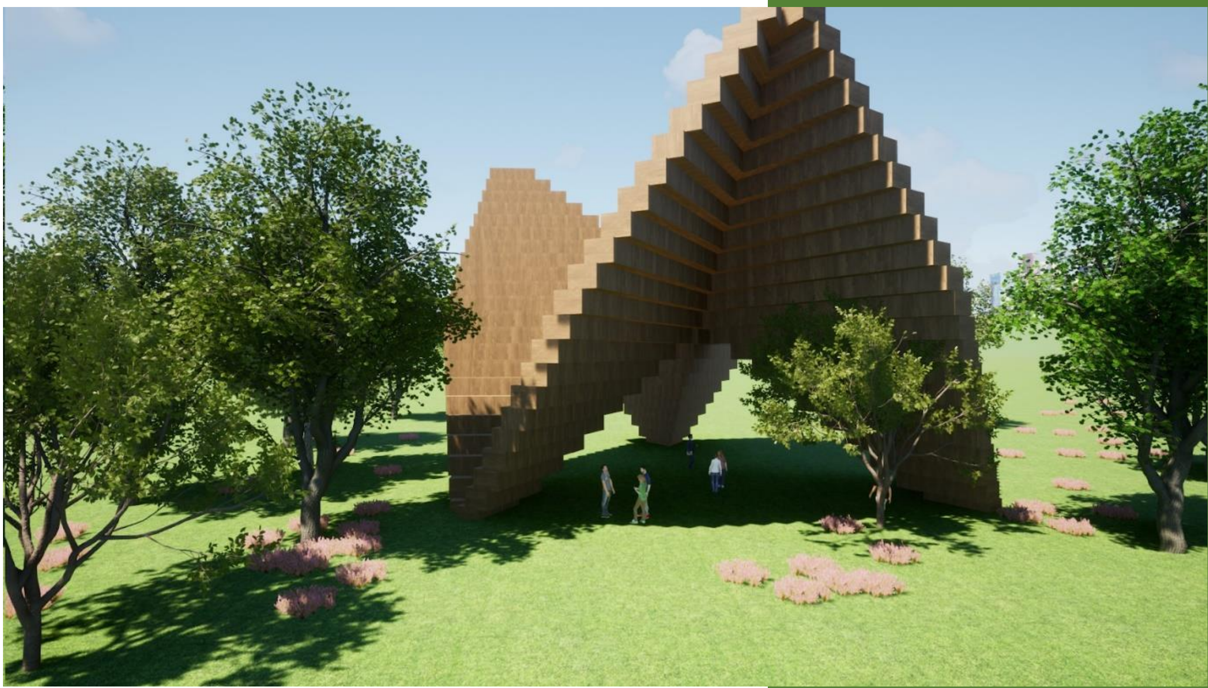
2023

Shell structures



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Preface

This report is written on behalf of the minor-course 'Bend and Break Shell Structures'. In this report our minor-group worked on designing a shell structure. The aim of this report is to understand material behavior and to learn how to design a shell structure. Readers which need a little inspiration or are interested in shell structures can get information from this report.

Delft, December 2023.
Marijn Tol
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Summary

'A shell structure is a three-dimensional solid structural element whose thickness is very small compared to its other dimensions'. (Shell (structure), 2023) To get the understanding of how this structure works and how to build one, a lab was reserved at TU Delft in the building Civil engineering and geoscience. All the (non-electrical) tools and materials needed, are provided by the TU Delft, and supervision is given by Mr. Hoogenboom.

This course exists out of 3 weeks. First a week of material testing, getting to know the tools and starting with the design. Then a week of lectures and a design presentation with given feedback. And lastly a week of building and testing.

The design process started with choosing a material. In this design wood was chosen. After the main reference picture was chosen. Then the design could be thought out in more detail and the measurements could be determined. This is done with drawing on paper, making calculations and a Rhino model, to get a grip on how the structure needed to be assembled.

After the model was perfected, technical drawings could be made with the specific measurements of the shell structure. These measurements were used to saw the wooden slats to the correct sizes with a corner of 30 degrees. Then all the wooden slats were glued together with wood glue.

After this, the drilling of the holes began. The surface of each 1/6th of the structure was divided with the model in Rhino in smaller even surfaces. The center of gravity of these surfaces is then determined. At the center of gravity of the surfaces is a hole drilled in the wood through which a string can pass, on which wooden blocks can be hung to evenly distribute the load. The block will be put together again with new stings and blocks until one hole remains for the loading platform.

The prediction of the load was an important step to really understand the forces going through the shell. The prediction was 250 kg but when the test started it was soon clear that the structure could bear a lot more kilograms. Eventually at 440 kg the frame broke which caused the entire shell structure to fail.

Table of content

1. Introduction

At the course of CT3280 Shell Structures the goal is to design, build and analyze a shell structure model. This is the assignment for the 10 teams participating in this course. There are different ways to construct such a shell structure and in this report one variant will be designed, built and tested.

This report will clarify the following: 'how do you build a shell structure, how do you model it, how do you test it, how much load can it bear and how does it relate to a real size shell?' To find answers to these questions the following chapters will be treated:

The contents of this report are as follows. First, in chapter 2 a list of the materials and tools is presented. In chapter 3, 4 and 5 the design process, the design itself and the building process is explained respectively. In chapter 6 the stress of the wood is calculated with a wood test. In chapter 7 a prediction is made for the failure load with help of Scia Engineer. Subsequently, in chapter 8 the test procedure with the experimental failure load is highlighted. Chapter 9 takes a look at a real size shell. Chapter 10 compares our test with tests of other teams. In chapter 11 the building, predicting and testing is discussed, and finally in chapter 12 a conclusion will be drawn for the project.

2. Materials and tools

2.1 Materials

To build the shell structure there was a list of materials provided. There's also the possibility to bring your own materials. The next list summarizes the available materials:

- Wooden laths
- Cardboard
- Cement
- Sand
- Plaster
- Steel wire
- Nails
- Screws
- Rope
- Tape
- Glue

2.2 Tools

To start building it is useful to have good tools. The next list contains the tools available:

- Saw
- Hammer
- Pincers
- Screw drivers
- Scissors
- Bucket
- Trowel
- Drill
- Drill bits
- Screw bits
- Scale
- Test weights

One item which is not mentioned above is a crosscut saw which was used at home.

3. Design process

First, a material needed to be chosen. The preference for the material was wood, this because it is environmentally a good choice, it looks esthetically pleasing to the eye, it is relatively strong and very versatile. The initial idea was to build the shell structure of a wooden grid made out of triangles, because triangles are the strongest shape. As inspiration, the following figures below were used. Where figure 5 was a preference.

Figure 1: Wooden square grid (Revit Architecture Forum, sd)

Figure 2:Wooden triangular grid (Adelzadeh, 2023)

Figure 3: Louvre, pyramid with triangular grid (Musée du Louvre, sd)

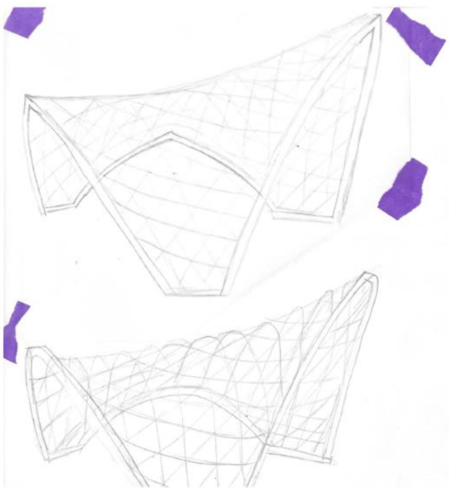


Figure 4: Organic wooden triangular grid drawing

Figure 5: Organic wooden triangular grid (Sheth, 2018)

It started with thinking how the wooden triangular grid could be constructed. This grid could be made out of lats which are curved, but it was observed that these curved lats are very fragile. Also, a very large span needs to be used to realize these curves. Then, the idea was to build the grid out of individual triangles, see figure 6. The sides of these triangles needed to be filed to connect them under an angle. To build a complete structure like this, at least 100 triangles were needed, so within the given time frame this was not the best idea.

Next, the idea of constructing the shell from stacked lats was conceived, as shown in figure 8. This was a more efficient way to build the shell structure. Additionally, a reference was discovered for inspiration, see figure 7.

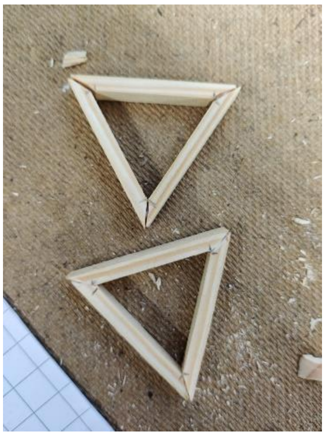


Figure 6: Individual triangles

Figure 7: Star shell structure (O'Shea, sd)

Figure 8: Stacked lats

4. Design

In the previous chapter, at the end of the design process, the inspiration for this chosen design was shown in figure … In this chapter, goes through the design process and explain the different steps to the final design that is going to be build.

This inspiration of a more different or unique shell structure became the base idea of this design. The way the stairs support each other in the vertical direction, but at the same time come together and lean on each other, seemed to be a really strong design. This way the forces could easily be transferred and remitted to the ground, while making use of the strongest shape; triangles.

To keep this base idea into the design, it needed to be changed and simplified. First, the time available to build the model was limited, so while determining the dimensions of the model, a change in the number of 'triangles' was made. In this design, only 3 support points (instead of 5) are made. Also, by changing the surface with glue between two slats to more mm^2, the structure would become smaller and stronger, this way a linear line cloud be drawn from connection surface to the connections surface underneath, like shown in figure 9. This way, in the vertical direction, no surface could collapse because of an overhang.

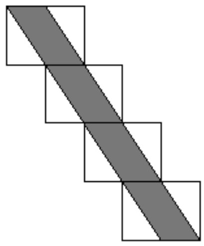


Figure 9: Stacked blocks

The end result of the design is made in a Rhino model shown in figure …. This model became a very useful tool to get a grip on the measurements and attachments of the structure before building it in the lab, to make as few mistakes as possible. The exact measurements and different views of the design are shown in the next chapter; 4.1 Technical drawings.

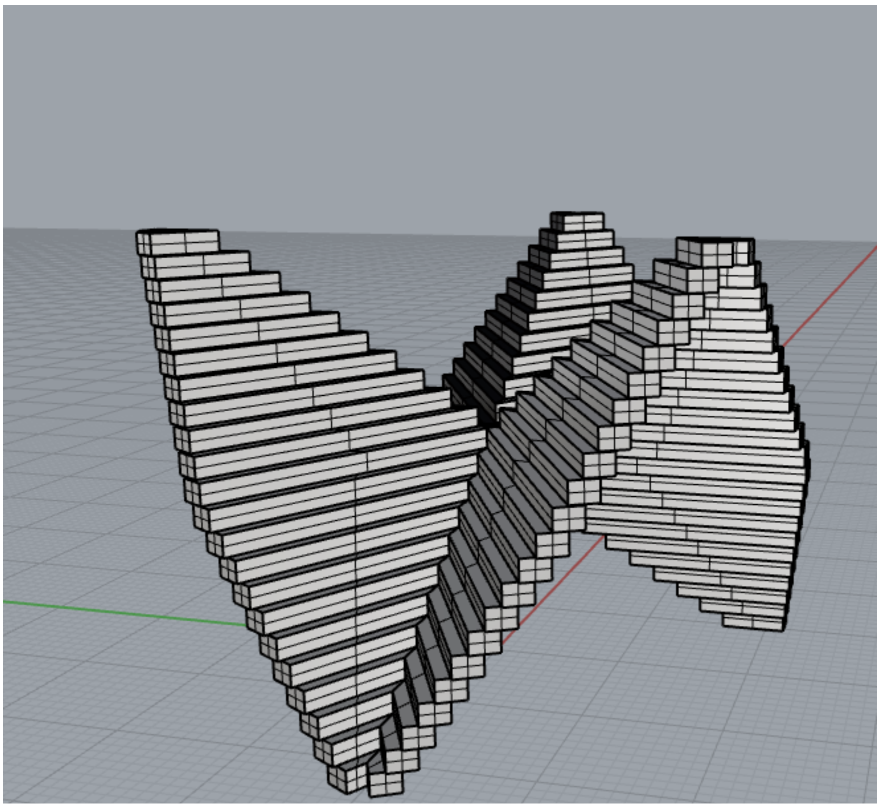
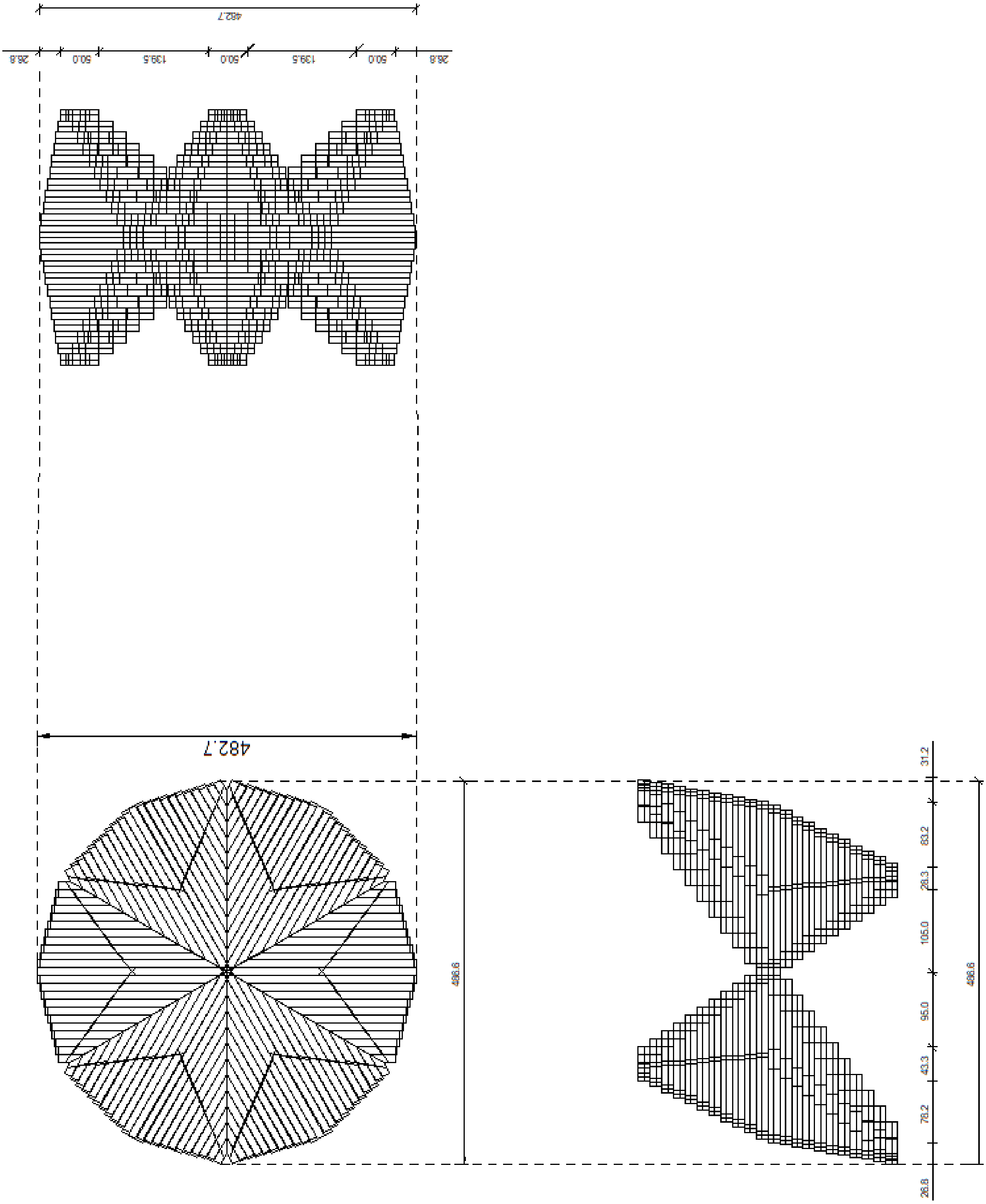


Figure 10: Rhino model of the design

4.1 Technical drawing



5. Building

In this chapter the building process will be explained in three parts. Beginning with the frame, following with the shell structure and finishing with the load dividing system.

5.1 Frame

To test the shell structure and predict how much force it will take for the structure to fail. A frame needs to be built. This frame will be used to hold the structure on a height so that it leaves room to hang multiple bricks on the structure that will imitate the downward force of snow and rain falling on the structure. The frame is shown in a Rhino model in figure 11. It is built of wooden slats. The total surface on which the structure can stand is 500 x 500 mm.

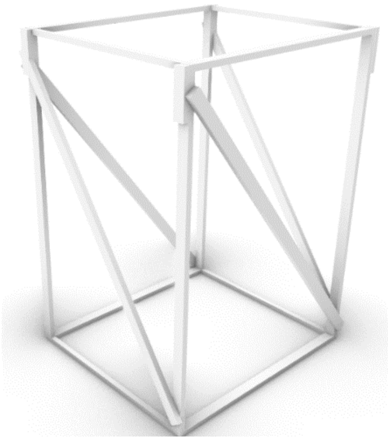


Figure 11: Rhino model of the frame

5.2 Structure

The structure is made out of 6 large pieces which are made out of stacked wooden slats with increasing lengths of 2 cm that are connected to each other with wood glue on an angle of 60 degrees. The 6 large pieces can be seen in figure 12. These wooden slats are cut at the beginning with an angle of 30 degrees at home with a crosscut saw. After they have been cut the slats with corresponding lengths will be connected to the cut side. Here, possible errors made with sawing are taken into account and the best fitting angles are put together. Some of the slats connected with an angle of more than 60 degrees, for instance a maximum of 66 degrees. To correct this, these excessively large angles were adjusted with a file. See chapter 11.1 for further explanation.

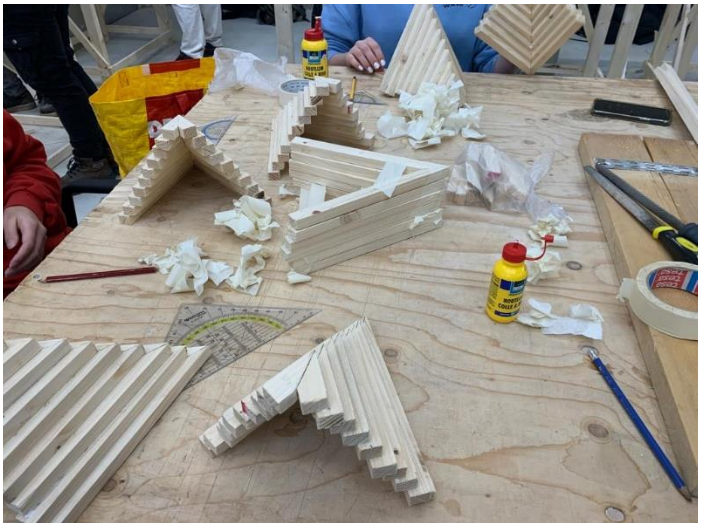


Figure 12: The building of the shell

The longest wooden slats with the length of 25 cm will be kept separately and are joined together in a kind of star shape which is shown in figure 13. This piece will be put in the middle of the structure. A separate part of the center piece is shown in figure 14 , where a sawed-off corner can be seen.

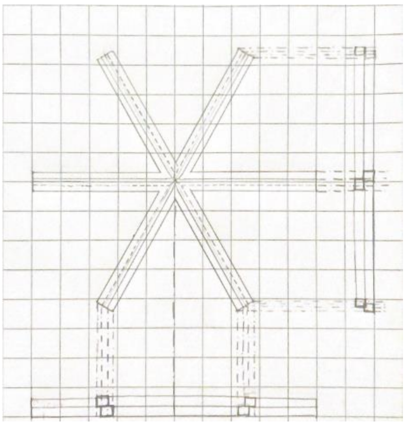


Figure 13: The 25 cm wooden lats put together

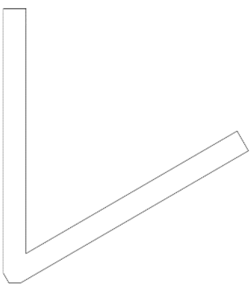


Figure 14: Two wooden lats put togher with sawed-off corner

5.3 Load divider

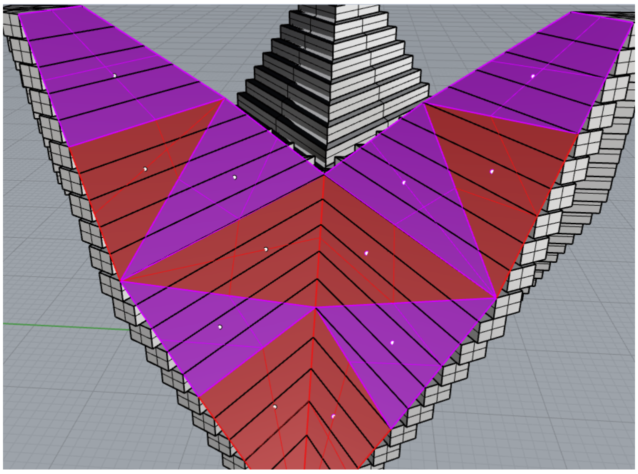


Figure 15: Rhino model of the load distribution

The next step in the building process after building the structure is to build a load divider to simulate a distributed load. This load divider consists of ropes and small wooden slats which are connected with each other to support a platform to put bricks on, which serve as the load. The load divider is shown in figure 16. To attach this load divider, holes need to be drilled in the structure. With the help of Rhino, even sections of the surface of the wooden structure are chosen which is shown in figure 15. The holes then need to be drilled in the center of gravity of these sections so that the load can be distributed evenly. These sections are calculated on only one surface of the structure and mirrored onto the surface next to it. There is also a small ring above the holes, which can be seen in figure 17.

Figure 16: Load divider

Figure 17: The rings on the shell structure

5.3.1 Rope distribution

In total there are six sections per “plane” in Rhino, so this adds up to 36 sections for the whole shell structure. Therefore, the amount of holes that needed to be drilled is 36. In these holes 36 yellow ropes will be attached where 18 wooden blocks will hang, each on 2 ropes. This is well demonstrated in figure 18 In the middle of these wooden blocks there is a hole for a new rope underneath. This is repeated once so that there are 9 ropes left. Because there are now 9 ropes left it’s impossible to divide it further with 2, so for the next two layers wooden triangles with 3 connected ropes are used. The last wooden triangle is made out of 2 layers as this one carries all the load and needs to be strong enough to support it. In the middle of the lowest triangle there is a hole for the metal rod which holds the platform for the load. On the figure on the right the rod and a small platform is shown.

Figure 18: Rope distribution layer one

Figure 19: Complete rope distibution

6. Wood test

To make the SCIA engineer calculations, the stress of the wood that is used, needs to be known. This can be done with a simple wood test. The setup is shown in figure 20. It is a manual machine which increases the pressure so that a force is exerted on the wooden slat. The surface area of the wooden slat is 2 cm * 4,7 cm = 9,6 cm2. Figure 21 shows the scale that measures how many kilo Newtons are on the wood. In the end, the wooden slat took it until 52.7 kN, then a sudden sound of breakage sounded and the nerves were broken. Wood has the characteristic of not yielding but suddenly breaking. The damage is shown in the figure 22.

Figure 21: The scale of the machine

The stress can be calculated:

σ= F/A = 52700 N / 960 mm2 = 54,90 MPa (N/mm2)

Figure 20: Test setup

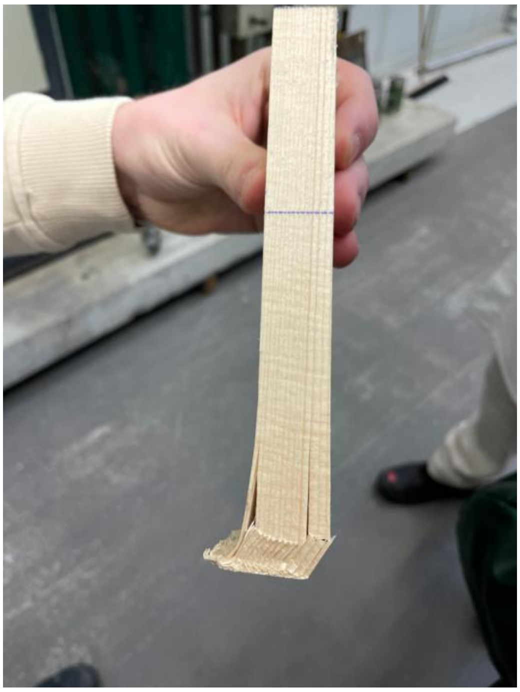


Figure 22: Failed test sample

7. Prediction of the load

The load which the shell structure can take will be predicted using Scia engineering. First a simplified model has to be made in Scia engineering. The model has six shell elements which are connected. This shell structure could be modeled easier as a shell with six walls, instead of multiple beams stacked together as stairs, see figure … The thickness of the model is going to determine how much force the structure can take. To determine the thickness on each side, the weakest link (the smallest surface of the wooden slats glued together) of the wooden structure is measured. This number is taken into the Scia engineer model and made as the thickness of this shell element. This is done for all 6 parts of the structure and these ranges from 4 mm to 8 mm thickness.

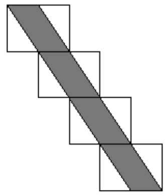


Figure 23: Stacked block

The model in Scia has a bit less material than the actual model, but this amount can be neglected as shown in the next calculations.
0.5 * 1 * 1.5 = 0.75 cm^2 is the area of one triangle of the missing material next to the Scia model.
Per block two of these areas are needed, so 0.75 * 2 = 1.50 cm^2
5 + 7 + 9 + 11 + 13 + 15 + 17 + 19 + 21 + 23 + 25 = 165 cm * 2 = 330 cm is the length of every block added up to each other.
330 * 1.50 = 495 cm^3 : 10^6 = 4.95 * 10^-4 m^3
The mass density of the wood that has been used is 410 kg/ m^3.
4.95 * 10^-4 * 410 = 0.203 * 6 = 1.218 kg of all the 6 surfaces of the model.
The SCIA enigeer model is shown below.

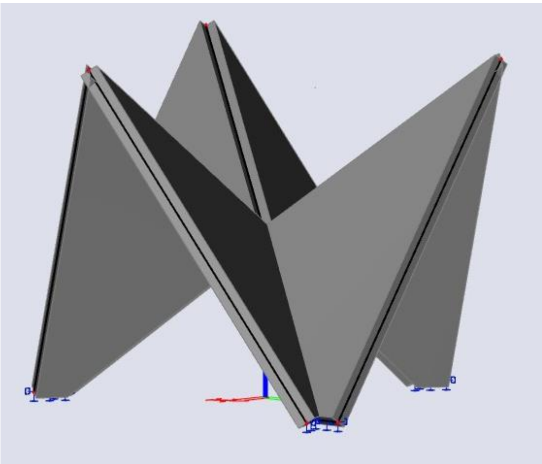


Figure 24: Scia engineering model filled

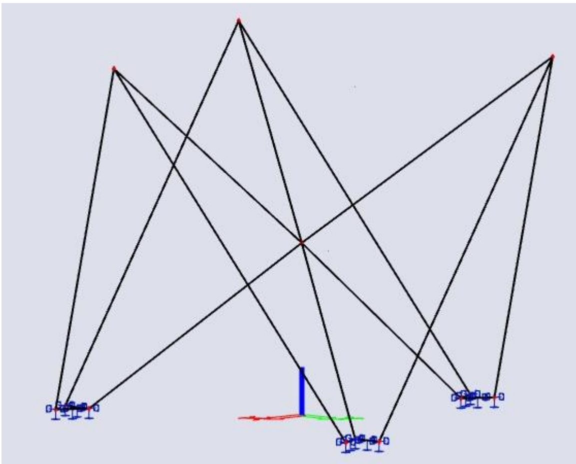


Figure 25: Scia engineering model lines

De coordinates of the nodes are shown below.

	Naam	X [mm]	Y [mm]	Z [mm]	Element	2D-element
1	K1	0,000	0,000	165,000		E1; E2; E4; E5; E6; ...
2	K2	133,300	198,210	0,000		E1
3	K3	105,000	181,870	0,000		E1; E2
4	K4	247,740	0,000	350,805		E1; E4
5	K5	105,000	214,549	0,000		E2
6	K6	-123,875	214,546	350,805		E2; E5
7	K7	133,300	-198,210	0,000		E4
8	K9	105,000	-181,870	0,000		E4; E6
9	K17	-210,004	-0,007	0,000		E5; E7
10	K10	-238,305	16,331	0,000		E5
11	K11	105,000	-214,549	0,000		E6
12	K12	-238,304	-16,347	0,000		E7
13	K18	-123,868	-214,550	350,805		E6; E7

Figure 26: Coordinates of the notes

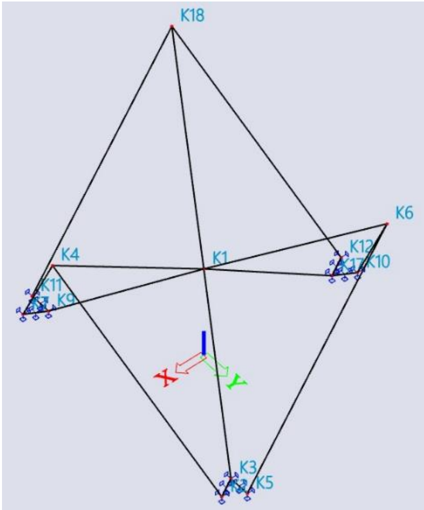


Figure 27: Scia model with labels of the nodes

At first a maximum stress of 54.9 N/mm^2 is used. With trial and error a distributed load was put on the Scia engineer model. At a load of 44 kN/m^2. The stresses in the structure are: σ_1 = 49.7 N/mm^2 (tensile) and σ_2 = - 54.7 N/mm^2 (compressive) shown in the figures down below.

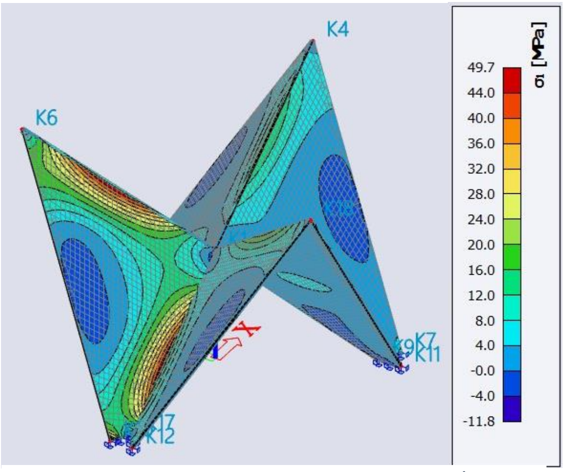


Figure 28: σ1 with a maximum stress of 54.9 N/mm^2

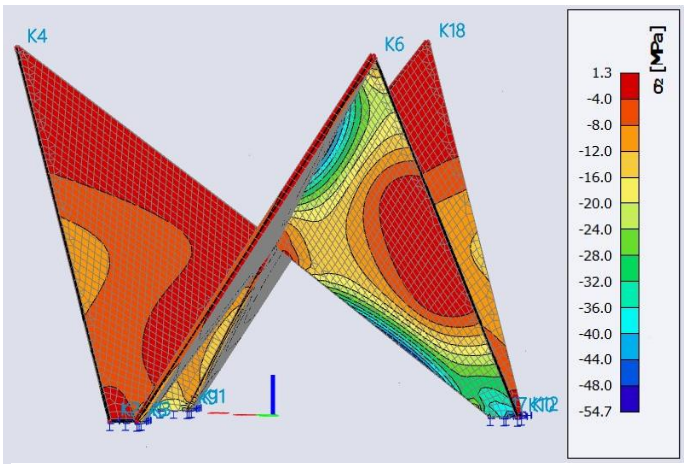


Figure 29: σ1 with a maximum stress of 54.9 N/mm^2

The load of 44 kN/m^2 is in total a load on the structure of 12.7 kN = 12700 N, obtained from the function 'result of reactions' from Scia engineering. This is the same as a load of 12700 / 9.81 = 1294 kg. This seems like a very large load on the shell structure.

It is also possible to determine the load on the structure with the area of the top of the structure. The area is 233143 mm^2 = 0.233 m^2, obtained from the Rhino model. The load in kg on the structure is area*distributed load*1000/g = 0.233*44*1000/9.81 = 1045 kg. Which still seems large.

After this it became clear that the direction in which the wood is loaded in the shell structure is not in the same direction as in the wood test. In the shell structure, the wood is loaded in the weakest direction. The maximum stress for this type of wood used in the weakest nerve direction is around 10 N/mm^2, informed by Mr. Hoogenboom. With trial and error a distributed load was put on the Scia engineer model. At first, a vertical load of 10 kN/m^2 was placed on the structure, the stresses in the model became higher than 10 N/mm^2, so the load was reduced to a load of 8 N/mm2. Now, the stresses of the σ1 = 9 N/mm2 (tensile) and σ2 = - 10 N/mm2 (compressive) shown in the figures down below.

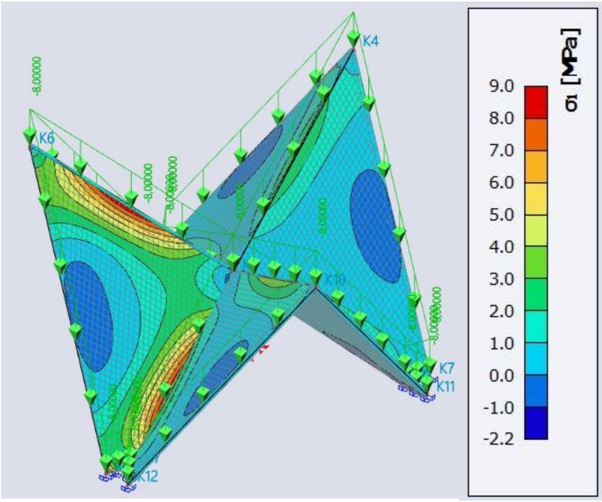


Figure 30: σ1 with a maximum stress of 10 N/mm^2

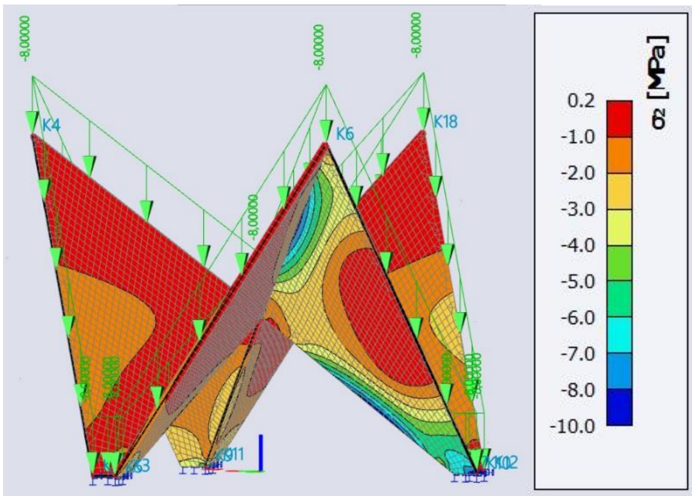


Figure 31: σ2 with a maximum stress of 10 N/mm^2

The load of 8 kN/m^2 is in total a load on the structure of 2.31 kN = 2310 N, obtained from the function 'result of reactions' from Scia engineering. This is the same as a load of 2310 / 9.81 = 236 kg.

It is also possible to determine the load on the structure with the area of the top of the structure. The area is 233143 mm^2 = 0.233 m^2, obtained from the rhino model. The load in kg on the structure is area*distributed load*1000/g = 0.233*8*1000/9.81 = 190 kg. Which seems like a too small load.

In the model the thickness of the 6 parts of the structure changes. At some places in the structure, the strength of the real shell will be higher as in the model so the prediction of the load which the shell structure will be able to take will be 250 kg.

The model will buckle by a load of 12.77 * 8 N/mm^2. As shown in the figures below. The shell structure will not fail because of buckling. The buckling load is much higher than the failure load because of the stresses.

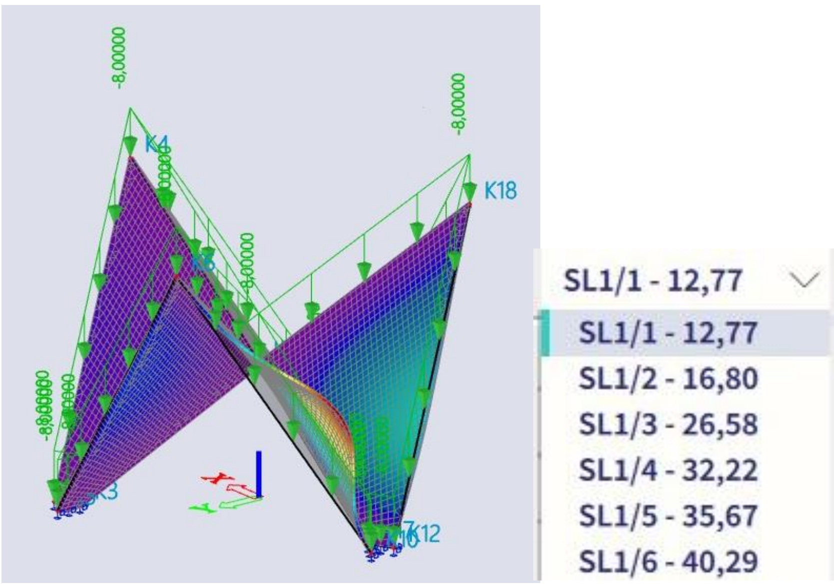


*Figure 32: Buckeling with a load of 8 N/mm^2 * 12.77*

8. Testing

After the prediction was made and noted, the test setup could be used to find out if the predictions were approximately correct.

8.1 First test

First, a test setup in the normal frame, mentioned in chapter 5.1, together with the force distribution blocks and threads structure mentioned in chapter 5.3, is used to screw on a hanging platform shown in figure 33. This platform is 0.45 * 0.45 = 0.20 m2 in measurements and is used to lay on sand-lime brick each weighing 2.085 kg. This setup only allows for 7 layers of 4 bricks which adds up to a total of 58.38 kg. The structure did not deflect or fail, so a bigger setup where more weight could be added onto the structure.

Figure 33: First test setup

8.2 Second test

In figure 34. the second test structure is demonstrated. The frame used in the test for this test is placed on four iron poles, this creates more surface area and height space to stack the bricks.

At a total of 17 x 12 = 204 bricks which is 425.34 kg, the structure failed. One slat broke as seen in the picture down below. This slat was already bending because the slat needed to be thicker to take all the weight of the structure while testing. Because this slat failed, the structure was standing on two instead of three supports. This one part of the structure hanging without support fell down and because of this, the two supported and wedged in points broke at the very bottom, shown in figure 36.

Figure 34: Second test setup

Figure 35: Failure of the broken slat

Figure 36: Failure at the supports

9. Real size shell

In Rhino 7, a model of this built design can be made. With this model, it is easy to see how to build the model from wood in the lab. In addition, this model is able to be scaled to the shell structure how it would function and look in real size. See figure 37 for the model.

The first scale that was used is 1:20. Figure 38 and 39 show the Rhino model exported and rendered in Twinmotion. This size is too small to really convey the feeling of the wooden structure that was initiated.

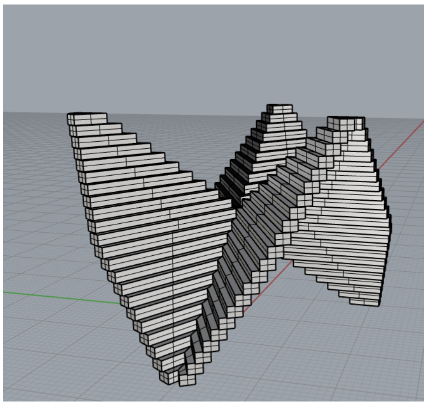


Figure 37: Rhino model of the design

Figure 38: Rhino model exported and rendered in Twinmotion scale 1:20

Figure 39: Rhino model exported and rendered in Twinmotion scale 1:20

The second scale factor that was used is 1:50. The twinmotion model can be seen in figure 40 and 41. This is the scale that is going to be used if the design was to be built in real life. This scale does the structure justice with its almost intimidating height, very open space, but at the same time only closed surfaces being used.

Figure 41: Rhino model exported and rendered in Twinmotion scale 1:50

Figure 40: Rhino model exported and rendered in Twinmotion scale 1:50

This shell structure then becomes a landmark, it has an urban look because of the shape, but the light wood that is used provides a more natural look and because of this it would fit in a nature environment like a park or an urban environment in a city to connect nature to the city.

In this scale every single block of wood used is 1 * 0.75 m in only the width and height. The length of the blocks will range between 2.5 and 11.5 m. In total, 132 blocks are needed. This structure would probably be able to be built if instead of wood glue, carefully designed connections of big nuts and bolts were used. However, this would need a lot of wood and therefore it would be more environmentally friendly to choose hollow blocks made with planks to reduce material use. The expectation for the structure on this scale is quite positive if the blocks are made of hollow wooden blocks attached onto each other with the nuts and bolts. This way the own weight will be reduced.

The model in figure 42 is 50 times bigger than the model used to build the structure in the lab, scale 1:50. To compensate for the own weight of the pieces of wood left out in the Scia model compared to the design of the structure. This is calculated from the prediction load of the left out pieces of wood in the model of 1.218 kg * 50^3 (because the model becomes bigger in three directions) = 153350 kg. Then, mass * g (to get the unit newton) / 1000 (to get the unit kilonewton) = 153350*9.81/1000 = 1494 kN

The surface of the shell from above is 233143 mm^2 = 0.233 m^2, from the Rhino model. In the enlarged version this becomes 0.233 m^2 * 50^2 (because the model becomes bigger in two directions) = 583 m^2, so the distributed load is 1494 / 583 = 2.56 kN/m^2.

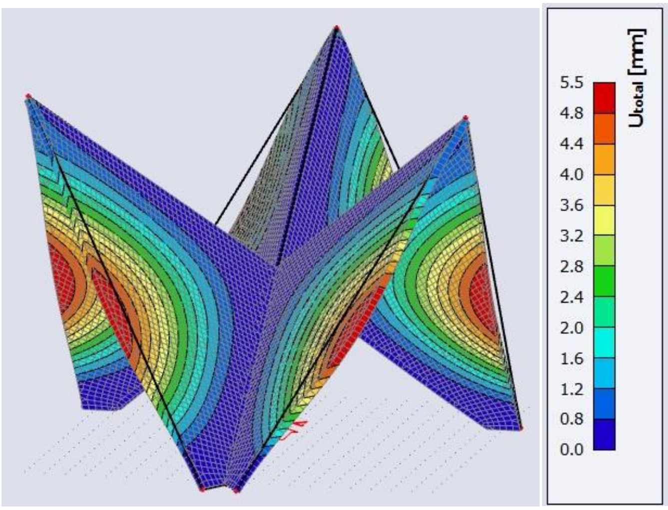


Figure 42: Scia engineering model deflection for self-weight

The maximum deflection is 5.5 mm. This is not too much deflection if only its own weight is taken into account. Next to this, the forces of possible chance of rain or snow laying on the structure also need to be taken into account. In the Netherlands, the value of snow loads on a roof is a maximum of sk = 0.7 kN/m^2 * µ1, with µ1 = 0.8 * (60 - α / 30) where α = the slope of the roof = 60 degrees. So, µ1 = 0.8 * (60 - 60 / 30) = 0.8. This gives a value of 0.8 * 0.7 = 0.56 kN/m^2 (appendix C, Kracht + Vorm). The amount of snow laying on a roof has a bigger force on the structure than rain could possibly have, so by calculating the snow impact on the structure, the rain force is already taken into account.

But next to rain and snow, wind also takes an important part in the forces on a structure. Depending on the region within the Netherlands, the height of the building and its context, a different wind factor needs to be taken into account. For this building around 1.16 kN/m^2. (Oosterhoff, 2008)

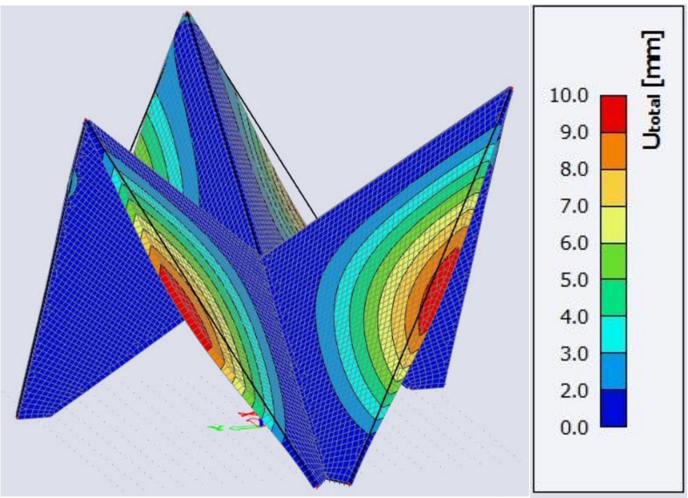


Figure 43: Scia engineering model deflection for self-weight, wind load and rain and snow load

In the figure above, the Scia model has not only taken the self-weight of the structure, but also the snow, rain and wind forces into account. All the forces together, it is still safe and realistically to get a deflection onto a wooden structure of 1cm.

10. Other tests

In addition to our test, there were 9 other groups which also conducted a test. Our group is the only one where the collapse mode is the foundation. The collapse mode of most of the groups were buckling.

10.1 Predictions and results

The predicted collapse loads, prediction errors, experimental collapse loads and the collapse modes of all teams is presented in the following table:

Team #	Predicted collapse load (kN)	Prediction error	Experimental collapse load (kN)	Collapse mode
Team 1	2,5	-2%	2,54	point load, crushing and punching shear
Team 2	1,25	-52%	2,59	buckling then breaking of the laths
Team 3	2,18	-7%	2,35	point load, punching shear
Team 4	1,96	68%	1,17	buckling at the point load
Team 5	2	0,5%	1,99	Local buckeling
Team 6	1,7	-39%	2,8	buckling of the laths
Team 7	2,56	77%	1,45	buckling of the laths at a damaged location
Team 9	6,5	48%	4,4	bending at the point load
Team 10	1,5	-54%	3,24	buckling then breaking of the laths
Team 11	2,5	-43%	4,4	foundation collapse

Table 1: Prediction + failure load

The average absolute prediction error is 39%. So our team, which is team 11, has made a slight above average error. When the absolute prediction error is ordered from smallest to largest then our place would be fifth. Furthermore, the collapse load of our team and the collapse load of team 9 have the highest experimental collapse load.

11. Discussion

During the building, predicting and testing there were a couple of things which could have been done better.

11.1 Building

In the shell which was built there were a few imperfections. The angles of the different slats had to be exactly 30 degrees at the tip that when two slats were put together the angle between the lats is 60 degrees. During building it became clear that not all slats had an exactly 30 degree angle at the tip and that this had to be corrected by properly filing the wood. This took a lot of time. Some wood, even though there was not a 30 degree angle at the point, together they formed a 60 degree angle, which was the angle the slats were supposed to form together. Then these were put together, which saved some time. In the end some slats put together were not exactly 60 degrees which caused some of the slats to not perfectly overlap by a centimeter everywhere.

11.2 Predicting

During the predicting of the strength of the shell it was not exactly clear how strong the wood was in the direction of the forces in our shell structure. It would have been better to test the wood in the direction of the forces in our shell structure. If it was known how strong the wood was in that direction the prediction of the strength of the shell would have been closer to the strength coming from the test.

11.3 Testing

The failure of the shell structure was due to the failure of the test setup, the foundation. Because the foundation failed the failure load of the shell was never determined. The failure load was at least a distributed load of 440 kg. The test setup had to be stronger to determine the failure load. It would have been better to first determine the failure load before building the test setup to determine how strong the test setup needed to be so that the test setup does not fail during testing.

12. Conclusion

The shell design made in this report is a complicated design. It consists of 6 parts which are exactly the same. The building of the shell required a lot of precision because the six parts together had to be 360 degrees otherwise there would be a gap in the shell.

The prediction of the load which the shell structure can take is a load of 250 kg, if the wood can take a maximum stress of 10 N/mm^2 in the weakest direction of the wood, the direction used in this structure. If the wood in the shell can take a maximum stress of 54.9 N/mm^2 in the strongest direction, the prediction of the load would be a load between 1045 kg and 1294 kg. The end prediction was the load of 250 kg.

In the end of the testing the foundation failed which caused the shell to fail. The shell could at least take a load of 440 kg. With the load of 440 kg there was no sign of failure from the shell structure but only a sign of failure from the foundation. The load would probably be a lot more if the foundation did not fail. The prediction of 250 kg was not correct. It was too low, this can be because the maximum stress used for the prediction was too low or the thickness of the shell in the model was not correct. Finally, it was not clear how much the shell structure could take.

In real life the shell structure can be used as a landmark in a nature environment like a park or an urban environment in a city to connect nature to the city. The scale factor would be 1:50. This scale does the structure justice with its almost intimidating height, very open space, but at the same time only closed surfaces being used.

Sources

Adelzadeh, A. (2023, 10 20). *timber shell system fuses polygonal framing & reciprocal bracing for efficient construction*. Opgehaald van Designboom: https://www.designboom.com/design/timber-shell-system-polygonal-framing-reciprocal-bracing-efficient-construction-reciprocal-shell-10-20-2023/

Musée du Louvre. (sd). Opgehaald van Lonely Planet: https://www.lonelyplanet.com/france/paris/louvre-and-les-halles/attractions/musee-du-louvre/a/poi-sig/372123/1322719

Oosterhoff, J. (2008). Bijlage D Windbelasting. In J. Oosterhoff, *Kracht + vorm* (pp. 194, 195). Zoetermeer: Bouwen mer staal.

O'Shea, J. (sd). *SHELL STRUCTURES*. Opgehaald van JOHN O'SHEA: http://www.johnoshea.ie/p_shel.html

Revit Architecture Forum. (sd). Opgehaald van Autodesk: https://forums.autodesk.com/t5/revit-architecture-forum/gridshell-roof/td-p/8733431

Shell (structure). (2023, 11 20). Opgehaald van Wikipedia: https://en.wikipedia.org/wiki/Shell_(structure)

Sheth, U. (2018, 12 30). *Digital Crafts: Timber Gridshell*. Opgehaald van CEPT portfolio: https://portfolio.cept.ac.in/archive/digital-crafts-timber-gridshell/