STUDY CASE: DESIGN AND CONSTRUCTION OF A HALF SPHERICAL DOME [RECIPROCAL STRUCTURE COVERED WITH A TENSILE MEMBRANE "NEXORADE"]

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Location of Project: *Sant Cugat, Barcelona, Spain.*
Structural Type: *Nexorade – Reciprocal Dome*
Project Scale: *6.20m diameter, 4.30m height*
Owner/Client: *UPC – MPDA'18*
Architect/Engineer: *Angel Antequera, Orlando Torricos, Tiago Medeiros, Uri Lewis.*
Construction: *Angel Antequera, Dimitar Doychev, Kavi Khushiram, Orlando Torricos, Rachid Nabousli, Tiago Medeiros, Uri Lewis.*
Construction year: *From: June 20th, 2018 - June 28th, 2018.*

Keywords: *Half spherical dome, Nexorade, reciprocal structure, wood, active bending, pavilion, tensile membrane, truncated polyhedron.*

ABSTRACT

The objective of this paper is to show the process, pros and cons of our research, design and construction in a half spherical dome structure and tensile membrane. An important application of nexorades is for shelters of various sizes and shapes for temporary or permanent purposes. In such a shelter, the structural skeleton is provided by a Nexorade and the cover is provided by a tensile membrane.

INTRODUCTION

The Nexorades are a new name for an old class of interwoven space structures also known as a multi-reciprocal grid. Such reciprocal frame structures are clearly close to tensegrity structures.

Each one of the elements that constitute a Nexorade is referred to as a 'Nexor'. A Nexor has four connection points, two of which are at the ends of the Nexor and the other two are at two intermediate points along the Nexor. The term 'Nexor' is a Latin-based word meaning a 'link' and the term 'Nexorade' implies an 'assembly of nexus'.[1]

RESEARCH AND DESIGN PROCESS

We have few restrictions at the time of designing, but very important ones: a. Half sphere dome or as close as possible to it; b. That the structure has a 3m radius and covered by a stretchable membrane.
For this, we created different tests (mock-ups) with different types of structures and materials, we started with a "Quad Gridshell with planks" [fig.1.1] in which we put staples simulating screws, but when we lifted it we had problems with the rotation of the planks. Then we recreated the same Gridshell design with rods [fig.1.4] and a node that has free rotation on the Z axis; This structure showed an optimal behavior compared to the previous model however we decided to explore more options. [2]

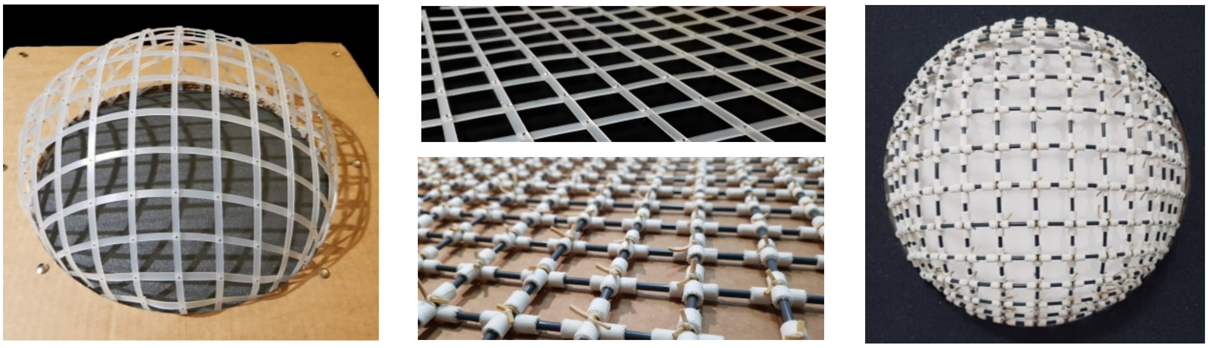


Figure 1: *Left: Quad Gridshell with planks; Middle (Top): Flat quad Gridshell with planks; Middle (Bottom): Flat quad Gridshell with rods; Right: Quad Gridshell with rods.*

As we continued investigating we decided to analyze the behavior of an active bending system which consisted of generating the desired curvature through fitting small planks at different lengths in the middle of another plank, so these generate a desired angle. The first node gets through the plank right in the middle of other, then we join 3 of these together to create a triangle module [fig. 2.1], then we put two planks on each of the long sides of the main plank, with two pins to fix them we generate the curvature, and then we tested it on a truncated icosahedron. [fig. 2.2] This system did not work as we expected, so we decided to try a similar system to the one of the reciprocal structures, 3 planks joined in each node; unlike the traditional reciprocal system, only two of them go on top of each other and the third goes below both. [fig. 2.3] This was done thinking about the material, since it's not possible to put all the ends of the planks on top of each other with this node configuration that only has 5 ° of rotation.

Figure 2: *Left: triangular test module; Middle: truncated icosahedron made with one principal plank bended with two more planks; Right: kind of reciprocal structure with only 5° rotated angle.*

The nodes needed to open more so we made another model in a truncated icosahedron scaled 1:6 to the needed radius, but this time with the nodes rotated 10 °, we did load tests [3] and get better results but needed to have more stability; We designed a system based on tension where a double set of cables tensed the structure and at the same time they work to completely stretch the membrane. [fig. 3.2] The load tests were performed with 1.5-liter bottles and were hung equally in the upper nodes.

Structure without cables:

original height = **642mm**

7.5kg load = **634mm**

1 bottle = 1.5kg

Structure with cables

Original height = **642mm**

15 kg load = **634mm**

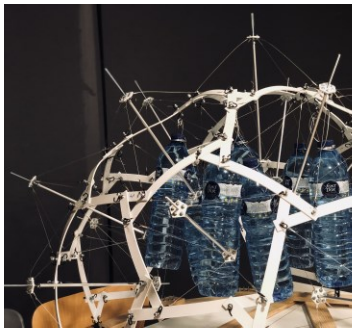


Figure 3: *Left: Load test for structure without cables; Right: Load test for structure with cables.*

The structure improved a lot with the tensor cables, and we could start designing the mesh pattern for the dome; For aesthetic reasons we designed the structure with spikes of 1.15m long (in 1:1 model metrics) with holes in the membrane at the end of each spike, so the structure could get a game of lights and shadow generated by the holes at specific hours of the day. [fig. 4] the material used in the mockup was 3mm PVC planks.

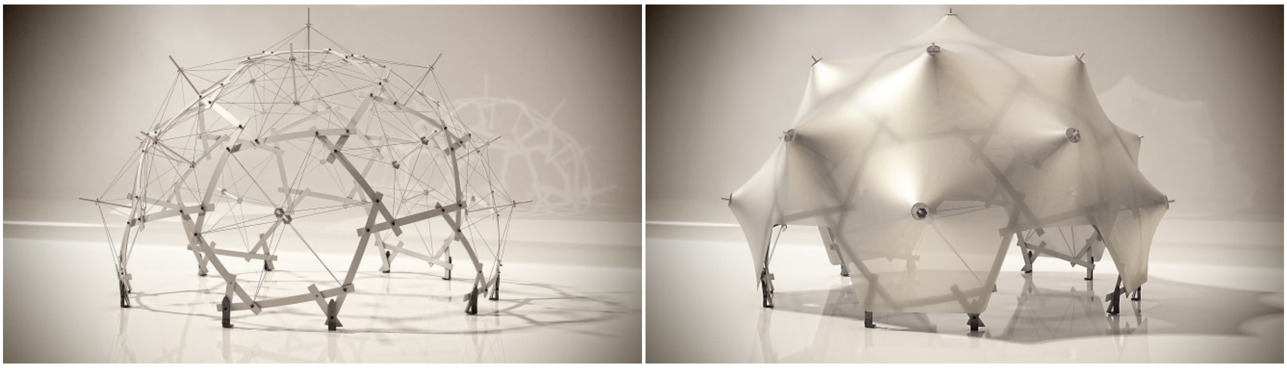


Figure 4: *Left: Render of the structure; Right: Render of the tensile membrane.*

MEMBRANE PATTERNING

For the original design of the dome patterning we draw first a triangular mesh then applied a dynamic relaxation to generate the final shape of the mesh with the desired curvature, then we chose the pattern that most approached the curvature of the mesh [Fig. 5]; geodesic lines were drawn, and the calculation of linear meters was generated on rolls of 1.45m of fabric.

In total, 4 different pieces were needed, 2 of them were used to create hexagons and 2 for the pentagons; with the two mold pieces together you create a side of the polygon, therefore, to create a pentagon you need separate 10 pieces and for the hexagons 12 pieces; doing a nesting of all the pieces, we end up having a total of 44 lineal meters Fabric that is necessary to cut, join and assemble; this pattern is so easy to work with that you only need to worry about learning how to weld one polygon to fully understand how to get the whole membrane and then just repeat the process for the remaining polygons. [3]

For the built model we had to reduce some pieces and modify the design of the membrane (without holes) so we removed the steel rings with which the membrane was stretched and included a half sphere of polished wood at the ends of each spike to be able to stretch the membrane without breaking it.

Then the pattern also had to change for another more complex with fewer parts, and larger polygon sizes to reduce the price of the joints, so, we designed an exact plan of how to cut and join the pieces. [Fig. 8]

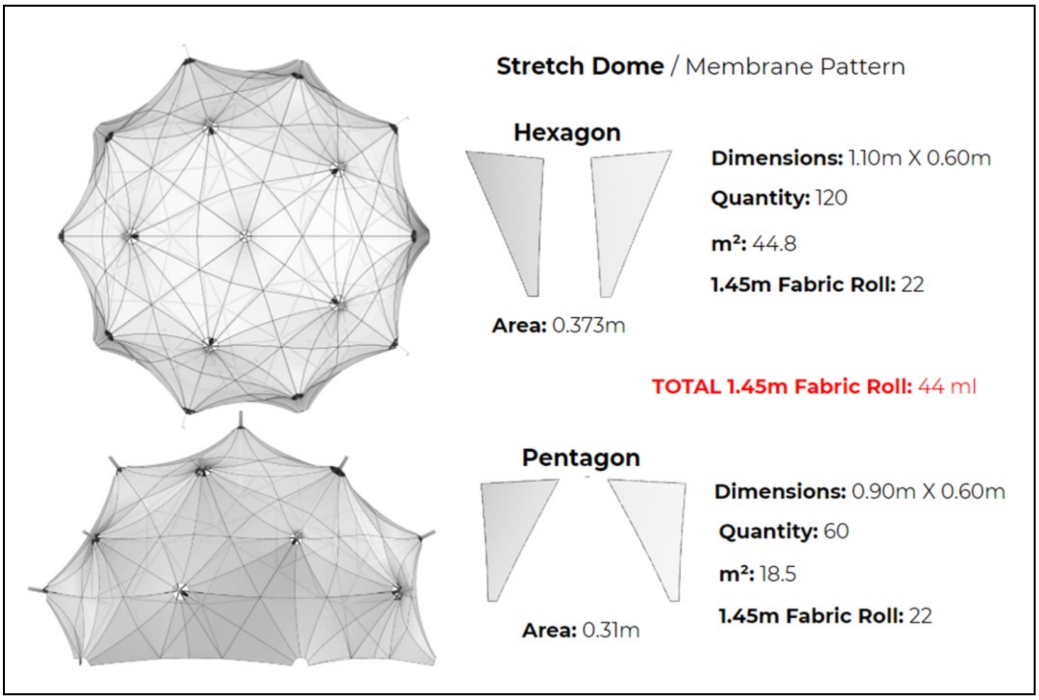


Figure 5: *Original Dome Membrane Pattern*

This is the physical model of the finished structure [Fig. 6] and then the model with the membrane stretched on the structure. [Fig. 7] The dotted lines are due to stapling the fabric for a matter of time. The best option would have been to sew the membrane, so we could be able to stretch it to the maximum without having to worry about the joints being opened; This model was exhibited in the final presentation, where we won the prize to build it in full scale.

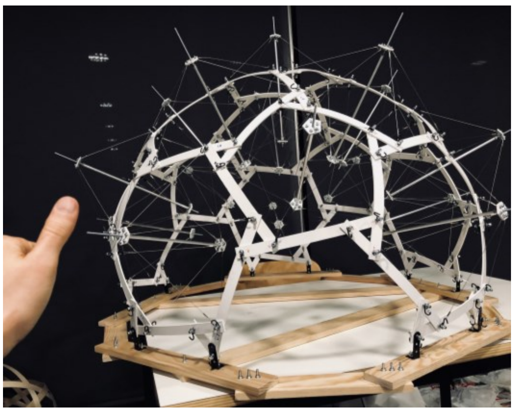


Figure 6: *Structure mock-up [scale 1:6]*

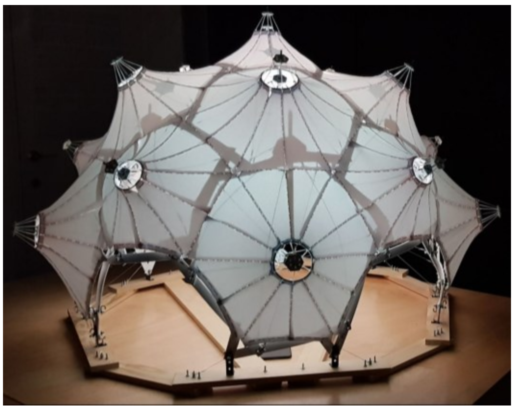


Figure 7: *Final mock-up [scale 1:6]*

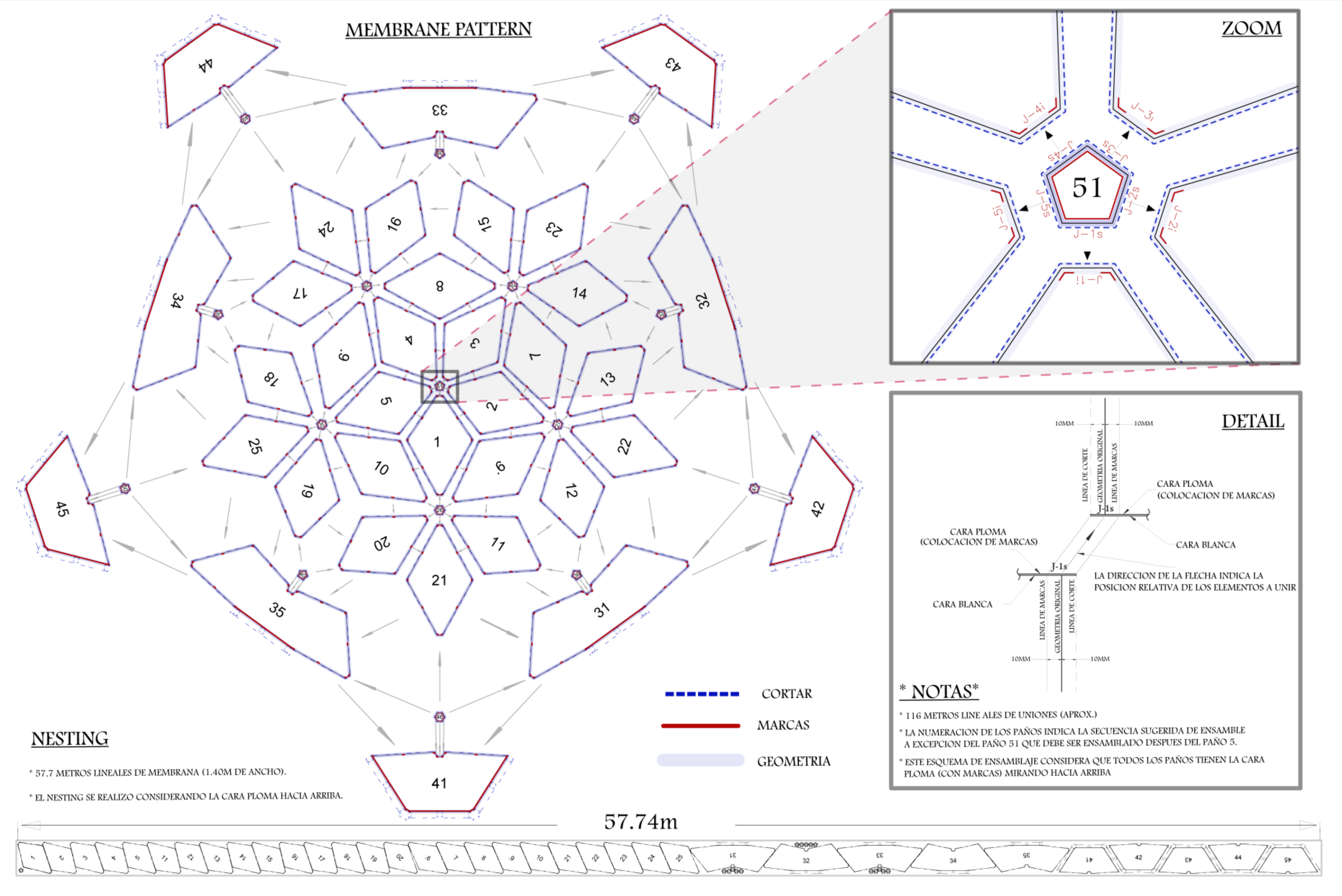
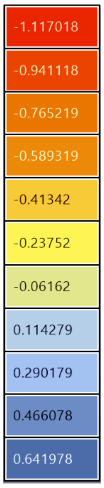


Figure 8: *Plans of the final dome membrane Pattern*

STRUCTURE ANALYSIS

For the structural validation of the chosen model, several simulations were carried out using the K2Enginnering plug-in for grasshopper, this plug-in offers the advantage of being integrated in an environment that allows us to test different configurations without leaving the working environment of the Grasshopper.

For the first structural model, "fiberglass-reinforced plastic" or GFPR was used as the material of the elements, all the bars were composed of 100x10mm planks curved to a radius of 3m and assembled in such a way that they form a system like a reciprocating structure. This base structure was subjected to the action of 5 nodal loads of 500N in five nodes located in the upper part of the model, the initial results showed a great initial deformation due to these loads as can be seen in figure [Fig. 9]



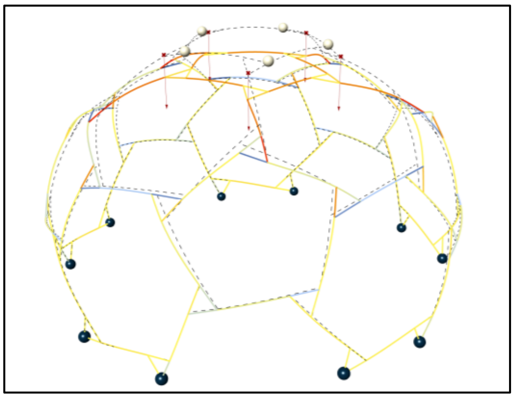


Figure 9.1*: Min & Max Axial Force*

Min & Max Axial Force (kN): -1.1171 ***to*** *0.6419*

Min & Max Axial Stress (MPa): -1.117 ***to*** *0.642*

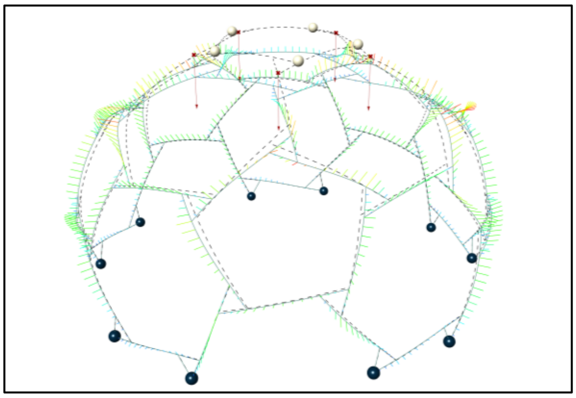


Figure 9.2*: Min & Max bending moment*

Min & Max Moment (kN.m): 0.000052 ***to*** *0.250142*

Min & Max Bending Stress(MPa): 0.031 ***to*** *150.085*

To increase the stiffness of the system, floating masts connected to the main plank structure were installed by means of prestressed steel cables and laid out in a cross way following some guidelines of the tensegrity structures, this resulted in a substantial increase in rigidity of the whole system, a fact that is appreciable in the calculation model that carries the cables. [Figs. 10 & 11]

Min & Max Axial Stress (MPa): -1.118 ***to*** *0.033*

Min & Max Axial Force (kN): -1.118124 ***to*** *0.032*

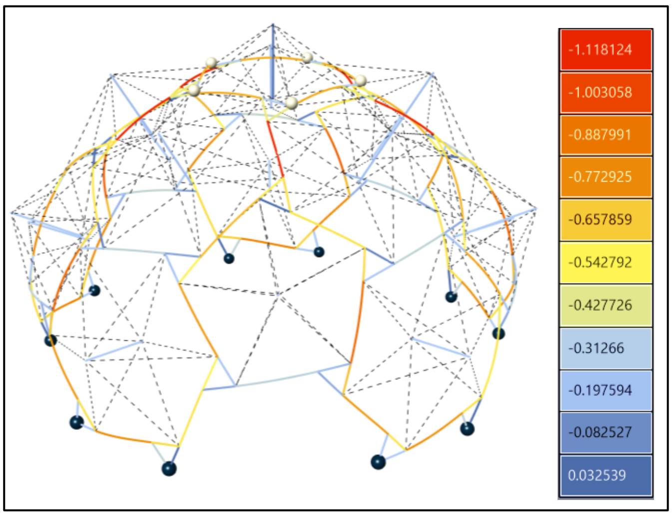
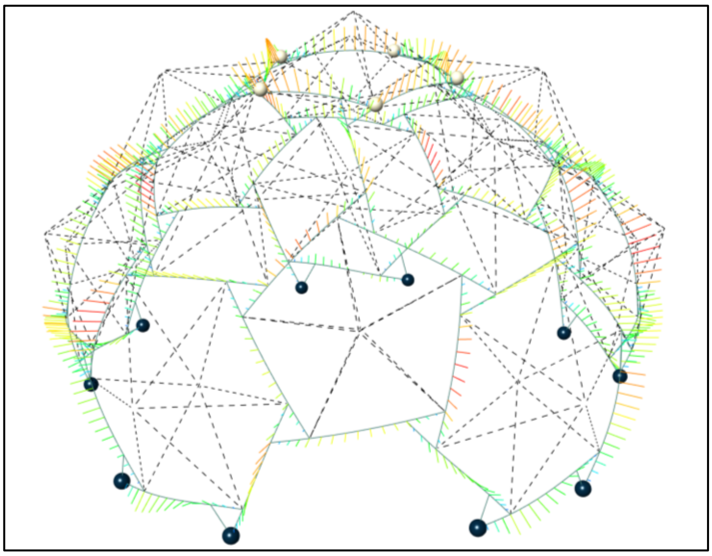


Figure 10*: Structural Analysis (Planks + Cables): Initial relaxation + Self Weight + Live Load (5 Nodes, - 500N by node)*



- *Min & Max Moment (kN.m): 0.000058* ***to*** *0.174381*
- *Min & Max Bending Stress (MPa): 0.035* ***to*** *104.628*
- *Min & Max Horizontal Reactions (kN): 0.306753* ***to*** *0.372076*
- *Min & Max Vertical Reactions (kN): 0.336398* ***to*** *0.495493*
- *Sum of Vertical Reactions (kN): 4.149237*
- *Total Weight of Structure (kN): 4.35319*
- *Weight / Sum of Reactions: 1.049154*

Figure 11*: Structural Analysis (Planks + Cables): Initial relaxation + Self Weight + Live Load (5 Nodes, - 500N by node)*

For the construction model it was decided to change the material to laminated wood planks of high resistance, we proceeded to carry out a new analysis and this time using a calculation program that takes into account the six degrees of freedom of the elements that make up the As in the K2 model, the same tests were performed and similar results were obtained. In addition, the first 100 modes of global vibration of both models were evaluated and the results allow us to appreciate the substantial increase in the rigidity of both systems. [Fig. 12]

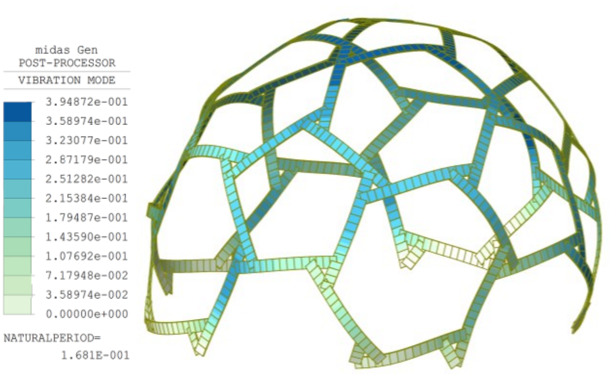


Figure 12.1*: Structure - Vibration Mode 01*

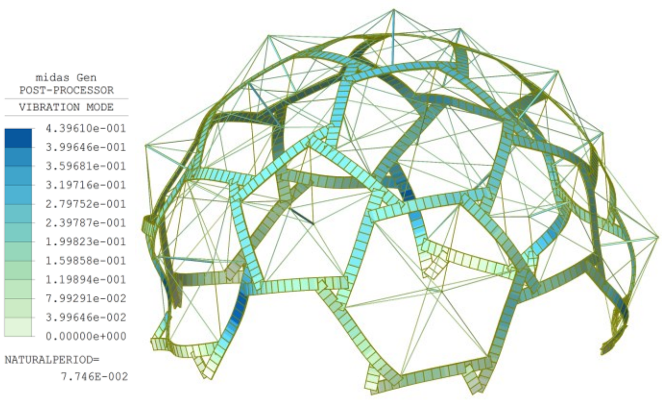


Figure 12.2*: Structure With Spikes - Vibration Mode 01*

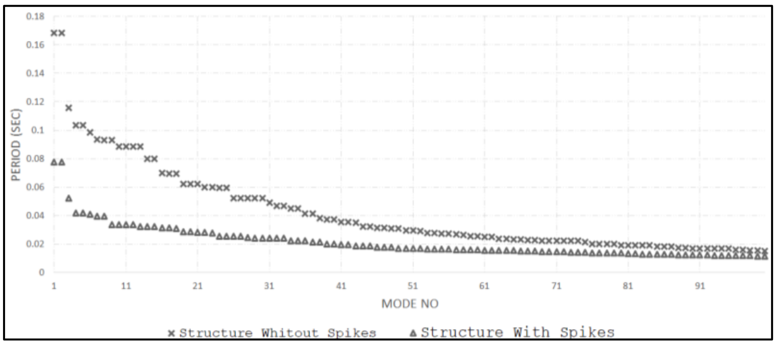


Figure 13*: Eigenvalue analysis control*

CONSTRUCTION PROCESS

Thanks to the parametric tools we used for designing the dome we could easily get the list and quantity of all the pieces to build the dome. We needed to manufacture all the pieces except for washers, nuts and the membrane because of the budget given, but this could be sent to a carpenter and blacksmith for only assembling it. After finishing all the pieces, we leveled the floor to started assembling the base to avoid extra loads on any side. As we finish fixing the planks of the base we started screwing the supports on the planks looking towards to the center of the dome. [Fig. 16]

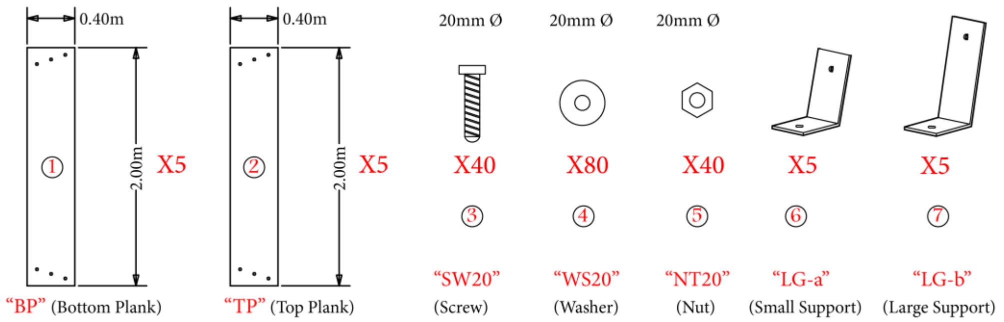


***Figure 14**: Elements we use for building the base*

The base was added to make this structure transportable, and not be fixed in an exact spot, so it can make the work of foundations, to keep everything in place; the drawings are part of the manual we did referring to build a 1:1 dome of the original design, with membrane holes and steel supports.

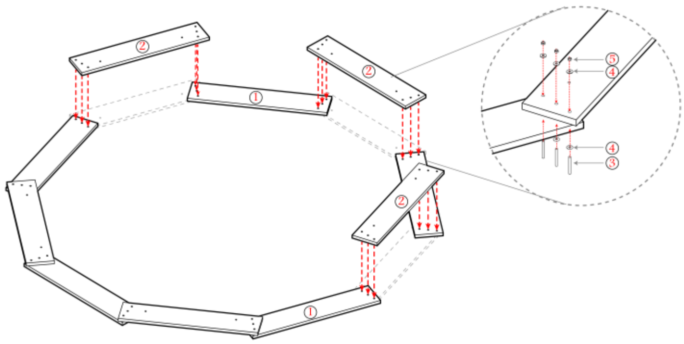


***Figure 15**: Assembly process of base planks*

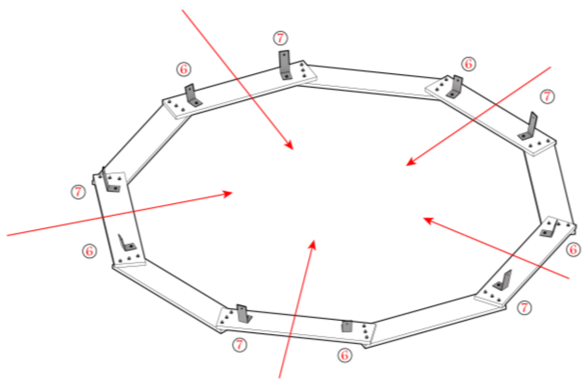


***Figure 16**: Assembly process for supports*

Then we assembled the main structure, which is divided into 5 rows. As it's shown in the next figure. [Fig. 18] As the last plank is assembled we started placing the spikes, it is important that the internal cables are fully tensioned, and the external cables be loose, so we can place the membrane and then stretch it by tensioning those last cables.

To finish we place the membrane and fix the boundaries with cables. Once we have all the edges fixed we proceed to tighten the external wires of the spikes by the mechanism of the upper flying mast until all the cables are 100% tensed.

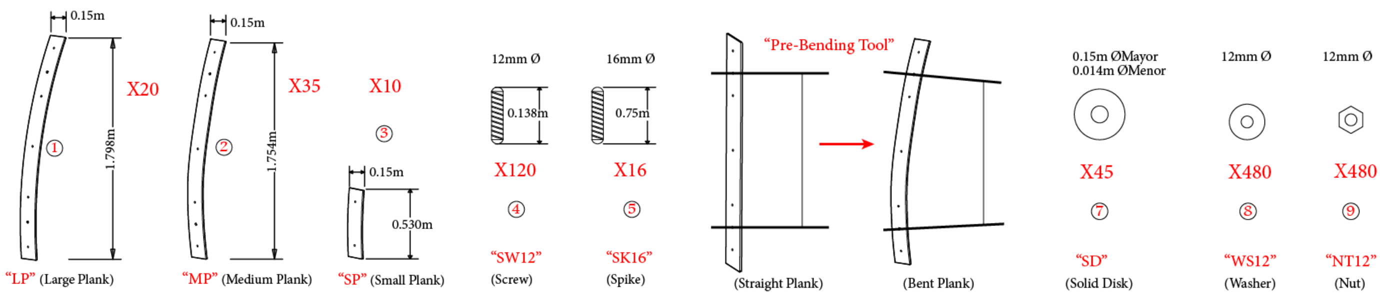


Figure 17: *Elements needed for building structure*

We are showing just some pages of the "construction manual" to show an idea of how we managed to build this 6m diameter dome. For detailed information and more visual understanding please watch the presentation with complete process in animated stop motion gif, and the rest of images.

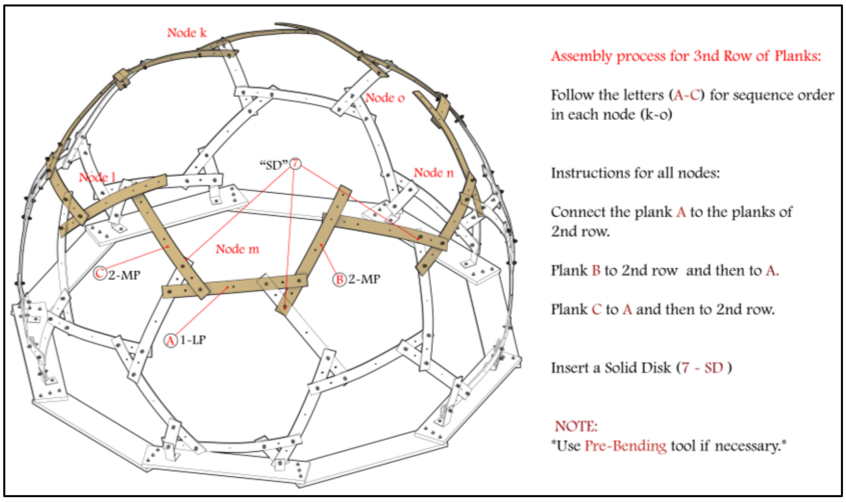


Figure 18*: Instructions for assembling the 3rd row of planks*

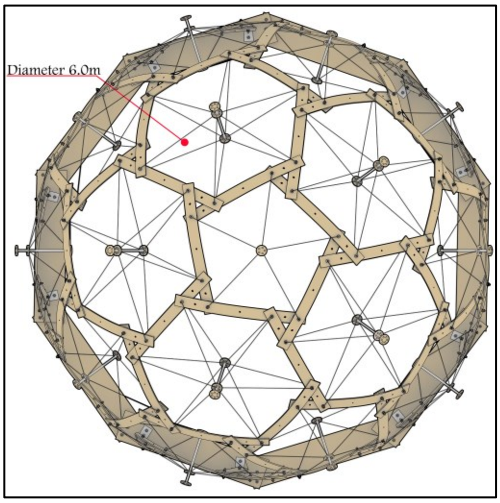


Figure 19*: Dome top view*

The construction technique is the same for both domes, it only changes for tensing the membrane.

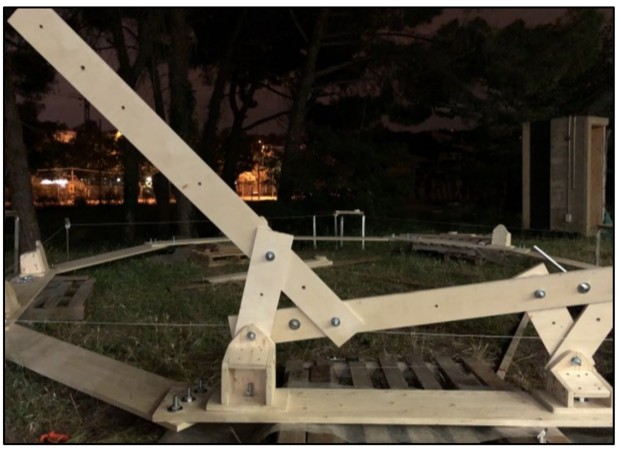


Figure 20*: Assembling supports and 1st row planks.*

Figure 21*: Assembling 3rdrow structure planks.*

__Figure 22__: Assembling cables and spikes

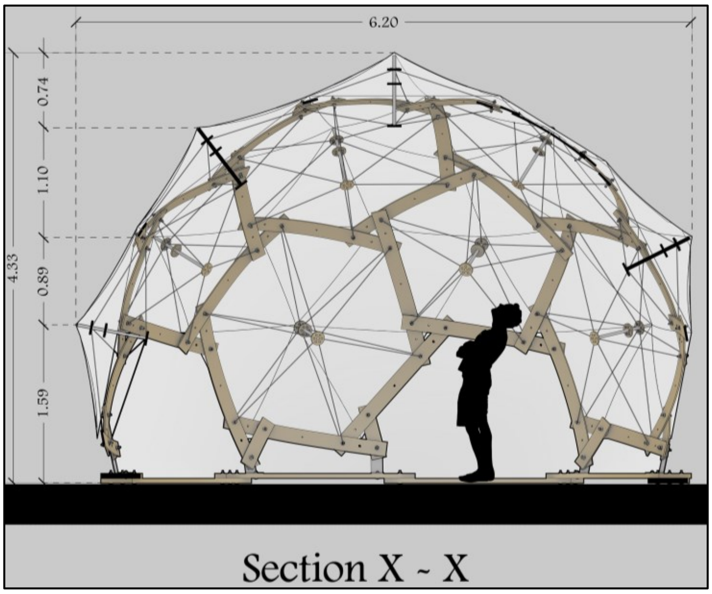


__Figure 23__: Section X -X drawing

***Figure 24:** Left (Top): Placing Membrane; Left (Bottom): Original design in 1:6 mockup with the final build 1:1 dome; Right: Fully stretched membrane. (photos by: Uri Lewis)*

CHALLENGES

The main challenge was to modify the original design and produce all the pieces for the construction in just a few days; and we had to changes some parts for the real scale dome like the steel support that we replaced with wooden handmade supports.

On the other hand, the membrane was glued instead of welded, so when we tightened 100% the cables to stretch the membrane, part of the membrane was detached so we had to re-glue it with more super-glue.

In case of being able to increase the budget, it is recommended to buy the specific joints for the corners of the membrane [4] that stretches completely the edges and they avoid you to struggle with the wrinkles. [Fig. 25]

Other challenging situation was trying to make all the structure analysis on the new grasshopper plugins like K2 engineering [2] but finally completed with Midas Gen. [3]

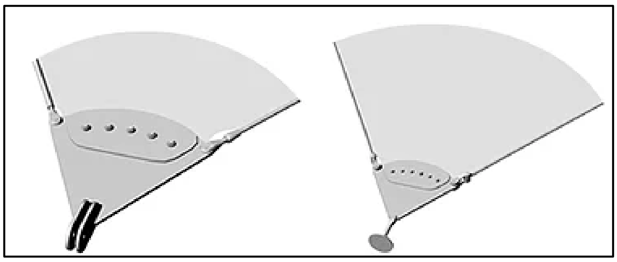


Figure 25: *Corner Plates with adjustable cables.*

CONCLUSIONS

After making the structural analysis and verifying the behavior of the structure by a couple of scaled models and nodes, we started to build; It took 6 days to fabricate all the pieces, 1 day to assemble the structure and half day for the membrane. For the assembly we needed 5 people, but thanks to our "Pre-Bending" tool, the dome could be assembled without problems by 3 people; The pieces were easy to manipulate, so we do not need any special machinery to build it. The tension of the cables was easy to manipulate due to the system that allows us to move the flying masts trough the spikes by rotating the nuts. at the same time, this made it easier to place the membrane, because this system reduces the amount of force required to adjust and tense the cables. It's easy to transport and assemble.

FURTHER RESEARCH

For further research we can evaluate the same system with a higher density and applied to larger scales. Can also try to apply it to different geometric shapes and solve problems with double curvature. The only rule that must be maintained in this system is that 3 elements must always arrive (in this case planks) to each node.

Figure 26*: Nexorade Dome - Panoramic View [photo by: Uri Lewis]*

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