Structural analysis of earth architecture

A report on the structural concept and performance of structures made of earthbags, earth filled bottles and adobe bricks at Al'Zaatari refugee camp, Jordan.

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Abstract

Building with earth is one of the earliest known form of construction in human history. It can be made with minimum number of tools, very low energy and soil, which is available everywhere. Thus by exploiting these benefits, different types of construction system is proposed at the Syrian refugee camp 'Zaatari' in Jordan. Bounded by the plight of minimal resources, the Zaatari camp gives us a platform for maximizing the use of the only available building material - sand and an investigation into extent of its use of mechanical properties in multiple variations. The report elaborates on the structural response of the three proposed types of construction methods,i.e., earth bags, earth filled plastic bottles and adobe bricks. This report is an extension of the laboratory tests conducted for the bottles and adobe bricks. A detailed discussion is provided on the challenges and optimization techniques for the stability of such structures. The experiment was a part of an academic curriculum for the building technology track under The faculty of architecture at TUDelft.

Key words: Earth architecture, Earth construction, Adobe, Earthbags, Plastic bottle, FEA, Zaatari Refugee camp, Compuational Design.

Content

1 Introduction

1.1 Background

The syrian civil war which erupted in March 2011 has created one of the most critical humanitarian problem of our time. Over half the pre-war population, more than 12 million syrians, have been killed or forced to flee from their homes (Mercy Corps, 2018) causing them to be the largest refugee population in the world. While these refugees have been forced to scattered all over the world, the most important official settlement is the Zaatari camp, located in the Mafraq district of Jordan. This camp was opened to the refugees on 28 July 2012 (Wikipedia,2018). With an initial population of 15000 in 2012, Zaatari now hosts 78994 people (UNHCR,2018). With 6 years of establishment, the camp is slowly taking form of a permanent settlement. The evolution of this settlement, thus demands a better living environment by replacing the tents with comfortable homes and providing the people a hygienic liveable environment with all facilities needed for a healthy life.
However, the development has to begin with the limited resources in the camp and make the most of the materials available. Thus, context provides an excellent opportunity to innovate with the available resources. The most modern concepts of 'reuse' and 'upcycle' can be used to rebuild a place for the war ravaged zone.

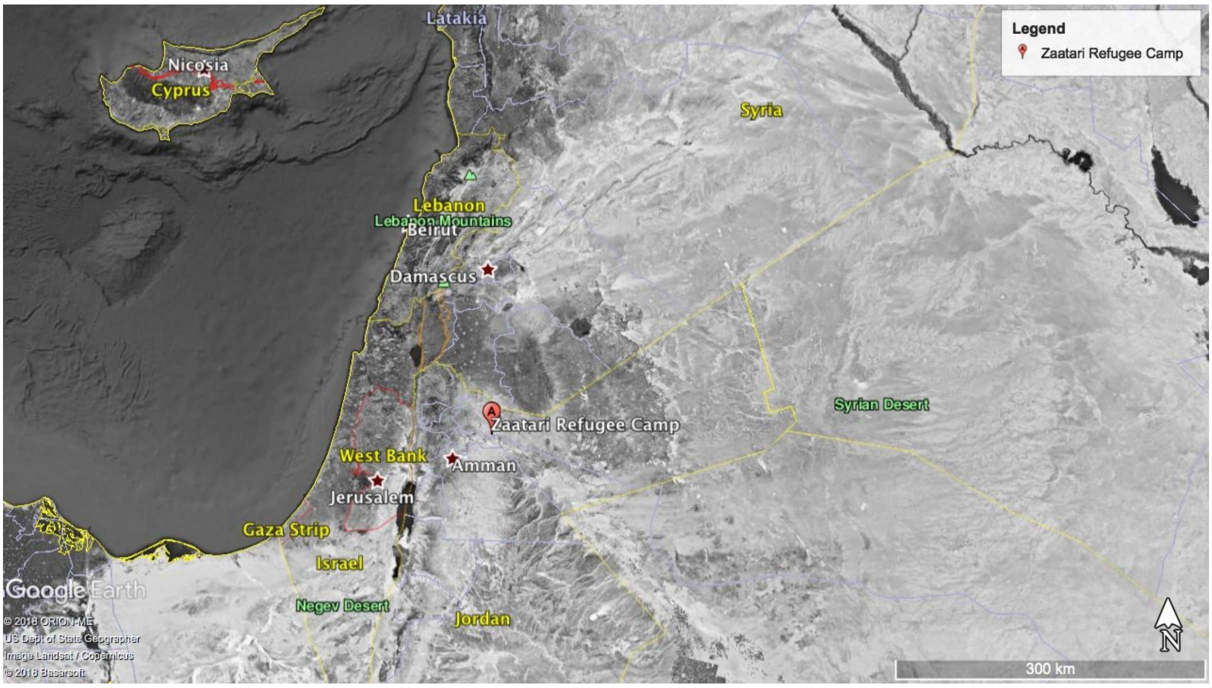


Figure 1: Location of Al' Zaatari refugee camp (Image source: Google Earth)

1.2 Project introduction

The opportunity is explored under the academic curriculum of the TU Delft Master programme - Building Technology. This experiment is a part of the architectural design studio - Earthy, whose aim is on devising computational methods, techniques and tools for analysis, synthesis and optimization of architectural configuration, form generation and

structural validation. The course focuses on designing of a zero-waste circular construction process.
The scrupulous analysis of the living situation in Zaatari camp led to a proposal of establishment of an institute, which can promote and aid in construction process and innovation in building technology using the locally available materials. Thus, the 'Earth institute' is strategically placed on the map of Zaatari to aid in future development of the settlement. Figure 2 shows the location of Earth Institute.

Figure 2: Location of earth institute in Zaatari Camp, Jordan.

This report is the elaboration of the structural understanding of the available building resources in zaatari and structural validation and optimization of the architectural design of the 'Earth Institute'. The process of computational form-finding, materials used for building, physical tests of these materials and final optimization of the structure.

1.2.1 Material palette

The building materials recognition and material selection has been the skeleton of the entire design concept of the 'earth Institute'. As the resources in Zaatari are scarce, and importing materials from other countries to this village is an expensive affair, the best way to build is to use whatever is available locally.
Sand, which is available in abundance has been traditionally used as building material by the Syrians. This building material can be used in various ways to construct affordable, quick and comfortable living structures with minimal tools. A common way of using sand was to make bricks out of it. These bricks are called adobe. Adobe is a composition of sun dried sand, silt, clay and water bricks. This material has been tested in a laboratory to maximize its potential within the framework of academic curriculum and the test results have been used to generate load bearing structures.
Also, the potential construction material was is limited to adobe brick. A further step was taken to research on the lifestyle of the people at zaatari, the products they use, their current environment and the various supply of goods. It was found that the camp generated a lot of waste which came from packaged products from all over the world, also upgradation into

better materials led to the wastage of old products. These tons of waste were the source of inspiration for building the earth institute. Certain other prominent aspects like lack of water and availability of manual labour in abundance were the driving force in material selection and development of construction techniques. From the experiment carried out in the university lab, it was found that for every 10 kg of earth mixture 1 litre of water was required to make the adobe bricks. This means that making millions of bricks for structural construction will demand a large quantity of water supply in the camp.
Also, the lack of unemployment in the camp can be seen as an opportunity to develop labour intensive building techniques and vise-versa techniques which use less machinery and energy. Another critical aspect was the waste management problem at camp, due to concentration of thousands of people in an area and lack of infrastructure facilities and management, waste treatment is a problem. Oxfam, an international organisation in Zaatari, has initiated a waste collection system in the camp. Its statistics show that 27% of the total waste generated consists of mixed plastics (Moodley,2017). Thus it was proposed that pet bottles and unused tent material/fabric, which were available in abundance at Zaatari, could be used as construction material for the earth institute. These materials were backed by literature research to initialize the construction concepts. Further sections elaborate on the derivation of mechanical properties for each of these materials and structural analysis of the form using the same.

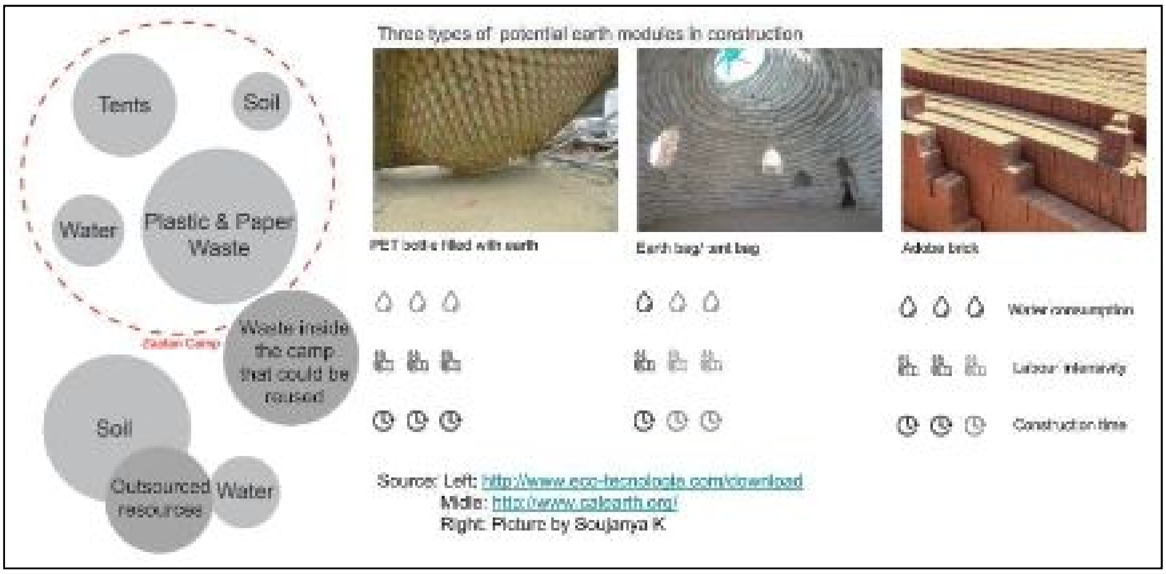


Figure 3: Proposed construction materials for the earth Institute at Zaatari.

1.2.2 Architectural concept

The idea is a response to the current problem of inadequate infrastructure and housing which has failed to keep up with the increasingly permanent nature of the lives of Zaatari residents. The design therefore, caters to activities like prototyping and testing of earth blocks and techniques in earth construction, conducting classes and workshops to teach theoretical and practical aspects of earth relating building and places for cooking and socialising. The proposed location for the institute as shown in the figure 2 is just outside the eastern edge of the plot, at the end of Al.Yasmin Street. It has access for vehicles by road and existing truck parking space in the vicinity. Al. Yasmin Street is currently dotted with markets and shops on the western half of the camp. The earth institute will function as a node on the other end of this axis, thus creating a potential landmark for Zaatari camp.

2 Research methodology

2.1 Research question and objective

The objective includes identifying the major structural challenges in the design and investigating on the material properties of each of the three identified construction system:

- Earth Bag construction
- Sand filled pet bottle construction
- Adobe bricks

and identifying the combinations and sizing of the construction system, given the architectural layout and initial design concept. Also how could the mechanical properties of the three materials be used to derive at a structurally sound structure? What strategies can be adopted to improve the structural performance and will it have an impact on the architectural language? What are the construction methods that can be adopted to safely build the structure?

2.2 Method

Structural validation is an iterative process between structural and architectural optimizations governed by the material capacity. A method has to be defined to clearly portray the role and objective at each step in order to meet the requirements within a given timeframe. Figure 4 shows the outline of workflow network of the structural design process which was followed to achieve the final design.

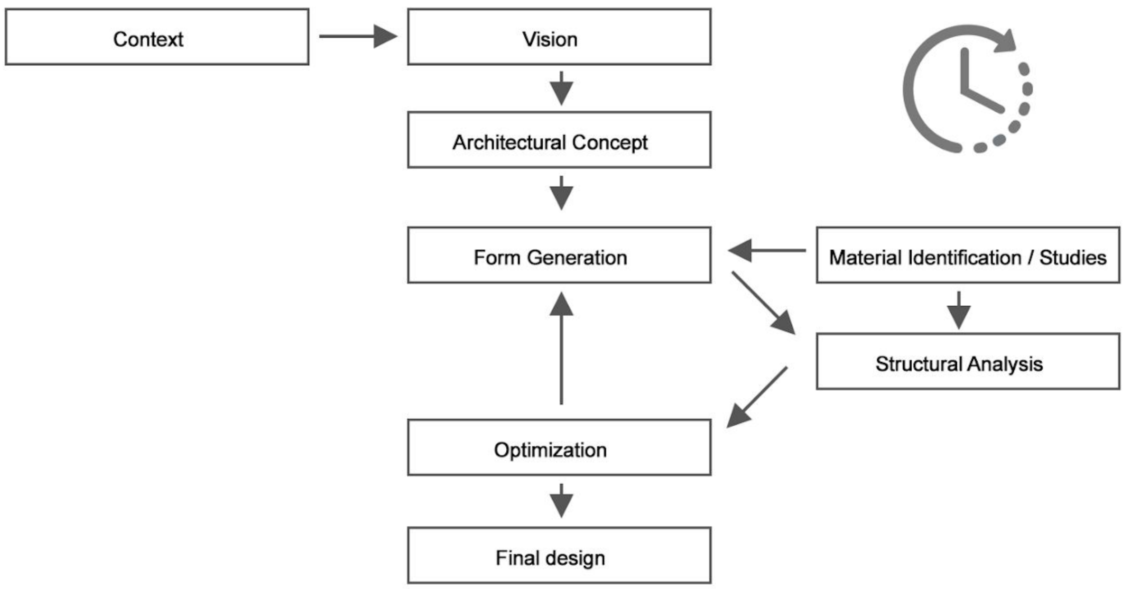


Figure 4: Workflow outline of the design process

The following steps is an elaboration of the workflow outline:

1) Context analysis: The first step of design involves understanding the context and interpreting the problems at the site. Context studies include all the physical, sociological, cultural and historical aspects of the people and built environment.
2) Vision: The vision was the most important aspect of the design which acts as a guidance throughout the design process. Vision was derived from the contextual analysis, focusing on one or more aspects of the zone.
3) Architectural Concept: The third important step is the architectural concept which was translation of the vision in the form of an intervention in the built environment. It included urban level spatial configuration, area programming and planning based on various architectural considerations and guidelines. An effort was made to take a computational approach and generate a plan by developing an algorithm. However, the detailed discussion about the development of architectural concept is beyond the scope of this report.
4) Material identification and studies: A detailed research on the available resources and their potential as a construction material ran parallel to the architectural concept development. Thorough understanding of building materials in terms of availability, logistics, environmental impact, mechanical properties, available research and feasibility has to be determined before determining the material. Both form generation and structural analysis was directly dependant on the properties of the material.
5) Form generation: This step tied the gap between of architectural concept and material studies. A computational approach had been used to generate the form based on the mechanical properties of the materials and governed by the architectural concepts. The form generation was a continuation of the algorithm used to generate the architectural layout. Form generation was a visualisation of the 2D concept into a 3D spacial setup. It was an iterative process. The various iterations are explained in further chapters.
6) Structural analysis: The most technical and critical part of the design was structural validation. This step converts the project from concept to a real life situation which is controlled by various technical parameters. These parameters contribute to generation of a sound livable building. The mechanical properties used in this report are derived from the laboratory test of the materials and literature research. Structural analysis has been done by using the FEM (finite element method) using computational tools. This report specifically elaborates on the process of structural validation of the 'Earth Institute'.
7) Optimizations: Optimization of the form was driven by the structural analysis. It included revising parameters like the shape, the height, cross-section thickness and architectural layout based on structural forces. It also included optimizations in the computational model for form finding and structural analysis like adjusting the mesh properties and geometry types to generate a virtual model as close as possible to reality.
8) Final form was the derivative of the above process. It was determined by various limitations and governed by the academic curriculum in a given timeframe.

2.3 Theory and Equations

2.3.1 Form-finding theory

The form was designed computationally using the particle-spring systems. Particle-spring systems iterative calculations approach an equilibrium state where the sum of all forces is zero (Tedeschi,2014). It is based in accordance to Hooke's law. **Hooke's law** is a law of physics that states that the force (F) needed to extend or compress a spring by some distance x scales linearly with respect to that distance. That is:

$$F = kx$$

where k is a constant factor characteristic of the spring: its stiffness, and x is small compared to the total possible deformation of the spring (Wikipedia, 2018). The main components of a particle-spring system are:

- particles
- springs
- forces
- anchor points

Since particles in this system behave like spherical hinges without the capacity to resist moment forces, equilibrium solutions carry defined loads exclusively through axial forces. This is the ideal condition for form-finding strategies (Tedeschi,2014).
For finding equilibrium states of a particle spring model the dynamic relaxation method has been used. This has been computationally performed in grasshopper using the plugin - Kangaroo.

2.3.2 Structural evaluation standard

The structure is analyzed by Load and Resistance Factor Design (LRFD) method, which is proportioned to sustain all actions likely to occur during its design life, and to remain fit for use, with an appropriate level of reliability for each limit state. Limit state design requires the structure to satisfy two principal criteria, the ultimate limit state (ULS) and the serviceability limit state (SLS) (Wikipedia, 2018).

According to ULS,

$$\gamma_o \, Sd \leq Rd$$

Where:
γo = Important factor for structure
Sd= Design value of structure reaction under the load combination
Rd= Design value of structure resistance

The structure reaction in this project does not include earthquake action and thermal effect. The formula used is shown below.

$$\mathrm{Sd} = \sum_{j=1}^{m} \gamma_{g,j} S_{g,j} + \gamma_{q,1} S_{q,1} + \sum_{i=2}^{m} \gamma_{q,i} \varphi_{q,i} S_{q,i}$$

Where:

S_g= Dead load

γ_g = Dead load partial factor

S_q= Live load

γ_q = *Live load partial factor*

ψ_q = combination coefficient

In this project, the important factor for structure is 1.0. Partial factors for dead load and live load are 1.2 and 1.4 in Jordan(Assi, 2005). Design values of structure resistance are described in Chapter 3.

According to SLS, a structure exceeds one of the limits (excessive deflection, vibration, local deformation) would regarded as a serviceability failure. Serviceability limits are not typically defined by building code developer, government or regulatory agency. Building codes tend to be restricted to ultimate limits related to public and occupant safety (Wikipedia, 2017).

In the literature, walls with other brittle finishes (snow or live load) is H/240 (H stands for span height)(IBC 2015), also total settlement of masonry walled structure is from 2.5cm to 5cm(Mishra, 2018). For masonry structure, allowable storey displacement is H/400 in International Building Code(Newman, 1997) and H/550 in small earthquake in China (zhulong, 2018).

In this project, the deformation limit in for the domes (self-weight and live load) would be H/300 vertically and H/700 horizontally.

2.3.3 FEA method

The finite element method (FEM) is a numerical solution method for field problems, which are described by differential equations or by an integral expression. The field problem is used to formulate finite elements which can be seen as small pieces of a structure. In each finite element a field quantity is allowed to have only a simple spatial variation which is an approximation of the real variation in the region spanned by the element. The elements are connected to each other at nodes and their arrangement build up a so called mesh. The mesh is represented by a system of equations with unknowns at the nodes. The degrees of freedom (DOF), the ability to rotate or move, at the nodes as well as the stiffness of the structure governs the spatial variation of the field. The solution is acquired by interpolating between elements using shape functions, usually polynomials denoted Ni , and the number of elements generally dictates the accuracy of the results. (Cook et al., 2002).

3. Materials Analysis

The properties need to be input for structural analysis are Density, young's modulus,
In-plane shear modulus, Yield strength, Safety factor.
The shear modulus are calculated following the formula below.

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

Where:
G = Shear modulus
E = Young’s modulus
Υ = Poisson's ratio

3.1 Adobe

The material properties are defined based on the laboratory test and the literature, details can be found in the laboratory test report.
In the making process, thirteen specimens were made by a group of 10 students, the variants including the size, the composition, adobe or bottle, with or without mold. After 7 days of curing in the tent without turning them over, they were sent to have the uniaxial compression test. They shared the similar behavior of failure, first the cracks appeared and the side surfaces began to fall off. Then the cracks propagated into fractures and more pieces fell off from the four sides. Finally the side surfaces had significant damages, the central remained integer. However, straws, paper shreds and extra coarse sand helped reducing the peeling.
To gain the result, assumptions are the adobes having a rectangular cross section which was constant before cracking and the infinite friction between different coarse. Also, the failure load(F) was set at the moment when the first fracture generated. Young’s modulus are
calculating from the range where F/2 sit in.
The compressive strength and the young’s modulus of the adobes were from 0.319 MPa to 8.919 MPa and from 4.710 to 77.774 MPa respectively. According to the literature, compressive strength ranges from 0.5 to 3.2 MPa at 5% deformation, young’s modulus ranges from 51MPa to 340 MPa.
The compressive strength was chosen from the samples and young’s modulus was defined according to the literature because the test results were much smaller than the literature’s.
Tensile strength would be taken 2% of compression for safety.
The composition of the materials were clay, fine sand, coarse sand and water in the proportion of 3:3:4:1 (by weight) and extra 10% Straw(by volume) were chosen for the project.

- Density = 1300 kg/m3
- Young’s modulus = 135MPa
- Poisson ratio = 0.35
- In-plane shear modulus = 135 MPa
- Compressive strength = 1.2 MPa
- Tensile strength= 0.024 MPa
- Safety factor = 2

3.2 Bottles

The material properties are defined only based the laboratory test due to the lack of literature, the test procedure could be found in laboratory test report.
Two bottles were filled with high density sand for the compressive test. The differences between these two bottle are the infilled sand density, the size and the stiffness. After testing, the bottles were compressed but did not receive damage when the displacement achieved 30mm and the machine stopped loading.
To gain the result, assumptions are as followed. The pressure area of the bottles was the equal to their volume divided by their height (Area= Volume/ Height) and remaining the same during compressing. The bottle wall have the same mechanical performance as the bottles
Finally, the values of the weaker bottle was chosen for the project, considering the unpredicted plastic quality and the local soil infill. Tensile strength would be taken 2% of compression for safety.

- Density = 1418 kg/m3
- Young's modulus = 26.260 MPa
- Poisson ratio = 0.30
- In-plane shear modulus = 10.1 MPa
- Compressive strength = 4.853 MPa
- Tensile strength= 0.097 MPa
- Safety factor =2

3.3 Textile

The material for the textile roof is made of 200GSM High Density Polyethylene(HDPE), in details it would be woven high-density polyethylene black fibre fabric laminated on both sides with low-density polyethylene coating. The chosen value are from AZoM Material(AZoM, 2001) and Polymerdatabase.com(2015)

- Density = 960 kg/m3
- Young's modulus = 1250 MPa
- Poisson ratio = 0.46
- In-plane shear modulus = 428 MPa
- Tensile strength= 70 MPa
- Safety factor = 2

3.4 Earthbag

Assumptions are as followed, the stress ratio distributes evenly in the filling material, volume is constant and interface between the soil and the wrapping bag is frictionless.

Based on the literature study, the density ranges from 13.7 to 20 kN/m3 (Canadell, et, al, 2016)（Vadgama, 2010), compressive strength ranges from 1 to 3 MPa among different unit sizes, infilled material and bag material(Canadell, et, al, 2016). It's observed that the strength would decrease by around 0.3MPa due to the increase of the stack height(Croft, 2011). As for the tensile strength, both in Canadell and Vadgama's study, the earthbag is likely to fail at the top and bottom faces hence it can be assumed the bag reaches tensile capacity only at these points. The earthbags are made of polypropylene in different densities and thicknesses. The tensile strengths are from 8 MPa(Vadgama, 2010) to 70MPa(Tantono, 2008) which are all made of polypropylene but In this case, the eathbags are made of 200GSM HDPE, which are better than those in the literature. However, the barbed wires affected the strength by providing friction to the bag material which inhibits tensile failure of the bag(Croft, 2011). The tensile stress would be taken as 4MPa for safety concern. Since the results are based on qualitative and quantitative experiments and the chosen values are not high, the safety fact would be 1.5.

- Density = 1700 kg/m3
- Young's modulus = 20 MPa
- Poisson ratio = 0.3
- In-plane shear modulus = 7.69 MPa
- Compressive strength = 2.4 MPa
- Tensile strength= 4 MPa
- Safety factor =1.5

3.5 Safety factor

The adobes in the project would be all man-made, quality difference would exists between adobe bricks or bottles or the integration with mortar. Also, the mechanical properties may suffer deterioration which cause the performance worse than the new built buildings. Moreover, due to serviceability, the deformation should not be visible or unrecoverable (avoiding fractures and large strains) The safety factor for them was set to be 2. As for the recycle textile, since it may be already deteriorated and the mechanical performance various on different directions, The safety factor in this project was set to be 2. The safety fact would for the earthbag would be 1.5 due to the adequate and reliable research information.

4. Structural types

The architectural concept was a composition of two major structural elements (domes in compression, the retaining walls and columns to span the tent roof) and three different building materials to achieve a play between the closed, open and semi-open spaces. Figure 5 shows the various elements used in the composition of the design.The structural features had gone through multiple phases of development explained in section 4.1. These were specially governed by changes in architectural layout which determined the spans. The total area requirement for each function was determined by referring to international standards and various case studies relevant to the building typology. These area requirements were then equated with the background research to determine the maximum spans that could be safely achieved with the building materials.

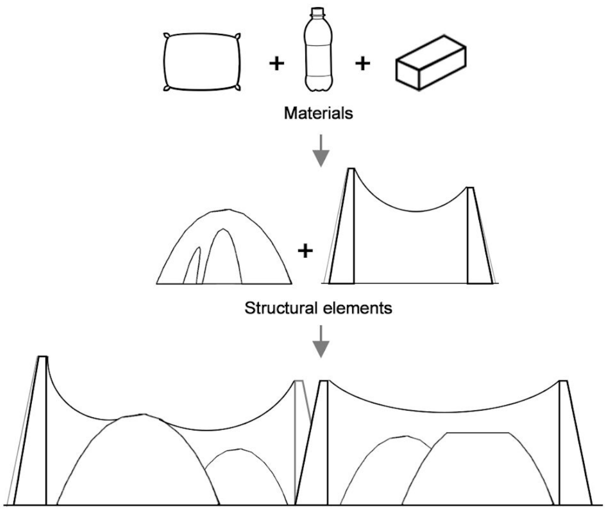


Figure 5: Elements of design- the three building materials (earthbags, earth filled plastic bottles and adobe bricks) and the two structure types (catenary domes-compression and tent roofs-tension).

4.1 Architectural layout

The plan has been developed on the basis of a grid. Since the plan is composed of different geometries, a nomenclature system was set up depending upon the individuality of the domes. Cluster of domes which were attached with the arches, and thus behaved as a single mesh was considered as one unit, while those that were individual were separate for the structural analysis.The attached figure 6 of the plan shows the nomenclature of different groups of domes based and the distinction based on their construction materials.

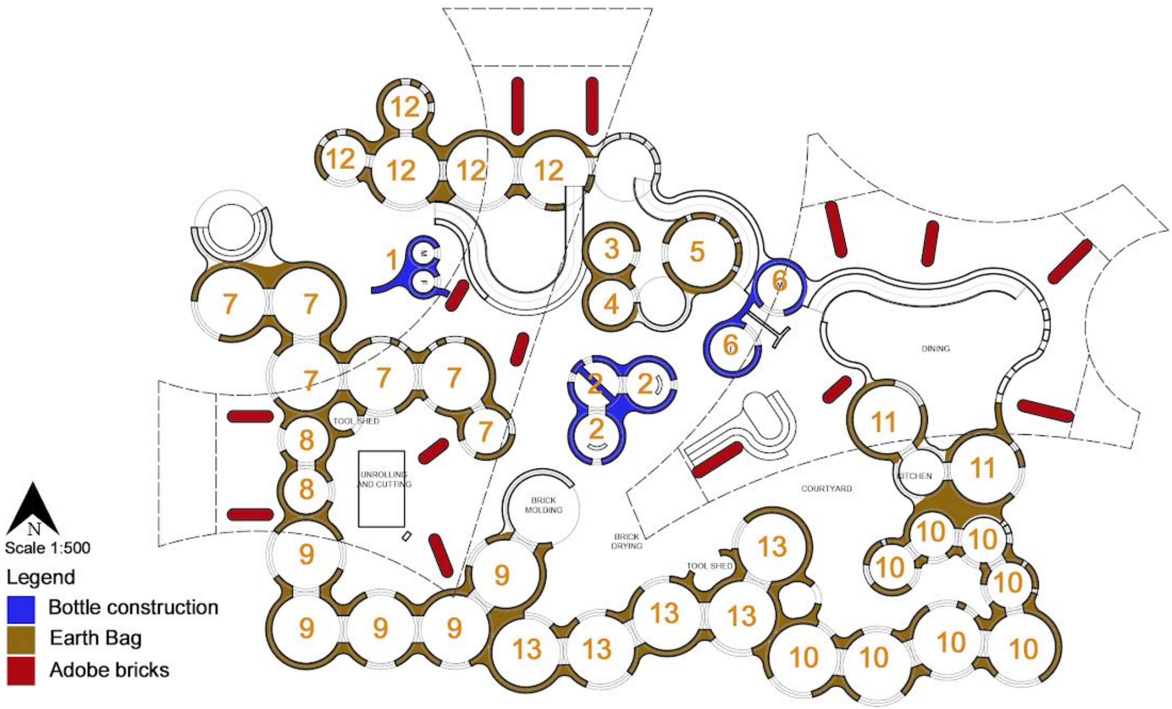


Figure 6: Architectural Plan showing the grouping of domes and building materials.
The perspective view and list of each group is attached in Appendix C.

4.2 Shape development

The final structural elements shown in figure 5 is the result of different stages of form development. These stages were iterations of various construction techniques, material capacity and contextual feasibility. The form development was a continuous debate between what could be architecturally achieved with the computational tools and what could practically be built in the war torn region with limited resources and skills. The final form output was the middle ground for between these two extremes. While the detailed process of form finding using computer simulations is explained in section 5, a broad outline of the different stages of development is shown in figure 7 and explained as follows:

- Stage 1: The first 3D structural iteration consisted of singular catenary domes composed over the given space. Three diameter of circles of 6m, 4m and 2m were used as a base plan for the dynamic relaxation.
- Stage 2: The domes in stage 1 comprised of complete catenary forms. These forms has a limit to the opening sizes and number of openings on its face which lead to the creation of dark interiors. Thus, it was decided that areas which need more light could be open from the top creating well lit area.
- Stage 3: These half open domes created in stage 2 of the design process needed some kind of shade from rain and dust. Thus, the idea of spanning waste tent material on the domes was experimented with. These tent materials were the waste from the refugee tent houses all over the camp. A construction detail for a sandwich structure, in which the tent material is anchored between two layers of adobe as shown in figure 7 was developed.
- Stage 4: While the tent detail was being experimented, further developments in the form of the domes form were made. Since the spatial requirement needed spans which were continuous, free form structures were explored. These structures were deviated from the standard dome like shape. They consisted of large span compression-only structures, which had similar features of the tent roof spanning as explained in stage 3.
- Stage 5: The structures developed in stage 4 resulted complex unique shapes. Hence their construction involved special knowledge and tools which could not be found at Zaatari Camp. Thus, the final stage of form development was the simplification of the shapes for the construction process. These shapes were standardized and comprised of two domes connected by an arch. Also, the tent that was supported initially on the domes by the sandwich method were structurally adding to the stresses and tension at critical points. In order to meet up these stresses, the thickness of these earthbag domes had to be increased significantly. This led to the separation of the two structural members, the domes and the free standing columns to support the tent.
- Stage 6: The final intervention in the form was addition of 500mm high supporting plinth against the domes of the walls. These additional plinth significantly helped in maintaining the displacement values. These plinths were incorporated in the architectural layout as sitting spaces and raised platforms.

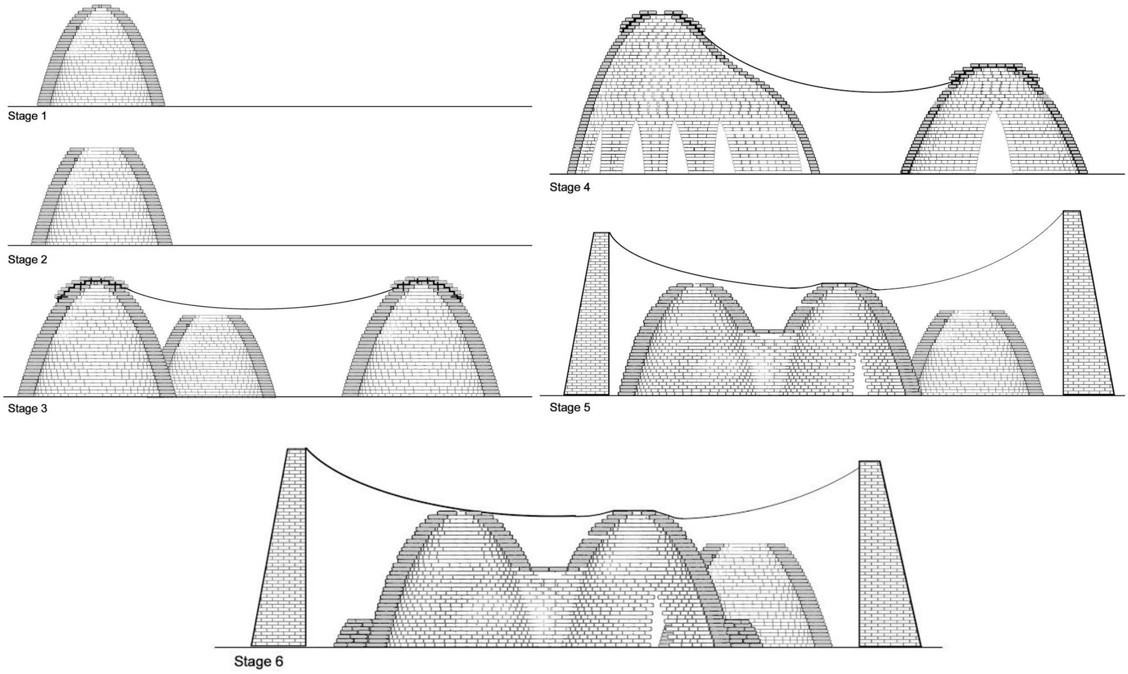


Figure 7: Six stages of form development

5. Form-finding

The particle spring system has been used to form find the compression only dome structures. As mentioned in part 2.3.1, Hooke's law is the driving principle behind the simulations made by using Kangaroo. Three types of forms generated by kangaroo were used for the form generation, they include use of cable simulation for generation of arches, membrane simulation for the tent structure and shell simulation for the domes. The kangaroo workflow is illustrated below in Figure 8:

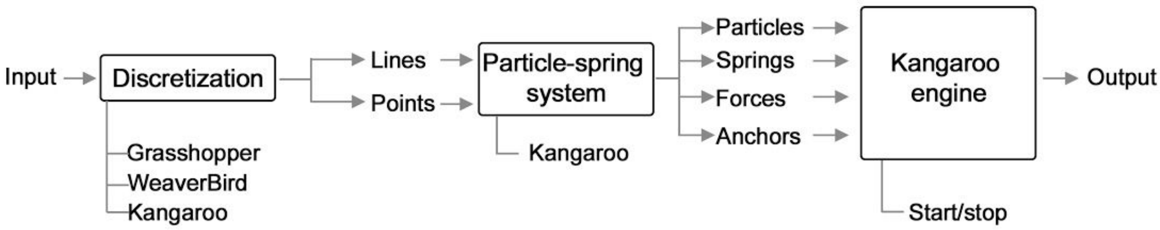


Figure 8: The kangaroo workflow [Redrawn, (Tedeschi,2014)].

- Discretization: a deformable body is created and processed. The main components used for discretization are hosted within the extract panel of WeaverBird.
- Particle-spring system: after a geometry has been discretized, lines are converted into springs and points into particles using specific components hosted within the Kangaroo toolbar. Vectors representing forces are applied to particles, and the anchor points are assigned.
- Kangaroo Engine: particles, springs, forces and anchor points are connected to the Kangaroo engine in their respective slots.While the simulation is running, particles move until an equilibrium state is reached. For this reason the engine's output can be considered dynamic.

As a detailed example, the form-finding for domes is illustrated in following section.

5.1 Simulation process

In order to create a dome, its footprint is first drafted in Rhino. These footprints can be of varied shapes, depending upon the desired end result. For this illustration we take a group of circles as our primary input. A grid of springs is needed for the simulation, it can be generated using various methods.

- Discretization: To construct the discretized model: first a set of NURBS surface is converted into mesh using the component Mesh surface (Mesh>Util), then the components wbEdges (Weaverbird>extract) and deconstruct mesh (Mesh>analysis) are used to extract the mesh edges and vertices respectively as shown in figure 9.
- Particle-spring system (method adopted from Tedeschi,2014): after the model has been discretized, the edges are connected to the connection-input of the springs. The rest length-input is defined as a multiple of the start length. The output of the vertices from deconstruct mesh is connected to the input (point) of the Unary Force; a force vector with a defined magnitude acting the z-direction is applied to each particle. This force is commonly expressed in Newtons. Next, the points on the periphery of the circle are extracted using the naked vertices component (Kangaroo>utility) and connected to the anchor points input of the Kangaroo component.

  Lastly, the output (springs) of the component Springs-from-line and the output (U) of the component Unary force are connected to the Force objects-input of Kangaroo, in flatten mode. The wbEdges component output (L) is connected to the geometry-input of the Kangaroo component to define the geometry for the simulation to output. Double-clicking the boolean toggle switching from true to false initiates the simulation. The grid anchored at the edge is deformed by the Unary force vectors and resisted by the spring stiffness value which is a derivative of the property of the material. Its value is expressed in N/cm (Tedeschi, 2018).

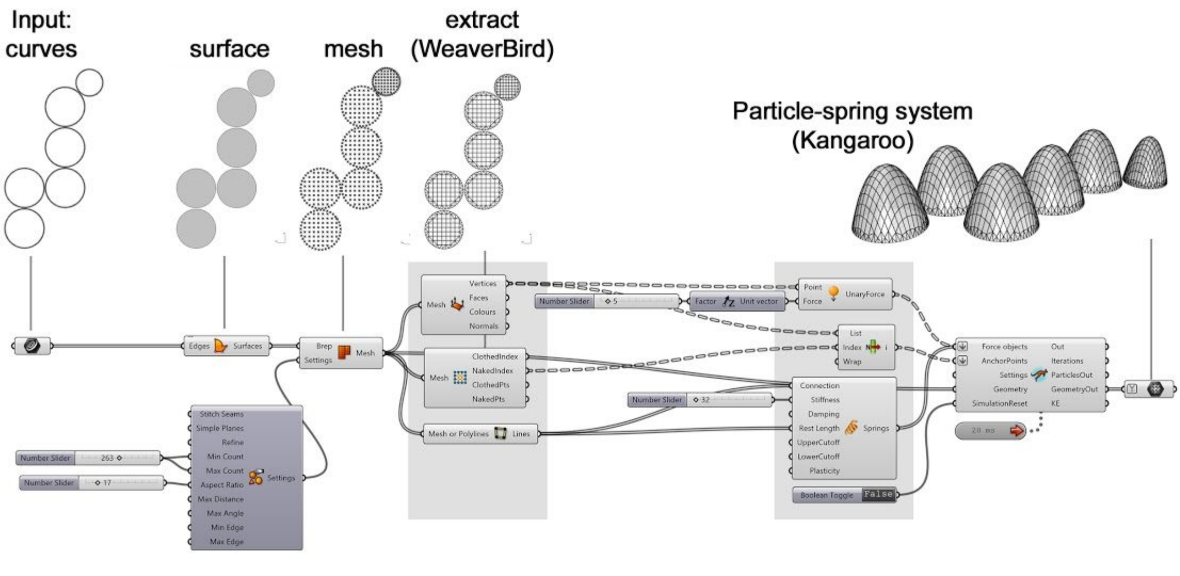


Figure 9: Kangaroo script for generation of domes

Additionally, the different mesh configurations, i.e., mesh with or without diagonals can be tested for varying results. Mesh with diagonals are stronger. The direction and number of these diagonals can determine the asymmetrical/symmetrical behaviour of the mesh. Also, the density of the vertices affects the smoothness of the mesh which in turn influences on the structural behaviour.
Figure 10 shows an complete cluster with doors, windows and connection arches. The complete form-finding kangaroo script for all elements is attached in appendix A.

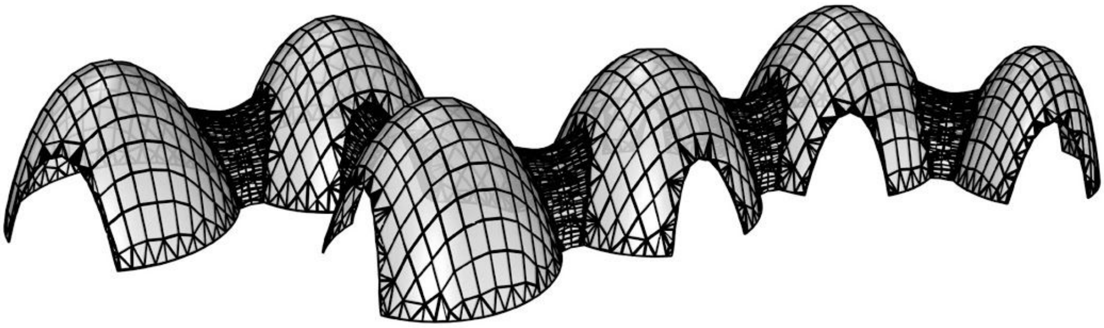


Figure 10: Complete dome module simulated on kangaroo with doors and arched connection.

6. Structural analysis

The finite element analysis (FEA) method has been used for the structural analysis using the grasshopper plugin Karamba. The karamba workflow are as follows:

1. Modelling of the static scheme and the definition of the boundary conditions.
2. Elaboration of the finite element model
3. Model analysis
4. Visualization and analysis of the results

Karamba works with SI and imperials units, but if SI is chosen then it always assumes that the model is in meters.

6.1 Domes

In this part, the process of the structural analysis would be illustrated using Group 10 and 12 as examples (see lay-out) which are most critical among the bottle and earthbag domes. The complete script for Karamba analysis is attached in appendix B. Results of all other dome groups are shown in the Appendix D.

6.1.1 Modeling

- Structural type
  Considering the 3D form and the materials, the models were regarded as shell structures in Karamba.

- Materials
  The bottles and the earthbags are used for dome construction which were marked The materials properties inputs are density, Young's modulus, shear modulus, compressive strength. The values are taken based on Chapter 3.2 and 3.3.

- Cross section
  The initial thickness for the bottle wall and the earthbag wall are 40cm and 50cm respectively due to local climate, bottle size and earth-bag size.

- Loads
  The loads for simulation are self-weight and roof live load, which are all vertical load. The live load is 0.6 KN/ m², which is for a non-accessible roof in Saudi Arabia (SBC, 2007). Snow load is 0.375 KN/ m²calculated based on the Jordanian code (JNBC, 2006), but it is eliminated because it's smaller than live load and these two load types are not taken into account simultaneously. Other loads such as wind load and earthquake action are not taken into consideration in this simulation.

- Supports
  The initial supports are set at the bottom edge of the domes, where the domes transfer their load to the foundation. They would be fixed supports since the constraints are in x, y, z directions both translational and rotational.

6.1.2 Result & Analysis

The domes result are shown in Table 1.

Table.1 Structural Analysis of Domes

Group number	Material	H [m]	L [m]	Zd [mm]	XYd [mm]	Disp. Z [mm]	Disp. XY [mm]	σc,max [MPa]	σt,max [MPa]	ULS	SLS
1	bottle	3.31	2.50	11.03	4.73	3.11	0.72	0.0659	0.0022	✔	✔
2	bottle	4.18	4.50	13.93	5.97	6.18	0.73	0.2211	0.0167	✔	✔
3	earthbag	4.11	4.00	13.70	5.87	8.84	2.73	0.1157	0.0044	✔	✔
4	earthbag	3.13	4.00	10.43	4.47	6.29	1.06	0.0999	0.0017	✔	✔
5	earthbag	4.00	6.50	13.33	5.71	12.33	1.70	0.1459	0.0090	✔	✔
6	bottle	3.25	4.50	10.83	4.64	6.50	0.80	0.0796	0.0014	✔	✔
7	earthbag	4.03	6.50	13.43	5.75	15.37	4.14	0.2613	0.0846	✔	×
8	earthbag	3.12	4.50	10.39	4.45	7.17	1.67	0.2137	0.0047	✔	✔
9	earthbag	4.27	6.50	14.23	6.10	16.63	5.65	0.3036	0.0862	✔	×
10	earthbag	4.69	6.50	15.62	6.69	15.90	3.40	1.5566	0.6023	✔	×
11	earthbag	3.74	6.50	12.47	5.34	11.98	2.46	0.1416	0.0029	✔	✔
12	earthbag	4.57	6.50	15.23	6.53	16.62	5.65	1.9806	0.2907	×	×
13	earthbag	4.76	6.50	15.87	6.80	14.98	5.60	0.5632	0.0764	✔	✔

Note	H: The mesh height of the domes in the group L: The span of the domes in the group Zd: Vertical deformation limit XYd: Horizontal deformation limi σc,max: Maximum compressive stress σt,max: Maximum tension stress	Disp. Z: Maximum vertical deflection Disp. XY: Maximum horizontal deflection ULS: bottle: σc=2.53MPa, σt=0.0485MPa; earthbag: σc=1.6MPa, σt=0.032MPa; bag: σt=4MPa SLS: Zd & XYd

Since the bottles are used for domes with small span and the earthbag are used for large span beforehand due to the literature experiments and the construction complexity, as well as the structural types are both shell, the results here would not used for the structural comparison of these two material.

Group 5 is a representative of individual earthbag domes (Group 3, 4,5), which has the biggest diameter (6.5 meter). When the height ranges from 3 to 4 meters, It's concluded that the larger diameter of the individual dome has, the larger vertical deformation, compressive stress and tensile stress it has.

Group 6 encounters the worst structural condition among the bottle groups. Group 2 is a cluster of three bottle domes and their structural performance seems better than Group 6. In other words, if the cluster are more symmetric and compact, it could be behave better than single dome.

Stress

Only Group 12 failed the ULS. The compression are at least 2 times smaller than the design strength, except Group 10 and 12, which are big clusters of domes.

Tension happens at the openings and the bottom of the domes, which are the edges of the domes(Figure 11). One reason is the thrust ends at the bottom of the domes where the supports locates. Another reason is that centripetal force could not counteract each other since the ring is broken by the openings.

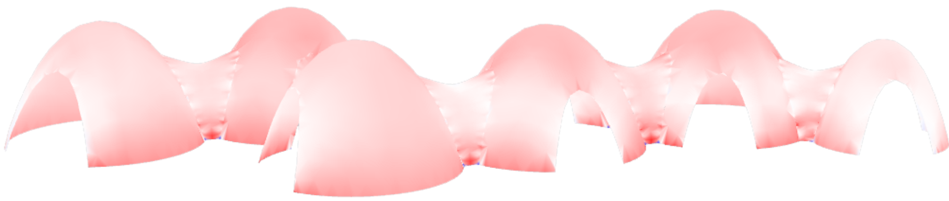


Figure 11: Tension at the openings and the bottom of the domes, Group 7

For the earthbag, failure occurs when there is a loss in confinement provided, i.e. when the bag material is stressed to its stress limit (Vadgama,2010), the earthbag tensile strength varies from 8.3MPa(Vadgama, 2010) to 70MPa(Tantono, 2008) which are all made of polypropylene but in different densities and thicknesses. In this case, the eathbags are made of 200GSM High Density Polyethylene(HDPE), which are better than those in the literature. The tensile stress would be taken as 4MPa for safety concern. Some of the domes exceed the tensile strength limit of the earthbag structure (marked in yellow in Table.1), which is taken as 2% compressive strength. However, they don't exceed the bag tensile strength, still considered under ULS.

Deformation

The horizontal deformation increases when the height increase, but they are all within the limit. This may due to the increase of the self-weight and the flatter surfaces (smaller altitude angle). The largest vertical deformation happens on the top because of the deformation accumulation(Figure 12). The largest horizontal deformation happens at the bottom due to the thrust accumulation.

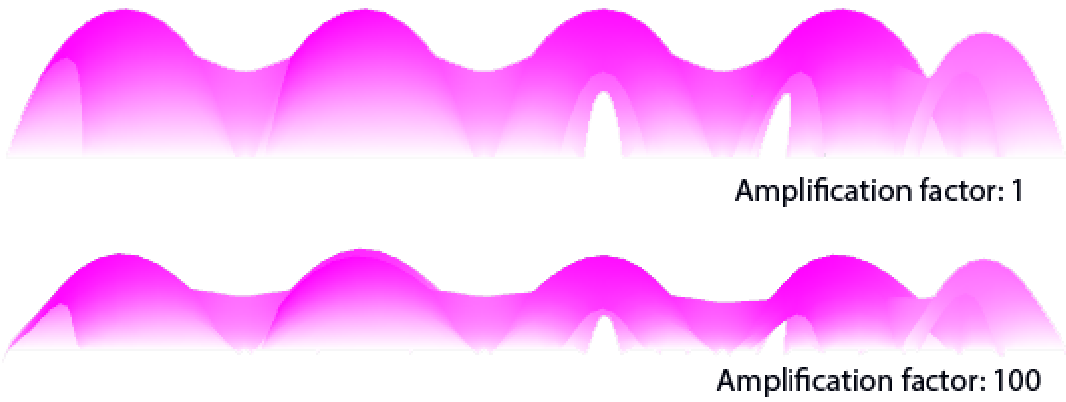


Figure 12: Deformation of the domes, Group 7

All the domes that fail the vertical deformation limit have the span of 6.5 meter(marked in red in (Table.1).

Sum-up

In general, the self-weight load is dominant factor for the stress（Figure 13）The height and span of the domes which determine the shape have greater influence than the openings size and the shell thickness (cross section).The domes that form the cluster have large values both in deformation and stress than the independent domes. The reason causing the stress of some groups much larger than others may be due to the meshes defect in FEA.

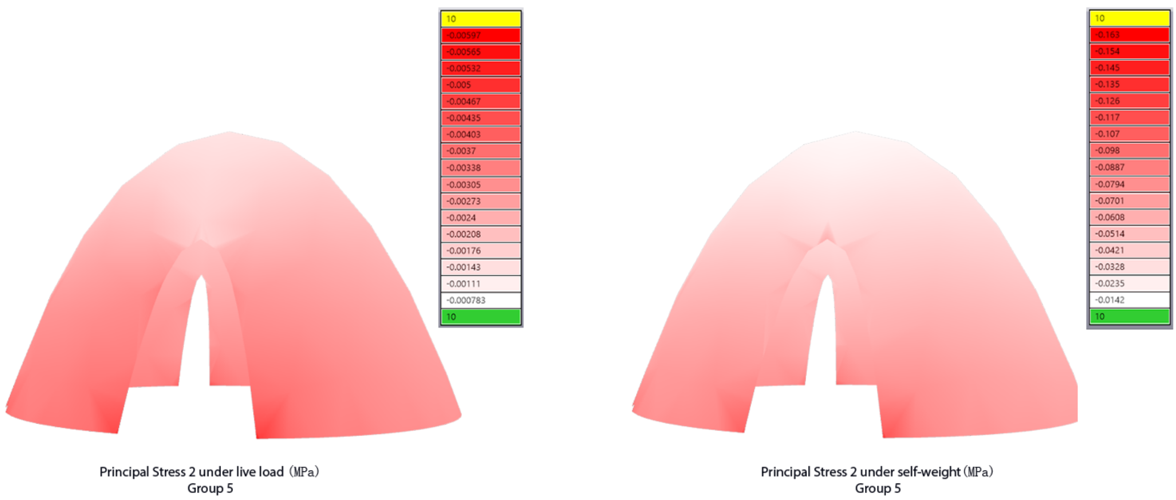


Figure 13: Principal stress 2 under different loadcase, Group 5.

Except Group 7, 9, 10 and 12, other groups fulfill the requirement of reliability (ULS & SLS), which mean their stresses and deformations are all smaller than the limit. As for stability, the bottles are connected with ropes and the earthbags are connected with barbed wires, which ensure them settle vertically and prevent them from collapsing. To increase the stability, adding buttresses and plinth would help (Figure 14).

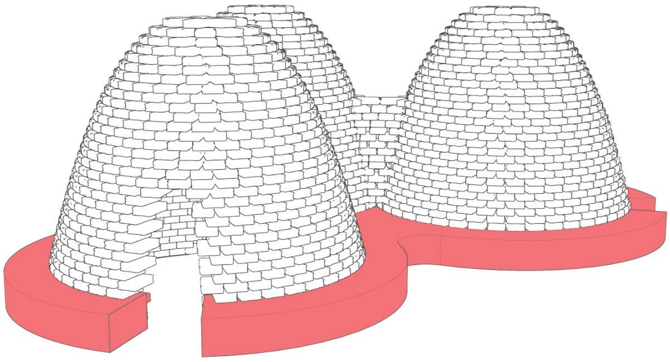


Figure 14: Adding plinth acting like the ring beam.

The catenary lines changes after adding openings but they're still covered by the shell thickness. In this case, Group 7, 9, 10 and 12 would not come across the failures of roll-over and buckling, Also, the deformation mostly happen after the domes are finished, regarding as the foundation settlement. However, these groups need optimization and reinforcement

6.1.3 Optimization

These four groups all consists of big diameters and discontinuous domes. In the optimization process, plugin 'Galapagos' is used in a single dome to test how different parameters affects the mechanical behaviours. Because the mesh of group 7, 9, 10 and 12 for FEA become complicated so that when using Galapagos, it causes error of assemble model in Karamba and Galapagos(e.g. olution exception:Could not find node at where point-load number 1 is attached), so here will not use iterations, which means the parameters are modified manually. Group 7, 9 and 10 are using the same method for optimisation since they have the same ground level and the domes adjoins closely to each other (hard to seperate the foundation). Here would use Group 10 as an example to illustrate.

Pre-tests shows that changing the cross section wouldn't help much to reduce the deflection or the stress, because the stiffness to weight ratio and the strength to weight ratio are low. In addition, the local climate also require the certain thickness. The driving factors would be the buildings span and shape. Since the span of the buildings are fixed in the lay-out (Figure 6), so the first optimization would be changing the height and the opening sizes of the domes.

Group10:
Reducing height would cause deformation, tension and compression decrease. Reduce openings' size would result in tension decrease, deformation and compression increase.
Since Group 10's compression stress already larger than the allowable value(1.6 MPa),

reducing height is more effective than reducing the opening sizes.The latter one is only suitable when the compression stress and the deformation are excess but the tension exceeds the limit.
The results is in Table.2 below. The final result of the whole project is in Appendix E.

Table.2 Group 10 Optimisation									
Varible	H [m]	Zd [mm]	XYd [mm]	Disp. Z [mm]	Disp. XY [mm]	σc,max [MPa]	σt,max [MPa]	ULS	SLS
(origin)	4.69	15.62	6.69	15.90	3.40	1.5566	0.6023	✔	×
Opening size	4.69	15.62	6.69	16.26	2.59	2.0300	0.8901	×	✔
Height	3.59	11.96	5.13	11.66	2.19	1.5582	0.5585	✔	✔

Group12:
Using another approach for Group 12 is because the domes in Group 12 have different ground level, which means they should have different foundations according to the height. Furthermore, their structure should be separated to prevent uneven settlement. In the first step, the dome are separated (Figure 15) and added extra supports(because the domes below ground plane would be surrounded by soil) for analysis.

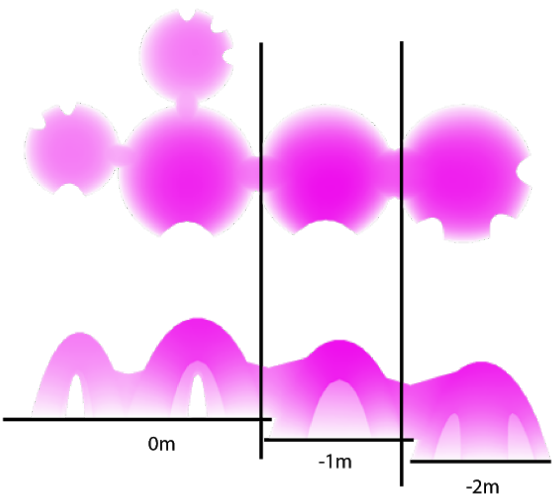


Figure 15: Separation of domes in Group 12.

For the domes whose ground level is 0m, the supports are at 0m.
For the dome whose ground level is -1m, the supports are supposed to be from -1m to 0m. Due to the model defect, instead taking the whole dome, the part that above 0m are taken for analysis and the supports are set at 0m.
For the dome whose ground level is -2m, the supports are from -2m to -1m.

The final result of Group 12 is as follow(Table.3).

Table.3 Group 12 Optimisation									
Varible (Ground level)	H [m]	Zd [mm]	XYd [mm]	Disp. Z [mm]	Disp. XY [mm]	σc,max [MPa]	σt,max [MPa]	ULS	SLS
(origin)	4.57	15.23	6.53	16.62	5.65	1.9806	0.2907	×	×
0m	4.57	15.25	6.53	15.41	3.42	0.4759	0.4389	✔	✔
-1m	4.57	15.25	6.53	11.56	2.72	0.5027	0.0348	✔	✔
-2m	4.57	15.23	6.53	12.10	2.93	0.18	0.0702	✔	✔

6.2 Roof & Column

The roof and column structural concept are shown in Figure 16, the textile are stabilized on all along one side of the column which functions similar to the retaining wall and distributed the horizontal force(f3) from the fabric. The fabric is fixed under the column and transfer its own vertical load to one bottom side of the column. In order to balance the moments, the column must have enough self weight. A simple calculation is presented below to show the initial requirement of the dimension of the column. In this case, the live load on the column is ignored and the tensile inclined angle is taken as 45°.

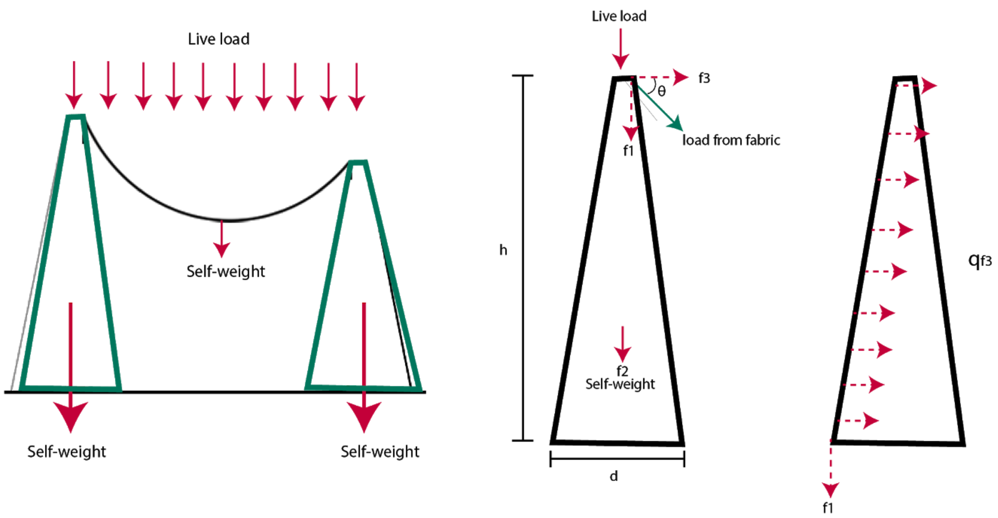


Figure 16: Load distribution on the tent roof and column.

Load balancing equation:

f1 x d + f3 x h = f2 x (d/2)

Where:

f1 = fsinθ

f3 = fcosθ

d = thickness of column

h = height of column = 6m (design requirement)

f2 = self weight of column = (1.2 x (volume x density) x 9.8)/1000

f2 = (1.2 x (dx1x6) x 1520 x 9.8)/1000

f2 = (107.25 x d) KN

θ = 45° (assumption)
f = force on column due to tent fabric
f = live load on tent fabric x area of one tent x no. of tent units considered
f = 0.6 x 1.4 x 23 x 6
f = 115.92 KN

f1 = fsinθ = 115.92 x sin45° = 81.96 KN
f3 = fcosθ = 115.92 x cos45° = 81.96 KN

f1 x d + f3 x h = f2 x (d/2)
81.96 x d + 81.96 x 6 = ((107.25 x d) x d)/2
163.92 x d + 491.76 x 6 = 107.25 x d^2
107.25d^2 - 163.92d - 491.76 = 0

d = [-b +/- √(b^2 - 4ac)]/2a
Where:
a = 107.25
b = -163.92
c = -491.76
d = 3.03 m

7.Discussion

7.1 Validity of the result

The result is validated on different aspects below.

- Material properties
  The mechanical value of the adobes and bottles are taken from the laboratory test during this course. Even though the quantity of the sample is small, the proportion of the raw materials are not precise and the structural element or a different size might have different values than a single adobe or a bottle, the mechanical properties chosen in this project are still regarded effective after comparing to the literature and taking adequate safety factor, the same for the earthbag, textile.

- FEA Model
  The FEA models are regarded as shell structure. In construction, the materials would be stacked layer by layer. The friction resistance between different layers may be larger or smaller than that in the model depending on the bridging materials, which also means the deformation would be different. In the model, the windows are opened from the ground but in real life the window height would be much higher as long as they fulfill the light and ventilation requirement. This would induce tension at window height.

The mesh inputted for analysis have some defect after trimming or merging, causing error in assembly model and the large value difference among different groups. The resolution of the mesh also matter a lot. For example, in Figure17， Group 12 is a cluster of the domes have the different ground levels (which are 0m, -1m, -2m) and fail the serviceability. Biggest tensions happen on the ground where don't have load, that means these critical condition may not exist, but the analysis still regard them as part of the result and validated them.

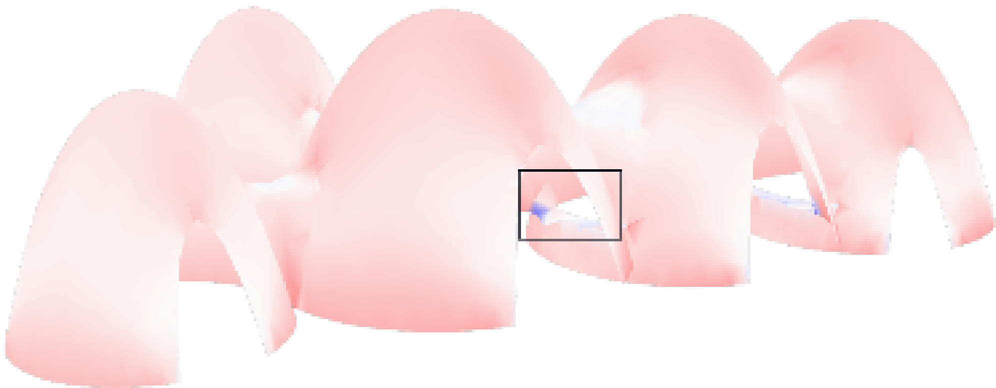


Figure17: mesh defect of Group 12 causes extra tension.

- Environment
  The local material composition and mechanical performance, the quality of the construction, the climate are influencing factors for the structure. The calculation method and input may be different from the local requirement. Since the calculation already adopt the Load and Resistance Factor Design (LRFD) method, in which the loads multiple an amplification factor, the result are still within the limit, so it's considered trustworthy.

In conclusion, although there are some limit in the structural analysis, considering the low mechanical properties and allowable deformation, safety factor, partial load factor the result is regarded as valid.

7.2 Limitation and further optimisation

The experiment was conducted under an academic framework which had to comply with the university guidelines. Thus certain limitations governed the results of the experiment. Also the availability of resources like materials and budget constrained our extent of research. Since the curriculum demanded a timely submission of the output, the experiment had to be modified to suit the time frame, thus time was limited during the scope of study. The setup was made in the university in Delft, thus these results are an approximation of what can be expected in Jordan. As the materials for experiment ie. sand, clay and silt were not procured from Jordan, the results might vary from its actual values. Also the bricks were dried in the natural temperature and not a controlled environment, thus the relative humidity and temperature during the drying process could affect the strength of the bricks.

In this report, the influence of the foundations and the horizontal force on the structure are not considered. If considering the wind load and the earthquake load, the structure would have more deformation both vertically and horizontally. Loads like wind and earthquake need to be taken into account.The windows and the bottom of the domes are most critical locations where the cracks would develop.

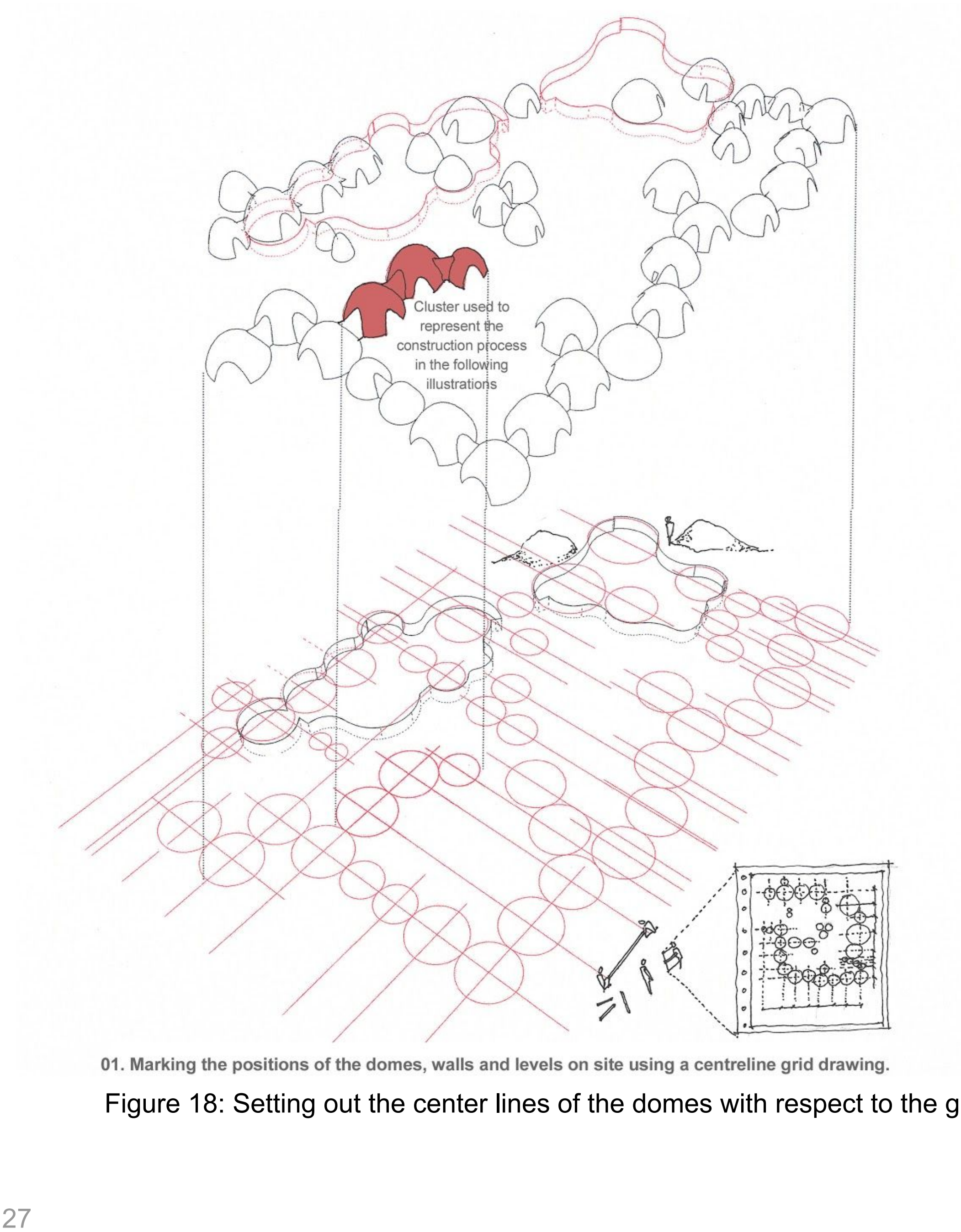
For further optimisation, group 9 need to be fixed for the mesh defect. The meshes for analysis need to be more refined and different types of meshes (meshes with diagonals) can be experimented with. To increase the stability of the domes, adding buttresses and raising the plinth would help. Also, the construction process and lack of building tools and machine greatly limited the material quantity optimization. In order to keep the building technique simple, the cross-section of the domes could not be optimized. The load calculations for fabric roof and the retaining wall are analytical, thus it also needs to be checked computationally.

8. Construction design

The construction process consists of two phases:

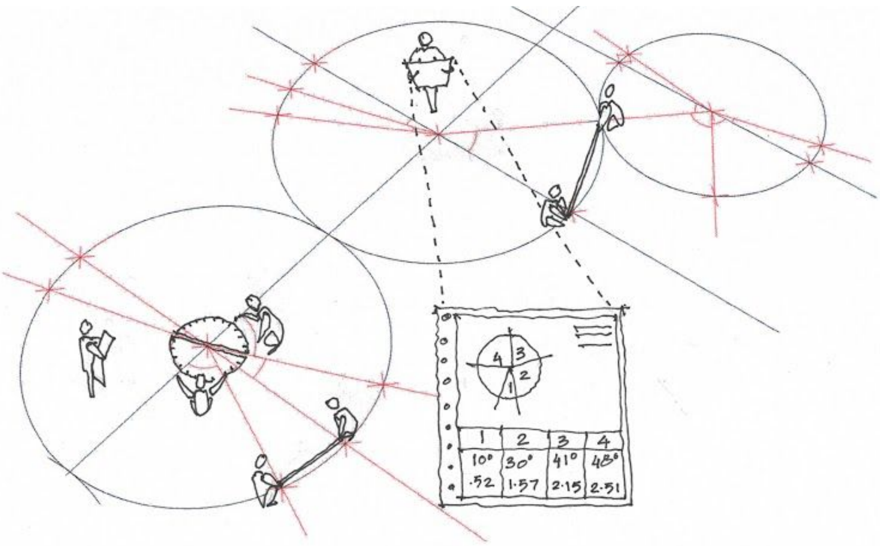
1. The first phase includes construction of the tall adobe brick columns and installation of the tent.
2. The second phase consists of building all the domes with the two construction materials.

This report illustrates in detail the proposed construction process for building the domes.The process has been developed keeping in mind the less availability of tools and advanced construction technology and machines. The tools used for construction are locally available. It should be noted that in the above calculation process for the domes, the cross-section optimization was not made for the thickness of the walls, i.e., the walls are of constant thickness of 0.5m. This has been done to ease the construction process and standardize the manufacturing of the building units (earthbags).



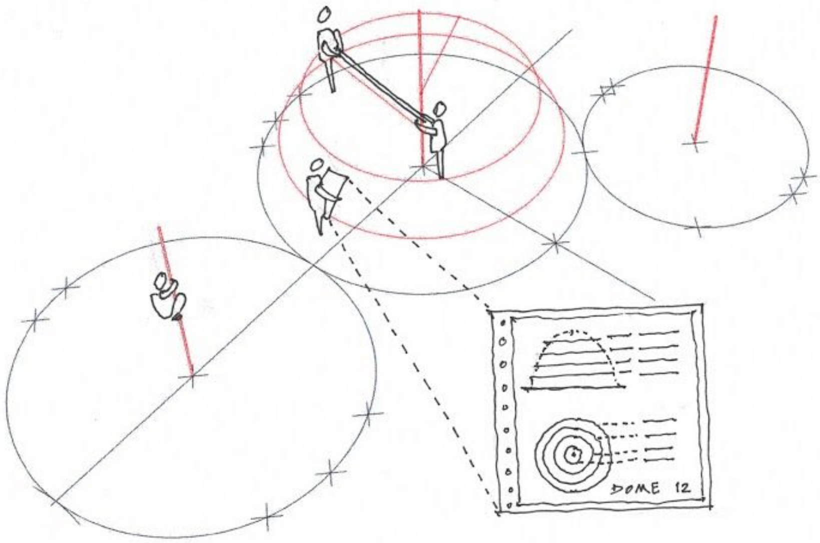
01. Marking the positions of the domes, walls and levels on site using a centreline grid drawing.

Figure 18: Setting out the center lines of the domes with respect to the grid.



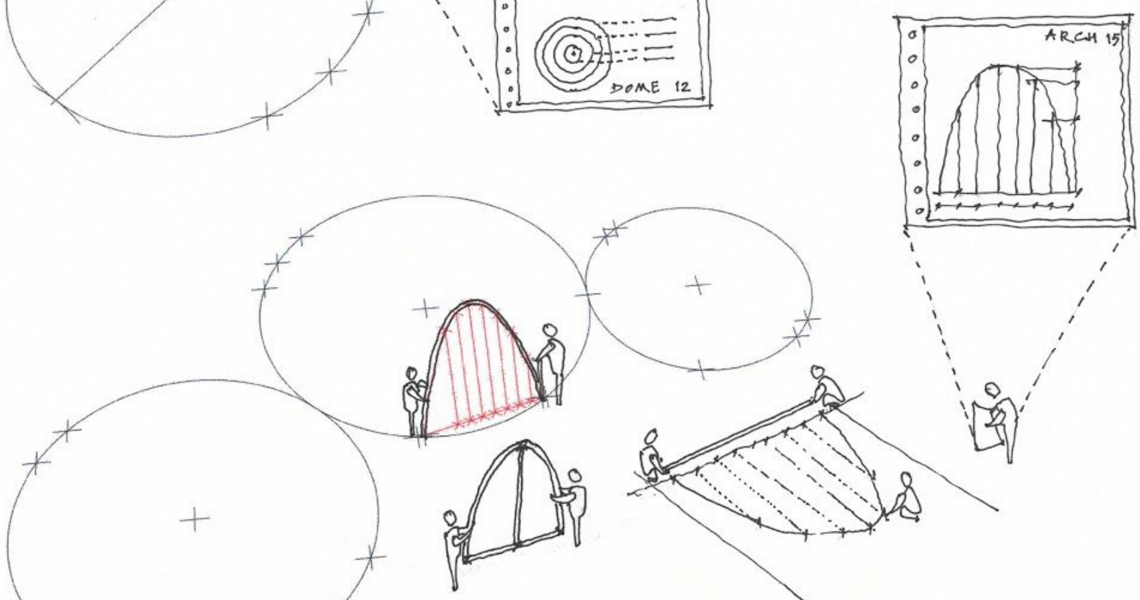
02. Marking of openings using angles and arc lengths.

Tools needed:
Protractor or plate with angle markings
Measuring tape



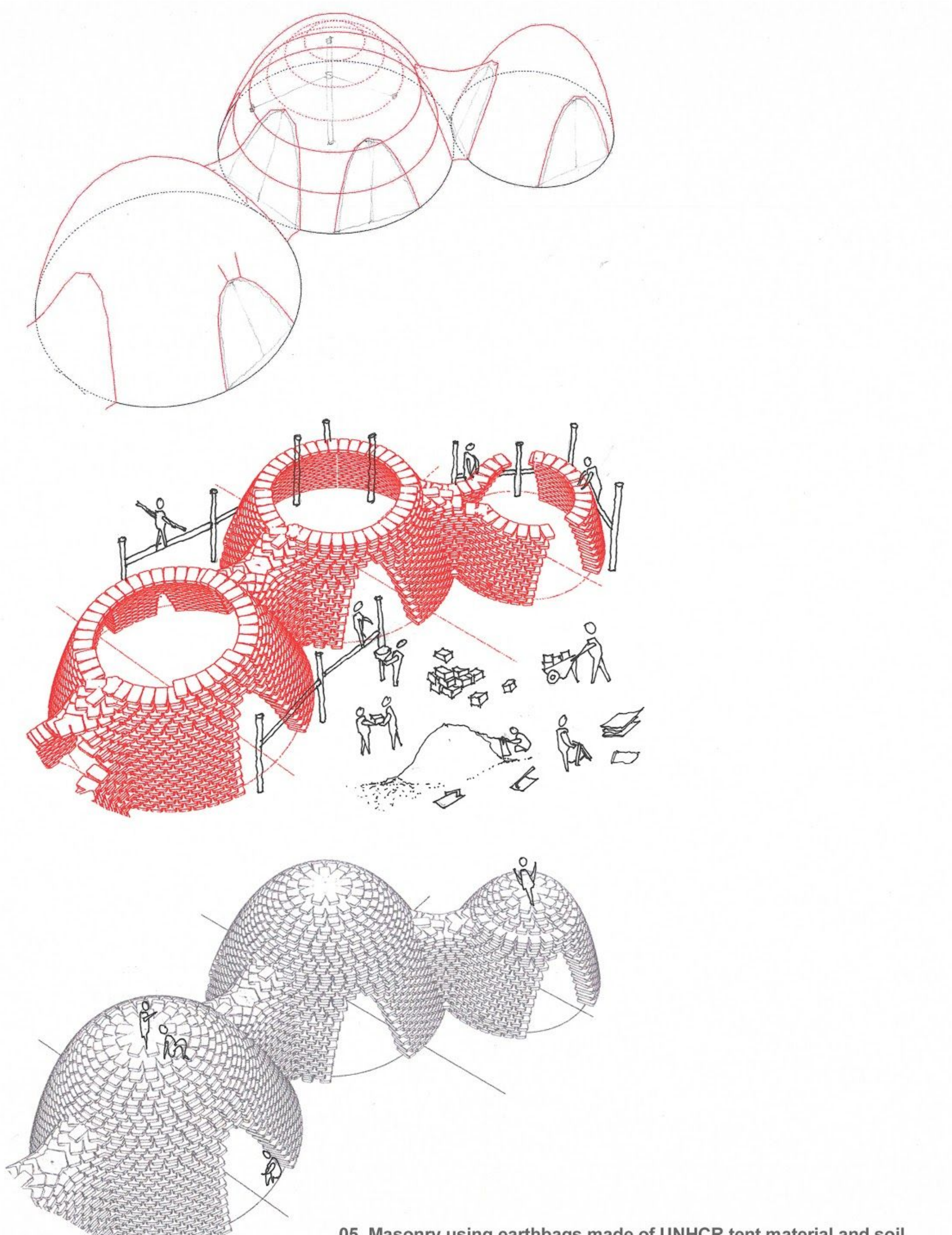
03. Marking of courses using given radius for each course or every alternate course.

Tools needed:
Pole for marking centre of each circle
Rope
Measuring tape

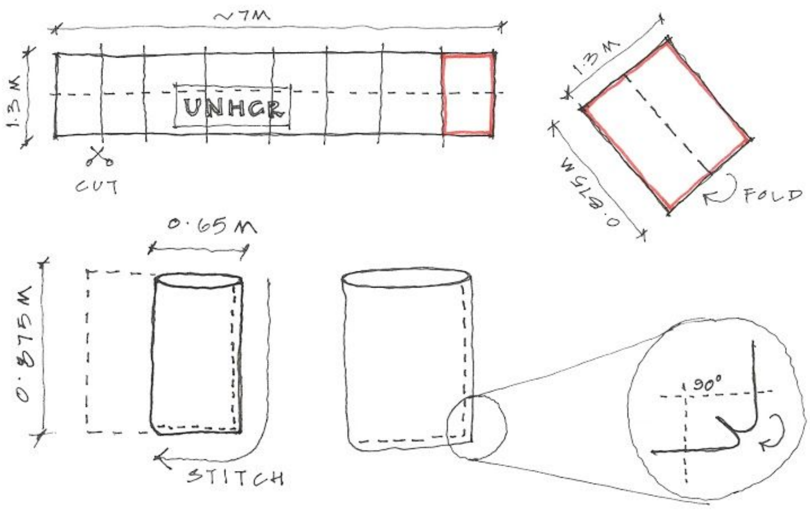


04. Marking arches. The shape is first marked on ground. A flexible wire is used to transfer the shape from ground to its actual position.

Tools needed: - Flexible wire - Measuring tape

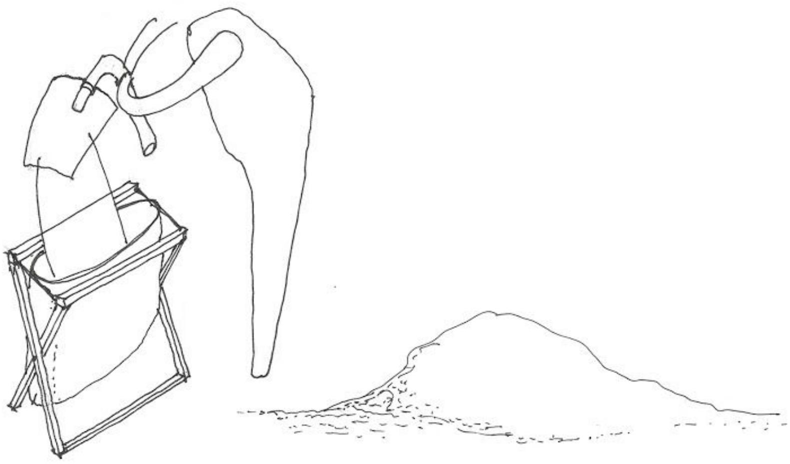


05. Masonry using earthbags made of UNHCR tent material and soil.



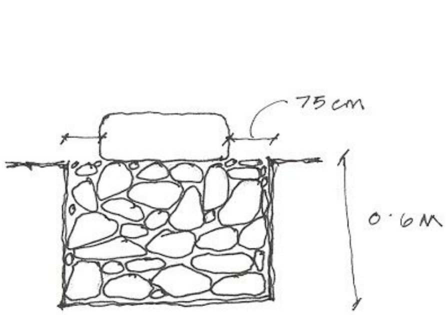
01. Making earthbags from UNHCR tent walls.

Tools needed:
Industrial scissors
Industrial sewing machinery
Measuring tape

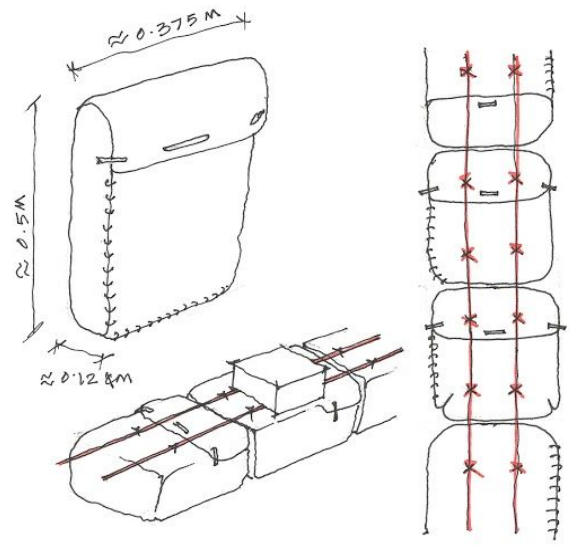


02. Filling the earthbag using a bag stand

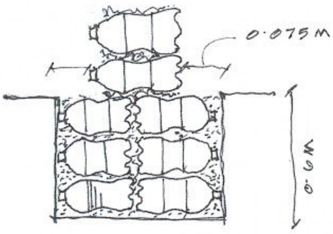
Tools needed:
Shovel
Bag stand
Soil
Earthbag



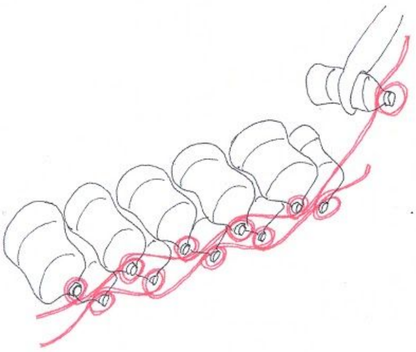
03. Making the foundation using large and small aggregates



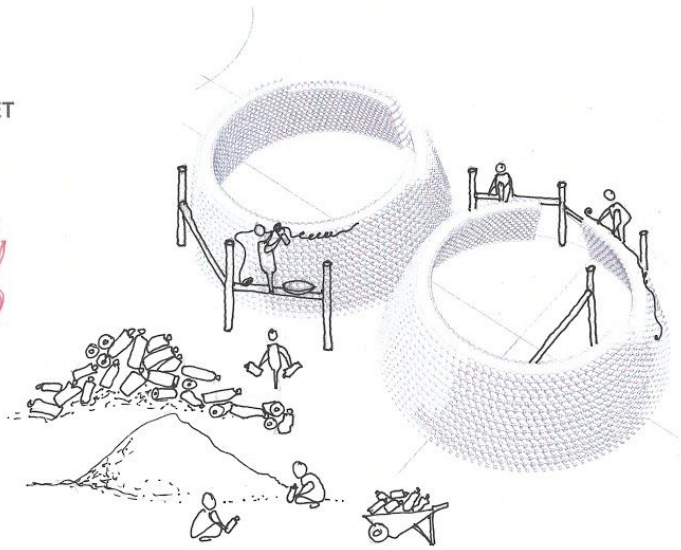
04. Bonding adjacent courses using barbed wire



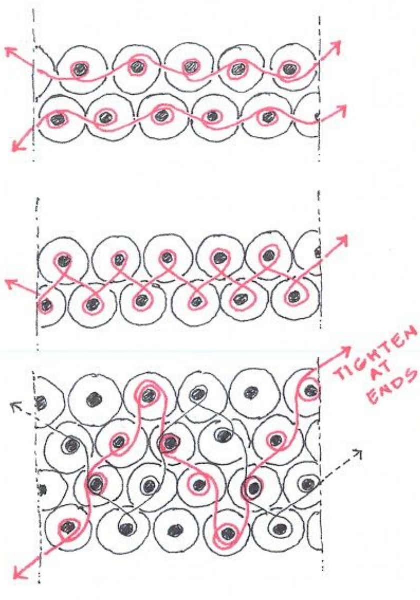
01. Making the foundation using PET bottles.



02. Tying each bottle to the adjacent one using nylon threads or ropes.



04. Masonry using PET bottles filled with soil.



03. Various patterns of tying the PET bottles during or after masonry.

9.Conclusions

The project aims at developing earth as a building material and minimizing other resources in the construction of refugee camp ‘Zaatari’ in Jordan. To fulfill the aims, recycled materials like tent fabric and plastic bottles are introduced to the project. In detail, the domes(main structure) would be made of earthbags, bottles. The retaining wall and column would be made of bottles and adobe bricks. The textile roof would be made of tent fabric and anchored at the retaining wall(or column).

Before structural analysis, density, Young’s modulus, Poisson’s ratio, shear modulus, strength and safety factor need to be defined. Except the Young’s modulus of adobes and Poisson’s ratio, other mechanical properties are correlated to the the laboratory tests conducted for the bottles and adobe bricks. The values of earthbag and textile are chosen from the literature study.

In the form-finding process, the inputs are particles,springs,forces and anchor points, which are retrieved from a given lay-out. First the domes are generated ad catenary structure using dynamic relaxation method.Then adding arches to connect different domes and creating openings for function requirement. The whole process has been computationally performed in grasshopper(GH) using the plugin - Kangaroo. The spring and the openings size are adjustable in a given range in case of the optimization needs.

With the initial 3D forms and the material inputs, the structural analysis is performed in GH using plugin Karamba, combined with Load and Resistance Factor Design (LRFD) method. The self-weight load is dominant factor for the stress. The height and span of the domes which determine the shape have greater influence than the openings size and the shell thickness. Except Group 7, 9, 10 and 12, other groups fulfill the requirement of reliability (ULS & SLS), which mean their stresses and deformations are all smaller than the limit. As for stability, the bottles are connected with ropes and the earthbags are connected with barbed wires, which ensure them settle vertically and prevent them from collapsing.

In optimization, pre-tests shows that changing the cross section does not help in significant reduction of the deflection or the stress, also the local climate of Jordan also requires thick walls for thermal mass. Thus, the final driving factors that determine structural calculations would be the buildings span, openings and shape. Since the span of the buildings are fixed in the lay-out, so the optimization parameters would be height and the opening sizes of the domes. This method works for Group 7 and 10.

The construction are divided into two step, first is the construction of the tall adobe brick columns and installation of the tent, then comes the second, the domes with the two construction materials.

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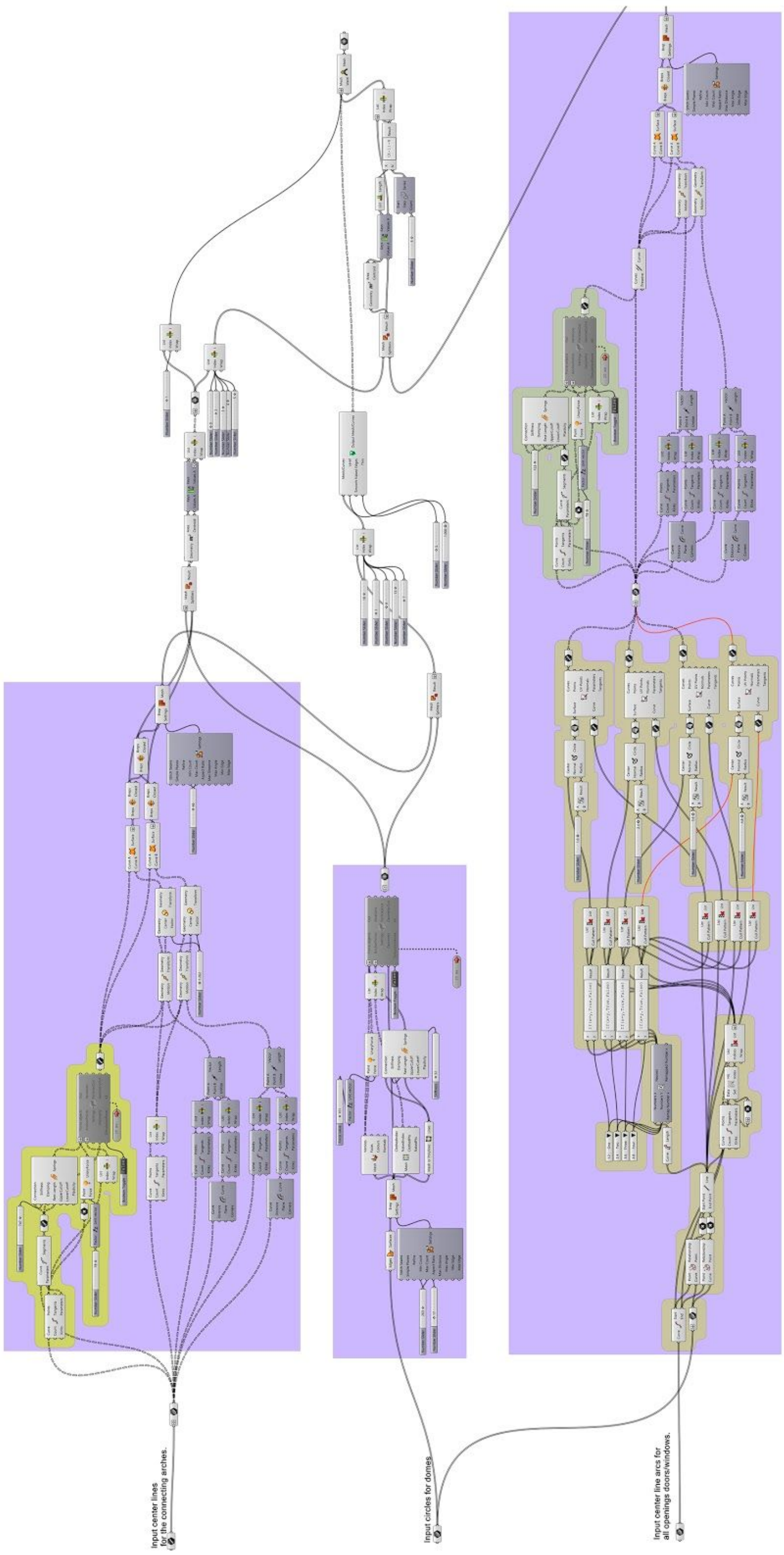
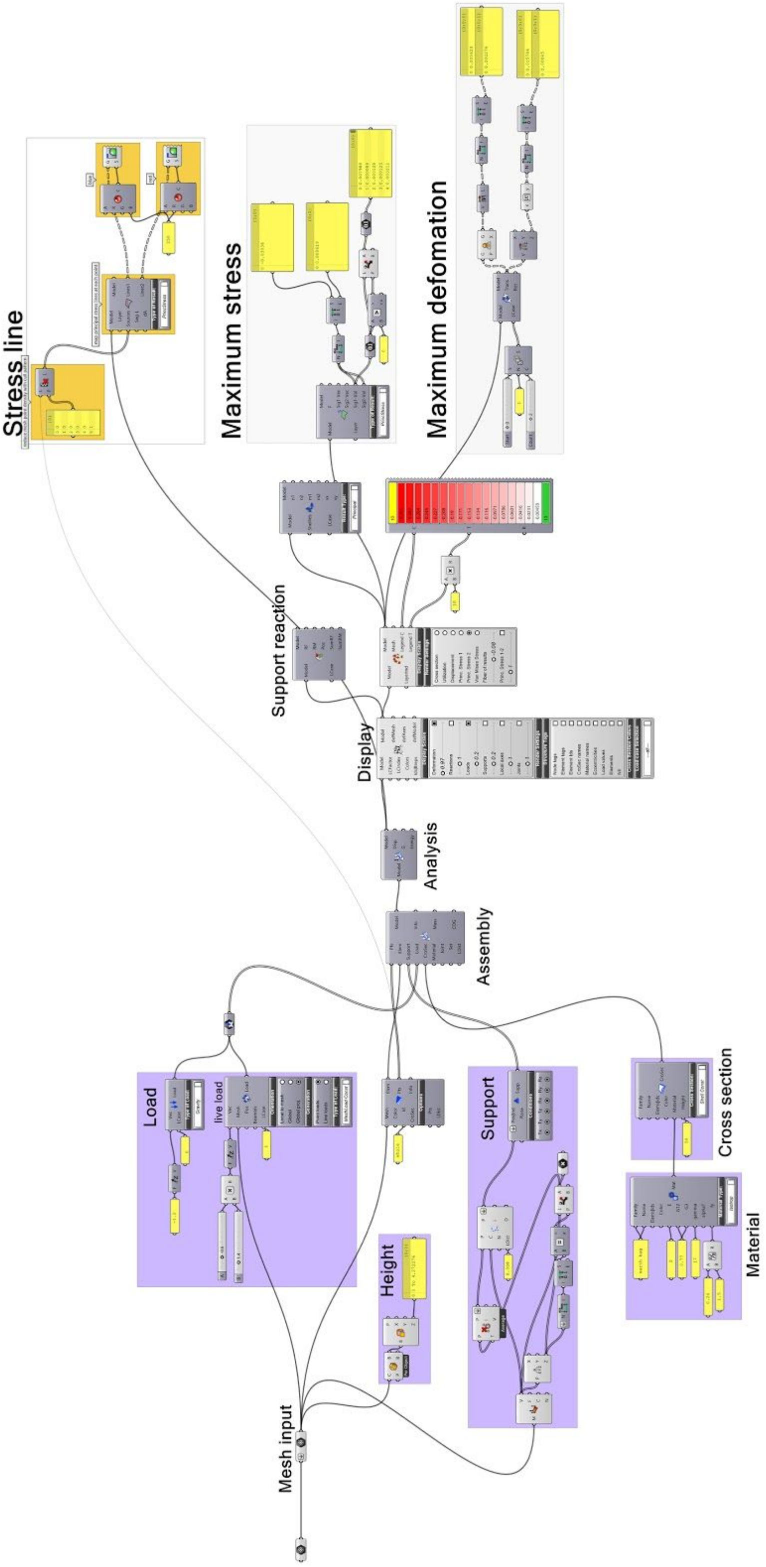
Appendix A

Kangaroo script for form-finding.



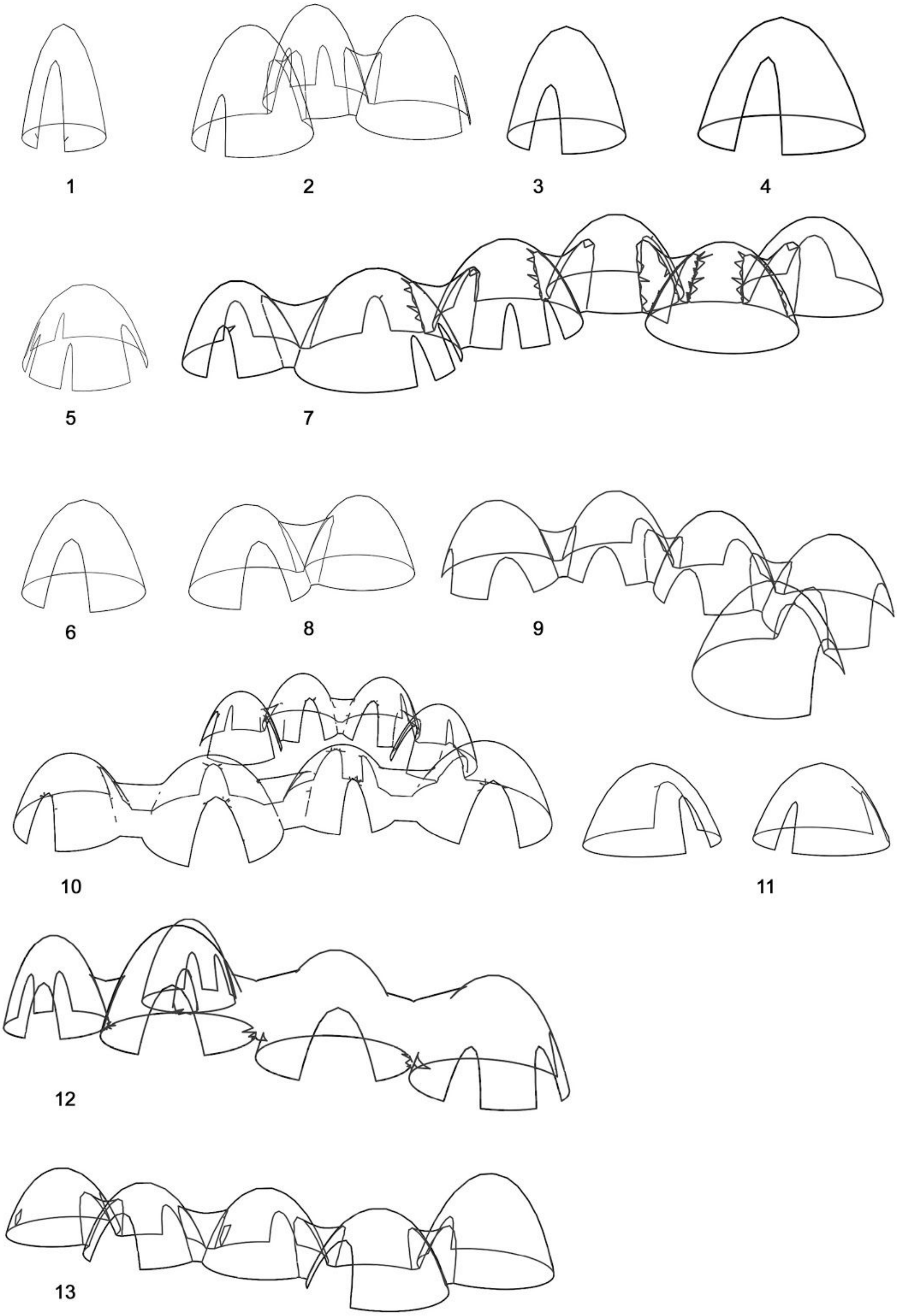
Appendix B

Karamba script for structural analysis. The output mesh of kangaroo is the input for karamba.



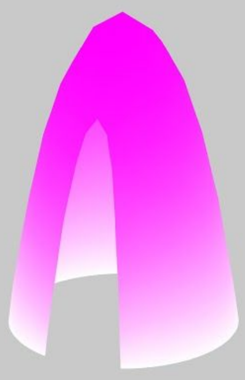
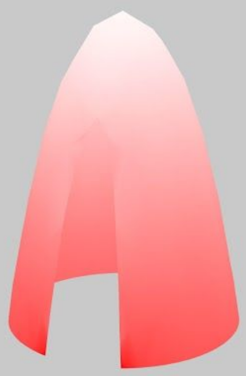
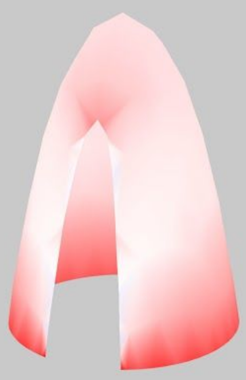
Appendix C

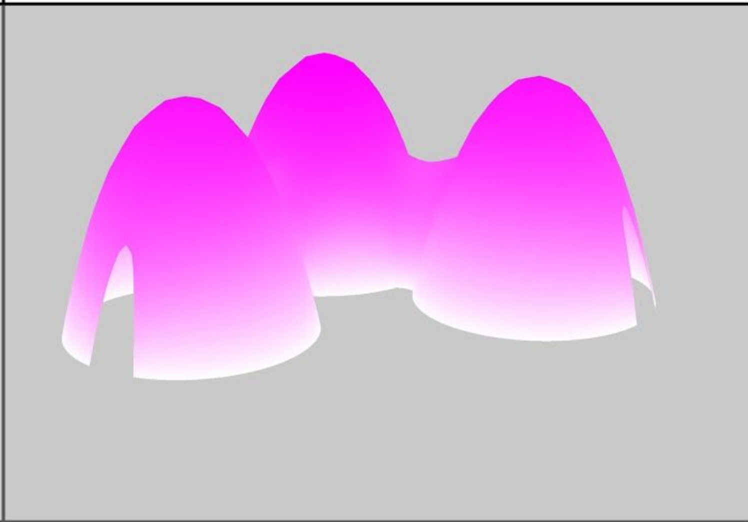
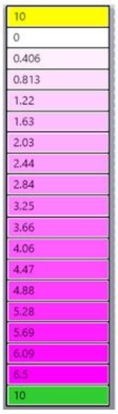
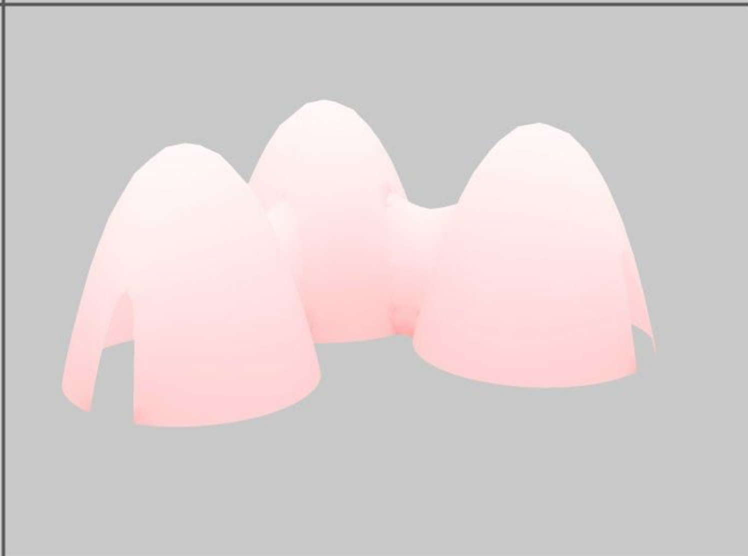
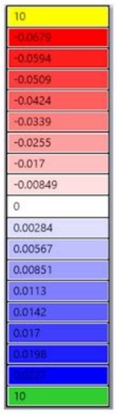
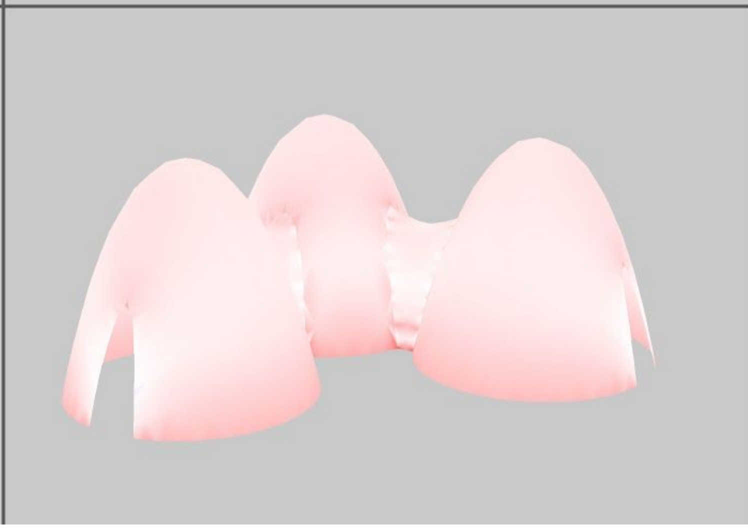
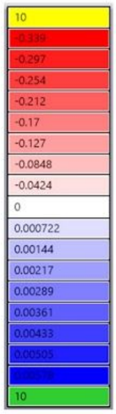
Perspective view of the list of groups for structural analysis.



Appendix D

FEA (Karamba) structural analayis results

Parameters	Group 1	Value
Displacement		mm 10 0 0.199 0.397 0.596 0.795 0.993 1.19 1.39 1.59 1.79 1.99 2.18 2.38 2.58 2.78 2.98 3.18 10
Principle Stress 1		MPa 10 -0.0181 -0.0159 -0.0136 -0.0113 -0.00906 -0.00679 -0.00453 -0.00226 0 0.00077 0.00154 0.00231 0.00308 0.00385 0.00462 0.00539 [illegible] 10
Principle Stress 2		MPa 10 -0.0665 -0.0624 -0.0583 -0.0543 -0.0502 -0.0462 -0.0421 -0.038 -0.034 -0.0299 -0.0259 -0.0218 -0.0177 -0.0137 -0.00961 -0.00554 -0.00148 10

Parameters	Group 2	Value
Displacement		mm 
Principle Stress 1		MPa 
Principle Stress 2		MPa 

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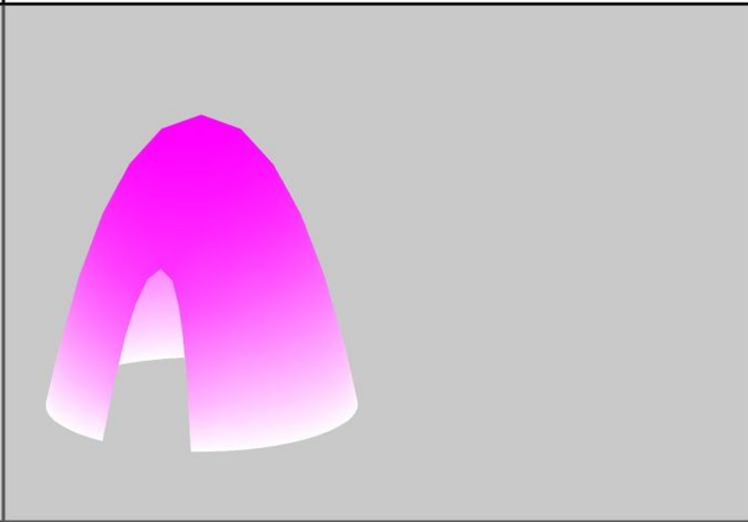
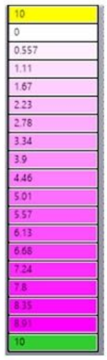
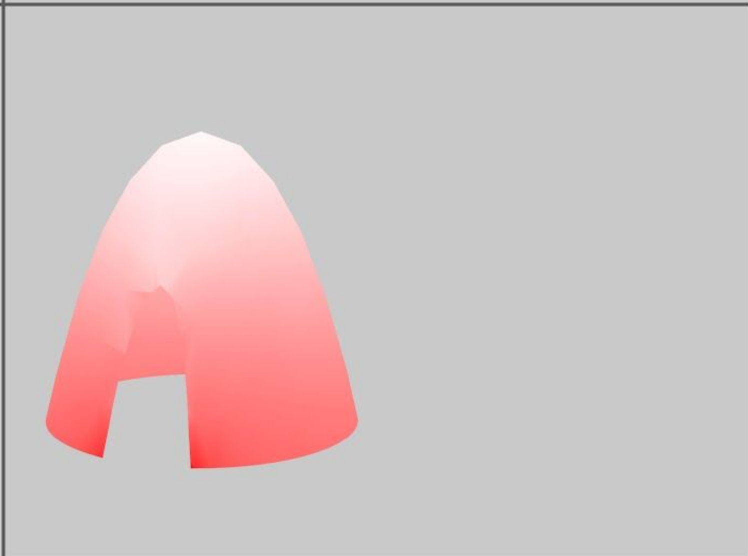
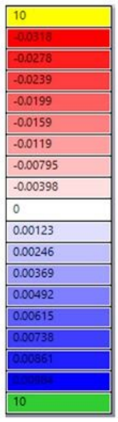
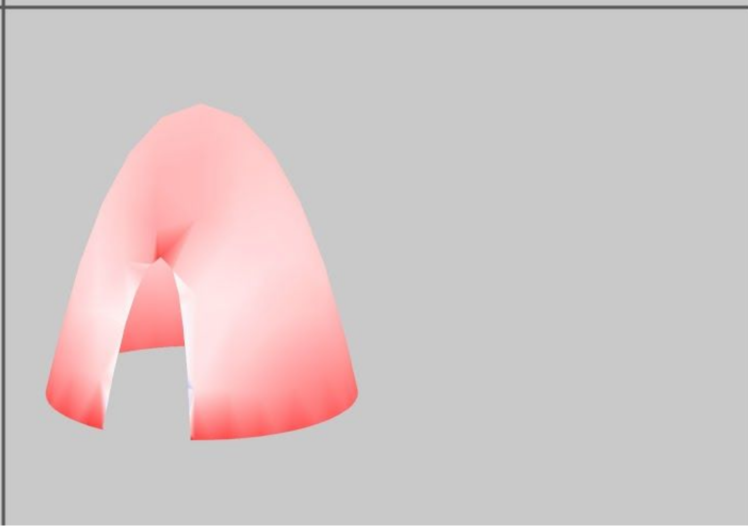
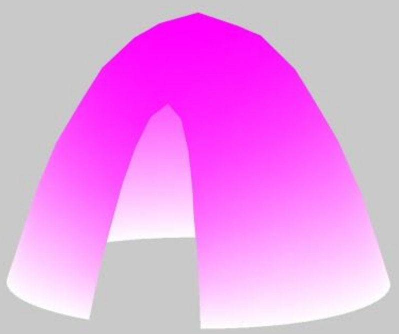
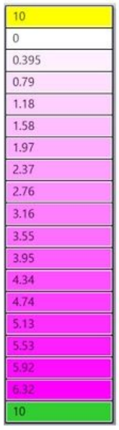
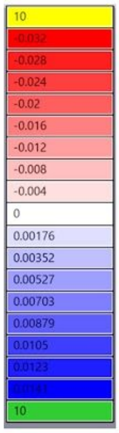
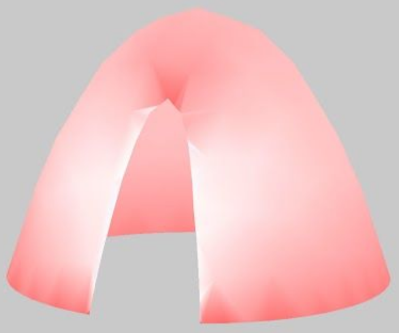
Displacement		mm 
Principle Stress 1		MPa 
Principle Stress 2		MPa 

Parameters	Group 4	Value
Displacement		mm 
Principle Stress 1		MPa 
Principle Stress 2		MPa 

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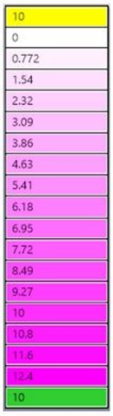
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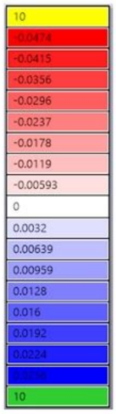
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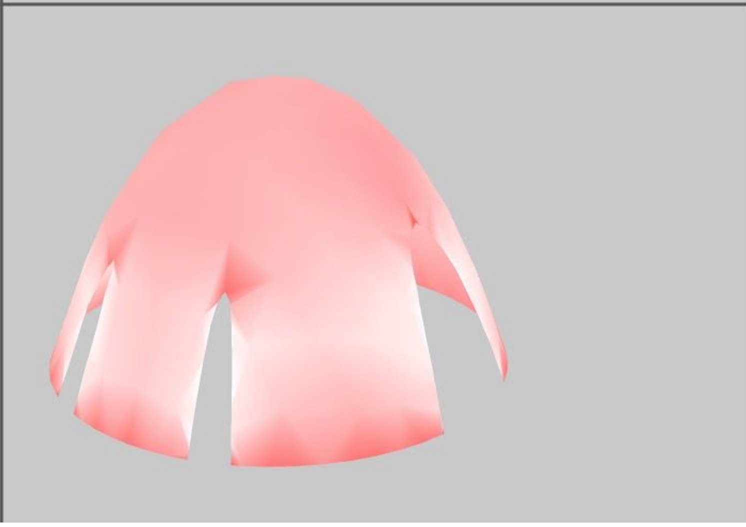
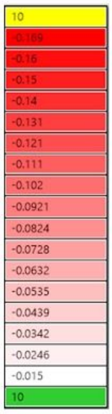
<tr><td>Principle Stress 2</td><td></td><td>MPa

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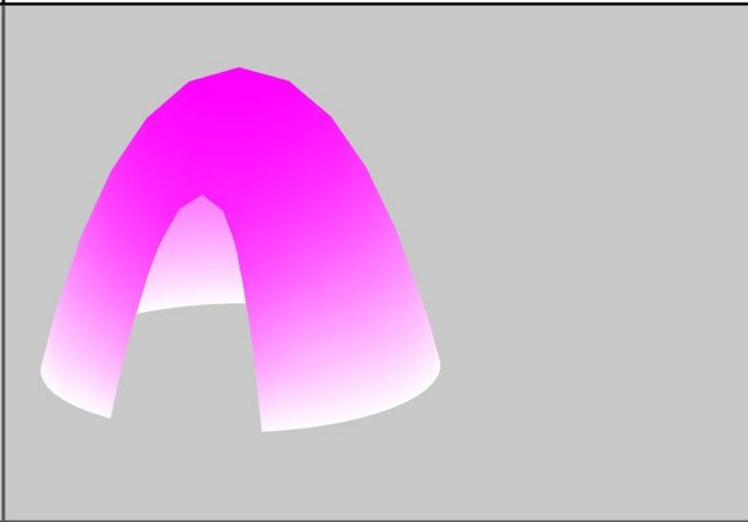
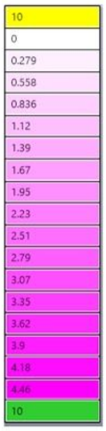
<tr><td>Displacement</td><td></td><td>mm

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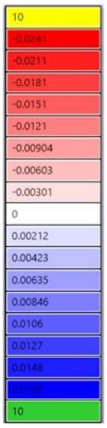
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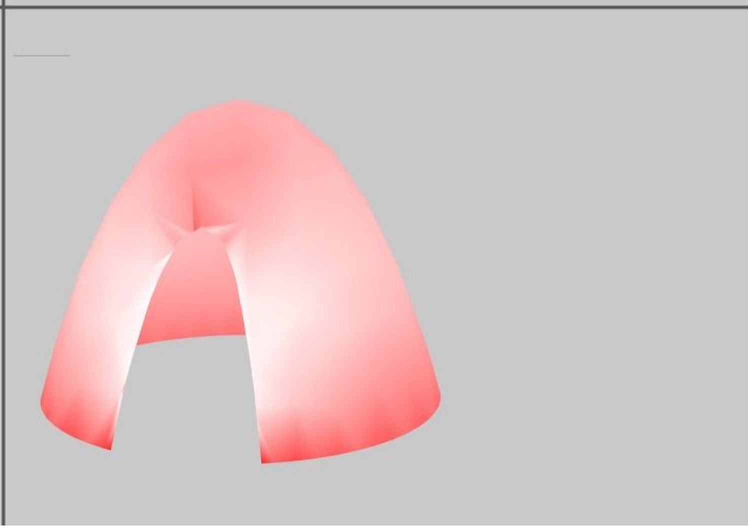
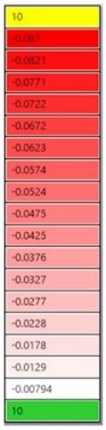
<tr><td>Principle Stress 2</td><td></td><td>MPa

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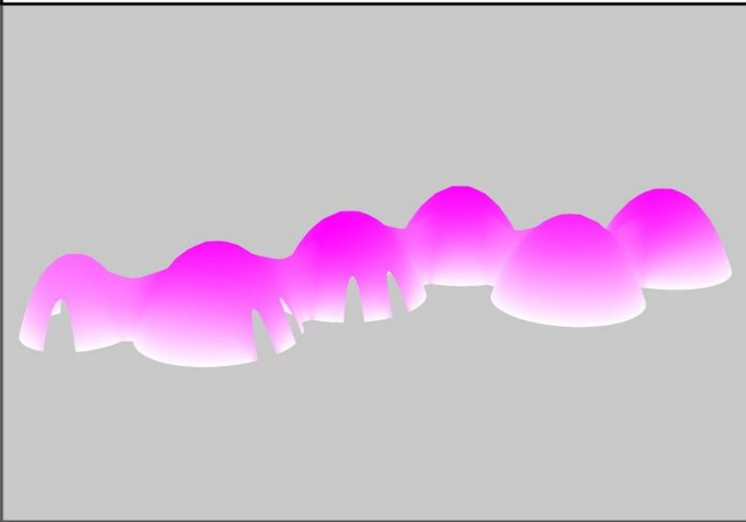
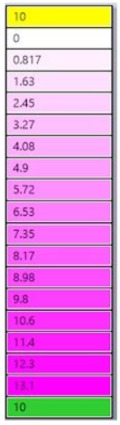
<tr><td>Displacement</td><td></td><td>mm

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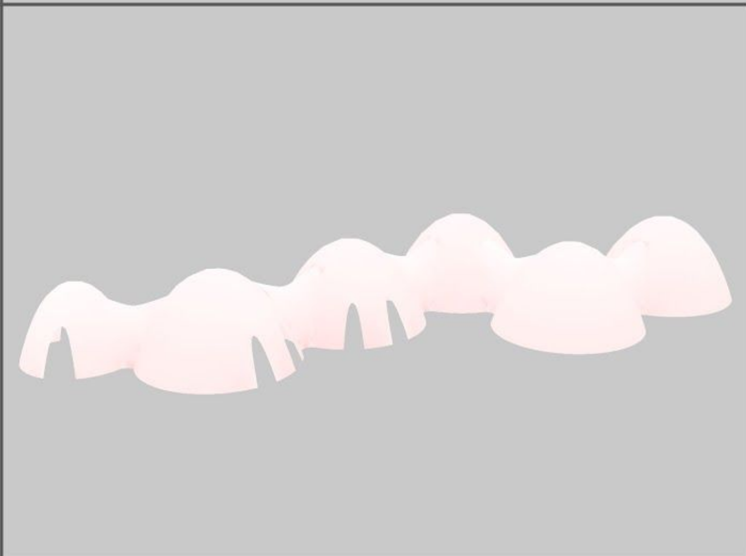
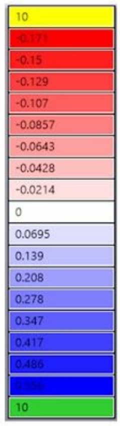
<tr><td>Principle Stress 1</td><td></td><td>MPa

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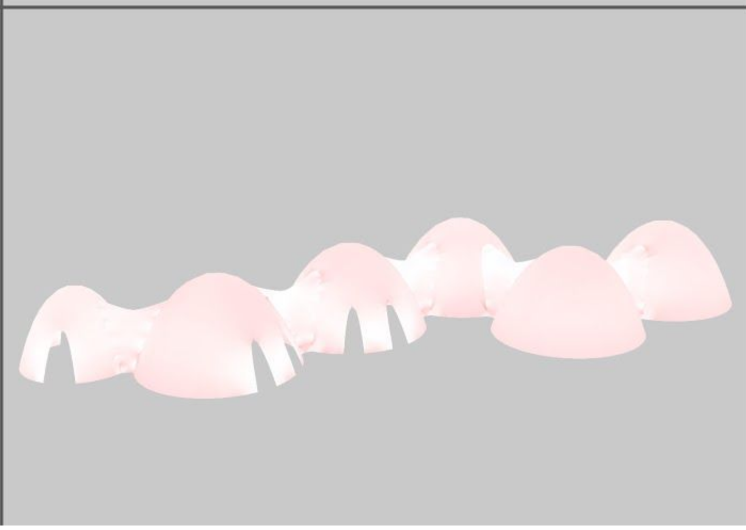
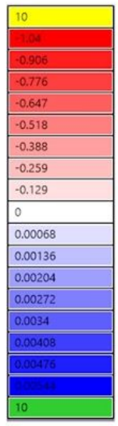
<tr><td>Principle Stress 2</td><td></td><td>MPa

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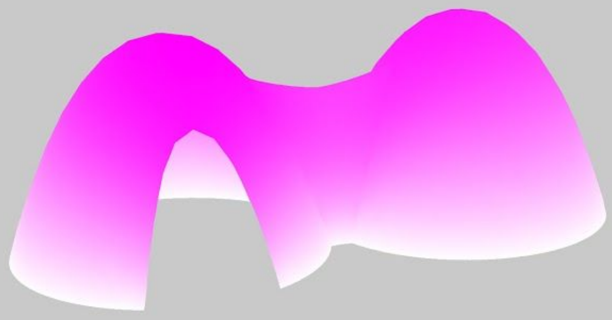
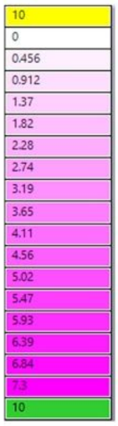
<tr><td>Displacement</td><td></td><td>mm

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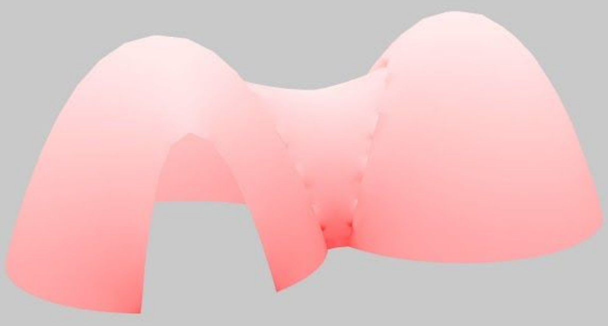
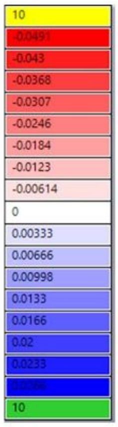
<tr><td>Principle Stress 1</td><td></td><td>MPa

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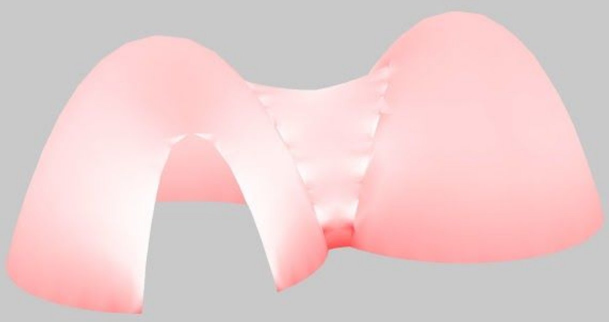
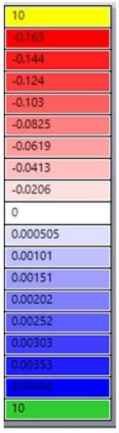
<tr><td>Principle Stress 2</td><td></td><td>MPa

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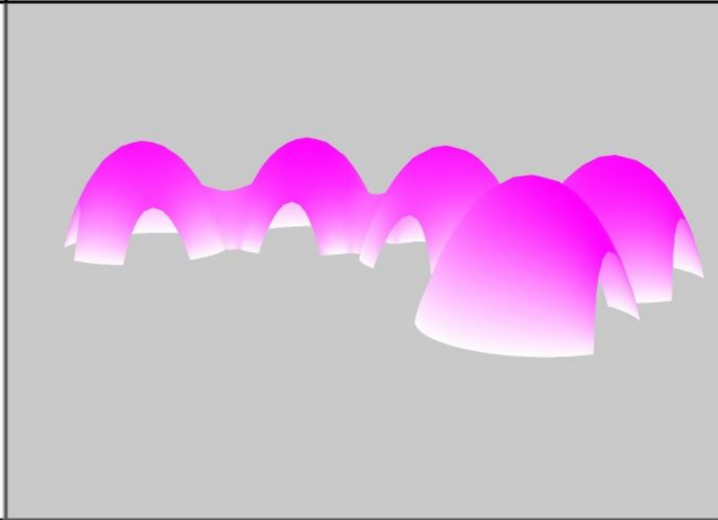
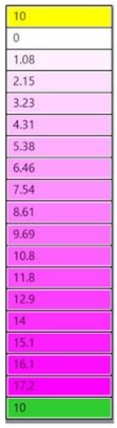
<tr><td>Displacement</td><td></td><td>mm

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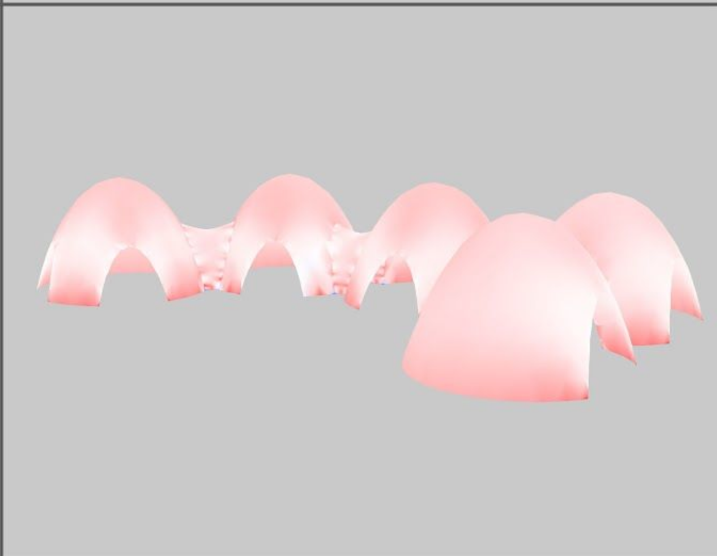
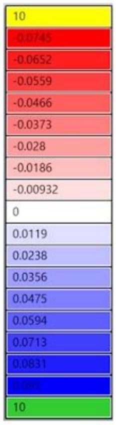
<tr><td>Principle Stress 1</td><td></td><td>MPa

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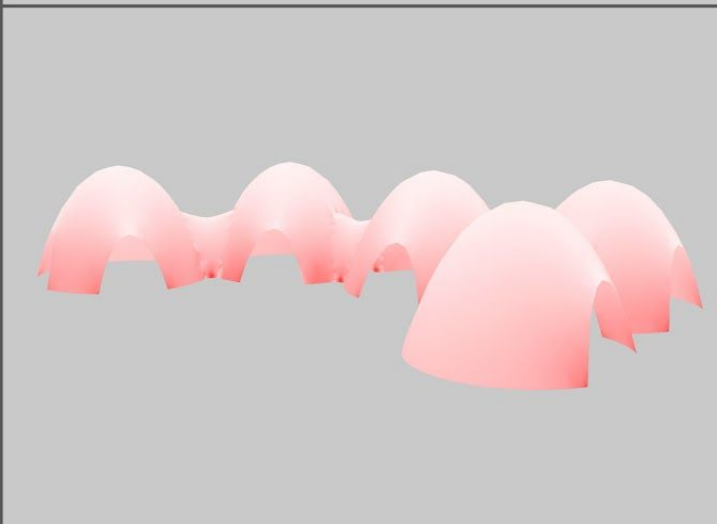
<tr><td>Principle Stress 2</td><td></td><td>MPa

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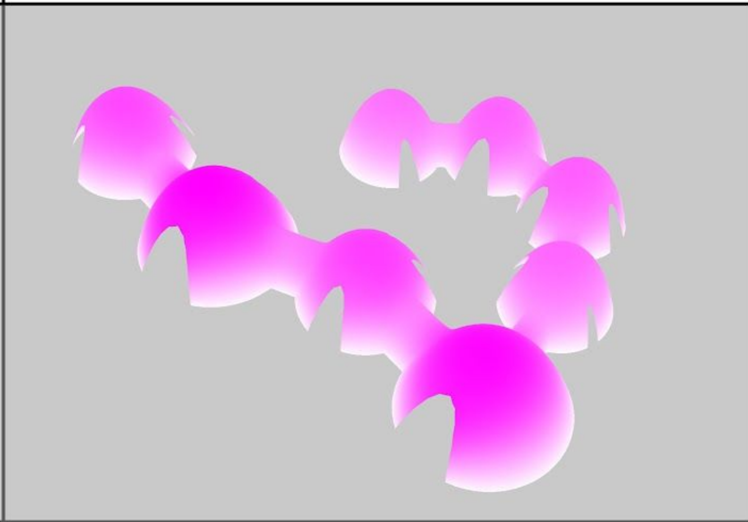
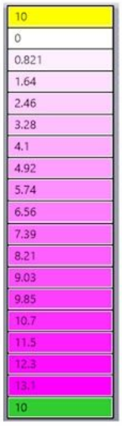
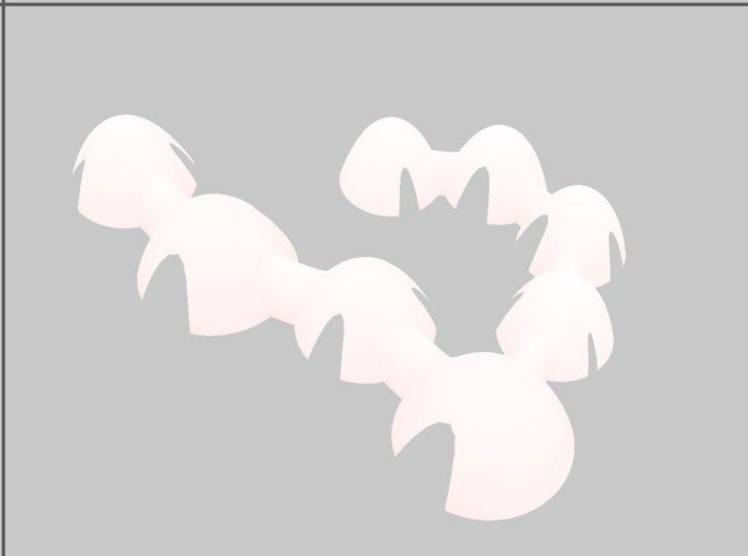
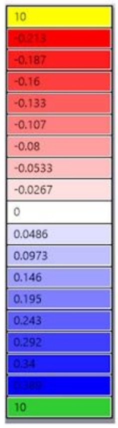
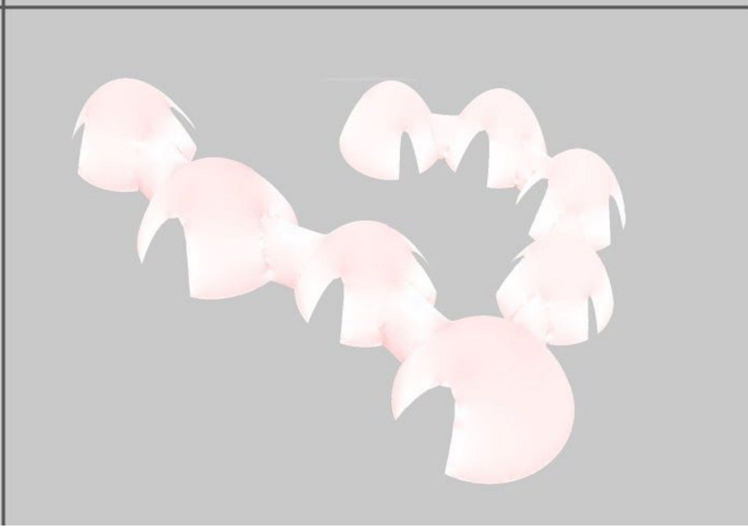
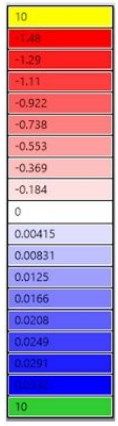
Displacement		mm 
Principle Stress 1		MPa 
Principle Stress 2		MPa 

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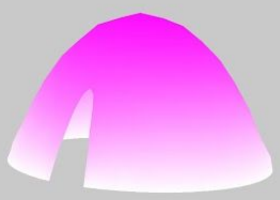
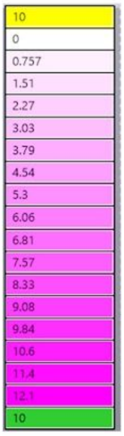
<tr><td>Displacement</td><td> </td><td>mm

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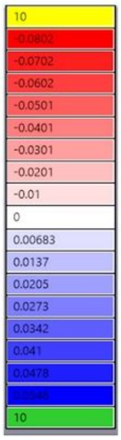
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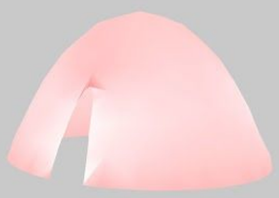
<tr><td>Principle Stress 2</td><td> </td><td>MPa

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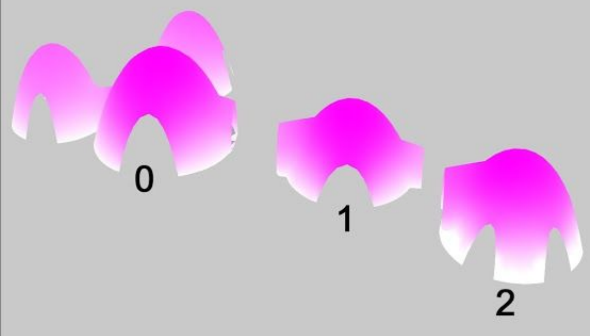
Parameters	Group 12	Value

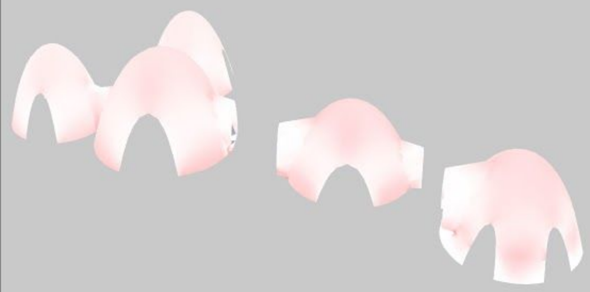
Displacement



mm

0	1	2
10	10	10
0	0	0
0.98	0.735	0.762
1.96	1.47	1.52
2.94	2.2	2.29
3.92	2.94	3.05
4.9	3.67	3.81
5.88	4.41	4.57
6.86	5.14	5.33
7.84	5.88	6.09
8.82	6.61	6.86
9.8	7.35	7.62
10.8	8.08	8.38
11.8	8.81	9.14
12.7	9.55	9.9
13.7	10.3	10.7
14.7	11	11.4
15.7	11.8	12.2
10	10	10

Principle Stress 1



MPa

10	10	10
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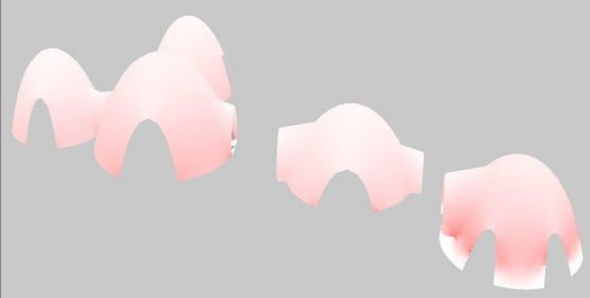
-0.122	-0.0992	-0.0984
-0.104	-0.085	-0.0844
-0.087	-0.0709	-0.0703
-0.0696	-0.0567	-0.0562
-0.0522	-0.0425	-0.0422
-0.0348	-0.0283	-0.0281
-0.0174	-0.0142	-0.0141
0	0	0
0.0478	0.00981	0.0288
0.0956	0.0196	0.0576
0.143	0.0294	0.0864
0.191	0.0392	0.115
0.239	0.049	0.144
0.287	0.0588	0.173
0.335	0.0687	0.202
[illegible]	[illegible]	[illegible]
10	10	10

Principle Stress 2



MPa

10	10	10
-0.444	-0.555	-0.289
-0.389	-0.486	-0.253
-0.333	-0.416	-0.216
-0.278	-0.347	-0.18
-0.222	-0.278	-0.144
-0.167	-0.208	-0.108
-0.111	-0.139	-0.0722
-0.0555	-0.0694	-0.0361
0	0	0
0.00314	0.000876	0.0104
0.00628	0.00175	0.0207
0.00941	0.00263	0.0311
0.0126	0.00351	0.0415
0.0157	0.00438	0.0518
0.0188	0.00526	0.0622
0.022	0.00613	0.0726
[illegible]	[illegible]	[illegible]
10	10	10

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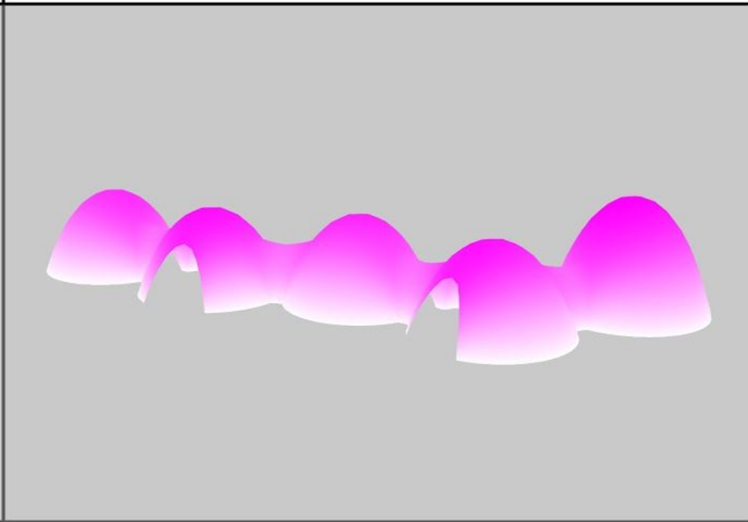
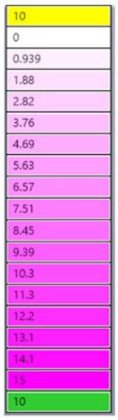
<tr><td>Displacement</td><td></td><td>mm

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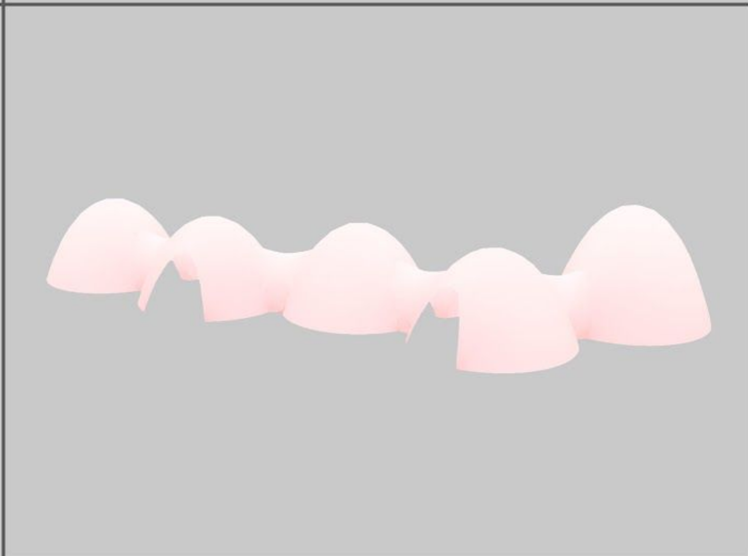
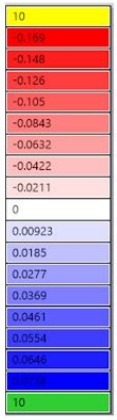
<tr><td>Principle Stress 1</td><td></td><td>MPa

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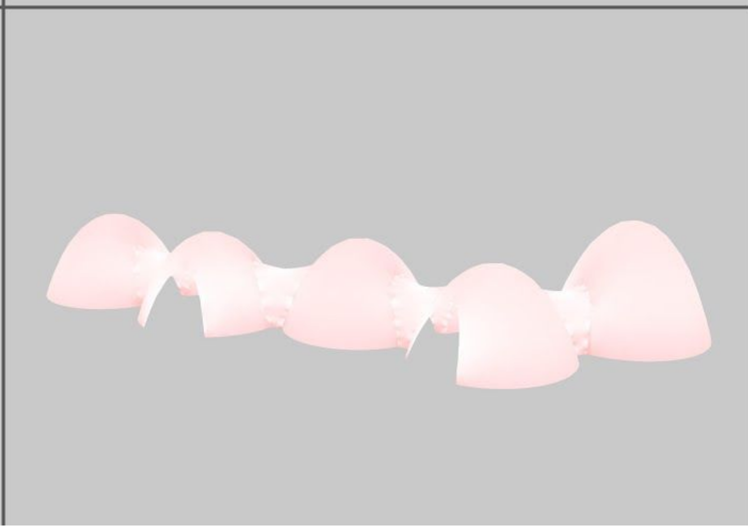
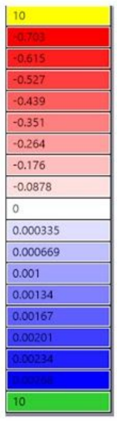
<tr><td>Principle Stress 2</td><td></td><td>MPa

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Appendix E

Final structural Analysis of Domes

Final structural Analysis of Domes											
Group number	Material	H [m]	L [m]	Zd [mm]	XYd [mm]	Disp. Z [mm]	Disp. XY [mm]	σc,max [MPa]	σt,max [MPa]	ULS	SLS
1	bottle	3.31	2.50	11.03	4.73	3.11	0.72	0.0659	0.0022	✔	✔
2	bottle	4.18	4.50	13.93	5.97	6.18	0.73	0.2211	0.0167	✔	✔
3	earthbag	4.11	4.00	13.70	5.87	8.84	2.73	0.1157	0.0044	✔	✔
4	earthbag	3.13	4.00	10.43	4.47	6.29	1.06	0.0999	0.0017	✔	✔
5	earthbag	4.00	6.50	13.33	5.71	12.33	1.70	0.1459	0.0090	✔	✔
6	bottle	3.25	4.50	10.83	4.64	6.50	0.80	0.0796	0.0014	✔	✔
7	earthbag	4.03	6.50	13.43	5.75	12.99	2.45	0.9503	0.2510	✔	✔
8	earthbag	3.12	4.50	10.39	4.45	7.17	1.67	0.2137	0.0047	✔	✔
9	earthbag	4.27	6.50	14.23	6.10	16.63	5.65	0.3036	0.0862	✔	×
10	earthbag	3.59	6.50	11.96	5.13	11.66	2.19	1.5582	0.5585	✔	✔
11	earthbag	3.74	6.50	12.47	5.34	11.98	2.46	0.1416	0.0029	✔	✔
12(0m)	earthbag	4.57	6.50	15.25	6.53	15.41	3.42	0.4759	0.4389	✔	✔
12(-1m)	earthbag	4.57	6.50	15.25	6.53	11.56	2.72	0.5027	0.0348	✔	✔
12(-2m)	earthbag	4.57	6.50	15.23	6.53	12.10	2.93	0.18	0.0702	✔	✔
13	earthbag	4.76	6.50	15.87	6.80	14.98	5.60	0.5632	0.0764	✔	✔
Note	H: The mesh height of the domes in the group L: The span of the domes in the group Zd: Vertical deformation limit XYd: Horizontal deformation limi σc,max: Maximum compressive stress σt,max: Maximum tension stress					Disp. Z: Maximum vertical deflection Disp. XY: Maximum horizontal deflection ULS: bottle: σc=2.53MPa, σt=0.0485MPa; earthbag: σc=1.6MPa, σt=0.032MPa; bag: σt=4MPa SLS: Zd & XYd					