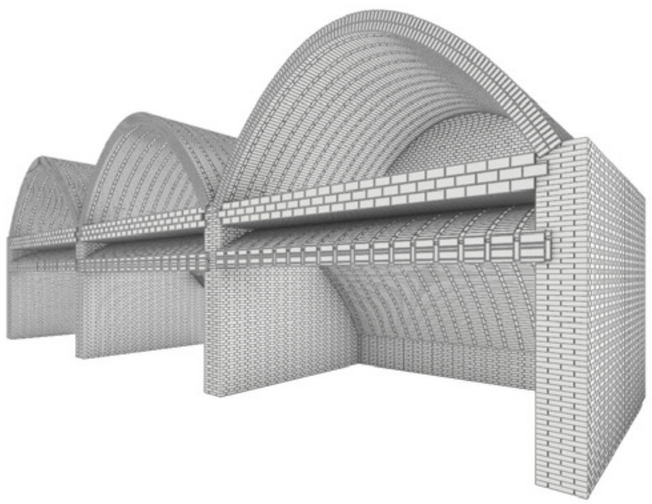


Figure 148 - Step 1 & 2: Foundation and levelling the site

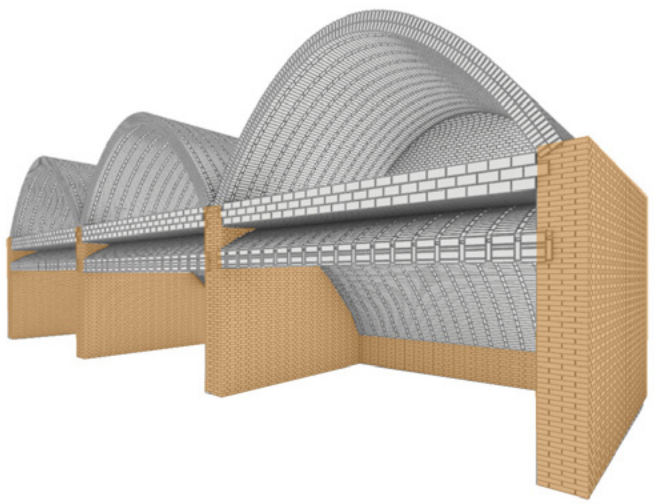


Figure 149 - Step 3: Construct the walls

Source: authors

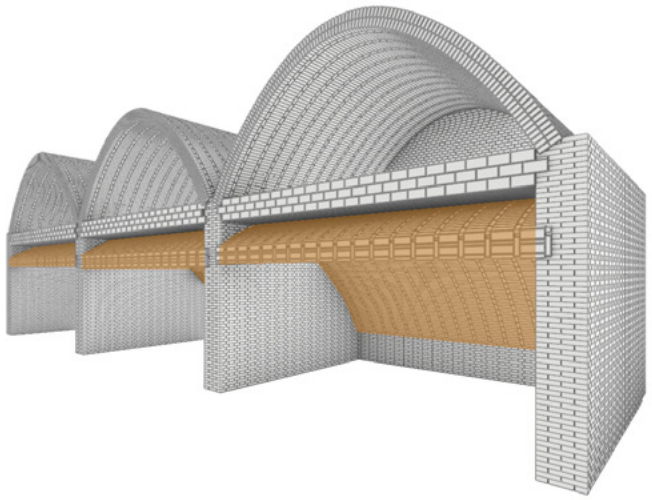


Figure 150 - Step 4: Construct the vault using the same formwork as before

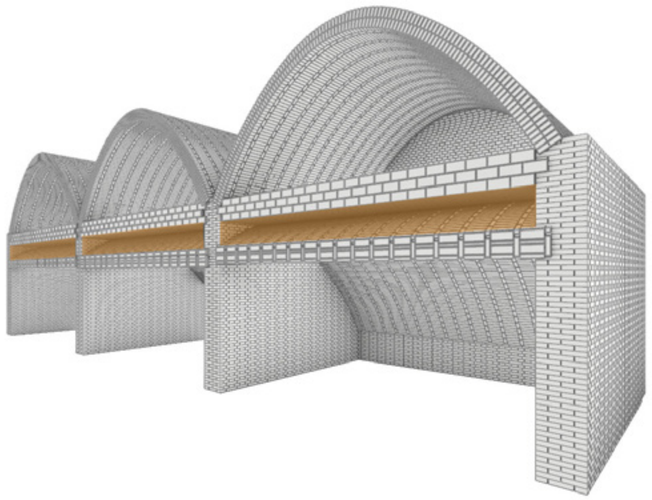


Figure 151 - Step 5: Fill in the gap with sand

Source: authors

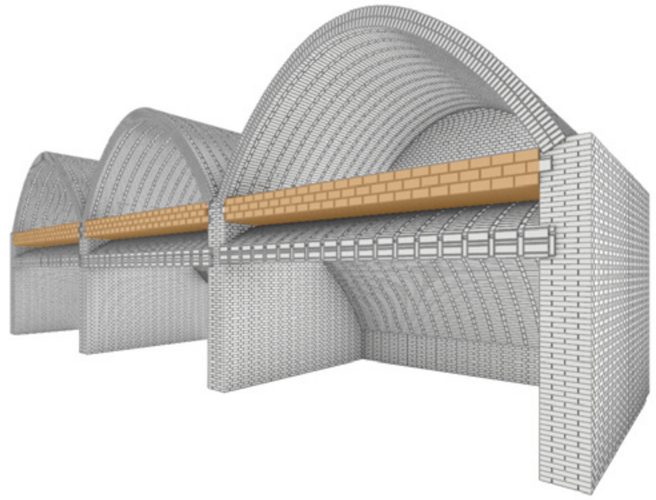


Figure 152 - Step 6: Level the sand and construct the first floor

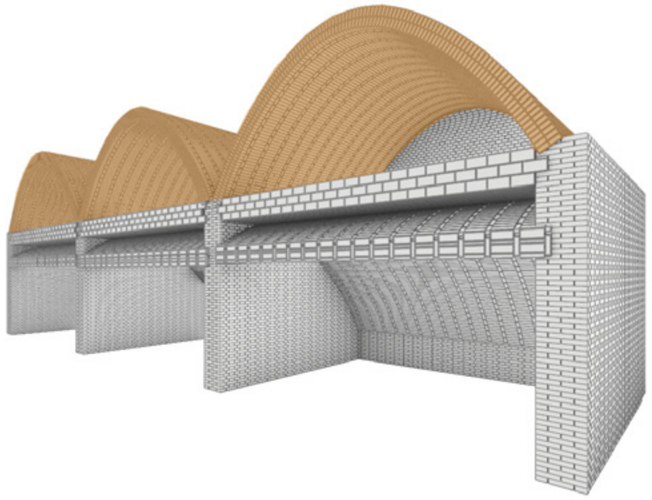


Figure 153 - Step 7: Construct the next vaults using the same formwork as before

Source: authors

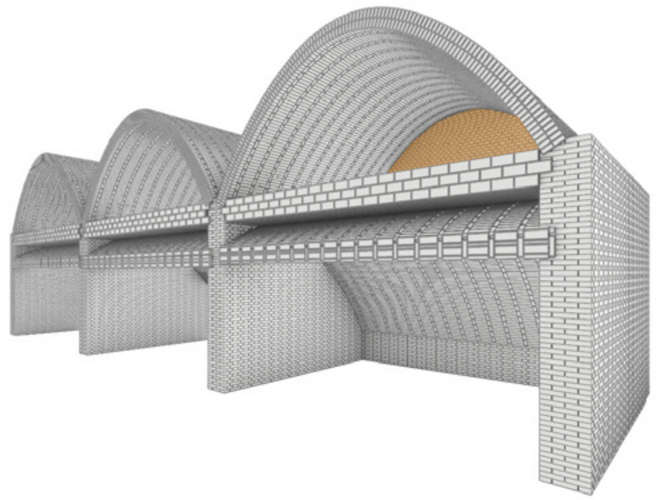


Figure 154 - Step 8: Construct the last wall, which can be completely filled or with a mashrabiya pattern

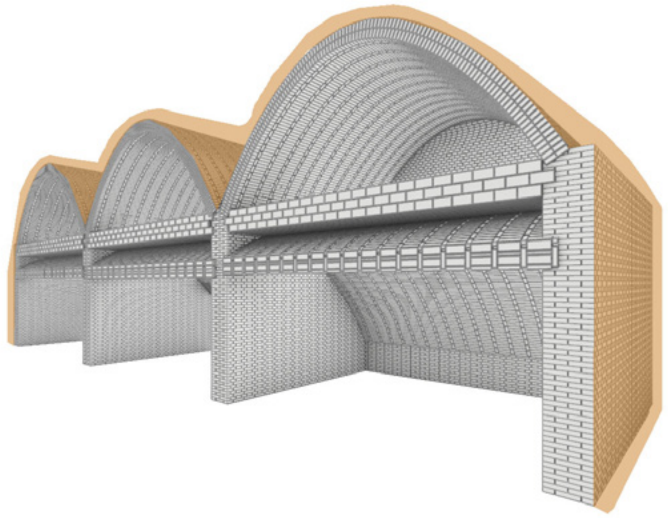
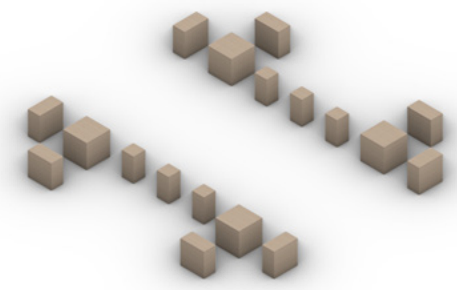


Figure 155 - Step 9: Finish with sand in between arches and mud plaster against weather conditions

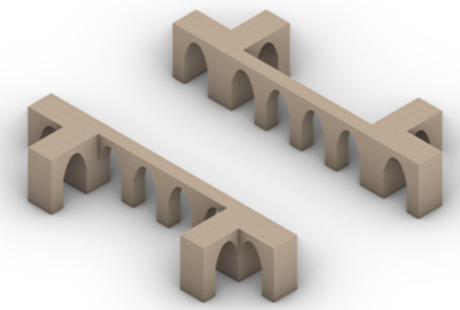
Source: authors

5.5.3 MUQARNA DOMES

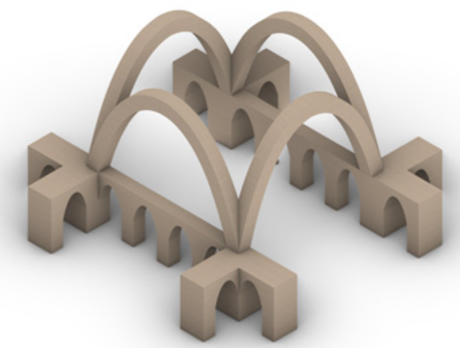
The following series of steps explain the construction sequence of the Muqarna domes.



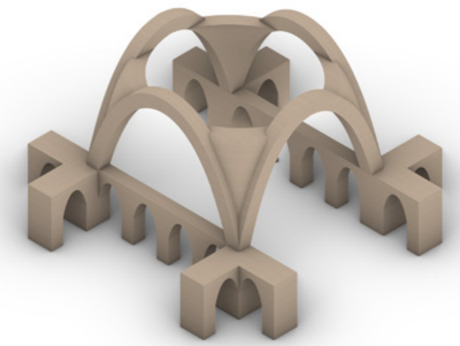
Step 1. After the foundation is made and the site is levelled, bricks are laid according to the plan upto 1.2 m height.



Step 2. The intermediate Riwaq catenary arches are constructed simultaneously upto a height of 2.4 m from the ground.



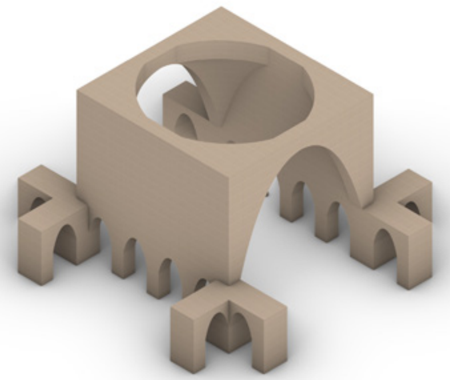
Step 3. Four catenary arches are constructed on four sides of the structure upto a height of 7.2 m from the ground.



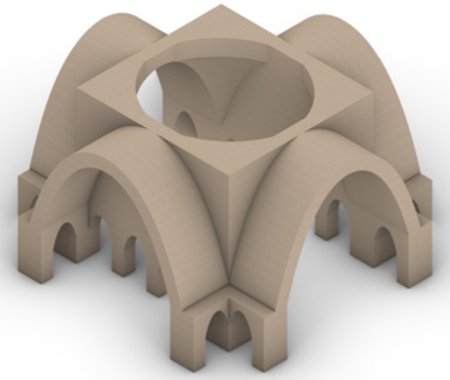
Step 4. The inner wall of the pendentives are made along these arches.

Figure 156 - Muqarna domes, Step 1 to 4 I Source: authors

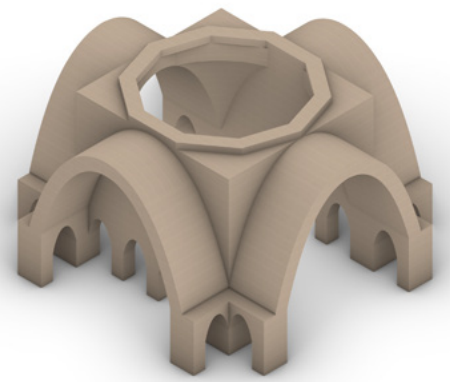
Step 5. The exterior face of the pendentives are made to form an orthogonal profile and the brick walls are made between the two arches.



Step 6. The catenary arches are extended according to the design to give stability to the central structure.



Step 7. A decagon ring is made to define the starting points of the Muqarna modules which sits on top of the pendentives.



Step 8 - 20. The 12 tiers of Muqarna dome have a corbelled dome stacking approach that are laid layer by layer from the inside with the help of bamboo scaffolding whenever necessary. Each tier uses modules as highlighted at the bottom of the image. The last tier of the dome is finished from the outside and a top element is laid consisting of regular bricks.

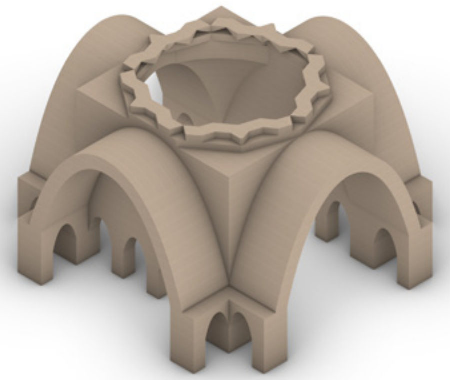


Figure 157 - Muqarna domes, Step 5 to 8 I Source: authors

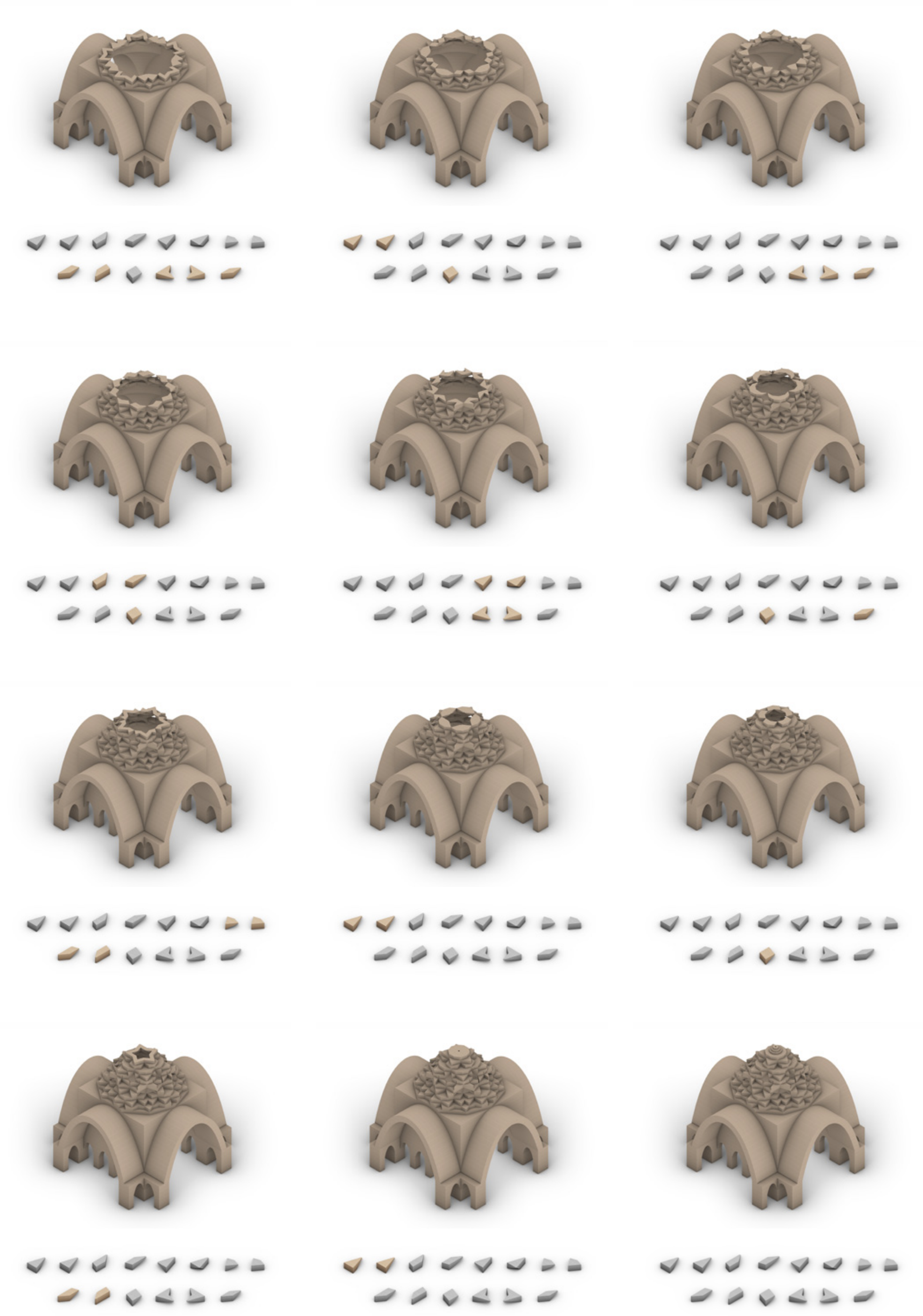


Figure 158 - Muqarna domes, Step 9 to 20 I Source: authors

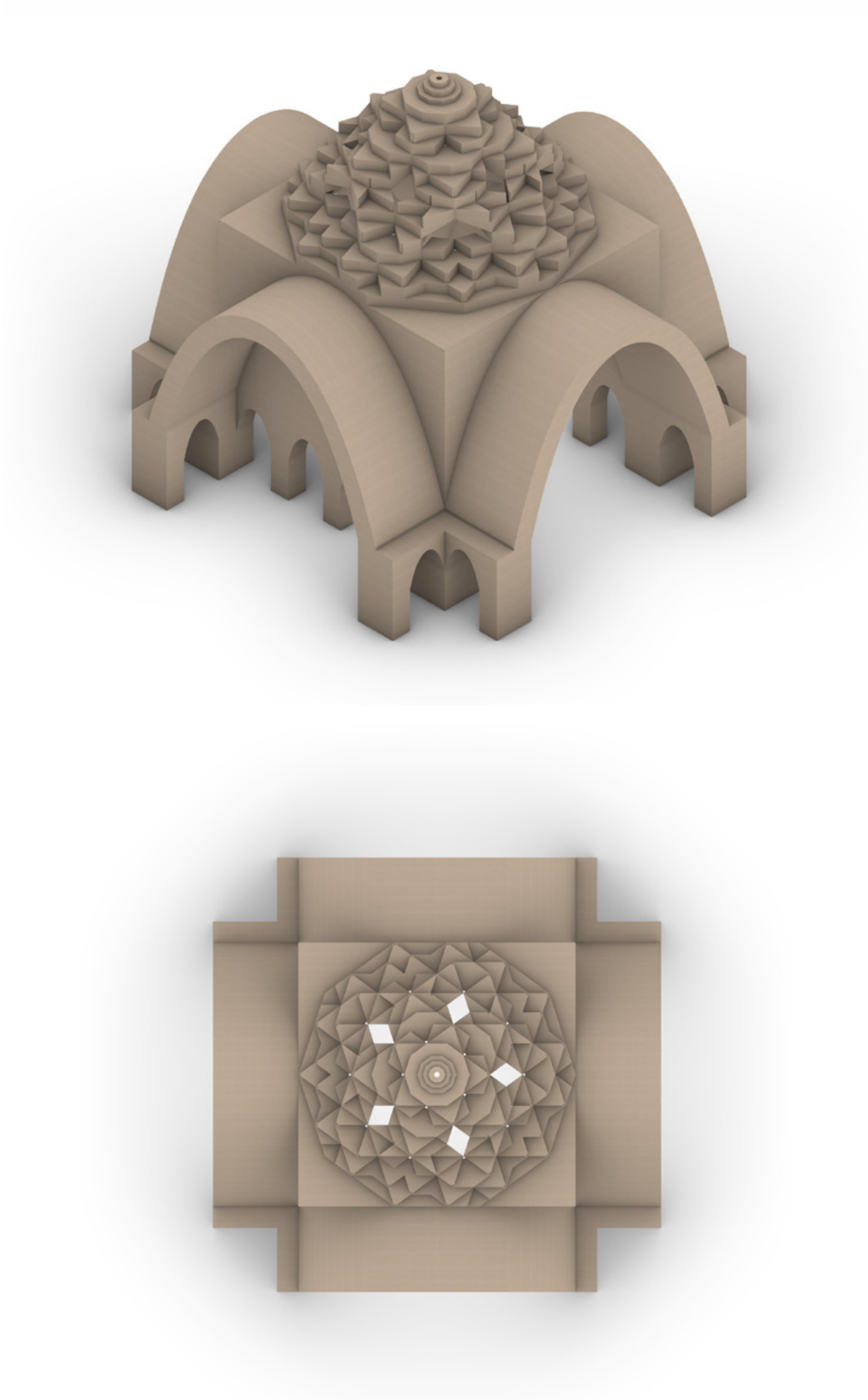


Figure 159 - Completed isometric and roof plan of the Muqarna construction I Source: authors

5.5.4 OPENINGS

For the opening we opted for two types. The first one can be seen in figure 81. It is a simple catenary curved opening. These will be located on the walls facing the inside of the building as the courtyards are a more private environment. In the same way the openings for entering spaces are made.

The windows facing the outside of the building a mashrabiya pattern was chosen to give more privacy for the users. This pattern called Herringbone Jaali screen can be found on many traditional buildings as can be seen in figure 83 and 84.

In figure 86 it is showed how the mashrabiya patter will be build, this is done form the inside after the curve is already in place.

Figure 160 - Simple catenary opening I Source: authors

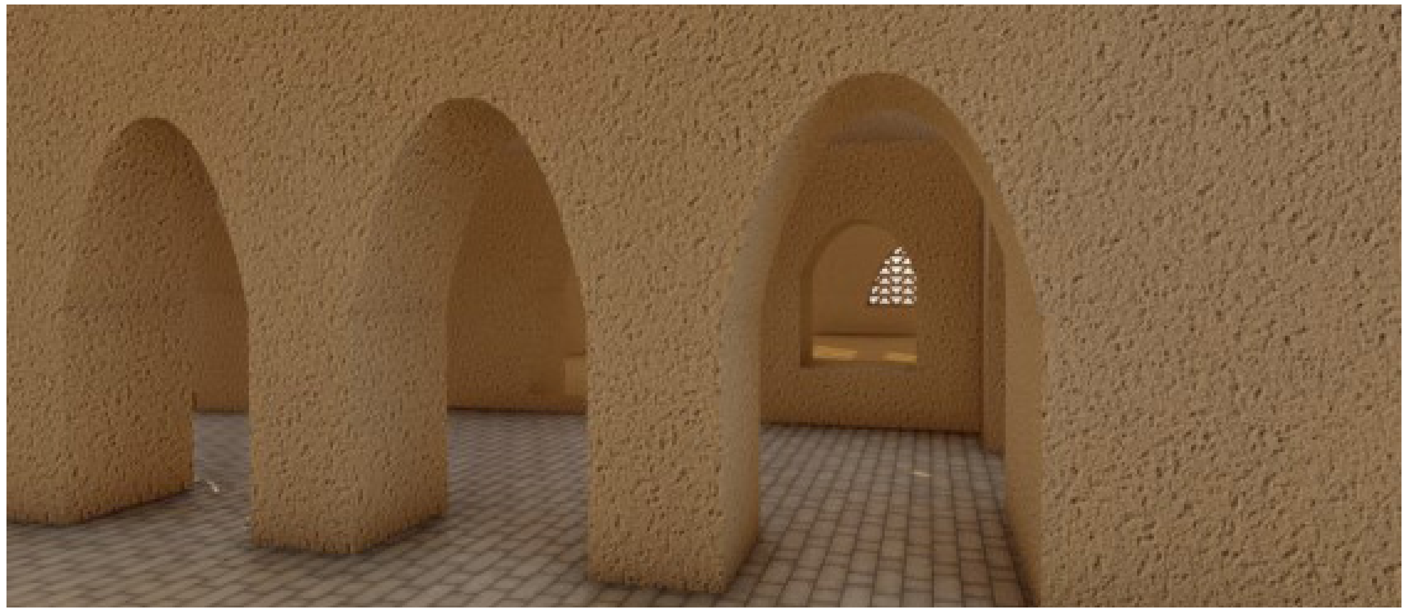


Figure 161 - View from inside the courtyard I Source: authors

Figure 162 - Mashrabiya ex. I Source: see bibliography

Figure 163 - Mashrabiya ex. I Source: see bibliography

Figure 164 - Masharabiya window I Source: authors

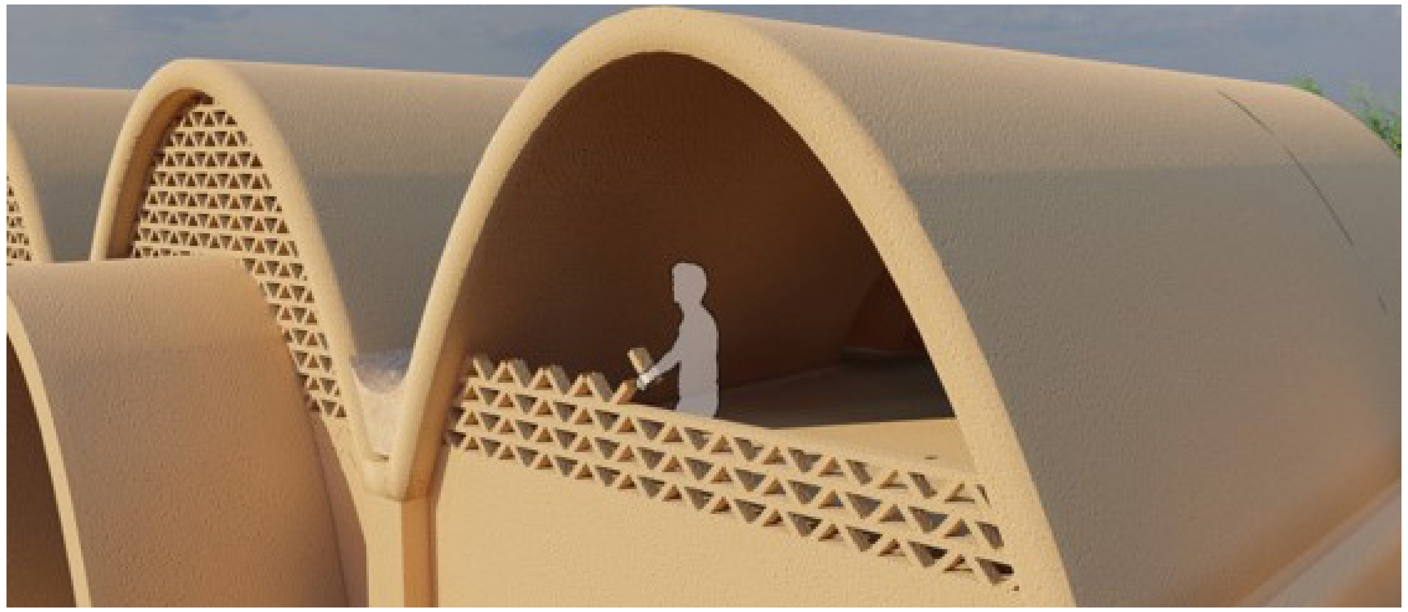


Figure 165 - Mashrabiya window being build I Source: authors

6 REFLECTION

We are so used to the modern way of building that we so often forget why ancient methods were used in the first place and how that is more effective than one would initially think. During this course a greater insight to the roots of building brought a better understanding of construction principles. Furthermore it allows us to see that even though we can build everything computationally, which helps, we always need to take human error into account, so simplification is keen. One thing we think will be interesting to develop further is the muqarnas domes. The current tool creates the dome we envisioned, however a topological approach can allow this tool to create even more domes based on the Penrose or other triangular patterns. Configuration can also be improved in the future by making sure the room adjacacies defined orthogonally to ensure proper room clustering.

In general the final aesthetic achieved by the final chosen method of creating the muqarnas is precisely as it was envisioned. The variability in the pattern, along with the final limited amount of modules, creates a dome which mimics the muqaranas ideology while being its own distinct evolution of the concept.

Some specific methods used within the steps could be expanded upon, due to the main downfall of the script which is its lack of responsiveness. The final script, up until Piece Four: Pairs, is completely responsive. The generation and sorting of the polylines have the ability to react to any subdivision of the penrose pattern. However from this piece of the code onwards, too many elements were manually defined for the computer which shall now be elaborated upon.

As it currently exists, the python evaluates and manipulates geometries from the center of the shape outwards. However, due to the many start and stop points of the 'strings' . This method could more logically begin at the outer edges of the dome then work inwards. This simple shift in logic, unfortunately not realized earlier, will result in a displacement method which functions in a way aligned with the transfer of loads down the blocks, and will be compatible with a topological approach.

Sorting
The radial and distance sorting for the triangles became a sound method for dealing with the geometry, however in later steps the geometries are displaced vertically. While there are other critical faults within the displacement method, the potential to spherically sort the elements could prove helpful in future developments of the script (scratchapixel 2016). The modules themselves require a structural evaluation step, which will primarily concern adding mass to the flat portion of the modules in order to prevent a tipping motion, and to properly transfer the loads down vertically.

Should the modules be further manipulated, already displaced into their dome-like form, then having the elements sorted spherically will be a key functionality to have.

Topological Approach
The method employed to obtain the heights to which blocks must be displaced, along with the literal displacement, is the most non-responsive portion of the script. The approach is somewhat topological, but relies on giving the pattern to the script which means that any other level of subdivision will be unsuccessful. However, changing the number of sides of the polygon is an element which the script is able to respond to.

Public square
There is a possibility of creating a garden with water feature in the main public square as shown in the image alongside. However, since this is an intersection of major roads, there could also be some vehicular movement around it. Therefore, this part of the design is still flexible.

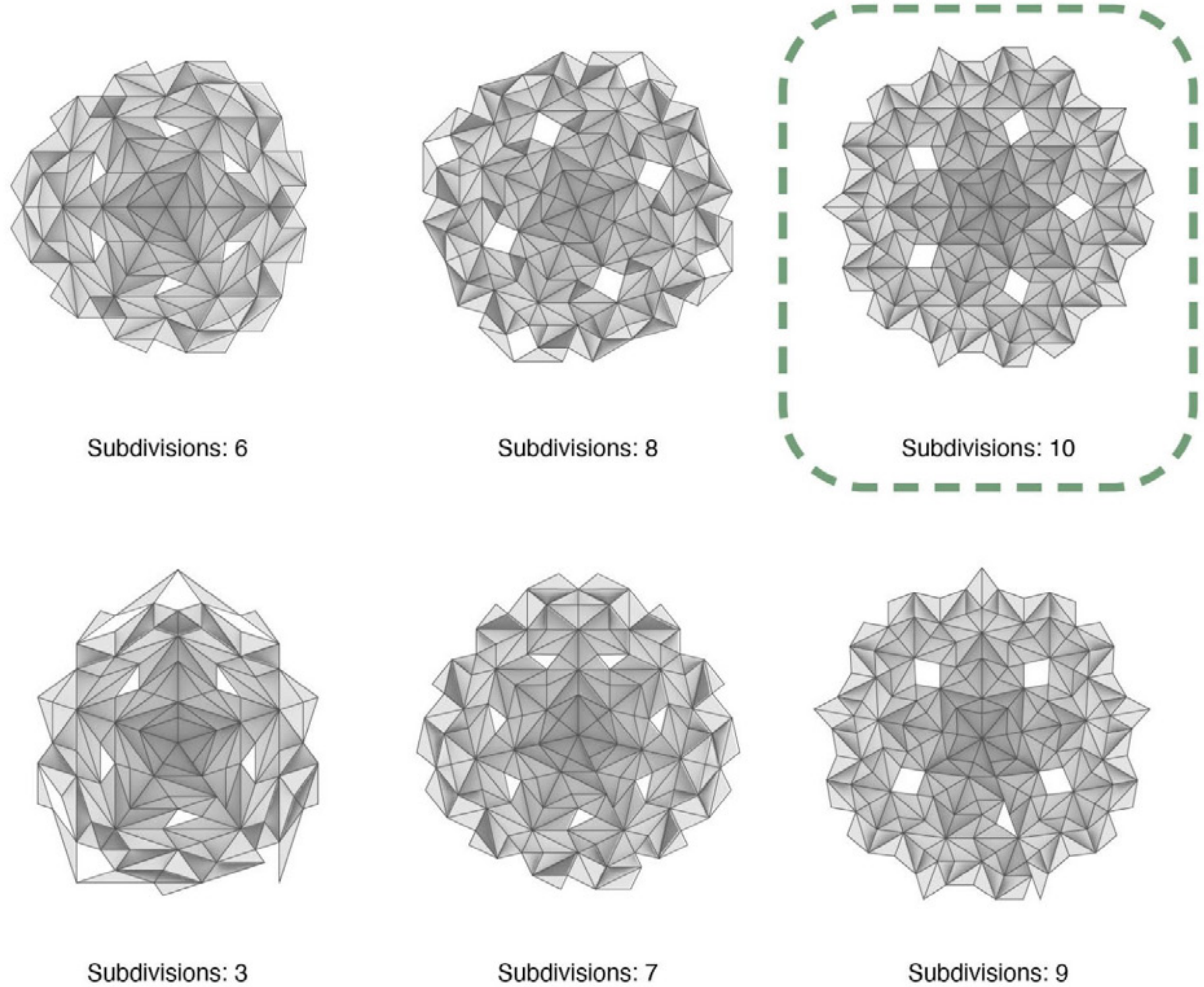


Figure 1 - Domes with different no. of sides I Source: authors

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FIGURES

Figure 1 - https://www.refugeesinternational.org/reports/zaatari-camp-and-not-city

Figure 2 - https://www.simplypsychology.org/maslow.html

Figure 18 - https://archnet.org/sites/1840/media_contents/37248

Figure 19 - https://www.goodfreephotos.com/turkey/other/entrance-gate-of-the-yesil-cami-in-bursa-turkey.jpg.php

Figure 20 - https://archnet.org/sites/2030/media_contents/8845

Figure 21,22,23,24,25,26 - http://www.lovedamascus.com/en/syrian-handicrafts

Figure 27 - http://www.xinhuanet.com/english/2019-06/23/c_138165155_5.htm

Figure 28 - http://www.lovedamascus.com/en/syrian-handicrafts

Figure 29 - https://alshahidwitness.com/ancient-syria-mosaic-weight-war/

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Figure 119 - whttps://en.wikipedia.org/wiki/Jameh_Mosque_of_Isfahan#/media/File:Gran_Mezquita_de_Isfah%C3%A1n,_Isfah%C3%A1n,_Ir%C3%A1n,_2016-09-20,_DD_34-36_HDR.jpg

1 INTRODUCTION

However, the struggle for refugees is multi-dimensional. The Syrians face a lot of humanitarian problems which does not support a good quality of life. The Youth sector of the

8 APPENDIX

8.1 PROGRAM OF REQUIREMENTS

Here the full program of requirements can be found.

Program	Sub-Spaces	approx. sqm	M2 per person	Number of Occupants	Space Type
Entrance lobby		35	1.5	20	Closed
Multipurpose hall		120	1.5	80	Closed
Main Courtyard		100		40-50	Open
Public square		200			Open
Secondary Courtyard		60		20-30	Open
Textile	Al aghabani Workshop Room	40	2	20	Closed
	Weaving workshop room	40	2	20	Closed
Pottery	Workshop Room	40	2	20	Closed
	Firing room	10		n/a	Closed
Storage 1 (textile + pottery)		20		n/a	Closed
Wood Work (2 rooms)	Workshop Room (also has spraying area)	80	2	40	Closed
Construction Skills (2 rooms)	Workshop Room- for lectures, demo	80	2	40	Closed
Storage 2 (wood work+ construction)		20			Closed
Shop (divided into multiple shops)		100	2	20	Closed
Exhibition Room		60	3	20	Closed
Chidcare		40	2	20	Closed
Office (small/admin)		15	1.5	10	Closed
Library		60	3	20	Closed
Conference/Meeting Room		30	1.5	20	Closed
Toilet		20		n/a	Closed
Storage		15		n/a	Closed
Kitchenette		10		n/a	Closed
	Net-area	**835**			
	Total area including open spaces	**1195**			

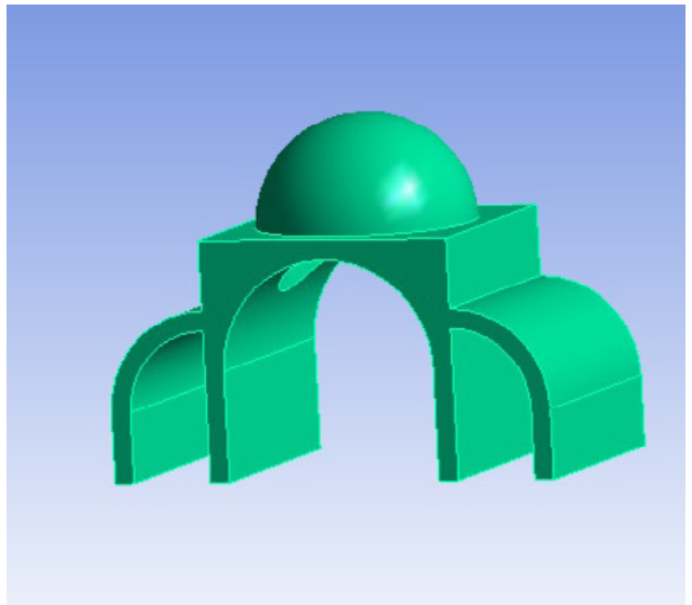
Figure 2 - Program of requirements I Source: authors

8.2 INPUT FOR CONFIGURATION

	Spaces	Orientation	Length	Width	Area	Grid size (m)		R	G	B
1	**Spaces**	**Orientation**	**Length**	**Width**	**Area**	**Grid size (m)**		**R**	**G**	**B**
2										
3	Lobby	S	7.2	6	43.2	1.2		50	50	50
4	Exhibition	N	9.6	6	57.6			253	228	155
5	Child care	W	7.2	6	43.2			255	125	145
6	Office	W	4.8	3.6	17.28			155	200	225
7	Toilet	W	4.8	4.8	23.04			217	231	253
8	Main storage	W	3.6	3.6	12.96			217	217	217
9	Kitchenette	E	3.6	3.6	12.96			145	215	220
10	Multipurpose hall	E	14.4	8.4	120.96			55	170	180
11	Weaving workshop	N	7.2	6	43.2			255	165	100
12	Pottery workshop	E	7.2	6	43.2			255	165	100
13	Firing	S	3.6	3.6	12.96			192	0	0
14	Storage 1 (textile, pottery	W	6	3.6	21.6			217	217	217
15	Wood workshop	E	7.2	6	43.2			255	165	100
16	Construction workshop	W	7.2	6	43.2			255	165	100
17	Storage 2 (wood, cons)	W	6	3.6	21.6			217	217	217
18	Wood workshop	E	7.2	6	43.2			255	165	100
19										
20										
21	Shop	S	7.2	6	43.2			100	100	100
22										
23										
24	Al aghabani workshop		7.2	6	43.2					
25	Library		9.6	6	57.6					
26	Conference/meeting		6	4.8	28.8					
27										

8.5 MUQARNAS DOMES STRUCTURAL ANALYSIS

Within this part of the appendix a more stepped way can be seen of the process of optimizing the arched passageways structurally. An important thing to take into consideration is that the deformations results seen on the right side only take self-weight of the structure into account. The other loads only where applied later on, that result can be seen in the report within chapter 4.2.



humanitarian problems which does not support a good quality of life.

Figure 3 - Base Model I Source: authors

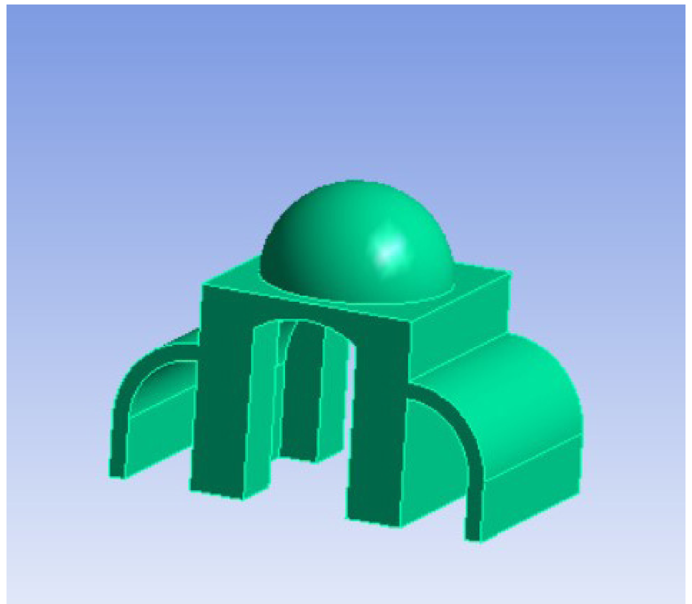


Figure 4 - With columns I Source: authors

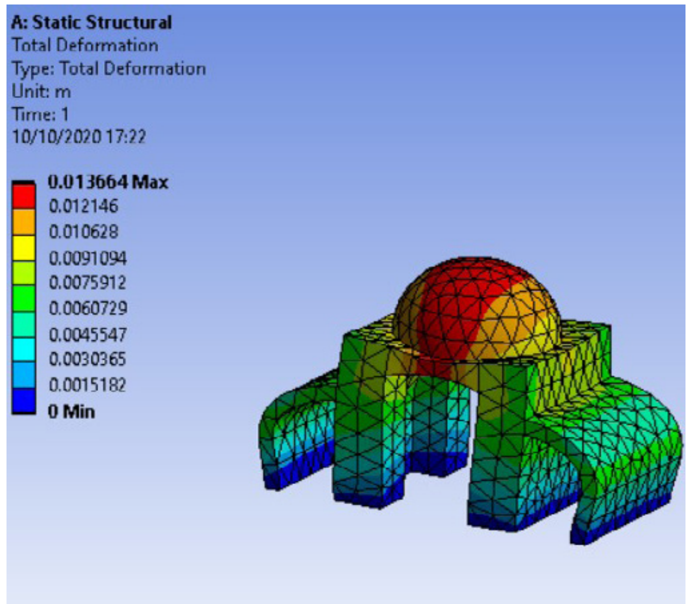


Figure 5 - With columns deformation I Source: authors

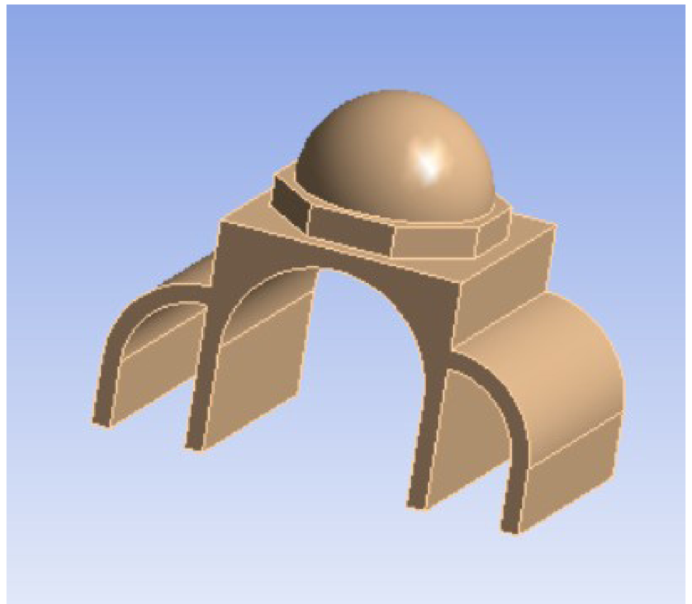


Figure 6 - With tension ring I Source: authors

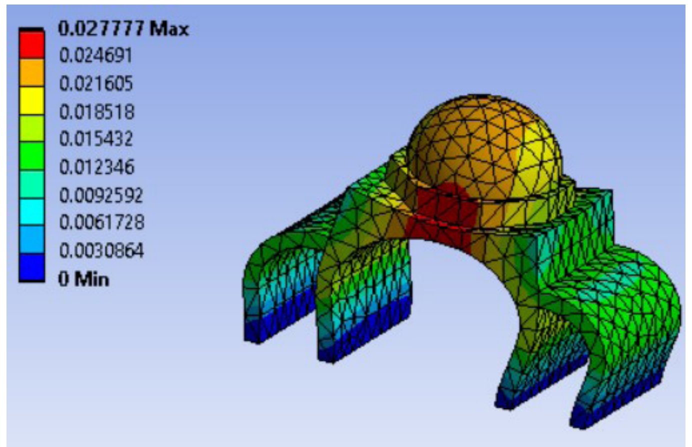


Figure 7 - Tension ring deformation I Source: authors

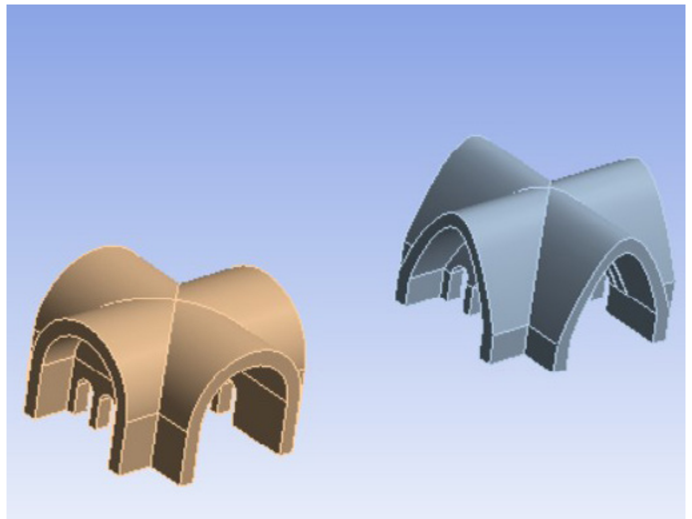


Figure 8 - Round arch vs catenary I Source: authors

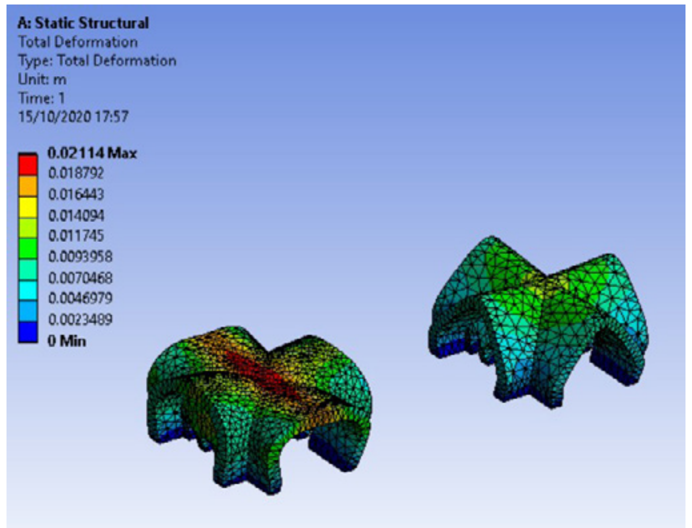


Figure 9 - Round vs catenary arch I Source: authors

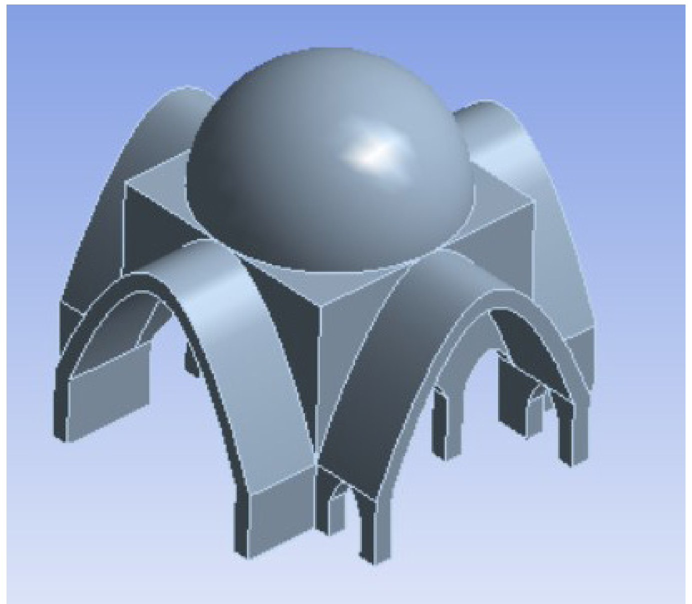


Figure 10 - Roughly final shape I Source: authors

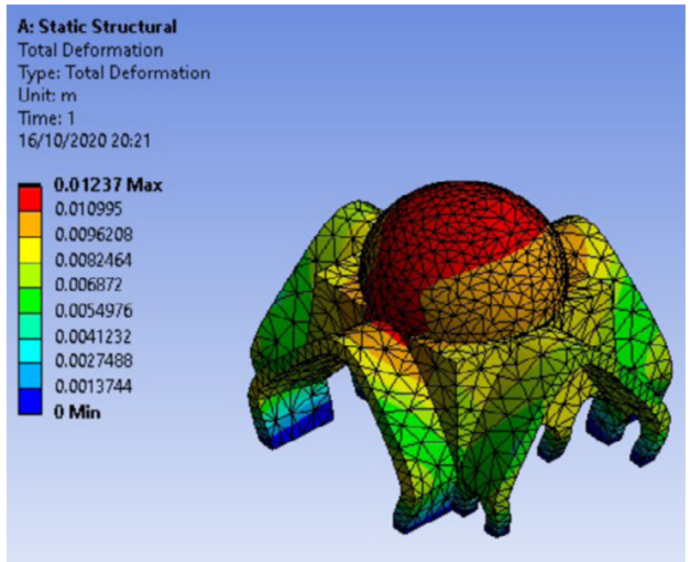


Figure 11 - Roughly final shape I Source: authors

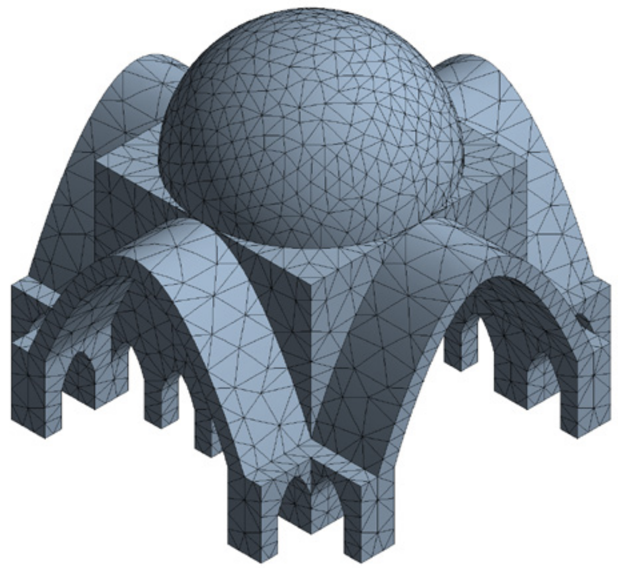


Figure 12 - Final shape I Source: authors