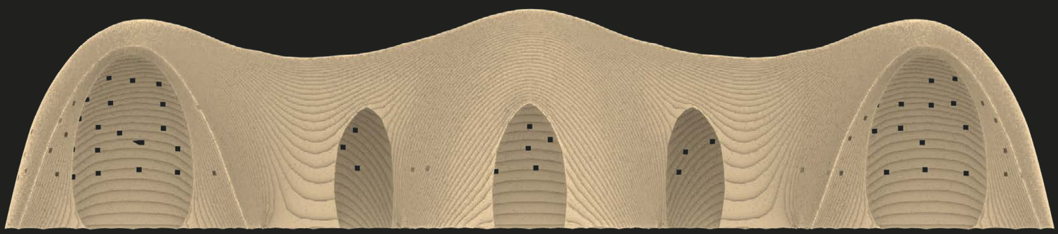

EARTHY STRUCTURE REPORT | **SKILL** DEVELOPMENT CENTER

AL ZAATRI

DATE October 2018
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TU Delft

Ariel view of the Skill Development Center, Zaatari

Perspective of the complex from the Entrance

00CONTENTS

01INTRODUCTION

Zaatari refugee camp has been a major destination for the Syrians since 2011 when the major unrest erupted in Syria. It hosts about 83000 people according to UNHCR data. The refugee community's major concern is the lack of availability of food supplies, good accommodation and employment opportunities. A skill development center has been proposed to project the rich Syrian culture of the past and create a sense of security for the future.

Construction using adobe would be the most suitable and viable option as an economical and environment friendly solution. Adobe block is one of the oldest building materials which is used throughout the world. Almost 30% of the world's population lives in adobe structures. Its availability in abundance, durability and potential to offer a high thermal mass for hot and dry climate makes them significantly advantageous for a context of Jordan.

Over generations the adobe vaults and domes have evolved in terms of form and spans. But, it is less common to see a parametric approach using adobe as a building material. The goal of this project is to address the architectural demands and explore the form finding process by understanding the capacity of adobe blocks. In this report, the various approaches towards form finding has been elaborated and the structures have been validated using Finite Element Analysis (FEM) in Karamba 1.3.0.

Also, various methods of construction using compass and simplification of form using voxelization had been experimented. However, ancient construction techniques have also been studied to find relevance to this scenario and improvised to suit the design. The validated structures were then translated into a realistic building data to be used at site.

Fig. 1.1 View into the workshop

02ARCHITECTURAL CONCEPT

The war has moved people away from their home and they have lost a sense of identity, culture and livelihood, it's important to regain their past and secure their future. A center that could provide them employment and enrich them with culture is quintessential.

The project addresses the 41% target group of the age 18-45 years. The programme focuses on giving construction skills, education and traditional crafts. The dual nature of the center as an expression of space and knowledge hub induces a sense of belongingness to the community. Hence, the built form becomes a part of their lifestyle targeting the neighborhood.

The program is arranged around three courtyards which act as interactive social working areas. Two clusters consisting of workshops and art classes are interconnected by their respective courtyards, while, the cluster with educational classrooms are given more isolation. Mastabas (an islamic architectural feature) have been provided on the inside and outside for people to gather and express their culture. Moreover, the configuration and orientation of the built mass addresses passive climate design. Small perforations in the structure have been made to allow diffused daylight and cross ventilation inside the spaces ,henceforth, reducing the energy consumption during operation.

The form of the complex was developed using a Form finding Process based on the topological requirements of each space. The form was also influenced by understanding the structural stability of a shape during earthquakes. Also, the form was influenced by the constructibility of the form by the local inhabitants of Zaatari camp.

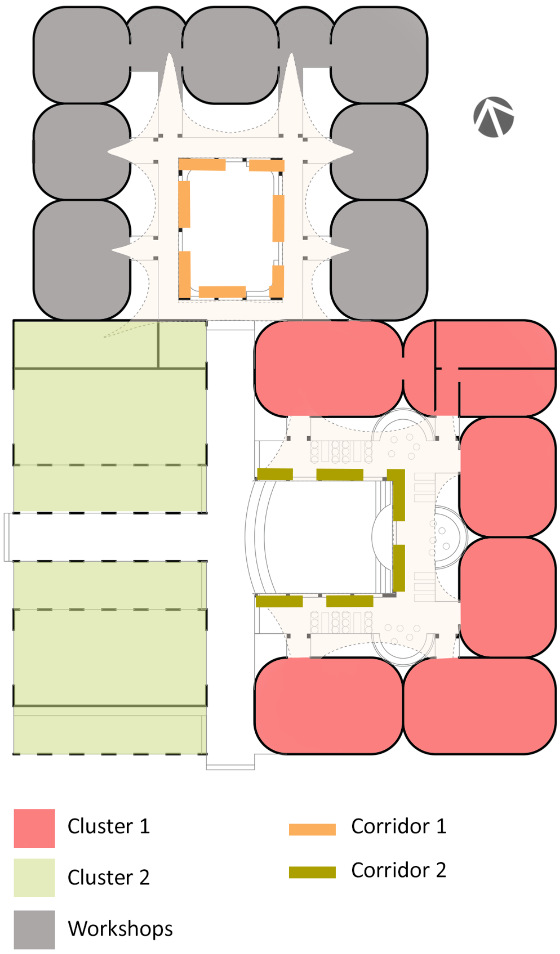


Fig 2.1 Key Plan

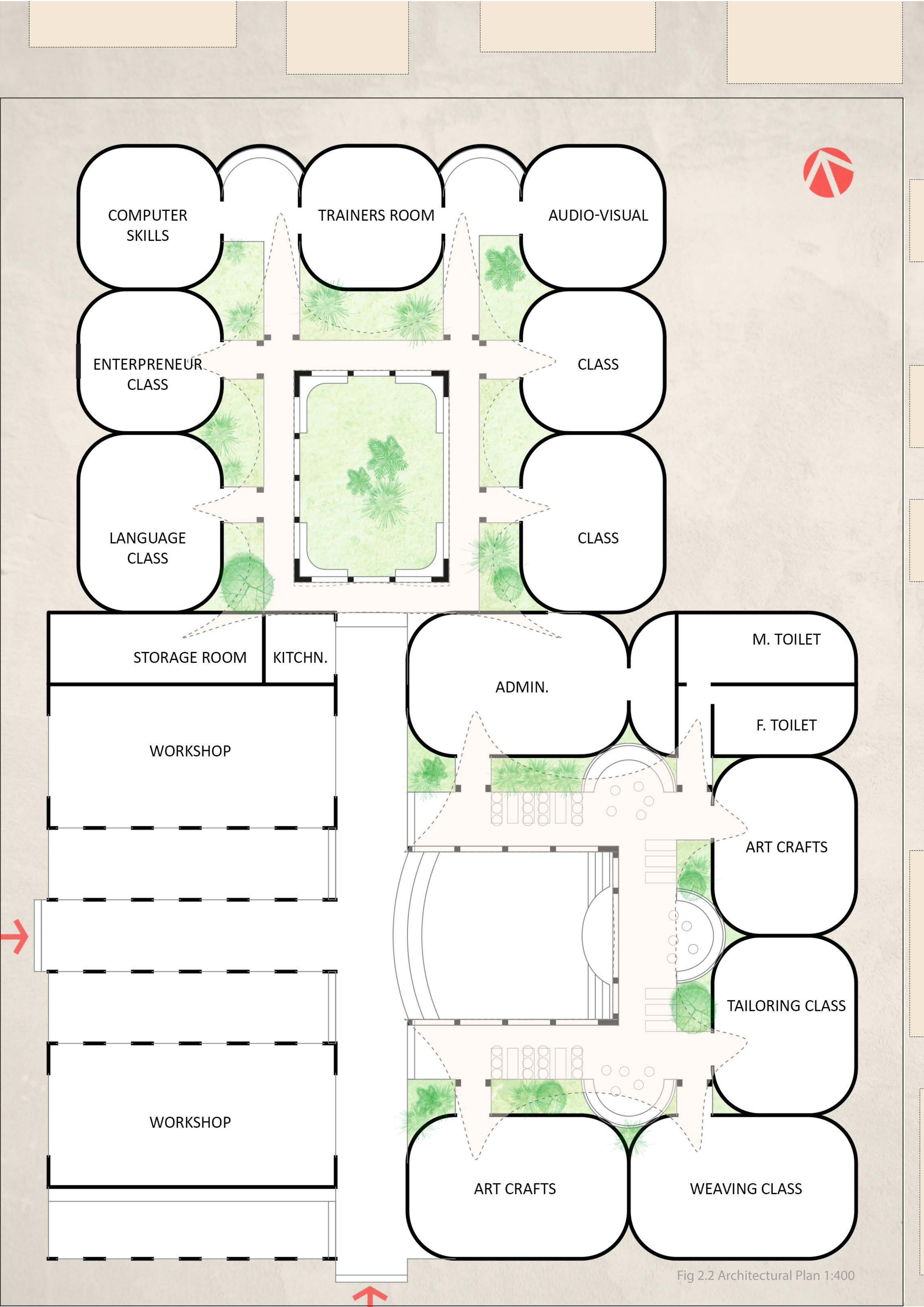


Fig 2.2 Architectural Plan 1:400

03FORM FINDING PROCEDURE

The architectural and spatial quality demands has helped in creating a plan of the various rooms. The profile of each room has been the driving factor in modeling the geometry of a space. This geometry is iterated further to create openings based on the circulation principles that are predefined by the architect which is explained in the next section.

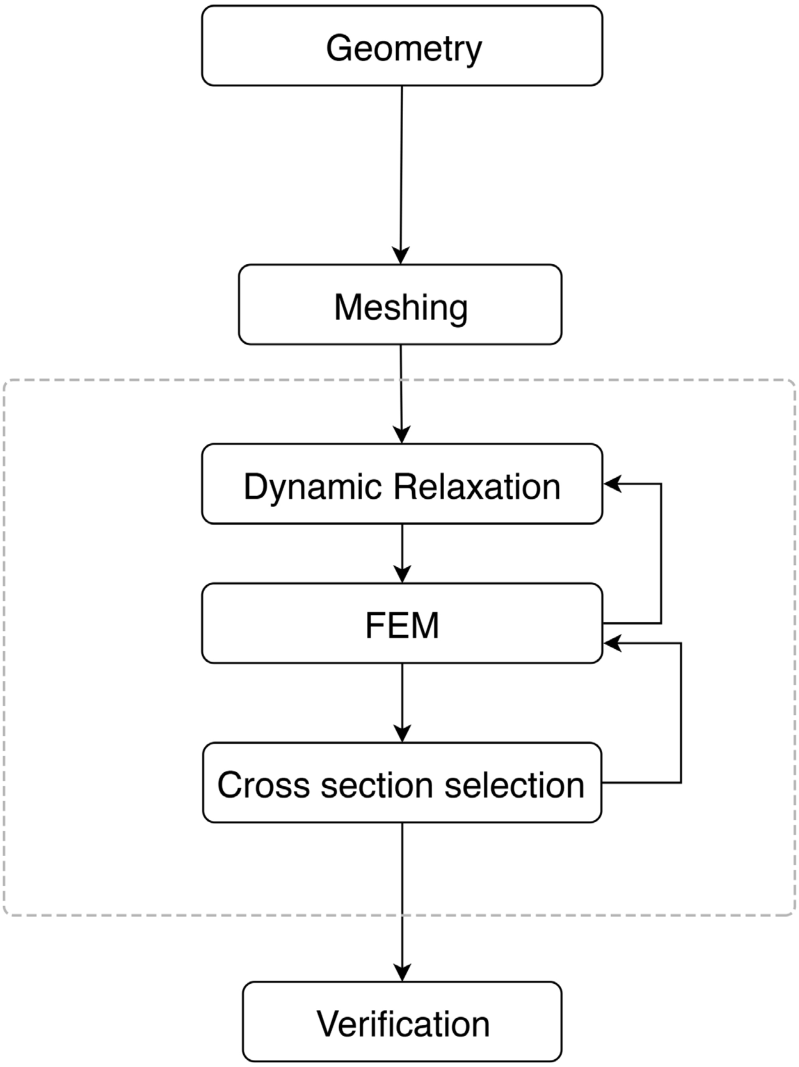


Fig 3.1 Form Finding Methodology

3.1 GEOMETRY

It is important to define the geometry before form-finding. Two types of preliminary geometries were used to approach this aspect. In approach 1, a surface was modelled into a mesh and relaxed in Kangaroo (a physics plugin in grasshopper). In approach 2, the plan was extruded into a 3d geometry that consisted of walls and a roof. This geometry was modified by making the required openings on the wall.

3.2 MESH GENERATION

Right mesh generation is the key to appropriate form finding. A fine mesh helps in a creating a smooth mesh output. Hence, mesh with a square grid size of 0.25 m had been found suitable to use for a structure of this scale. This grid size had been decided after exploring the mesh resolution of 0.15, 0.25 and 1m grids. The square grids have been triangulated further using the weaverbird triangulate component of grasshopper. The triangulation component diagonally sub-divides each of the square grid into two triangles.

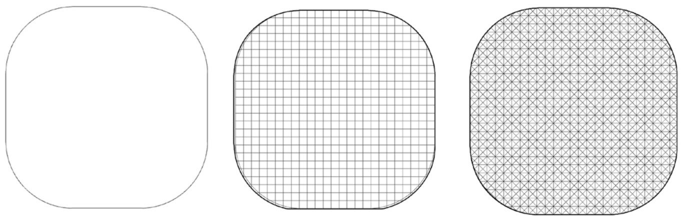


Fig 3.2 Mesh Generation

3.3 DYNAMIC RELAXATION

The Kangaroo component in grasshopper has been used for dynamic relaxation of the mesh. The components input are the mesh edges as springs, mesh points as particles where the load is applied and anchor points at the base for supports. The control on anchor points decides the form of the structure. The spring lengths from the mesh are set to original length which helps in avoiding tension in the form found structure. Load to be applied at each mesh point depends on the material properties. From calculation, it is understood that force vector between 3 N and 10 N could be applied for an adobe structure. (Appendix B)

3.4 FINITE ELEMENT ANALYSIS

Karamba 1.3.0 component of the grasshopper plugin has been used to analyse the form found structures. The structural mesh from Kangaroo is smoothened using weaverbird laplacian smoothing component before inputting it into Karamba. When a mesh is an output of 2d geometry relaxation, the surface edges are picked as the support points. If a 3d geometry is relaxed, the points of the edges of the base are the support points. The supports are fixed in translation along x, y and z direction while they are free to rotate along x,y and z axis.

The deflection for the structure must be:

$$\delta \leq L/400$$

Where, L = Maximum Span of the structure

3.4.1. Load Considerations:

There is no permanent load on the structure except the self-weight. Hence, two load cases have been considered with self-weight and prevailing winds. The highest wind speed in the region of Zaatari is 4.2 m/s [1] which is almost negligible. But, a uniform load of 8.47 N/m2 with a safety factor of 1.5 has been used to analyze the geometry.

Load case 1 = 1.2 x Self-weight of the structure

Load case 2 = (1.2 x Self-weight of the structure) + (1.5 x Wind load)

[1] https://weather-and-climate.com/average-monthly-Wind-speed,Amman,Jordan

Although region of Zaatari experiences earthquake once in every three years, no seismic loads have been calculated or applied for analysing the structural performance. The infill between the vaults and the walls on which the vault was standing resulted in the failure of the structures in Bam, Iran. So, while designing the form and relaxing the mesh in Kangaroo, these two major ideas were considered. Hence, special measures have been taken to design the form such that it avoids non-uniform loading and unnecessary dead load. The filleted rectangular form also adds to the stability during earthquake.

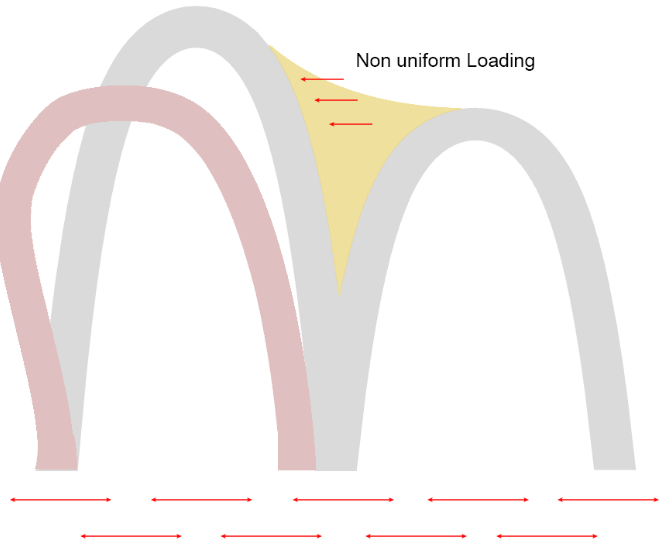


Fig. 3.3 Non Uniform Loading of infill between vaults resulting in failure during seismic movement

3.4.2. Material Properties

Brick making and testing at Material Science laboratory at TU Delft, Netherlands has helped us to understand the material properties of adobe with various stabilisers. Bricks were made with various stabilizers like straw, cardboard, fabric and paper strips were made and tested. Although cardboard is locally available at Zaatari, insufficient samples for testing made the results unreliable (Appendix-A). But 7 samples of plain adobe blocks were analyzed whose results for compressive strength and Young's modulus (E) were compared with the literature research to pick a value that could be used as material property. But values for shear modulus and specific weight had been selected from scientific papers.

The Young's Modulus :

From the experiment conducted the highest Young's modulus was calculated for specimen B1 (Table 3.1) with a value of 24 MPa, which is 4 times lesser than the minimum E of 100 MPa suggested in literature readings. From the specimens tested by Blondet and Vargas (1978) [2] mean elasticity modulus E= 100 MPa. They also suggest using values around 170 MPa for E, which were indirectly computed from full adobe wall tests. Hence, the result obtained from the laboratory tests were discarded and a value of 150 MPa has been chosen.[1]

Shear Modulus:

Blondet and Vargas (1978) [2] suggest using a shear module G MPa 70 (varying from 36 to 90 MPa). So, an average value of 63 MPa was assumed.

Specific Weight:

According to New Mexico State University, specific weight of the material has been calculated to be 19 KN/m3 .

[1] Sabino Nicola Tarque Ruiz (2011), Numerical Modelling of the seismic behaviour of adobe buildings (https://www.scribd.com/document/122179620/Numerical-modelling-of-the-seismic-behaviour-of-adobe-buildings)
[2] Blondet and Vargas (1978), Recommendations for Design and Constructions of Adobe Houses
[3] https://aces.nmsu.edu/pubs/_g/G521/

Yield Strength/ Maximum Allowable Compressive Stress

The table below indicates the results of compressive strength obtained from the experiment:

Specimen Label	Composition	Compressive Strength
B1	Plain Adobe Block	1.17
B2	Plain Adobe Block	0.79
B11	Plain Adobe Block	1.03
B12	Plain Adobe Block	0.81
B13	Plain Adobe Block	1.19
B14	Plain Adobe Block	0.65
B20	Plain Adobe Block	3.99

TABLE 3.1: Compressive Strength of the Bricks

The above mentioned specimen's average value of compressive strength at 5% strain is 1.37 MPa. According to Blondet and Vargas [1978] compressive strength of adobe ranges between 0.6 and 5 MPa. Hence, a value of 1 MPa is chosen as the compressive strength. But with safety factor of 2, 0.5 MPa is used as yield strength for the analysis. And 0.05 MPa is used as the yielding tensile stress (10% of the allowable compressive strength).

Cross-section selection:

A brick size of 240 mm x 240 mm x 120 mm has been chosen to allow for construction by guiding rod system. The reason for the preference of this size is explained in section 9.3.4. The cross-section size that is to be used in the analysis is decided based on the width of the brick. This has led to selection of 120mm, 240mm, 360mm and 480mm.

04FORM FINDING & FEM ANALYSIS

Two approaches were tested and one that performed satisfactory in terms structure has been taken forward. Approach 1 dealt with form finding a roof that rest on walls while approach 2 was a wholistic approach towards finding a unified form that included walls, openings and roof. The pros and cons of both the approaches have been dealt in detail below.

4.1. APPROACH 1:

The roof surface of the classrooms were generated with a mesh as defined in section 3.2. This mesh was processed in Kangaroo component for dynamic relaxation (Fig 4.1)

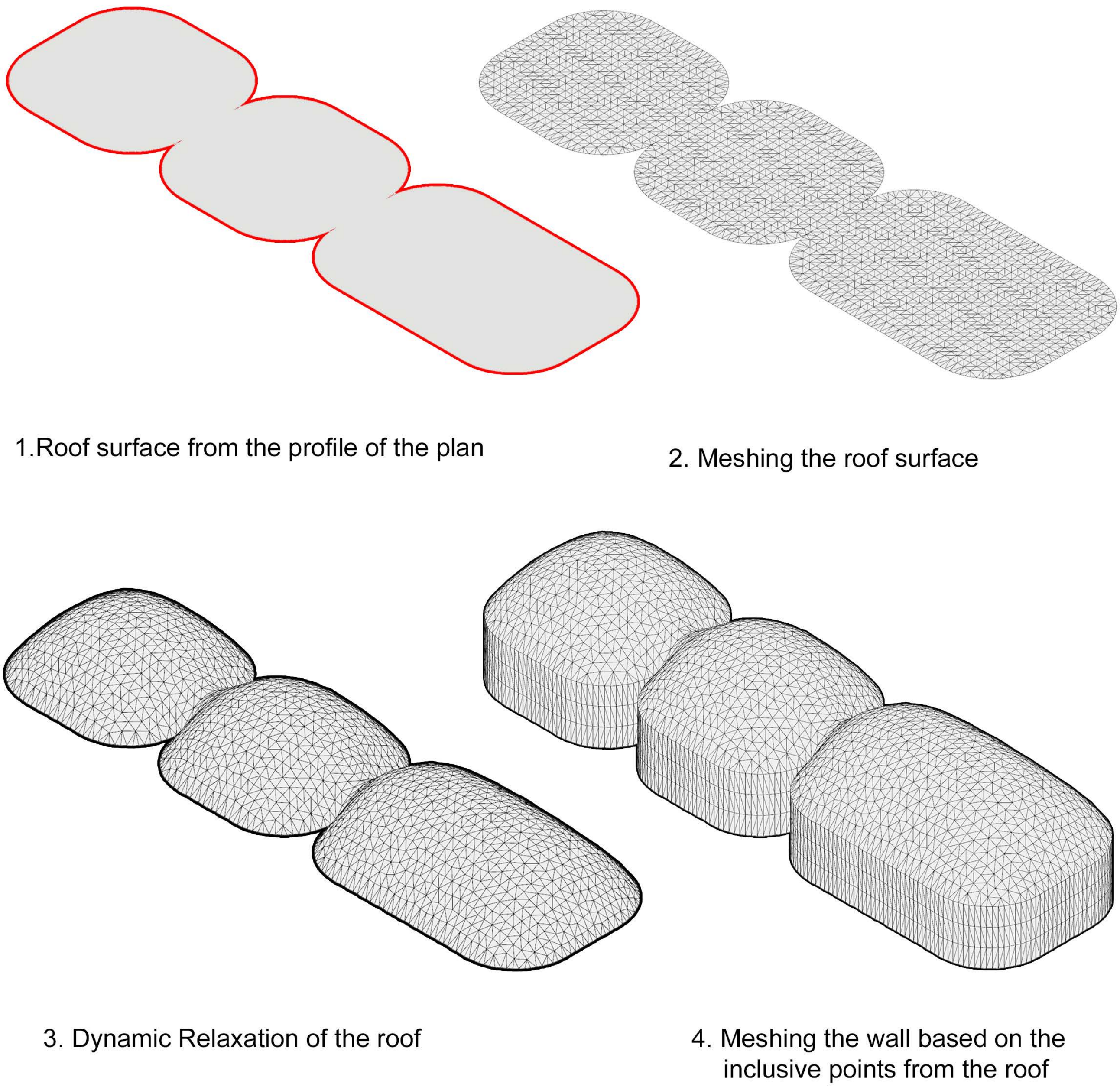
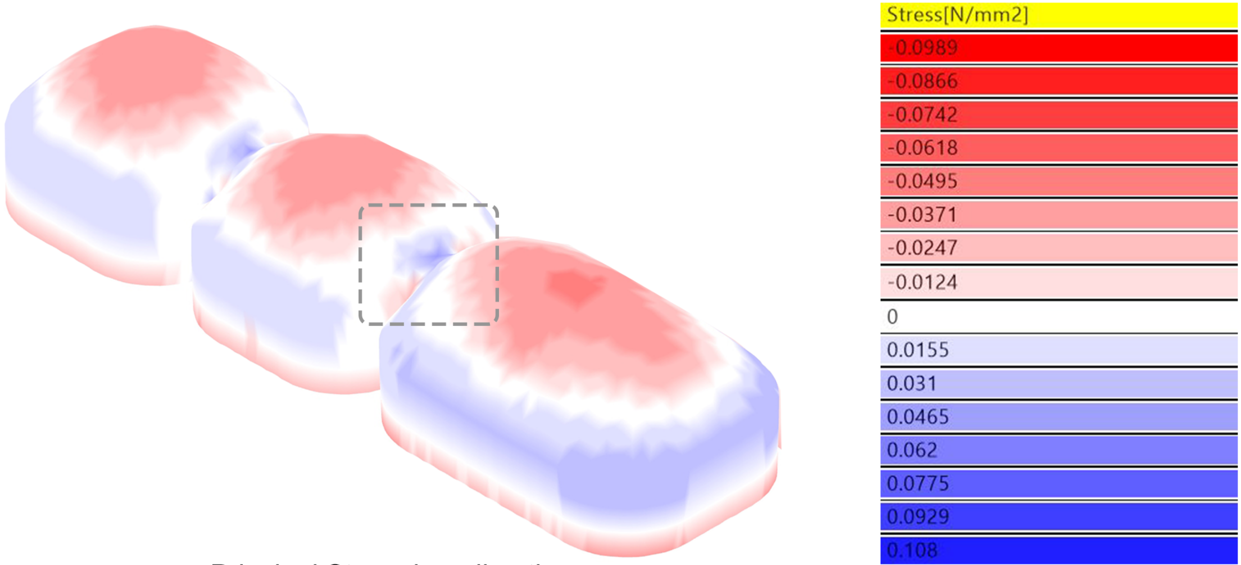
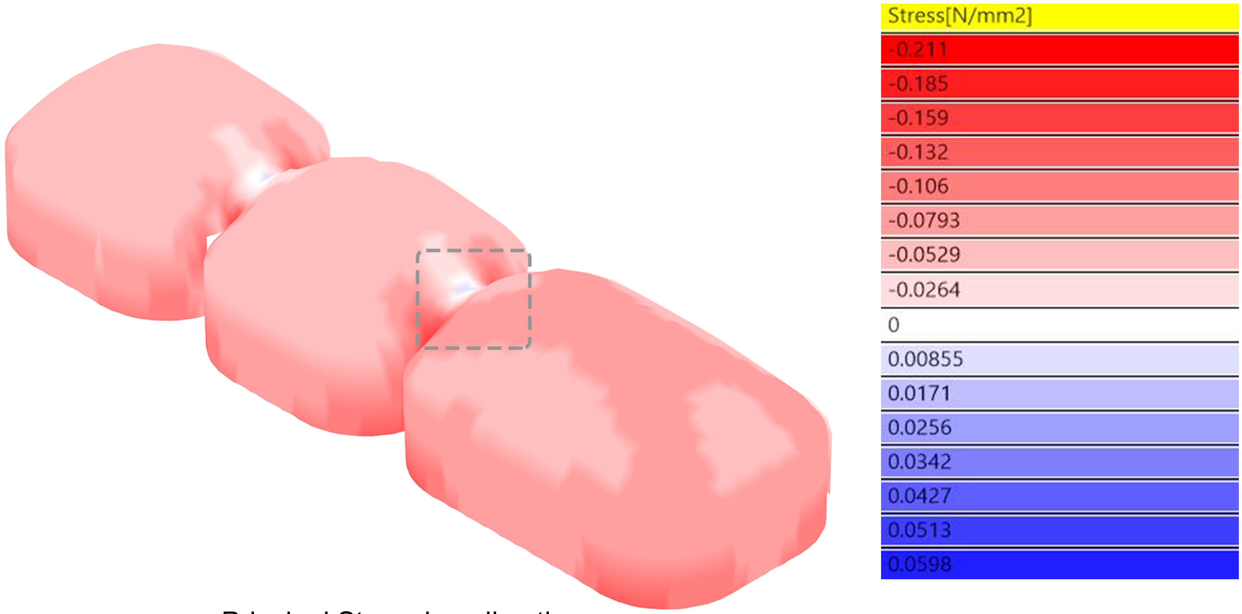


Fig 4.1 Form Finding using Approach 1

The form was further analysed in Karamba for various cross sections ranging from 200 mm to 800 mm to understand the maximum tensile and compressive stress in the structure. (Table 4.1)



Principal Stress in u direction



Principal Stress in v direction

Fig 4.2 Principal Stresses in u and v direction

C.Section = 800mm
Maximum Span : 6 m
Max allowable deflection : 15 mm
Load Case 1 = 1.2 x Self- weight

S.No	Cross section (mm)	Displacement (mm)	Tensile Stress (MPa)	C.Stress (MPa)
1	240	8.0	0.21	0.28
2	360	7.8	0.16	0.25
3	480	7.0	0.14	0.23
4	800	5.0	0.10	0.20

TABLE 4.1 : Karamba Analysis of the geometry

It can inferred that for various cross-sections, compressive stress is under a permissible value of 0.5 MPa. However, tensile stress is much higher than the permissible 0.05 MPa. Even for a wall thickness of 1500mm, a value below 0.05 MPa is not achieved. Also, this analysis is done without openings which indicates a further increase in stresses once the openings are created and increase in usage of material. Hence, an alternate approach is required for more efficient structure.
Also, high tensile stresses can be noticed at the junctions between two geometries. Hence careful attention has to be paid to this part of the structure in forthcoming analysis.

4.2. APPROACH 2:

4.2.1. CLASSROOMS

4.2.1(a) Form finding for the classrooms:

The profile of the different spaces were evolved from rounded square and rectangle respectively. Instead of a surface, a bounding volume is extruded from the curve, punctured with required openings, meshed and dynamically relaxed. The openings are made as pointed arches before meshing the geometry. The steps are illustrated in the figure 4.3 for two types of structures found in this project.

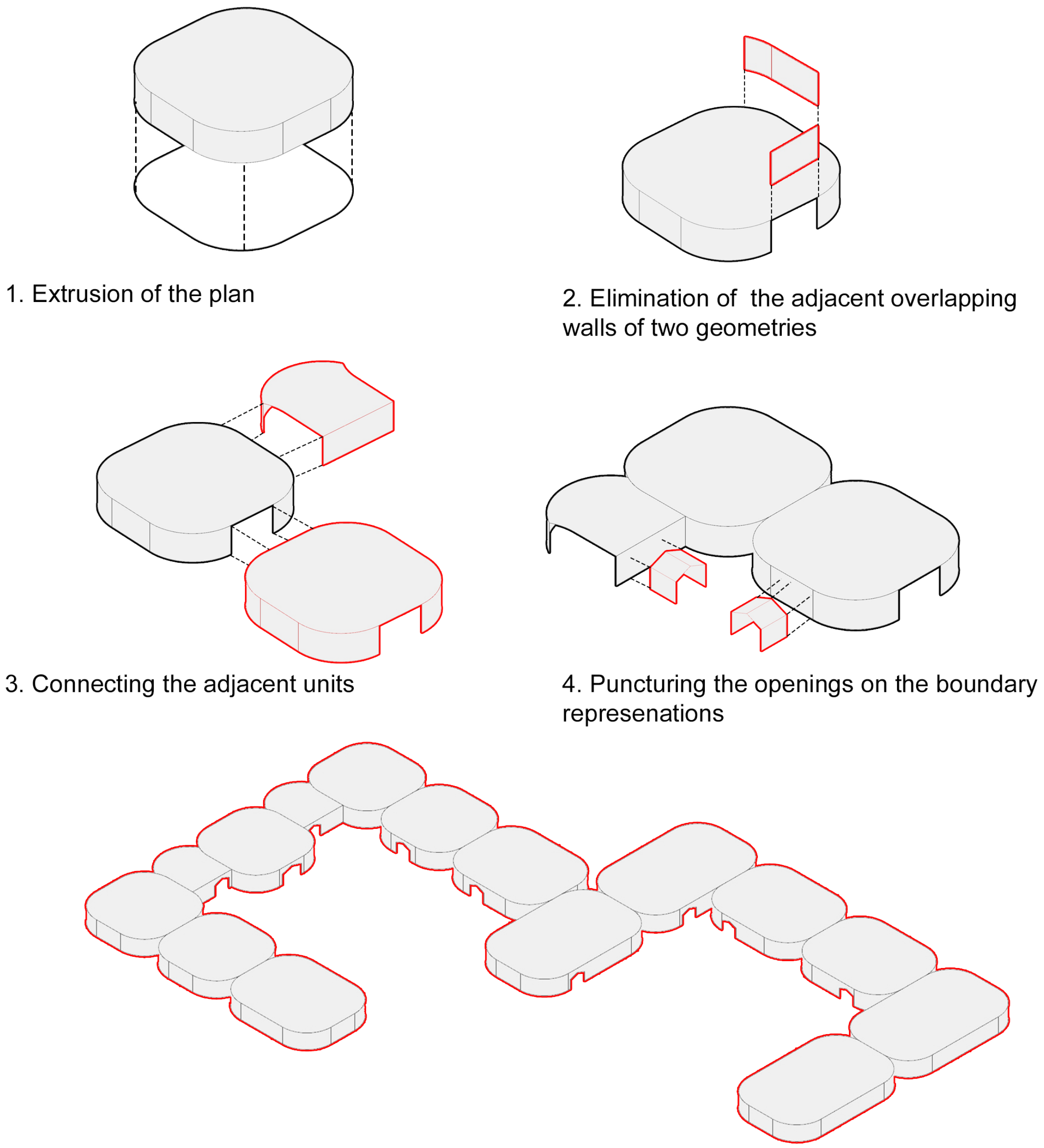


Fig 4.3 Form Finding for Class rooms using Approach 2

The geometry is converted into mesh and relaxed with a force of 5 N force vector at every particle (Vertex of each mesh face) and the figure below illustrates the form obtained. The fig. 4.4 illustrates the mesh obtained after smoothing. The resultant form was validated with a FEM analysis.

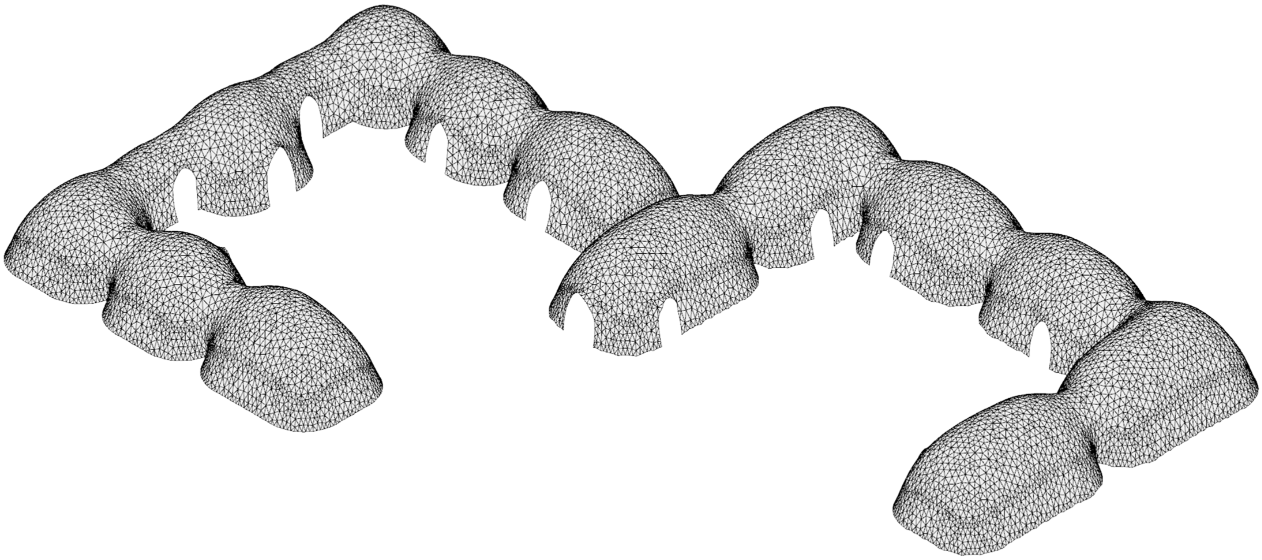


Fig 4.4 Form Found after dynamic relaxation

4.2.1(b) Finite Element Analysis of the Classroom:

The tensile and compressive stresses in the structure was checked for various cross-sections along the longitudinal (along u direction) and transverse directions (along v direction). The fig 4.5 shows the stress analysis for the selected shell cross-section of thickness 240mm. Major tensile stresses of 0.019 MPa can be seen above the openings and at the transition between the roof and the wall. A maximum compressive strength of 0.12 is attained. The deflection for the chosen cross section is 2.5 mm. They are not optimized further as the stresses and deflection are within the permissible limits.

4.2.1(c) Unity Check

Unity Check for Classroom Cluster 1:

Deflection:
15/2.5 = 6 > 1

Maximum compressive stress
0.5/0.12 = 4.17

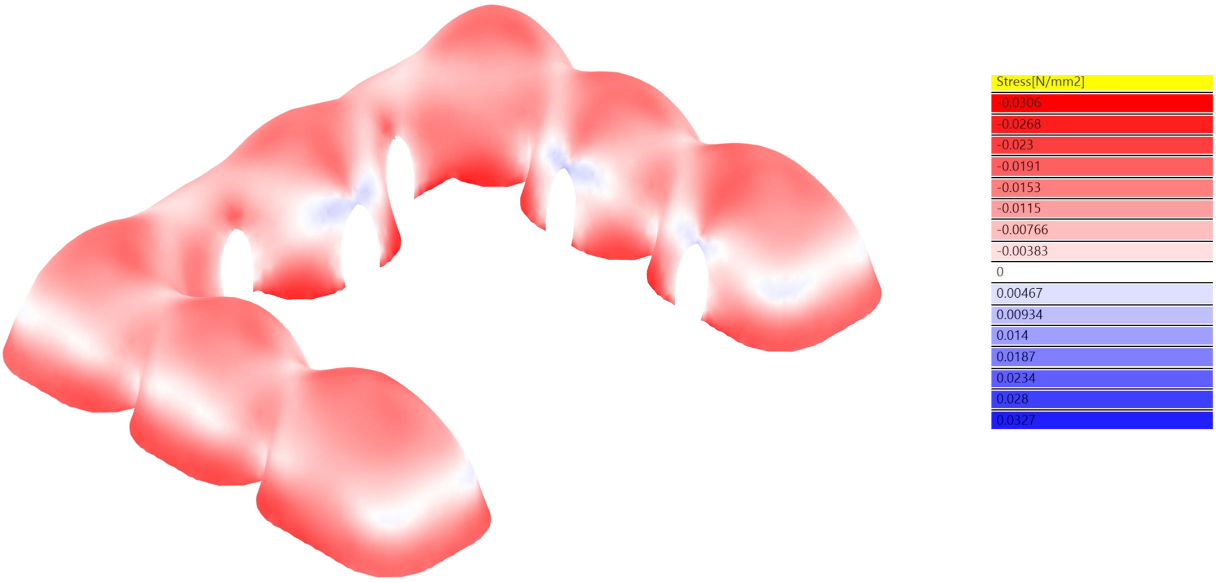
Maximum tensile stress
0.05/0.03 = 1.67

Unity Check for Classroom Cluster 2:

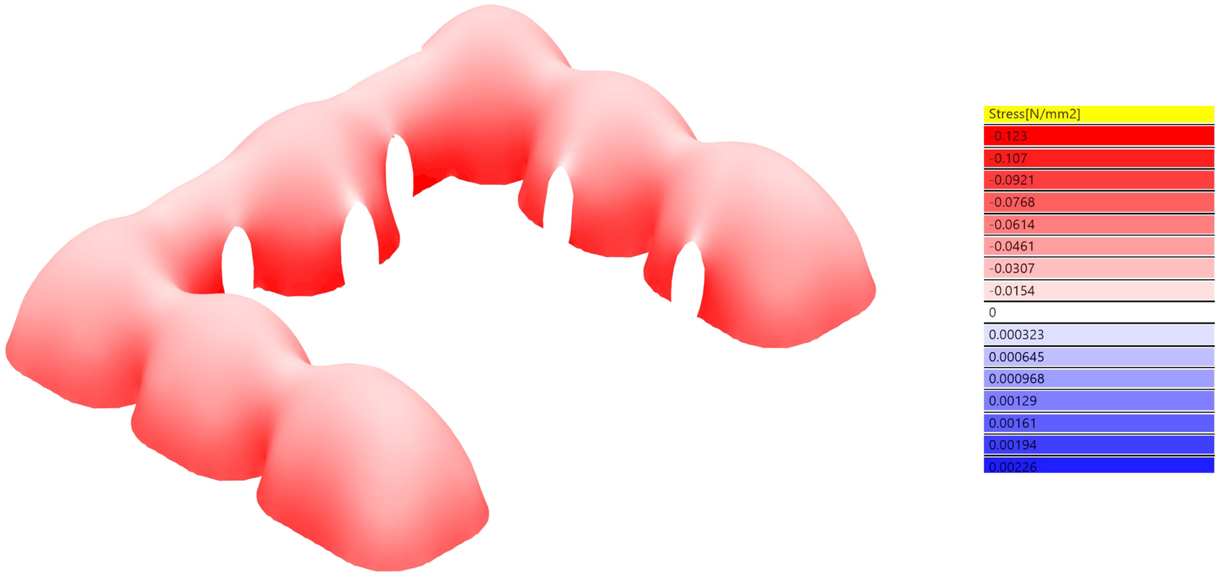
Deflection:
15/2.5 = 6 > 1

Maximum compressive stress
0.5/0.14 = 3.6

Maximum tensile stress
0.05/0.017 = 2.9



Principal Stress in u direction



Principal Stress in v direction

Fig 4.5 Principal Stresses in u and v direction of Cluster 1

C.Section = 240 mm
Maximum Span : 6 m
Max allowable deflection : 12 mm
Load Case 1 = 1.2 x Self- weight

S.No	Cross -Section (mm)	Displacement (mm)	Tensile Stress (Mpa)	Compressive Stress (Mpa)
1	120	2.2	0.047	0.14
2	240	2.5	0.03	0.12
3	360	2.4	0.019	0.12
4	480	2.4	0.011	0.12

TABLE 4.2 : Karamba Analysis of the Cluster 1

In the analysis for block 2 of the complex, the chosen cross-section is 240 mm. Major tensile stresses can be noticed along the transition from wall to roof. However they are a maximum of 0.02 MPa which is the highest above the openings. Fig. 4.6

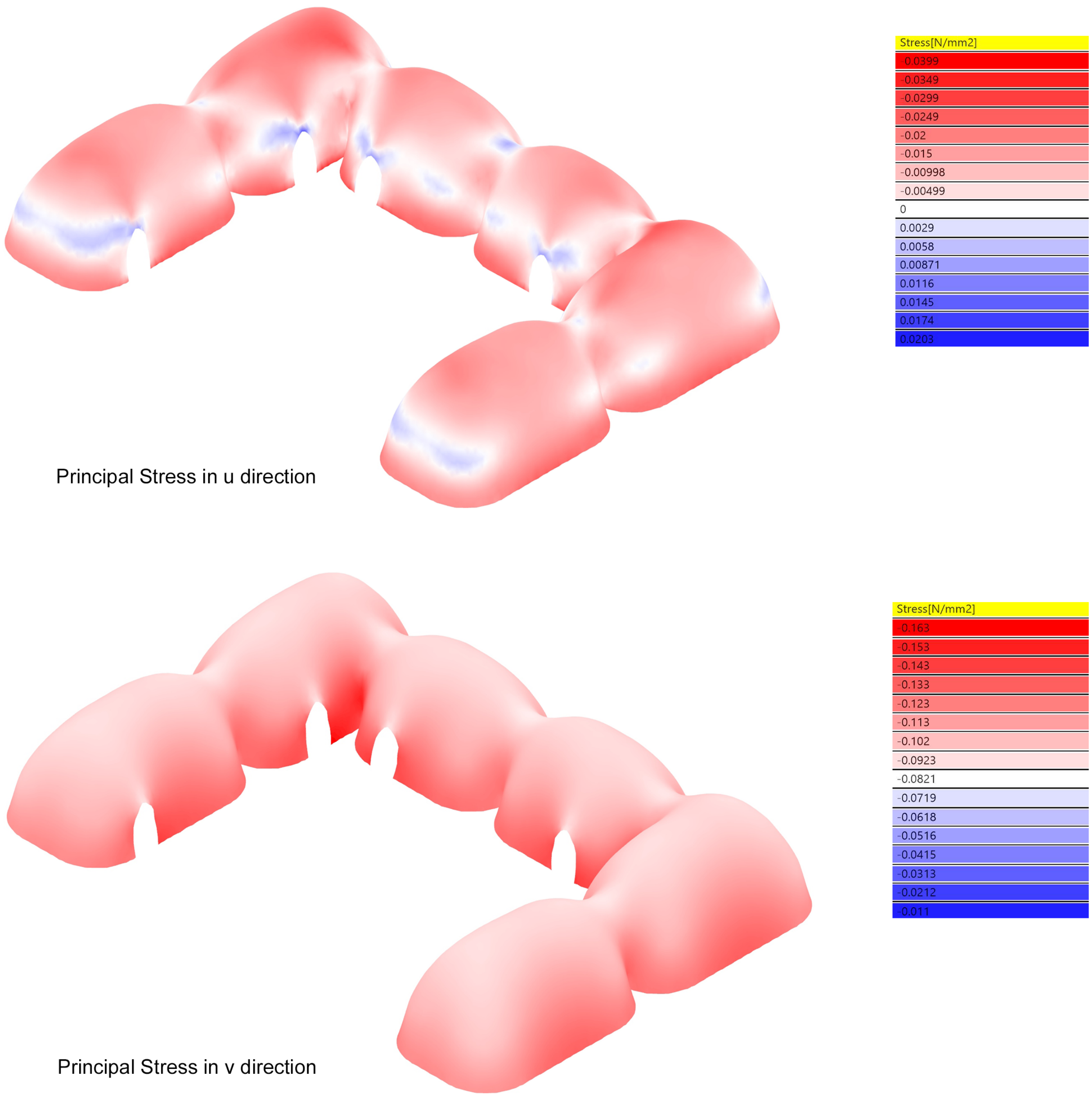


Fig 4.6 Principal Stresses in u and v direction of Cluster 2

C.Section = 240 mm
Maximum Span : 6 m
Max allowable deflection : 15 mm
Load Case 1 = 1.2 x Self- weight

S.No	Cross -Section (mm)	Displacement (mm)	Tensile Stress (Mpa)	Compressive Stress (Mpa)
1	120	3.0	0.03	0.14
2	240	2.5	0.017	0.136
3	360	2.8	0.018	0.15
4	480	2.7	0.016	0.15

TABLE 4.3 : Karamba Analysis of the Cluster 2

4.2.2. WORKSHOPS

4.2.2(a) Form finding for the Workshops:

Unlike the classrooms that required a closed environment to get focussed interiors spaces towards the centre, workshops demand a more open spatial quality similar to vaults that establishes connection with the outdoors. The challenge relies on the fact that the corridor and the workshops have to be connected directly with frequent openings on the wall (1.2m wide). A simple vault was unable to accommodate multiple openings. Hence, a hybrid vault that satisfied the architectural demands was required. In a regular vault openings (1.2m) at every 0.8 m could not be created as it exceeded the stress limits.

The geometry for form finding is different compared to the one opted for the classrooms. The rectangular curves that determine the spatial dimensions are extruded into a volume. The shorter walls on either sides are removed to ensure the mass is supported on two edges. Openings are punctured onto the surface (Fig 4.7)

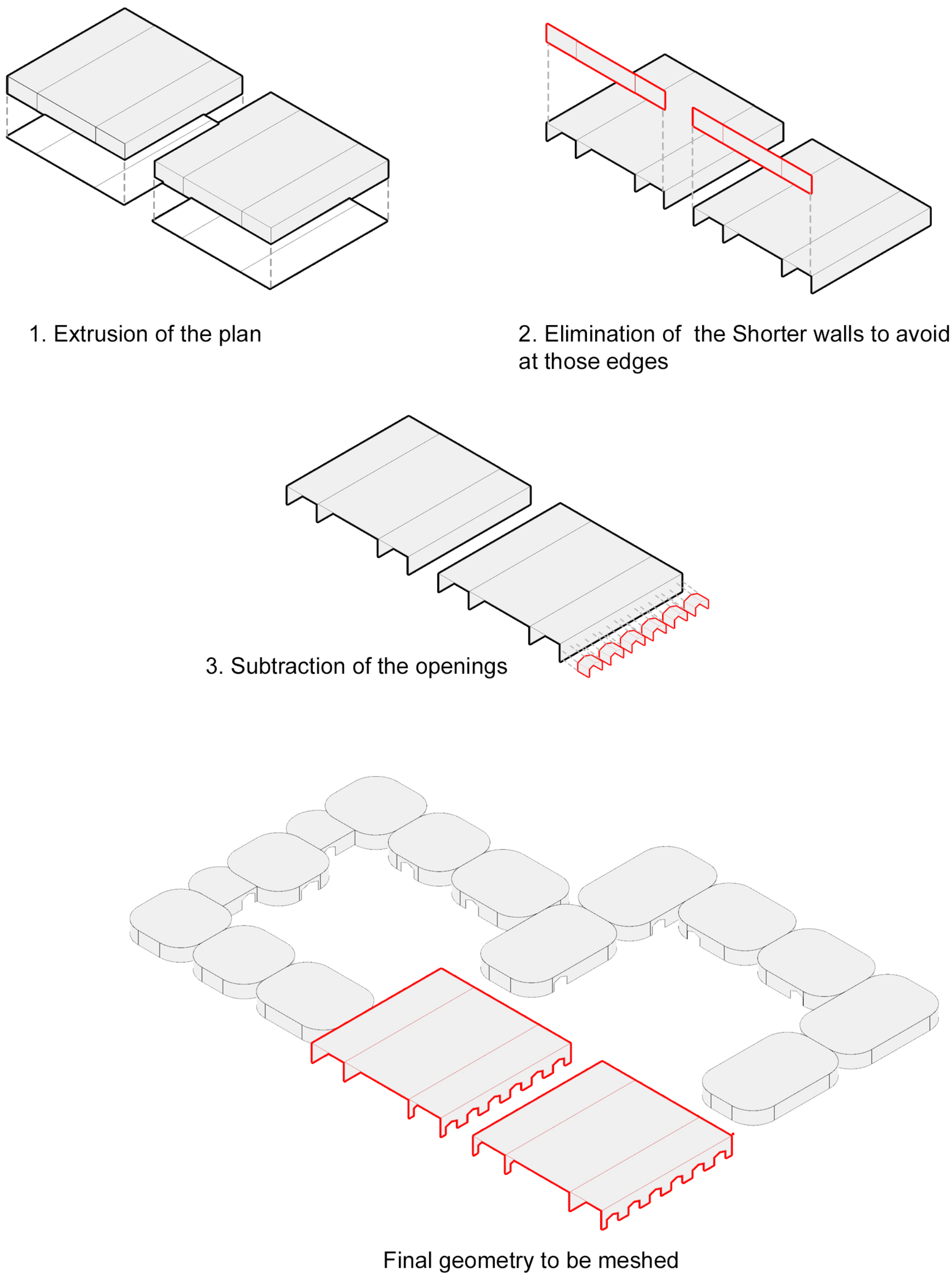


Fig 4.7 Form Finding of Workshop using Approach 2

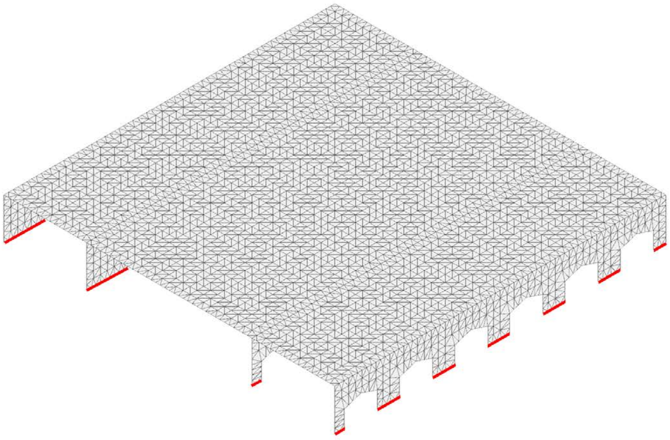


Fig 4.8 Unified Mesh for workshop

The final surface are united and meshed with a grid size of 0.25 m and dynamically relaxed with the kangaroo component.

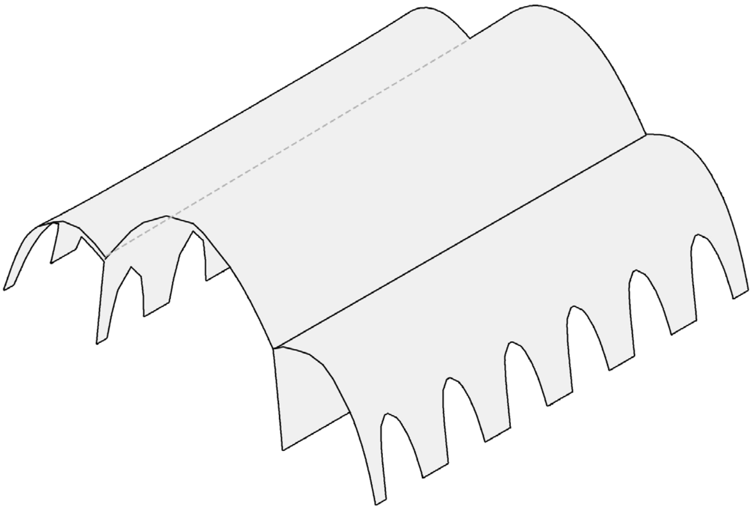
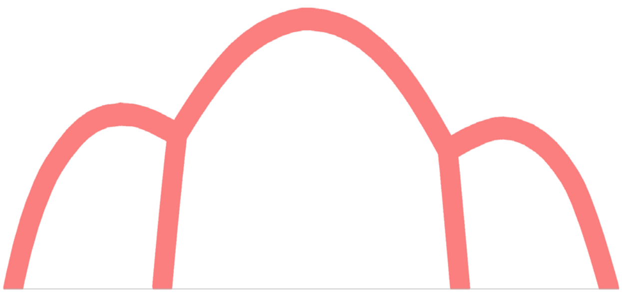


Fig 4.9 Form Found after Dynamic Relaxation

A regular vault for the same enclosed volume of space and openings uses much more material and has higher concentration of stresses. While the form found vault works with a thickness of 480 mm and establishes a strong connection between the corridors and workspaces.

A regular vault where the corridors and workshops are treated independent meshes and relaxed.

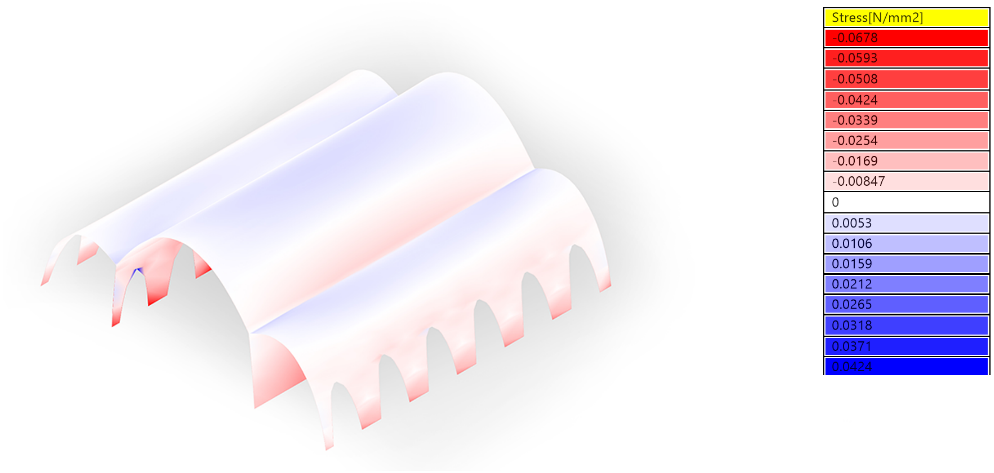


Evolution of the form into a monolithic structure when the meshes of the corridor and the workshop are unified.

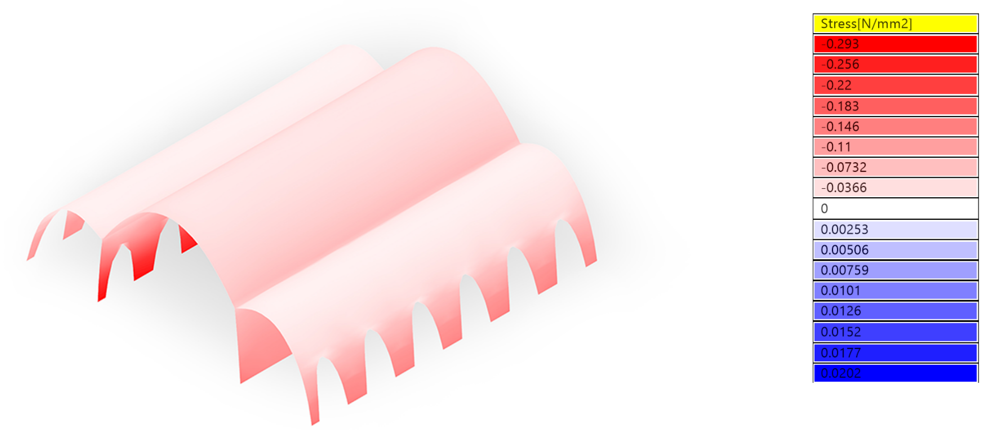
Fig 4.10 Two types of workshop typology

4.2.2(b) Finite Element Analysis of the Workshop:

The analysis was done for cross sections from 240 mm to 480mm. Along the longitudinal direction, the maximum stress found for the cross section of 240 mm thick vault was 0.13 MPa which is twice higher than the permissible limits. Hence, analysis was repeated with cross section of 360 and 480 mm thickness. A final cross section of 480 mm was chosen as it resulted in a maximum tensile stress of 0.04 MPa and compressive stress of 0.29 MPa which was under the permissible limits.



Principal Stress in u direction



Principal Stress in v direction

Fig 4.11 Principal stresses in u and v direction of Vaults

C.Section = 480 mm
Maximum Span : 6 m
Max allowable deflection : 15 mm
Load Case 1 = 1.2 x Self- weight

S.No	Cross -Section (mm)	Displacement (mm)	Tensile Stress (Mpa)	Compressive Stress (Mpa)
1	240	13.6	0.128	0.31
2	360	8.0	0.066	0.30
3	480	6.2	0.042	0.29

TABLE 4.4 : Karamba Analysis of the vault

4.2.2(c) UNITY CHECK:

Unity Check for Vault

Deflection:

20/6.2 = 5.5 > 1

Maximum compressive stress

0.5/0.29 = 1.72

Maximum tensile stress

0.05/0.042 = 1.19

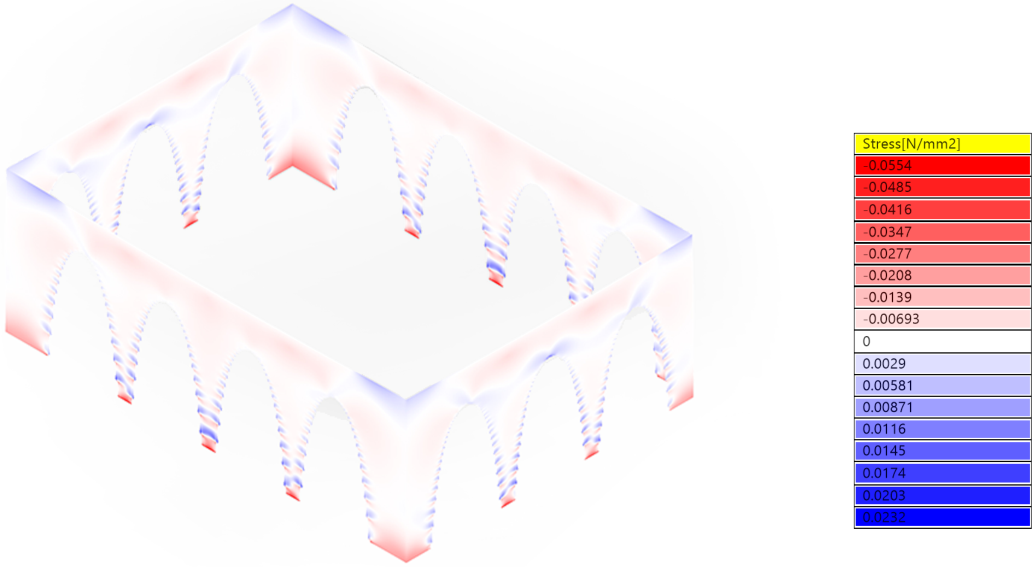
4.2.2 CORRIDOR WALLS:

The walls along the corridor are straight walls with accessibility to courtyards through series of openings (Catenary arches that follow the design language of the classroom block). Each arch is 1.5 m wide and 2.3 m high. The corridors are covered with tent fabric as a roofing material that is procured from the Zaatari camp. Lighter materials were preferred for the corridors to avoid bulky structures. These walls don't have any load on top of it but supports one half of the tent fabric which acts as a roof for the corridor. The wall has been modeled as a mesh as mentioned in section 3.2.

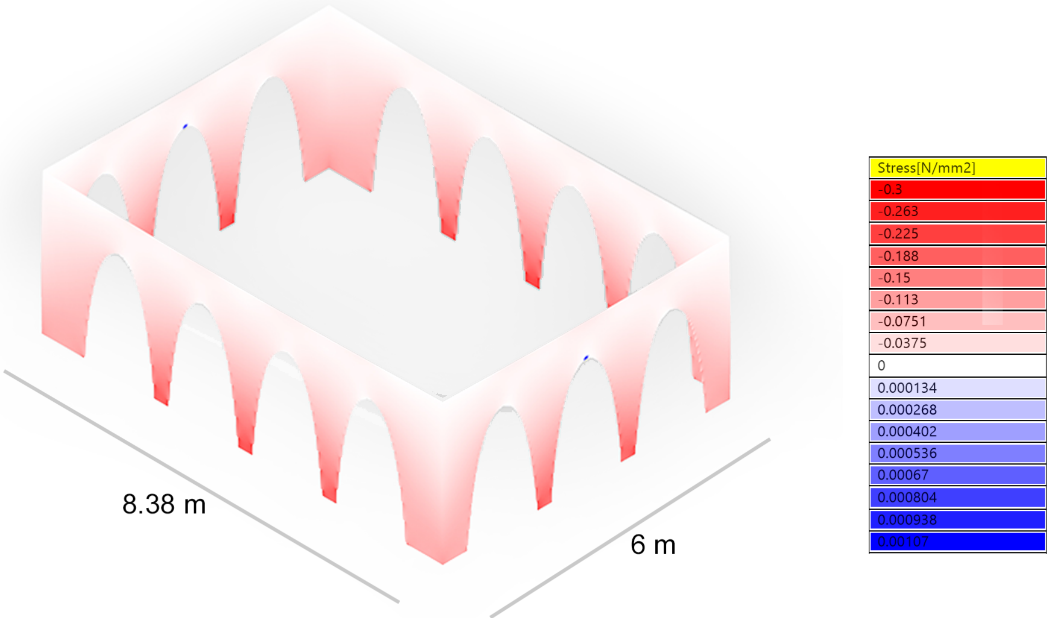
4.2.2(a) Finite Element Analysis of the Corridors:

The wind load of 8 N/m2 has been applied at the vertices of the mesh along the horizontal direction. The corridor wall being a free standing element is analysed with load case 2 that includes the self-weight and wind load.

For the selected wall thickness of 240 mm, the wall has maximum tensile stress of 0.023 MPa on the upper part due to wind and a compressive strength of 0.3 MPa which are allowable.



Principal Stress in u direction



Principal Stress in v direction

Fig 4.12 Principal stresses in u and v direction of Corridor 1

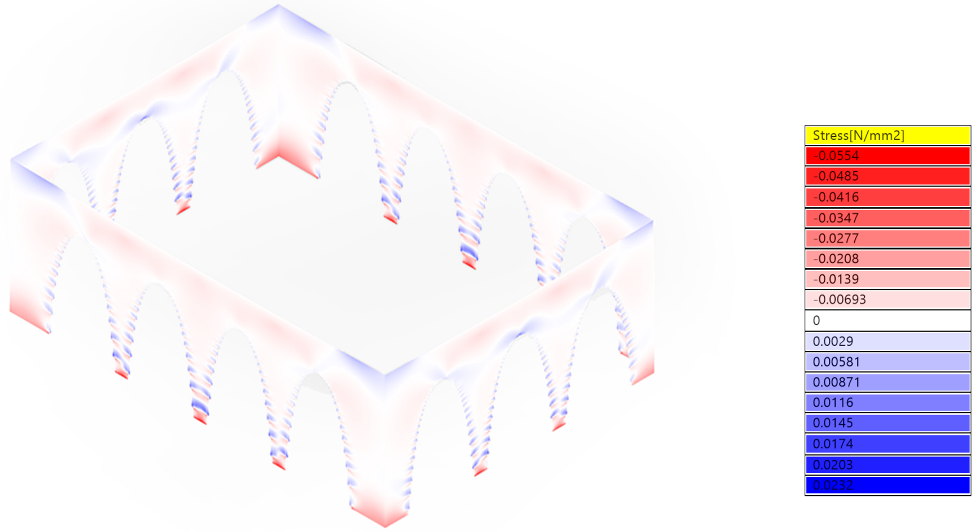
C.Section = 240 mm
Height of the Wall :3 m
Span of the Arch: 1.5 m
Load Case 2 = 1.2 x Self- weight
1.5 x Wind Load

S.No	Cross -Section (mm)	Displacement (mm)	Tensile Stress (Mpa)	Compressive Stress (Mpa)
1	240	1.8	0.023	0.30
2	360	1.6	0.021	0.29
3	480	1.6	0.020	0.29

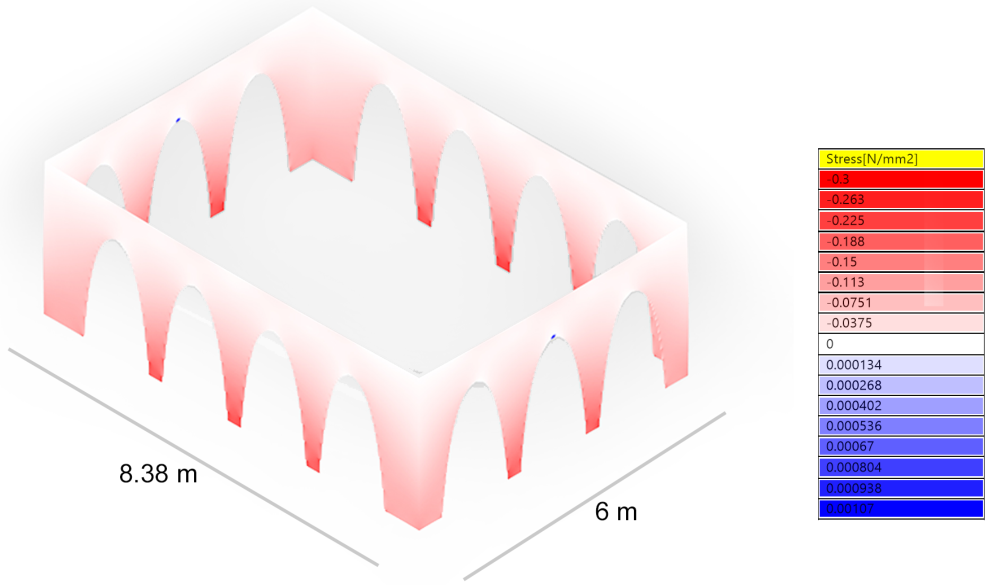
TABLE 4.5 : Karamba Analysis of the corridor 1

A similar corridor is designed as an enclosure for the amphitheater in the arts block. Its an open ended wall unlike the other corridor which forms an enclosure with its four walls. Two wall are identical with arches of 1.5 span and 2.3 high. The arch behind the performance arena is the widest one with a span of 3 m and height of 1.3m.

A 240 mm wall thickness of the structure has a maximum tensile stress of 0.032 MPa and the compressive stress is equal to the safety limit irrespective of the thickness of the wall.



Principal Stress in u direction



Principal Stress in v direction

Fig 4.13 Principal stresses in u and v direction of Corridor 2

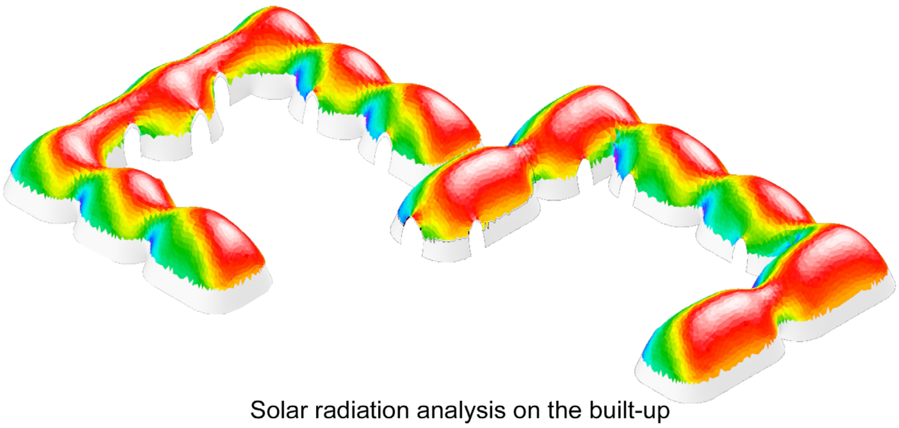
C.Section = 240 mm
Height of the Wall :3 m
Span of the Arch: 1.5 m
Load Case 2 = 1.2 x Self- weight
1.5 x Wind Load

S.No	Cross -Section (mm)	Displacement (mm)	Tensile Stress (Mpa)	Compressive Stress (Mpa)
1	240	1.8	0.023	0.30
2	360	1.6	0.021	0.29
3	480	1.6	0.020	0.29

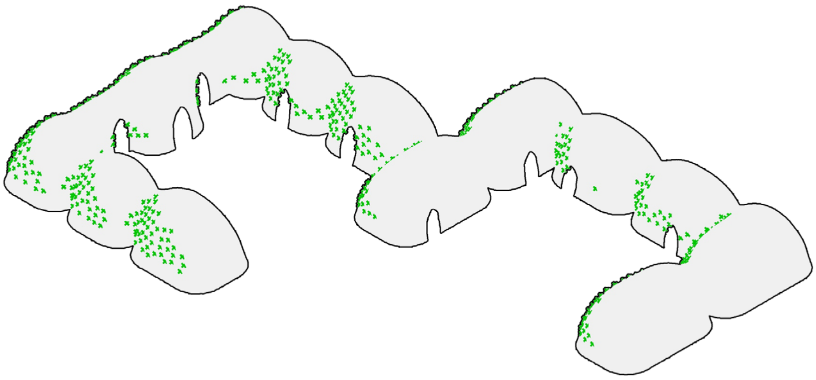
TABLE 4.6 : Karamba Analysis of the corridor 2

05PERFORATION IN CLASSROOMS

It is necessary to have a comfortable indoor lighting and ventilation for the classrooms especially during the day. Hence, existing doors are insufficient to attain the indoor comfort. To induce cross ventilation and additional lighting, a simulation was done from ladybug and honey components of grasshopper plugin was used to analyze and the conclude optimum position of the openings. The optimum points were picked at the spots of lowest solar radiation that were at least 1.2 m away from the base of the structure. The size of the openings were based on the size of the bricks. A half brick size (120 x 120 mm) is used. Also, it was ensured that distance between two points at least 500mm (Twice the size of the brick).



Solar radiation analysis on the built-up



Points with minimum solar radiation

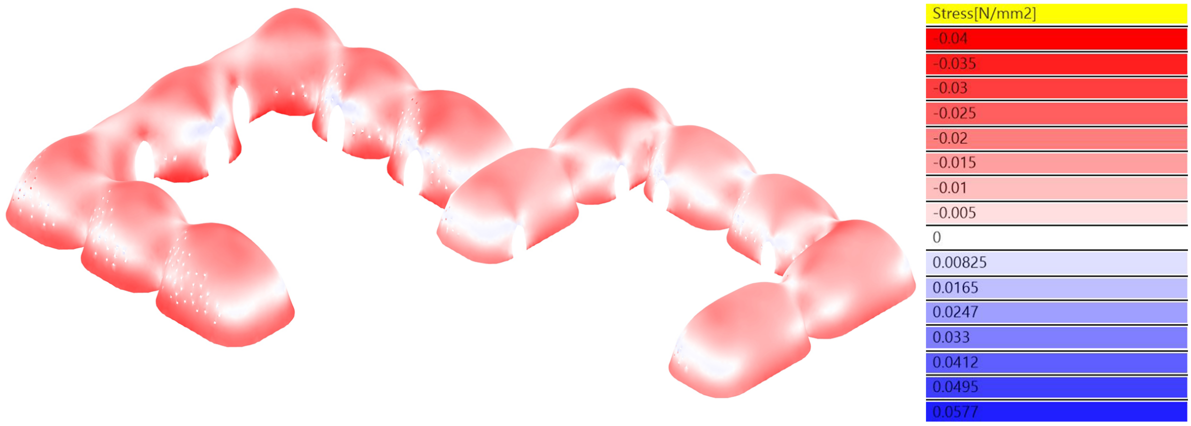
Openings on the structure

Fig 5.1 Derivation of opening points on basis of Solar Radiation

Size of the Openings	Total no:of openings	Percentage % of openings
120 x 120 x 240 mm	682	0.97

TABLE 5.1 : Size and Percentage of Openings

From the points obtained on the mesh, punctures were created on structure. Extra care has been taken to avoid openings closer to the doors, critical arches that connect two geometries and supports. 682 openings that account for 0.97% of the structure were created. The model was further analyzed to check the stress levels.



Principal Stress in u direction

Principal Stress in v direction

C.Section = 240mm
Maximum Span : 6 m
Max allowable deflection : 15 mm
Load Case 1 = 1.2 x Self- weight

Fig 5.2 Derivation of opening points on basis of Solar Radiation

S.No	Cross -Section (mm)	Displacement (mm)	Tensile Stress (Mpa)	Compressive Stress (Mpa)
1	240	3	0.06	0.03
2	360	2.8	0.08	0.05
3	480	2.7	0.09	0.025

TABLE 5.2 : Karamba analysis of classrooms with openings

UNITY CHECK:

Unity Check for Classrooms with perforations

Deflection:

20/6.2 = 5.5 > 1

Maximum compressive stress

0.5/0.29 = 1.72

Maximum tensile stress

0.05/0.042 = 1.19

It can be seen from the table that the overall stress readings are affected with a high amount of tensile stress of 0.06 MPa which is higher than the permissible. But closely looking at the stress diagrams it can inferred that high tensile stresses are concentrated at the openings.

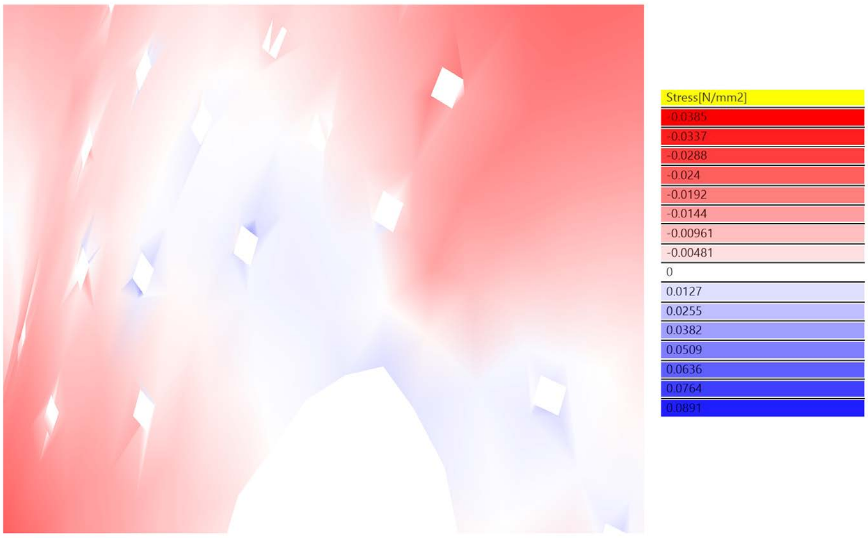


Fig 5.3 Concentrated stress levels at the openings

These local stresses are induced due to two reasons:

1. Profile of the openings
2. Change in the mesh pattern after puncturing the openings
3. Openings being smaller than the mesh face

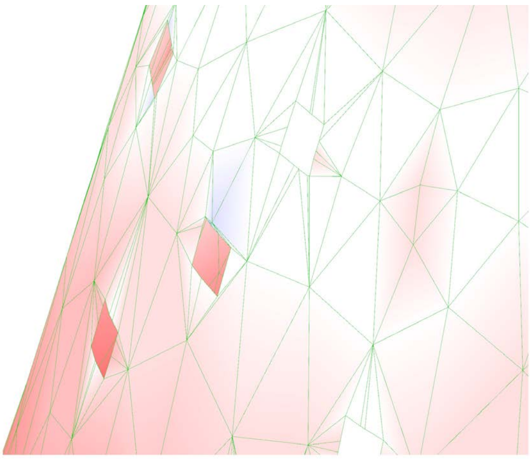


Fig 5.4 Irregular Meshing around the perforations

Hence, it can be concluded that the concentrated stresses does not affect the overall performance of the structure but might lead to small cracks around the openings. To calculate the accurate amount of stresses around the openings a finer mesh generation is necessary to analyse it further. Due to time constraints, the option hasn't been explored further

06ADOBE 2.0

Creating a doubly curved surface with adobe is a challenge as adobe is good in compression but very poor in tension. So, the valleys in the structure doesn't correspond well with the material properties that result in tension as seen in section 4.1.
Since the shape of the structure was form found using Kangaroo by applying a load proportional to the mass of the material, the structure has a good stability.
But to understand how the structure works at the connections, three models are analyses from an individual scale of an arch, doubly curved surface to a shell. The analysis in section 8.1, 8.2 and 8.3 uses load-case 2.
Structural model was simplified by choosing a small part of the complex with 2 class rooms attached to each other as shown below.

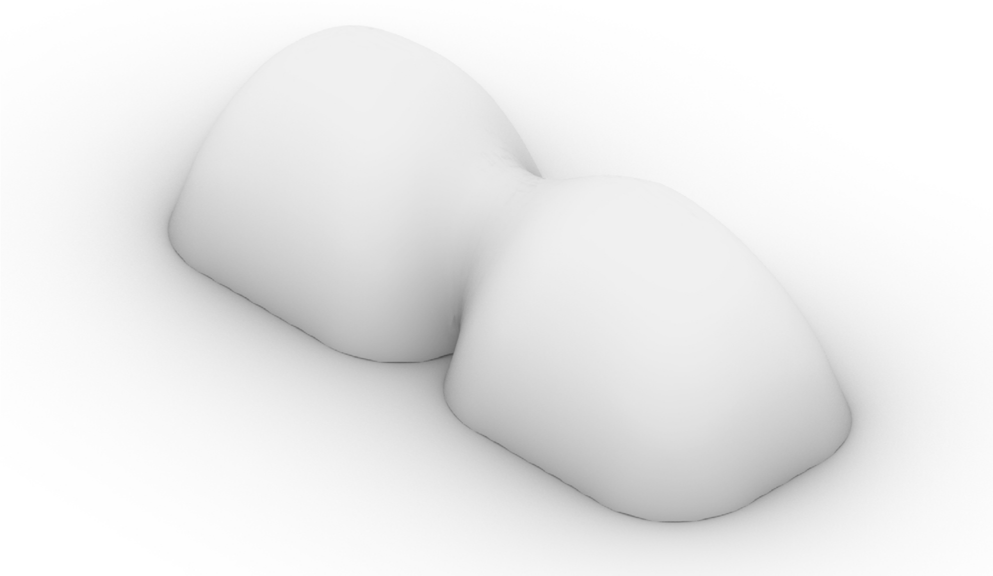


Fig 6.1 Chosen segment of Classroom complex to be analyzed

6.1. Case 1 - Analyzing the critical arch

The tension in the critical connection between two geometries is assumed to be counteracted by an arch as seen in Fig 6.2.

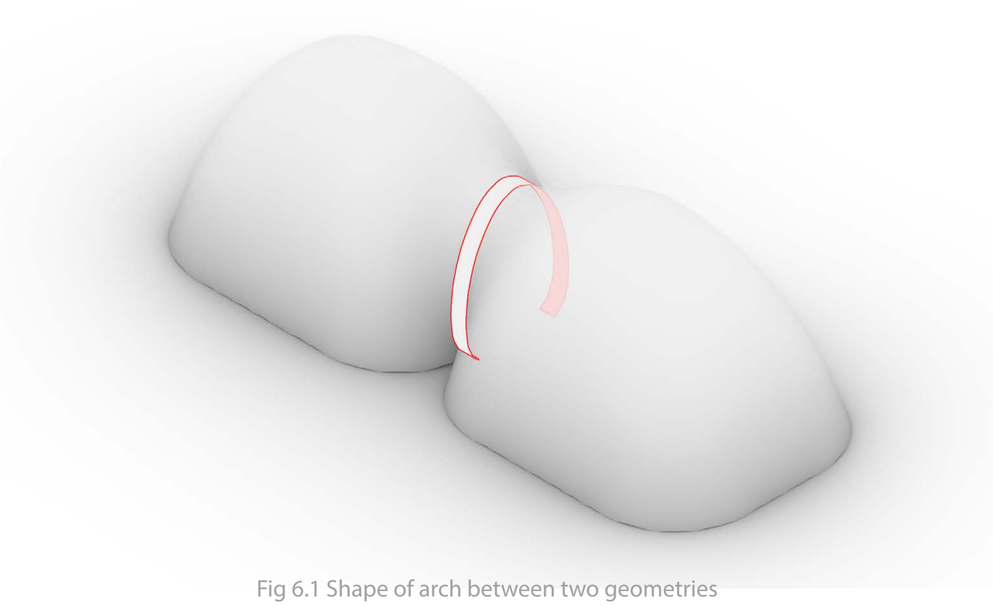


Fig 6.1 Shape of arch between two geometries

The curve of central opening was extracted from the geometry and reaction forces due to the classrooms were calculated at various points along the curve. The fig. 6.3 shows the points of mesh intersections at which the reaction forces are calculated.

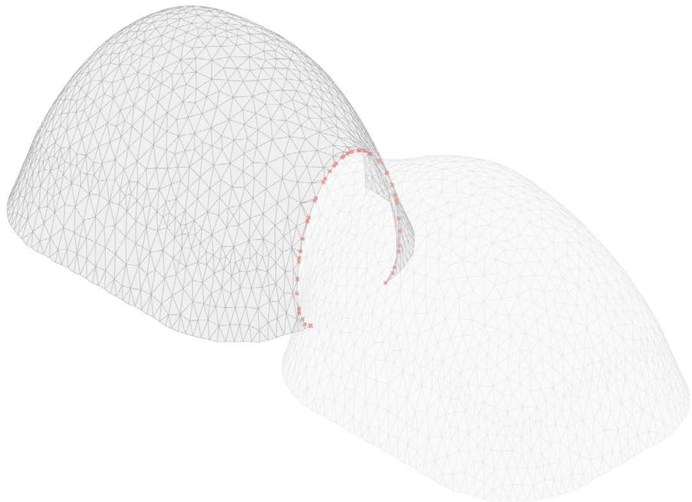


Fig 6.3 Reaction Forces as Point loads on the arch for Analysis

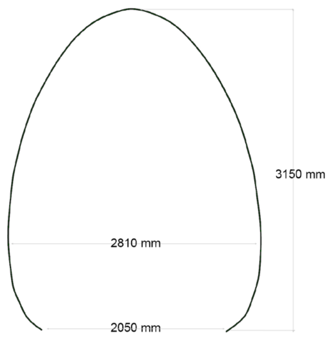


Fig 6.4 Dimensions and the cross section of the arch

These reaction forces were used as point loads on the arch to analyze how the arch performs as an individual unit. With a thickness on 720mm and width of 200mm a deflection of 10.1 mm was found which is higher than the allowable deflection (allowed deflection is 5.0mm). Also the tensile stresses along the top of curve were more than 3 times the permissible limit. (Fig 6.5)

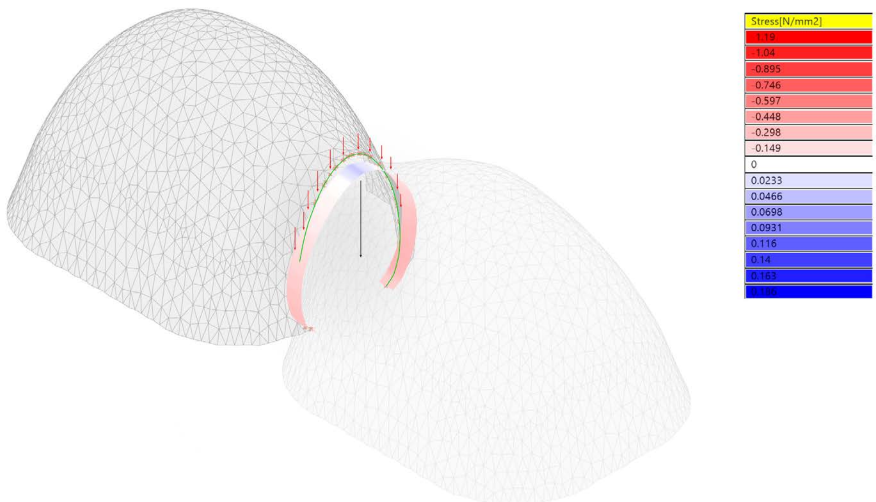


Fig 6.5 Karamba analysis of the arch

It can be inferred that arch alone cannot cater to the tensile forces on top. The support at the bottom of arch has a concave corrugation which offers stiffness to the whole arch. The change in the shape of the support of the arch is depicted in the below image (Fig 6.6)

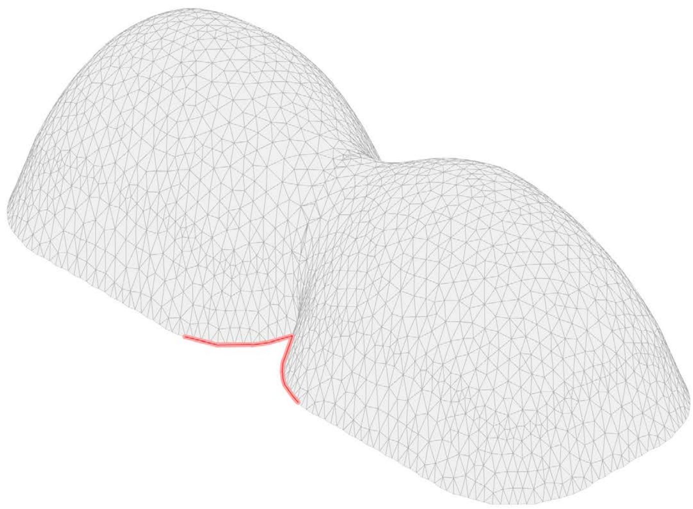


Fig 6.6 Concave corrugation at the support of arch

6.2. Case 2 - Analysis of the double curvature

On analyzing this shape in karamba, the structure appeared to be unstable having tension at the top surface (3 times the allowable tensile stress). Since there was no compression along the u direction of principal stress, the tension increased in the structure along that direction.

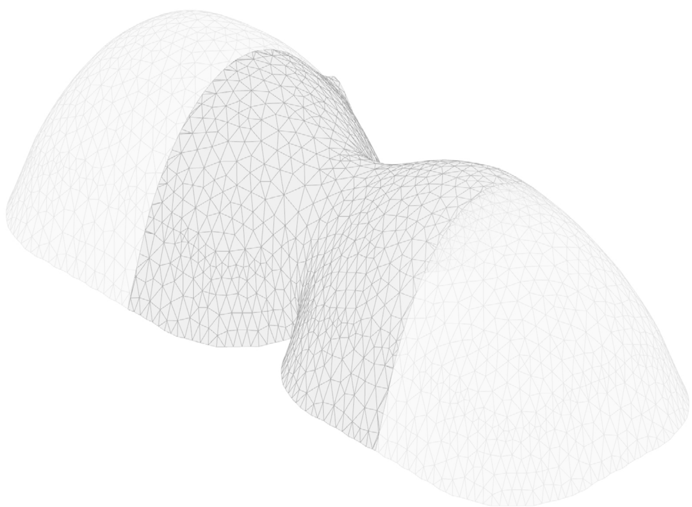


Fig 6.7 Double curvature part between 2 classes

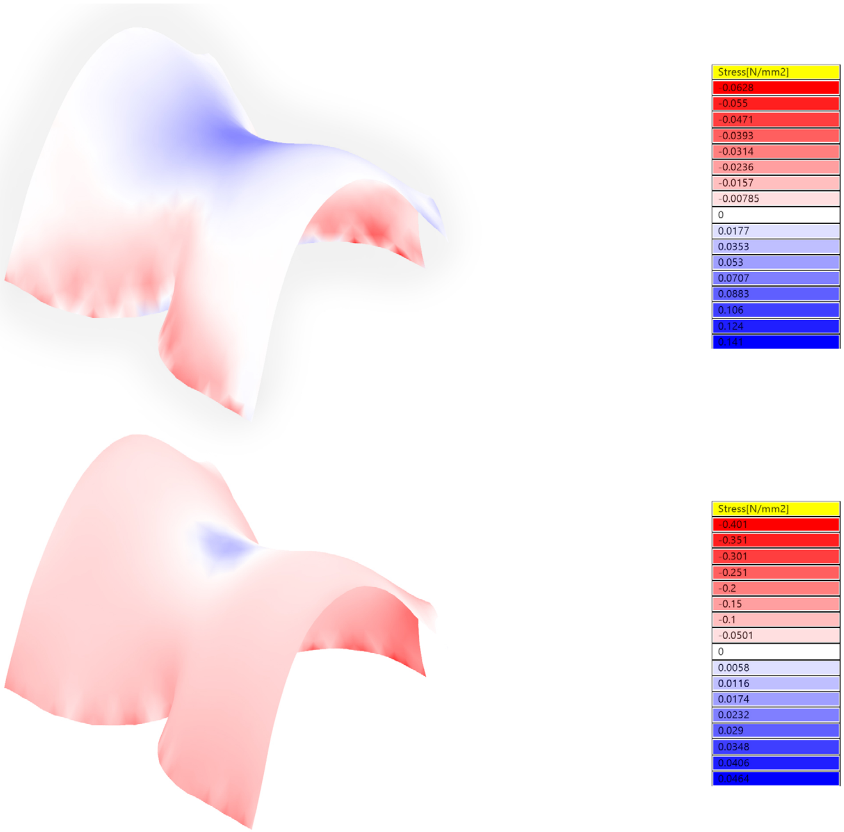


Fig 6.8 Karamba analysis of double curvature between 2 geometries

6.3. Case 3 - Analysis of the shell

Lastly, two classes were analysed together in order to prove the functionality of the structure. Fig 6.9 shows the stresses in the structure having a uniform thickness of 240mm. The maximum tensile stress in the structure is 0.02 MPa and maximum compressive stress is 0.19 MPa which are under the allowable limits.

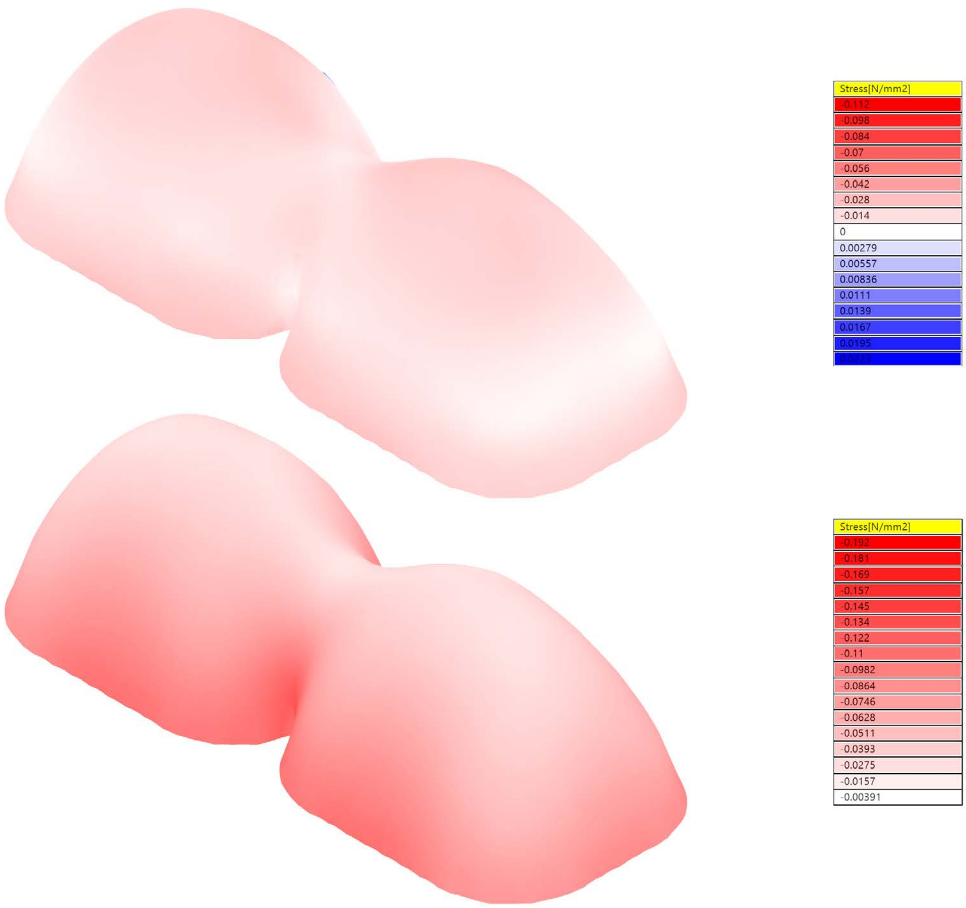


Fig 6.8 Karamba analysis of shell

Hence, it can be concluded that the structure works as an efficient shell in compression counteracting the tension. So, the connection cannot perform efficiently in absence of the compression in the longitudinal direction. The profile of the classroom, the shape of the arch in the center and the corrugation near the support of the arch adds to the stability of the structure.

07FABRICATION

Fabrication plays a crucial role in construction, the entire process needs to be designed as a system which enables people to understand, build it by themselves. The spaces have been developed on the basis of form finding with mesh relaxation due to gravity to get the structurally optimal solution with few modular principles which governs the style. So the resulting structure is not a regular form (domes, vaults etc.,) but rather a combination of them with more organic connections.

7.1 AIM:

The aim of the fabrication techniques are:

- Attain the closest possible form, as deviation in form leads to significant change in load transfer.
- Create a simple system which can be taught and increases the efficiency of workability.
- Low tech solution which requires less engineering and can be easily produced on site.
- Creating a less or a no form work as the availability of wood is scarce and expensive.

7.2 TECHNIQUES:

Multiple approaches were made to realize the form such as :

- Compass
- Voxelization
- Guiding Rods

7.2.1 COMPASS:

A building compass will help bricklayers by pointing out where to place a brick and under which angle. The compass is based on an old Nubian technique and merely functions as a pointing device. On the image below on the left, the generated bricks on an arbitrary surface can be seen as well as the compass in green which points to the specified brick. The bricks are stacked neatly and in the input area, which can be seen below on the right, it is possible to: select which brick to point to, define different brick sizes for different layers of bricks, create extra openings on the specified layers and rotate all the bricks on certain layers.

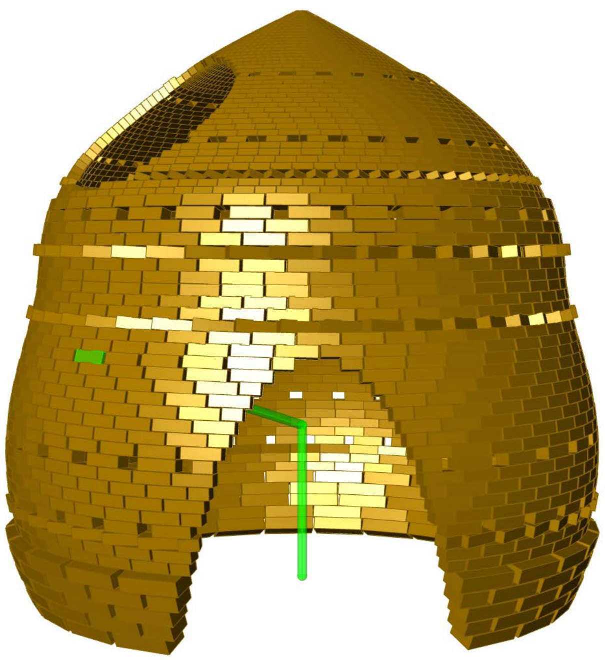


Fig. 7.1 Compass positioning the brick

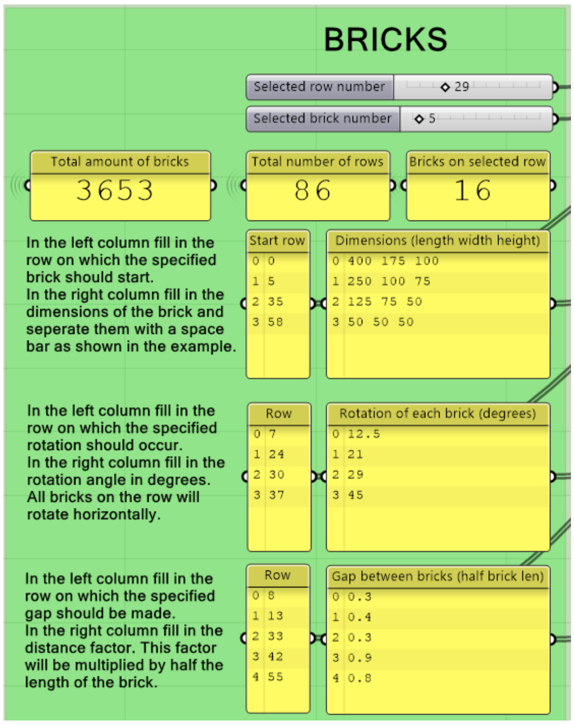


Fig. 7.2 Input for the compass

Fig. 7.3 Compass by Fabrizio Carola

Fig. 7.4 Dome structure by AION architects

Output:
The algorithm also generates numerical data, which refer to the settings of the compass. Applying this data to the compass would allow the bricklayers to see where and under which angles each brick should be positioned. The data consists out of five variables, being: compass arm length; compass arm inclination; compass arm azimuth; local brick inclination, so the inclination of the brick relative to the inclination of the arm of the compass; local brick azimuth, so the azimuth of the brick relative to its own central z-axis. The output can be seen on the image below.

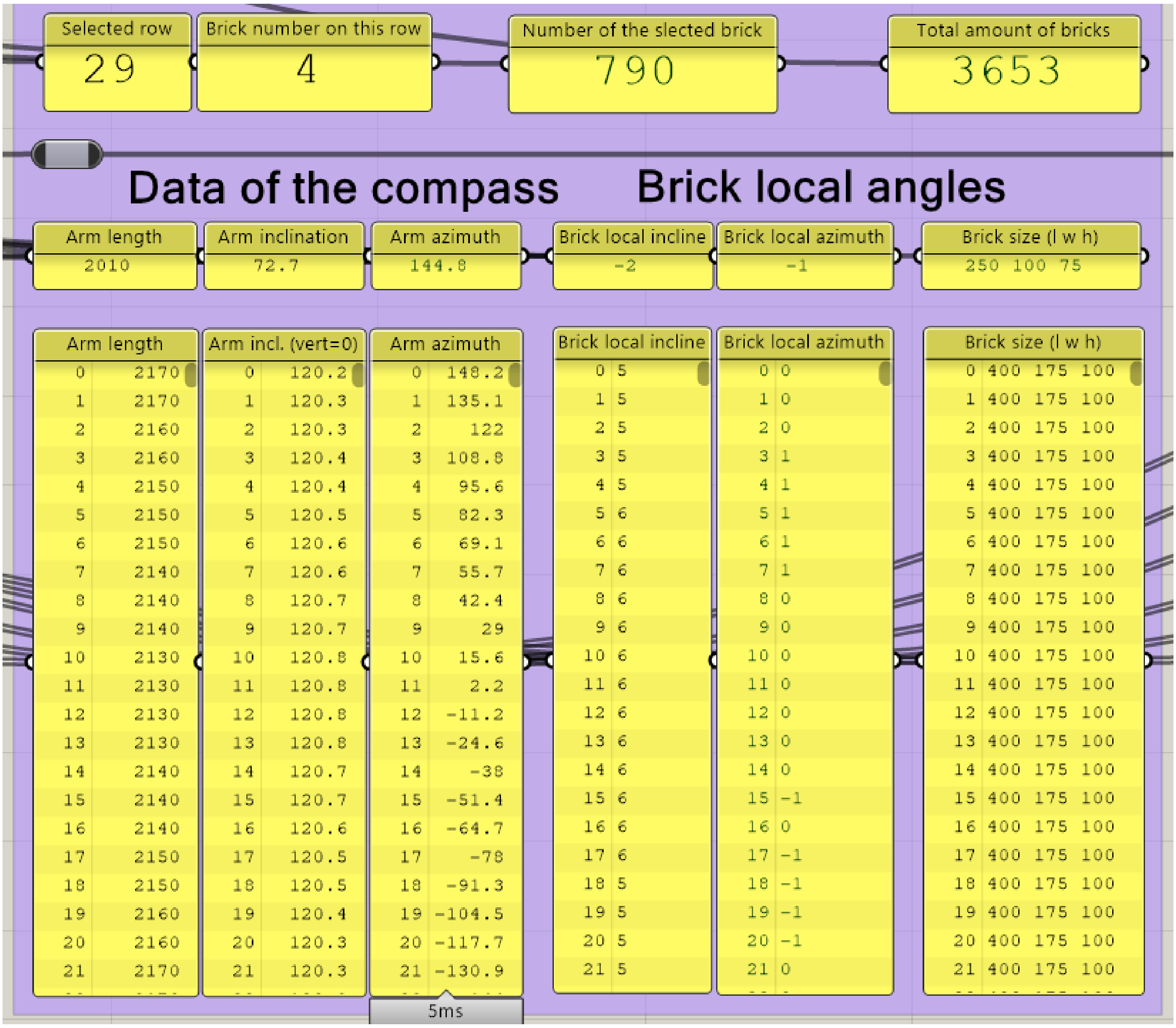


Fig. 7.5 Output from the compass

Limitation:
The output values are rounded off to a certain degree. The length of the arm for example is rounded to 10 mm and the angles of the compass arm to 0,1 degree. In order to visualise how the rounded data would influence the building another algorithm was written which places each brick based on the rounded values. The left image below shows the bricks when they are placed using the data from the previous image, the bricks hardly move and the shape looks nearly exactly similar to the original generated bricks. The image right of it shows how it will look like when the angles of the compass arm are rounded to whole degrees. Gaps between some bricks appear and the rounding becomes visible.

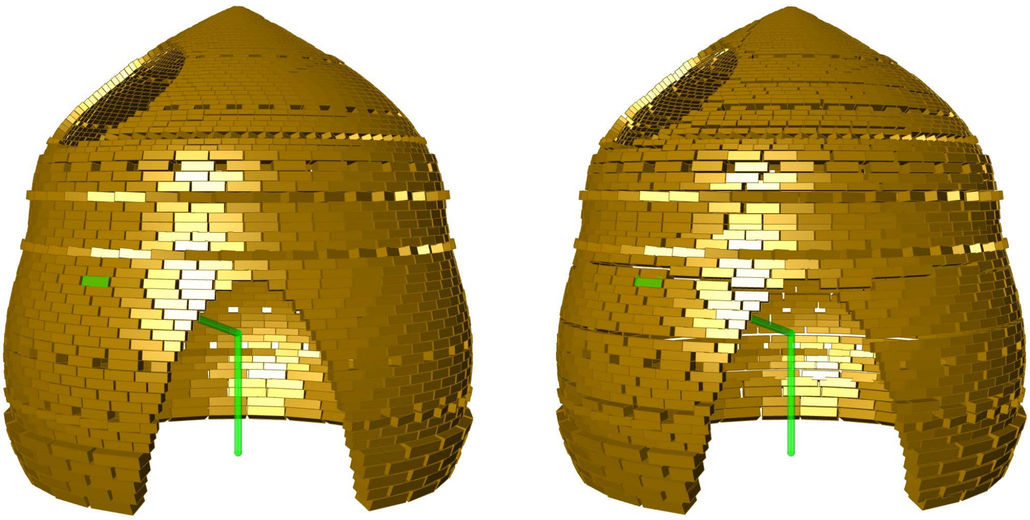


Fig. 7.6 Precise value (left - without gaps), Rounded off(right - with gaps)

7.2.2 VOXELIZATION:
Voxelizing the building and placing bricks on these voxels will help the bricklayers to construct the building as if it were a building designed with lego. Due to limitations of computational power only a part of the building is voxelized with the written algorithm.

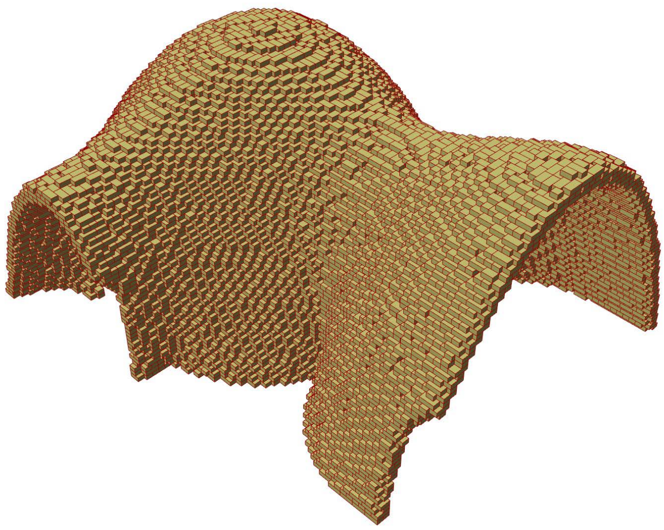


Fig. 7.7 Voxelized Classroom

Limitation:
It is not possible to create the desired shape with the specified bricks using voxelization. Bricks will fall because they are not supported by other bricks as can be seen in the section below. A possible solution could be to disregard a number of highest layers or construct the roof using a different method or material. Another potential option could be to use bricks which are more flat. It would allow creating openings with a lower slope, as what happens at the roof. However, it is unsure if a flat brick would be strong enough to transfer the loads.

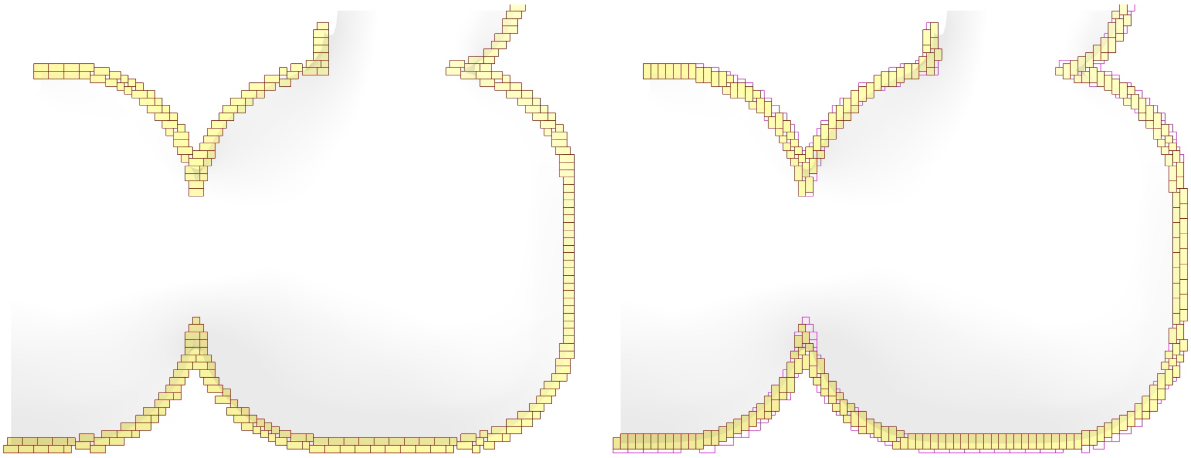


Fig. 7.8 As an example a top view of the first and second layer generated by the algorithm are shown here below. In the second layer, the contours of the previous layer can be seen in magenta.

7.2.3 GUIDING RODS:

The guiding rods combines a tool and a traditional brick laying technique which has been practiced for centuries. The skill centre has two different structures, a high spanning vault as workshops and classrooms. The research consist of woodless construction from the past and this has been developed to suit our needs.

7.3 AFGHAN AND PERSIAN DOMES:

In Afghanistan, a technique for building domes without formwork has been used for centuries. With this technique, bell shaped flat domes are produced to cover square rooms by constructing reclining arches which are set at angles of ca. 30° to the horizontal. Fig.7.9 show the construction process of a dome (over a 4 x 4 m room), which can be built in half a day by five to six people. [1]

With this technique, the adobe blocks forming the arch should touch at their lower edges, and wedges should be inserted into the upper gaps . Since this method allows the arch action to come into effect before the mortar has dried, laborers can even stand on the dome while it is under construction. Different models were built at the BRL(Building research Laboratory, University of Kassel) in order to show that a wide variety of architectural forms can be covered with this technique, and that it can also be combined with the Nubian dome technique (7.11 to 7.14).

In former times this was often used in Persia and is therefore called the Persian dome technique. Here, reclining arches are started from all four corners of the base. This construction technique is more suitable for all the classrooms and the arts spaces but needs to be developed further to attain the desired form.

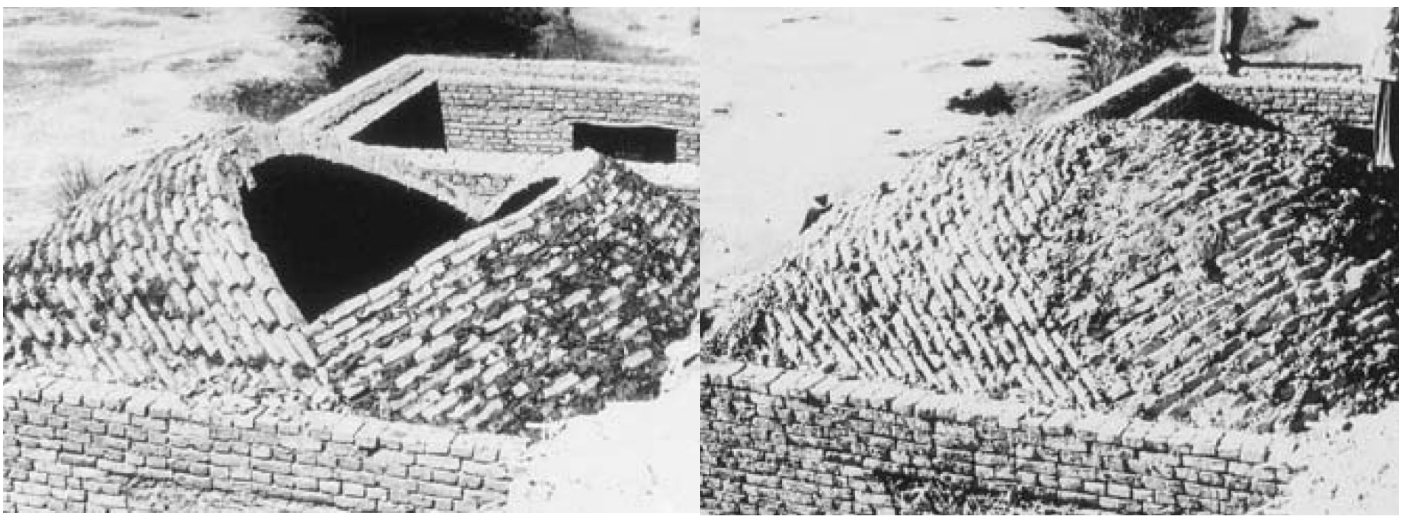


Fig. 7.9 Construction of a Afghan dome.

[1] Building with Earth- Design and Technology of a Sustainable Architecture by Gernot Minke

Fig. 7.10 Placing wedges between stones

Fig. 7.11

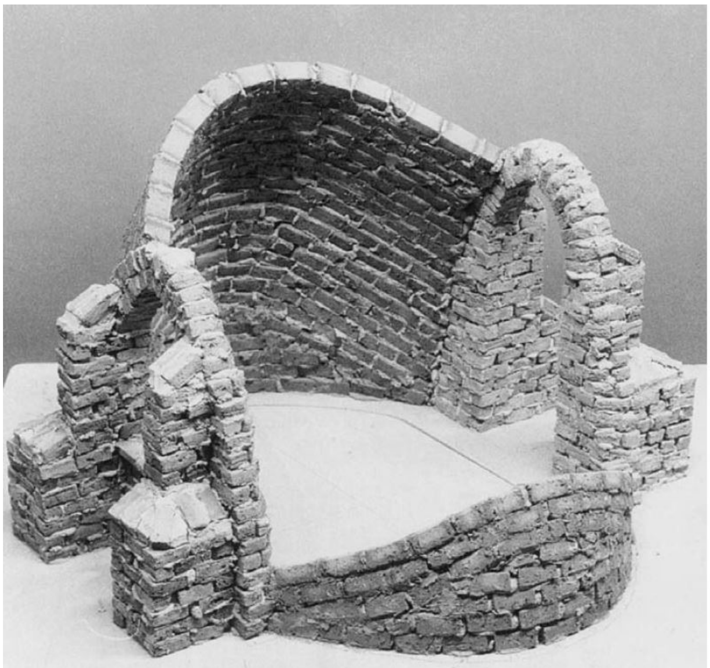


Fig. 7.12

Fig. 7.13

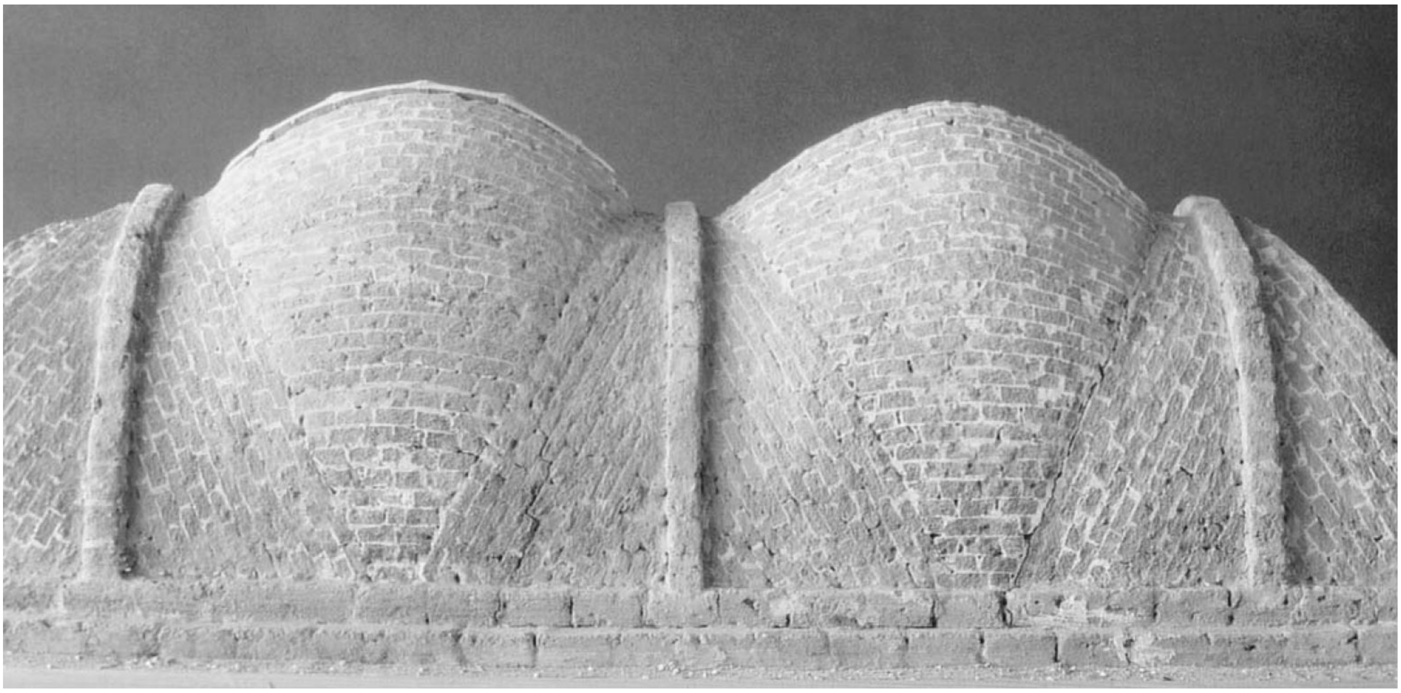
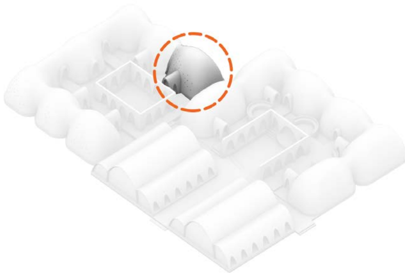


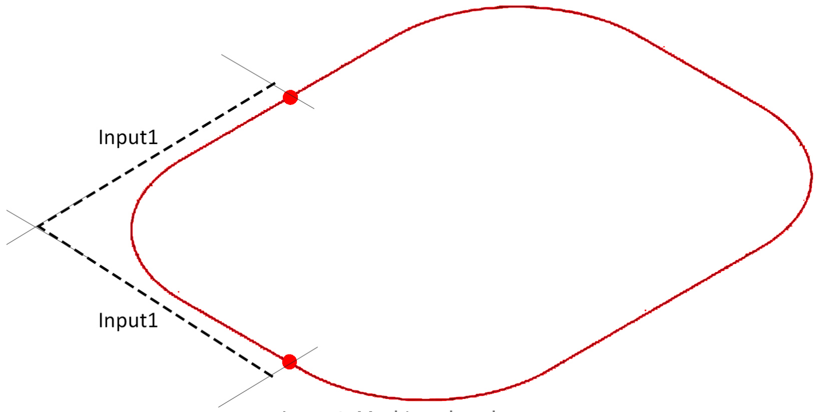
Fig. 7.11,7.12,7.13,7.14 Models of different dome shapes deriving from the Nubian and Afghan techniques (BRL)

7.3.1 Marking on site:

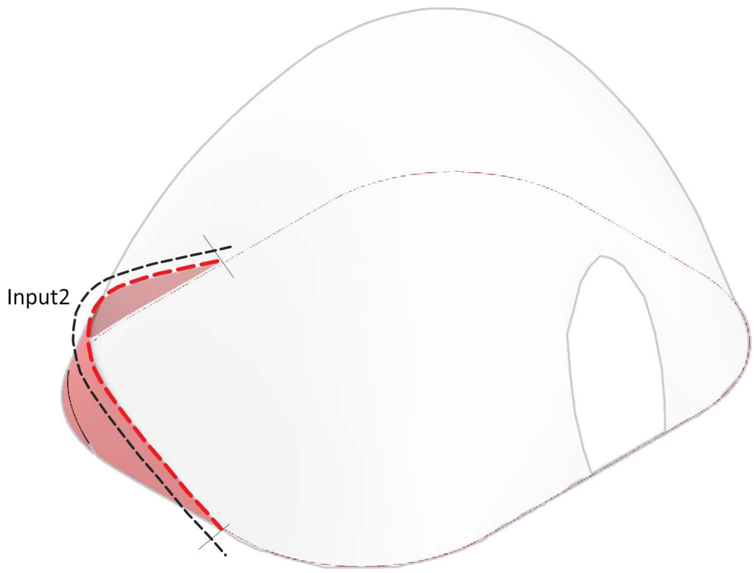
In order to achieve a precise form, a curve inclined at 30 ° needs to be placed on the plan which act as a guiding system it informs the masons where the bricks needs to be placed. Three inputs needs to be given to create a precise curve. The x and y distance of the point on the plan for the arcs origin from a reference point(Input 1), length of the arc(Input 2) and angle of the arc (Input 3) to the origin.



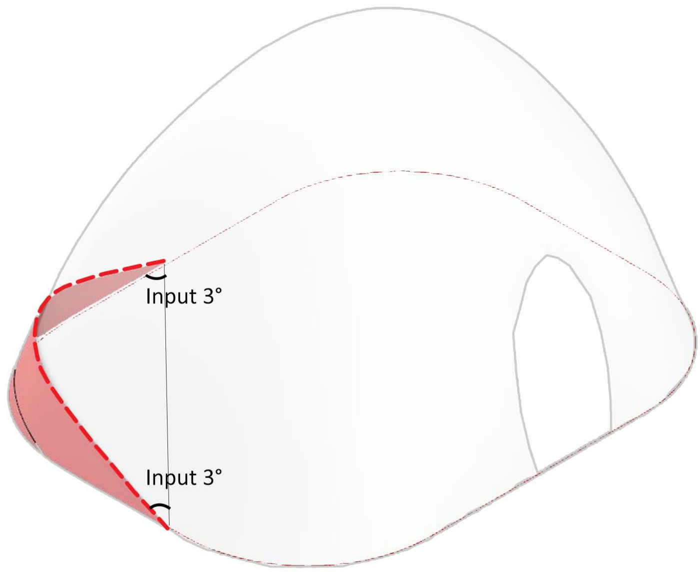
Keyplan - Classroom



Input1: Marking the plan



Input 2: Length of Arc



Input 3: Angle of Arc to the origin

Fig. 7.15 Inputs required to form the guiding arc

7.3.1.1 Measuring Tool:

To facilitate the construction and to create the guiding curves a low tech tool needs to be built over the site. This is a preliminary design and it can be developed further in detail. Arc can be built by using a measuring tool at the origin and a recycled plastic tube as the curve and the inputs.
The tool consists of a wooden piece with the slit along which angles are marked and a Pivot to which a hollow PVC tube is fixed. The tube has screw to which the plastic tube is fixed. The entire tool is tilted at 30 degree mounted on wooden piece which is fixed to a base plate.

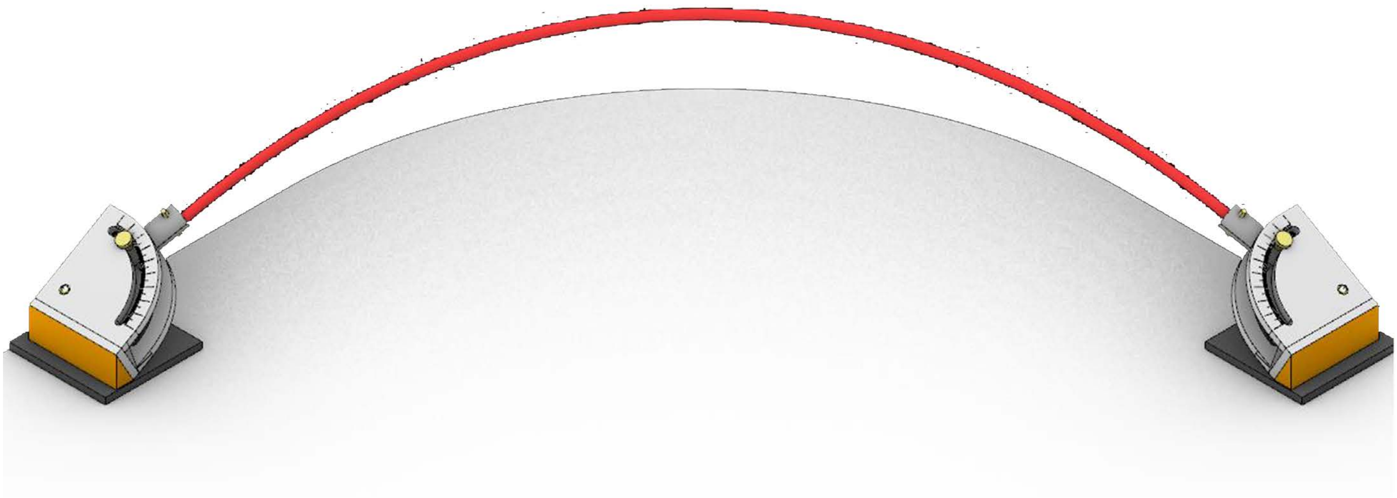


Fig. 7.16 Guiding Rods creating a desired arc

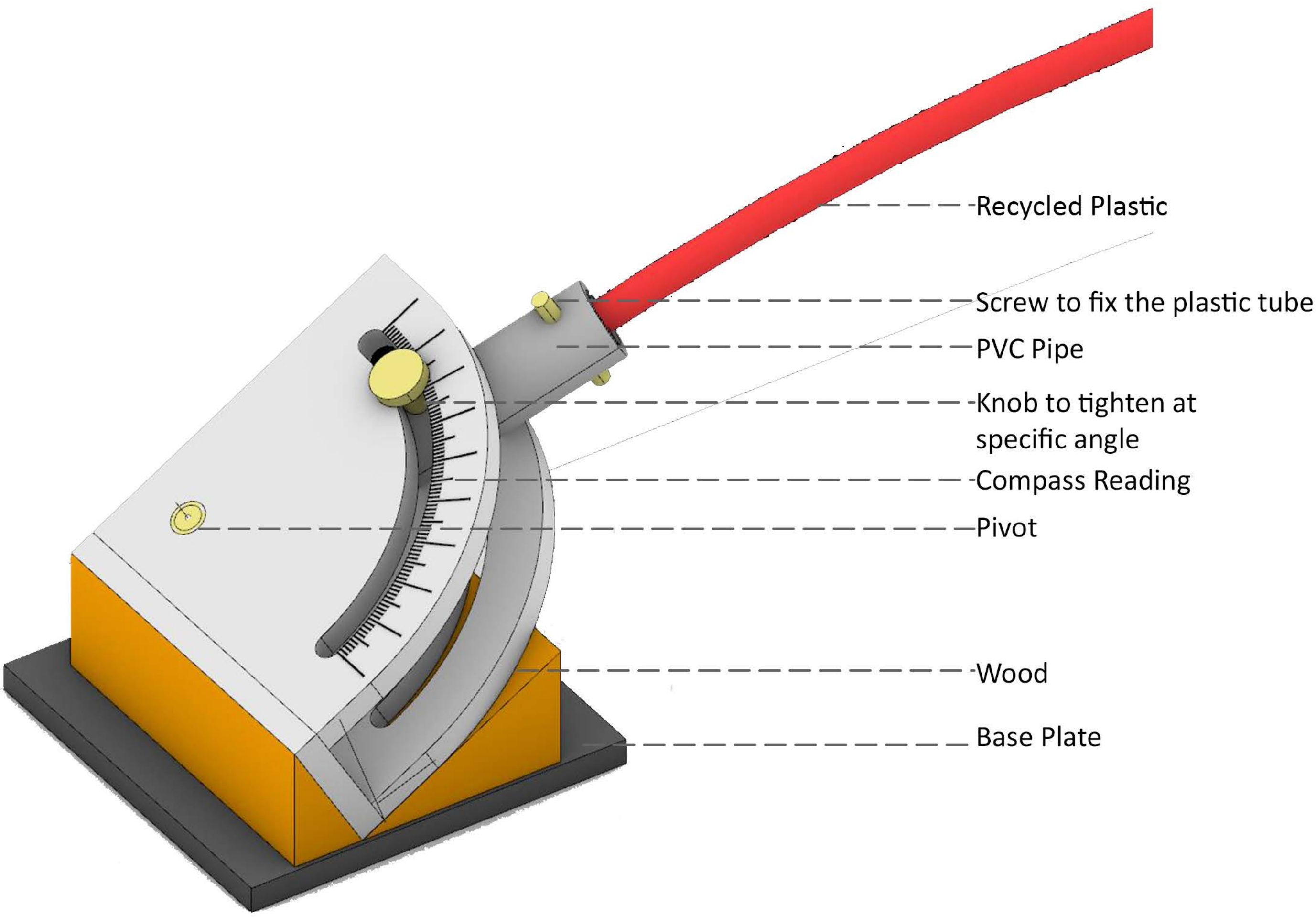


Fig. 7.17 Guiding rods in detail

7.3.1.2 Recycled Plastic Tube:

The plastics at the refugee camp can be recycled using the open source design of Precious plastic a global community fighting against plastic. The plastics collected at the site is shredded and extruded as a long solid tube, which needs to be cut based on the arc length. These cut tubes can be reused on the construction of the other structures.[1]

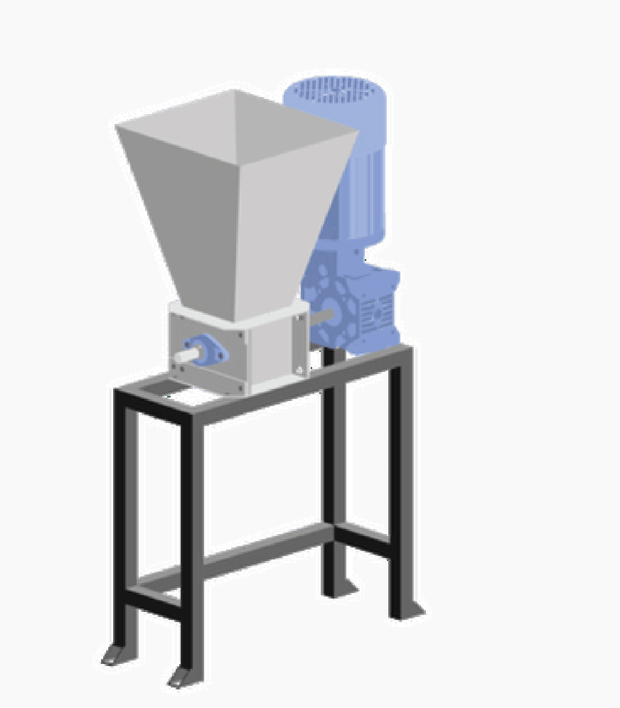


Fig. 7.18 Shredder machine by Precious Plastics

Fig. 7.19 Extruder machine by Precious Plastics

7.3.1.3 Input:

The inputs for the construction is provided by the computational tool which slices the form and gives various inputs for construction.

Sl.No	INPUT 1 (On Site)		INPUT 2(Plastic)	INPUT 3(Tool)
	Position X	Position Y	Arc Length	Angle
1	1.6m	1.6m	2.42m	18
2	2.35	2.35	5.5m	22
3	3.00	3.00	7.3m	26

Table 7.20 Input for marking and construction

And so on...

7.3.1.4 Brick Placement:

The bricks needs to be placed on the longer side for thermal comfort. A small wedge needs to be placed between the bricks and a sticky mortar probably lime or mud to hold it in place. Once the arch is formed the wedge comes into action before the mortar dries.Holes where created on the structures for diffused lighting. Half bricks where used to create the openings, only the wedges needs to be placed, which can be removed later. The wedges are placed on the outside and the less mortar on the inside, with the physical contact of the bricks.

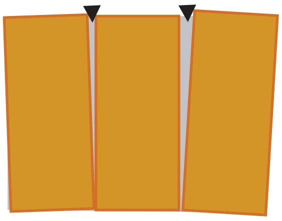


Fig. 7.20 Brick Placement

[1] https://preciousplastic.com/

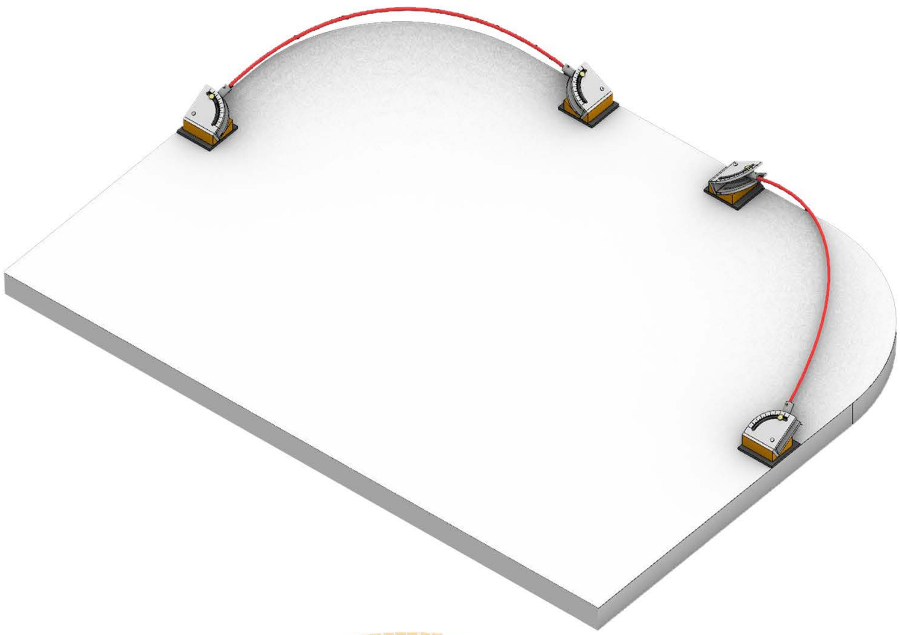


Fig. 7.21 Positioning tool on the plinth

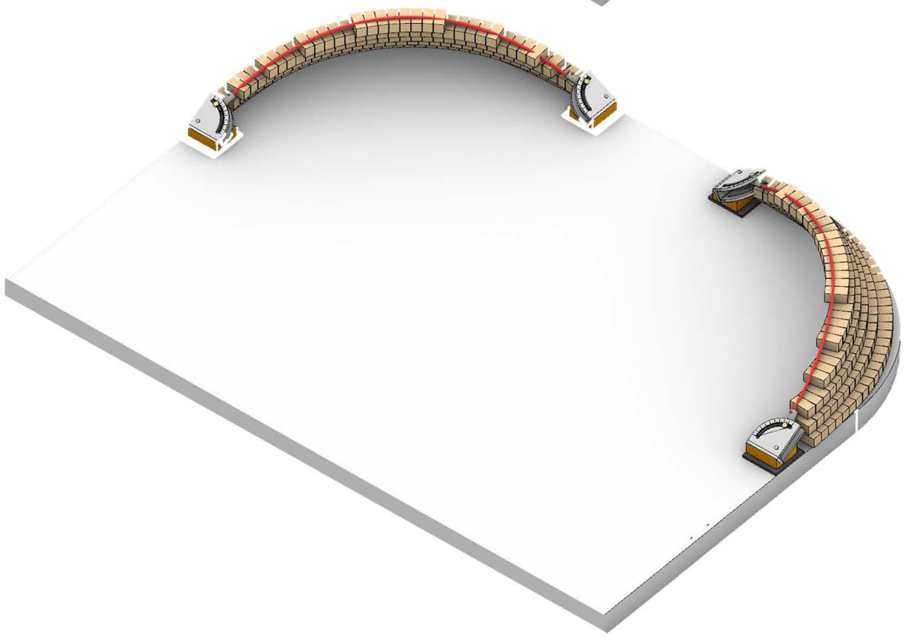


Fig. 7.22 Laying of brick beneath the guide

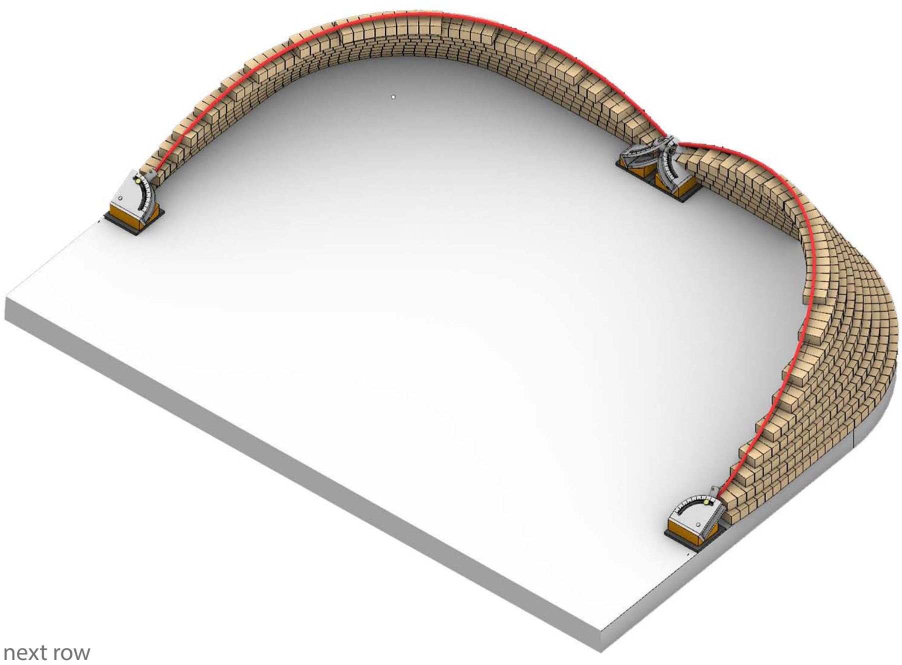


Fig. 7.23 Move the guide and start laying the next row

7.3.1.5 Sequence:

After the plan is marked on the site, the opening arches needs to be constructed, the guides needs to be positioned and then the bricks needs to be built in an order along the four corners and inwards. After building a layer the guide needs to be moved and the next layer is placed over them. Instead of giving measurement of all the arcs, every third arc's measurement is given and the bricks to be placed between them visually. Once the bricks are placed on the ground, additional layers are placed over it. The layers of the bricks are placed over the opening arches and the load transfers via the arch. The dome is constructed like a spiral, the sequence of construction is BLUE, RED, GREEN, GREY, BLUE, RED and so on like weaving a basket. The order needs to be continued till the closing the form.

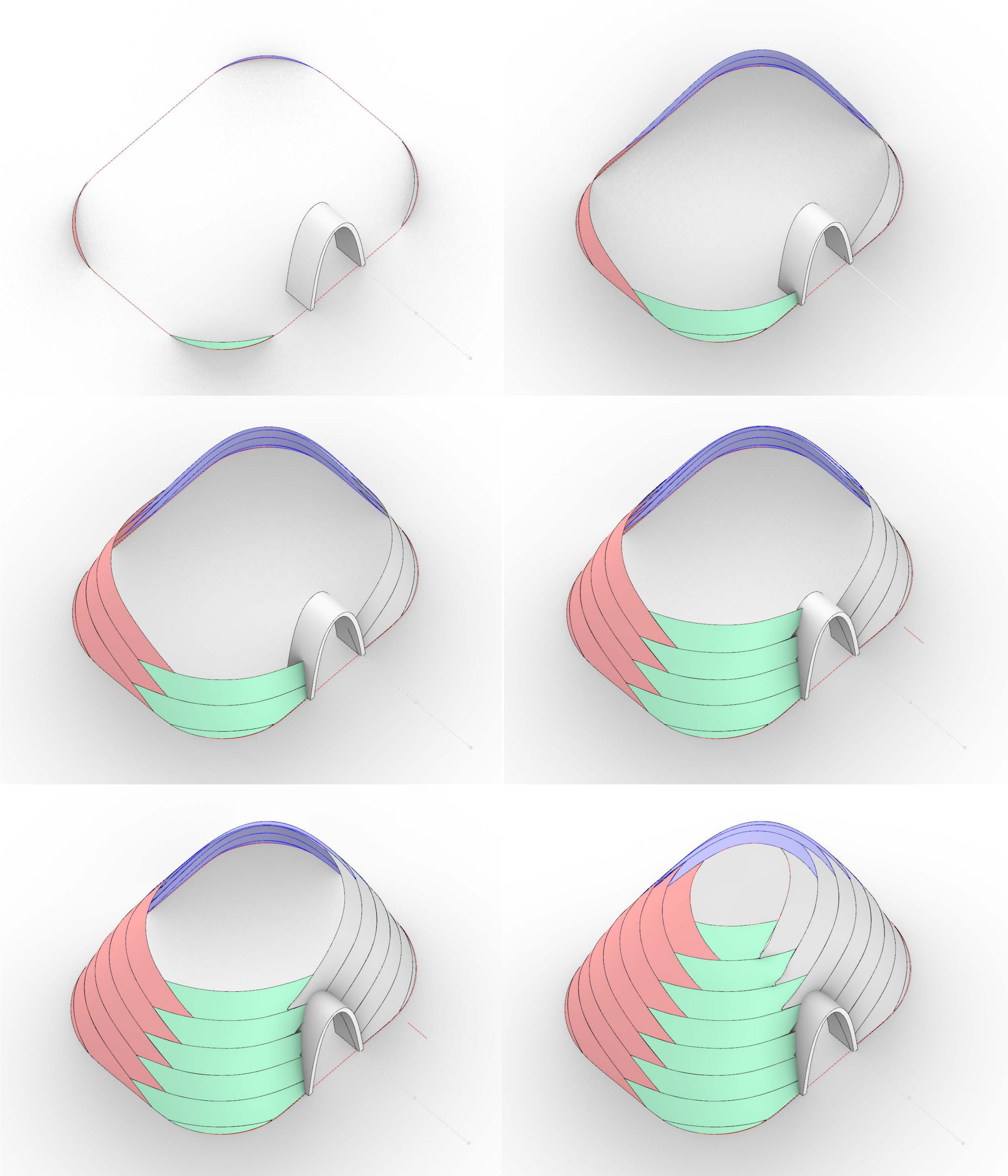
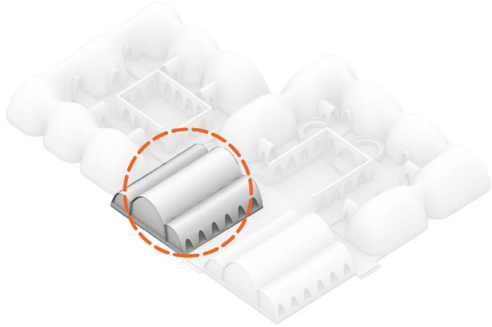


Fig. 7.24 Sequence of construction

7.4 NUBIAN VAULT TECHNIQUE:

With the Nubian vault technique, used for centuries in Upper Egypt, vaults can be built without any formwork by using reclining arches made of adobe. The degree of inclination of the arches is a decisive factor in the construction process. This should be between 65° to 70° with the horizontal if the arches are built up at a lower angle, the lower part of the vault might collapse during construction, while if the angle is larger, the adobes might slide off the top. [1]



Keyplan - Workshop

Nubian vaults need one or two vertical walls onto which the inclined arches lean. It is also possible to lean the arches against a central "supporting arch," which typically has the section of the vault and has to be made with shuttering It was found that by using an optimum mortar composition with high binding force, it is also possible to use adobes with thicknesses of up to 10 cm. When building the reclining arches, it is advisable that the blocks forming the arch are held together by keeping them touching on the inner edge with hardly any mortar in between, and wedging with a stone chip on the outer edge if required, so as to display arch action even before the mortar.

This construction can be implemented for the large spanning vaults of the workshops. The central arch needs to be built which acts as a vertical wall on which the bricks are laid at an angle. The bricks needs to be placed simultaneously on both the sides which counter balances the weight exerted on the arch.

Fig. 7.25 Workshop after construction

[1] Building with Earth- Design and Technology of a Sustainable Architecture by Gernot Minke

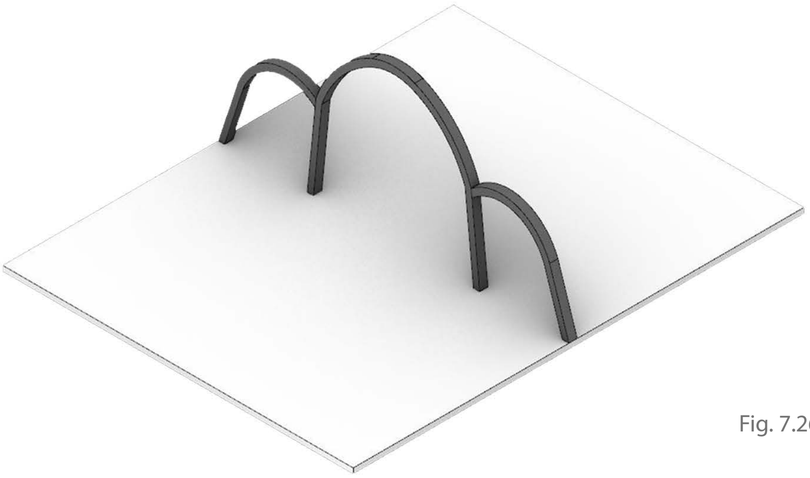


Fig. 7.26 Central arch

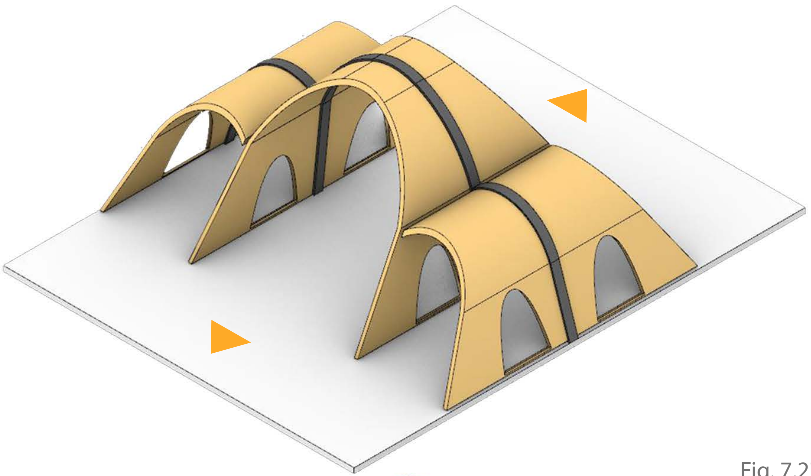


Fig. 7.27 Brick laid at 65 degree on both the sides

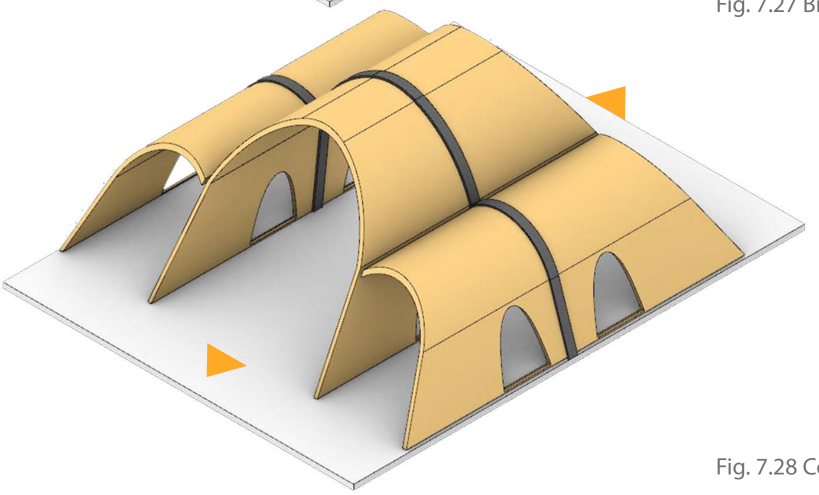


Fig. 7.28 Continue the construction

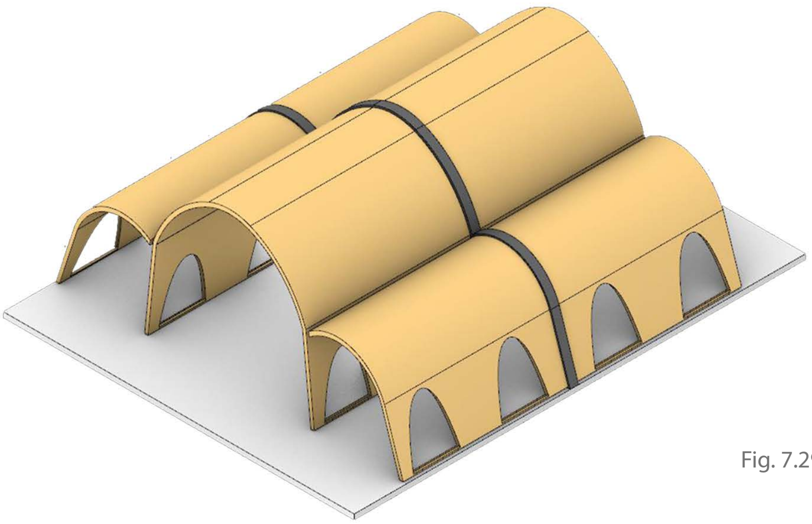


Fig. 7.29 Workshop after construction

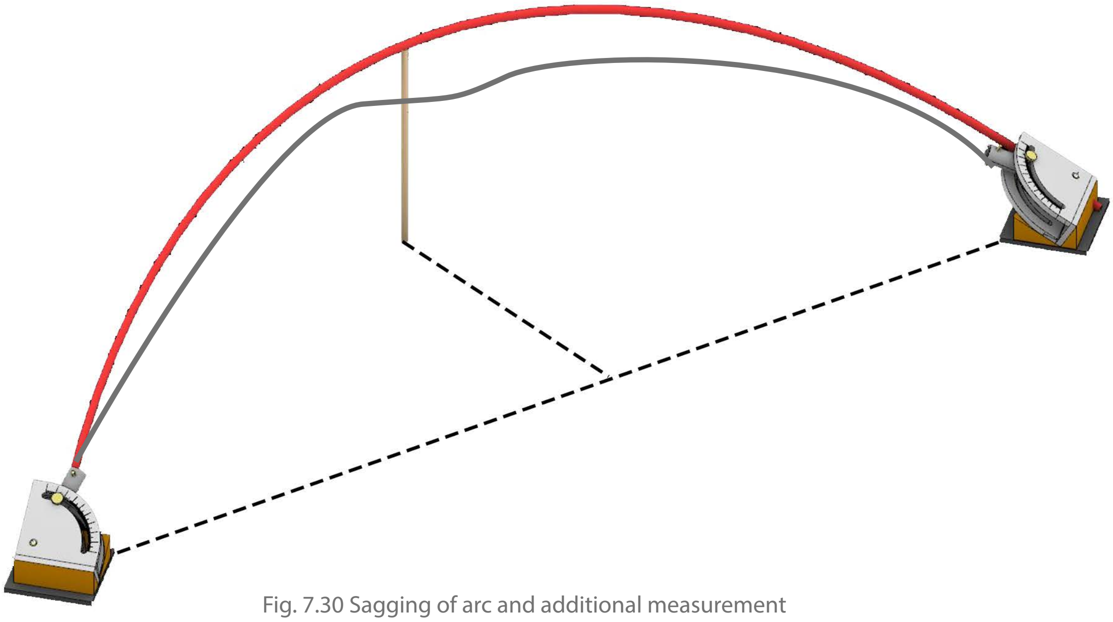


Fig. 7.30 Sagging of arc and additional measurement

7.4 LIMITATIONS:

- The recycled plastic tube which forms the arc, might sag due to the long arc length. Either the tube needs to be thick and strong or an additional support at the centre needs to be provided.
- The precision of the angle might differ while constructing, its better if the arcs are constructed based on their height from the ground.
- An unskilled labour needs certain amount of practice to understand, but inorder to create the weaving pattern a better understanding is required and needs to be developed over time.
- The size of the tool and the precise positioning them at the points can be developed further.

7.5 DECISION MATRIX:

The decisions matrix below was created to choose the best suited construction method for this building from these three methods. The guiding rods system will be the best based on our specifications, weights and ratings.

Decision matrix			Methods (rate from 1 = bad, to 5 = good)					
			Compass		Voxelization		Guiding rods	
Specifications		Weight	Rating	Weighted	Rating	Weighted	Rating	Weighted
Objective evaluations	**Constructability**	**5**	3	**15**	5	**25**	4	**20**
	Amount of info required on-site	**3**	1	**3**	2	**6**	3	**9**
	Shape freedom	**3**	3	**9**	1	**3**	4	**12**
	Low tool costs	**4**	2	**8**	5	**20**	3	**12**
Subjective evaluations	**Pattern**	**2**	5	**10**	3	**6**	5	**10**
	Aesthetics	**1**	5	**5**	2	**2**	4	**4**
Total of the weighted ratings:				**50**		**62**		**67**

Table. 7.2 Matrix of all the techniques

View from the Workshop toward the Amphitheater

08CONCLUSION

Refugees have lost their home and are looking for new survival means in an alien country. It is important to give them a piece of their home and skills to make a home. Proposing a skill development center would keep them engaged and provide an alternate means of security. The hot and dry context of jordan requires a built form with high thermal mass. Also, Jordan is fourth in line of water shortage which demands a resource saving construction strategy. The goal of this project was to create an architecture that responds to the context, climate by using available resources.

To develop free flowing structure, a 3d mesh was formulated based on the architectural plan and circulation principles. The mesh was dynamically relaxed using loads proportional to the mass of the adobe. This process was repeated for various blocks and validated using FEM in Karamba. To break the solidness in the interior and improving the indoor quality, openings were made on the points of lowest solar radiation and validated in FEM to ensure that all structures worked under a maximum permissible tensile stress of 0.05 MPa and maximum compressive stress of 0.5 MPa.

The structure works based on the compression of each element of the structure (section 8.3). Every element's performance is important in the sustenance of the structure. Hence, it is necessary to maintain a uniform material property in the brick. Hand made bricks have varied properties and are not standardized as can be seen from the section 3.4.2. Use of Compressed Stabilised Earth Blocks composed of earth, lime, sand and water would help in standardisation and less consumption of water. Also, these materials are available within the radius of 50 km.

Having developed a new construction technique that is based on the old Persian dome and nubian vault techniques assures easy constructability of the resultant complex geometry by unskilled local inhabitants. This Process of File to Production by locals provides a building that inherits the sense of belonging to the People and assures it's sustainability. The guiding rods for persian dome techniques are made of waste plastic from the camp and can be reused for similar structure throughout the building process. This minimises the need for form work.

09APPENDIX

APPENDIX 1:

S.No	Cross-section (mm)	Weight of adobe per (Kg/m3)	Weight of the Material per grid (0.25 * 0.25) (Kg)	Load factor per vertex of the mesh (N)
1	120	1693	12.6	3.15
2	240	1693	24.3	6.0
3	360	1693	38.0	9.5
4	480	1693	50.9	12.7

APPENDIX 2:

S.No	Name	Big/Small	Stress/Mpa	Y.M (E)	Yield Strength with safety factor 2	Stress@5%
B1	Plain Adobe	B	1.168081494	24	**0.584040747**	0.92
B2	Plain Adobe	S	0.794444444	8.03	0.397222222	**0.19**
B3	Adobe with Fibre 20%	B	2.579881657	29	1.289940828	**0.735**
B4	Adobe with Fibre 20%	S	1.298701299	13.07	0.649350649	**0.122**
B5	Adobe with Woodchips	B	1.010416667	8.625	0.505208333	**0.153**
B6	Adobe with Woodchips	S	1.094047619	18.83	0.54702381	
B7	Adobe with 15% sand etc	B	0.642666667	3.5	0.321333333	0.07
B7-S	Adobe with 15% sand etc	S	0.644444444	6	0.322222222	
B8	Adobe with cardboard 1/3 of volume	B	6.89122807	26.45	3.445614035	0.064
B11	Plain adobe	B	1.02962963	15.6	0.514814815	0.728
B12	Plain Adobe	S	0.809090909	6.8	0.404545455	
B13	Plain Adobe	B	1.190283401	24.5	0.5951417	0.1
B14	Plain Adobe	S	0.647204969	3.01	0.323602484	0.02
B15	Adobe with cardboard 1/3 of volume	S	1.074534161	6.75	0.537267081	0.028
B17	Adobe with Straw	B	1.305263158	15.33	0.652631579	0.324
B18	Adobe with Clothes	B	3.572156197	12.35	1.786078098	0.09
B19	Adobe with Paper strips	S	1.049142857	13.68	0.524571429	0.81
B20	Plain Adobe	B	3.992740472	21.1	1.996370236	0.33