Delft University of Technology

Shell Roofs

Minor Bend and Break

CT3280 (2023/24 Q2)

Shell roof model

Group 9:

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Table of context

1 Summary

For this project each group needed to make a design for a shell structure and build it, a approximation of the load it could carry before it fails needed to be calculated with hand and computer analysis that was made with the computer program SCIA. The project is supposed to be creative with the design but at the same time think about the possibility for it to be build in real life size. At first many designs had been drawn before choosing a top 3, the final design wasn't in that top 3 because it was to hard to make that design with the tools available.

The design was a reinforced concrete sphere with a height width ratio of 1/3. We bought the material to make a mold for the concrete and then put the steel wire around it for reinforcement, for final we poured our concrete mixture and let it set for 7 days. On the testing day a measurement device for deflection was added to the test setup and by adding bricks the load would increase to failure. With the hand and SCIA calculations we predicted the shell to fail around 6.5 kN but it could only take 4.5 kN. The main reason for this we believe is the unevenly spread concrete on the mold and and the low number of days the concrete had to harden to its full strength. In real life this shell could be used for a shelter against wind and rain, but that much concrete isn't that economic so maybe another material can be used in the future.

2 Introduction

All over the world you see shell buildings, take Sydney opera house as an example. This building is extremely beautiful and a real eye-catcher, but it is important that the building is as strong as a normal building. How do you design a shell that is strong but can also be built as efficiently as possible?

The assignment submitted to us is as follows: Design a shell structure of wood or reinforced concrete, build it and then predict what the distributed load is going to be before the shell fails. The various design steps, construction process and calculations are explained in the report.

The aim of the assignment is to design and build a shell structure, thereby gaining knowledge of the technical side of design and calculation but also practical knowledge about working with wood and concrete. This report explains the difficulties encountered during design and construction. Our understanding of skills and disciplines has broadened with this assignment.

The program SCIA and P. Hoogenboom's handout website will be used for this project. The technical drawing of the shell will be made in Skechtup and the calculations will be made using SCIA, the results of the assignment will be presented through tables, graphs and SCIA screenshots in the report.

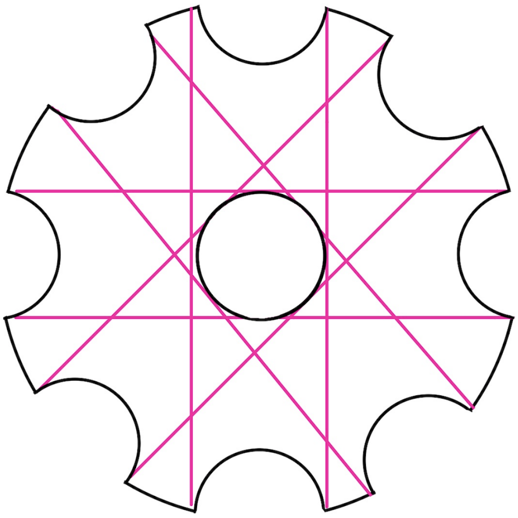
The report is presented in the following structure; First, the different ideas that Group 9 came up with will be discussed, then the elaborated design will be presented with the help of a technical drawing. Chapter 5 will show the construction process. Then a handcalculation was done for the distributed and point load values, in chapter 7 the Finite Element Method analysis done in the program SCIA will be described.
Then the tests will be described in chapter 8 with immediately afterwards in chapter 9 the results. Finally, we want to know how the shell performs in real life and that outcome is in chapter 10. Finally, a conclusion is written, the appendices can be found at the end of this report.

3 Ideas

It is important that several ideas are thought of before choosing the best design. The design should have a maximum area of one by one meter, so the 3 ideas discussed in this chapter are designs based on circles so a lot of surface area is used.

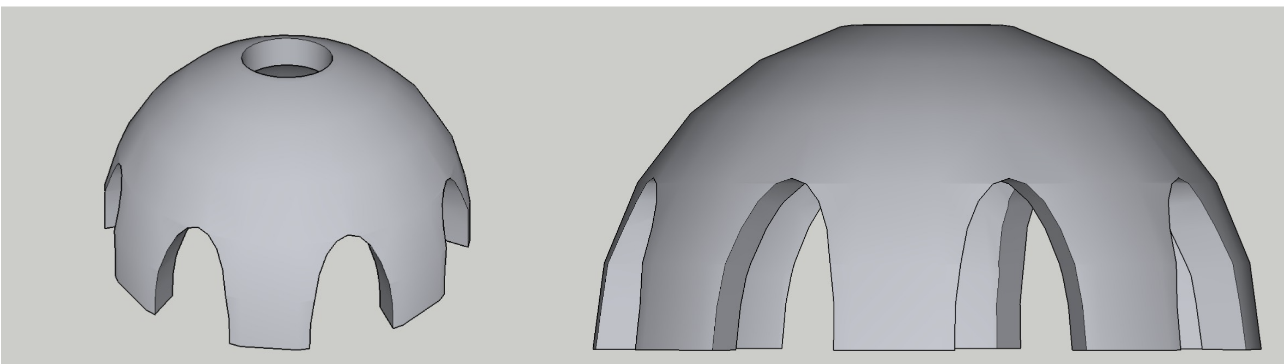
3.1 Idea 1

The first idea is a semicircle with semicircles around and a circle in the middle. Figure 1 contains the sketch of idea 1. The black lines is the outer circumference and the pink lines sketch an idea of the reinforcements with wooden slats.



Figuur 1: Idea 1

The first design was drawn in 3D drawing program SketchUp, the model can be seen in figure 2. Looks wise the design does not contain many complicated or interesting features. But it has some nice symmetry. We wanted a little more, so we continued creating more designs.

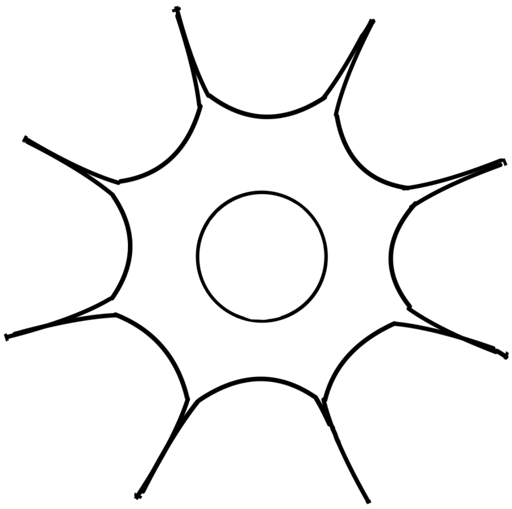


(a) *Sideview* (b) *Frontview*

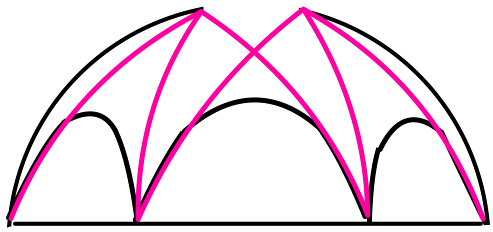
Figuur 2: SketchUp idea 1

3.2 Idea 2

The second design is a variation of the first design but then the paws that are on the ground are smaller and the circles all around connect to each other, the second design is shown in figures 4 and 3. No SketchUp drawing was made of idea 2.



Figuur 3: Idea top view

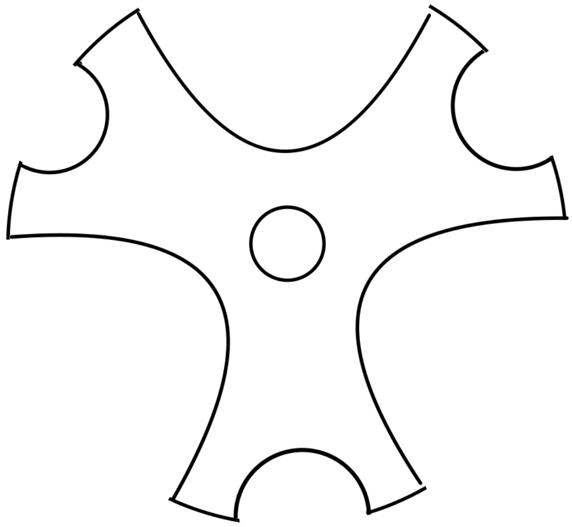


Figuur 4: Idea 2 side view

There where thoughts that the thin legs might not be very bad for structural support. So this design does not have our preference.

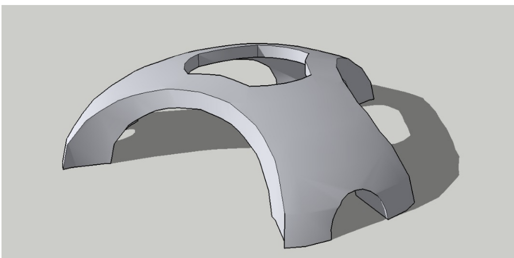
3.3 Idea 3

The third idea is similar to the other two. Except the number of legs is reduced and the legs are made bigger,. This design idea is presented in figure 5. Furthermore in this idea we tried to remove the least necessary material, compared to idea 2, to allow more light in if it were built and reduce the self-weight. This resulted in a big hole in the top and cuts in the legs.

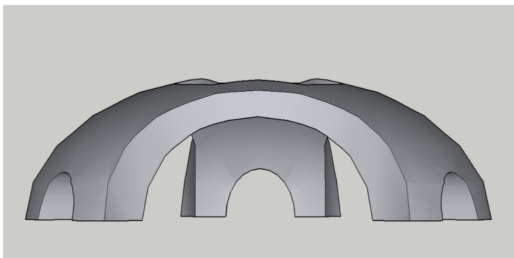


Figuur 5: Idea 3, sketch of top view.

A further detailed SketchUp model of this design was created and the 3D drawing can be seen in figures 6 and 7.



Figuur 6: Idea 3 in SketchUp, 3D view.

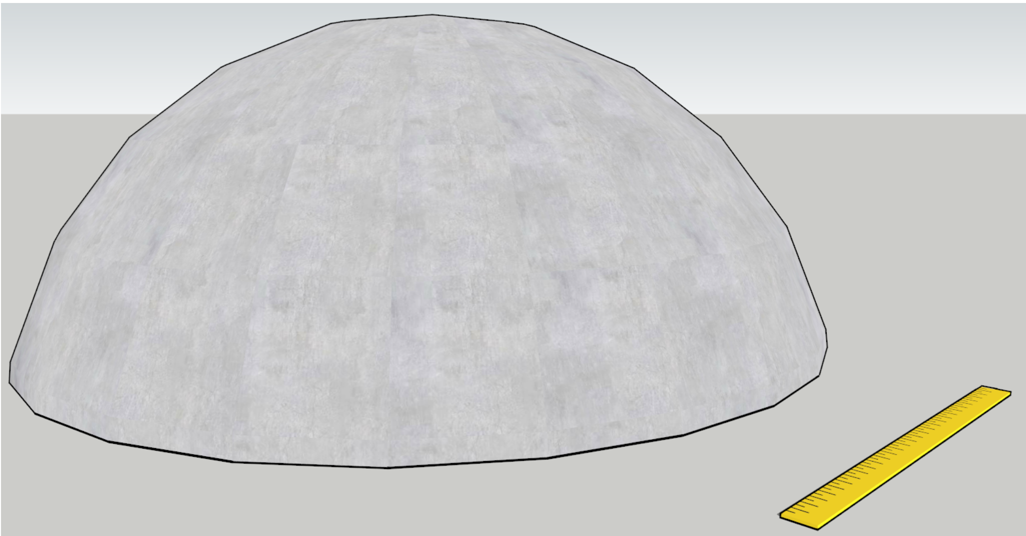


Figuur 7: The same model, front view.

3.4 Idea 4

The group agreed that idea 3 was visual the most pleasing and interesting.
However, at this point the manufacturing method became a problem. While it is technically possible to build Idea 3, construction of a mold to cast it was deemed unfeasible within this course. A simpler version of this design was therefore decided upon.

Idea 4 is our simplest design. It consists simply of a dome, chosen for the practical reason that we did not see a way to add the features of the other designs to it. This simplification later turned out to be a good idea, since the dome was difficult enough to construct without holes or cuts in it.
Since the other designs are all variations on it (each with a different set of holes added), idea 4 also best represents an estimate of the performance of the other designs. As with any model, one should first build something simple that works, before adding features to extend its applicability.
This idea 4 became our rudimentary design and can be seen in figure 8.



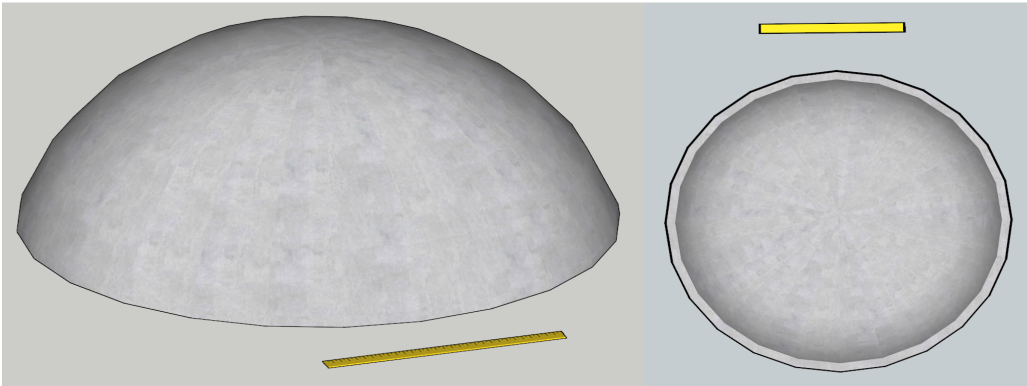
Figuur 8: Sketchup model of Idea 4. A 30cm ruler is added for scale.

4 Design

In this chapter the design to be made is determined, describing the arguments where this design was finally chosen and presenting a technical drawing of this design.

4.1 Chosen design

The design chosen comes from chapter 3. The 4th design (figure 8) is going to perform the best in our opinion. Reverting from Idea 3 to the dome of Idea 4 made our design a hemisphere with a 1/3 height/width ratio.



(a) 3D view

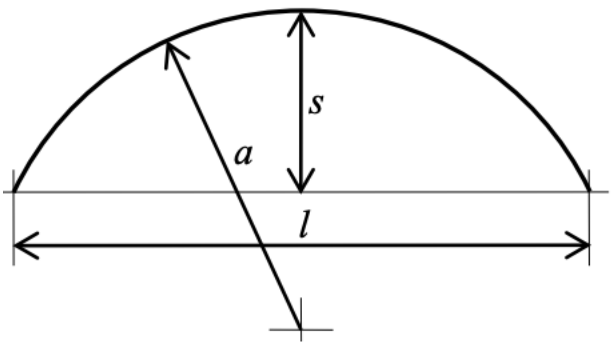
(b) Bottom view, showing the thickness.

Figuur 9: More views in SketchUp of Idea 4, the final design.

4.2 Arguments for this design

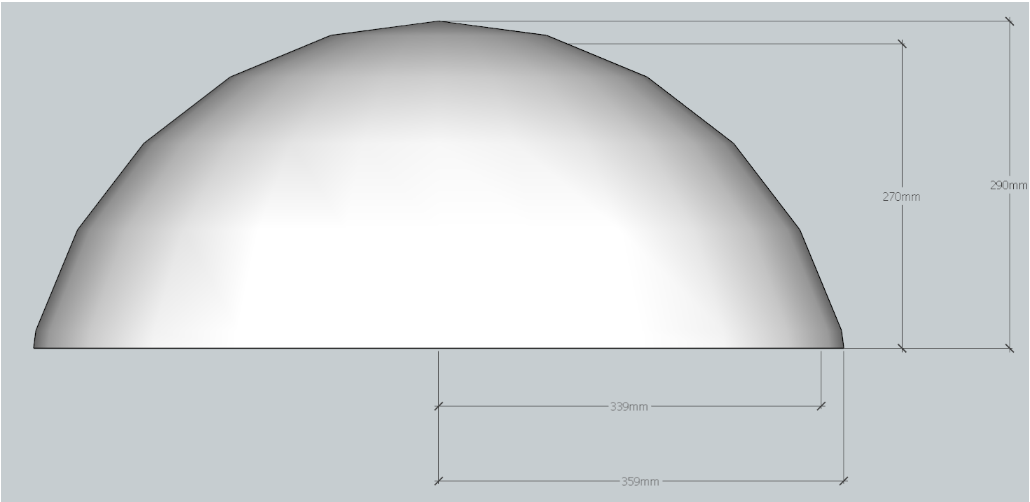
The radius of the design is 35 cm, it is easy to work with this radius because the mold comes often in 70cm diameter. The height is calculated with formula 1(Hoogenboom, P. (2023b, november)). The variables are explained with figure 10. In the previous ideas all hemispheres had holes in them, but with the concrete casting and the kind of mould we want to use, that's going to be very difficult so the design has become without holes.

$$a = \frac{1}{2} * s + \frac{1}{8} * \frac{l^2}{s} \tag{1}$$

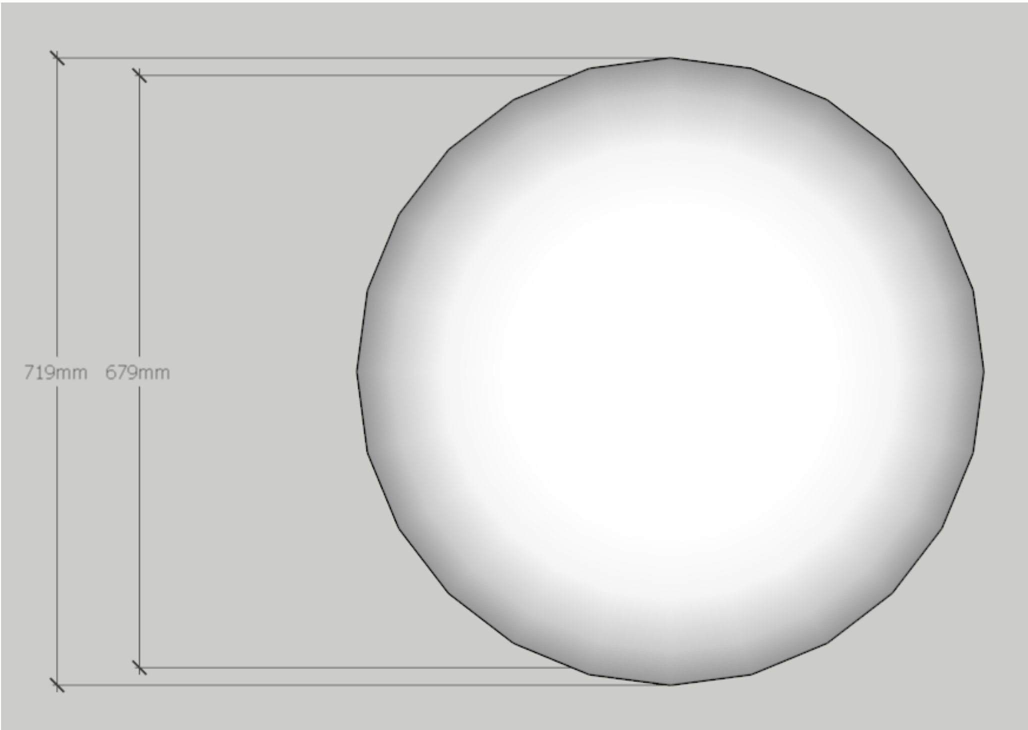


Figuur 10: Formula for finding the radius of our dome.

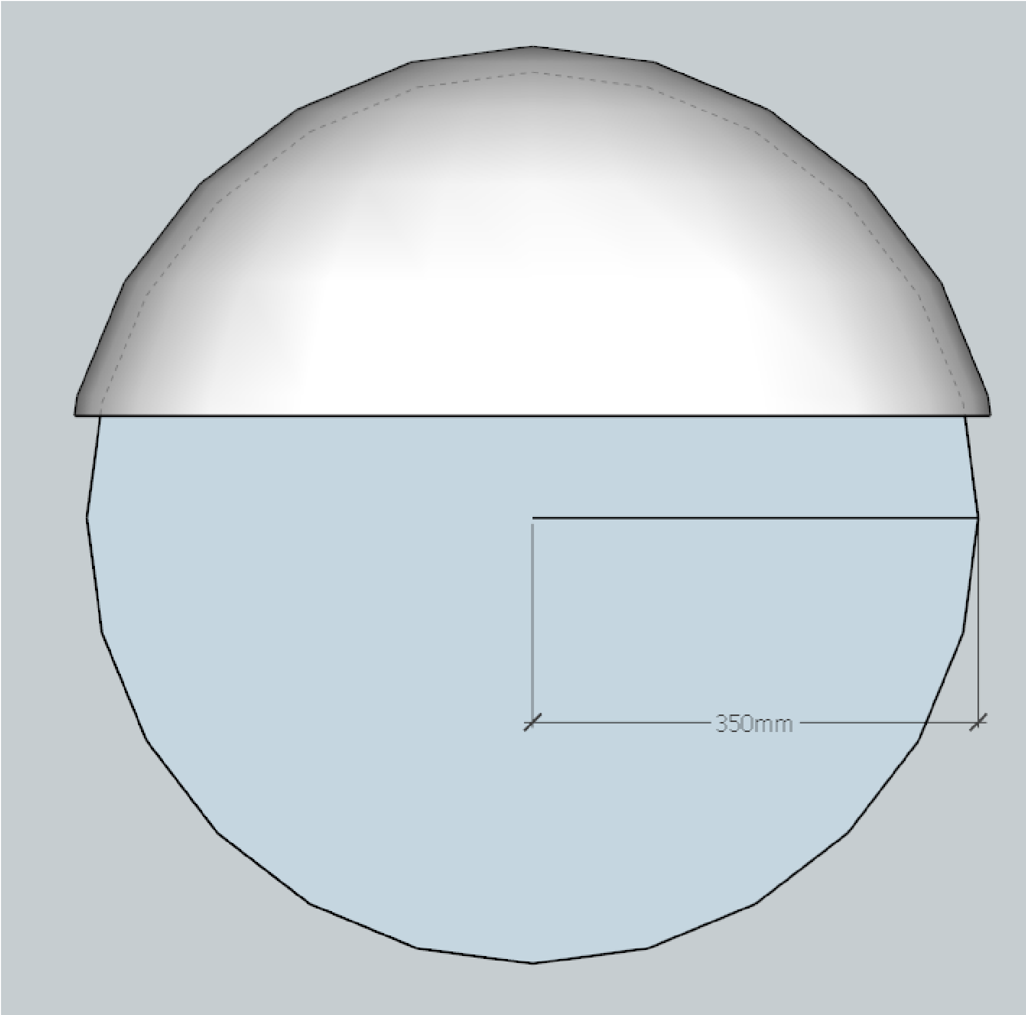
4.3 Technical drawings



Figuur 11: Side view with dimensions.



Figuur 12: Top view with dimensions.



Figuur 13: Side view with dimensions and the base circle, as mentioned in formula 10. The base circle can be seen as the inner diameter of the dome (dotted line).

5 Building process

In this chapter we discuss the steps in the building process that were followed to make our test piece of a shell roof. First the materials that we used are explained and then the first step (making the hemisphere) is discussed. After the first step the form was dressed by putting steel wire around for extra strength and to hold the concrete. At final the concrete mix and step is explained.

5.1 Materials

The materials used to make the shell are explained per category.

5.1.1 Paper mache

A skippybal with diameter 70cm is ordered from website bol.com, it will be used as a mold for the paper mache. We used 2,5 kilo "vliesbehanglijm" of bison from the Praxis store. The paper we used were newspapers and placed foil after paper mache was done.

5.1.2 Reinforcement

For the reinforcement steel wire was used, we connected the pieces with smaller steel wire and cut the form with scissors.

5.1.3 Concrete

For the recipe masonry sand is needed, just as cement and water. The holes for later are filled with straws and cotton swabs.

5.1.4 Distributed load construction

Slices of wood made out of multiplex 6 mm and felt 10 mm to damp the force, the slices wood are made with a big holes drill and constructors glue to hold it all together.

5.2 Paper mache

The paper mache is made with the materials noted in chapter 4.1.1. The skippybal was inflated to 70cm diameter. The bal was cleaned an then the newspaper pieces were glued to the bal till a height width ratio 1/3. We kept going with the newspapers till we ran out of glue.

(a) Glueing newspapers (b) Skippybal mold

Figuur 14: Paper mache

The final step was to add foil on top of the paper mache mold so when the concrete is poured, the newspapers don't take water out of the concrete.

Figuur 15: Foil on paper mache mold

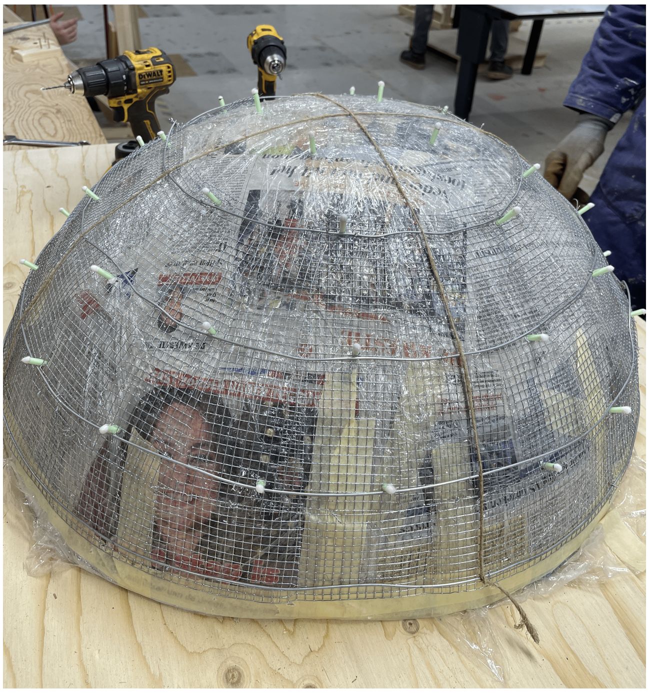
5.3 Reinforcement

The next step was to add reinforcement around the papier mache mold. The first try was to cut rectangle pieces and bend them around the mold, if the concrete were poured the reinforcement would unfortunately not connect properly. After taking the first design off the mold we chose a better design. This consisted of a strip around the lower part of the paper mache and attached forms on it as shown in figure 16b are shown. As these arcs they fit nicely tight around the mold. The instructor advised making the arming to 52 degrees from the top point, that part needs the rebar and the rest does not. The reinforcement is shown in figure 16a.

(a) The form (b) The form on the mold (c) All the steel wire

Figuur 16: Reinforcement

After the rebar was firmly in place, it was time to make the holes for the distributed load. The idea was to drill the same number of holes on each quarter of the sphere and then insert a straw, to keep the straw open when the concrete would be poured we stuck a cotton ball in it. The total number of holes were 40, the location of the holes were chosen wisely so it was workable to make the distributed construction. Figure 17 shows the final result.



Figuur 17: The straws in the mold

5.4 Concrete

The final construction step was designing the concrete mixture, making the mixture and pouring it on the mold. The mix design that Group 9 felt would give the best properties is as follow:

100 ml cement to 300 ml cement sand 0-2mm to 35 ml water.

We made this recipe times 35 to cover our sphere, then filled a few more test pieces so we could test them for compression strength before our test. The results of the compression test can be found in chapter 8.1 The final look is shown in figure 18.

Figuur 18: Concrete poured on mold

6 Hand calculation

This chapter contains the hand calculations used to predict the behaviour of the dome.

6.1 Shell characteristics

To calculate the thickness of the dome, the location with the highest stress has to be determined. This is at the top of the arch.

We use the following forumla:
$\sigma = 0.5 * p * \frac{a}{t}$
Gives: $\sigma = 0.5 * p * (0.5 * s + \frac{1}{8} * \frac{L^2/s}{t})$

Where:
σ = Stress at which the concrete will fails, Unknown $[N/mm^2]$
p = the distributed load, Unknown $[N/mm^2]$
a = radius of the curve, 350 $[N/mm]$
t = the shell thickness, Unknown $[mm]$
s = the sagitta, 280 $[mm]$
L = the span, 699 $[mm]$

While we haven't made concrete yet, so strength is unknown. We were given that the crushing stress of home-made concrete is about 5 N/mm

To determine the distributed load we will need to know the self weight, which depends on the thickness. It is very difficult to calculate the distributed load without assuming a thickness, since the self weight plays a big part. We have decided to make the thickness 20mm, mostly for manufacturing and building reasons. A very low thickness if difficult to construct with concrete.

Filling these values in the formula above, gives that the shell can widstand a distributed load of: $0.558N/mm^2$

The selfweight of concrete is around $2500kg/m^3$. We can calculate the self-weight per roof surface area by multiplying this with the thickness. This becomes: $2500 * 0.002 = 50kg/m^2$, or 0.49 kN/m^2

The snowload is assumed to be 1 kN/m^2, the selfweight is 0.49 kN/m^2. The total strength of the shell is 0.558 N/mm^2, when redefining the units gives total strength of: 558 kN/m^2.

The differnce between the strength and the static load is: 558 - 0.49 - 1 = 556.9 kN/m^2.
This means that the shell is quite strong.

A little bit of elaboration on the thickness design choice:
When we create the concrete by hand there will be errors in the thickness. This will always be a couple milimeters no matter the size we make. So that means that a bigger thickness should lead to proportionality smaller errror's. Which improves the calculations of the ultimate shell strength. This is what we reasoned.

7 FEM analyses

In addition to hand calculations, computer calculations were used in the form of finite element analysis (FEA). This required some input though: to run the analyses, the software needed information that we needed to calculate or assume.

7.1 FEM program that was used

For our analyses we used the SCIA Engineer software. It offers a wide variety of template structures and parameters for specific types of FEA. In our experience it takes some getting used to, but once understood SCIA is a very powerful tool.

7.2 Input

The model we used for our analyses was made using the "surface of revolution" sub-template of shell structures. Its radius is 350mm and thickness is 18mm, in accordance with Idea 4. The concrete strength class was chosen to be C12/15 (the lowest possible, to account for our inexperience with mixing and pouring concrete). The supplied cement was CEM 52.2 and the selected reinforcement was the default B 500B reinforcement steel. The mesh was generated with a 2D element size of 1 cm. All loads were combined with the self weight of the shell.

The analysis will be compared to the compressive strength of the concrete: if the stresses exceed it, that will determine the failure load.
Using the formula for concrete strength:

$$f_{cm}(t) = \beta_{cc}(t) f_{cm} = f_{cm} e^{s(1-(\frac{28}{t})^{0.5})} \tag{2}$$

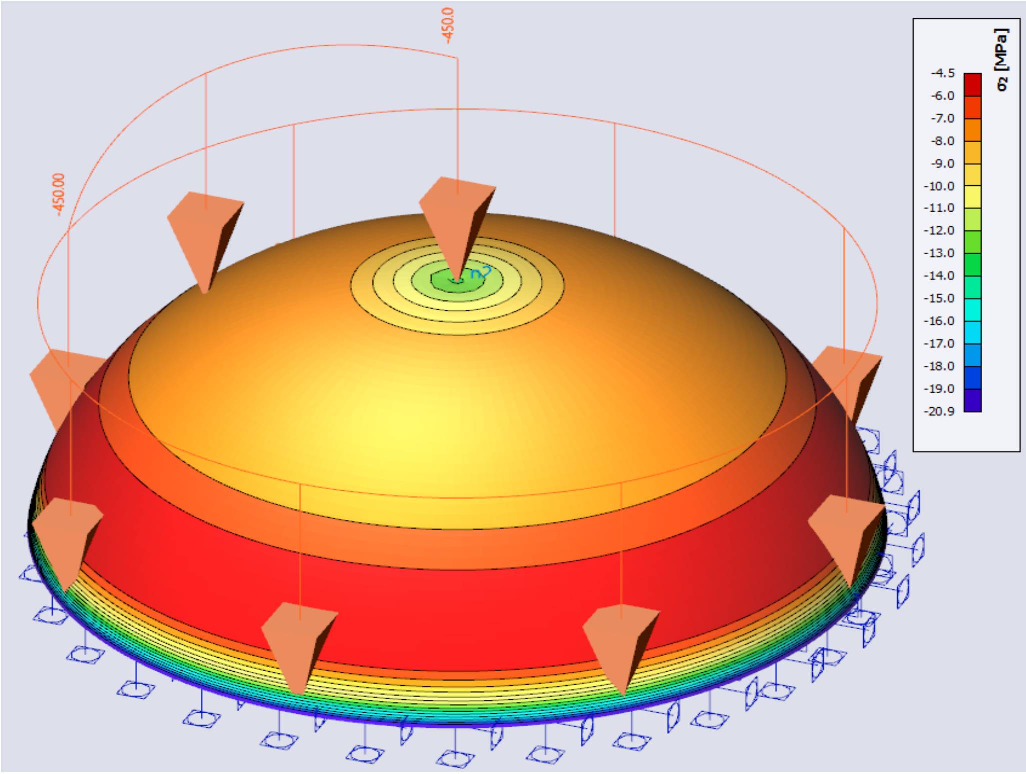
where
$f_{cm} = f_{ck} + 1.65\sigma = 15 + 1.65 * 6 = 24.9MPa$ for the C12/15 strength class and a standard deviation of $\sigma = 6MPa$;
$s = 0.2$ for CEM 52.5 cement;
$t = 7$ (in days) since the concrete was poured on 13 December and tested on 20 December 2023.
This results in a compressive strength of about 20.4 MPa at the time of testing.

7.3 Analyses

Since maximum load that the test setup could deliver was close to the maximum load that our analyses showed, we ran each analysis both with a distributed load and with a point load.

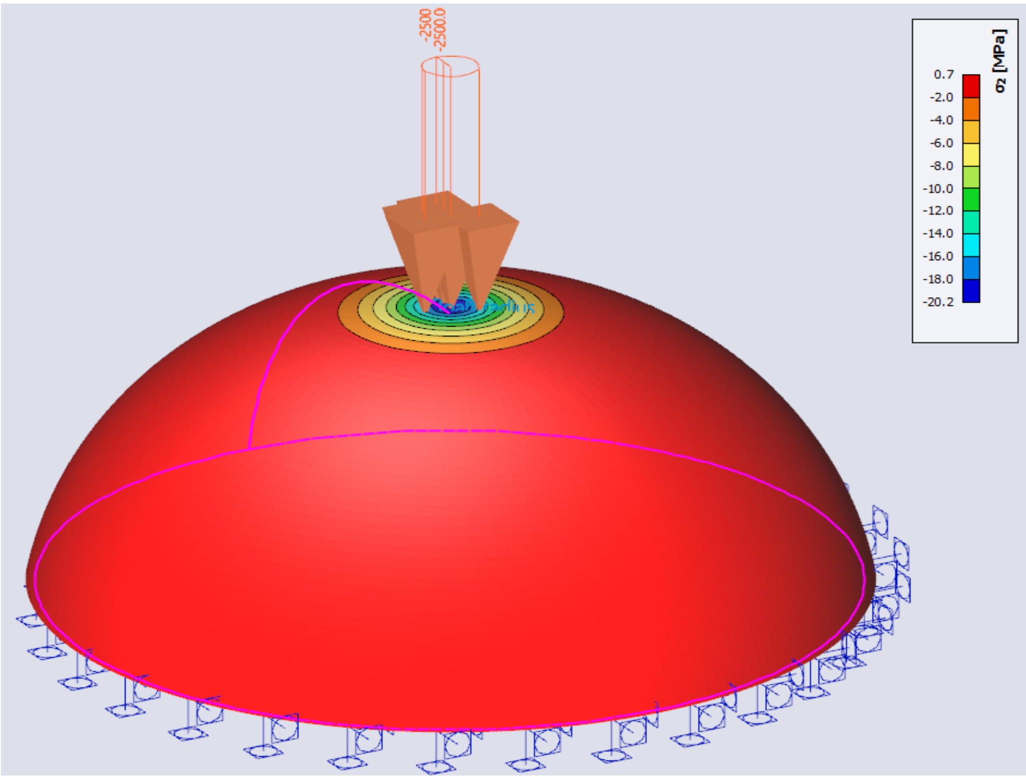
7.3.1 Linear

In linear analysis, the distributed load was tried first and the failure stress of 20.4MPa was found at a load of $450\frac{kN}{m^2}$. This is shown in figure 19.



Figuur 19: Screenshot of the SCIA distributed load analysis result, applying $450\frac{kN}{m^2}$.

In the test setup, a distributed load would have required an extreme weight of 173kN or 17.7 metric tons. This weight was not available, so the other method of using a slightly distributed, practically point load was used. This delivered a more realistic result. We applied a surface load over a circular surface at the top with radius 25mm, the size of our load distributing discs. The failure stress was found at a load of $2500\frac{kN}{m^2}$. Over a surface of $\pi * 25^2 = 1963mm^2$, this gives a total load of about 4.9kN. This is shown in figure 20.

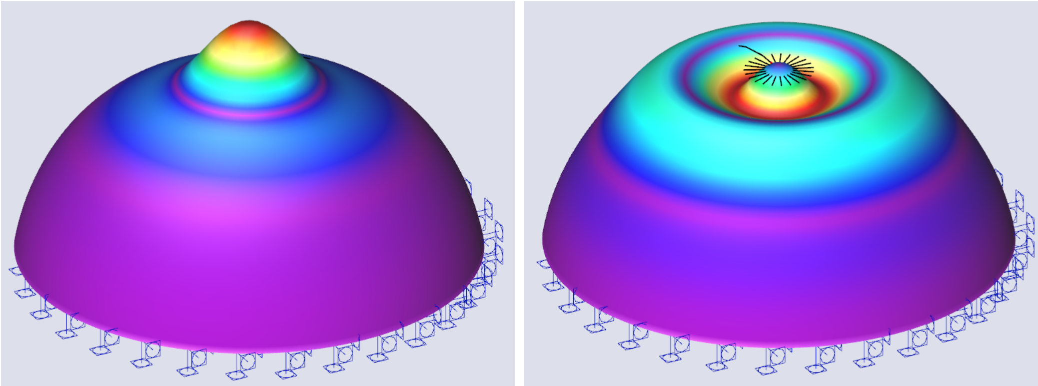


Figuur 20: Screenshot of the SCIA point load analysis result, applying 4.9kN spread over a 25mm radius circle.

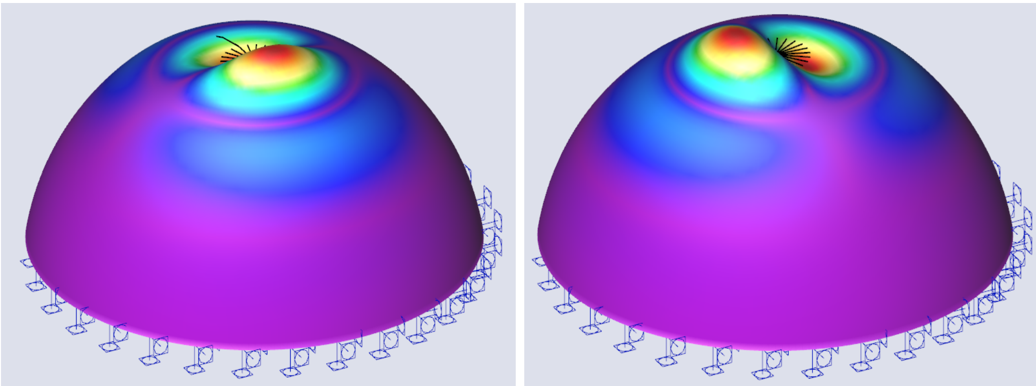
The deformation at the point load analysis was 0.1mm.

7.3.2 Linear buckling

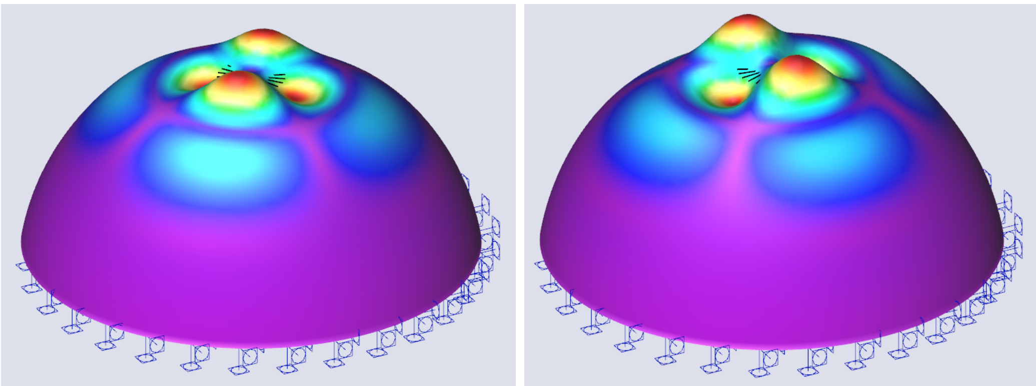
The linear buckling analysis shows nice symmetries, due to the spherical shape of the dome. It has circular symmetric modes at 418.96 and 936.51, double-bulge modes at 596.29 and 596.35 and quadruple-bulge modes at 1094.64 and 1094.74. These sets are shown in figures 21, 22 and 23.



Figuur 21: Circular buckling modes 418.96 and 936.51.



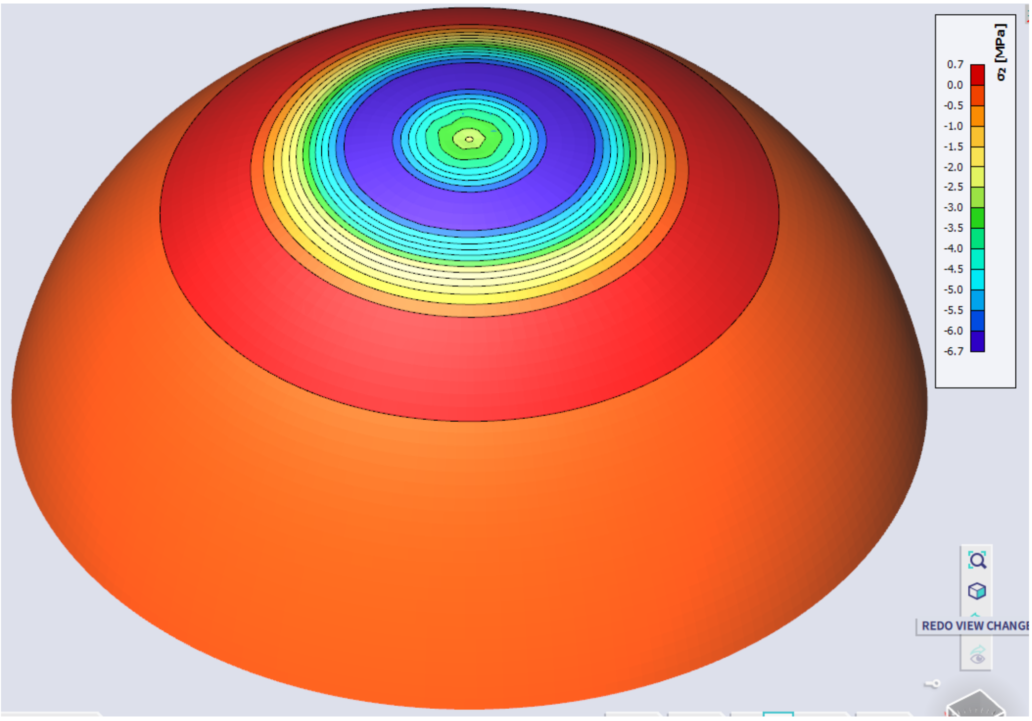
Figuur 22: Double-bulge buckling modes 596.29 and 596.35.



Figuur 23: Quadruple-bulge buckling modes 1094.64 and 1094.74.

7.3.3 Non-linear buckling

The non-linear analysis was performed last, inputting a maximum deformations of +36 and -36mm (twice the thickness). In this analysis mode, stresses are reduced to a maximum of 6.7MPa but are spread over a wider area (see fig 24). The stresses also turn in on themselves: the maximum stress is not in the center, but a few centimeters away from it. In the non-linear model, the dome processes a semi-point load more efficiently and moves the failure region.



Figuur 24: Screenshot of the stresses in the non-linear analysis by SCIA.

Checking the buckling simulation, the loads from both self-weight and the semi-point load were increased by factor 418.96. This was done in 100 increments. The result is exactly the same as with the original load in figure 24.

8 Test that were performed

It is important to know how strong the materials are so that a good estimate of the ultimate failure strength can be calculated. A small part of the mix we poured over the mall was divided into 5 cubes so that the test could be performed 5 times for optimal results.

8.1 Concrete cube compression test

The cubes were tested for compression; the results are shown in table 1.

Test number	Compression strength till failure
1	9.8 kN
2	6.6 kN
3	7.3 kN
4	6.4 kN
5	6.3 kN

Tabel 1: Results compression test

As can be seen from the table, the first test piece proved to be the strongest. The average of the test pieces was found to have a compression strength of 7.28 kN. Photos were taken of the first test piece after it failed, these can be seen in figure 25.

(a) Top view

(b) Side view

Figuur 25: Test piece one

By analysing these photos, information about our concrete mix was acquired, for example, it can be seen that the concrete has small holes. Air has entered the mix and these holes give the concrete less strength, the mix could have been improved by adding more fine dust and water.

Group 9 performed a tensile test on one cube, this result is less reliable because data was only acquired from one piece. Table 2 shows the result.

Test number	Tensile strength till failure
1	8 kN

Tabel 2: Result tensile test

8.2 Wood tensile and compression test

Group 9 worked only worked with concrete, so these tests are irrelevant.

9 Point-load Calculations

The shell structure did not collapse under a uniform distributed load. So with help from the professor it was decided that we would do a point load test instead. A lot of the calculations where made on that moment. So our guess at the point-load capacity was not very thought out. We did not have the time to rethink our calculations over.

We will use the following formula to calculate the concrete point load strenght:
P $= -8/Root(3) * Sigma * t^2$

Where:
Sigma = stress at which concrete fails, Explained here below[Mpa]
t = thickness of the concrete, 20 [mm]
P = maximum point load, [N]

There where some tests done to determine the concrete compression strength. The average value was 7.28 kN, the total surface area of the tested cube was 1225 mm^2. This gives a total of 5.94 N/mm^2 of compressive strength.

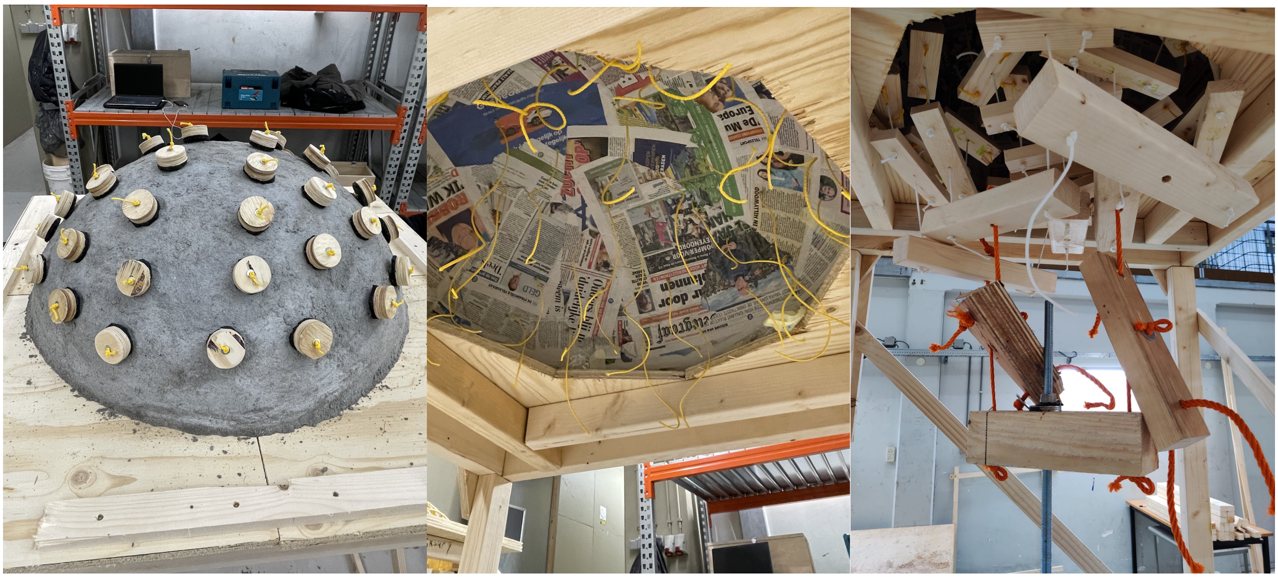
Filling in these values in the formula above gives:
P = 10974.27 N, or 1118.68 kg.

10 Results of the load and deflection

This chapter discusses the results of the test. First, the test setup will be described. Then the prediction made using the hand calculation and the FEM analysis will be repeated.Different results were measured during testing, for example, the measured deflection will be discussed but also the development of cracks will be shown. Finally, the ultimate strength before shell failure will be known. Lastly, we will analyse on which mechanism our shell failed and compare it with the results of the other groups.

10.1 Test setup

The test setup changed as the test went on. The first setup was with a distributed load as shown in figure 26, the strings used to create the distributed load have a limited tensile stress. The test was interrupted twice because strings were broken and needed to be repaired. After this happened a third time, it was decided to remove the distributed load and apply a point load, as shown in figure 27.



(a) Shell with strings

(b) The first layer of strings

(c) Full distributed load construction with failing strings

Figuur 26: Test setup

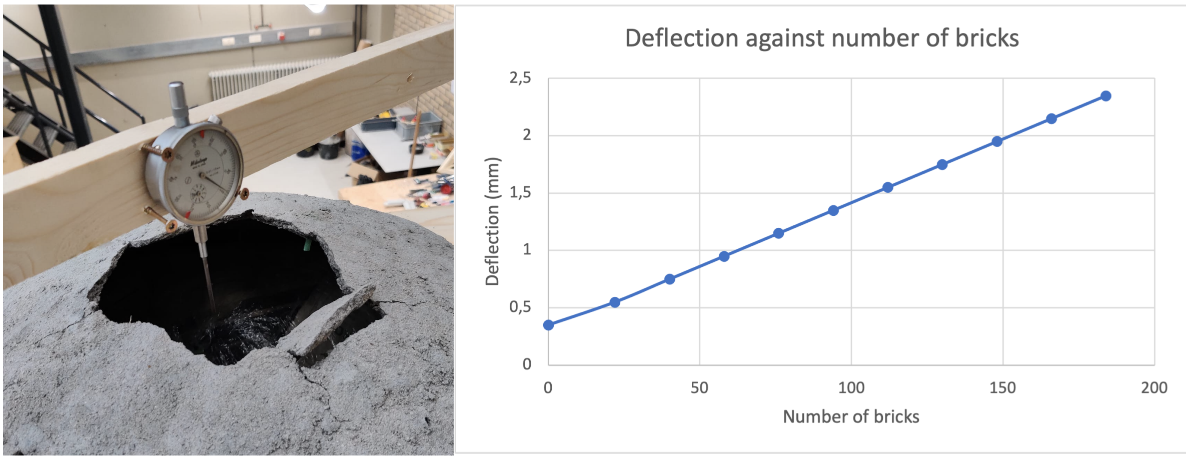
Figuur 27: Test setup point load

10.2 Prediction of the deflection and the ultimate load

The prediction for the ultimate load made using the handcalulcation and the FEM analysis is 6,5 kN. The prediction on shell deflection was minimum deflection resulting in shell fracture.

10.3 Measured deflection

The equipment used to measure deflection can be seen in figure 28. For every layer of bricks (18) the deflection was measured, the deflection is plotted against the number of bricks in figure 28. The relationship is linear and the maximum deflection is 2.35mm.



(a) Measurement equipment (b) Graph deflection

Figuur 28: Measured deflection

10.4 Development cracks

As mentioned in the paragraph above, the shell broke suddenly and there were no known cracks before it failed. The cracks after the failure can be seen in figure 29. The reason the hole is a round and in the middle of the top is probably that the concrete there was less thick compared with around the shell.

(a) Thickness of concrete (b) Crack away from hole (c) The hole

Figuur 29: Cracks after failure

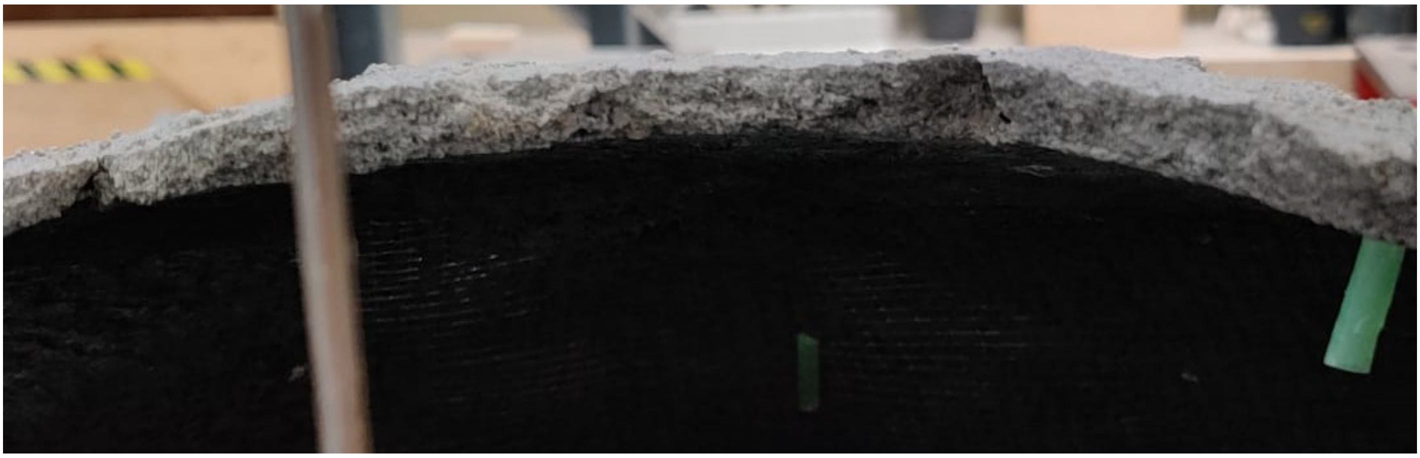
10.5 Collapse load

The collapse load is measured at 4,5 kN. The predicted load was 6,5 kN so the prediction was 48% over the prediction.

10.6 Analysis of the test

According to the professor, the shell failed on bending at the point load.

After failing we discovered that the shell was a lot thinner at the top than initially designed on.



Figuur 30: Shell photo, failing point-load

The green straw on the right-side in the picture above has a thickness of 6mm. We can compare this size with the rest of the shell to determine the thickness. When measuring the image with a ruler. We determine that the shell thickness in the image is around the range of 11mm. With the thinnest part being 8mm thick!, on the photo all the way to the left side.

If you would do the point-load calculations again with a 12mm thickness instead. The pointload capacity you obtain is: 4kN (using the formula's from chapter 9).

The 4kN calculated above is only around 10% off from the observed failing point-load of 4.5kN. So it is most likely that deficiencies in the concrete manufacturing was the lead cause of the discrepancy between the calculated and the observed strength values.

If we had made the concrete thickness more uniform the prediction would have been alot better.

Our shell is the only one that has failed on bending, and only 2 other groups have used concrete in their design. Those 2 groups had as their failure mechanism "crushing and punching shear" and "punching shear". These groups also applied distributed load first but the shell was too strong so switched to point load.

Their failure strength was around 2.5 kN there are no conclusions to be drawn whether that is due to less thick layer of concrete or the application of reinforcement or the entire structure of the shell.
In table 3 the predicted loads, failure loads and failing mechanism of the other groups can be found.

Team number	**Predicted collapse load**	**Experimental collapse load**	**Collapse mode**
Team 1	2.50 kN = -2 %	2.54 kN	point load, crushing and punching shear
Team 2	1.25 kN = -52 %	2.59 kN	buckling then breaking of the laths
Team 3	2.18 kN = -7 %	2.35 kN	point load, punching shear
Team 4	1.96 kN = +68 %	1.17 kN	buckling at the point load
Team 5	2.00 kN = +0.5 %	1.99 kN	local buckling
Team 6	1.70 kN = -39 %	2.80 kN	buckling of the laths
Team 7	2.56 kN = +77 %	1.45 kN	buckling of the laths at a damaged location
Team 9	*6.50 kN = +48 %*	*4.40 kN*	*bending at the point load*
Team 10	1.50 kN = -54 %	3.24 kN	buckling then breaking of the laths
Team 11	2.50 kN = -43 %	4.40 kN	foundation collapse

Tabel 3: Results other teams

11 Shell in real size

In these chapters we look at the feasibility of scaling our shell to larger real life proportions.
It was very difficult to scale up our model, most teams can do equations with a uniform load distribution, but we can not. It is very hard to know how big the "point load" becomes when there is only a shell structure and a very small amount of snow as a point load. Therefore these chapters are only an attempt to give an idea of scaling our shell.

11.1 Scale factor

In this section, we explore the concept of model scaling, investigating the acceptable size for constructing the model. Furthermore, we conduct an examination of the actual structural performance, taking into account elements like displacement and stresses.

In notes of the professor there is a scaling law given to easily calculate how big the shell structure can be constructed in real life. However this scaling law works with a distributed load. Since our shell was tested with a point load this is more difficult to calculate.

We configure this model a little to work for our setup, we get the following:
(Point-load / s) = n * self-weight-structure + snow-load

Where:
Point-load = load on the top in N
s = safety factor of 2.
n = scaling factor
self-weight-structure = weight in N
snow-load = in N

In this example we assume that only the tip of the shell is carrying any weight.

For simplicity sake we assume our shell to be perfectly a half sphere, for volume we get: Volume = $(2/3) * pi * r^3$
We can calculate the volume of the shell by calculating the volume of the outer radius minus the inner radius.
We get a volume of: 9856223 mm^3, or 0.00985 m^3.

We know the density of concrete $2500kg/m^3$, combined this gives a weight of: 241.72 N

The area of the point loading was very small, we therefore assume that snow-loading wont be taken into account.

Filling in all these values in the formulae above, and we get a scale factor of: 9.1

11.2 Shell deflection

The deflection of the shell is also an important attribute for the feasibility of a structure.

The value we obtained was a deflection of 2.34mm at a weight of 4.4kN.

For this chapter it was very difficult to find complimentary equations to calculate the scaling factors.

12 Discussion

In this chapter the imperfections of the project will be addressed. The writers of this rapport are students, so the goal is to get more knowledge about the topic rather then finding new inventions. We don't know if we used the program SCIA the right way and the handcalculations can be short or only partly right.

The building faze went okay, but our shell is not built by a machine so it could be asymmetric of have other imperfections like the reinforcement that was not in the right spot. The concrete that was poured could be unevenly distributed which may caused the shell to break, that concrete had only hardened for 7 days so was not at optimal strength.

The testing went in two parts, the one with the distributed load and the one with the point load. The shell was made with intentions for distributed load which means there were 40 holes in the shell for the strings to go through. After the strings kept breaking the shell was tested on point load, but the holes may have affected the original strength of the shell.

13 Conclusion

This project was all about shell structures, every group had to design, make and test one. The testing was not only to see how strong the shell structure was but also to check with if the prediction was correct, with the data from the test the shell was scaled to a real life size.

Group 9 chose a reinforced concrete shell structure and made that with a mold of paper mache on a skippy-ball, later reinforcement out of steel wire was added to the mold. The concrete mixture was chosen to be "100 ml cement to 300 ml cement sand 0-2mm to 35 ml water", we let that harden for 7 days and then tested the shell.

The prediction is made with a handcalculation and a finite element method analysis (with the program SCIA). The prediction of distributed load was 6 kN but the strings of the distributed load construction kept failing so the highest load that was achieved was 3.2 kN. After the failed test a new prediction was calculated for a point load test, the prediction was 6.5 kN, but at 4.5 kN the shell failed because of bending at the point load. The main reason is unknown but we think is because of the unevenly distributed concrete layer on the mold. The scale factor is calculated with a safety factor of 2 and with an snow layer of 1kN/m^2. The result is a scaling factor of 9.1, that means that our shell can be used as a small shelter but it is difficult and expensive to make due to heaviness so other material have more opportunity.

In the project we've learned to handle tools from a lab, make a mold, make concrete out of water sand and cement and work with SCIA to get a numerical analysis.

If we had to do it again we would harden the concrete more and place some reinforcement to the top of the shell. Maybe other materials are lighter and therefore more sustainable to make in a real size project.

14 References

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