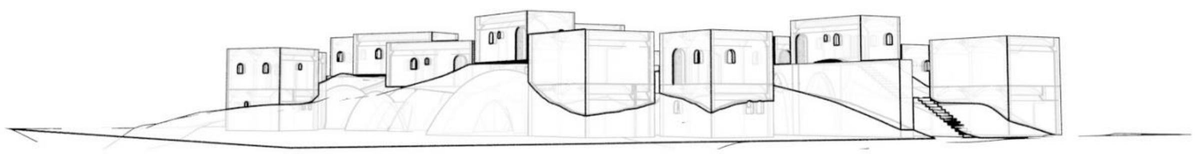
ADOBE 3.0

Communal housing for the Zaatari refugee camp

Structural Report



EARTHY | AR3BO11

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1. Introduction

This report is part of the EARTHY course offered by the Building Technology master track of the Delft University of Technology. The aim of this course is to design a building for the Zaatari refugee camp in the north of Jordan near the Syrian border. The building proposed for the refugee camp is a communal housing project made of adobe bricks. The design consists of a mound that contains the public functions. The mound is split in three parts by a street and two courtyards. On top of the mound private dwellings are placed. The entire structure is going to be built out of adobe bricks.

This report contains a structural analysis of the proposed building. First the design of the building will be described followed by a short description of the material properties of adobe. The main part of this report consists of the structural optimisation and a finite element analysis of the structure within the mound. Also, the structural performance of the retaining walls on the edges of the street and the courtyards will be briefly described. Finally, a method for constructing the design will be described.

2. Description of the design

2.1. Problem statement

Many refugees are living with exacerbated challenges due to the separation of families and broken social networks. Children suffer from the lack of structured space to play outdoors and there is inadequate safety and privacy. There are also infrastructural problems; the camp was built in a desert subject to heavy rainfall and sandstorms at certain times of the year. To improve the health and wellbeing of refugees, more permanent forms of housing that respond to environmental, social and cultural needs should be developed.

2.2. Design concept & description

A communal housing project is proposed for families in need of additional support. The housing brings together individuals and small families to share facilities and build a social support network. The design strategy is largely landscape driven, with the goal of managing water on the site to prevent deterioration of adobe structures due to stagnant stormwater. The landscape includes planted swales and retention basins to absorb excess stormwater and wastewater. Figure 1 shows an isometric view of the proposed design

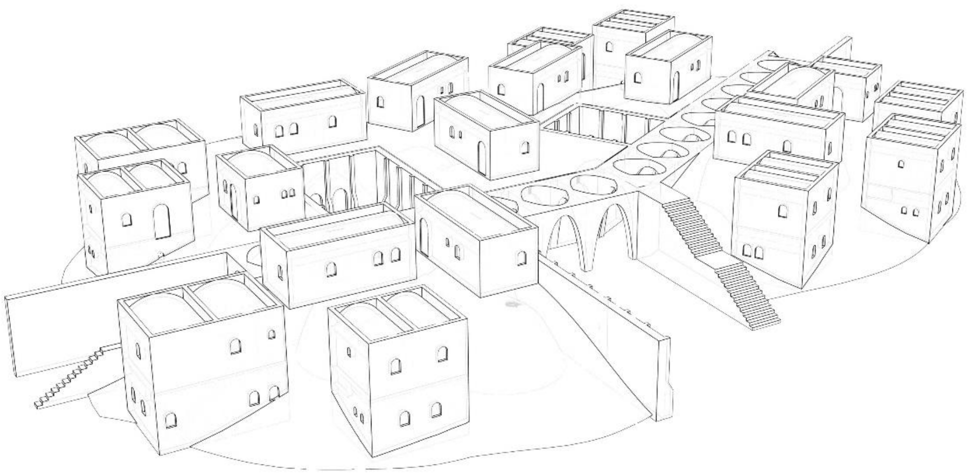


Figure 1: Proposed design, isometric

The communal facilities are located on the ground floor of the building and include safe play areas for children, space for single parents to work at home while caring for children, kitchen and dining facilities for group meals, wash facilities and a mix of spaces for gathering. The structure of these spaces is composed of a series of domes, which are joined to form a shell structure. The ground floor space is integral to the landscape, which is excavated to form retention ponds and redistributed over the domes to form a mound. The mound is then bisected with a central street, forming a connection to the main streets. Courtyards are placed along the central street to provide outdoor gathering spaces. Figure 2 shows an exploded view of the design.

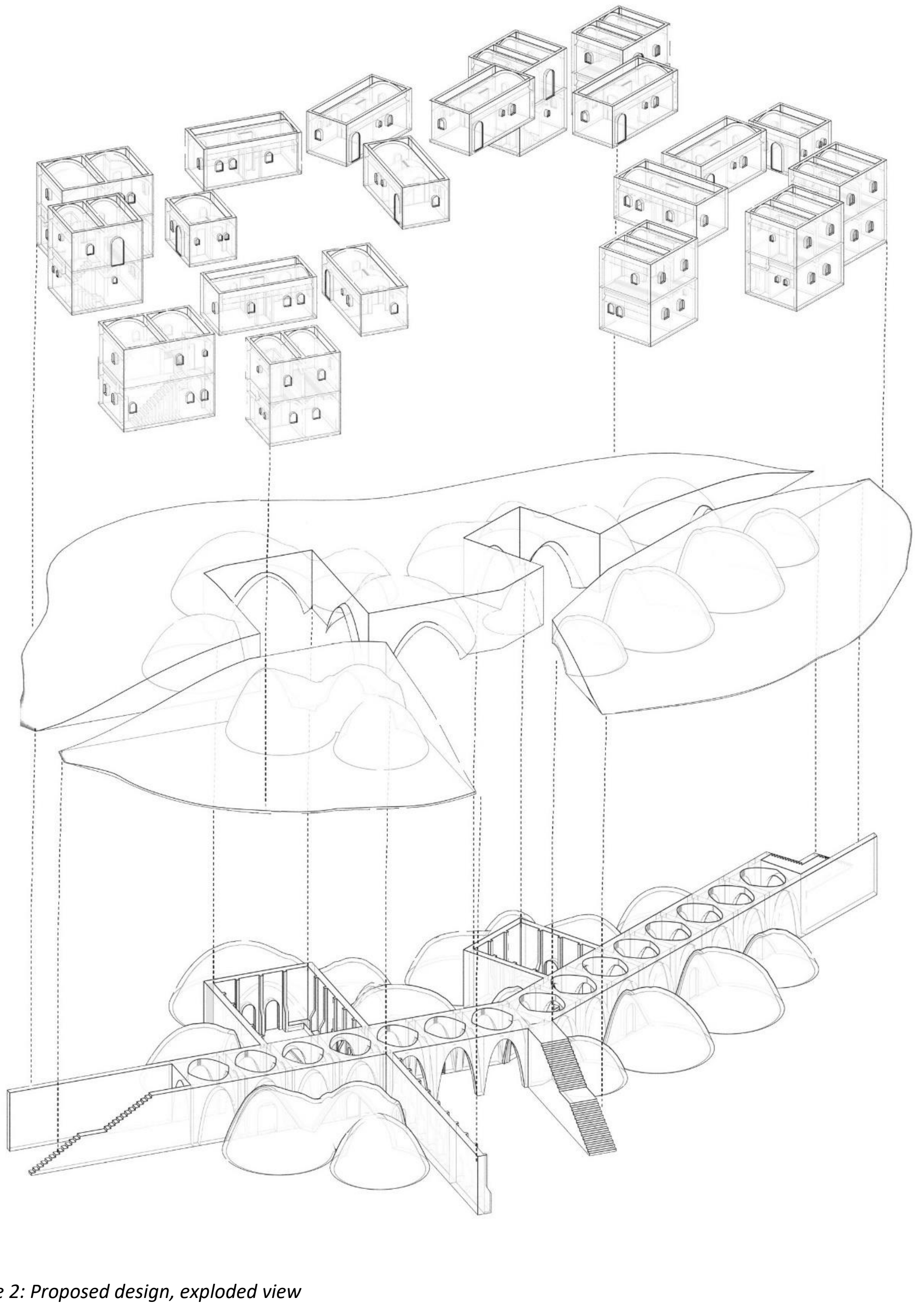


Figure 2: Proposed design, exploded view

On the first floor, dwelling units provide private areas for individual families. These units are placed on top of the mound, arranged around smaller courtyard-like spaces, overlooking the open courtyards below. There are four different dwelling modules to accommodate families ranging from one to six members.

3. Mechanical properties of adobe bricks

To do a structural analysis of the building, the mechanical properties of adobe bricks need to be known. As part of this course, research was conducted to explore these mechanical properties by making a batch of adobe bricks and performing a compressive test on them in a materials testing machine (Zwick Z100). However, the sample size was limited and the bricks were only dried for 9 days in a climate not comparable with the climate of Jordan. Therefore, it was concluded that the experiment was not reliable to determine the compressive strength of the adobe bricks used for the construction of the building.

Instead, literature was used to determine a strength and elasticity of adobe bricks used for the structural analysis. The value for the compressive strength of adobe ranges from 0.5 to 5.4 MPa (Brown & Clifton, 1978), (Minke, 2006). Clear data on different compressive strength for different types of sand and clay around the world used to make adobe could not be found.

Since the design of the building causes some structural challenges, using adobe with the lowest compressive strength of 0.5 MPa was not considered to be a viable option. Instead, a compressive strength of 2.0 MPa is used for the structural analysis.

Also, for the tensile strength different values are found in various sources. Minke (2006) describes the tensile stress as 10% of the compressive strength but says that the tensile strength is not relevant because earth structures must not be under tension. Since it is likely that a small amount of tension will be present in the structure, an extra safety measure is considered by assuming the tensile strength to be 5% of the compressive strength. This results in a tensile strength of 0.1 MPa.

Other properties important for the structural analysis are the Young's modulus (100 MPa) and the density (2000 kg/m^3)

4. Structural optimisation and FEA of the ground floor structure

4.1. Theory and methodology

To design a structure that is only stressed in compression and not in tension, the structure should be adapted to the loads acting upon it. For this structure we investigated form finding with hanging chains. An example is shown in Figure 3. Figure 3(a) shows a hanging chain in its initial shape. The stresses in the chain are only due to the dead load of the chain. Due to the nature of the geometry, the chain is only stressed in tension. Figure 3(b) shows the same chain with a point load applied to it. The point load is far higher than the dead load so for this example the dead load is neglected. Since the chain cannot take any compression, the chain deforms into a stable position that is shown in Figure 3(c). In this state the catenary is stressed in tension only. Note that during this process, the length of the catenary remains the same. When multiple point or distributed loads are applied to the chain, the chain will always take a position in which it is only stressed in tensile stresses.

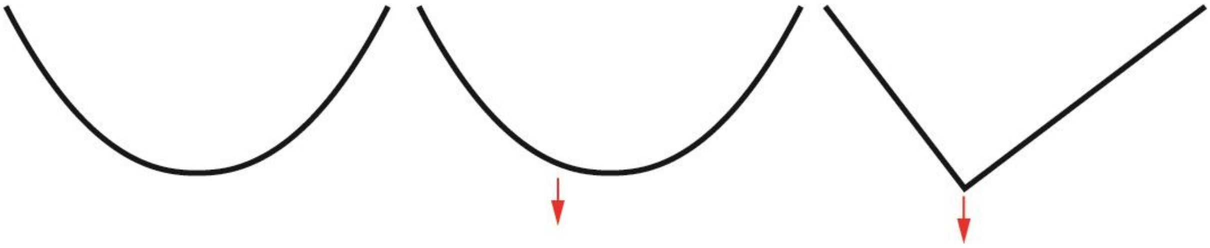


Figure 3: (a) chain in its initial shape (b) point load applied to the chain (c) chain in stable position

This theory can be applied to the structure of the communal housing project. When the catenary of the previous example is inverted, it becomes an arch loaded in compression only. Figure 4 shows a schematic section of the proposed design. It consists of domes inside a mound with multiple dwellings on top.

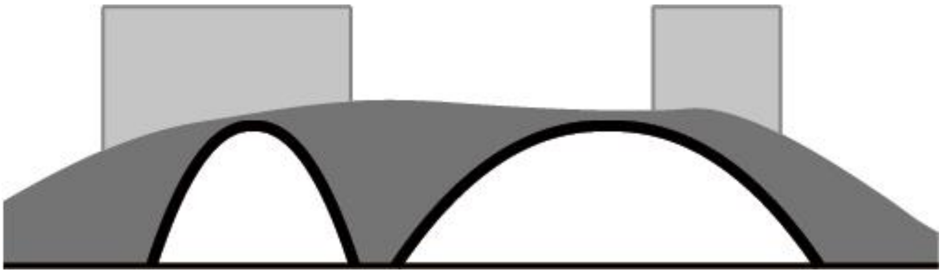


Figure 4: Schematic section of the proposed design

Figure 5 shows the load on the domes due to the weight of the mound and the dwellings. Since the domes are not optimised for these loads, tensile stresses will occur in the domes.

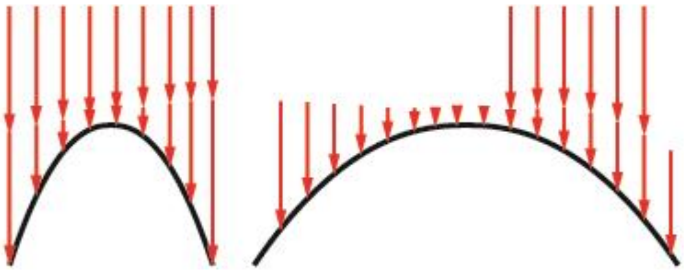


Figure 5: Loads on the domes

To optimise the domes, the loads are inverted as is shown in Figure 6.

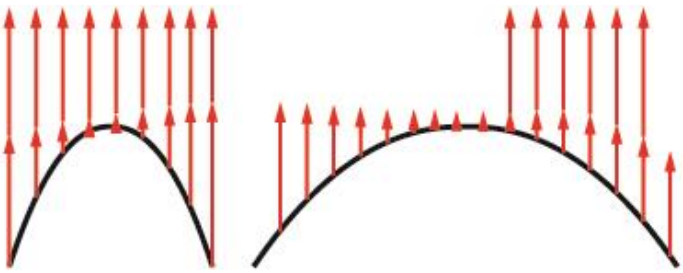


Figure 6: Inverted loads on the domes

If the domes would behave like a chain, they would deform into stable shapes that are stressed in tension only. As the domes deform, the weight of the mound on top of the dome will change. This will change the loads acting on the dome and thus affect the deformation. The deformed domes are shown in Figure 7.

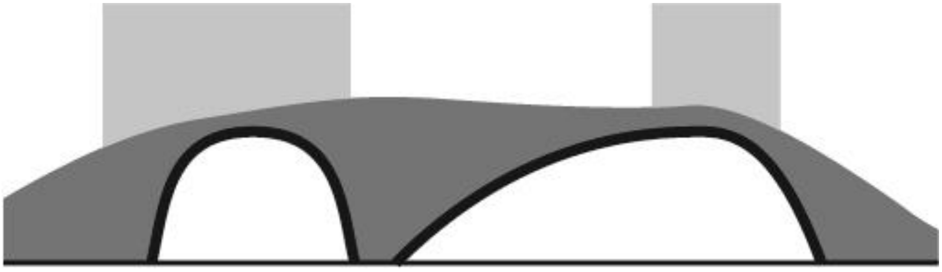


Figure 7: Deformed domes

When the forces are inverted back to their initial direction, as shown in Figure 8, only compressive stress will occur in the domes.

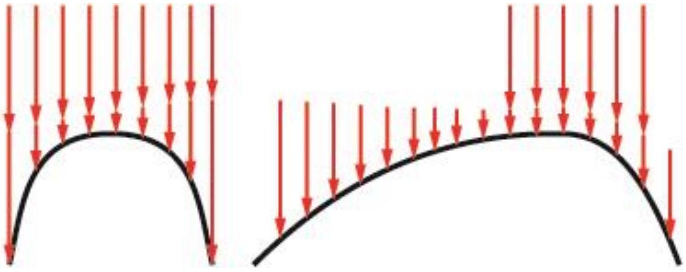


Figure 8: Loads on the deformed domes

However, the same theory does not directly apply to two dimensional structures with a double curvature. Let's consider a fabric surface as a two-dimensional version of a chain. Just like a chain, fabric can handle tensile stresses but becomes unstable under compressive stresses. Figure 9(a) shows the fabric surface in its initial shape, a catenary dome that is loaded in tensile stress only. Figure 9(b) shows the same catenary dome with point load applied to it. The point load is far higher than the dead load so for this example the dead load is neglected. Since the fabric cannot take any compression, the fabric deforms into a stable position that is shown in Figure 9(c). Note that there are wrinkles in the fabric. These wrinkles indicate that part of the dome is loaded in compression.

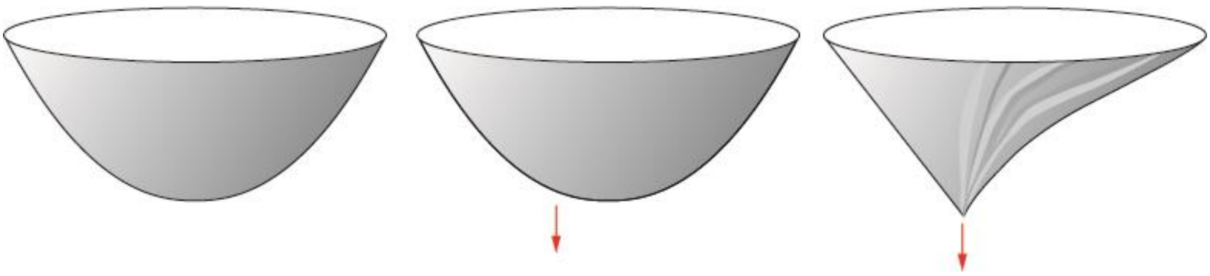


Figure 9: (a) fabric in its initial shape (b) point load applied to the fabric (c) fabric in stable position

The optimal shape that is stressed in tension only would be a conical dome as shown in Figure 10 Note that the surface area of the conical dome is different from the initial catenary dome.

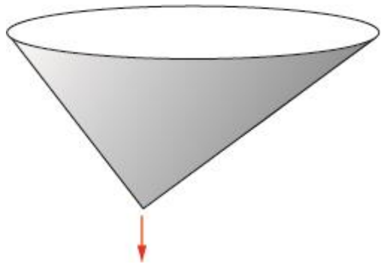


Figure 10: Fabric in optimal shape

In order to find the optimal shape for a double curved shape, the fabric should be able to shrink where compression occurs and stretch were tension occurs. This means that the fabric should be made out of an elastic material. When an elastic material is used for form finding, the resulting surface will be smooth and no wrinkling will occur.

Taking this theory into account when doing computational form finding, the domes should be modelled as a mesh in which each mesh edge acts as a spring. When loads are applied to the mesh, the edges in tension will stretch, resulting in an optimised shape without wrinkles for these particular loads. This can be done with the Kangaroo plug-in for Grasshopper.

4.2. Initial structure

First, an initial structure for the rooms on the ground floor is designed that is later structurally optimised by the previously described process. The initial structure is based on the floorplan which is generated based on the number of inhabitants and the spatial adjacency between the functions of the rooms. Figure 11 shows a schematic representation of the floorplan of the ground floor. The floorplan consists of several circles that are intersected at some points by the street or courtyards. The circles have diameters ranging from 4.0 to 10.4 meters.

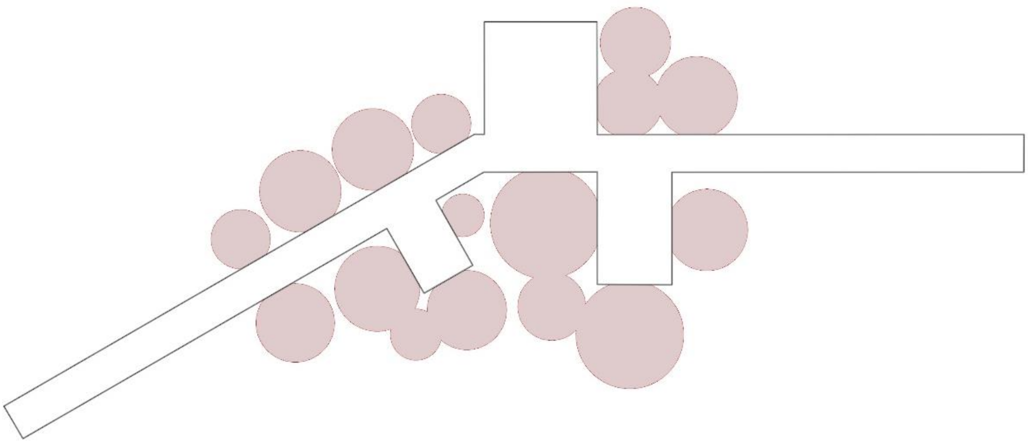


Figure 11: Schematic representation of the ground floor

Based on this schematic floorplan, an initial three-dimensional structure is generated. The initial structure is shown in Figure 12. The initial structure consists of a series of dome like shapes. Some domes are linked with each other by vaulted corridors. At the locations where the domes are adjacent with the street or a courtyard, an opening is made. It is made sure that all the domes have a height of at least 2.5 meters and the corridors have a height of at least 2.1 meters to ensure that the spaces are functional. Note that Figure 12 does not show the mound of earth on top of the structure, which consists of a large volume of soil. Also, in further diagrams of the structure the mound is not shown for visualisation purposes.

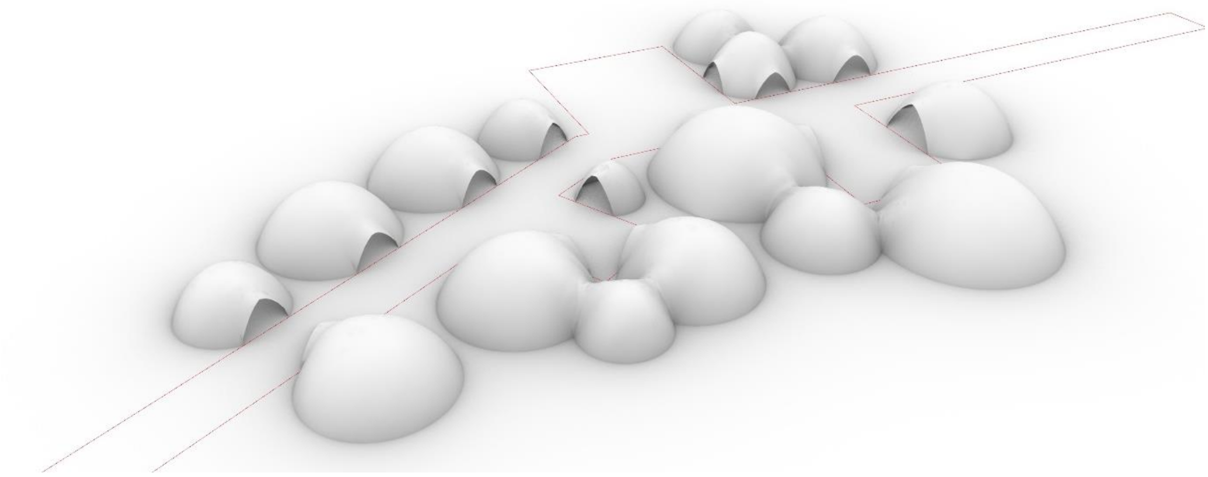


Figure 12: Initial structure

4.3. Loads

In order to find the optimal structure for the rooms within the mound using Kangaroo, the loads acting on the structure need to be determined. There are two types of dead loads acting on the structure; the load due to the soil of the mound and the load due to the dwellings on top of the mound. Additionally, the live loads are taken into account.

4.3.1. Loads due to the weight of the mound

The load of the mound is determined by calculating the volume of soil above every mesh face. This is done by measuring the vertical distance of the centroid of each mesh face to the top of the mound. Then, each mesh face is projected on the XY-plane and the area of the projected mesh face is measured. The volume of soil above every mesh face is calculated by multiplying the area with the distance to the mound. The volume is then multiplied with the density of the soil (2000 kg/m^3) and with the gravitational acceleration (10 m/s^2) in order to get the load acting on each face. This load is then divided over the number of vertexes of each face and applied to those vertexes. Figure 13 shows the load due to the weight of the mound acting on the structure. Note that the loads on the side of the domes are higher than the loads on top of the domes since a higher volume of soil is placed on the sides than on top of the dome.

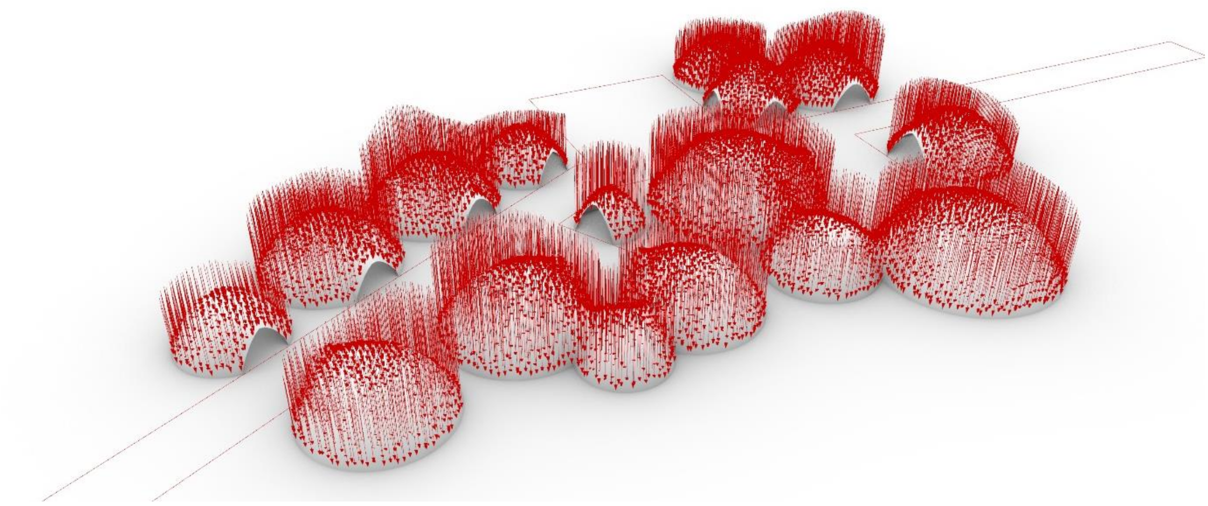


Figure 13: Loads due to the weight of the mound

4.3.2. Loads due to the weight of the mound

There are four type of dwellings placed on the mound named module 1, module 2, module 3, and module 4. Figure 14 shows an isometric view of the modules.

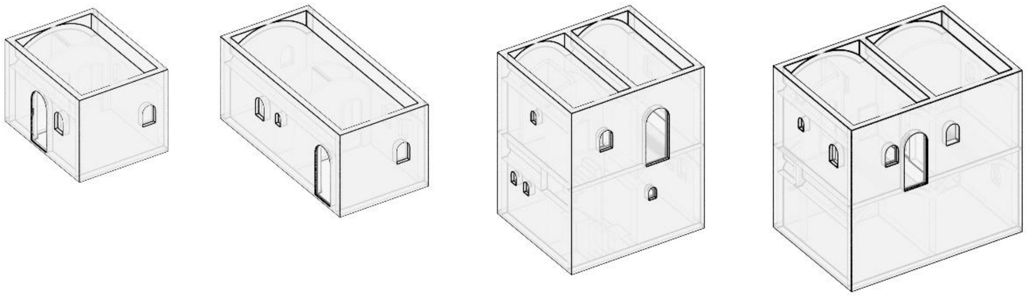


Figure 14: (a) Module 1, (b) Module 2, (c), Module 3, (d) Module 4

Module 1 and module 2 are one storey buildings that are built on top of the mound and thus cause a load acting on the domes. Module 3 and module 4 are two storey buildings that are built beside the domes and therefore do not cause loads acting on the domes. Figure 15 shows how the module 1 and module 2 dwellings (green) are placed, relative to the structure on the ground floor (red).

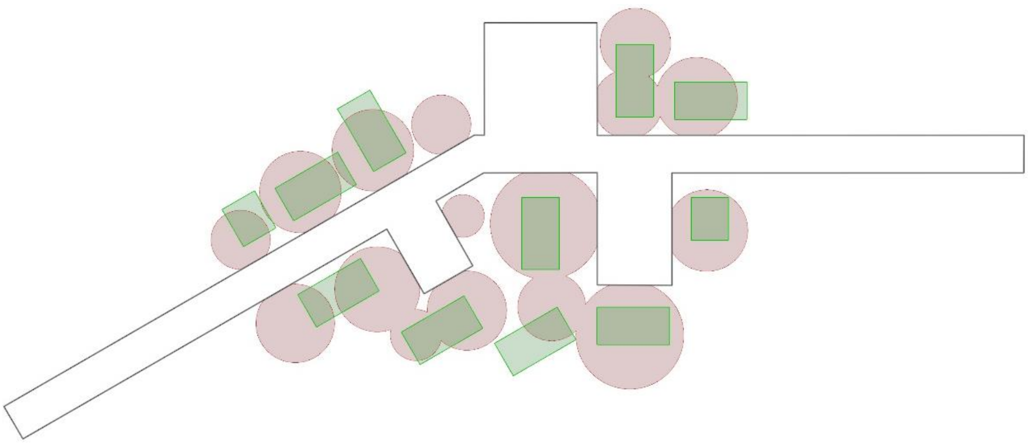


Figure 15: Layout of the module 1 and module 2 dwellings

Both module 1 and 2 consist of a raised vault roof with walls on both ends of the vault. Figure 16 shows a schematic footprint of module 1 and 2. In this figure the distributed load due to the weight of the walls and roof is shown. Since the load of the interior walls is small compared to the load of the outer walls, the load of the interior walls is neglected in order to simplify the calculation.

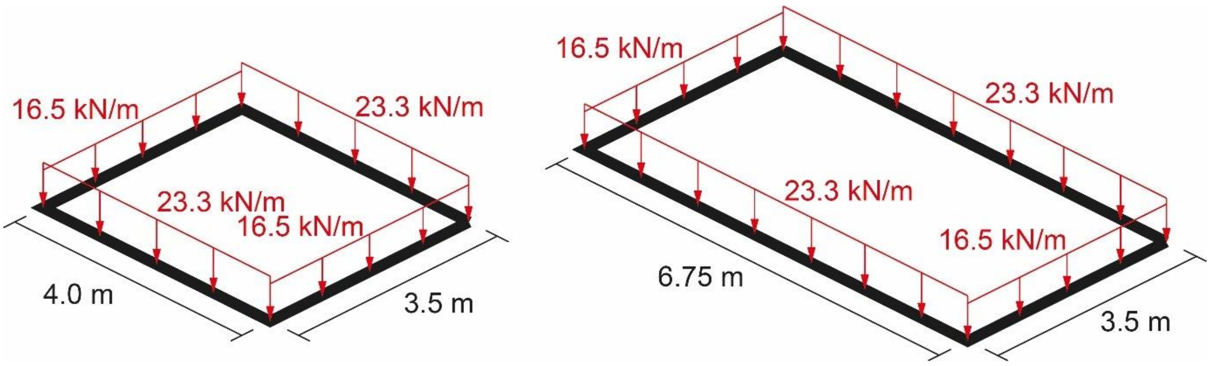


Figure 16: Footprint of module 1 and module 2

In order to determine which vertexes of the mesh the loads of the dwellings are assigned to, the footprints of the dwellings are divided into segments of 0.3 meters. The points where the lines are divided are projected on the XY-plane. The vertexes of the mesh are also projected on the XY plane. Then the five closest projected vertexes to each projected division point is found. The total load of each wall is then divided by the amount of divisions points and assigned to the vertexes that match the five closest projected vertexes of each projected division point. Figure 17 shows the load due to the weight of the dwellings acting on the structure.

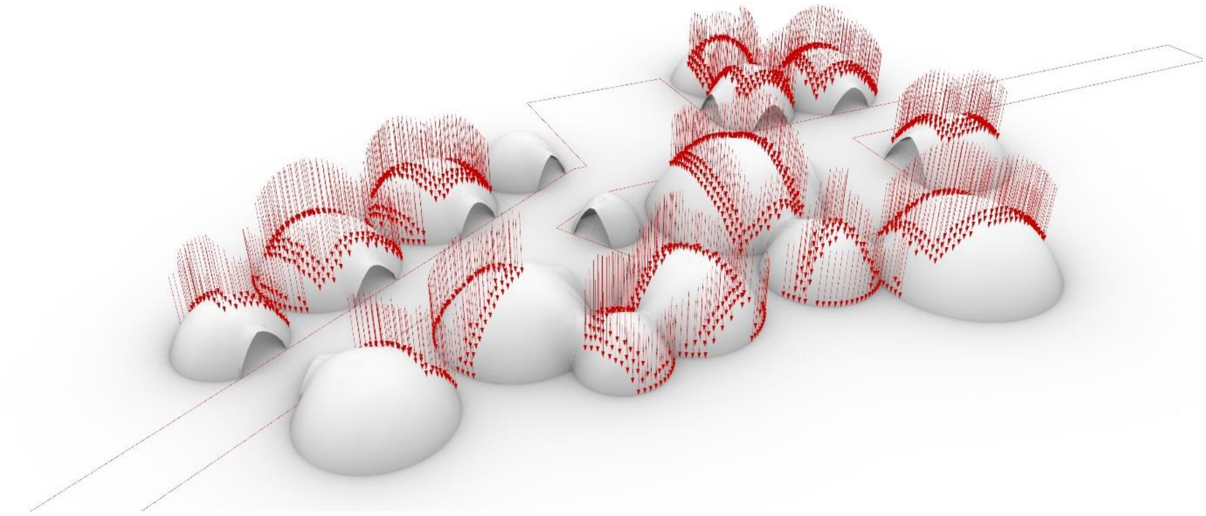


Figure 17: Loads due to the weight of the dwellings

4.3.3. Live loads

People walking on the mound and furniture placed inside the dwellings will result in live loads acting on the structure. These loads are assumed to be 1.0 kN/m^2. These loads are not taken into account while finding the optimal structure since these loads are not always present on the structure. However, the live loads are taken into account when the optimised structure is subjected to a finite element analysis since the optimised structure should be able to carry the live loads.

Due to the aerodynamic shape of the mound, the wind will smoothly flow around the mound. Therefore, the live loads on the structure due to wind will be limited and are not taken into account for both the form finding of the optimal structure and the finite element analysis.

4.4. Form finding

When the loads that act on each vertex are known, the Kangaroo solver can be configured. Anchor points are set at each vertex that has a z-coordinate of 0 and all mesh edges are converted into springs. The optimised structure is generated by the Kangaroo solver. Figure 18 shows the calculated optimised structure compared to the initial structure. The initial structure is shown in white and the optimised structure is shown in translucent red.

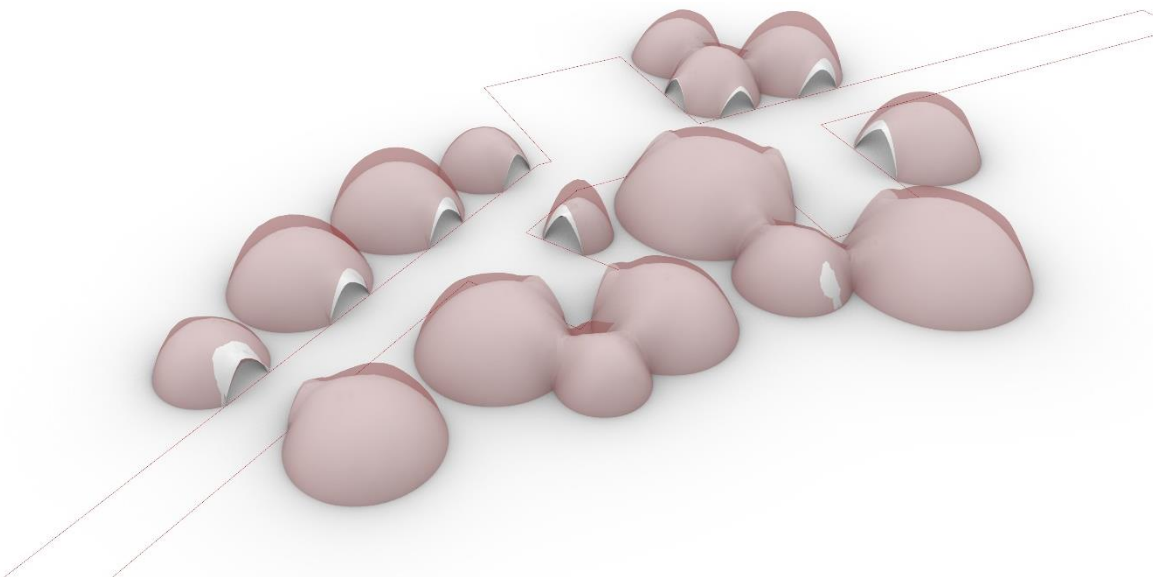


Figure 18: Optimised structure compared to the initial structure

4.5. Structural analysis

The optimised structure is then subjected to a finite element analysis in Karamba3D. For this calculation the loads are not inverted but follow the direction of gravity. Also, the live loads are applied to the structure. The dead loads are multiplied by a safety factor of 1.2 and the live loads are multiplied by a safety factor of 1.5. The Young's modulus is set to 100 MPa.

Three different load cases are tested with the finite element analysis. In the first load case, the dead loads which led to the structural optimisation are analysed. The dead loads consists of the load of the mound and the load of the dwellings. The second load case takes both the dead loads and the live loads into account.

During the construction phase a certain situation will take place. When the domes and the mount are built, the dwellings on top still need to be built. During this period the load case consist of the dead loads due to the weight of the mount and the live loads of construction workings that are working on top of the mount. The loads due to the weight of the dwellings will not be present yet. The structure should also be able to withstand this situation so a third analysis is done with the load case consisting of the load due to the weight of the mount and a live load.

Table 1 gives an overview of the different load cases.

Load case	**Mound**	**Dwellings**	**Live**
1	Yes	Yes	No
2	Yes	Yes	Yes
3	Yes	No	Yes

Table 1: Load cases

In order to find out the effect of the optimisation process on the performance of the structure, the analysis should also be done for the initial structure. For the initial structure, the analysis is only done for load case 1 and 2.

Several analyses are done with varying thicknesses of the shell. It found that 330 mm is the smallest allowable thickness to meet the structural requirements. The results of the FEA of the structure with a thickness of 330 mm are shown in the next chapter.

4.6. Results

4.6.1. Optimised structure

4.6.1.1. Load case 1

Figure 19 shows the calculated displacement of the finite element analysis for load case 1. The maximum displacement is 32.2 mm.

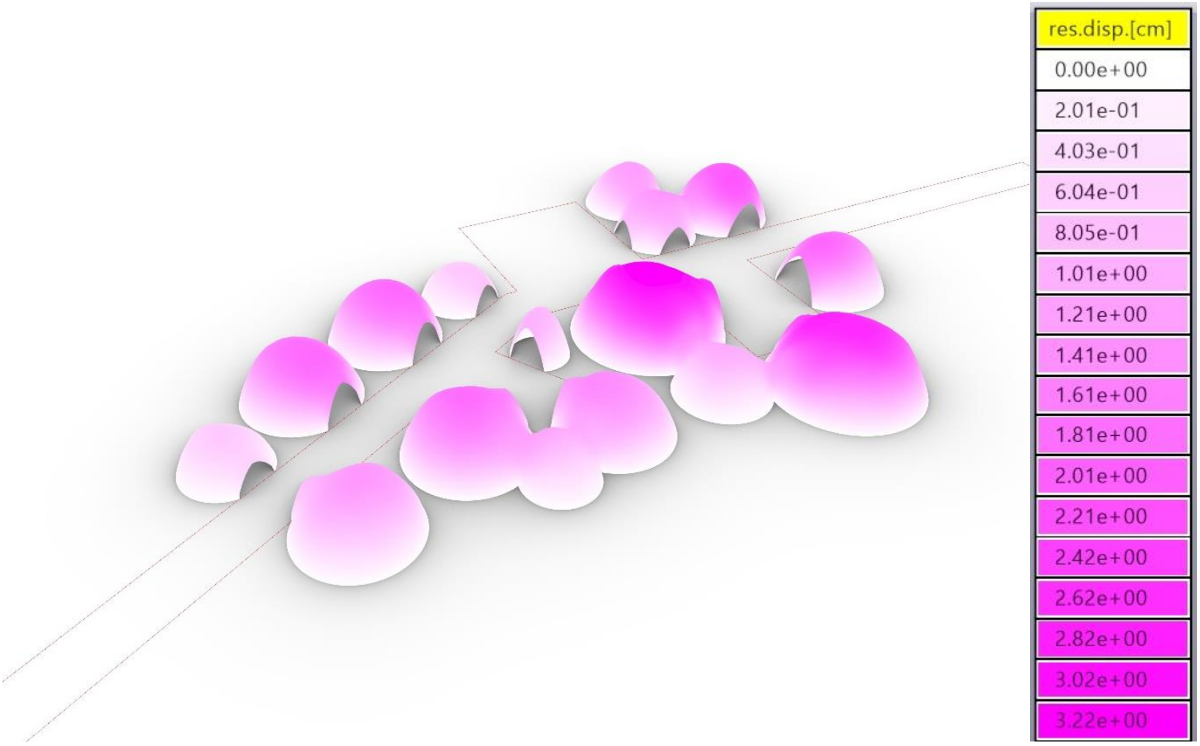


Figure 19: FEA optimised structure, load case 1, displacement

Figure 20 to Figure 23 show the calculated principal stresses of the finite element analysis for load case 1. The principal stresses are calculated in both the local X and local Y directions and in both the top and bottom layer of the shell. The maximum compressive stress that occurs is 1.24 MPa and the maximum tensile stress that occurs is 0.07 MPa.

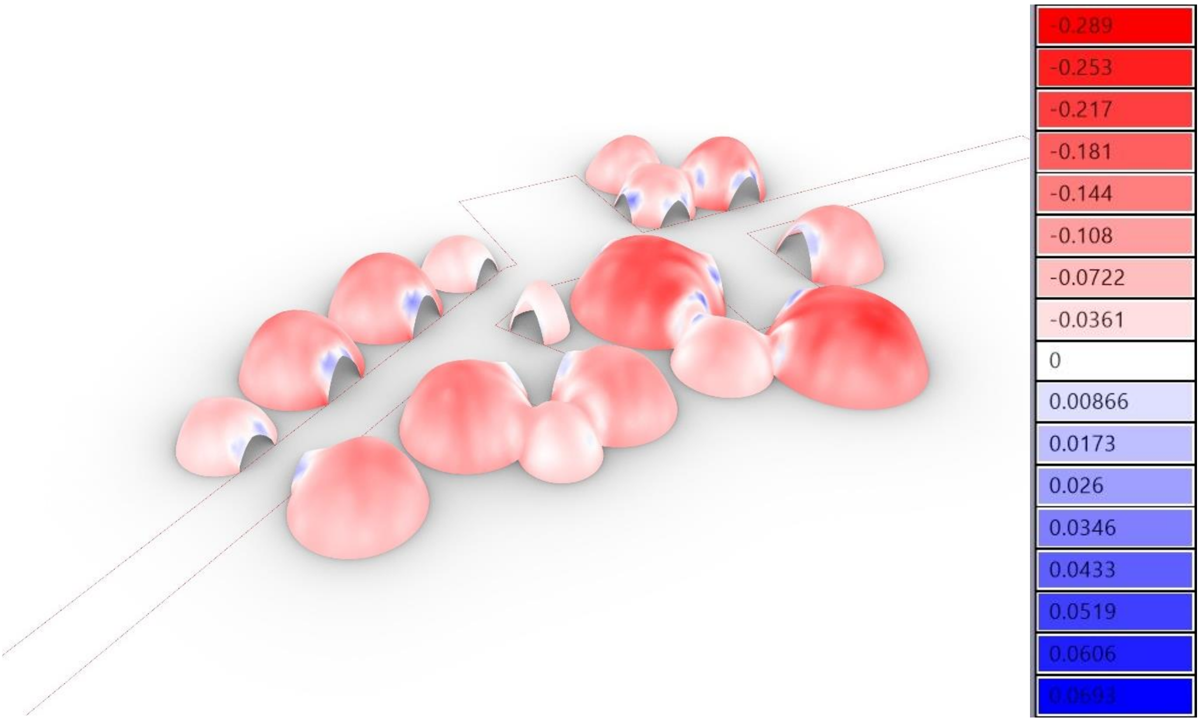


Figure 20: FEA optimised structure, load case 1, principal stress 1, layer 1

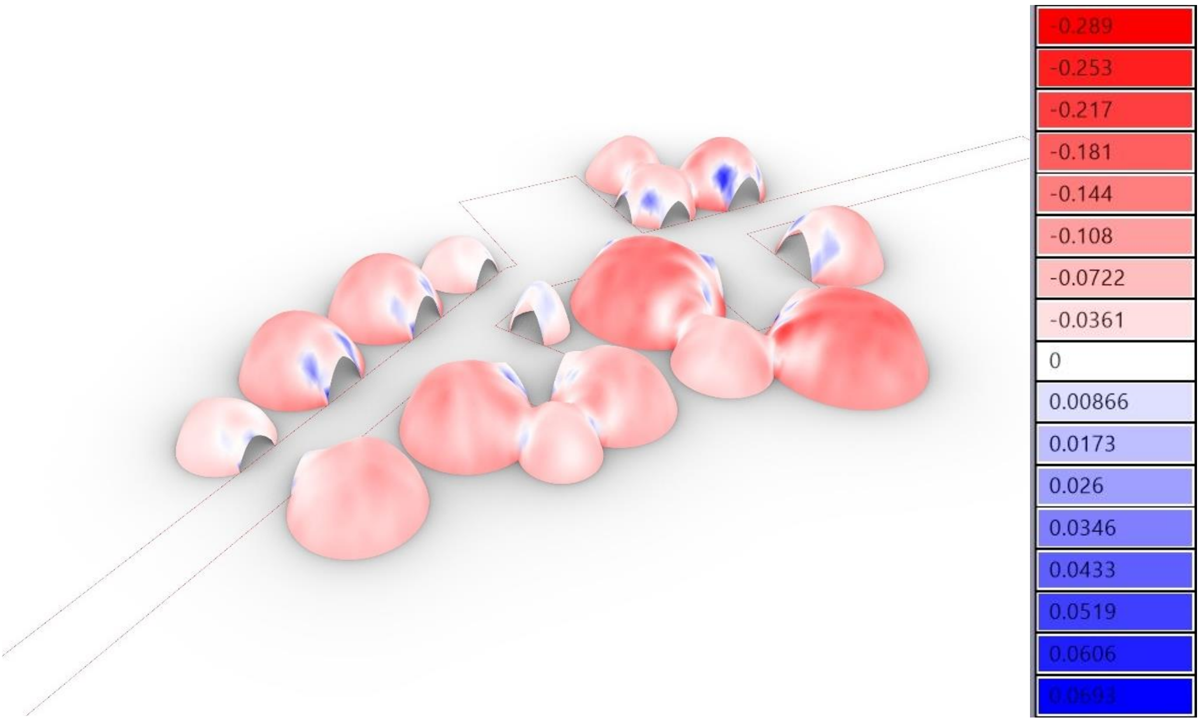


Figure 21: FEA optimised structure, load case 1, principal stress 1, layer -1

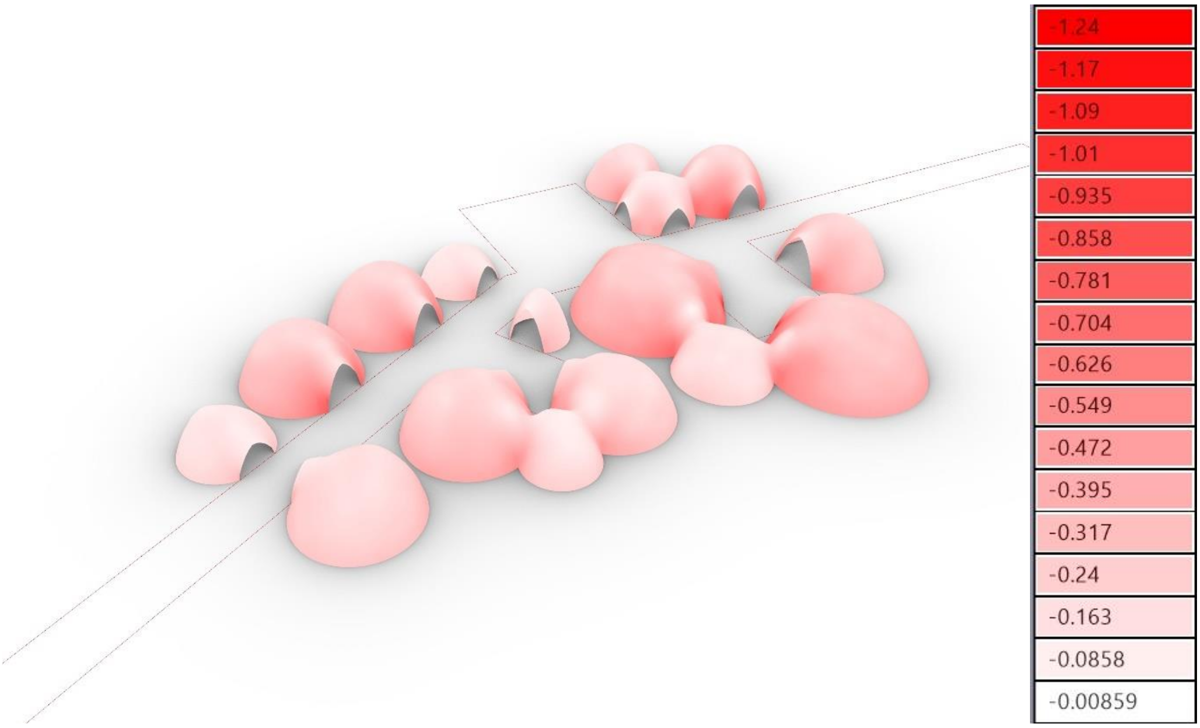


Figure 22: FEA optimised structure, load case 1, principal stress 2, layer 1

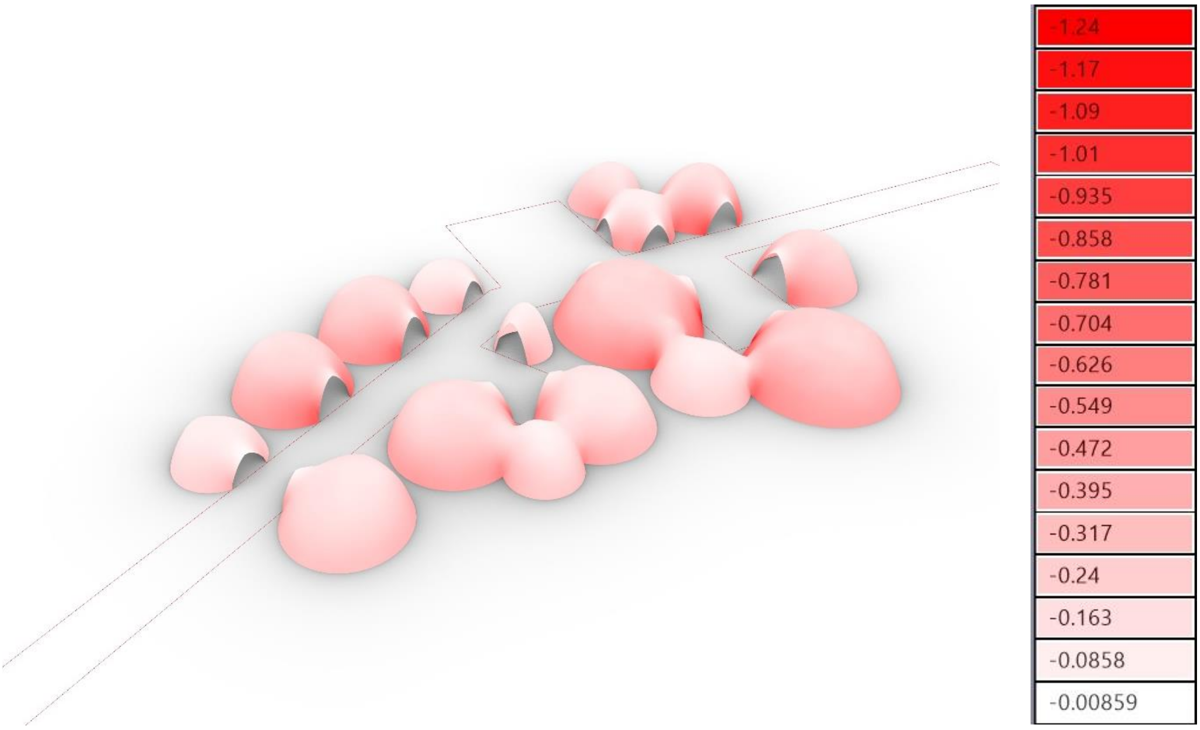


Figure 23: FEA optimised structure, load case 1, principal stress 2, layer -1

4.6.1.2. Load case 2

Figure 24 shows the calculated displacement of the finite element analysis for load case 2. The maximum displacement is 33.7 mm.

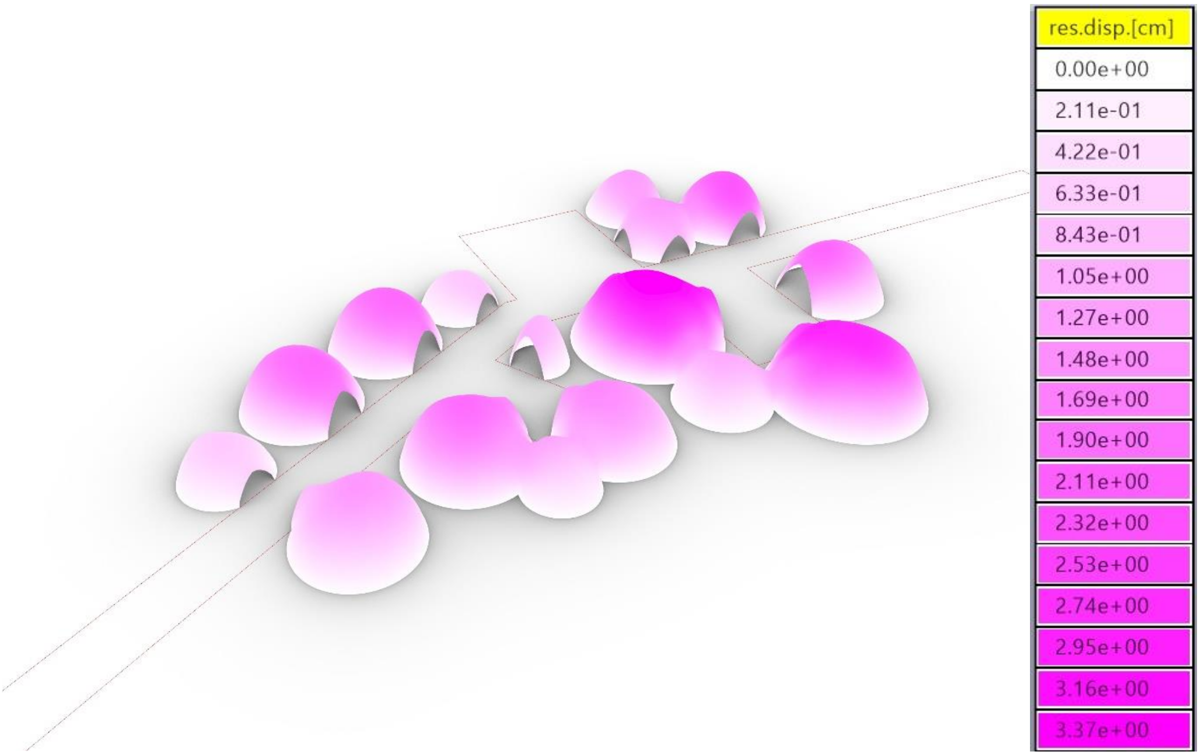


Figure 24: FEA optimised structure, load case 2, displacement

Figure 25 to Figure 28 show the calculated principal stresses of the finite element analysis for load case 2. The principal stresses are calculated in both the local X and local Y directions and in both the top and bottom layer of the shell. The maximum compressive stress that occurs is 1.28 MPa and the maximum tensile stress that occurs is 0.07 MPa.

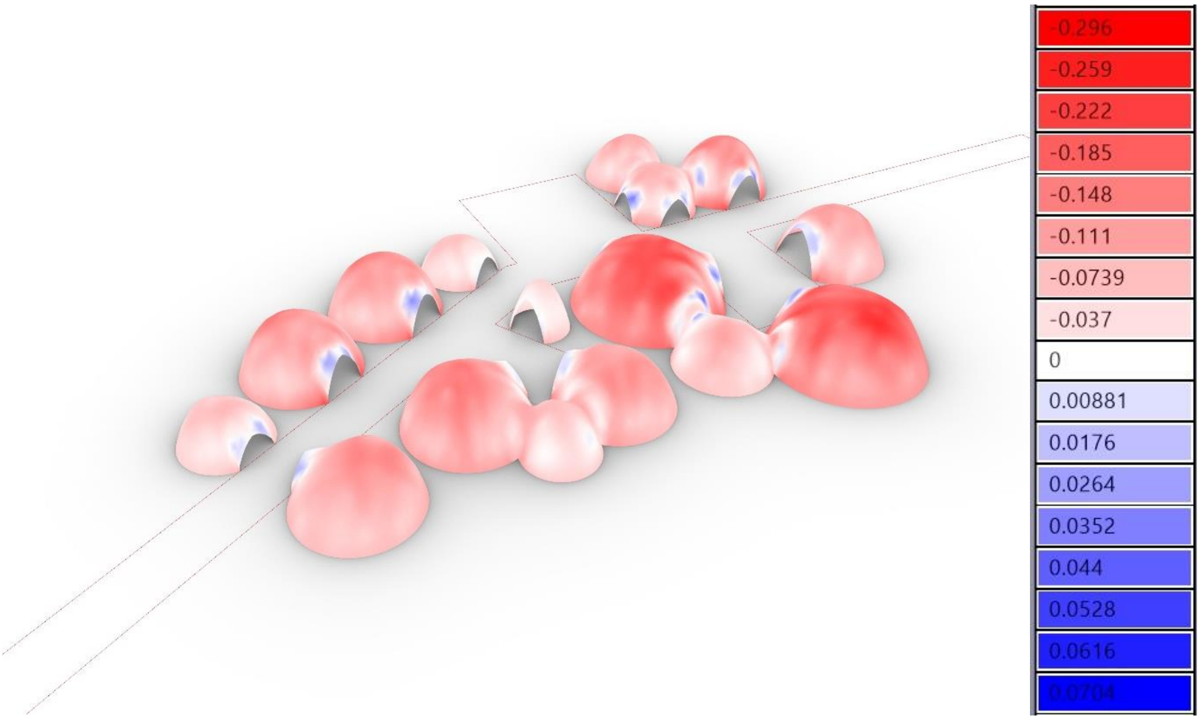


Figure 25: FEA optimised structure, load case 2, principal stress 1, layer 1

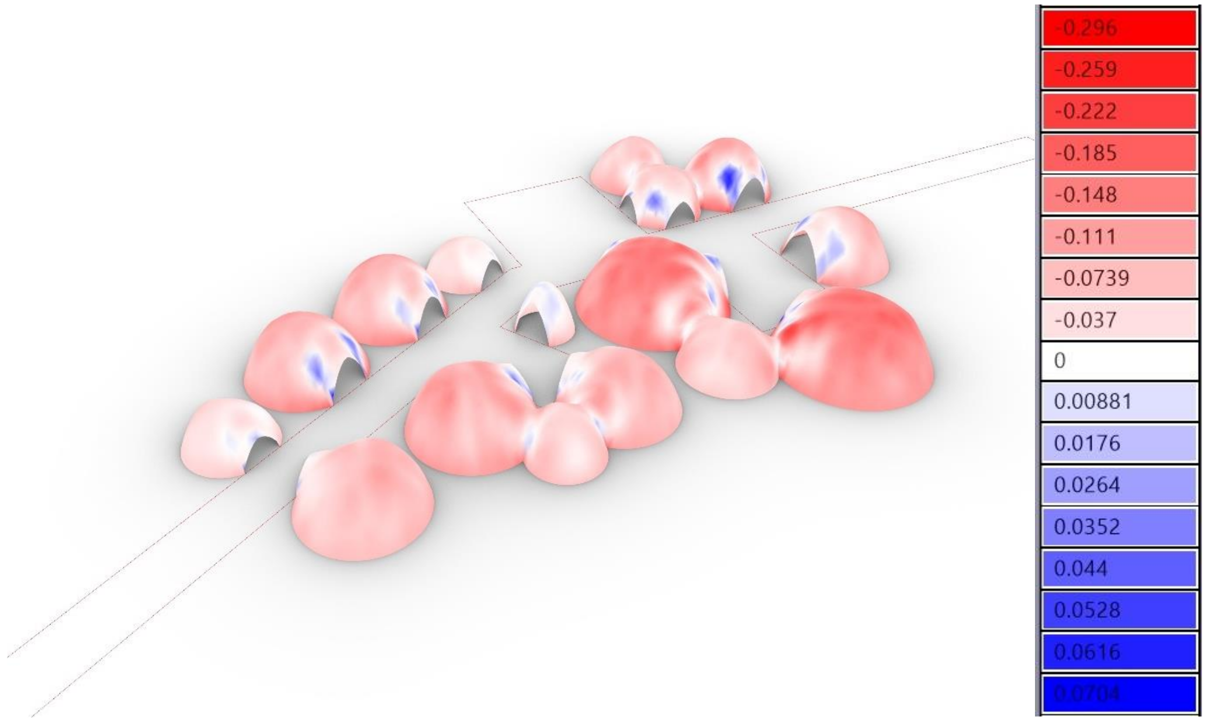


Figure 26: FEA optimised structure, load case 2, principal stress 1, layer -1

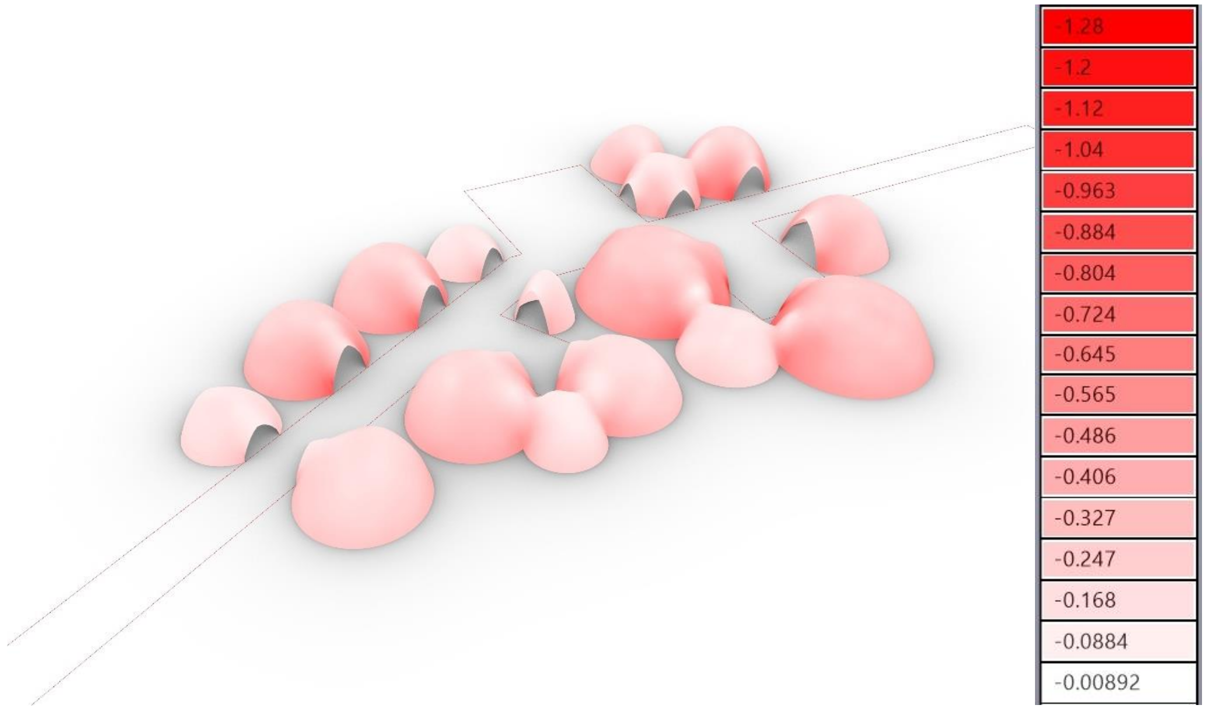


Figure 27: FEA optimised structure, load case 2, principal stress 2, layer 1

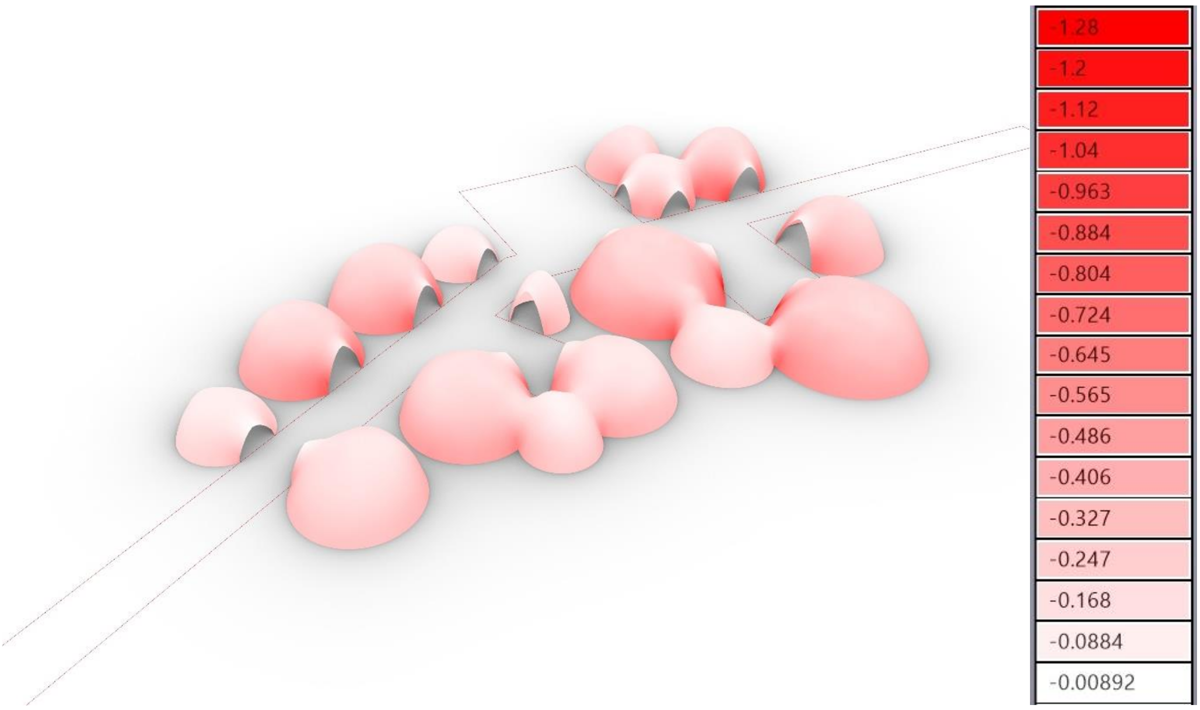


Figure 28: FEA optimised structure, load case 2, principal stress 2, layer -1

4.6.1.3. Load case 3

Figure 29 shows the calculated displacement of the finite element analysis for load case 3. The maximum displacement is 30.2 mm.

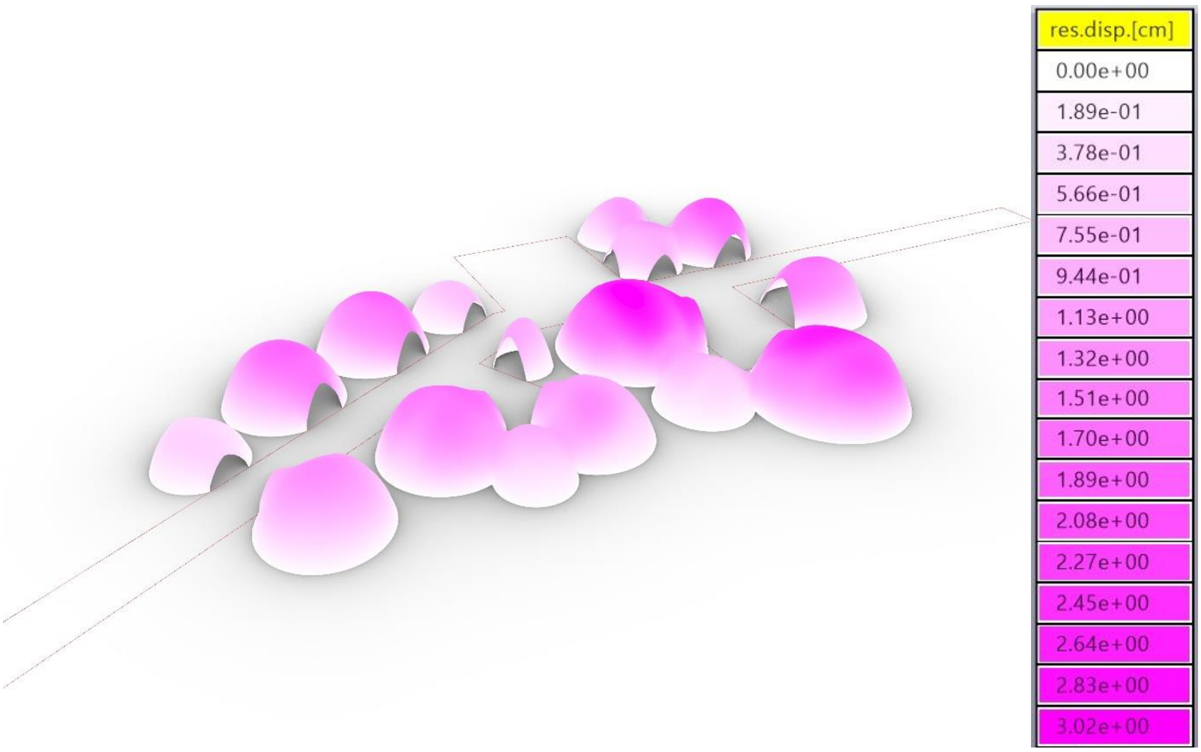


Figure 29: FEA optimised structure, load case 3, displacement

Figure 30 to Figure 33 show the calculated principal stresses of the finite element analysis for load case 3. The principal stresses are calculated in both the local X and local Y directions and in both the top and bottom layer of the shell. The maximum compressive stress that occurs is 1.18 MPa and the maximum tensile stress that occurs is 0.10 MPa.

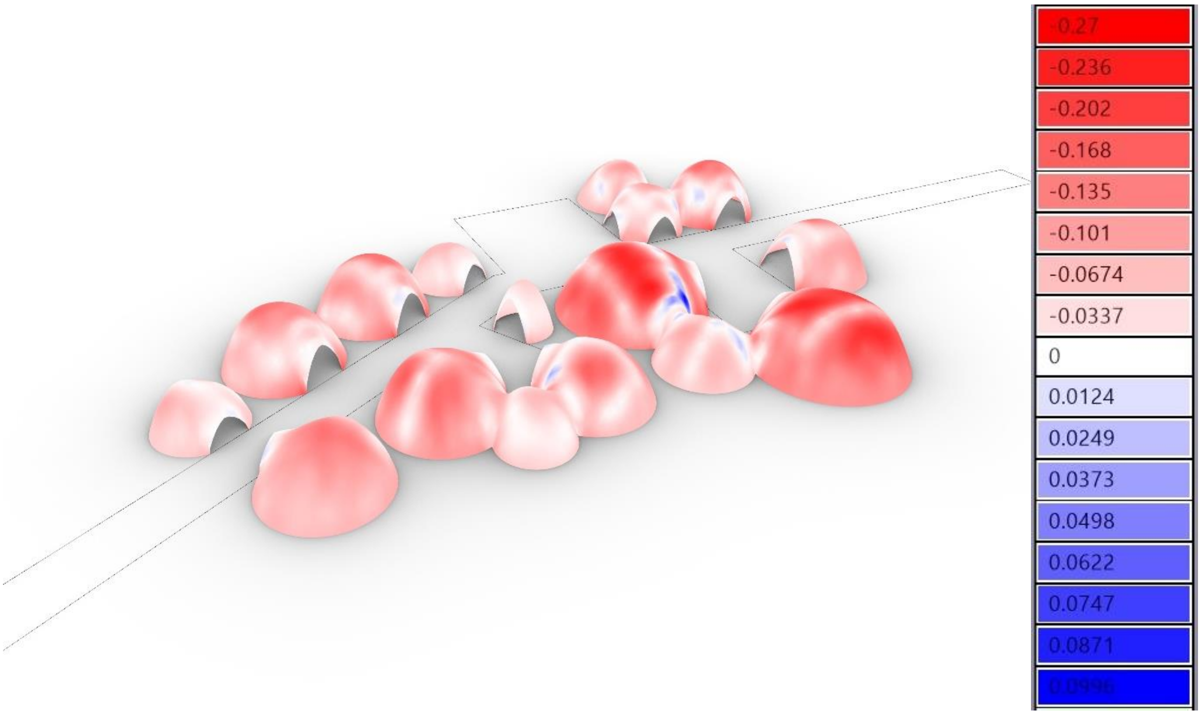


Figure 30: FEA optimised structure, load case 3, principal stress 1, layer 1

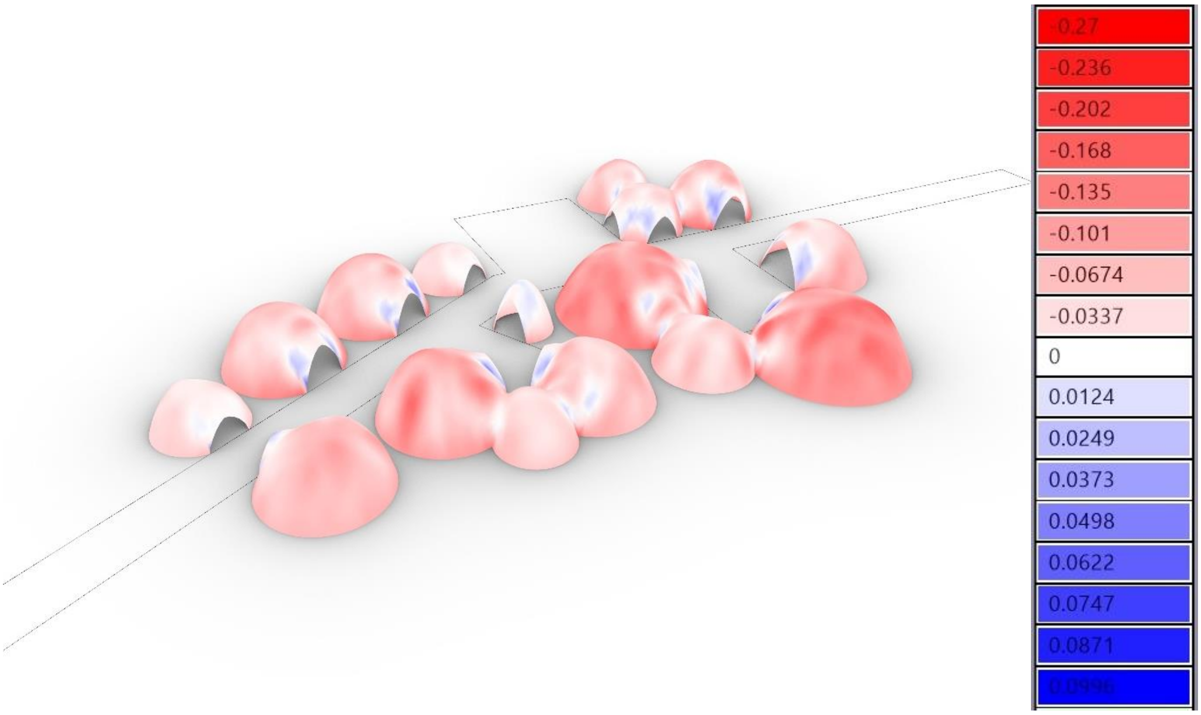


Figure 31: FEA optimised structure, load case 3, principal stress 1, layer -1

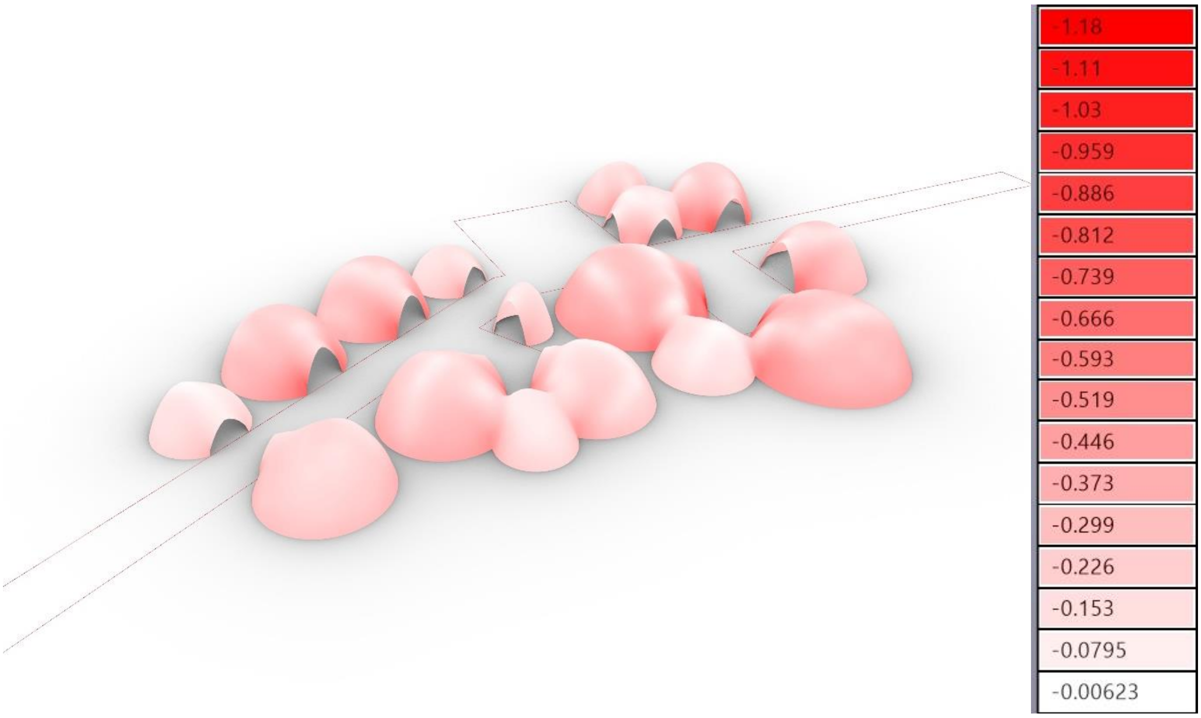


Figure 32: FEA optimised structure, load case 3, principal stress 2, layer 1

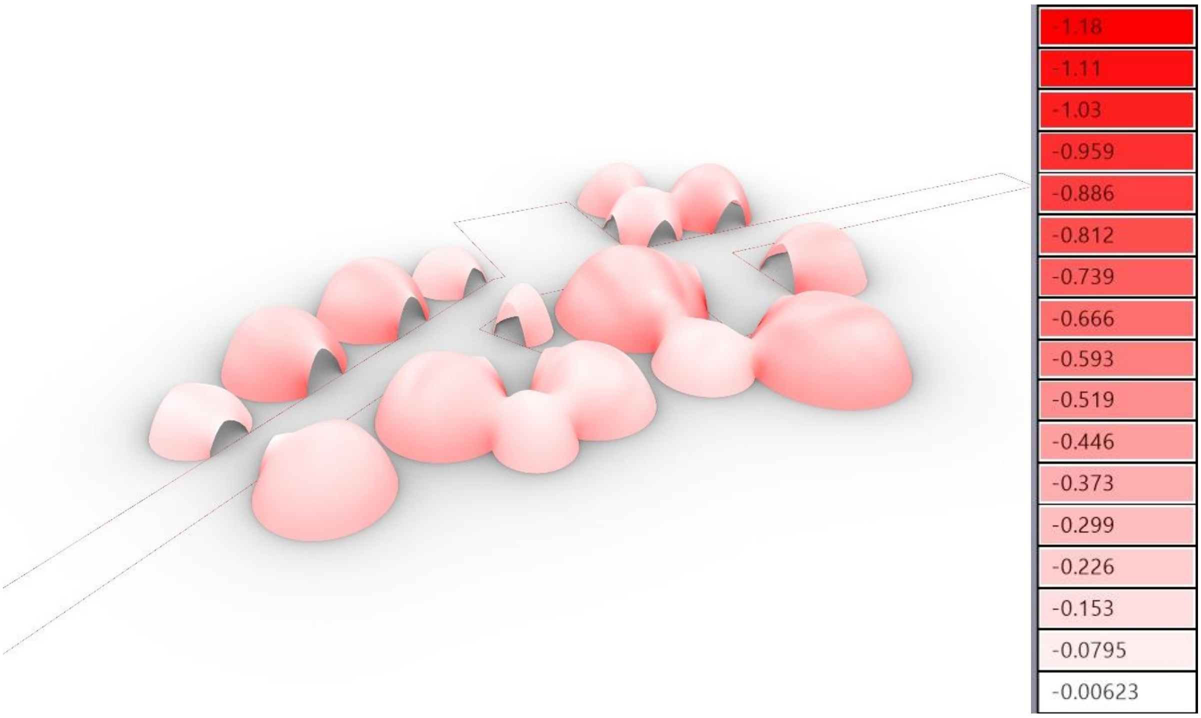


Figure 33:: FEA optimised structure, load case 3, principal stress 2, layer -1

4.6.2. Initial structure

4.6.2.1. Load case 1

Figure 34 shows the calculated displacement of the first finite element analysis for load case 1. The maximum displacement is 34.2 mm. Note that the highest displacement occurs on the two large domes where the load of the dwellings is acting on the structure.

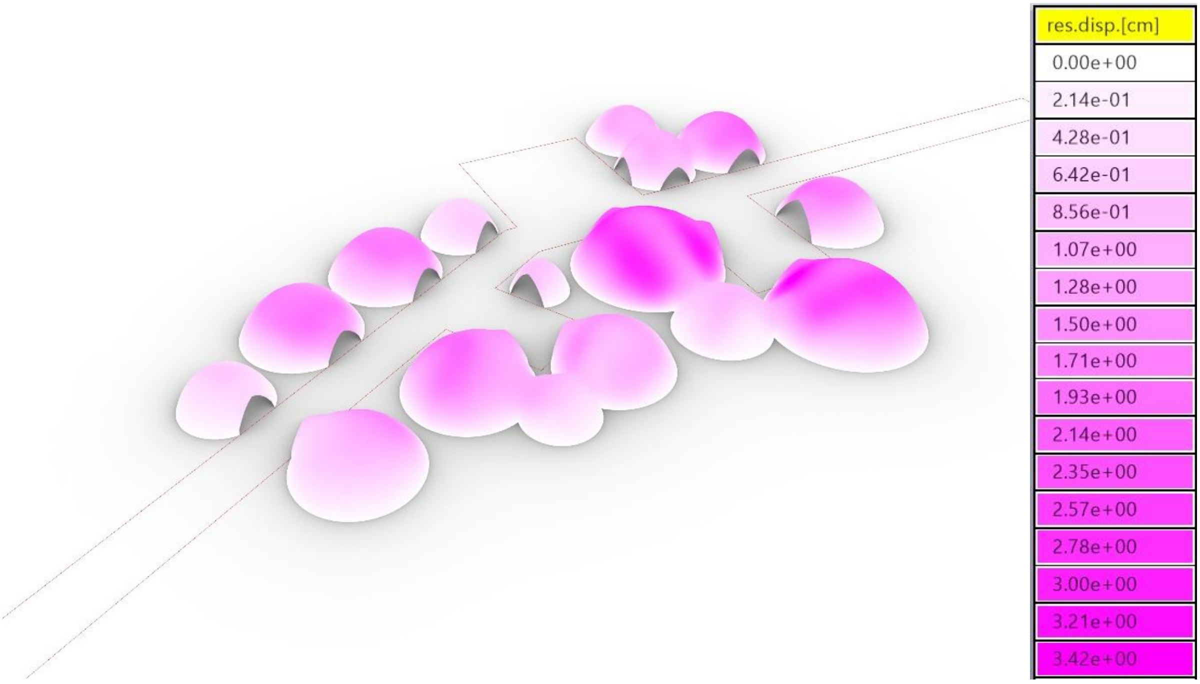


Figure 34: FEA initial structure, load case 1, displacement

Figure 35 to Figure 38 shows the calculated principal stresses of the first finite element analysis for load case 1. The principal stresses are calculated in both the local X and local Y directions and in both the top and bottom layer of the shell. The maximum compressive stress that occurs is 1.66 MPa and the maximum tensile stress that occurs is 0.23 MPa. Note that peak stresses occur at the spots where the load of the dwellings is acting on the structure.

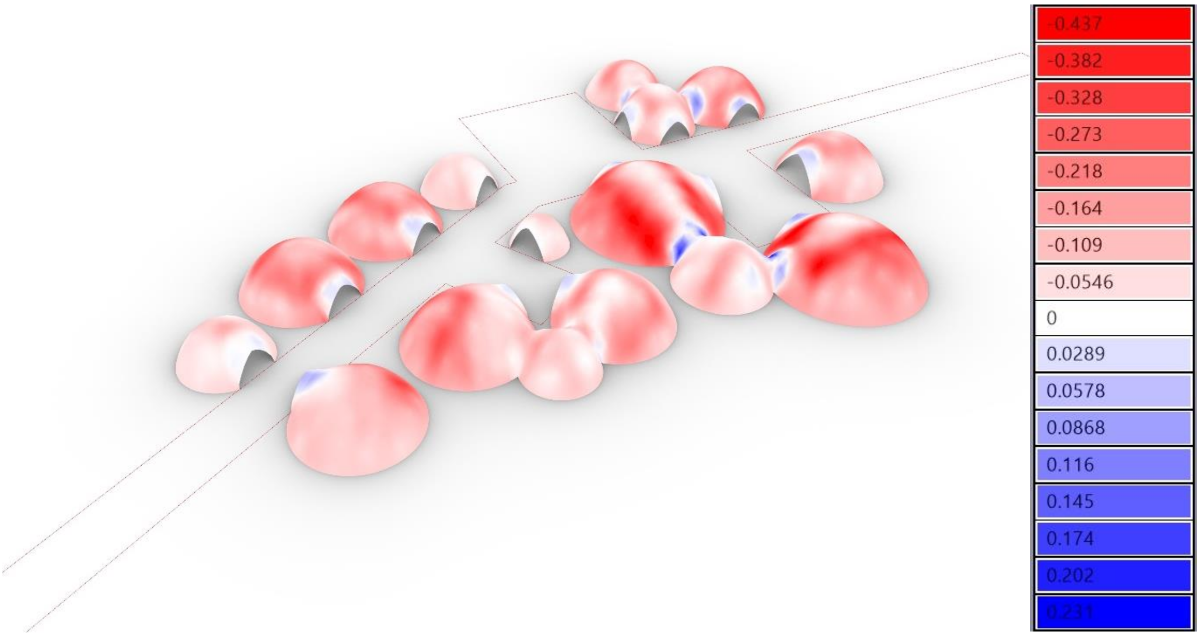


Figure 35: FEA initial structure, load case 1, principal stress 1, layer 1

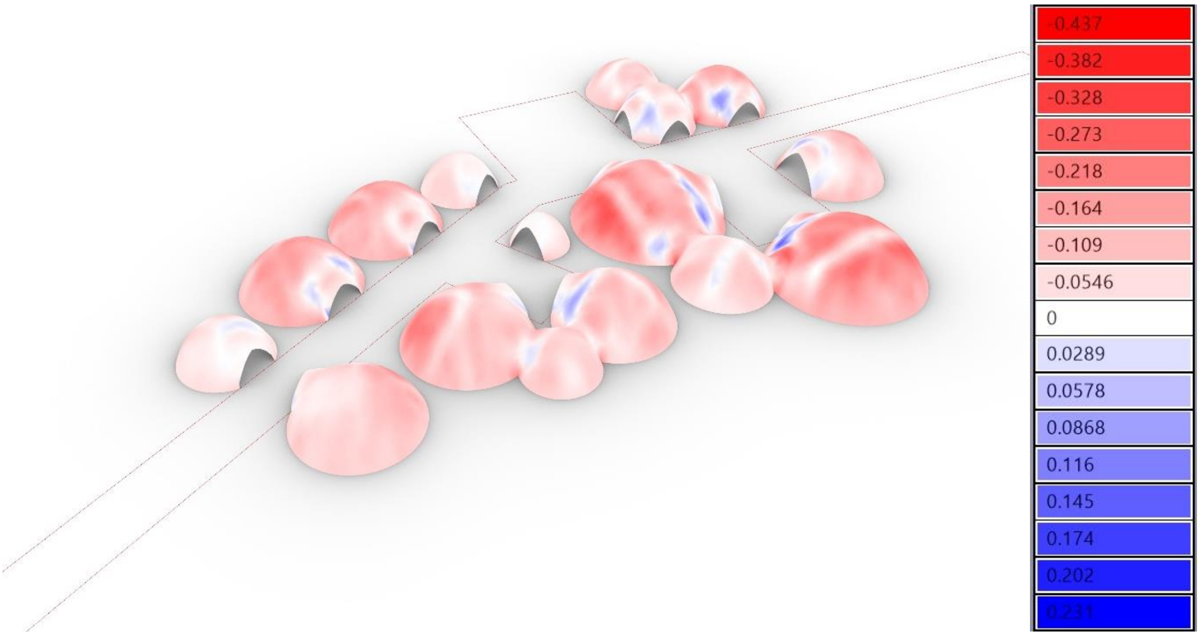


Figure 36: FEA initial structure, load case 1, principal stress 1, layer -1

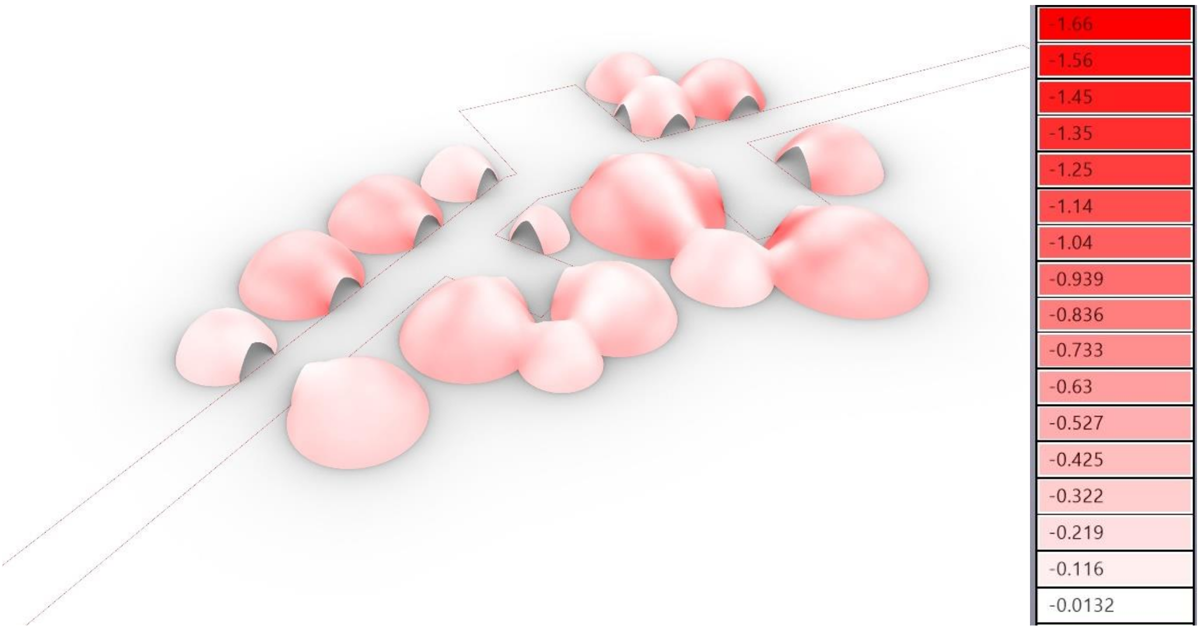


Figure 37: FEA initial structure, load case 1, principal stress 2, layer 1

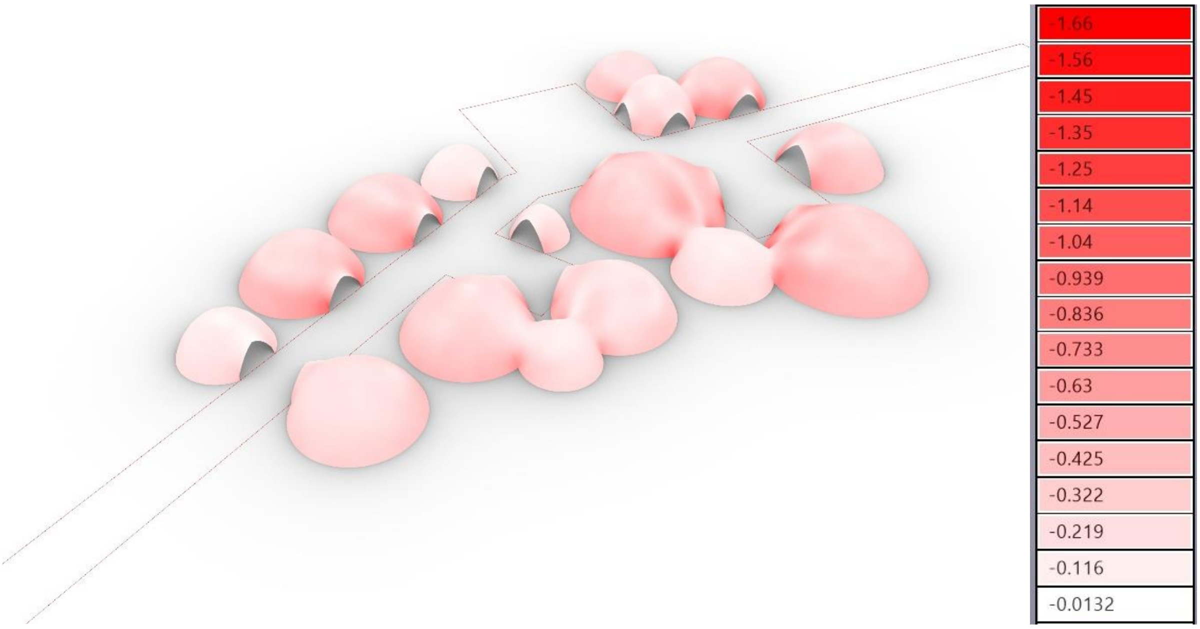


Figure 38: FEA initial structure, load case 1, principal stress 2, layer -1

4.6.2.2. Load case 2

Figure 39 shows the calculated displacement of the first finite element analysis for load case 2. The maximum displacement is 34.9 mm. Note that the highest displacement occurs on the two large domes at the spots where the load of the dwellings is acting on the structure.

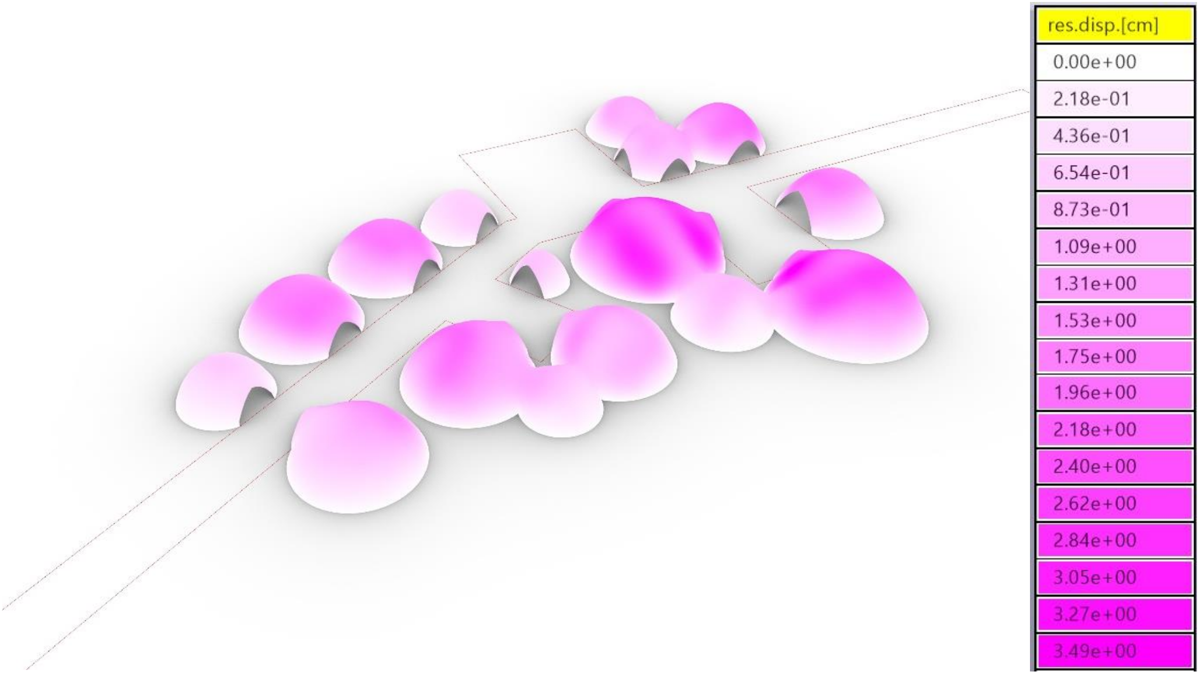


Figure 39: FEA initial structure, load case 2, displacement

Figure 40 to Figure 43 show the calculated principal stresses of the first finite element analysis for load case 2. The principal stresses are calculated in both the local X and local Y directions and in both the top and bottom layer of the shell. The maximum compressive stress that occurs is 1.69 MPa and the maximum tensile stress that occurs is 0.23 MPa. Note that peak stresses occur at the spots where the load of the dwellings is acting on the structure.

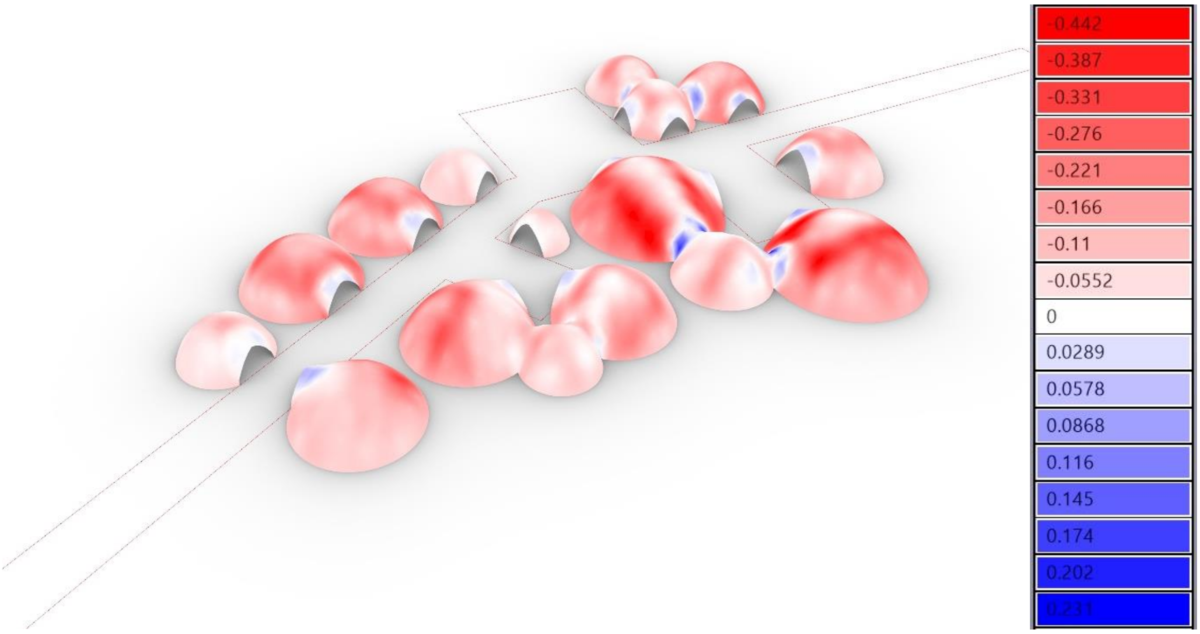


Figure 40: FEA initial structure, load case 2, principal stress 1, layer 1

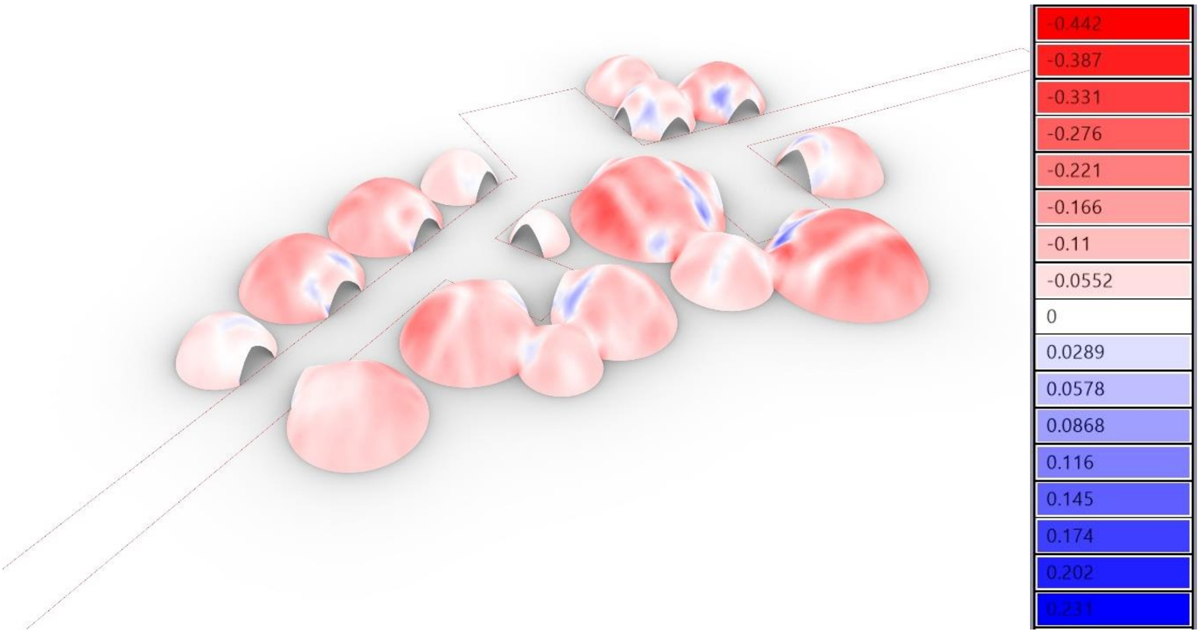


Figure 41: FEA initial structure, load case 2, principal stress 1, layer -1

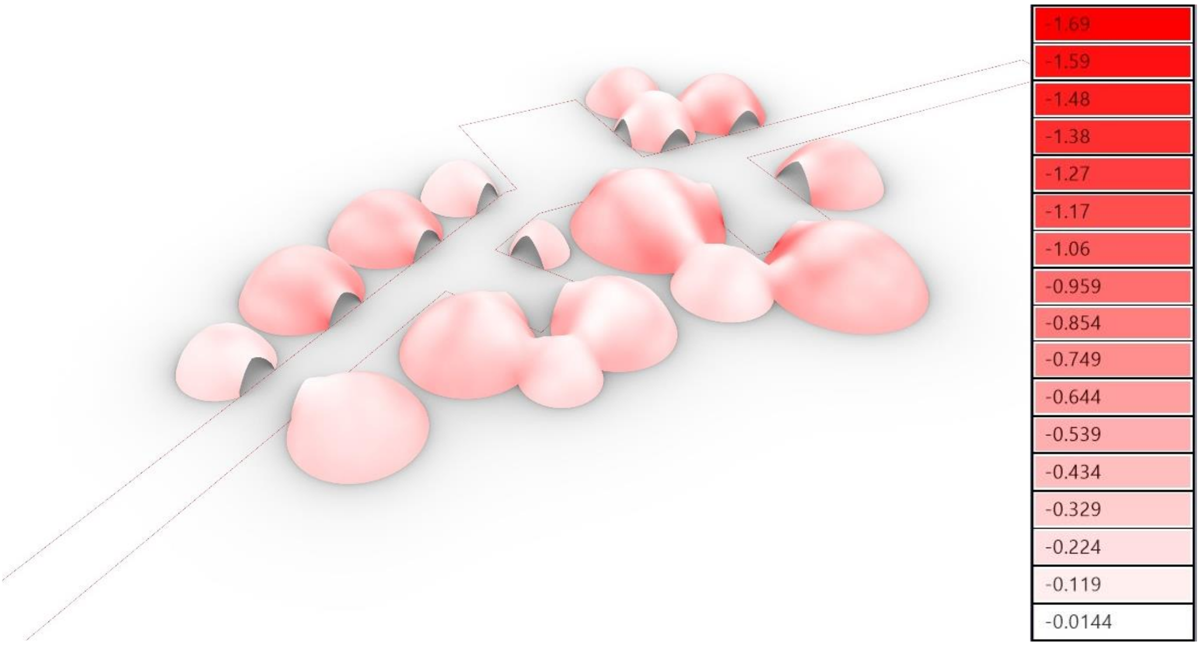


Figure 42: FEA initial structure, load case 2, principal stress 2, layer 1

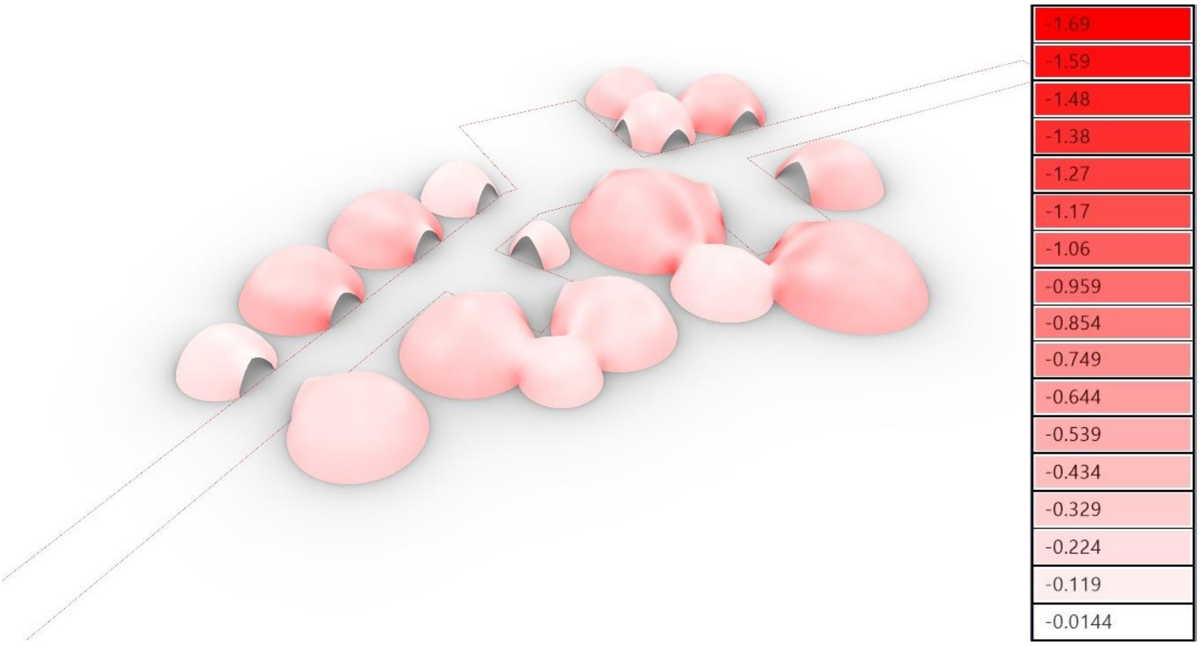


Figure 43: FEA initial structure, load case 2, principal stress 2, layer -1

4.7. Discussion

4.7.1. Structural performance optimised structure for load case 1 and 2

The acceptable displacement of the structure is equal to the span of each dome divided by 250. The maximum displacement of 33.7 mm occurs in the largest dome that has a span of 10.4 meters. The maximum allowable displacement of this dome is 41.6 mm. This means that the UC-value for displacement is 0.81 and thus it can be concluded that the structure is functioning properly in terms of stiffness.

The compressive strength of the adobe bricks is 2.00 MPa. The maximum compressive stress occurring in the optimised structure is 1.28 MPa. This means that the UC-value for compressive stress is 0.64 and thus the structure will not collapse due to compressive stresses.

The tensile strength of the adobe bricks is 0.10 MPa. The maximum tensile stress occurring in the optimised structure is 0.07 MPa. This means that the UC-value for tensile stress is 0.70 and thus the structure will not collapse due to tensile stresses.

4.7.2. Structural performance of the optimised structure during the construction phase

The maximum stress occurring during the construction phase is the maximum stress occurring for load case 3. The maximum compressive stress for load case 3 is 1.18 MPa. This is below the compressive strength of adobe so the structure will not collapse due to compressive stresses. The maximum tensile stress for load case 3 is 0.10 MPa. This is equal to the tensile strength of adobe so extra measurements should be taken in account to avoid that the structure collapses during the construction phase. For instance, studs could be placed below the structure to temporally support the structure.

4.7.3. Initial structure versus optimised structure

When comparing the performance of the initial structure to the optimised structure it becomes clear that the optimisation of the structure was necessary to prevent the structure from collapsing. The highest occurring tensile stress in the initial structure is 0.23 MPa. This is higher than 0.10 MPa, the maximum allowable stress. Therefore, the initial structure would collapse. When comparing the maximum occurring tensile stress in the initial structure (0.23 MPa), to the maximum occurring tensile stress in the optimised structure (0.07 MPa), it can be concluded that after the optimisation process the performance of the structure increased by a factor of 3.29.

5. Structural properties of the retaining walls

The mound is split into three parts by the street and courtyards. The walls along the street and courtyards are subjected to lateral loads due to the infill soil of the mound. Therefore, the walls are functioning as retaining walls. Figure 44 shows the a section through the street and the courtyard where the retaining walls and the loads that act on the walls are visible.

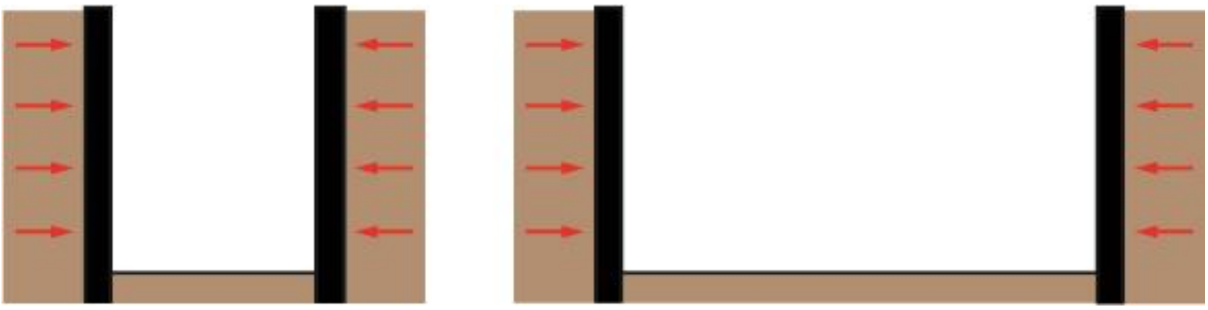


Figure 44: Retaining walls of the street and the courtyards

In order to prevent the retaining walls from collapsing inwards, buttresses have to be added. This works out well for the courtyards but when buttresses are place in the street, the street would get too narrow to function properly. This narrowness however, makes it possible to create a flying arch in between the walls that transfers the lateral loads from one wall to another and vice versa. This will create an equilibrium. Figure 45 shows the retaining walls reinforced with either flying arches or buttresses.

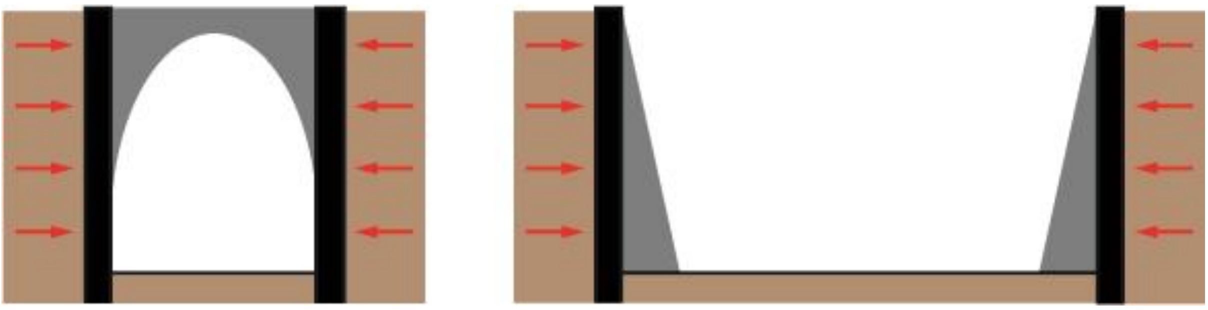
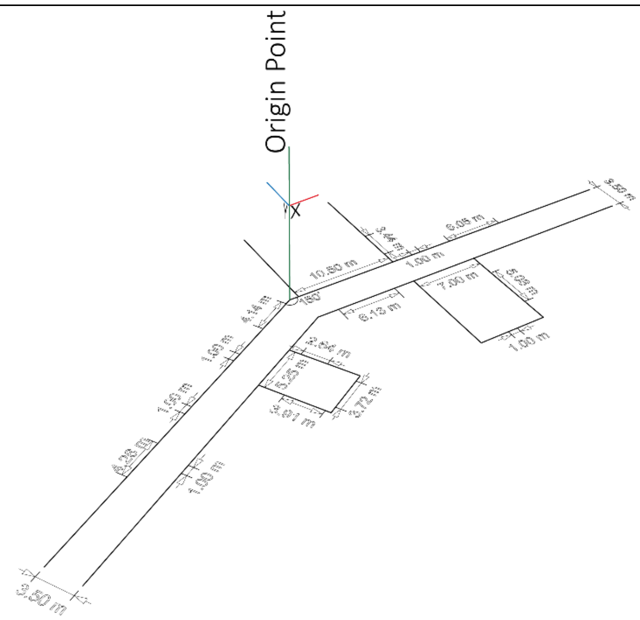
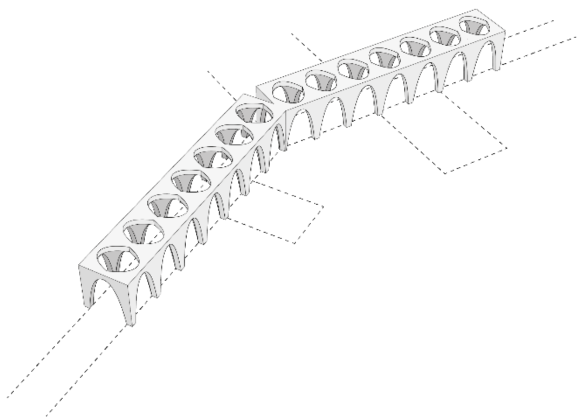


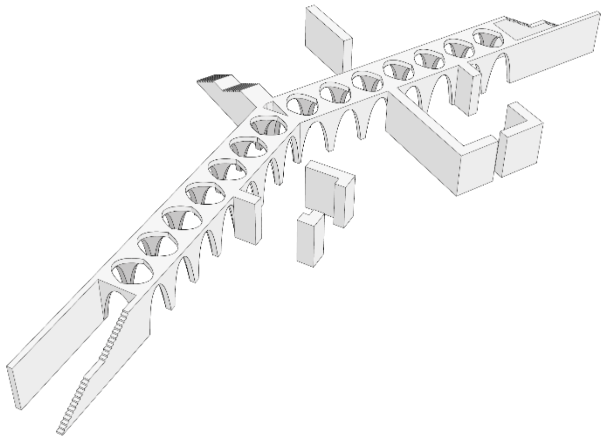
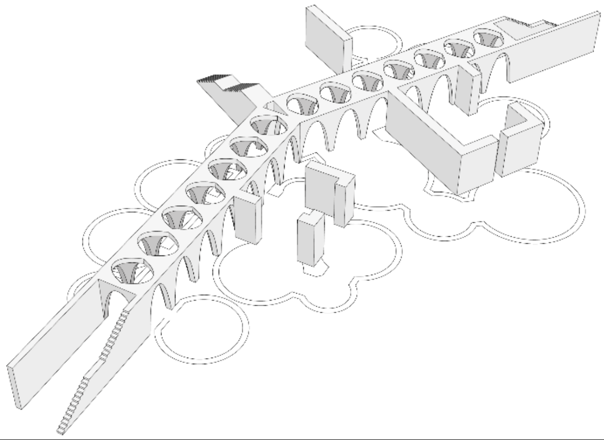
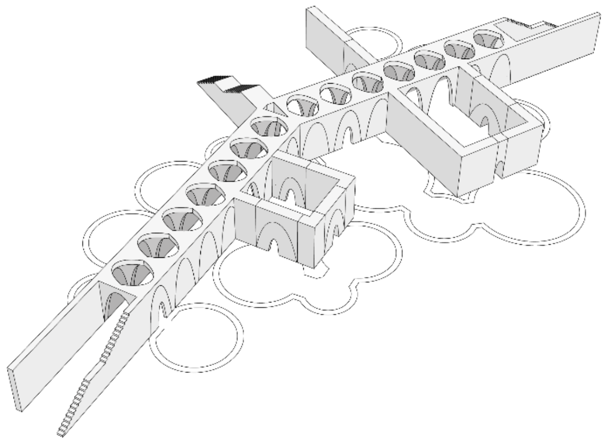
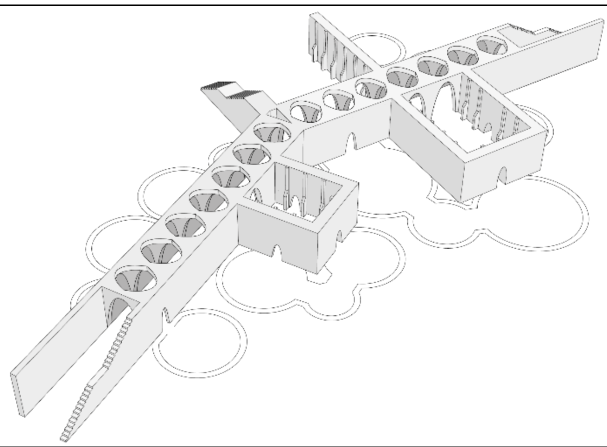
Figure 45: Reinforcement of the retaining walls with flying arches or buttresses

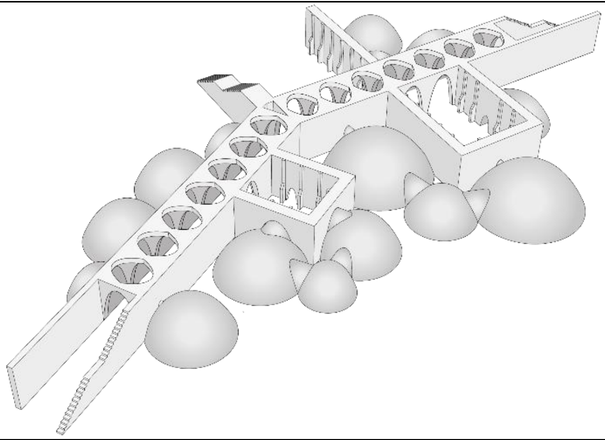
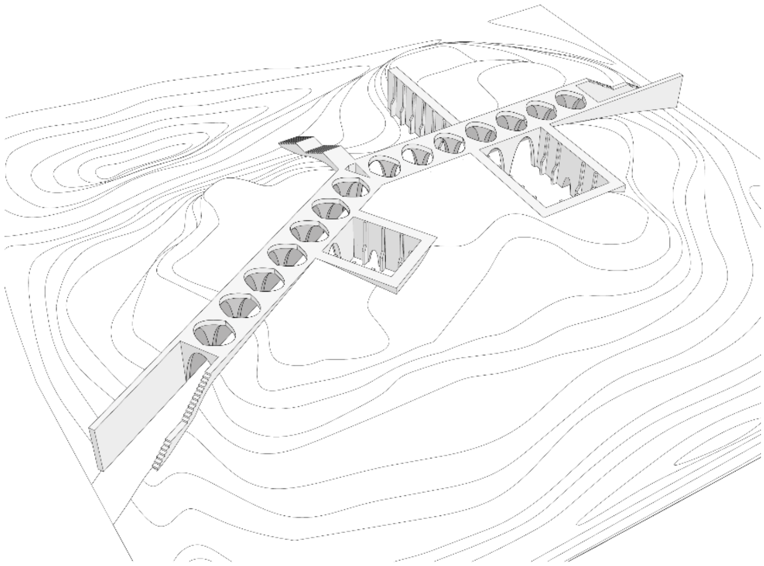
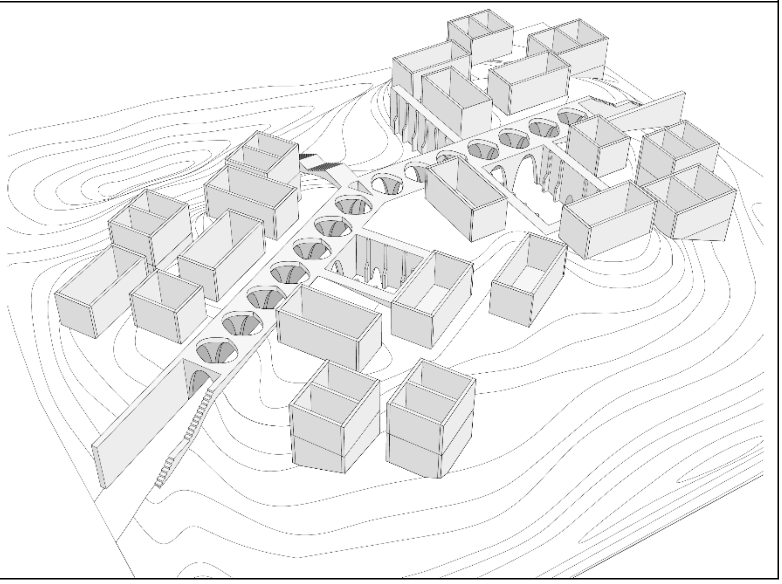
6. Construction

6.1. Construction sequence

Table 2 shows the construction sequence.

Step 1: Mark the street, ground floor courtyards, and openings on the ground based on the dimensions from the architectural floor plans provided. Dimensions can be marked in relation to the indicated origin point.	
Step 2: Based on the dimensions, use the standardised form work to build the 3-dimensional arches on the street.	

Step 3: Construct the solid walls and steps surrounding the arches.	
Step 4: Mark the origin points of the domes based on their distances from the solid walls, arched street and to each other. Draw the circles based on the given radii. Draw the door spaces for the connecting doors between the circles.	
Step 5: Infill the arches to create solid walls and create openings for doors where needed based on the architectural drawings provided.	
Step 6: Build buttresses in the courtyard areas as dimensioned on architectural floor plans.	

Step 7: Build the domes and connections between the domes as described later on in this report using the provided tool.	
Step 8: Use an excavator to create mounds on top of the domes and water retention ponds for water mitigation. Build brick foundations based on their distance from the street for the first floor dwellings to prevent unstable bases for the dwellings.	
Step 9: Build the walls of the dwellings on top of the brick foundations.	

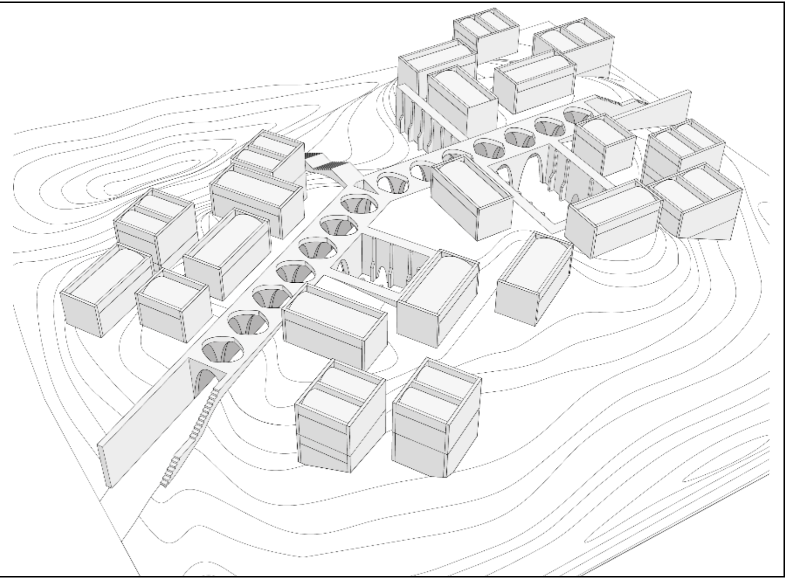
Step 10: Build the Nubian vaults on top of the units using the existing walls as guidelines.	

Table 2: Construction sequence

6.2. Construction method

The domes are a unique shape due to the structural optimisation and therefore require a customised construction process. To enable accurate placement of the bricks, two devices are proposed for the construction of the domes and connecting vaults between domes. Figure 46 and Figure 47 show a compass-like device which can be adjusted in length, rotated, and extended to find the exact position of each brick. The device would be used in conjunction with a script that numbers each brick and generates the specific measurements for the device to be adjusted accordingly. This can be built from a combination of wood and metal parts. The compass consist of 4 parts; An adjustable arm to determine the unique position of each brick from the centre of the circle (1), the base determines the angle of the brick in the XY plane (2), a rotating compass positions the arm at the correct angle on the XY plane (3), An adjustable pivot to determine the angle of the arm on the vertical plane (4).

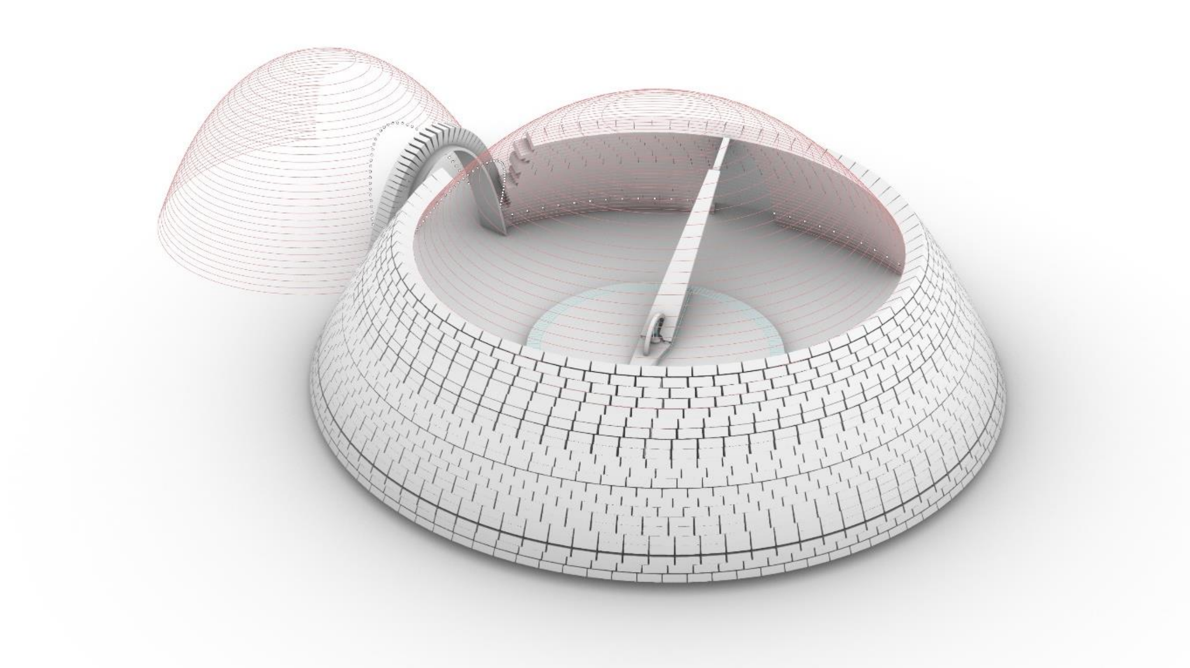


Figure 46: Proposed device for construction of the domes

Figure 47: Proposed device for construction of the domes

Figures 48 and 49 show the device used for the vaults which connect the domes. The device is composed of adjustable arms to create multiple sizes of vaults (1), a scored plywood sheet is attached to the end of the arms to provide a flexible base surface to place bricks on (2), a stable base (3), and a pivoting plate to connect the arms to the plywood sheet (4).

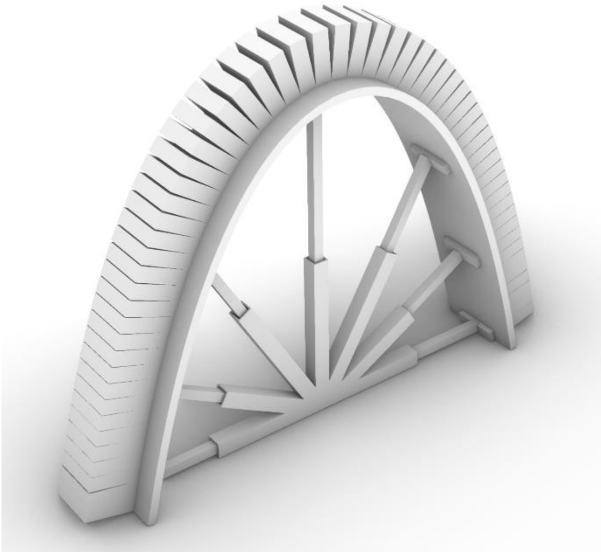


Figure 48: Proposed device for construction of vaults between domes

Figure 49: Proposed device for construction of vaults between domes

Although these proposed devices require some investment, they can be built once and used multiple times to construct many free form domes throughout the site and therefore provide a valuable tool for future developments.

7. Conclusion

Adobe is a material that has been used for thousands of years. Previously built structures made of adobe are usually limited to simple vaults and domes. With modern computational techniques it is possible to design structural adobe shapes that were not possible to convey in the past. For this proposal computational design is used to optimize the performance of the structure. Also, computational design is used in combination with new construction methods in order to construct the design. To conclude it can be said that through the use of computational design, adobe structures can be taken to the next level; Adobe 2.0 or even Adobe 3.0!

9. References

Brown, P.W., Clifton, J.R., (1978). Adobe. I: The Properties of Adobe. *Studies in conservation, 23*(4), 139-146. doi: 10.2307/150584

Minke, G. (2006). *Building with Earth: Design and Technology of a Sustainable Architecture.* Basel, Switzerland: Birkhäuser.