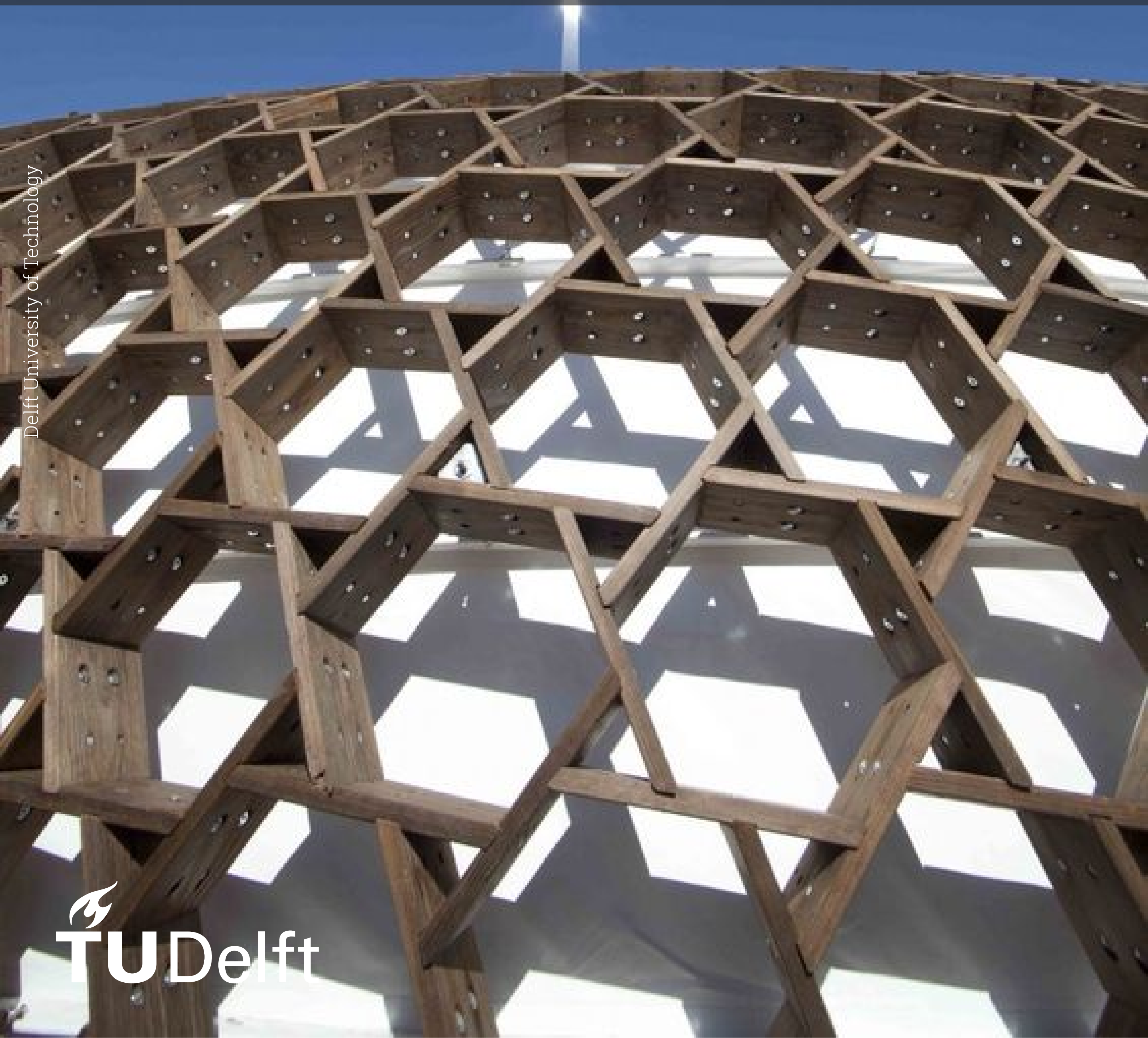
Shell structures

Report on the making of an orthogonal timber grid shell

CT3280-19: Shell structures

Ocker Ledenboer, Quentin Schouten, Warre Van Itterbeeck



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Report on the making of an orthogonal timber grid shell

by

Ocker Ledenboer, Quentin Schouten, Warre Van Itterbeeck

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Project Duration:	November 2023 - February 2024
Faculty:	Faculty of Civil Engineering, Delft

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Preface

A special thanks to dhr. P. Hoogenboom for his support and guidance during this project. The massive freedom we received during this project allowed us to create any shape of grid shell we wanted with the material of our choosing. We can confidently say that as a team we all massively improved our understanding of how to calculate the forces and failure modes of shells and how these shells can be modeled accurately using FEM software.

The use of the FEM program SCIA pushed our limits and allowed us to make very accurate predictions of the buckling load of our shell, the failure mode, and the stresses inside of it. Furthermore, we would like to thank the other students who had more experience with SCIA for taking the time to help us build our model and explaining in great detail how the program functions. Without their help, we would simply not have been able to deliver the same quality of analyses in SCIA.

Ocker Ledenboer, Quentin Schouten, Warre Van Itterbeeck
Delft, February 2024

Summary

This report forms the summary of the designing, building and testing process of a shell roof model over the course of about four weeks. The aim of this course was to build a shell roof model and predict the collapse load as accurately as possible. The results would then be scaled to a life-size model so that conclusions could be drawn about the feasibility of the structure in real life.

The design process started by exploring different concepts. Three initial design concepts were made, of which two were grid shells and one a bent plate. After some consideration, it became apparent that the only feasible concept was the orthogonal grid shell, as the triangular grid shell would not be able to be bent into shape due to its form stability. For the final design, a doubly curved orthogonal grid structure was chosen. This structure was then fastened to a foundation structure that limits the movement of every node on the perimeter of the structure. To properly simulate a distributed load acting on the whole structure, a loading structure was built which loaded the structure by using wooden circles which were tied to the loading structure underneath. The structure was made in a way ballast could be hung from the lowest rope, which distributed the weight of the ballast over the whole shell.

To predict the bearing capacity of the structure two types of analyses were made. First some calculations were made by hand, looking at different failure mechanisms, failure due to buckling, yielding and due to failure of the setup. From this it seemed like buckling was the most probable failure mode at about 3kN of loading. After this a model was made in SCIA to calculate when and why the structure would collapse. This model found that buckling was the most probable failure mechanism with 2.5 kN at failure.

During testing one of the first things that failed was the actual testing rig, which caused the load to distribute unevenly. This in turn caused the structure to fail only at a very specific area. After this happened we tried to improve the rig structure, rebuild the shell and tried testing again. This gave a final failure load of 1.448 kN.

In conclusion, our grid shell failed at a lower load than expected. This can be attributed to the failure of the loading structure, which massively compromised the strength of our grid shell. Building the structure in real life would require the beams to be over 10 meters long, this is not feasible, one way to alleviate this problem is to create sufficiently long beams by joining several beams to one another with finger joints. The real-life model would also have steel clamps holding the beams in place, in contrast to the binding wire used for the scale model.

Contents

1 Introduction

Shell roofs go far far back in history, already in Roman times an impressive shell roof was made spanning the Pantheon. This is because shell roofs are a very natural shape that can withstand relatively large loads and span large distances.

1.1. Problem analyses

In this day and age, we face increasingly difficult design challenges. Shell roofs are getting more complex and are made out of many different materials. The sizes of these roofs increase with time leading to ever bigger structures. In this course, CT3280, we will look at possible solutions for a shell roof and will replicate this in a scaled model. The assignment, research question and the different criteria which the design will have to satisfy are explained in this chapter.

1.2. Research question

The foremost goal is to build a shell roof model and predict its failure load and mechanism as precisely as possible. Moreover, an important question that needs to be answered is if our model could be scaled to a real-life model. The question of how this life-size model would behave and how it would be built also has to be answered. The design should be easily applicable in real life and therefore also simple and economical. Also, something important to note is that the aim of this course isn't necessarily to build a really strong shell, but to predict the failure load and mechanism as accurately as possible.

1.3. The assignment

During the course, CT3280, each group has 5 weeks to design a novel shell structure. Here this structure needs to support its weight and also the distributed load of concrete blocks till failure.

In the first week, we will orient ourselves in the shell structure world and will look at what kinds of designs there are. Here we also look at how the materials behave when there scaled down and what works. Then in week 2, we will present a current design and also do our first calculations on required thickness, size, etc. Then in week 3, we will finish our SCIA model and hand calculations and make a design. Then in week 4 we will create our design and start making the rig that distributes the load so that we can test in week 5.

The design is built as a scale model with a maximum size of 1m x 1m. Here you are free to choose what material u use but you are advised to use materials that are in stock. This can be wood in different sizes and shapes or reinforced concrete. The shell has to be on top of a test rig so that the load can be placed underneath. This load is to be chosen as gravity as a convenience. The rig to distribute the load is free to choose but it is advised to choose a rig as seen in figure 3.13.

2

First ideas

In the following chapter three ideas for a shell structure will be discussed. These concepts can all be described as wooden grid shells or reinforced concrete shells. Wooden grid shell roofs give the possibility of making a span as efficiently as possible with a minimum of material. Due to their efficient spatial framework, these types of roofs allow a lot of daylight to enter the building. The efficient use of materials also leads to a more sustainable construction method [4].

2.1. First concept

The first concept consists of a grid shell that has an orthogonal structure. This mesh consists of two layers of orthogonal laths in two directions. These laths can offer resistance against axial forces in both the x- and y-direction. The two axes also allow bending in both directions so the structure can reach greater heights.

Figure 2.1: a orthogonal wooden grid structure [9]

2.2. Second concept

The second concept is a wooden grid shell with 3 lines along which the shell is made. Firstly a 2d grid is constructed under a certain angle. Onto this shell a third row is added, creating a grid of hexagons. These different laths can be fastened by joints that can rotate, but can't move. Because of the way it is build it has a very

Figure 2.2: A hexagonal grid structure [2]

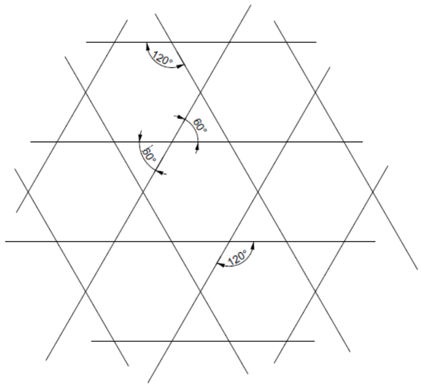

Figure 2.3: Underlying principle of the hexagonal grid

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2.3. Third concept

The third concept was a full metal plate, bent in 2 directions. This would have been a full shell and therefore a bit more rigid than the other 2 designs. The metal of course also has far better properties than the wooden structure of course, allowing it to be a lot more thin than the other two options.

Figure 2.4: a metal sheet shell [3]

2.4. The chosen variant

Ultimately the first idea is the one that has been chosen. This is for various reasons. Firstly the metal plate was excluded as an option. This is because it is extremely hard to bend metal evenly in two different directions. Even if that bend was achieved somehow, it would require a lot of plastic deformation, which weakens the metal a lot from its original state. You can also see in the example figure 2.4 that to achieve such a shape a lot of different bends were made. This would have been too complex of a task for us to do with our limited supplies and limited time.

Next the hexagonal grid was excluded. This was more of a limited supplies reason. To really showcase the capacity of this version we would need a lot of joints on every node, which we didn't have. Besides this we would need a lot of extra wood, which we also didn't have. Another problem with the hexagonal grid is that the wood would have to be bend in a very specific way. Every lath would need a different bend/curvature, which was just really hard to achieve. From a building point of view, given that we only had a few weeks to build the design, there was chosen not to do this version.

3 Our design

In this chapter, the design process of our grid shell will be discussed. Starting with a brief explanation of how the shape of the grid shell was determined. This is followed by a step-by-step explanation of how the design of the orthogonal grid was parametrically created. This model is easily adaptable due to its parametric nature and since it is drawn in 3d software, all lengths can be easily determined.

3.1. Shape of the grid shell

The shape of our grid shell can be described as a sphere with a radius of radius of 0.983m. This can be seen in the following figure 3.1. The fact that the Gaussian curvature of a sphere is the same everywhere saves a lot of time when modeling the grid shell in various programs such as Rhino 7 and SCIA Engineer.

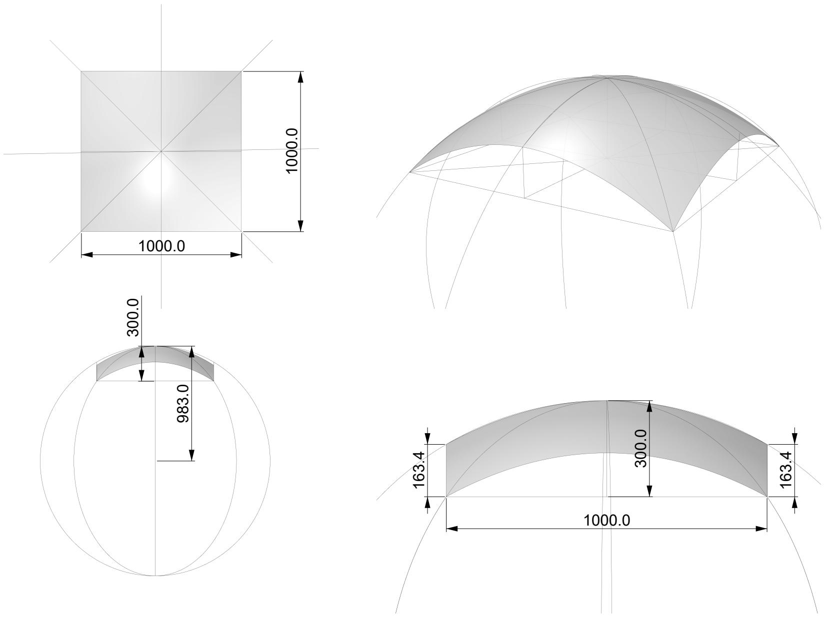

Figure 3.1: Form of the shell structure

To accurately model our wooden grid shell we used the 3d modeling software Rhino 7. To be able to parametrically model our timber grid shell we used the plug-in grasshopper. The full script used to model the roof is explained in appendix A. In brief, the operation of the script can be summarised as follows. The plane describing our grid shell is used as input to generate a timber grid shell. The plane is first partitioned into a grid that consists of a collection of curves. These curves are then extruded in both the x and y directions, giving the laths a width and height. The resulting grid shell can then be 'printed' in the program. The product in our case looks like this 3.2.

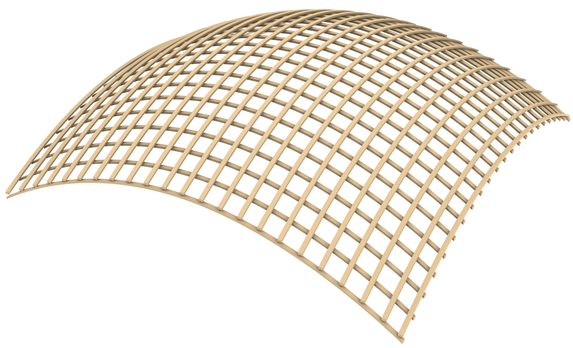

Figure 3.2: Model of the grid shell in Rhino 7

3.2. Hand calculations

To predict the strength of the design calculations were made to see how big the load will be that the full structure can take before it collapses, multiple failure mechanisms were looked at to find the most probable one. At first, we looked at some geometric problems to later phase buckling problems of the structure. After that, we looked design problem of the yielding and plastic deformation of the wood of the structure. And at last looked at when our test rig could fail.

3.2.1. Geometric calculations

First, the length of the arc had to be determined for determining the buckling length. Here we used the following formula. Where *a* is the radius of curvature of the shell and *w* is the width of the shell. In the figure 3.4 there is a more detailed explanation.

$$Slat\ length = \frac{4a\pi \arcsin \frac{0.5w}{a}}{360} \tag{3.1}$$

Figure 3.3: Equation for slat length

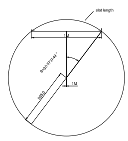

Figure 3.4: Schematic overview slat length calculation

For the total slat length, we found a distance of 1,049 meters. After determining the total slat length it was also necessary to look at the lengths in between the slats and also the heart till heart distance. This could be useful when determining higher-order buckling shapes. In principle, we say that the total slat length exists out of 20 slats of 10x5mm and 21 spaces in between them. This gives us a distance between the lats of 40.43 mm and a heart till heart distance of 50.43mm. A schematic overview of this is also seen in the figure 3.5.

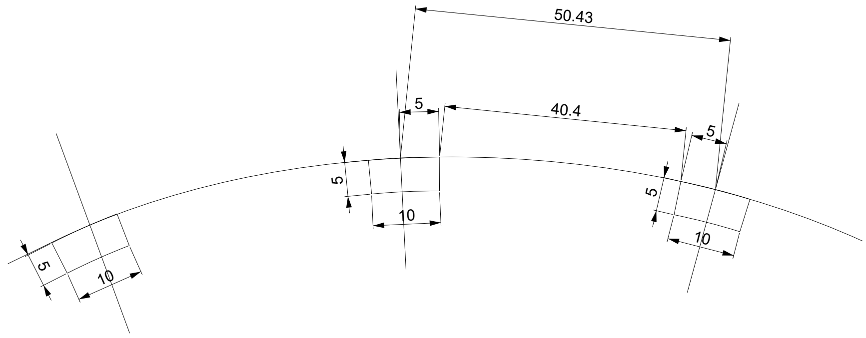

Figure 3.5: Heart to heart distance

3.2.2. Buckling

First, we look at the most probable failure, buckling. To find the critical buckling force in one single lath, we use the following formula.

$$n_{cr} = \frac{\pi^2 * EI}{l_{cr}^2} \tag{3.2}$$

Figure 3.6: Eulers buckling equation

For this formula the critical length is very important and depends on the buckling shape you assume. We assumed the largest length possible and therefore the first order buckling shape, the arc length of a single slat, this gives a l_{cr} of 1,049 from 3.2.1. In the figure 3.7 we see the two shapes the grid could buckle to. But after calculating the results for both shapes we found that the first-order shape can handle the least amount of force and so will occur first. From the timber we know that it has a elastic modulus E of about $13Mpa$. Lastly the I is found from $I = \frac{1}{12}bh^3 = 416,67mm^4$. Using this formula buckles with a maximum force of 49 N. On top of this, a knockdown factor of 1/6 is added to better approximate the real force where the shape is going to buckle. With the knockdown factor, we found that the buckling force of on lath is around 8.09 N.

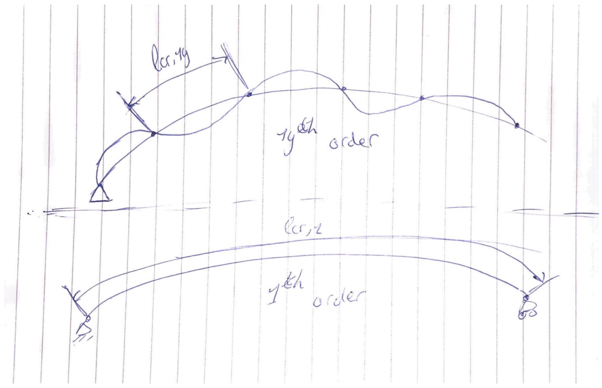

Figure 3.7: 1th and 19th order buckling shape

First we multiply our found force by 20, since there are 20 laths. Next, this force can be used to find the load on the structure that induces this reaction. For this, we use Barlow's formula:

$$N = q * a \tag{3.3}$$

Figure 3.8: Barlow's formula

Here the *a* is the internal radius of the arc, which is $0,983m$ from 3.1. From this, we find the distributed line load over all the laths. What we found is that with a distributed load of 164.59 N/m our shell structure is going to buckle. We will use this found load to find the load as a single-point load. First, we find how much force is in one single circle of the distribution setup.

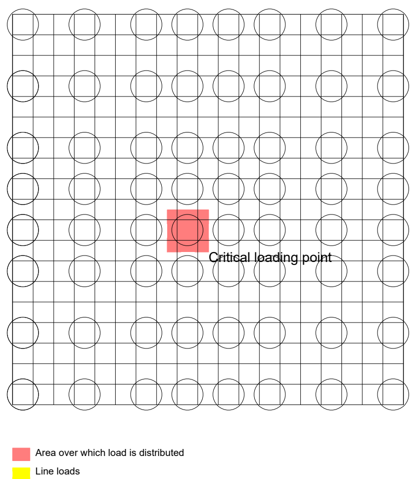

Figure 3.9: Example how one of the most critical circles distributes the load over the lines

In figure 3.9 you can see how the circles are distributed over the grid. The highlighted point is the most critical circle and the area around it is where the distributed load works. Here we see that the circle distributes its load over a certain area marked in yellow. This area comes down to 8 times the heart-to-heart distance between lats. If this gets multiplied by 64, the amount of circles we have, then we find our final load. This comes down to 4.25 kN.

$$F_{1\ rope\ of\ distributed\ loadsytem} = q * l_{heart-to-heart\ distance\ of\ lats} * 8 \tag{3.4}$$

Figure 3.10: Force in 1 rope of the distribution test rig

3.2.3. Yielding

Besides buckling our structure can also permanently yield. This happens when the wood exceeds the yielding stress and permanently deforms. This is something you want to avoid because the wood has anisotropic behavior it could suddenly fail. Within this chapter, we assume that the wood has the same yielding stress of 51 N/mm^2 in every direction when in reality this can differ a lot. This value has been provided by dr.ir. P.C.J. Hoogenboom has been tested in the lab. When using the yield stress we look at the following formula.

$$\sigma_{yielding} = N/A \tag{3.5}$$

Figure 3.11: Equation to find yield stress

When rewriting the equation we find that the maximum normal force in one lat is around 2550 N. Plugging this in the equation for determining the line load we find a line load of 2594.09 N/m. Which eventually translates into a maximum loading capacity of 66.980 kN.

3.2.4. Test setup

The shell itself is not the only thing that can fail, the test setup is also something to overlook. This test setup can fail in multiple ways. At first, the outside barrier which has contributed to the normal force can fail. But also the distribution rig itself can fail when the shell can take too much load. The wooden structure where the structure stands on we neglect because we assume this is significantly stronger. In figure 3.12 we see how the test rig forces are distributed.

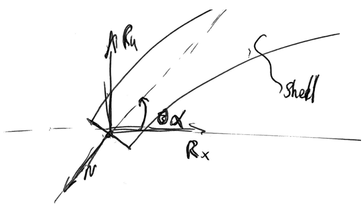

Figure 3.12: Schematic overview on how the load distributes into the rig

We find that for a normal force of 161.8 N, we find that the rig has to deliver a a horizontal force of around 93 N taking into account the structure buckles instead of yielding. We assume that our structure can easily take this force and that this won't be a failure. Besides that also the distribution rig could fail. Assuming the knots won't pass through the holes and the yellow rope is the weakest link so the rope would snap we have a maximum capacity load of 64x0.5 kN which ends up being 32 kN. This in our opinion seems to be more than enough because our shell structure would fail way earlier according to our calculations. The test setup as well as the grid shell can be seen in the following figure 3.13.

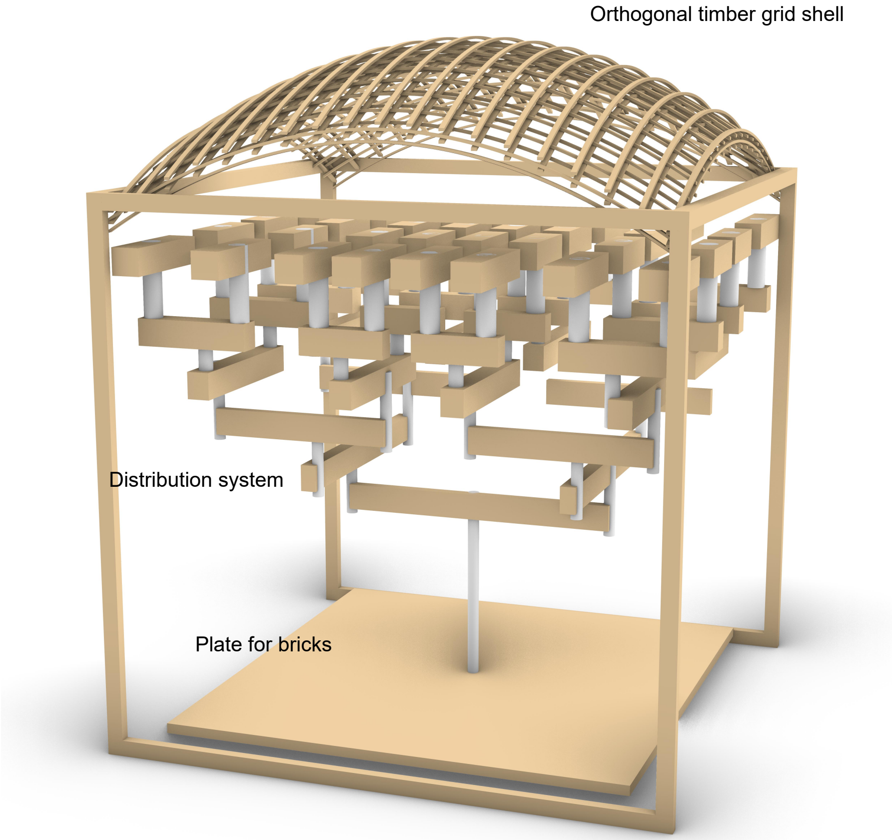

Figure 3.13: Schematic overview of the distribution rig

3.2.5. Conclusion

As a conclusion, we find that our structure is likely to fail under buckling and that the yielding of the wood won't be the problem. Most likely our test setup won't be the place where our structure fails. Of course in the real world, we find difficulties in manufacturing faults, and also the wood's behavior can change when going at smaller and smaller scales. This is because the wood's grain structure is at a certain size and that doesn't scale with the size of the shell structure. Therefore we scale our structure by a factor of 1.3x and find a final force of 3.29 kN that our shell structure can withstand before buckling.

3.3. SCIA Calculations

Finite element analysis was done in SCIA of the wooden grid shell. These calculations give a good impression of the behavior of the grid shell in the real world. SCIA is a program used for various finite element calculations for structures in the professional field, meaning that the measurement of our scale model will need to be multiplied by 10.

The calculation itself will give an idea of the deflection, the different buckling modes, and the natural frequencies of the grid shell. Lastly, a buckling analysis will be used to estimate the buckling load of the shell structure.

3.3.1. Modeling of the grid shell

The wooden grid shell is constructed using nine coordinates. These coordinates can be used to construct the circular arcs that describe the shape of the grid shell 3.15. Since the curvature is the same in both directions, the curves at the edges can simply be copied. All curves at the edges are divided into 20 segments, after this the curve of the side is simply copied and pasted, to arrive at a grid of 22x22 laths.

The resulting grid can then be used as a substrate for placing 1-D elements. These 1d elements are defined in SCIA as beams of 100x50mm, consisting of cross-laminated timber, or CLT. The CLT we used has the name C24 EN338. The 24 indicates the bending strength of the laminated timber, expressed in Newtons per square millimeter.

In addition to this two load cases were created, both permanent. One for self-weight and one for a snow load. As our grid shell is not a solid shell, a surface force exerted by snow is simulated by putting line loads on all the 1-D elements. In addition to this two load cases were created, both permanent. One for self-weight and one for a snow load. The 3kN/m2 is derived from the hand calculations in the previous part of the chapter, this is the self weight of the structure plus the snow load that is presumed to act upon it. This value is then divided by the length of one lath, multiplied by the amount of wooden laths. The answer is then multiplied by ten so that the value can be used in the SCIA model, which is ten times bigger that the scaled model.

$$lineload = 10 * \frac{3kN/m^2}{1.049 * 44} = 0.06499696681kN/m \tag{3.6}$$

Figure 3.14: Calculation of line load on 1-D element

To mimic the real situation as closely as possible, the outer edges of the shell were hinged. This hinge ensures that no translation is possible in both the x,y, and z directions. However, a hinged imposition was chosen so the connections can still rotate.

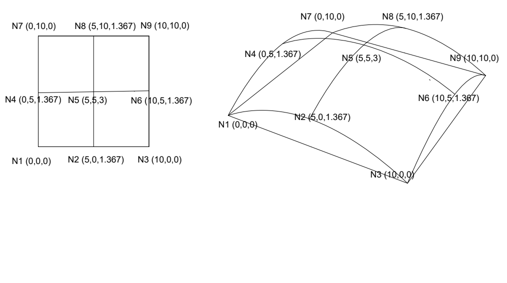

Figure 3.15: Coordinates used to define surface

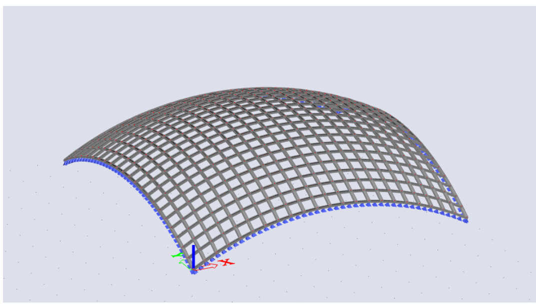

Figure 3.16: Grid shell modeled in SCIA

Figure 3.17: Creation of grid shell in SCIA engineer

3.3.2. Linear elastic analysis

First we did a linear analysis where put a certain load on the structure, and looked at how the grid deformed and where the largest stresses would occur. In the analysis the deformation due to shear forces are neglected, as the interest lies mostly on the von-mises stresses and the deformation that results.

When looking at the model we see in figure 3.19 you can see that the largest stresses occur near the edges of the structure. As a result the deformation is far and away the largest here. You can see that just before the actual edge it deforms down and then up again. This causes a lot of bending stress inside of those lower area's. This is a very clear example of edge disturbances.

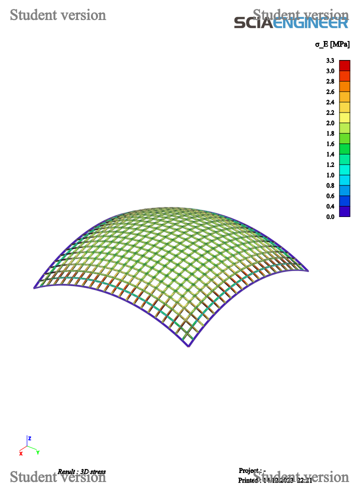

Figure 3.18: Stresses in the structure

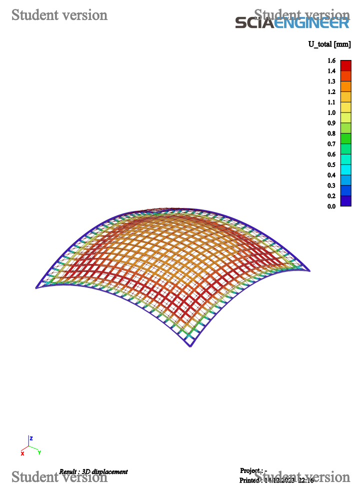

Figure 3.19: Deformation

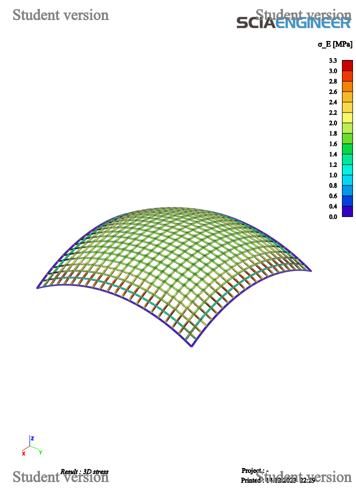

Figure 3.20: Stresses in a smaller mesh

3.3.3. Linear stability, buckling modes

In this subsection we will look at the stability of the system, and how it might buckle and lose it's stability. In shell buckling, we have two main shapes in which it can buckle. The ring buckle, where an entire layer starts to deform. Besides that we have the Yoshimura pattern buckle, or the chess board. Here different area's get disturbed and go in and out like a chess board.

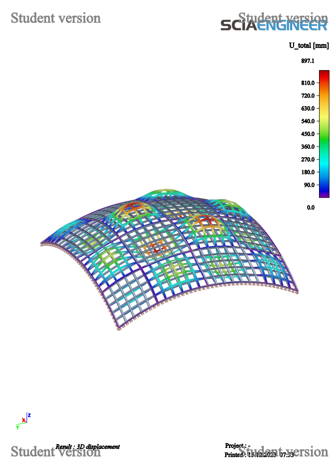

Figure 3.21: Linear buckling analysis

In the figure 3.21 you can see the Yoshimura pattern occurring inside of the shell. At loading the shell will start to more and more resemble this pattern, until the second order effects created by the bending get so big that the structure collapses. The critical load factor in this case is 6.12, so right now to find the load at which the structure buckles we should multiply the current load by 6.12. However the actual force a buckling shape can take is often a lot lower than the theoretical buckling force. This is due to initial imperfections in the shape, loading excentricities and other factors increasing the stresses. Ultimatly it can decrease the strenght by a factor of 6, so the factor is $6.12/6 = 1.02$. This means that only a very small factor has to be applied before the structure buckles.

3.3.4. Modal analysis

In this chapter there will be a quick look at time dependent load case, here the load gets added and removed at certain frequencies. This is not leading as a prediction for our test, because at our test we will add ballast untill failure. We won't periodically load the structure.

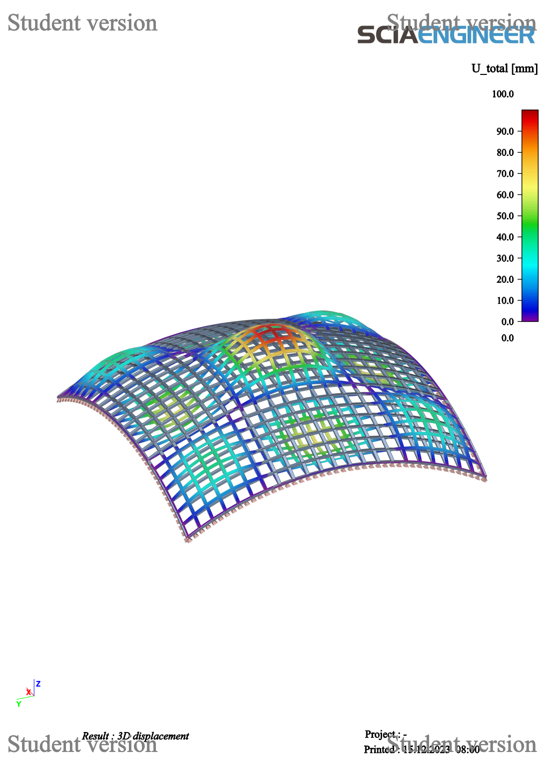

Figure 3.22: Modal analysis

What is very interesting to see coming back in the modular analysis is that it has a similar shape and deformation as the buckling analysis. You can see the yoshimura chess patern coming back, even if it is has 9 tiles now in comparison to the 16 tiles of the buckling analysis. This shape keeps coming back, it is therefore very likely that the entire structure will buckle in this shape, should it buckle. It is however not possible for the structure to collapse in this exact pattern, this is because we won't load it with a frequent, but linearly increasing load. This will therefore not be one of the failure modes.

3.3.5. Non-linear analysis

We then look at a non linear analysis. Here we add imperfections and go up with increments to our buckle load from the linear analysis to try and find if it actually is the buckle load. The imperfection we have chosen was an initial deflection as a buckling shape from the linear analysis. The maximum amplitude of this buckling shape from the initial shape has been chosen at 24 mm, this seems like reasonable deflection at the scale of 10 meter long laths. We do this because the theoretically calculated buckle load is often a lot higher than what the buckle load actually is. To compensate for this the buckle load is often multiplied by a knockdown factor. This factor is very usually about 1/6, a low estimation. We can however use scia to find a more realistic value that gets closer to our actual value.

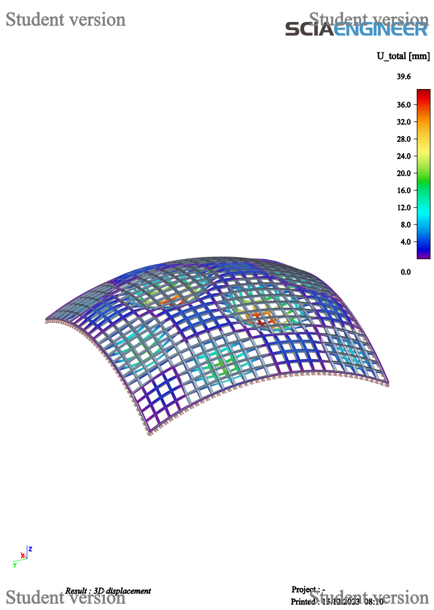

Figure 3.23: Deformation, nonlinear analysis

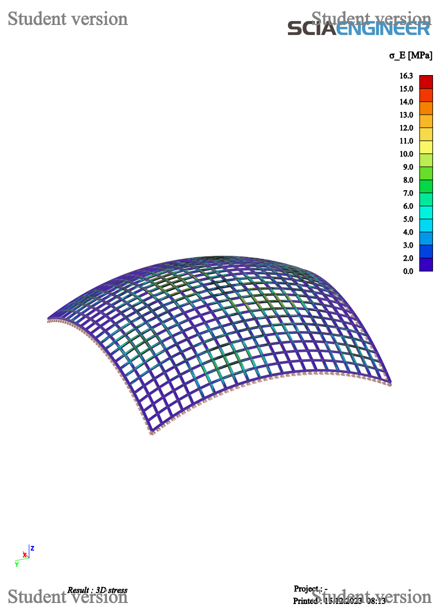

Figure 3.24: Von Misses stresses, non-linear analysis

It can bee seen again in the analysis that the buckling shape consists of the 16 squares chess board pattern. It is however important to note that the extremes go in different directions than the other buckle, implying that this is a different buckle shape than the linear analysis.

3.3.6. Maximum load

When we actually run the non linear test, and increase the load with increments, we find that the first buckling shape actually already occurs at increment 37 out of 90. This implies that our multiplication factor found in our linear analysis has to be multiplied again by 37/90 to find the actual buckle load. When applying this to the loads we find that $1_{(thesnowload)} * 37/90 * 6.12 = 2.516kN$. Looking back the correct calculation for the maximum load would be; $37/90 * 3kN/m2 = 1.23kN/m2$

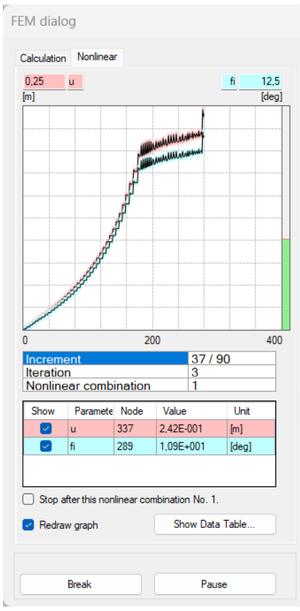

Figure 3.25: FE-calculation

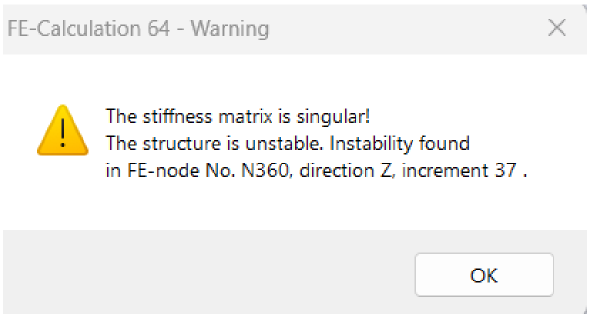

Figure 3.26: Singularity warning

Figure 3.27: Maximum load FE-calculation

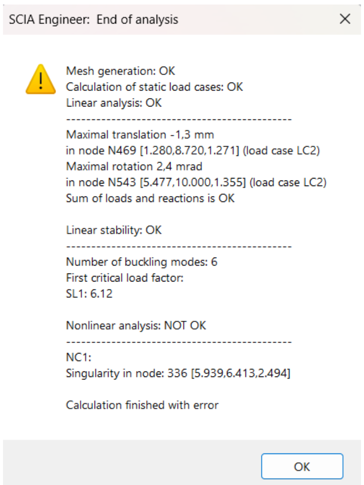

Figure 3.28: End of analysis summary

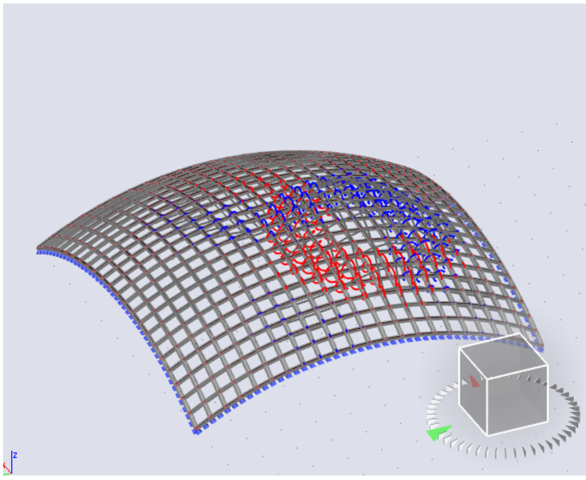

Figure 3.29: Buckling mechanism

Figure 3.30: Buckling at maximum load

4

Building process

In this chapter, we will explain how the shell was built and what was done to construct it. Step by step we will tell what was done in the lab to construct it and so we give a manual to construct the shell yourself.

The creation of the shell structure proceeded in multiple steps. At first, we went to the lab and looked at how the different materials behaved under loading. Here we did some compression and bending tests on different kinds of wooden slats. Whilst also looking at the workability of the concrete.

Figure 4.1: Assembly formwork grid shell

Figure 4.2: Soaking the slats

Figure 4.3: Preparations of building the grid

Afterward, we took the laser-cut underlay and put it together. The laser cut underlay was modeled in Rhino 7 and then laser cut from 4mm thick mdf boards at the Faculty of Architecture. The technical drawings for the underlay that were used for the cutting can be found in appendix B. The underlay was assembled by screwing scrap wood onto the laser-cut pieces to build a 1x1 meter formwork. This can be seen in the figure 4.1. Then to bend the slats we had to soak them in boiling water. In the figure 4.2 you can see we built a 1.5x0.3x0.3 meter wooden triplex chamber with trashbags inside and over the end. This is so the wooden slats could soak in the water and also sit in the steam to improve the bendability of the wood.

Figure 4.4: Laying the soaked slats over the underlying temporary formwork

Figure 4.5: Glueing and bonding the nodes of the gridshell

Figure 4.6: Assemblying the shell

After soaking the slats the building of the shell structure could begin. The first thing that needed to be done was to lay the wooden wet slat over the formwork and tape them so they were fixed in position and could dry in this shape. This was done so they become permanently bent when dried en are more workable. One important thing to note is that the slats have to be bend very delicately because they can snap very easily because of the grain structure.

After the slats were dried we bound and glued the nodes of the shell structure together to ensure good contact between the slats. This was done so the calculated models fit the real model and increase the stiffness of the shell structure. The bonding was done by winding steel wire around the nodes of the shell and pressing it to glue together. Unfortunately, not every piece around the side ensures a good bond because of the stiffness of the wood it twists and does not ensure full contact.

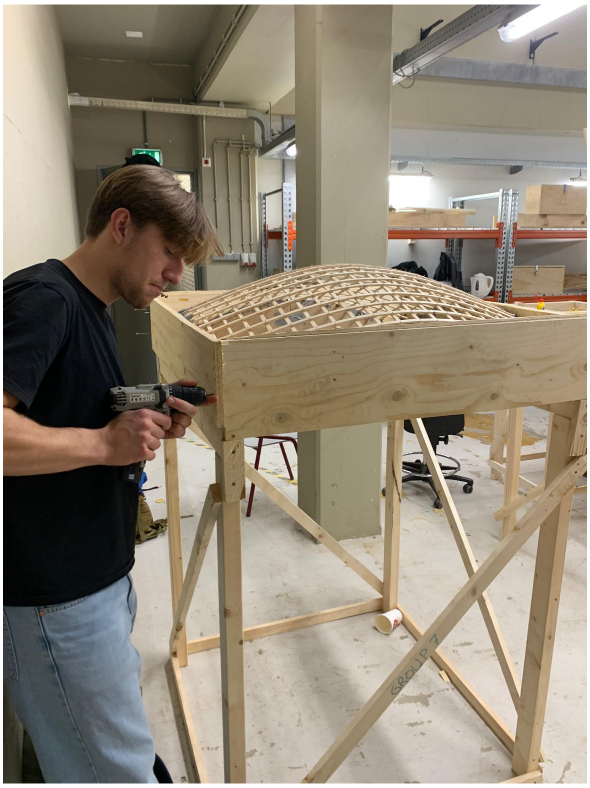

Figure 4.7: Surrounding formwork to cope with the expanding forces

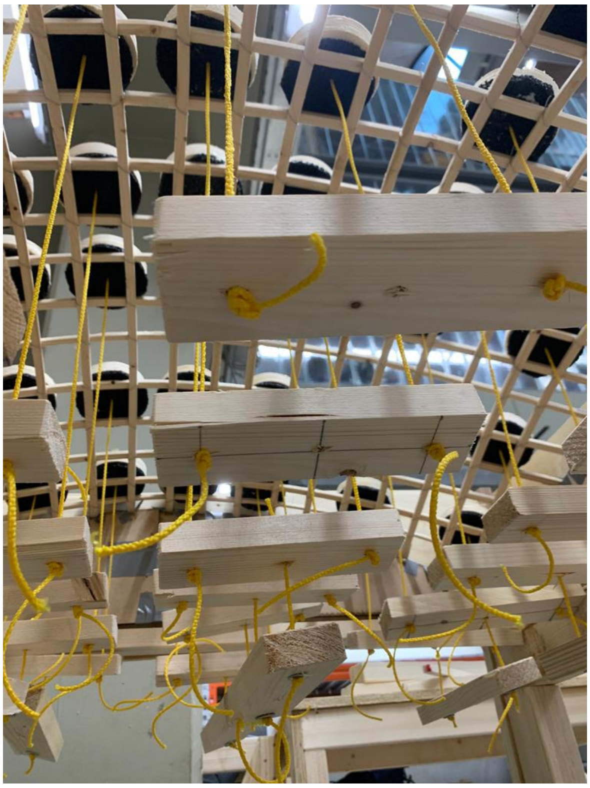

Figure 4.8: Assemblying the distribution system

Figure 4.9: Attaching shell to wooden test structure and finalizing the design

When the shell is finished it will be placed on top of the wooden test structure as seen in figure 4.7. Then the surrounding formwork is attached to the shell and the wooden structure beneath to ensure that the expanding forces of the shell structure will be dealt with. To make a solid structure we first use a triplex plate around it and finally put an extra wooden beam around to ensure it does not fail. Then as the final step, the distribution system was built. Therefore, we used the system that dr.ir. P.C.J. Hoogenboom provided and copied it. This was also the most easy to do because of the material selection we had. In short, we drilled wooden circles of diameter 80 mm out of a wooden plate and attached rubber patches to it so they have the most contact area with the shell. Then two circles are attached by pieces of rope to wooden beams beneath them as seen in figure 4.8. Then these wooden beams are attached together till we have one wooden beam beneath that holds a platform where the bricks can be placed on top off.

5
Testing

In the testing chapter, we will look at how our shell structure is tested and what the results are of our tests. First off the testing procedure will be overlooked and the step-by-step process of testing will be followed. Briefly, after that, we will tell in short what our predictions are. And then both tests will be analyzed and failure modes will be discussed.

5.1. Testing procedure

When testing the shell structure there is a certain setup you want to use. At first, we placed the test rig on top of 4 pylons so it was easier to place more bricks on the plateau and also made the situation more workable. After that, we placed on top of the shell an extensometer that measures the deflection of the shell whilst loading it. For loading the shell we use bricks that are each around 2.1kg which results in a force of 20.6 N per brick. Here we apply ten bricks to the platform and take a displacement measurement. We load the shell until failure and so find the load where the shell fails. Something to add is that we also film the testing to see what the failure mode is. All this can be seen in the figure 5.1.

Figure 5.1: Test setup

Figure 5.2: Constraint beams in second test

We predict that the shell will fail under buckling. Here it will buckle at a load of 2.56 kN which comes out to 124 bricks. At the testing site for convenience, we rounded this to 250 kg. This weight does not include the distribution testing rig that also is hanging from the shell.

5.2. First test

To test the structure first a platform was attached to the rig on which our load will be placed. This load was slowly increased to find the failure load. Initially, the test went alright, until the placement of the 38th brick. At this point, one of the wooden blocks in the weight divider shot loose, causing all the weight to fall on a quarter of the structure. This localized the stress in the structure and so broke a couple of slats. A more detailed example can be seen in the figures 5.6. Because of the sudden failure, the structure has undergone a bigger force because of the acceleration of the bricks falling and so did not work to its optimum performance. Looking at the displacement of the structure was not a great success because the structure suddenly shifted a couple of millimeters down a couple of times and also the wood had too much flexibility and so maxed out the capacity of the extensometer. After this, we tried to fix the structure and did a second test.

Figure 5.3: Moment failure weight divider

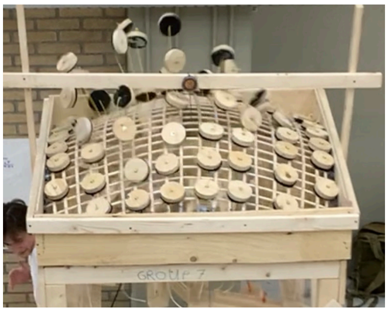

Figure 5.4: Shell acting as a spring and pushing stress dividers up

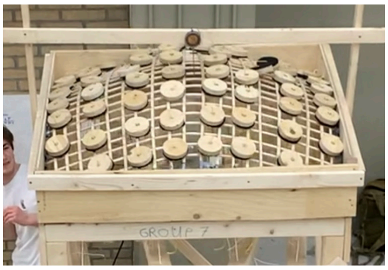

Figure 5.5: Shell back in original shape but with broken lats

Figure 5.6: Chronological order failure test one

5.3. Second test

In the second test, we tried fixing the structure by binding extra lats beside the broken lats as seen in the figure 5.7. Also, we prevented the failure of the weight distribution by screwing screws into the wooden beams and so constraining the rope around the beam as seen in figure 5.2. Unfortunately, this did not strengthen our structure enough and so our structure eventually failed at a load of around 144.8 kg to buckling. Something to note here is that the failure occurred in a way slower manner and happened in a couple of seconds instead of the first sudden failure. In figure 5.8 we see here that the structure slowly fails at the points where the first failure was as well. This was within our expectations but unfortunately, we think the structure could have carried a way higher load if it had not broken because of the first failure.

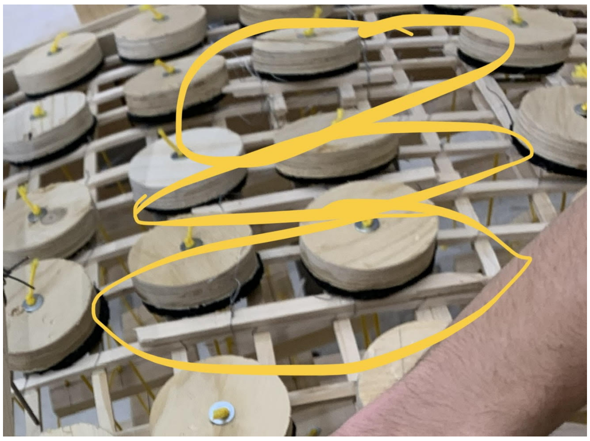

Figure 5.7: Extra strengthing shell structure after failure

Figure 5.8: Instant before repaired shell buckles and so fails

6
Real size model

In this chapter, the probability of scaling this model into the real world will be discussed. For this, the buildability, deformations, stresses and failure mechanism of the timber grid shell roof need to be considered. As said earlier the scaled-down model has a maximum size of 1x1 meter and is ten times smaller than the real-world version. This means that the real-life wooden grid shell roof measures 10x10 meters. In the following paragraphs, it is discussed how the real-life mode could be built. The chapter ends with a short discussion on the stresses and deformations of the timber grid shell roof.

6.1. Building of the life-size timber grid shell roof

First off in the scaled model, we have used wooden laths of 10x5x1049 millimeters. If we scale this to the real world that would mean that we need wooden planks of over 10 meters long. This of course not possible so came up with a solution to attach shorter planks seen in figure 6.1. This does decrease the compression strength of the planks. This is something to do on site however because of the increase in size of the wood we do not have to cope with the problem that wood behaves differently on smaller scales. Because of the grain structure of the wood, the lats could snap easily and this is something that will decrease by increasing the size. Still, because of the anisotropic behavior of wood, it is very useful to test the bigger beams that you ordered on-site. Another option would be to finger-joint pieces of wooden laths together 6.1. The Downland grid shell was able to achieve laths of 36m long by finger jointing laths to one another. To ensure safety with such long laths the knots and other defects were removed from the wood before they were joined together [5][1].

Figure 6.1: Example to join planks on site [8]

Furthermore attaching the planks with glue and also the wire we used for the scaled model is not going to work for the real-size model. One suggestion would be to use real reinforcement braiding wire to ensure a well-supported bond between planks when glued. Besides that, the surrounding formwork applied to the scaled model does not apply to the real-world version. This is the reason why we have looked at different kinds of models and found the model seen in figure 6.2. This a solution for the surrounding formwork but if this can withstand the same amount of normal forces is not clear and should be looked further into. Something to add is that with a snow load, our structure will not be loaded to its maximum per se so the surroundings won't be as well.

Figure 6.2: Real-world solution surrounding formwork

The laths of the orthogonal grid can also be joined to one another using steel clamps. This was done in the Downland grid shell. What is special about this nodal connection is that there is no need to drill through the laths, which decreases the likelihood of the wood splitting. The nodal connections work by using steel plates as spacers, through which steel bolts can be threaded. This approach also allows the layers to slide a little in the case of shrinkage. The installation of these nodal connections can easily be combined with the forming of the grid shell during the building process. As the grid shell is jacked up from below into the correct shape the node connections can be built by hand. This is similar to the way we built our scale model. The grid shell is pushed into the correct shape, after which the clamps are fastened, keeping the shell in the correct shape. Steel wire and roofing can also be connected to these metal clamps as can be seen in the following figures 6.5.

Figure 6.3: Metal Clamp

Figure 6.4: Jacks

Figure 6.5: Installing node connections and jacking the grid shell into shape

[6] [7]

To conclude on really big scales these wooden structures get difficult to build. Not because of material limitations but also because the shell structure lies on some kind of curvature and from the ground these shells are not so practical. Functioning as a roof for instance could be a better solution for these kinds of shell structures. For now, the maximum entrance height of the shell if it was placed on the ground like the picture in figure 6.2 would be 1,5 meters. Besides that, the flexibility of the shell plays a big role. When testing the scaled model we found that the wooden scaled version deflected over more than a couple of centimeters. This means that with high enough loads the bigger shell could deflect dozens of centimeters. This is something you wouldn't want especially when bringing this on the market. Another thing is that your warranty would drop because your product is made out of wood and so with the anisotropic behaviour is hard to predict the stresses and other properties in the material.

6.2. Stresses and deformation of the life-size timber grid shell roof

Seen as the calculations of the stresses and deformation of the grid shell were done for the life-size model in SCIA engineer, these results do not need to be scaled. Moreover, an applied load of 3kN/m2 was presumed for the calculations. This load included the weight of the applied load, structure and snow. This is wrong as SCIA engineer automatically calculates and includes the self-weight of the structure. This led to an overestimation of the applied load and an underestimation of the buckling factor. Given that the deflection of the structure is a maximum of 1.6mm for the real-scale model at a force of 3kN/m2, this should therefore not pose any problems. Especially since this force has been heavily overestimated by including the self-weight of the structure in this force.

6.3. Conclusion

It can be concluded that our shell can certainly be built. The measurements of our grid shell roof are comparable to existing structures. Many of the techniques used to erect these shell roofs can also be utilized for the building of our life-size grid shell roof like the joining of multiple beams using finger joints and metal clamps to hold the beams in place. The deformation in the shell has been heavily overestimated in the models in SCIA engineer by including the self-weight in the applied load. This is pointless, as SCIA automatically calculates the self-weight. This means that the structure was loaded more heavily than the snow load of 1kN/m2 that should have been applied. Even so, the deformation calculated was minimal at only 1.6mm. As a result, it can safely be concluded that the structure can resist the snow load applied.

7 Discussion

In this chapter the shortcomings of our report get highlighted and discussed.

Firstly it is important to note that this report is a student project and has as main goal to deepen the understanding of the writers about the subject, rather than making new findings. This should not be viewed as a serious research piece, as the probability is high that methodological mistakes were made.

Besides this it is important to note the shortcomings of our calculations, both in SCIA and by hand. All these calculations are estimations. They assume things about the material like uniformity of material properties (if they assume imperfections, they are not necessarily the same as the real imperfections).

Something to note as well is that while constructing the structure due to the materials we had at hand the design had some imperfections. To add to that the lats behave differently when on a smaller scale and so are not a scaled-down version of the big shell structure. Besides that, the weight distribution rig is not a perfectly distributed load and still focuses on 64 points. This could also be one of the reasons why our SCIA model does not fit the real world.

Then there are also problems with the testing. As said in chapter 5 the testing rig collapsed on the first test. This caused us to redo the tests, however, the structure was already damaged and the repairs didn't fully bring back the structure's initial strength. This is a big reason we believe that our found value differs so much from the found value.

One big mistake that was made was estimating the self weight of the structure and then adding it onto the scia model. This meant that the final calculated loads and factors did not make a lot of sense and either far overshot or far undershot the actual failure load. For this reason the prediction was quite off from the actual failure.

8 Conclusion

Within this report, it was the objective to find a novel shell structure that could withstand a distributed load given by bricks. One of the most important things is that our prediction of the maximum loading capacity is as close as possible to the real-world design. Later on within this report, there has also been looked in the scalability of this project.

As a design, we found a wooden grid shell structure that was built in real life in the Stevin-2 lab. By our calculations, this design could withstand a maximum distributed load of 2.56 kN. In reality, this was way lower with a maximum load of around 1420 N. One important note is that there was a mistake made in testing. It is important to note that the failure load is still higher than what was demanded from the shell structure in the design criteria (an extra load on the structure of 1 kN/m^2).

Out of our calculations, we found that our design is most likely to fail under buckling. This is also the failure we eventually saw in testing. Besides that, we found that an orthogonal grid was the easiest way to set up a wooden grid. This is also most fitted with the given materials of wood and concrete and the given tools.

In this project, we learned how to build and calculate on-shell structures. Whilst also gaining more insight into numerical analysis in SCIA. All this was done with a team effort and gave us insight on how to work on a civil project. If we could improve something in the design process it would be to further dive into the theoretical basis of shell structures and improve our models even further. Besides that trying other materials like plastic or carbon could also improve durability and sustainability of the shell. This whilst also testing properly with the distribution rig of the second test.

In conclusion, within this project, we pushed the boundaries of wooden shell structures. As we move forward, the lesson learned is to look into different designs as a working team and aim to get the most efficient design possible. And so predict and build a revolutionary shell structure.

References

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[6] Weald & Downland Living Museum. *jacking grid shell into shape*. Accessed on November 20, 2023. 2023. URL: https://www.wealddown.co.uk/buildings/downland-gridshell/image.jpg.

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A

Grasshopper script Shell structure

The following pictures are of the grasshopper script used to model the shell structure in Rhino 7. The script works by building a bounding box around the plane. The bottom vertices of this bounding box are then connected to form lines (cmd:Line). These lines form the basis of the grid that is constructed in the next steps. The lines form the outer edge of the grid, as it were. These lines are divided into a number of parts in the next step (cmd: Dividecrv), this number can be determined with a slider. The next step is to set up the orthogonal grid. This is done by connecting the opposite points created by the command divide curve. Since this is done in two directions, an orthogonal grid is created. This grid is then projected onto the predetermined plane (cmd:project). Finally, these curves are converted into volumes by extruding in both the x and y directions. The final product is a collection of volumes, or a Brep. This Brep is then copied and given a shift in the z-direction. Heird by this, a second layer is created. Then the second Brep's are merged again to form a new Brep. This can then be printed in Rhino.

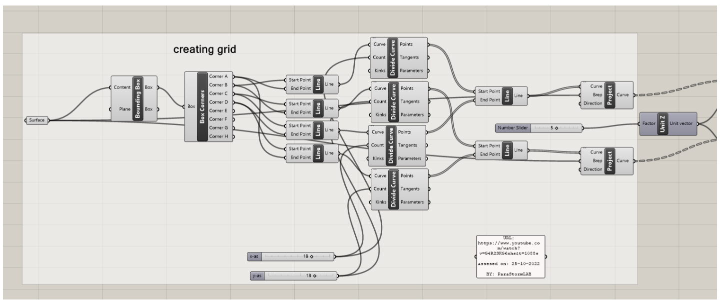

Figure A.1: Grasshopper script part 1

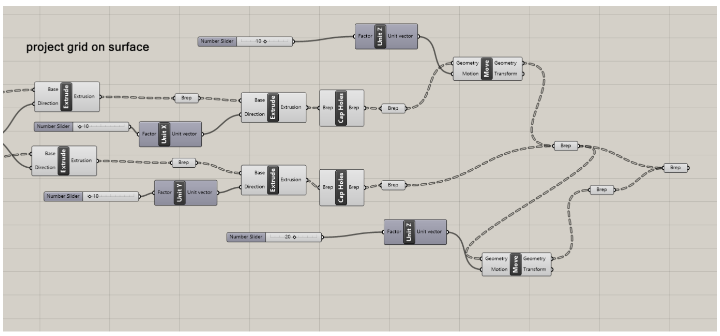

Figure A.2: Grasshopper script part 2

B

Technical drawings laser-cut underlay

These files were used at the faculty of architecture to laser cut the 4mm mdf board into the underlay for our grid shell. This underlay was made so that the grid could be built directly on it.

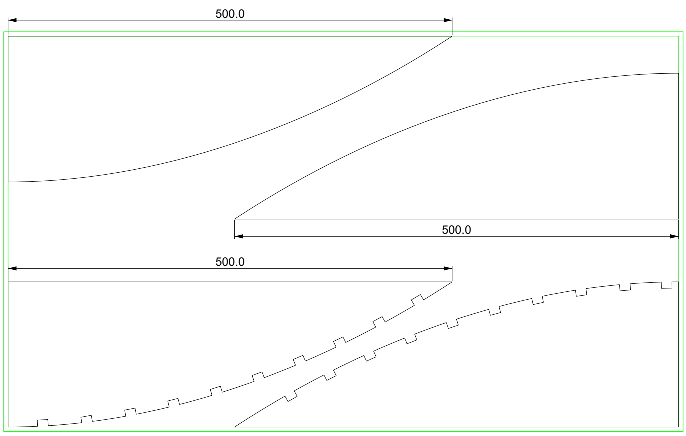

Figure B.1: Technical drawing underlay 1

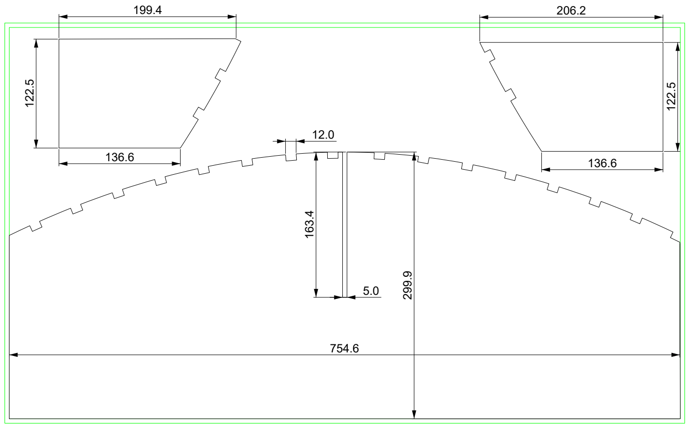

Figure B.2: Technical drawing underlay 2

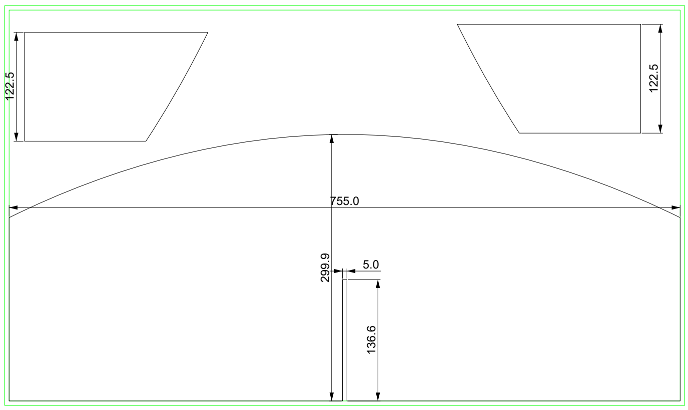

Figure B.3: Technical drawing underlay 3