MPDA
Master's degree
Parametric Design in Architecture

UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH
School of Professional & Executive Development

Form finding and efficiency for a bending active hybrid structure in a dome

Erika Alejandra Paz Yañez, Miguel Cárdenas Pantoja, Luis Jaime Domínguez Ramos

Abstract

The main objective of this thesis is to explore the framework of the textile hybrid structures made of carbon fiber bars and membranes in order to achieve a correct optimization as well as a complete test study by means of computer simulation that allows its future use in the practice of architecture. Concepts such as form finding, tensegrity and balance between tension and compression will be applied specifically to dome shaped form showing that is possible to obtain a graceful working system using active bending elements and a single watertight covering element.

Keywords: Parametric**,** hybrid structure, bending active, tensegrity, form finding, dynamic relaxation, non-linearity, stiffness.

1. Introduction

In previous studies we had the opportunity to explore light structures that can make use of active bending and that can be functional for practical uses, this has aroused curiosity in us and has led us to investigate more and try to achieve a suitable balance between the involved parts.

We believe that it is possible to make use of these structures more frequently in the field of architecture so we started using the same project we had before where we used a dome shaped geometry made of carbon fiber rods and membrane in the search of new ways to activate all bars, membranes and rods involved to reach a hybrid structure by balancing the efforts made by its elements, and now we have reached the point where computational design allows us to experiment with different elements at the same time, K2E (Kangaroo 2 Engineering) is the tool we used to extract by simulation, data that we need to demonstrate that each element in our design is working in a nonlinear behavior.

This paper shows the form finding process, optimization and manufacturing process of a dome shaped parametrized geometry. It makes a statement about hybrid structures and how they behave when they reach isotropic (balance).

2. Bending active Hybrid structure features

This section introduces the engineering background of hybrid structures according its mechanical behavior and material properties.

2.1. Bending active Hybrid Structural Systems

Textile Hybrid structure is a family of Bending-active structures, due to a system inherent residual stress state and elasticity, their load bearing behavior is characterized by nonlinearities in structural analysis. Regardless its complexity, it has been categorized by families in an abstract Engels definition in structural action.

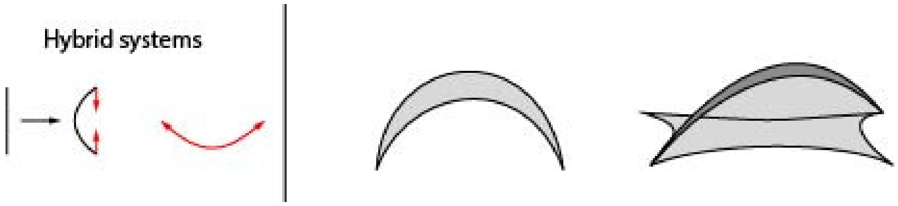


Figure 0: Hybrid systems categorized according to structural action [1]

In textile hybrid systems there exist a reciprocity between the mechanical behavior and load bearing in each one of the elements. This entails an improvement in favor of the structure stiffness, since each element of the structure is restrained by the other one.

2.1.1. Structural Action

The interdependence of form and force of mechanically pre-stressed textile membranes and bending-active fiber-reinforced polymers with the help of steel cables promote flexibility and lightness. Their reciprocal dependency of mechanical properties makes them a particularly interesting field of application for bending-active structures whose features are one of the main goals to achieve in the following chapters.

Functionally, the integration of elastic beams within a pre-stressed membrane and cables offers the possibility to minimizing tension forces and creating free ending points.

2.2. Basics of Mechanical Behavior

2.2.1. Nonlinearity

Systems that are defined differently from the normal static equilibrium equation are named nonlinearity, because the displacement and internal stress no longer change with only the external forces.

In the analysis of structural systems there exist several aspects of nonlinearity such us material behavior, boundary conditions. In the following chapters, we will analyze the relationship of external forces and deflection from a given geometry and how optimized this can be with different modulus section of the beams.

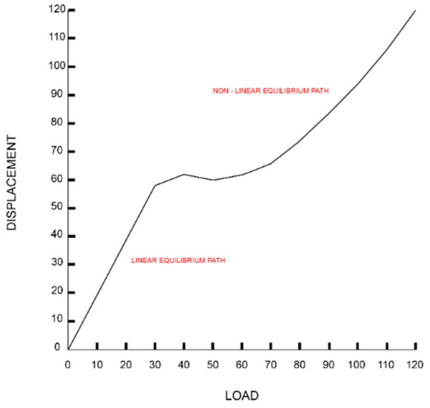


Figure 1: General load displacement diagram, with the load factor on the horizontal axis and displacement on the vertical axis. [13]

The diagram above (Fig. 1) is a graphical representation of the structural behavior, in which the proportional equilibrium of external load and displacement (continuous curve) differ when this element changes into a more elastic behavior.

Displacement diagrams is the key of the analysis. In this term, the degree in non-linear structures shows the critical points where the equilibrium becomes unstable, so the structure deflects without external work.

Aspects of nonlinear Analysis

For a nonlinear system behavior, equilibrium is only fulfilled in the deformed configuration where the stiffness (K) is no longer constant and is updated on the actual deflections with the unknown displacement vector (u). Here, an n times force vector (F) leads to an m times deflection, disproportionate to n. This phenomenon is generally referred to as geometric nonlinearity or initial stress-stiffness. [13]

Nonlinear:

$$K(u) \cdot u = F \tag{1}$$

$$F \cdot n = K(u) \cdot u \cdot m \tag{2}$$

With $n \neq m$

Stiffness

It can be generalized that in nonlinear analysis, the stiffness in the entire structure is influenced by the strains and stresses within the structural elements.

P-Delta effect indicates this large lateral displacement:

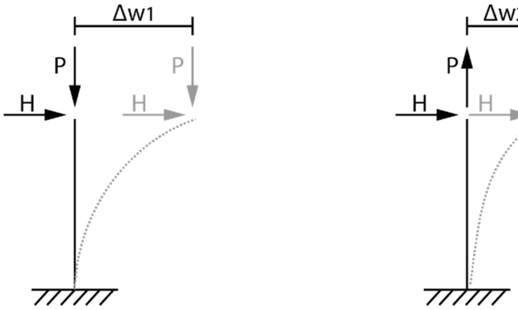


Figure 2: P-Delta, bending moment given by force (P) shows the deformation caused by (H)[2]

2.2.2. Pre-stress

A stated, pre-stressing of a structure will only increase its stiffness but not its load bearing capacity. [2]

Membrane pre-stress

A shell element can include pre-stress in two perpendicular directions. This so-called biaxial pre-stress state can be of same magnitude in the two directions. The effect of membrane pre-stress is similar to a cable. [13]

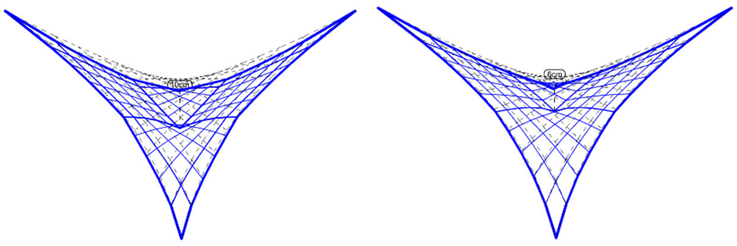


Figure 3: Non pre-stressed vs pre-stressed membrane

2.2.3. Elasticity

Elastic bent elements have an initial stress caused by bending. The higher the initial stress, the lower the stress reserve under external loads. [13]

2.2.4. Derivative of min. Radius (curvature)

On the assumption of linear elastic material behavior, the initial stress caused by bending along one axis is defined as:

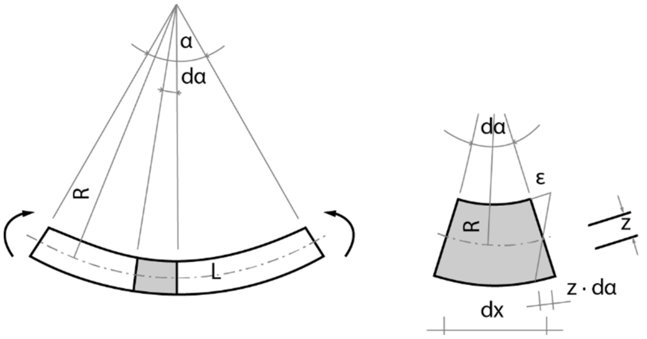


Figure 4: "Relationship between the stress, radius of curvature, and section depth in a deflected beam" [14]

$$\varepsilon(z) = \frac{\sigma(z)}{E} \tag{5}$$

$$\varepsilon(z) = z \cdot \frac{d\alpha}{dx} \tag{6}$$

$$\sigma(z) = E \cdot z \cdot \frac{d\alpha}{dx}$$

$$\frac{1}{R} = \frac{\alpha}{L} = \frac{d\alpha}{dx} \tag{7}$$

$$\sigma(z) = E \cdot z \cdot \frac{1}{R} \tag{8}$$

E represents the Young's modulus of the material, z the position of the height related to the neutral axis, and R the radius of the curvature". [14]

2.3. Bending-active hybrid materials

2.3.1. Rods

The quality of a bending-active structure relies in the characteristics of its materials. The main behavior of these materials is high in strength and "low" in stiffness.

Fiber reinforced polymers offer high potential in the field. These FRPs have a low density and high strength in combination with a relative low stiffness. Developments in the world of FRP's suggests that this material will even be more improved over the coming years.

From the equation of minimal bending radius, the minimum bending radius depends on elasticity, strength of the material and profile height. Thus, it is important to keep these properties and their ratio in mind while choosing a material.

Ashby introduced a graph to choose adequate materials for different systems. In his diagrams, he grouped different material properties and after that introduced limits.
With the help of Ashby's graph, it is easier to select an adequate material for certain designs. This table shows the behavior of typical material for construction. [4]

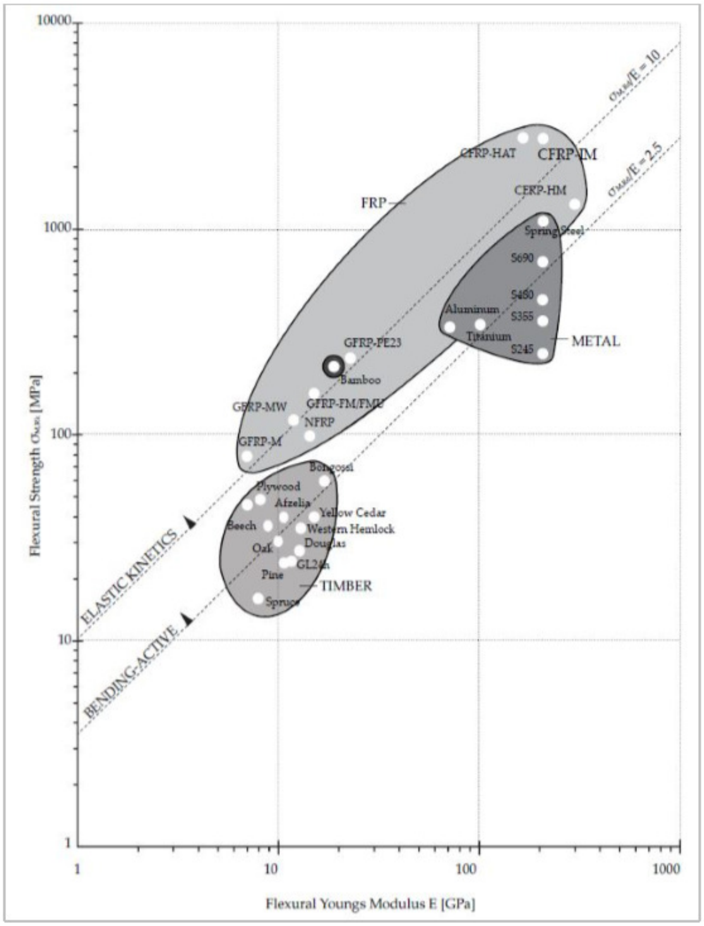


Figure 5: Material properties [4]

Based on the experience of the case study structures presented in the work of Lienhard [13] two different types can be described for adequate materials in bending-active structures (Fig. 5):

"It can be concluded from the diagram that certain types of timber can be adequate material for bending-active structures". However, we consider only GFRPs (Glass Fiber Reinforced Polymers) because of its better material properties for long-term behavior. If they are not subjected to yield stress, they will always be straight, i.e., dismantled.

2.3.2. Membrane

Textiles are semi-finished products made from woven fibers.

Fibers can be described in different ways by its composition:

- Filament: single fiber
- Roving: bundle of parallel filaments
- Yarn/Thread: bundle of twisted filaments
- Twine: bundle of twisted yarns

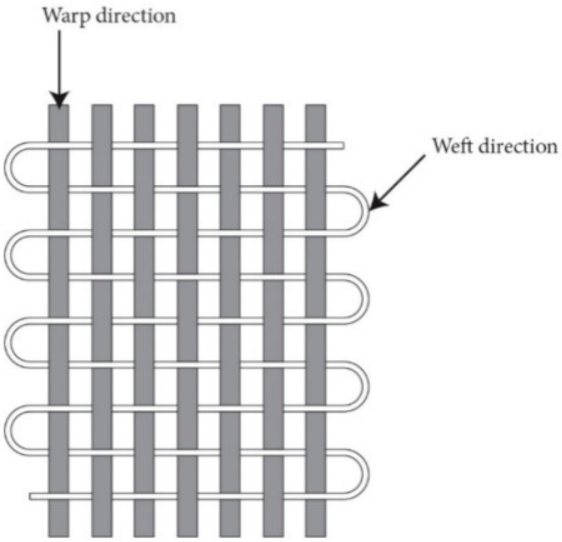


Figure 6: Warp and Weft.

Coating is usually applied either in one or both faces in order to provide a better behavior. This can be made with polyester or glass fiber fabric.

The properties differ in the warp and weft direction of the material. For each project it is important to check which properties are important for the desired membrane. For instance, PTFE coated glass fiber fabric have a high sensitivity to flexural cracking of the material (glass-fibers).

The tensile strength in membranes can be determined by uniaxial tensile tests on membrane strips of 5 cm wide. The values are often a little bit higher in the warp direction compared to the weft direction. The thickness of the material can be neglected and therefore the tensile strength is described as force per length (N/5cm). Membranes can be classified according to Knippers [5] in 5 types:

- Type I +/- 3000 N/5 cm
- Type II +/- 4000 N/5 cm
- Type III +/- 5000 N/5 cm
- Type IV +/- 7000 N/5 cm
- Type V +/- 9000 N/5 cm

The tear propagation resistance is tested by uniaxial loading a specimen which is insisted in the middle. These values represent the force a damaged membrane can still carry. This should be as high as possible to prevent sudden collapsing of the tensile structure by a local failure.

2.3.3. Cable

In the field of cables, we can find many different types of fibers given its continuous development:

- mild steel
- high strength steel (drawn carbon steel)
- stainless steel
- polyester
- aramid fibers.

Steel cables are either spiral strand, where circular rods are twisted together and "glued" using a polymer, or locked coil strand, where individual interlocking steel strands form the cable (often with a spiral strand core).

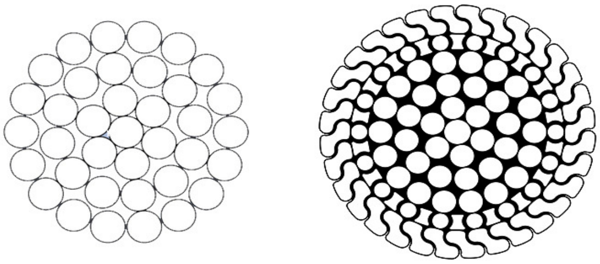


Figure 7: Spiral Coil Strand, Locked Coil Strand.

Spiral strand is slightly weaker than locked coil strand. Steel spiral strand cables have a Young's modulus, E of 150±10 kN/mm² (or 150±10 GPa) and come in sizes from 3 to 90 mm diameter, Spiral strand suffers from construction stretch, where the strands compact when the cable is loaded. This is normally removed by pre-stretching the cable and cycling the load up and down to 45% of the ultimate tensile load.

Locked coil strand typically has a Young's Modulus of 160±10 kN/mm² and comes in sizes from 20 mm to 160 mm diameter. The properties of the individual strands of different materials are shown in the table below, where UTS is ultimate tensile strength, or the breaking load [2]:

	E (GPa)	UTS (MPa)	Strain at 505 of UTS
Solid steel bar	210	400 - 800	0.24%
Steel strand	170	1500 - 1770	1%
Wire rope	112	1500 - 1770	1.5%
Polyester fiber	7.5	910	6%
Aramid fiber	112	2800	2.5%

Table 1: Cable breaking load.

2.3.4. Swivel Couplers

The joints in the structure must also satisfy the mechanical properties to avoid the snap of the structure, the following table shows the maximum force different types [3]:

Type of fitting	Loading types	SWL	
		KN	Kg
Right angle coupler	Slip along the tube	6.25	640
Putlog coupler or single coupler	Force to pull tube axially out of the coupler	0.59	60
Joint pins (expanding spigot c.)	Shear strength	21	2140
Sleeve coupler	Tension	3.1	315

Table 2: Cable breaking load table.

3. Building Structures system

A structural system can be defined as the interconnection of elements through an initial plot that allows get complex shapes providing different grades of stability and durability.

The materiality in each structural system allows us to evaluate the physical behaviors of the forms that we are getting, which allows us to define a universe of ranges of efforts and applied loads within of the types of structural System we are going to apply the following fields.

3.1. Active bending structures

The term bending-active refers to a structural system and a construction principle in which bending is used as an instrument to get different shapes and stabilize a form. Active Bending used as a self-formation process.

Various construction methods have been developed empirically from vernacular architecture. In this process the experimentation with many materials could establish the differences between light weight elements and heavy materials, having this in mind the use of elastic deformation materials allowed to reach a new option of constructive methods for double curved surfaces and shells.

The traditional materials to build building were wood, bamboo and reed which offered a wide application of active bending in vernacular constructions that have been applied in many cultures as complement of their edifications. The lack of alternative manufacturing techniques for curved buildings components or entire structures made active bending a pervasive building technique.

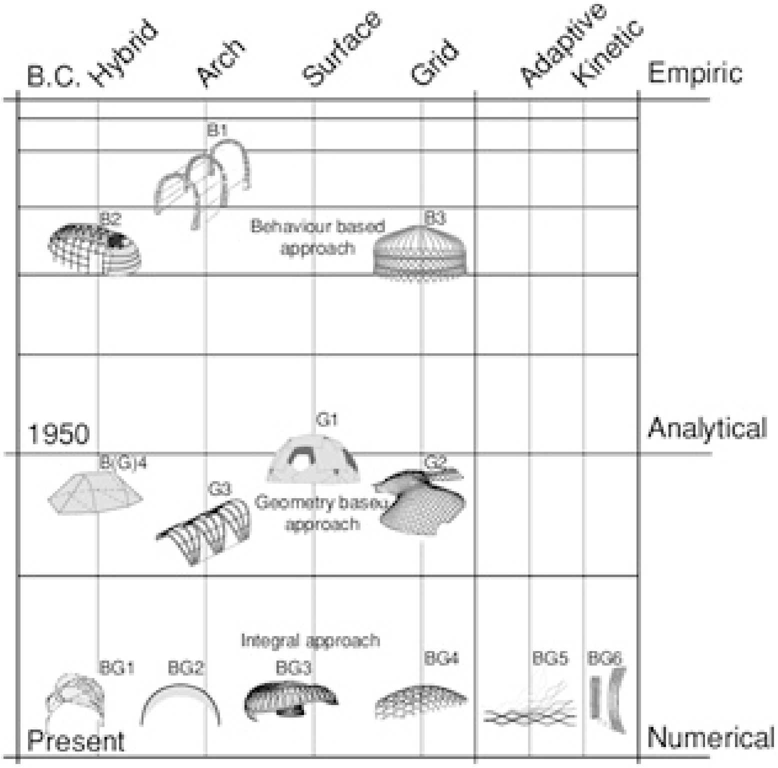


Figure 8: Development of bending active structures[15]

The development of bending active structures as is shown in Figure 8 have a different initial element that works by achieving several shapes and behaviors. For example, the second column (B1, G3, BG2) has in common the use of an arch as a result of a bending action.

The third column (G1, BG3) uses as a starting element a surface that could have any type of limits, since, at the time of grouping, the active bending of these flat elements would show the real behavior of the elements used. In G1 these compositions were conceived with more regulars' elements while in BG3 the surfaces and their active bending as composition is more complex due to the use of numerical programs.

The fourth column (B3, G2, BG4) uses a grid that can be rectangular triangular, etc. The concept of weaving element allows us to obtain different proposals of grids that function as a large structure that simulates a shell.

The first column (hybrid) and the fifth column (adaptive kinetics) are the combination of the above-mentioned structures with other elements that allow in one case to increase their stiffness and in others, make static structures more dynamic. In hybrid structures as it is shown, membranes or cables would be the second element that help the initial structure in sharing efforts and in adaptive kinetic structures are adaptable to multiple uses since it has an integrated movement system.

The empirical process obtained by mistake and test from the first buildings in attempts to generate structures, allowed to establish classifications of structural systems under the criteria of many engineers who from ancient civilizations have been employed trying to explain the nature of the behavior of the different applications conceived. Henio Engel is an engineer who, under criteria such as the development of a structural system and the essence of his function of load transmission, made them a more precise classification, especially of 2 important points for the system we are studying.

3.1.1. Structural Systematization

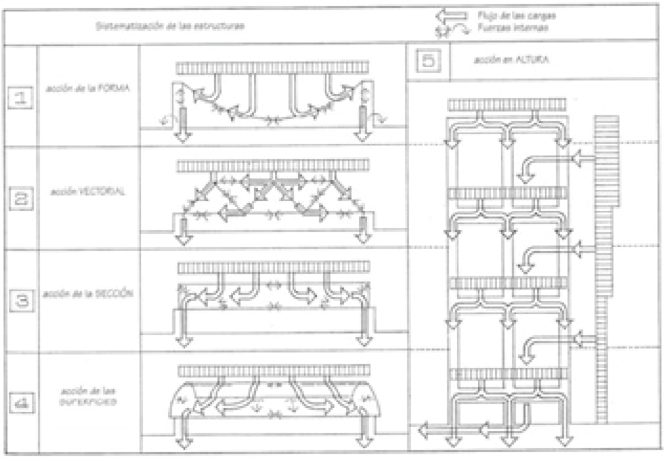


Figure 9: Structural Systematization. Systematic basis. Editorial Gustavo GilliS L. Barcelona, 2006. 1edicion,4 Tirada. [17]

This structural systematization establishes a classification through the elements used that define the typical mechanisms of nature as an exploratory part of the first civilizations. This could be understood and used under the empirical conception of naturally functioning systems that can be applied in various buildings.

Understanding the action of the form, the division of the forces, the confinements of the sections and the dispersion of each of these forces allows us to understand the general behavior of an applied system.

3.1.2. Classification of structural Systems

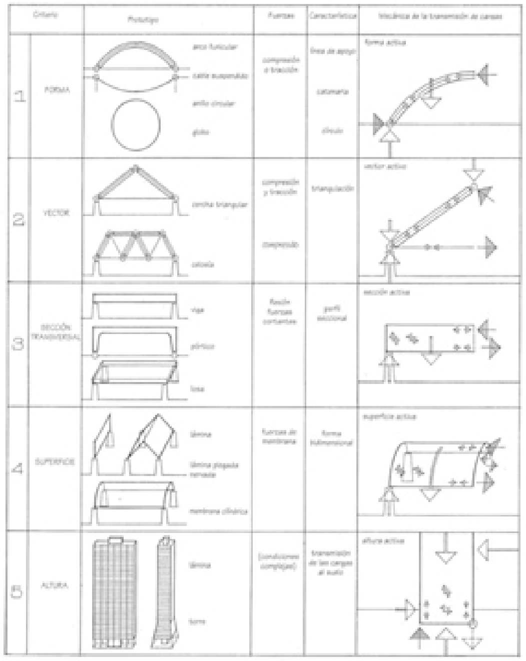


Figure 10: Structural System. Systematic basis. Editorial Gustavo GilliS. L. Barcelona, 2006. 1edicion,4 tirada.

Henio Engels classified structural systems by its structural action. In the process of receiving transitions of loads, there are an additional bending stress over the structure that make them different of other structural typologies. This type of bending active structures has an important capability of application.

It is a publication that identifies the forces applied in the structural system, what kind of forces are applied and the graphic schematics of their mechanical behavior.

- Form
- Vector
- Cross section
- Surface
- Height

3.2. Tensile structures (lightweight roofs)

Lightweight roofs appear in many ancient cultures as an easy way to build dwellings or places to have meetings since there were no places in the middle of a long road when trips were too long and people used to move frequently. The first elements employed were branches, wood, leather, etc.

The idea of generating temporary and removable structures seemed a good option to have habitable spaces easier to build than permanent constructions that use heavy materials such as stones or wood, which are even heavier than the loads they must bear. The evolution of technology helped to apply new materials and in the conception of lightness in construction.

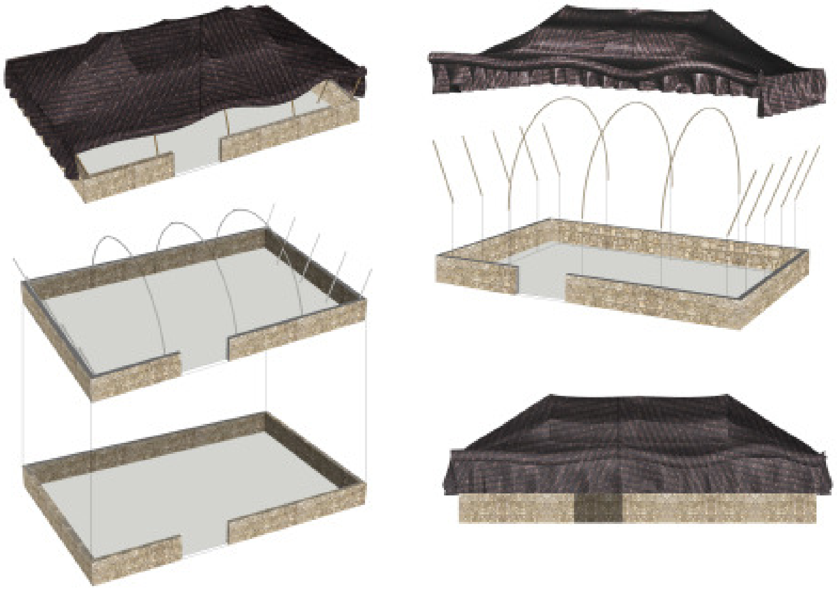


Figure 11: Vernacle architecture Beduinos[21]

The most common building materials for years have been stone, wood, metal and glass. But the use of the membrane during these years has been increasing, which makes this material more popular due to its new applications.

The technological advances with steel allowed develop huge structures as bridges and roofs in USA and Europe. The concept about light structures was very important, the best load bearing using materials with minimum was the principal challenge.

In Germany, Frei Otto began working under this idea of lightness. Basically, he experimented with surfaces through the soap bubbles and cable networks. His wide research in natural principles established new concepts that were applied in architecture.

Figure 12: Munich Olympic Stadium. Frei Otto , Gunther Behnisch 1968-1972. Germany.

3.2.1. Membrane Structures

Membrane structures consist of thin, flexible surfaces that carry loads primarily through the development of tensile stresses. These surfaces can have a synclastic and anticlastic shape.

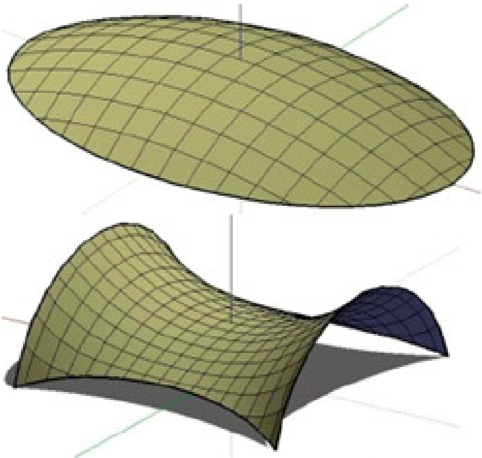


Figure 13: Synclastic (up) and Anticlastic(down) shape.

The main elements that are part of a tensile structure could be divided into 3 categories: membranes, cables and conventional structural elements. These are the basic elements that allow to define a tensile structure to be able to interact the efforts of each element through the fixing accessories in the balance of efforts as a unique system.

There are several typologies to configure a final membrane depending on its shape, where the needs for an efficient pluvial evacuation should not go down less than 10% of the slope from the zenith or highest point intersection of any synclastic or anticlastic membrane.

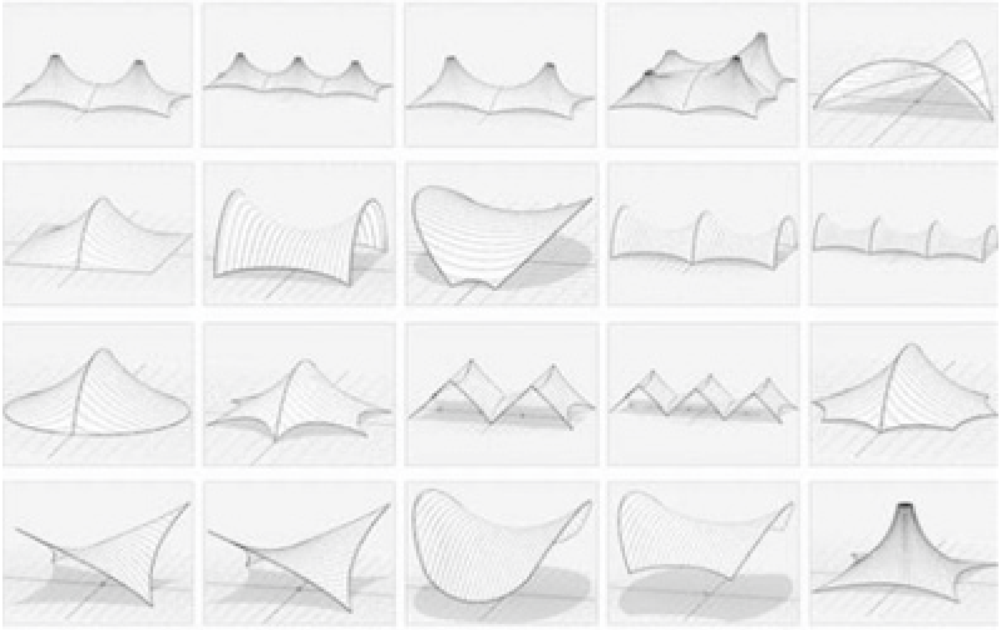


Figure 14: Some typology shapes that are used to get anticlastic shapes. [22]

3.2.2. Considerations for an initial tensile structure

The initial geometry defines the limits of any tensile structure, this structure responds to the design of the membrane that will interact through other accessories to achieve a stable final composition. The way to fix the membrane to the structure will define the final details of the accessories that will help balance tension throughout the structure. There are several types of membrane according to their capacity of effort that are established in their data sheets according to their use and durability.

The sizing of the cables and the structure respond to the forces that each element will receive, not only considering the own weight of the elements that compose it but also the external forces that increase the tensions throughout the coverage; as well as being able to establish a type of common or less repetitive fixation of all the elements.

In the case of the membrane, the pattern allows to reach the desired surfaces. The more templates you have, the closer to the shape, however the idea is not to have a membrane with many sealing lines because it would not be efficient as a manufacturing process.

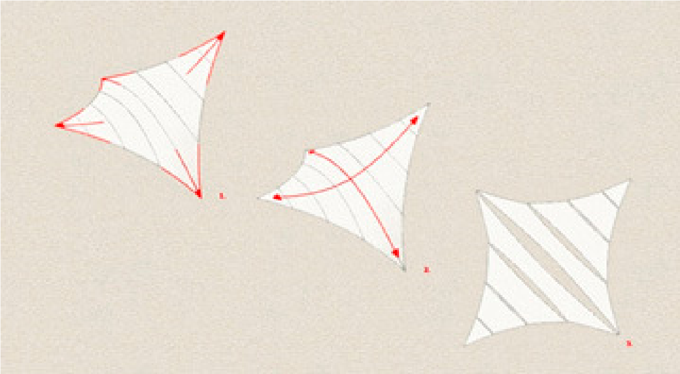


Figure 15: Manufacturing of a typical tensile membrane.

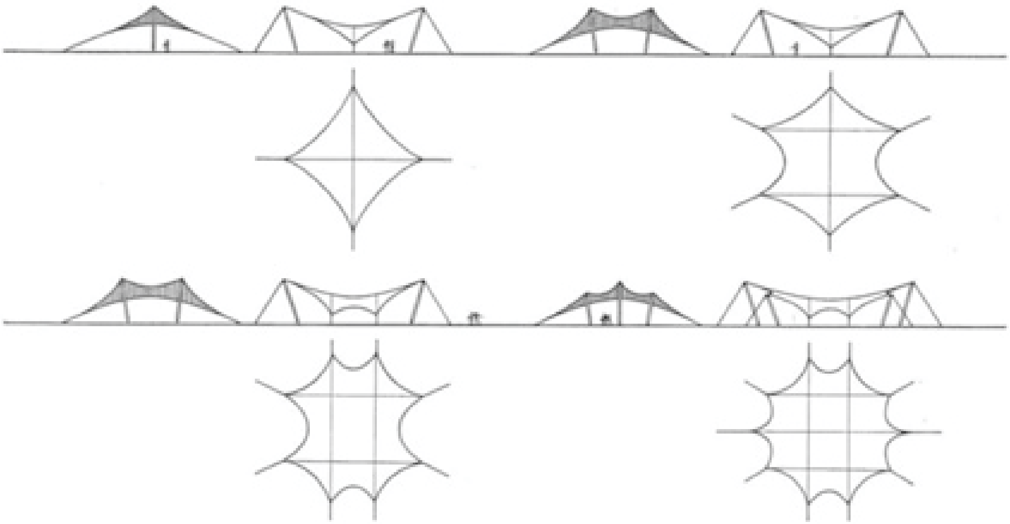


Figure 16: store-shaped systems with external supports with compression bars.

3.3. Cables Structures

This structural system uses cables as the principal means of support since cables have high tensile strength while the resistance to compression or bending is not possible. All the elements have to be used in purely tension in order to take advantage of all the transmission of forces. When more cables are added. When we take a cable and we pull it from the 2 ends what we will have is a straight line that to keep it in that position generates a lot of tension, if we start to release a little we will have the shape of an inverted arc, this naturally formed inverted arc will call it "Catenary."

A catenary is an ideal curve that is physically represented through a chain, rope or cable that only with the gravitational force suspended by 2 ends defines a position of equilibrium loads along its geometry.

The geometry of a catenary has a similarity to the geometry of the parabola in small curves and it was not until 1646 that Christian Huygens demonstrated that it was not a parabola until after some years together with other collaborators in 1691, he was able to obtain the equation of the catenary.

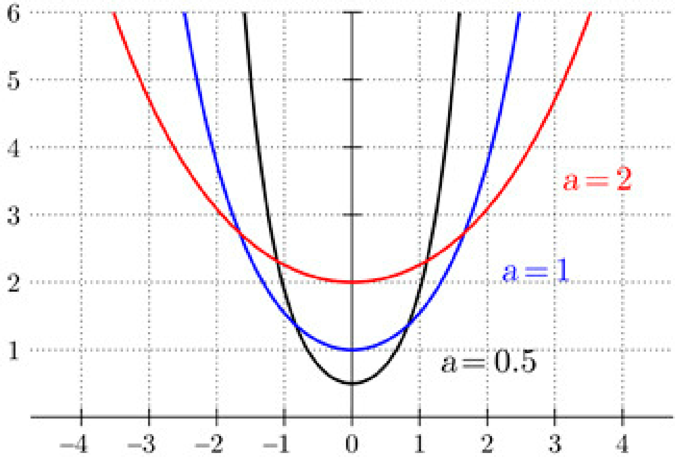


Figure 17: Equation y graphic of a catenary. [18]

Antoni Gaudi had the imaginative ability to project most of his works and used to recreate them in a three-dimensional model. The catenary was one of the elements used deeply, since very young he was interested in reading about the virtues of the use of the catenary curve that was used more in suspended bridges as a mechanical element.

The applications in the architecture allowed a new structural conception with a greater performance, for Gaudi the catenary gave elegance and spirituality to the arch and to the construction, avoided buttresses and made the buildings less heavy.

3.3.1. Geometrical shapes of a cable

The final geometric shape of a cable is defined according to the type of load applied, understanding the physical characteristics of each shape can show some geometric shapes defined by Heino Engel. The loads applied in each case allow us to understand the physical behaviors to be considered in the initial approach of any complex system.

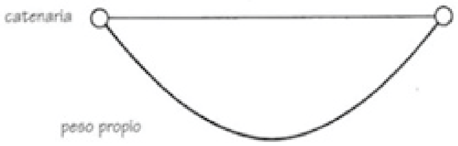


Figure 18: Catenary. [17]

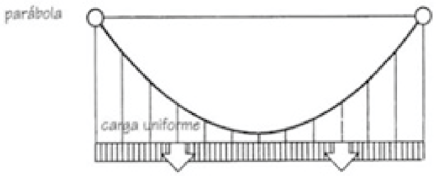


Figure 19: Parable. [17]

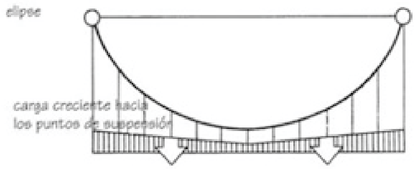


Figure 20: Ellipse. [17]

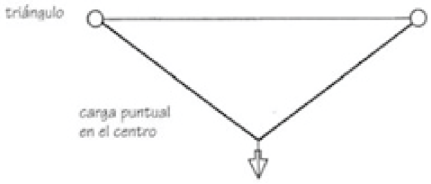


Figure 21: Funicular (triangle). [17]

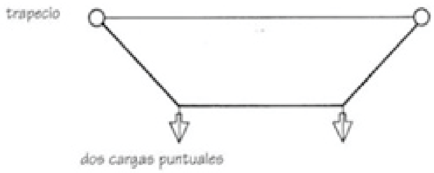


Figure 22: Funicular (trapeze). [17]

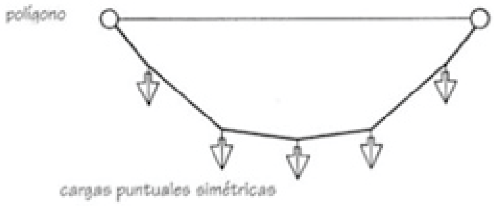


Figure 23: Funicular (Polygon). [17]

3.3.2. Stabilized special parallel systems

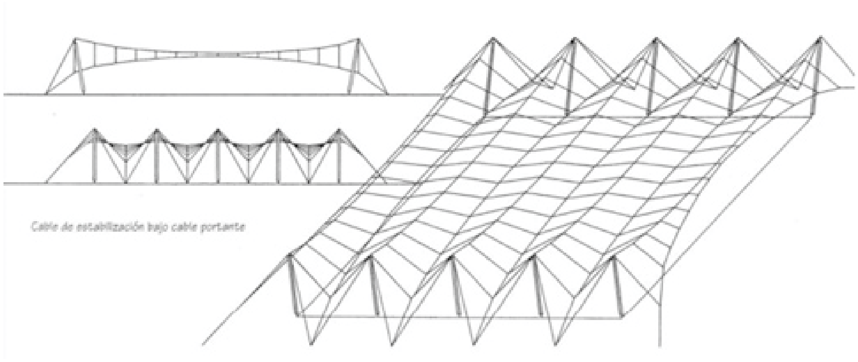


Figure 24: Stabilization cables under carrier cables. [17]

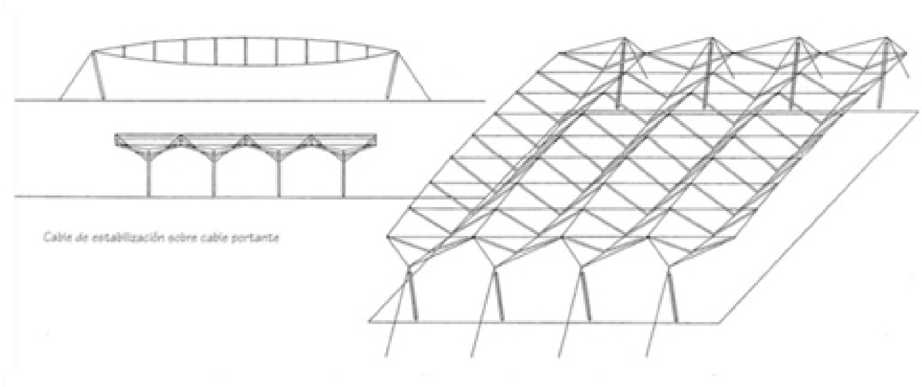


Figure 25: Stabilization cables over carrier cables. [17]

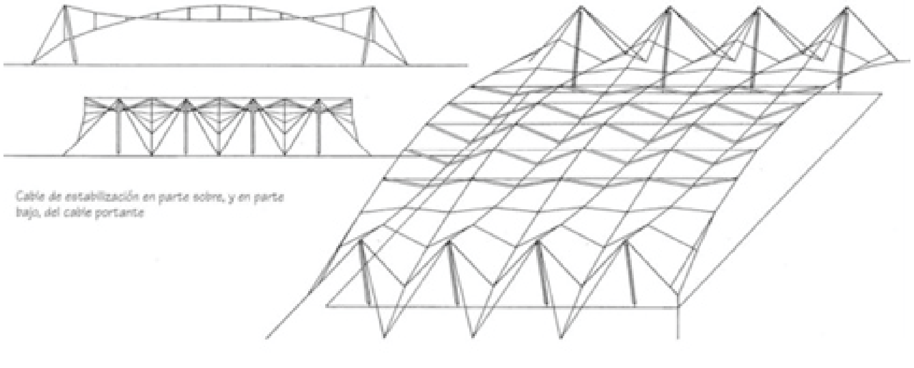


Figure 26: Stabilization cables partly up and partly down, of the supporting cable. [17]

4. Examples

4.1. Elastic grid shells

Flexible grid shells include an at first planar system of versatile poles that are incited into a shell-like structure by stacking their furthest points. The subsequent incited structure gets from the versatile clasping of the bars exposed to inextensibility. [8]

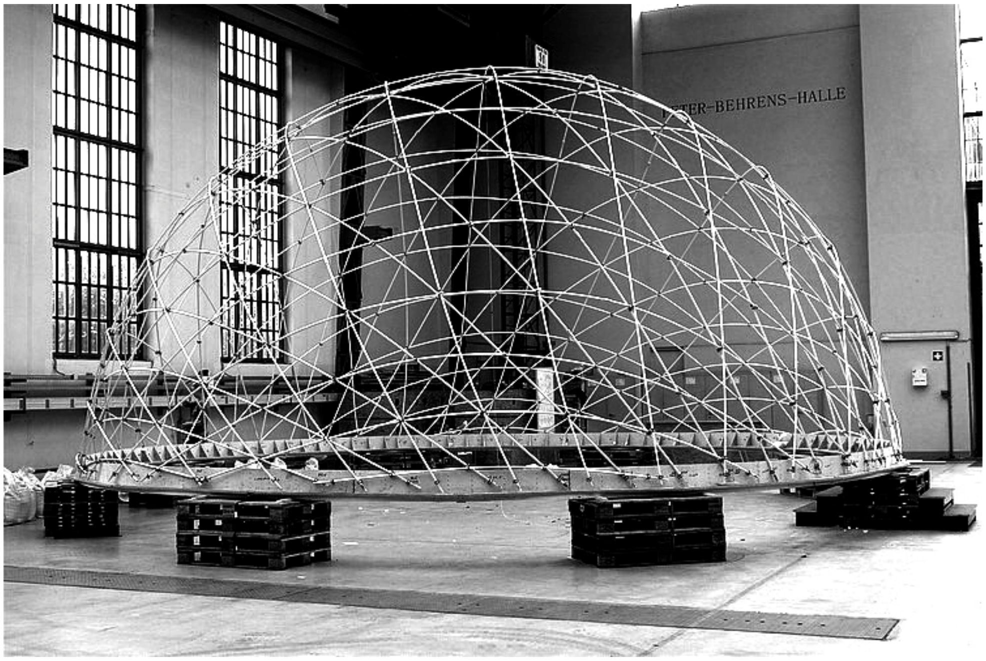


Figure 27: Christoph Gengnagel & Elisa Lafuente-Hernández grid shell, Berlin. [8]

Outdoors tents make bended shell-like structures in three measurements (3D) through flexible clasping of a system of bars. During the 1970s, the engineering network moved this thought into the domain of enormous scale development by presenting the idea of a versatile grid shell, a customary matrix of flexible poles that is impelled into a shell-like structure by stacking its furthest points. [8]

The clasped types of flexible grid shells (Fig. 27) propose a nontrivial utilitarian connection between the at first level, standard matrix and the resulting incited geometry, making both forward and backwards configuration testing errands. This relationship compares pole versatility and inextensibility, which are surely known in 1D as old style Euler's elastic, with a system of 2D limitations that manage the development of a shell-like structure. [8]

This system can be displayed, from one perspective, from the viewpoint of cooperating obliged elastic, a methodology that is basic in the investigation of arbitrary 3D polymer frameworks, however not too investigated for organized 2D systems. Then again, a versatile system can be displayed as a continuum of inextensible poles exposed to bowing or shearing, which results in Euler–Lagrange conditions however whose tractable arrangements are regularly limited to a plane or specific basic geometry. [8]

Rather than the variational approach, one can encode a versatile network as a simply geometric article utilizing the differential geometry of surfaces. This methodology was taken by P. L. Chebyshev during the 1880s while examining the distortions of woven texture. [8]

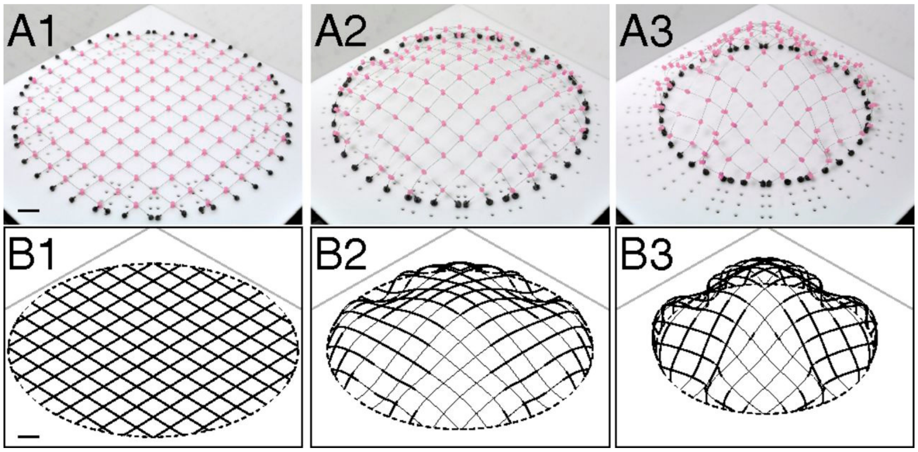


Figure 28: (A and B) Actuation of an elastic grid shell from (A) experiments and (B) DER simulation. The edge points of a planar and unloaded footprint (A1 and B1) are gradually moved toward a prescribed actuated boundary (A2 and B2) to yield an actuated shape (A3 and B3). (Scale bar, 20 mm.). [8]

4.2. Hybrid grid shells

Flexible grid shells are financially savvy lightweight structures utilizing a quick development process, in which the geometry of the grid shell is gotten by twisting an at first level network. This specific forming procedure permits to spare time during the erection of the structure, as the matrix bars must not be twisted separately yet the lattice can be molded overall. In addition, the gathering of the associations between the superposed pole layers of the lattice should be possible on the ground on a level geometry, which results simpler than interfacing single components reporting in real time. By the by, so as to be given by sharing firmness, the framework must be propped after the forming procedure by extra components as a third layer of poles or corner to corner links. The collecting of this supporting layer is typically tedious and requires extra supplies as careful chooser or portable platforms. [8]

As such one of the incredible points of interest the quick deployability of flexible grid shells - is unmistakably decreased. So as to quicken the development procedure of deployable flexible grid shells, a few creators spread this grid shell with material films as hardening and simultaneously cladding surfaces. [8]

4.2.1. Hybrid Tower

“Hybrid Tower” is a hybrid structure made of two principal elements:

1. Bend GFRP rods
2. custom-made CNC membrane

The combination of these two elements / materials makes a lightweight and stiff structure that balances external forces by the combination of compression and tension elements.

The structure was installed on the world cultural heritage side of the central square of Guimaraes/Portugal for three months and survive any environmental challenge. [9]

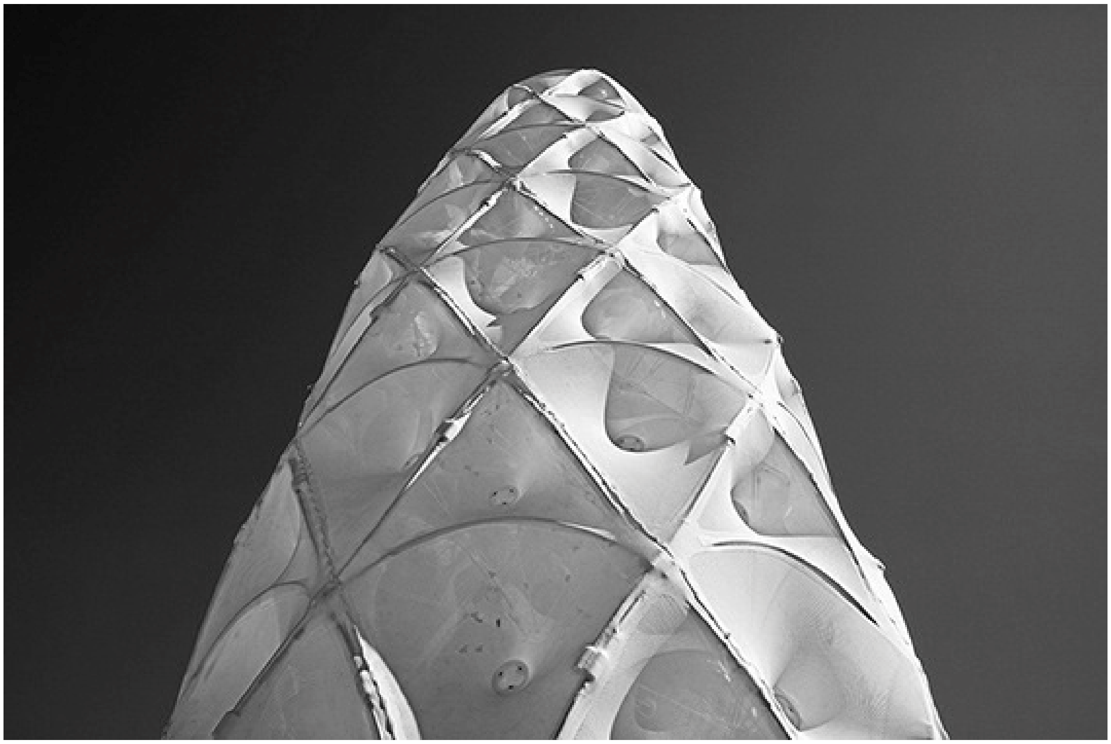


Figure 29: Hybrid tower, Udk – Universitat der Kunste Berlin / Berlin, Germany: Christoph Gengnagel, Riccardo La Magna, Michael Schmeck, Photography: Anders Ingvartsen. [9]

The tower was made by a collaboration of architects (CITA, Copenhagen), structural and textile-engineers (KET, Berlin, Fibernamics, Guimaraes), specialists in material testing and the knitting company AFF (A. Ferreira & Filhos).

Together they reached a highly detailed project that allowed others to get inspired in new ways to build structures such as this one.

4.3 Permanent Textile Hybrid Structure

4.3.1 Umbrella for Marrakech

The Marrakech membrane was made by Lienhard and Knippers and is a lightweight roofing system made with membranes it was made with the HFT Stuttgart for a schoolyard roofing in Marrakech, Morocco. The structure is made principally by 7.5 bended carbon fiber rods. [10]

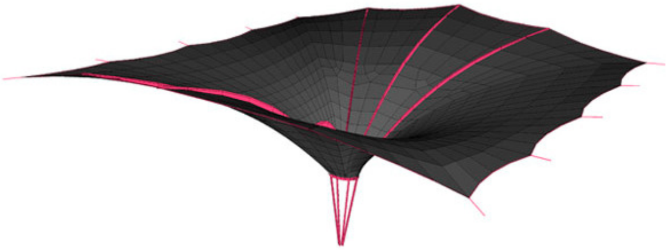


Figure 30: Form finding analysis. [10]

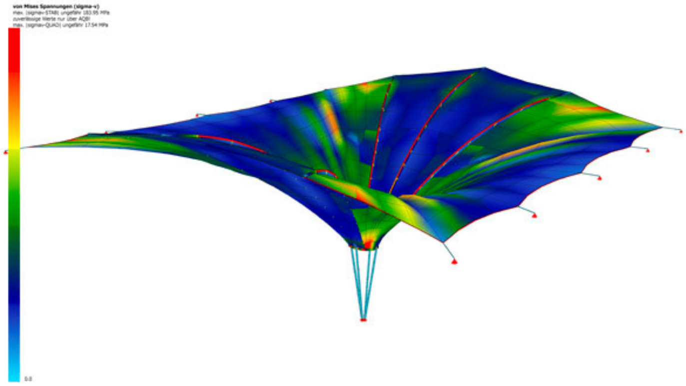


Figure 31: Displacement analysis. [10]

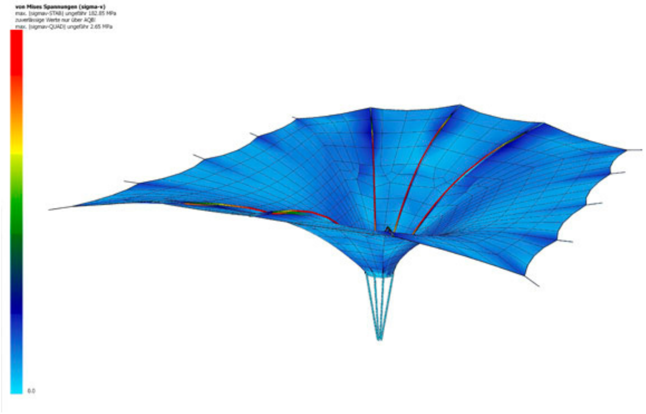


Figure 32: Bending stress and tension analysis. [10]

Lienhard and Knippers proposed, a device at the end of the bending-elements for introducing tangential prestress after erection because the friction between the pocket and the curved bending element causes the elements to get stuck. [10]

Figure 33: Special device for tangential prestress. [10]

This device ad some silicon inside the pockets, eliminates the friction and ease the set-up of the prestressed hybrid. [10]

The pocketing works with a plate element only as long as this plate is planar. When the plate start twisting around their axis, the use of pockets is no longer possible due to an association between the tensioned membrane and the curved bending elements. The use of the *roped edge* and the related secondary connection on the other hand is a more suitable process. The roped edge detail can be replaced by a sewing detail and the process can be extended to an easy- assembly approach. Any eccentricity in this detail will end in a disadvantage for the geometry and structural performance. [10]

Figure 34: Special device for tangential prestress. [10]

At the first moment the most suitable assembly process for plate-hybrids consisted out of initially flat elements that will be bent in a temporarily way and fixed so they keep their geometry and position; next the membrane is added and the structure find the desired equilibrium. In this process they also introduced the prestress in the membrane. However, the prestressing was a challenge to the assembly and could only be made by hand. Instead, the biaxial prestress was added in a final step, introducing another large geometrical deformation as a post-erection tensioning, proposing a novel approach to the realization of form- and bending-active structures. [10]

Now if was possible to demonstrate the technique in a larger model with a span of 11 x 12 m with a success installation in the Stuttgart Park, a patio roofing was installed in Marrakech in March 2012 by a group of Moroccan and German students of architecture. [10]

4.4. Temporary Textile Hybrid Structure

4.4.1. M1

The structural concept of the M1 is oriented to a design of a canopy that adds minimal forces to the surroundings like near buildings, this causes the structure to avoid any sensitive archeological material while the design makes a perfect articulation. [11]

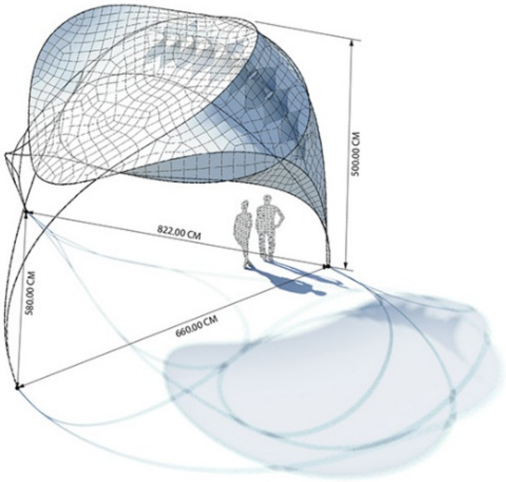


Figure 35: Textile Hybrid M1 computational model, generated through specialized form-finding methods in both Sofistik and Processing. [11]

Computation of material behavior

Basic to achieving these complex incorporated power dynamic morphologies was the alignment of plan and expository examinations done through both physical tests and computational techniques, inside the setting of a structure studio. The computational methods were constantly best in class and adjusted through investigations of physical practices at different scales. Such prototyping was important to comprehend the elements of oneself sorting out framework just as test the connections between changing material parameters (relative solidness and pre-worry between composite bars and materials) and achieving a steady structure. The plan technique spread over various computational conditions and degrees of particularity. [11]

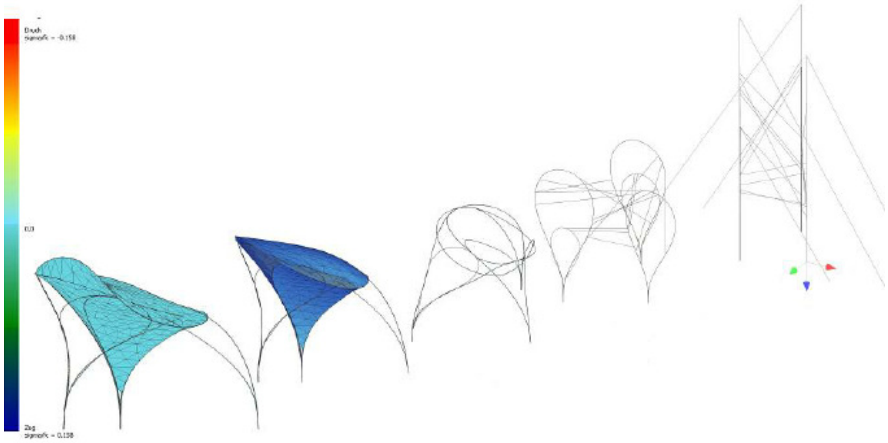


Figure 36: Sequence of form-finding steps in Sofistik® FEM, based on rod associations from physical model, utilizing fully automized incremental form-finding strategy by Julian Lienhard which tracks all stress conditions. [11]

The equilibrium of the elements was first explored to determine the geometry and structural viability, Sofistik program was used in order to see great degrees of displacement and to form find the rod positions, after this a pre-stressed membrane was added to the equation while the final form appeared.

The geometry was determined by a physical model to define the lengths and association points for all rods. Thus, all three design models; the physical and both generative and specific simulation techniques informed each other in this iterative design process. [11]

Textile hybrid system

The structural techniques are proceeded at the base of the structure where the bars are integrated with packs and bound to the GFRP establishment posts. Together with the films, the structure beneficially collects different layers, following past research in Deep Surface Morphologies, and spatial frameworks with auxiliary flexibility. Such highlights empower the framework to withstand fluctuating worries of wind, downpour and day off bounce back to its underlying structure discovered state, while additionally intervening spatially similar powers through numerous differential layers. Attempting to deteriorate the homogeneous idea of the material film, the cells are steady in their topology, yet separated in their structure. [11]

The geometry is made by glass-fiber reinforced polymer (GFRP) rods with diameters of 3mm-24mm in combination with a textile membrane. The highly elastic rods gain their stiffness from active bending into *curved leaf shaped modules* which are networked into a global structural system. [11]

Stiffening effects are reached by the further deformation of the system through the integration of a pre-stressed membrane surface, and that’s how a fully textile hybrid system is created. [11]

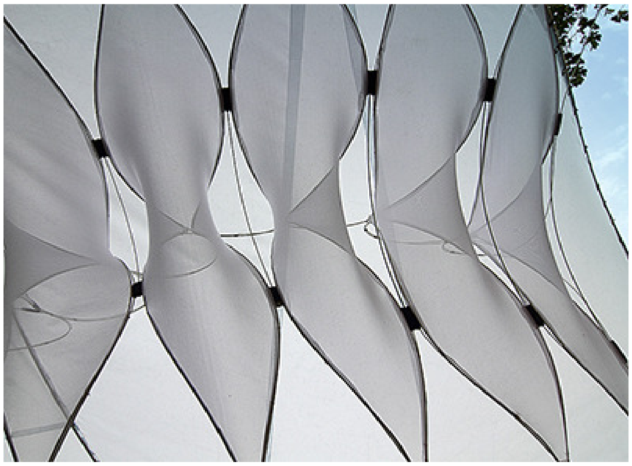


Figure 37: Internal cell structure connected to top membrane and rod assembly. [11]

The M1 system explores the structural capacity and viability of a hybrid lightweight structure made by carbon fiber bended elements and membrane surfaces, the nature of this kind of system demands the study of equilibrium and meanwhile the study of the final geometry and its performative capacity of usage. [11]

5. Research Hypothesis

At the beginning of this investigation, we consider using 3 different structural elements (rods, cables and membrane) in a single integrated structural system. In the case of the structure with rods, we are first interested in being able to develop different possible frames, being able to evaluate different degrees of stability, on these options we can integrate the use of cables and membranes as complementary elements to achieve a more stable and efficient hybrid structure. The evaluation of the different proposals allows us to understand when a hybrid structure is efficient and how the elements that make it up have an active role in sharing efforts. This initial idea of understanding the shared efforts in a multi-element structure leaves some important questions for this research: What effect does the optimization and rationalization process have on the construction of a plot that will be under tension?

1. How is it that a structure composed of a single structural element when it becomes a hybrid structure of three different structural elements makes it more rigid?
2. How do I optimize the elements that make up a hybrid structure considering functional solutions for a living space?
3. What variables exist on a non-efficient hybrid structure to make all its elements really involved in the distribution of efforts?

Next, we will show through this case study the paths followed as an experimentation methodology as well as the different research and evaluation scenarios.

6. Study Case: Hybrid Dome

Nature shows us a mathematical order of geometries inscribed in all the elements that make them up, allowing us to explore new applications with the same patterns in the approach of different conceptions.

The creative process naturally follows geometric patterns that start from simple shapes to more complex shapes that can be two-dimensional and three-dimensional. Having studied most of the universal forms since the beginning of civilizations, man has been able to decipher these particular natural orders in an empirical and proven manner, being able to systematize with the use of software to have sharper tools that allow understanding and developing complex structures under an initial elementary criterion.

The parametric world is another step in the development of controlling complex structures defined by specific algorithms, where you have more control over the evolutionary process of an initial planning, where we can consider limits and ranges to evaluate better geometric order options in a first stage.

6.1. Form-finding and Initial Geometry

It was proposed to work the geometric scheme of a “leaf”, two arches at the ends and a valley arc in the middle, in this case the use of 3 elements for its final composition; structure, cables and membrane.

The idea was making the simulation of two opposite arcs that are connected through a surface defined by a cable evaluating the different results using parametric variables in all its elements.

These two initial arcs have as an anchor points the geometric path of a circle in a XY plane that defines the universe of this study.

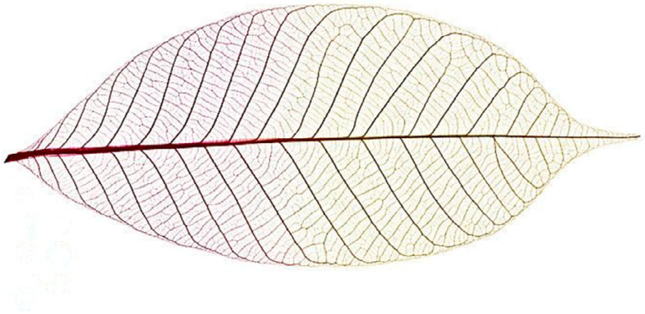


Figure 38: Form-Finding Process /structure

In this first stage it was defined by an algorithm the control of the angle of inclination of these initial arcs, the arrow of each arc in its plane and the angle of rotation on its center of gravity to obtain different weaving options.

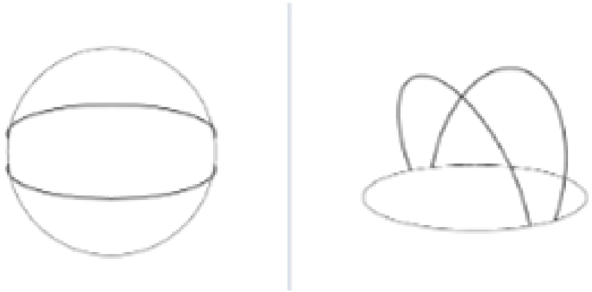


Figure 39: Initial arches.

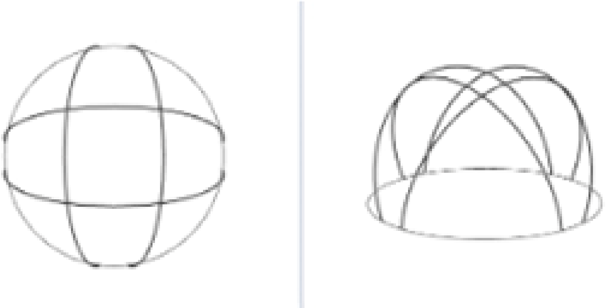


Figure 40: 4-arch crossing - 4 intersections.

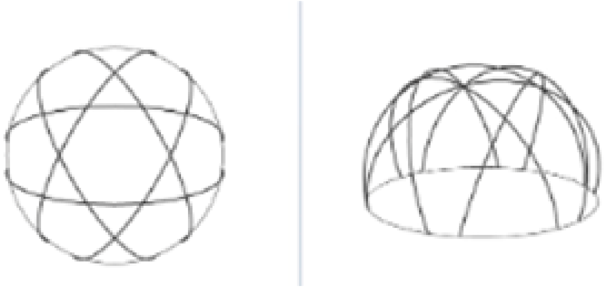


Figure 41: 6-arch crossing - 12 intersections.

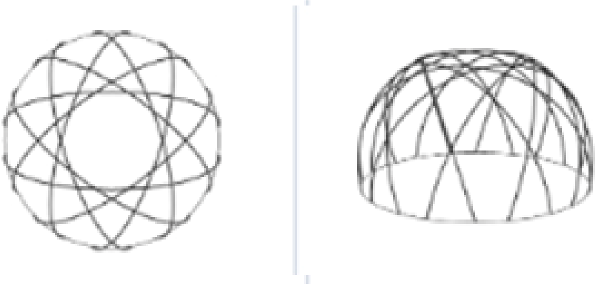


Figure 42: 10-arch crossing - 24 intersections.

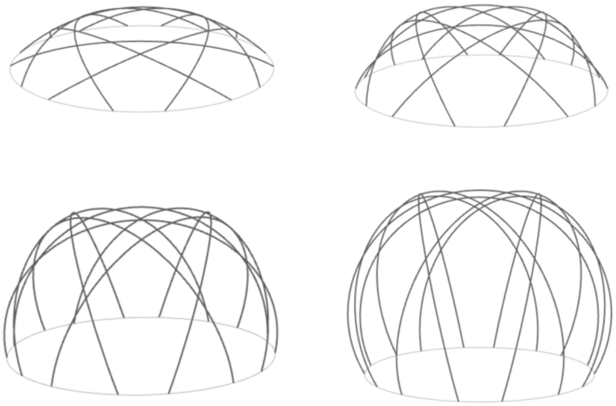


Figure 43: Structure height parameter.

6.2. Form-Finding Process /membrane

Until this stage we establish the geometric configuration variables to define with the intersection points the limits of the initial membrane pattern to repeat to form the final membrane. So, this initial surface appears as a basic configuration of a possible option of an anticlastic surface.

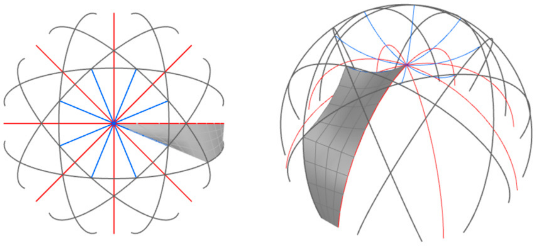


Figure 44: Basic anticlastic membrane configuration.

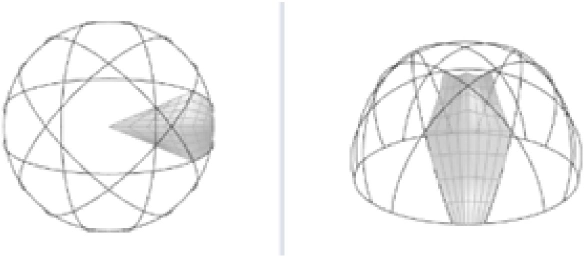


Figure 45: Membrane module.

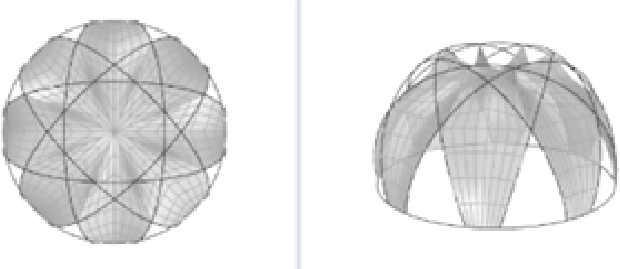


Figure 46: Full coverage.

6.3. Form-Finding Process /cables

The limits of the membrane that are not defined by the structure are formed by 2 types of cables that started as imaginary curves that defined the final basic module of the membrane, type 1 pushes the membrane up and type 2 down which allows to distribute the efforts in the membrane and structure through the cables. The criteria for water evacuation from the center of the coverage are evaluated based on the final slopes of the shape.

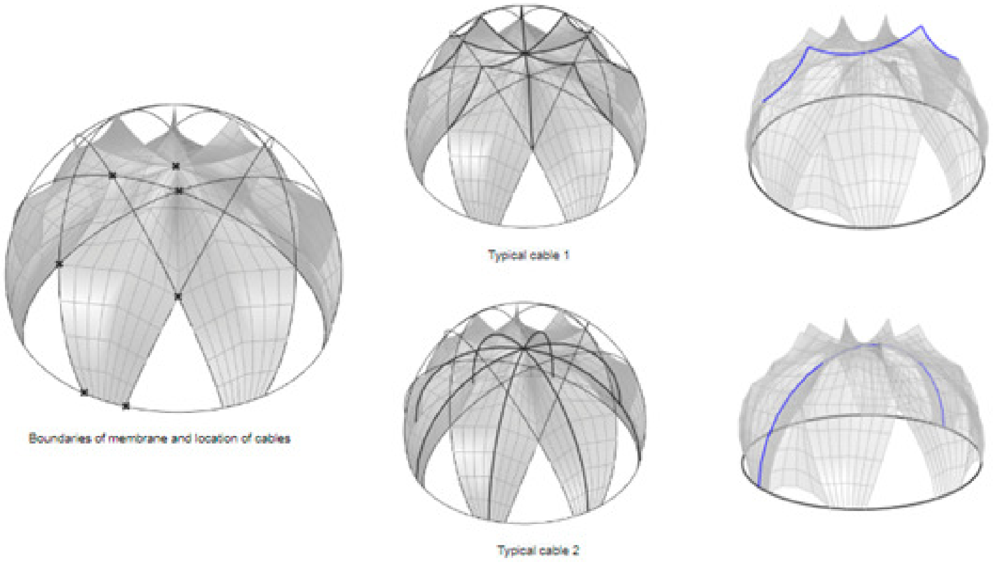


Figure 47: Anchor points / Typo 1 & Typo 2 cable.

6.4. Parametric geometric variables

Having the defined conception of the morphology of this structure composed of 3 elements (rods, cables and membrane), the control of the arc opening angle was established parametrically together with the surface and cables achieving several possible dynamic configurations. Another variable would be the control of arc intersections that allows the amount of subdividing of surfaces and cables. The various options obtained would give us possible options to be evaluated for a next stage.

In these graphs we can appreciate the various control options in the opening of arcs and the subdivision of intersections.

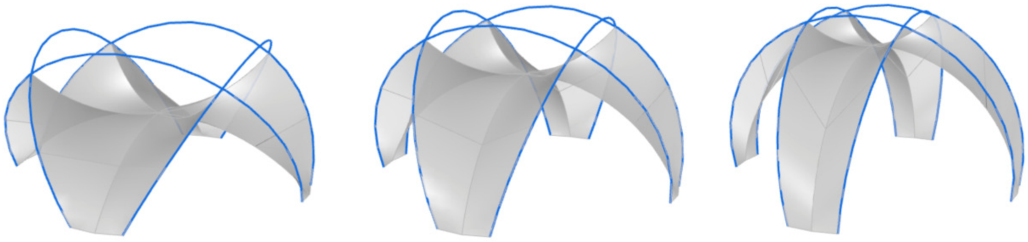


Figure 48: Parametric opening angle control.

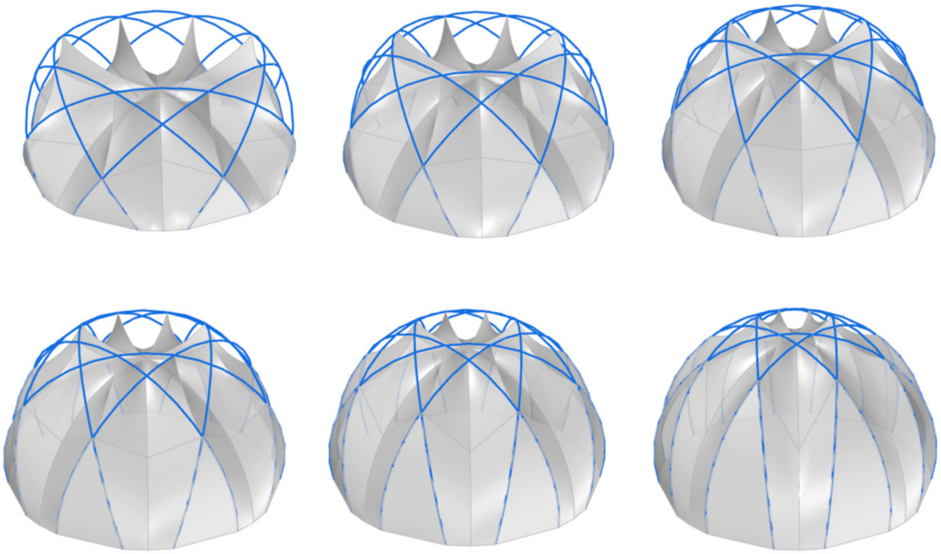


Figure 49: Parametric subdivision control.

6.5. Rationalization and Optimization (Dynamic Relaxation with kangaroo)

Until this stage we have only worked a composition with parametric variables to define a structure that responds to a final form under an initial geometric criterion without applying some kind of external and proper effort. Applying now the 3 structural systems mentioned before. (Active bending structures, tensile structures and Cables Structures) in a single structural element of shared efforts we will study the various behaviors of its elements through dynamic relaxation with Kangaroo and in physical models.

Figure 50: Physical models.

6.5.1. Initial grid densification (Bracing System)

In this first structure a new additional structure was proposed. The first structure defined the limits of the surface, this second structure is to increase the stiffness of the initial grid, especially in the most open spaces.

In the first proposition it is considered to add rings to create triangulations, the detail with these rings is that the intersections increase their valence to 6 vertices, which implies a more complex intersection detail.

Figure 51: Parametric subdivision control option A.

In this second proposal, it was considered that the second structure maintained only the intersection of 2 structures to solve a single fixing detail. Also achieving better distributed triangulations and a ring of stars at the top of the structure as a result of the intersections of the rods.

Figure 52: Parametric subdivision control option B.

In this third proposition, the initial plot was increased to have a more subdivided plot with the same language, in this case generating a diamond pattern throughout the structure that could give us new structural behaviors and performances to reach the most hybrid structures possible.

6.5.2. Dynamic Relaxation of new Structural approaches

Applying dynamic relaxation with kangaroo in the options of mixed structures seen previously, we notice the physical differences of the elements when all the elements are under tension, which allows us to visualize the final deformation of these structures.

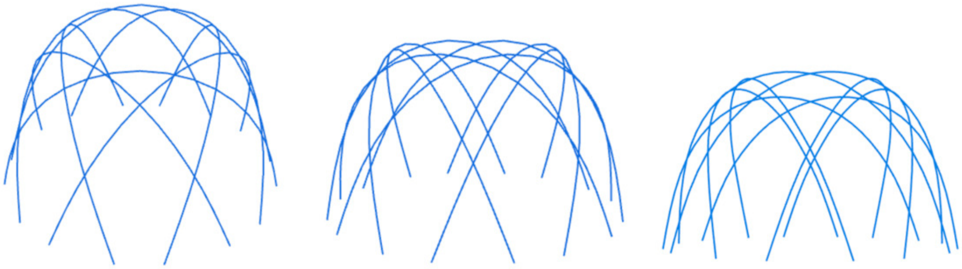


Figure 53: Dynamic relaxation / option Grid A.

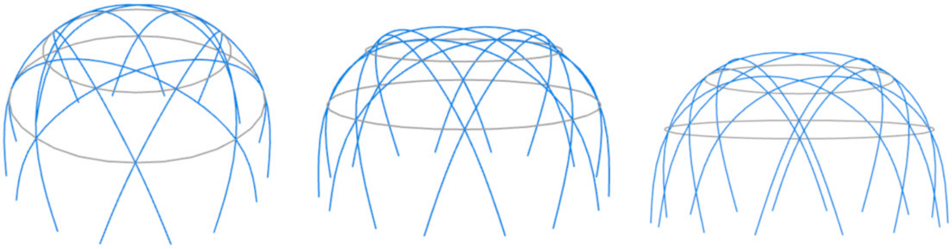


Figure 54: Dynamic relaxation / option Grid B.

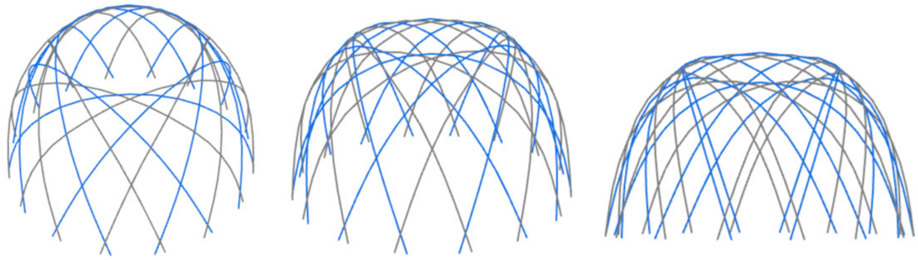


Figure 55: Dynamic relaxation / option Grid C.

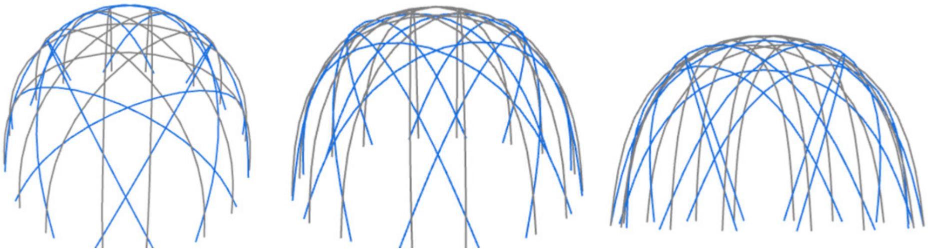


Figure 56: Dynamic relaxation / option Grid D.

6.5.3. Dynamic Relaxation with membranes and cables

The morphology of the membrane together with the cables reacts together with the active flexion of the bars reaching a final composition in equilibrium that allows to share efforts in the 4 options, in this case it is considering anchor points for the bars in an XY plane inscribed in a base circle.

When applying dynamic relaxation in the Option 1 structure, we can graphically visualize the behavior of the different parametric options of geometric variability where the morphology of the membrane and the cables adapt to their new limits.

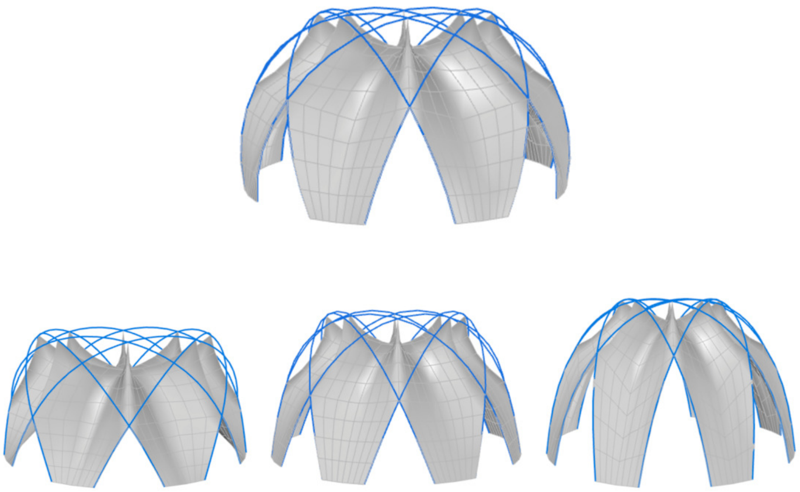


Figure 57: Dynamic relaxation with membrane and cables / option Grid A.

In the Option B structure, we have added 2 rings to complement the previous structure a little more and thus give it some stability to visualize what new behavior we can obtain with our parametric variables. The detail of this option is that we began to create vertices of Valencia 6, when we had considered maintaining an intersection constant of only 2 elements.

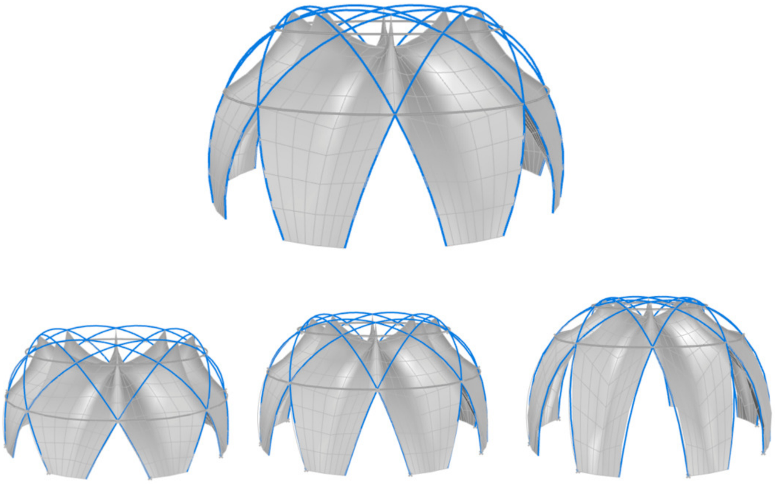


Figure 58: Dynamic relaxation with membrane and cables / option Grid B.

In the structure Option C, we have a second structure of the same language that allows densifying the previous structure without triangulating it and maintaining an intersection constant of only 2 elements, thus giving it some stability to visualize what new behaviors obtained with our parametric variables. In this option we create a regular plot of diamonds of different intersection angles.

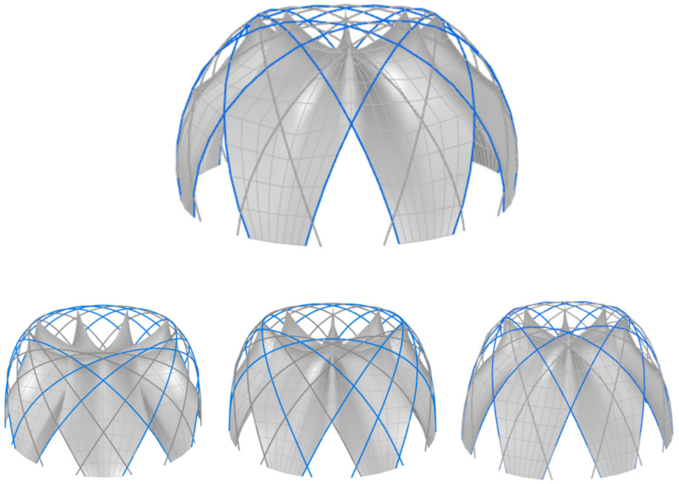


Figure 59: Dynamic relaxation with membrane and cables / option Grid C.

In the Option D structure, we have a second structure of a different composition that allows densifying the previous structure but with triangulations only some areas and maintaining a constant intersection of only 2 elements, which gives it some stability to visualize that new behaviors obtained with our parametric variables.

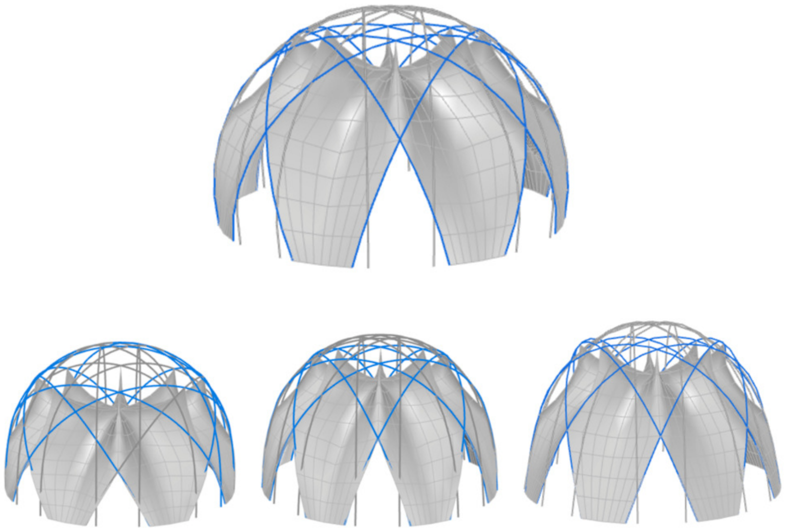


Figure 60: Dynamic relaxation with membrane and cables / option D.

These are the 4 options that start from the same initial structure to which a second structure is added to evaluate the different parametric options integrated into a single structural composition. Based on the evaluation of each alternative for the 4 options it was important to maintain a regular and minimum valence of intersection to simplify details of joining and manufacturing. These proposals and their variables were made considering fixed anchor points in the XY plane.

6.5.4. Dynamic Relaxation without a Ring Base

On the same geometric composition as before, it was proposed the idea of eliminating the ring where the bar anchor points are fixed that would be changed by cables, which would give us other structural options with our parametric variables. In one case, a perimeter cable would be joined with cables of the structure, and in the other way the option of having cables from one end to the other.

In addition, with the same idea of eliminating the ring, it was thought the use of a membrane instead of cables on base, so we will see the variables of these two options.

Base with Cables

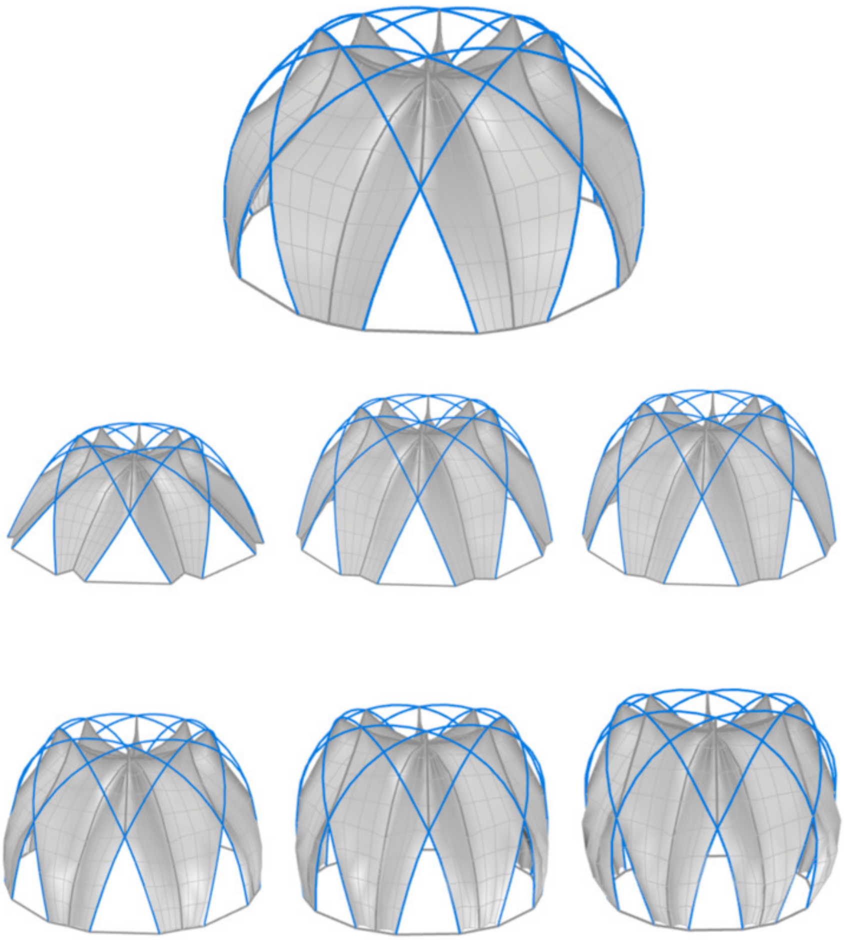


Figure 61: Dynamic relaxation with membrane and cables / option A.

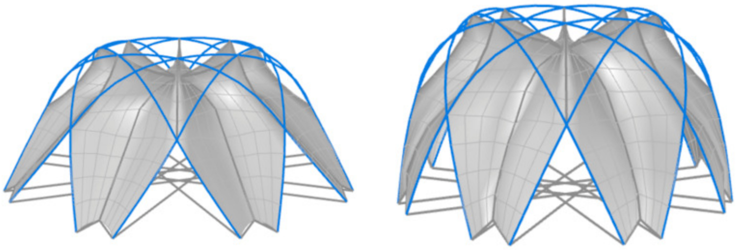


Figure 62: Dynamic relaxation with membrane and cables / option Grid A with cables B.

Base with Membrane

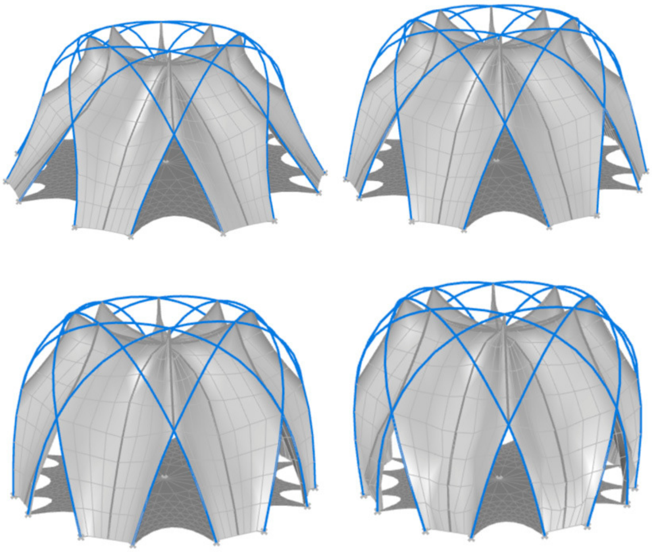


Figure 63: Dynamic relaxation with membrane and cables / option Grid A with membrane base variables.

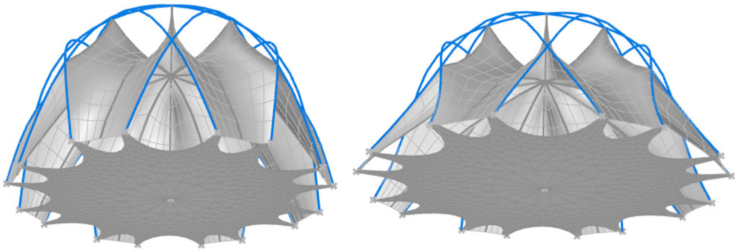


Figure 64: Dynamic relaxation with membrane and cables / option Grid A with membrane base. Bottom view.

7. Simulation and analysis tool

In this chapter, we studied the stress levels and behavior under external loading, looking for system in equilibrium, we evaluate many possibilities in the basic structure to stay within stress capacities and prevent form buckling and failing.

In this parametric field we can find a couple of computational tools that have been developed over the years. Furthermore, these computational programs are continuously improved and released, resembling more and more real life.

Kangaroo plugin from grasshopper, which is indeed another plug in from Rhinoceros, has stablish as the main tool in this prototype, to rely in a real live simulation. helping to realize the conceptual project, although there exist other programs such as Wintess, Grasshopper from Rhinoceros had the facility to undergo all of the analysis constrains thereafter simulate the geometry until find and equilibrium first in another plug in named kangaroo physics K2 which later on was plugged to kangaroo engineering K2e, whose focus rely on real materialization of the model with different library materials and its respective technical requirements.

The observation from its physical behavior it has an immediate impact on structural performance in 3d that are be helpful for the designer or engineer. And hence, obtain directly the physical information data from each element.

7.1. Calibration

The main purpose of this plugin is to offer a direct output of meaningful structural values that can be used to evaluate the performance. Whilst it is possible (in most cases) to input appropriate stiffness values for the existing goals and subsequently back-calculate the forces from the displacements, this approach has the advantage of avoiding duplicate functionality, simplifying the process of mapping the results back to the structure and making it more clear which properties are needed for the calibration and their correct units.

The plugin currently contains a bar, cable, rod and support goal from which the axial forces, reactions, shear and bending moments can be extracted. A number of additional components have been developed to ease the modelling setup and further advance the structural output. These include a number of different loads to quickly define realistic load scenarios, calculation of cross section properties for circular and rectangular profiles, evaluation of displacements and summation of axial and bending stresses. The plugin also focuses on the visualization of forces (axial, shear and moments) in relation to the three-dimensional geometry in order to obtain an intuitive understanding of the structural behavior and identify load paths without inspecting the specific values.

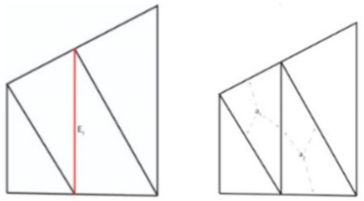
Whenever we need parametric analysis to rely in real live, it is easier to see different options with different kinds of optimization.

Script definition is based on different parameters, from here, the goal was constructing the geometrical definition that will represent each element, the following method works discretizing the geometry in segments of 20 cm to for a fast an accurate calculation. as many elements possible to simulate in the Grasshopper definition. Rods, cables and membrane were represented as polylines.

First of all, we plug all the rods segments into a bar nod that measures the technical properties of the material and its thickness. These rods also needed to simulate the bending moment of the thickness elements, due to its deferent behavior from cables and member. In here, we could specify the rest angle of the rod.

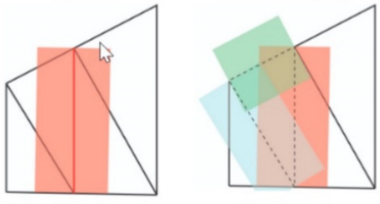
In the case of cables, they were only represented as continuous segments that interact with each other form its star point to its initial point, in this node, we were able to also specify technical data of the material, such as diameter, elasticity and whether is prestressed or not.

In the case of the membrane, it was necessary to discretize the surface into a triangular net, taking the adjacent faces and divided into its respective edge, so each element would represent a strip of the membrane. [Ramon Sastre methodology, Wintess] see figure 65.



Triangulate mesh

Take the adjacent area per edge



Set at the width dimension per edge

Take ½ of the density

Figure 65: Membrane definition

Later on, we add the swivel couplers, which were located in two closest points from each intersection, where they were also dynamically relaxed during the process.

There exist some limitations when simulating wind behavior in k2e, since complex analysis and equations are required to analyze real wind, the approach of this simulation has been made from a coarse mesh made from the rod's configuration, this mesh represent the vertices where the direction of the wind is going to apply its load. We analyses this mesh as a simple coverage and apply wind in only one direction as if it where and external force in x axis.

7.1.1. Material Beauvoir

When we design a hybrid structure that combines cables and membrane, we expect that each element during form finding, it was plugging the structure with cables and membrane trough dynamic relaxation until reach the desirable shape, each element was expected to have an important contribution when interacting with each other as a hybrid system. In the graph below (Fig. 66) we can observe that whenever each element reaches its maximum capacity more rigid is. However, as we are working under bending systems, it is important to understand the impact of its elasticity that cause a nonlinear behavior and thus it can be explained how deformation occur in different areas. These vulnerable areas clearly depend on the lack of connections according to the span.

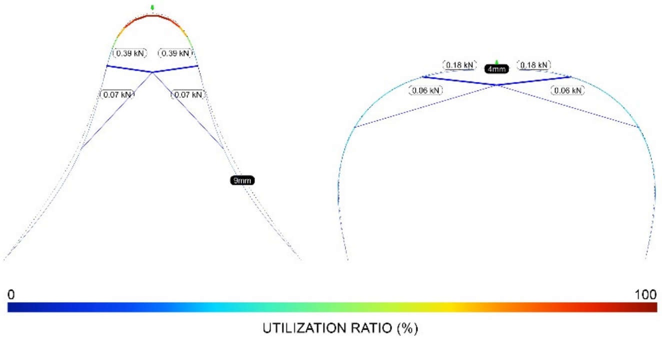


Figure 66: Rod utilization ratio according different curvature.

After the discretization of every element in the structure, we proceed to understand graphically the breaking point in each diameter.

As previously studied, the maximum curvature of the stem is proportional to its diameter, and inversely proportional to the radius. That means the smaller the radius, the more elastic (deformable) is. See figure 67.

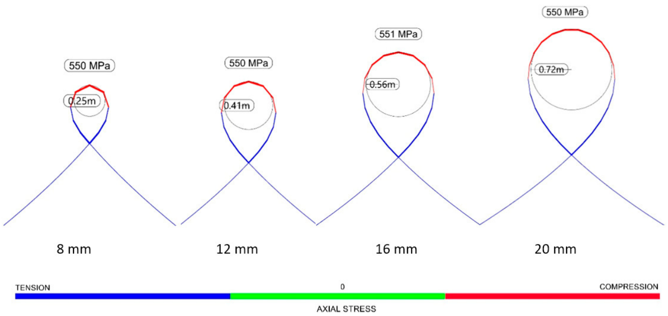


Figure 67: Rod thicknesses utilization ratio (current stress/design stress).

Unlike cables and membranes, rods can work both completion and tension. That is why we can observe in the picture above (figure 67) how some segments of the rod are under tension and others under compression.

The maximum bending stress of rods where measured at the university laboratory. There, a piece of GFRP reached a maximum of 550 MPa plus safety factor; from here, it was possible to compare directly from the output of K2e and thus link the maximum stress with the actual stress.

$$\%\ \text{Utilization ratio} = \sigma_{\text{max}} / \sigma_{\text{a}} \tag{3}$$

7.2. Deformation from initial geometry

Having explain this procedure, the prototype was subjected to different loads such as self-weight, point loads and wind load.

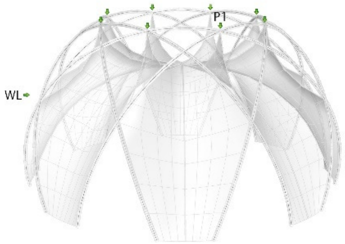


Figure 68: F Load cases in structure A1 (Initial hybrid geometry).

The following graphics display the diameter characteristic of the material under self-weight, wind load to 50 km/h, which is catalog as a strong wind, and 25 kilograms point load scattered on top of the intersecting rods.

7.2.1 Geometry possibilities

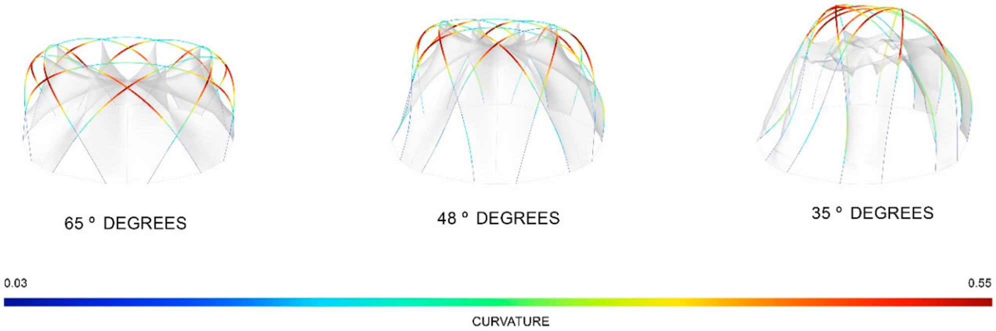


Figure 69: Curvature of different geometry possibilities.

In early stages of form finding, it was possible to control the angle of the arc, parametrizing the geometry, the physical behavior of this possibilities rather than functional aspects, present les deformation where the structure reaches similar dispersion between the connections.

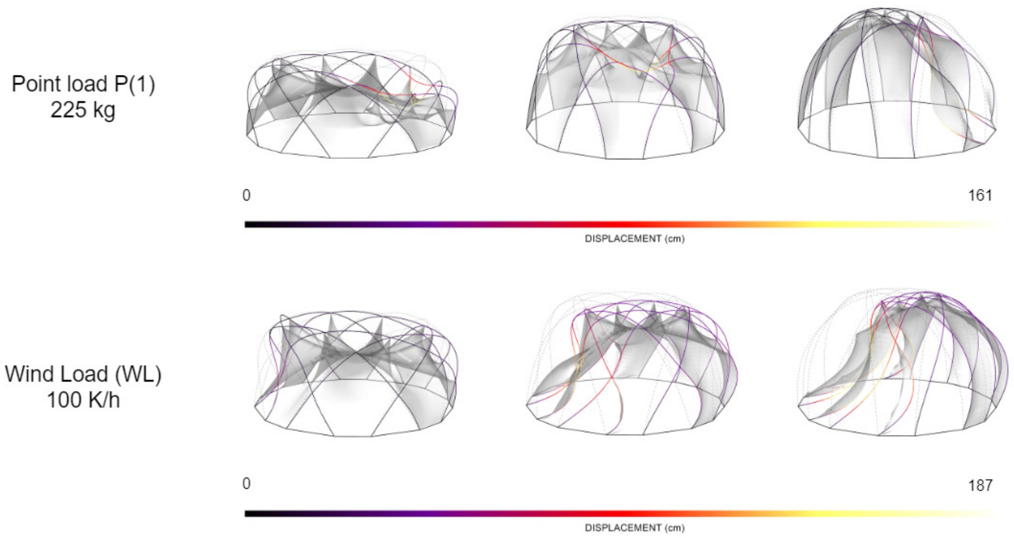


Figure 70: Displacement with loads P1 and WL of different geometry possibilities.

In the graph above (fig. 70) The structure with 35 ° of rotation present bigger deformations on the structure.

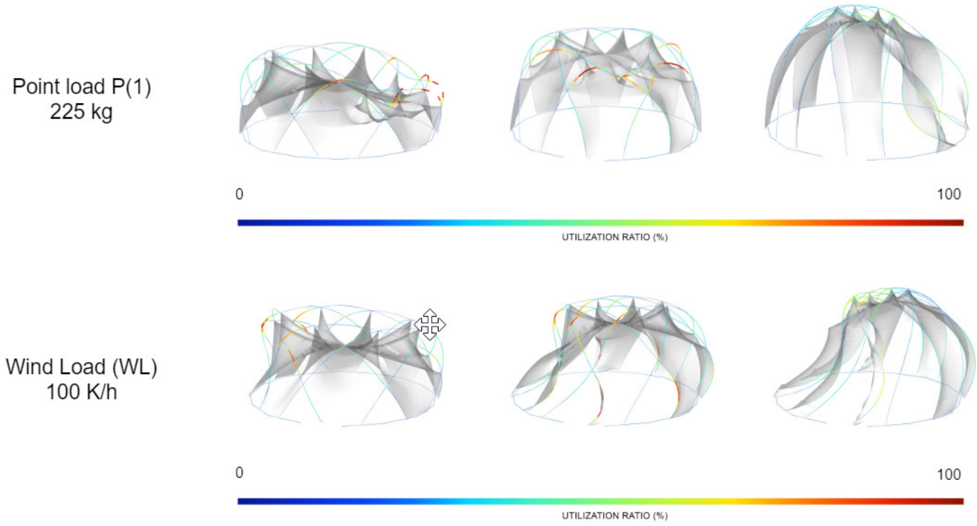


Figure 71: Utilization ratio with loads P1 and WL of different geometry possibilities.

In the graph above (fig. 71) The structure with 65 ° of rotation present an early breaking load capacity since the geometry has past the utilization ratio before the other options.

For this reason, we continue analyzing the structure with 48 ° of rotation.

7.3. Comparison between Hybrid structure vs Curved rods

In this chapter, the structure was subjected to a point load P1 to observe the different behavior from bend rod to curved rod.

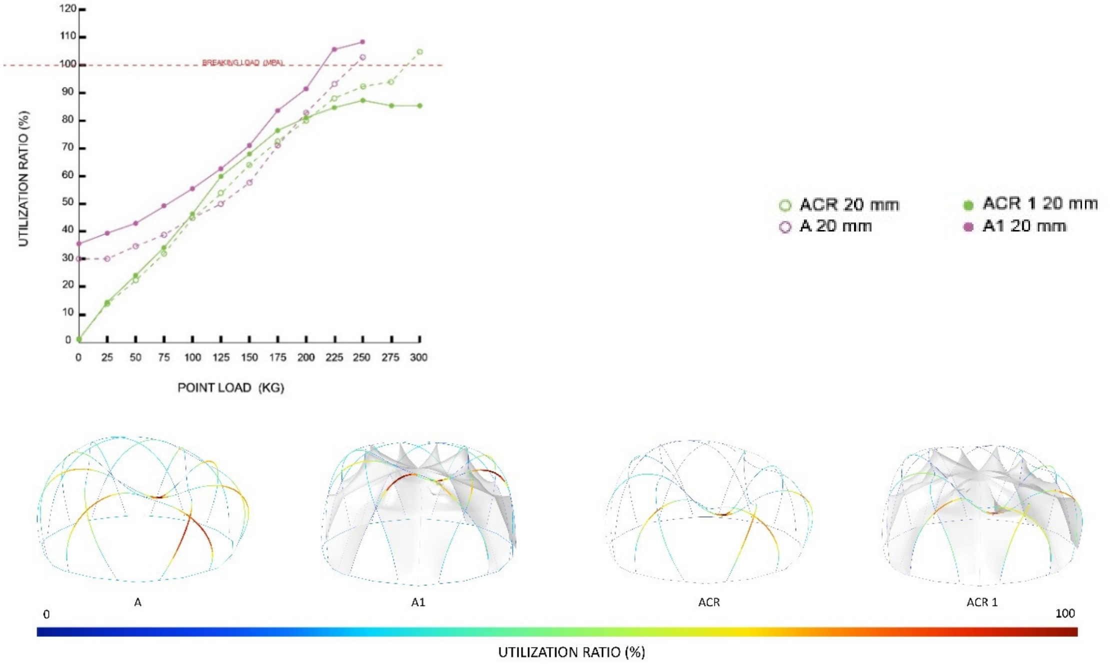


Figure 72: Utilization ratio of A, A1, ACR and ACR 1.

As Bending active achieve a stronger stiffness do to the prestress subjected to bent, curved rod achieve a higher material resistance. Furthermore, the possibility of straight rods makes an easy transportation.

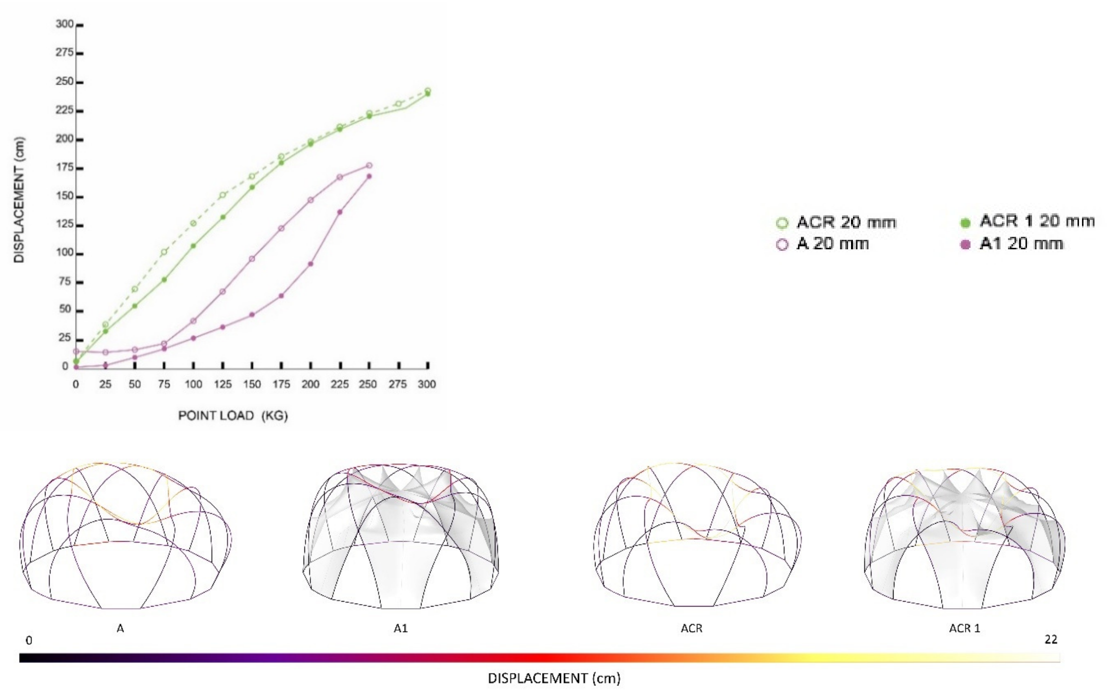


Figure 73: Displacement of A, A1, ACR and ACR 1.

The displacement graph (figure 73) also expose a stiffer behavior on the structure A and A1 (initial geometry), both structures only and hybrid present less deformation in the dome than ACR and ACR 1 (initial geometry with rest angle 1, i.e. curved rods).

$$\Delta_{\mathrm{A}} < \Delta_{\mathrm{ACR}}$$

7.4. Bracing possibilities

Beside climates advantages in a hybrid structure, in this part we focus on mechanical behavior of the prototype. Thus means, the structure does not respond to hybrid neither functional requirements.

Under the necessity to apply extra stability to the structure because of the assembly process, some studios have been made to prove the affordability of having another rod skeleton.

After an exhausting evaluation of each one of the configurations (A, B, C, D), which densify grid number A with 3 kind of options, it is clear that the structure achieves certain stiffness after triangulated locks that avoid movement. In the graphs below a load F has been applied to each case option in one common intersection point (P1). See figure 74 and 75.

F is the load in P1 produces different reactions and deformations in every structure, until they reach its max.

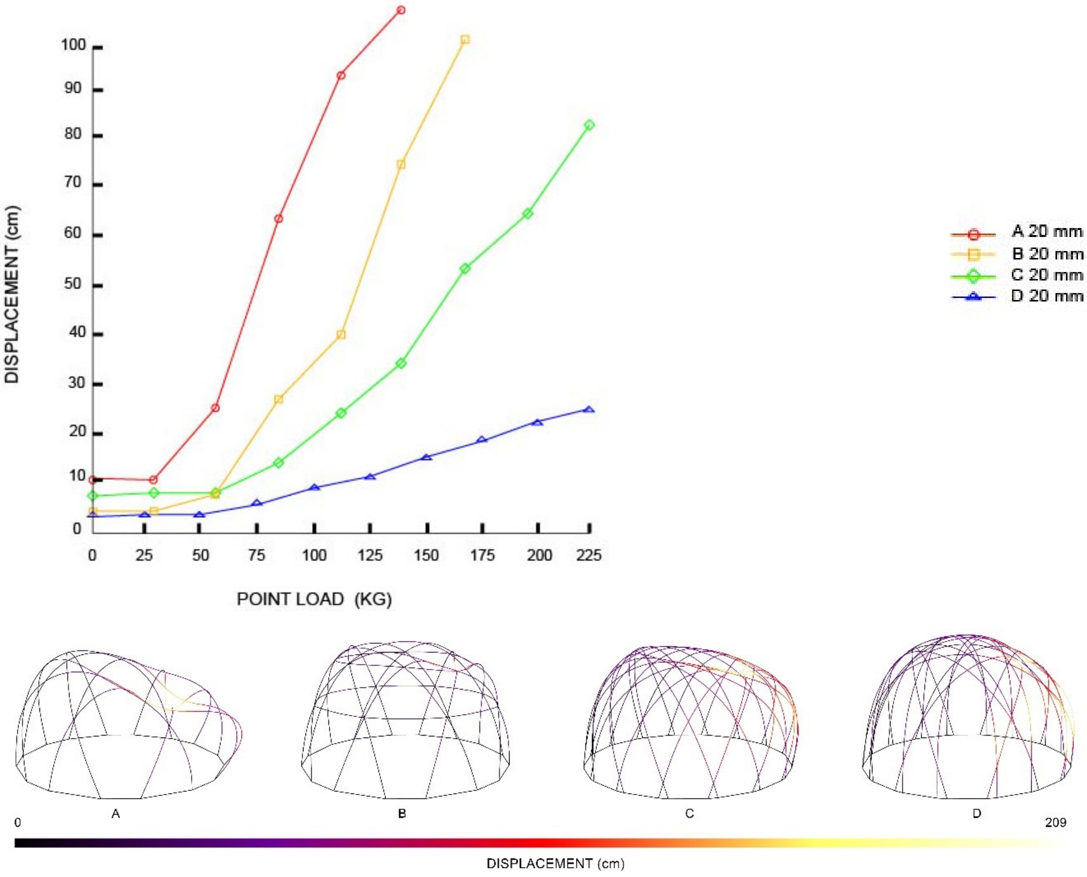


Figure 74: Point load displacement in grid configuration (A, B, C, D).

The graphic above display a comparison graph that shows the behavior, a load of the physical experimentation demonstrates the stiffness of this structures according the density of the grid and the triangulation of it.

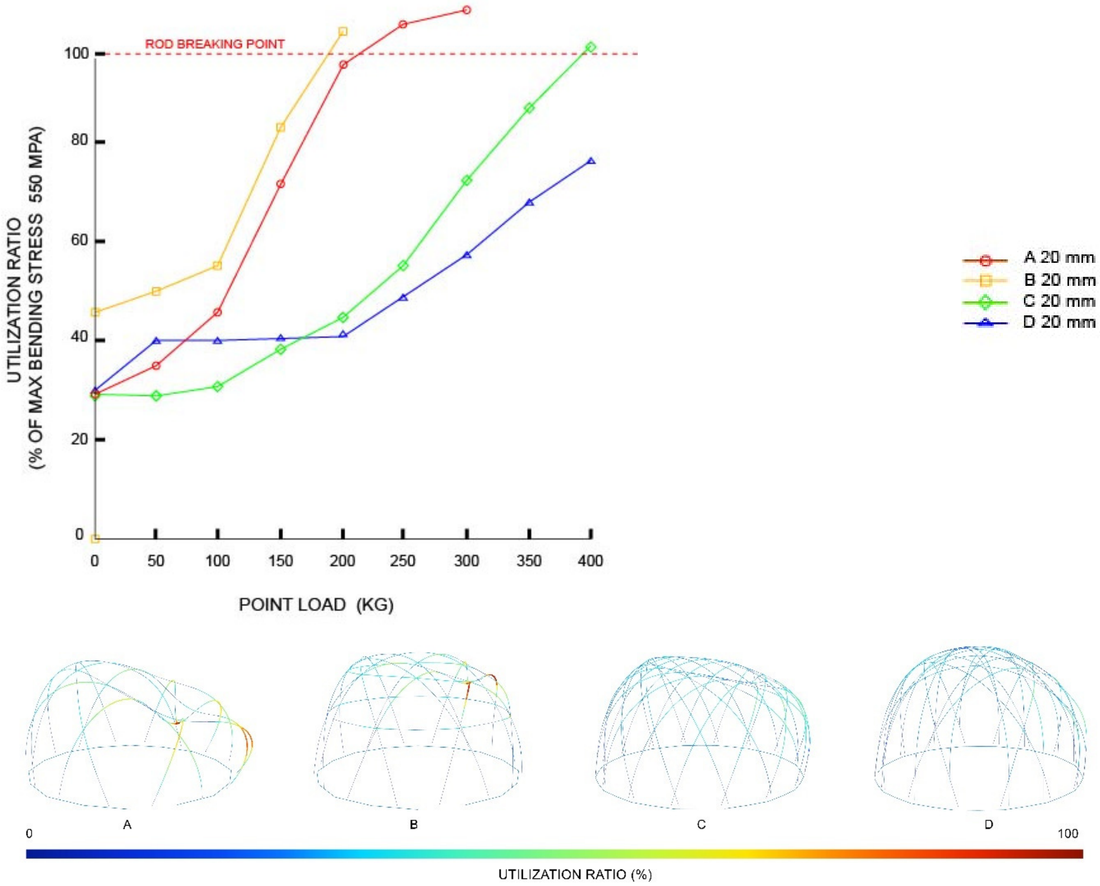


Figure 75: Point load utilization ratio in grid configuration (A, B, C, D).

The given locks, prevent the break of the structure, in as much as the forces are distributed now along the both structures.

In option D, thanks to its geometry approach, it locks many of the weakest areas which are the ones with bigger elements with no connections, performing clearly stronger than the other options.

7.5. Scaling and Stiffness

Consequently, it was proposing the possibility of a second skeleton as part of the system, to improve the stiffness during the assembly process. At this point, we tried to blend the whole system in order to not lose the hybrid concept. So, it was necessary to destabilize the prototype with different rod diameters. Rods of 8, 12, 16 and 20mm count with different section modulus which affect its elastic behavior. Hence, the structure might have an important impact of deformation.

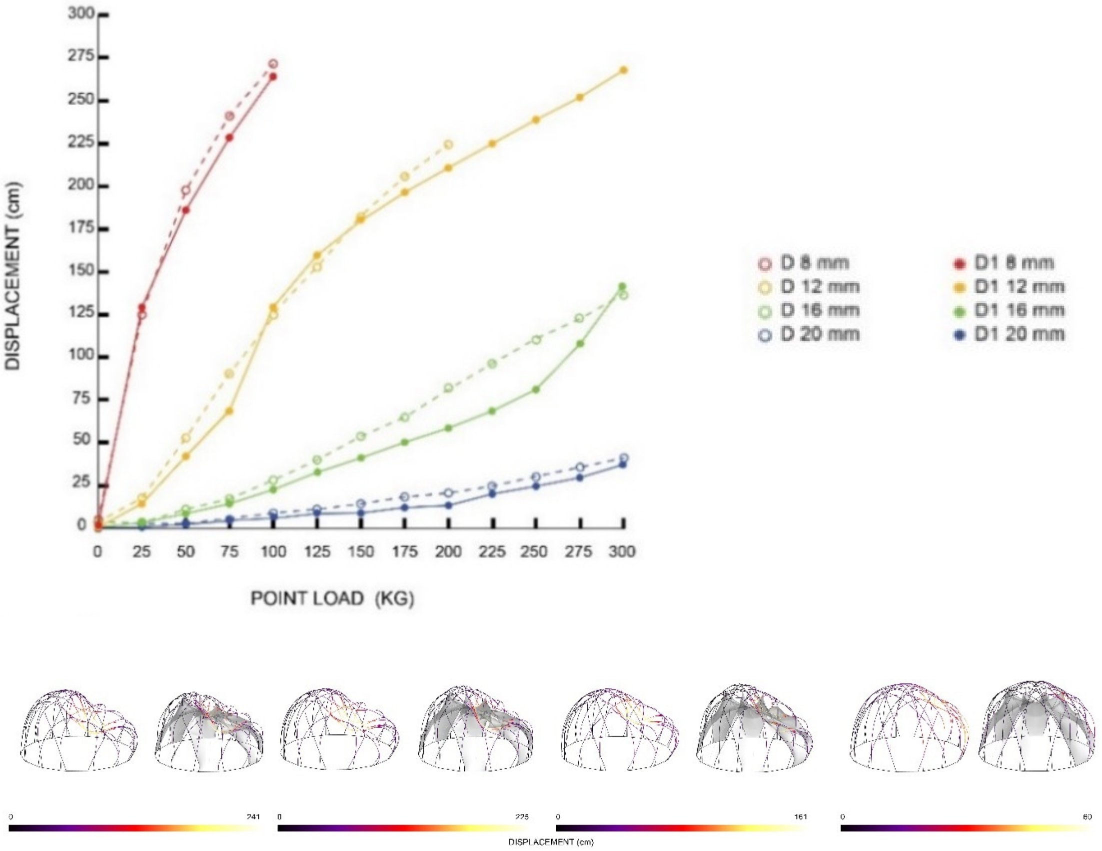


Figure 76: Point load P1 displacement in grid configuration D vs D1 (8, 12, 16- and 20-mm thickness).

The graph above (fig. 76) display the impact in each different diameter, compared the simple structure A with its hybrid option A1. Unfortunately, there difference does not give a significant contribute to a better performance.

An important aspect to take in account, it is the stiffness that the hybrid system provides in localized areas. Somehow, the membrane and cables lock the structure in certain points, causing a local deformation rather a global one.

Aside from this, we can observe large displacements in smaller rod dimensions under the same load. This explains that when the structure reaches a high level of stiffness, the addition of other element won’t have an impact on it.

To verify if the hybrid system is not directly related to the section of the rod, the structure A, who prove to have a better hybrid performance, it was evaluated with the same diameters as structure D.

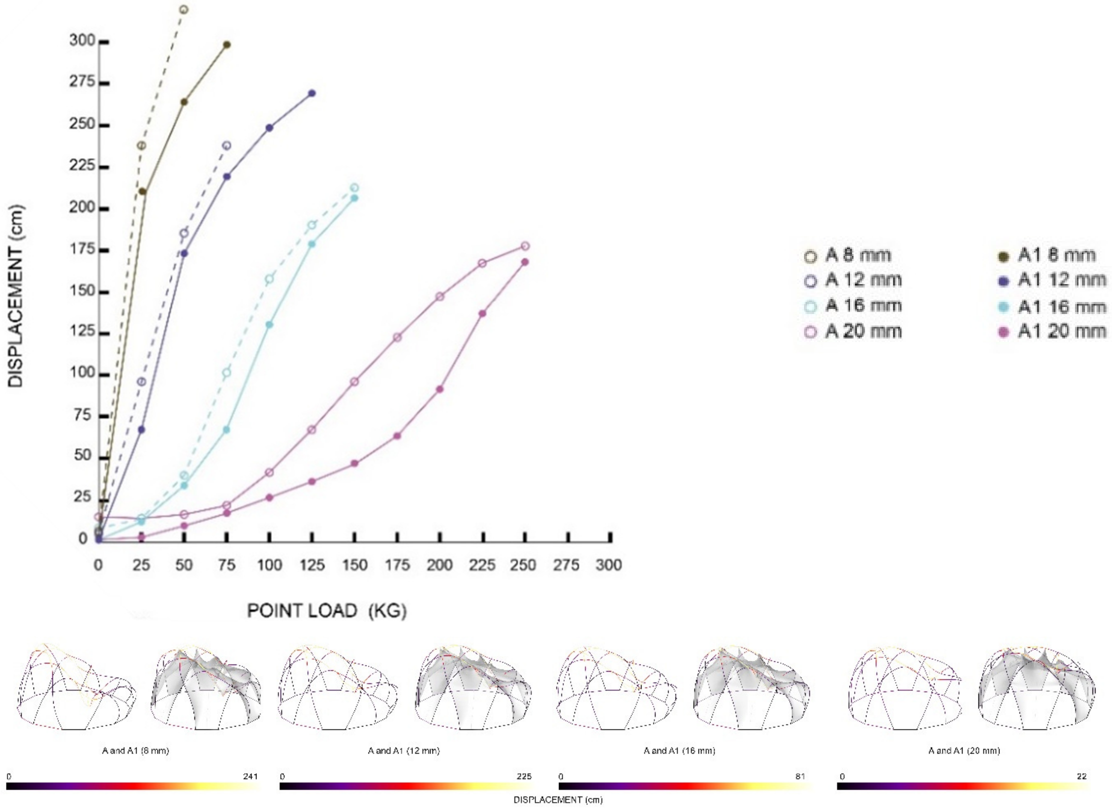


Figure 77: Point load P1 displacement in grid configuration D vs D1 (8, 12, 16- and 20-mm thickness).

Impressively, the displacement of the structures from A to A1 does not have a huge impact neither. It seems that the better hybrid performance is reached with 20 mm diameter, this could imply that at that point, the design reaches its maximum hybrid balance.

7.6. Assembly data

7.6.1. Assembly energy

After all of the analysis, it is important to know whether the system can be rationally assembled with the tools and human energy for a light weight structure.

The reaction forces for only rods, indicate a load average of 67 kg in order to bend them, I.e. one person could be able to push inward. See figure 78.

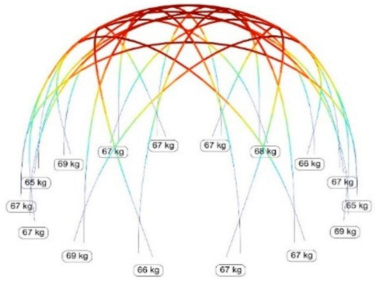


Figure 78: Axial stress colored in gradient and energy assembly.

The color gradient of stresses goes from cold colors to warn colors to illustrate bending area of biggest force.

7.6.2. Swivel couplers strength

The following graph illustrate the axial stress that receive the polylines who connect the grids, whenever this are close from each other. The closest points to the intersection of the roads, simulate the tension according the distance from its neighbor.

- Breaking load Chinese swivel coupler 3.15 Kn
- Breaking load German swivel coupler 6.25 Kn
- Swivel coupler simulation = 2.00 Kn < 2.44 Kn

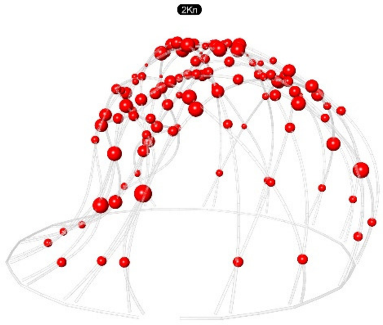


Figure 79: Axial stress indicating supports strength

On site, we had the facility to use two kinds of connections, ones with 3.1 kn strength and others with 6.25 kn as breaking strength.

In the picture above (figure 79), on left side, Axial stress of swivel couplers are represented as polylines acting in tension and on the right side, red dots are a scaled representation of the strength implied. This information involves the possibility to skip some connections where high stresses are shown or to place the strongest swivel couplers if the structure allows.

After the first assembly process, the prototype had suffered other aspects of physical behavior that had not have been talked in account. That is why we simulate a more accurate approach with the generation of eight surfaces offsite from the initial sphere, each two rod have been projected, simulating the layering in real life, after the separation, previous points from the grid have been connected, from the normal and thus shatter the line in every intersection.

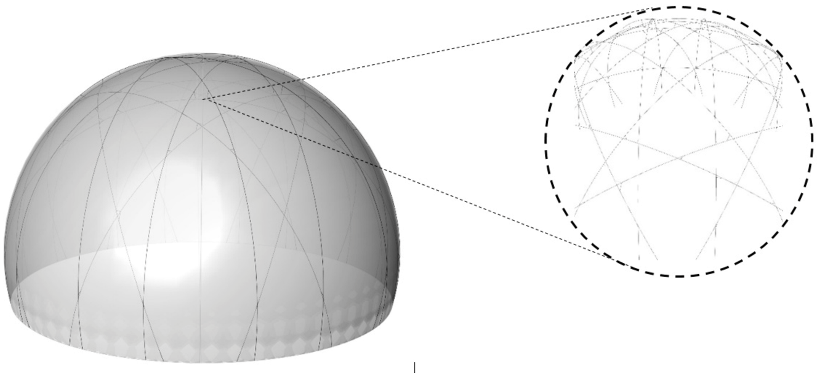


Figure 80: Real configuration of rods.

Back in the simulation, it was possible to simulate some missing connection impossible to connect in real life. However, the graph shows that the previous simulation was closer to the real behavior than the third one.

7.6.3. Cable strength

According to the simulation, the 2 mm cable that we propose will withstand the stress since the graph shows (fig. 81) an axial force below the breaking load.

- Breaking load 2.44 kn
- Cable simulation load = 0.81 kn < 2.44 kn

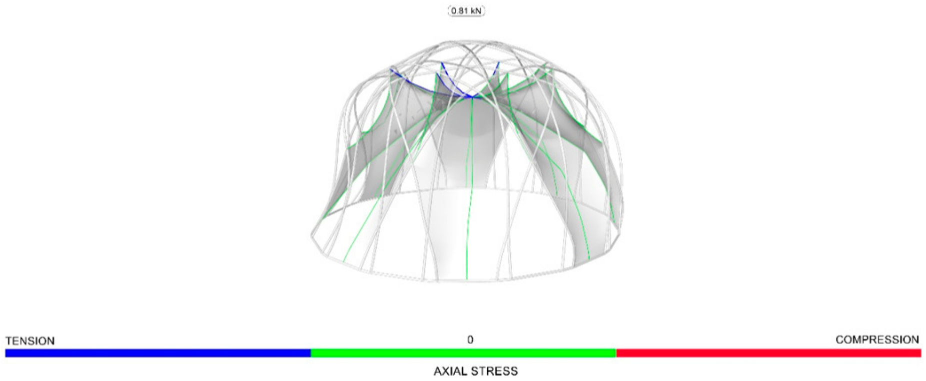


Figure 81: Cables strengths.

7.6.4. Membrane strength

In this case the prototype will be facing a membrane type I, tensile strength of Type I 3000 N/5 cm.

According to the simulation, the membrane will also withstand the stress, since the graph shows (fig.80) an axial force below the breaking load.

As the fabric was analyzed as a cable net, the strength value is taken from the area of each thickness and then we assumed a thickness of 1 mm to compare with the technical sheet.

- Breaking strength = 50 N/mm²
- Membrane simulation strength = 42 N/mm² < 50 N/mm²

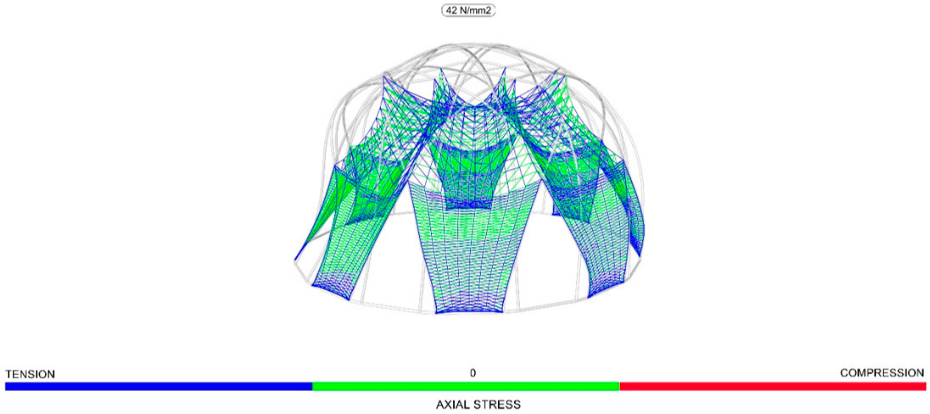


Figure 82: Fabric strength.

7.6.5. Supports reaction

The simulation has been made with all supports fixes in z axis and one of them fixed in the 3 axes to avoid the displacement of the whole structure.

The reaction forces on bottom, see figure 83, indicates the required resistance of the supports for a sever tropical storm, which means 115 km/h wind speed.

We can observe on the graph below (fig.81) a maximum of 542 kg to consider per each 16 anchor points to support forces in different directions.

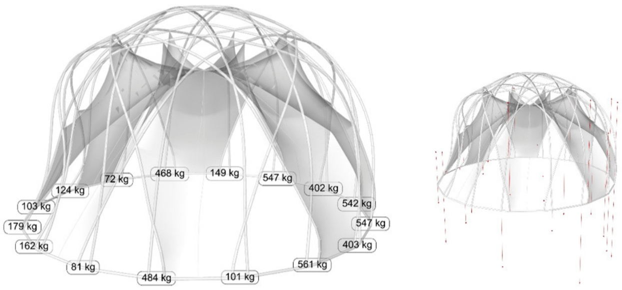
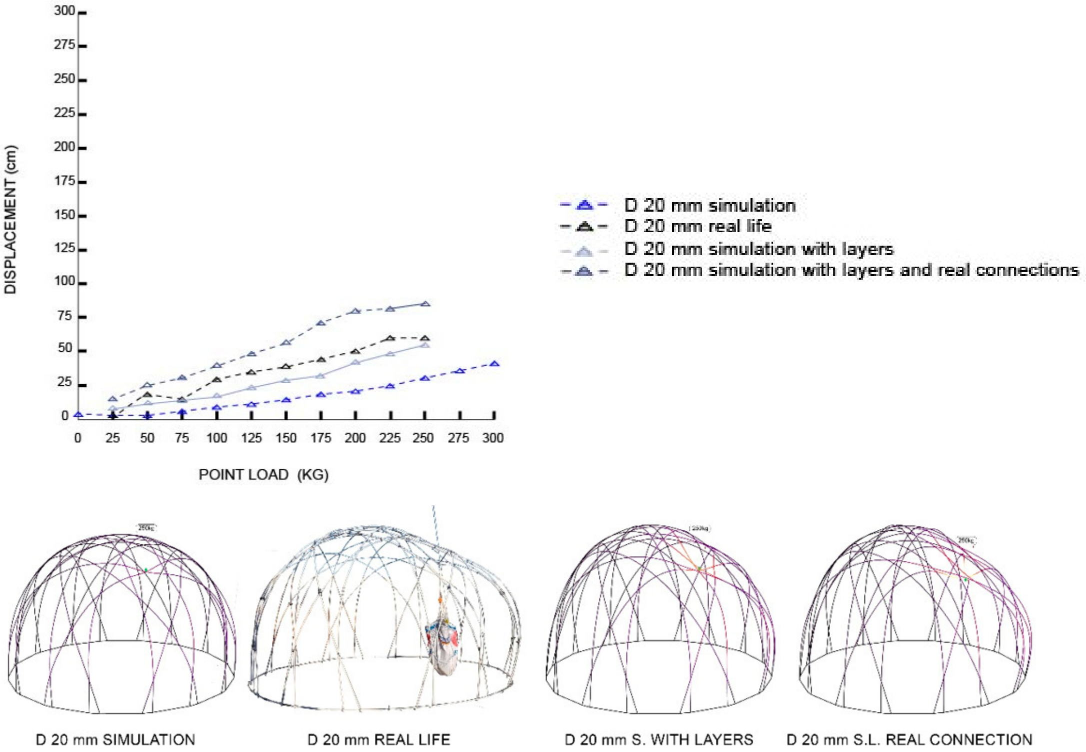


Figure 83: Reaction forces.

7.7. Simulation accuracy

The accuracy of the plug-in simulation was measured on a real-life prototype, scaled 1: 1.

The structure was subjected to point load P1 loaded with 25 kg cylinders to 250 kg.



D 20 mm SIMULATION

D 20 mm REAL LIFE

D 20 mm S. WITH LAYERS

D 20 mm S.L. REAL CONNECTION

Figure 84: Simulations approach / max displacement 250 kg.

During the assembly process, there were bigger tension in some connection, since it was impossible to connect some swivel couplers on the second structure. Thus, there was a stiffness variation on the displacement due to the load distribution was no longer continuous.

The graph shows a variation of 4 different approaches of the grid. Also, we can appreciate the difference since the first attempt it is the simulation with all points fixed in the same surface until the latest simulation with the same swivel couplers projected as in real life.

8. Membrane patterning

After performing the analysis relevant to the structure and membrane, it is time to perform the cutting pattern for the membrane, also is required that it be completely parametric to be able to make changes in real time if necessary. Even if the manufacturer does not require as such parametric design formats it is possible that at the time of exporting the final files they happen unexpectedly and having a computer on which to make last minute changes is always a good choice.

To begin, it is important to select the module that is obtained from the final relaxed design obtained from grasshopper.

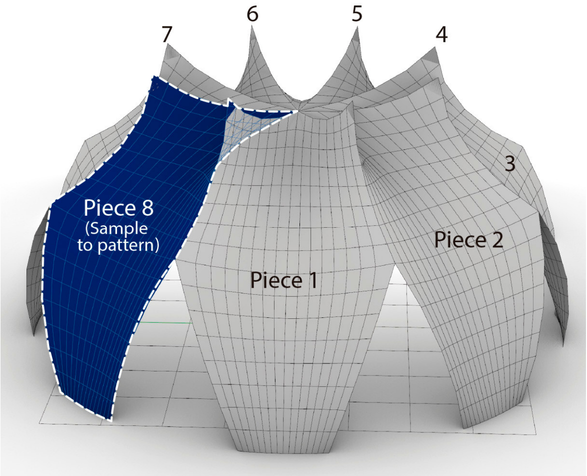


Figure 85: Identification of a repetition module.

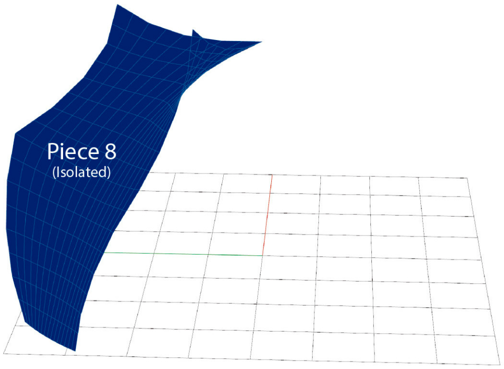


Figure 86: Selection of a module to work.

Subsequently it will be necessary to subdivide the part as much as possible so that it fits in the cut-out outlet for the membrane, even if the design is symmetrical and requires mirroring the piece 50% of the time this will not affect the final dimensions or the shape on the membrane, however it will help to ease its handling.

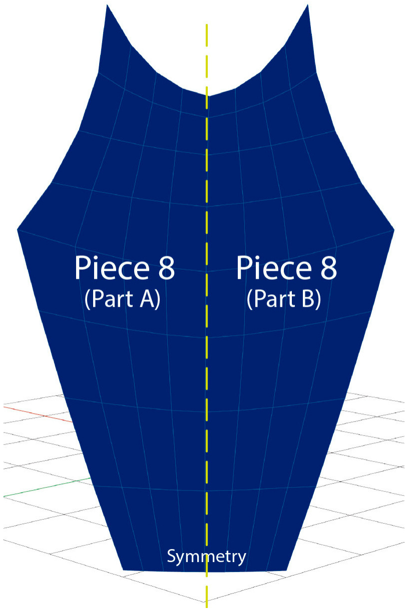


Figure 87: Breaking problem in the less amount of geometry.

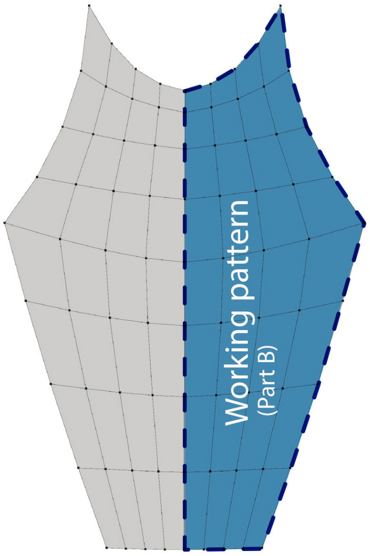


Figure 88: Selecting the pattern to work with.

To achieve an adequate pattern it is necessary to make a new parameterized mesh that favors the planning of the module selected to work, we have to remember that the curves must be rationalized before being manufactured, and the best idea is to divide the problem into smaller parts, in this case we can manufacture a new simple mesh using the boundary points.

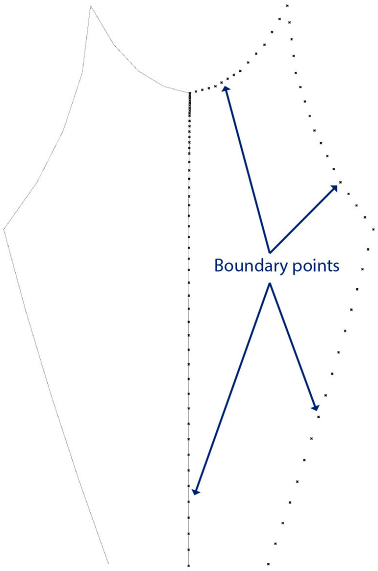


Figure 89: Way to start a new mesh for rationalization

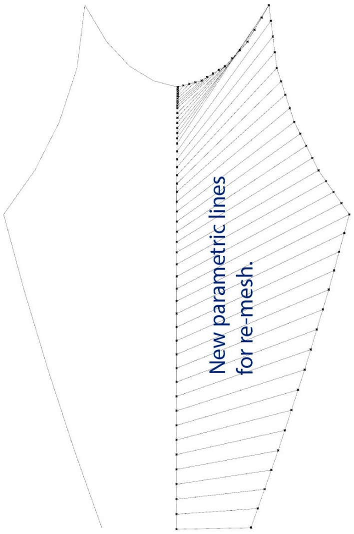


Figure 90: Parametric lines for the new mesh

The result is a simple mesh that can be mirrored to create a module that will later form the entire membrane.

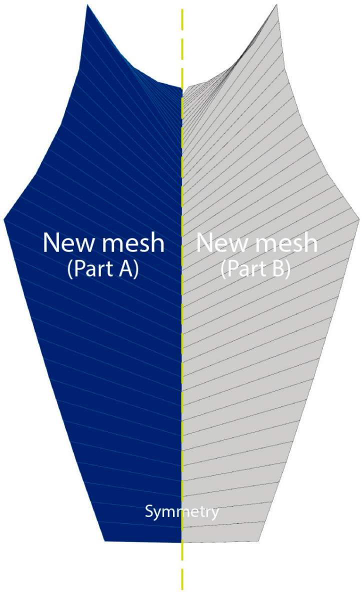


Figure 91: Remeshing results

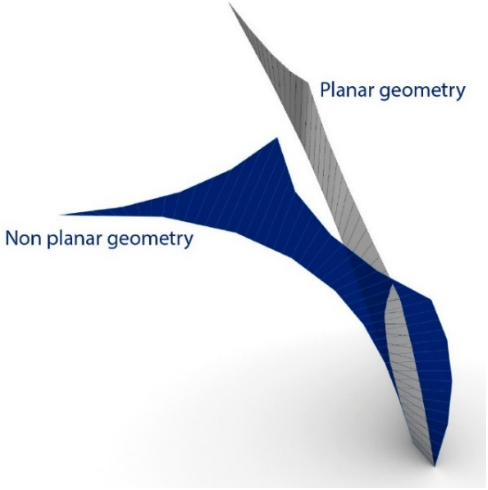


Figure 92: 3D geometry to planar

The next part of the process is to planarize this small fragment of the mesh to be able to work in 2 dimensions and ease its manufacturing process, we did it by using the Kangaroo Unroller. In addition to performing this first process, the planarized geometry is required to be in a plane like the xy, this is because we will work in programs that doesn't allow 3-dimensional environment ones we jump to manufacturing

Once having the work piece finally planarized and in the correct plane we proceed to start the manufacturing details required to meet the needs of the design, it is required to perform certain cuttings to the membrane as well as extensions to be able to glue the modules with each other and form the entire membrane. It should be noted that once the cut piece must be done a manual work in which by means of a special glue (Cyanoacrylate) on all the small pieces to form a complete membrane.

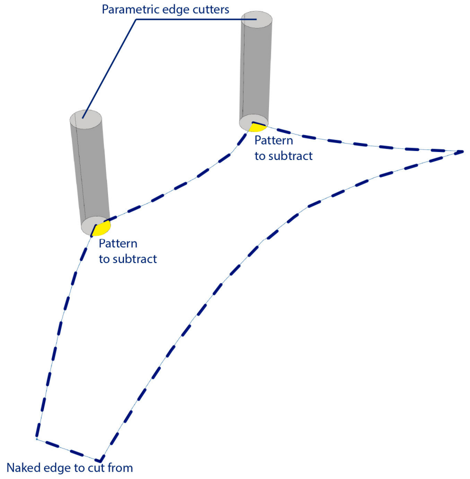


Figure 93: Geometric elements to cut from membrane

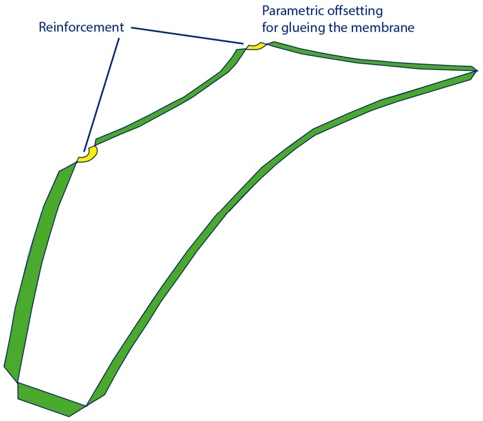


Figure 94: Membrane extensions (5-10 cm) and reinforcements

It is important to know that as this membrane will be under stress efforts, it will also be necessary to place a parametric pattern of holes that could be like a shoe, tighten and tighten the mesh once placed, as shown in the following figure.

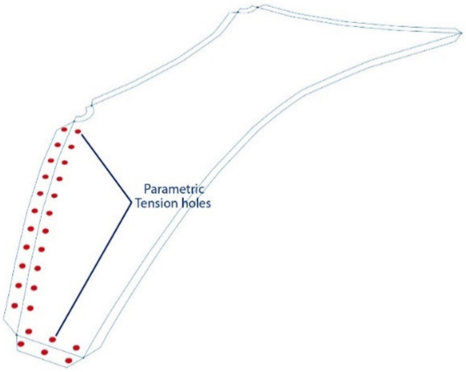


Figure 95: Membrane extensions (5-10 cm) and reinforcement holes

The holes should be reinforced by special stainless-steel eyelets or a strong material so that the membrane does not tear while we tense it.

9. Manufacturing

In order to begin with the manufacturing of the structure, different factors were taken into account, which are part of a process to follow in which the order is important since the structure is completed progressively. It is necessary to complete the design and analysis part in its entirety because once the pieces have been cut and assembled it is very difficult to modify them, accuracy is a key factor in this part of the project, so sufficient time must be invested in the phase design to not have many problems at the time of manufacture.

9.1. Manufacturing process of rods and connections

The rods have a limited factory modular size, and a continuous curve of each structure could not be an entire piece but the composition of 3 bars and for this a typical fixing accessory is necessary to join all the pieces. It is considered a metal tube with 2 holes to place the screws and fix the joints.

For the junction of intersections, it is considered that it has only the superposition of 2 bars in the whole structure to avoid the complex union of multiple elements and only to use a typical metallic accessory with 2 clamps connected by means of a rotation axis that allows an integrated movement of parts.

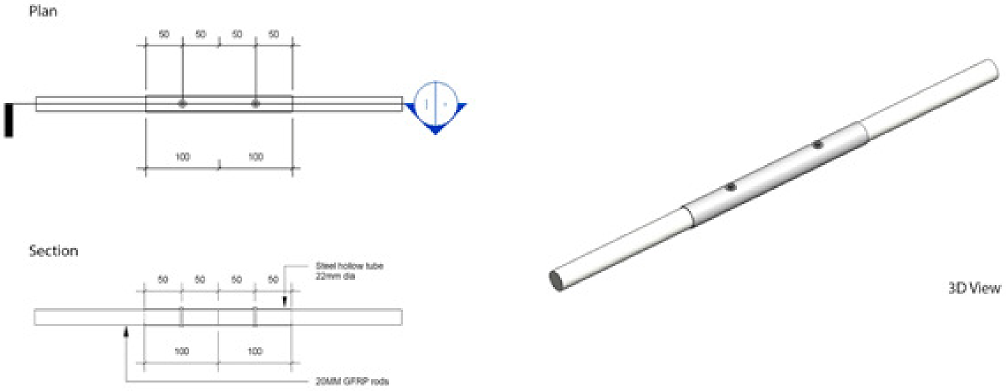


Figure 96: Detail for join extension.

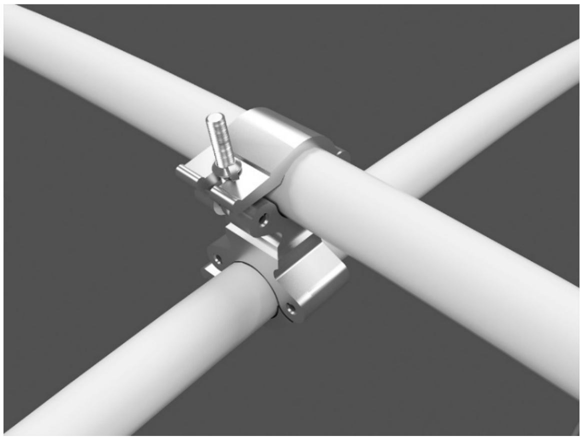


Figure 97: Rod joining system

The correct scheme of placement of this system is defined by two fundamental parts:

1. The points of coincidence between two bent bars.
2. The efforts generated at these points of coincidence.

In this way it is necessary to calculate how much force is generated at each point in order to know what type of connection to make, so the more effort the coupling must be more resistant and the less effort the coupling can be normal following the following diagram.

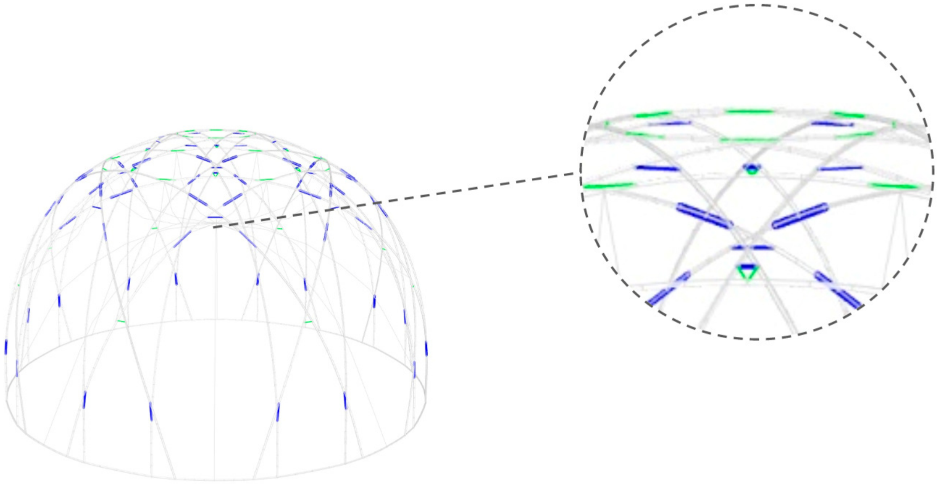


Figure 98: Rod extension and swivel couplers map

9.2 Manufacturing process of membrane and cables

In the case of the membrane to weave the edges to the structure an edge with eyelets and halyard was used. In the case of the use cables a typical detail of accessories was developed at the ends of the cables to be able to calibrate the tension of the cables.

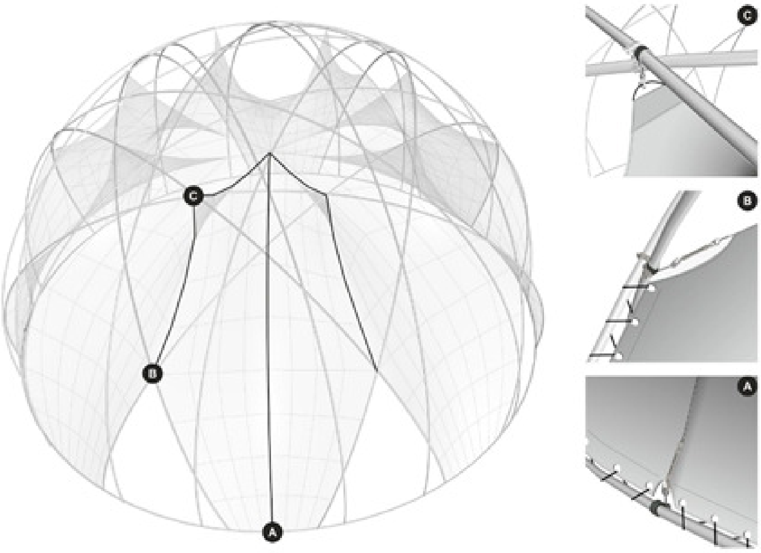


Figure 99: Typical details of membrane installation

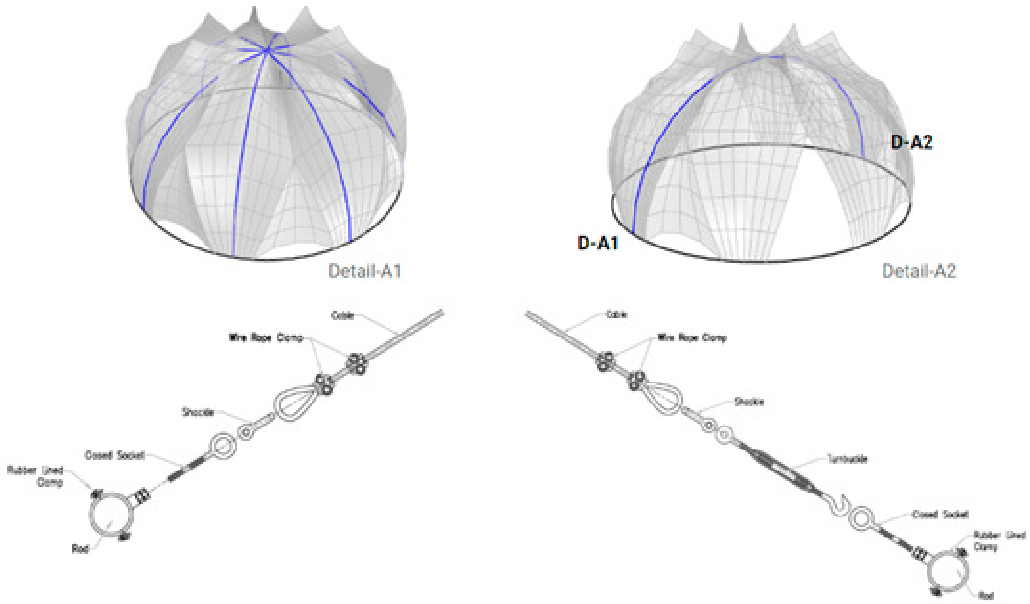


Figure 100: Typical details to fix cable 1

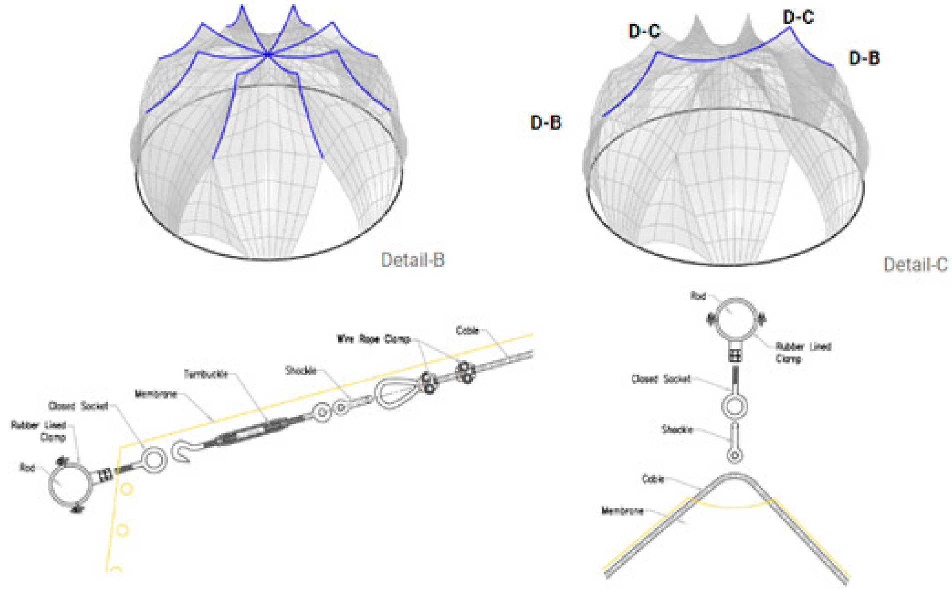


Figure 101: Typical details to fix cable 2

9.3. Getting prepared

Every design requires a guide plane that helps to carry out the work, this is also the case and to place the fiberglass bars correctly it is necessary to mark the initial starting place on the floor with chalk before bending, then we raise the entire structure by a scaffold to begin bending the structure, from this moment you will begin to see the bending effort that is generated by gravity, however there is a long way to go before the structure comes alive and works properly.

Figure 102: Structure up the scaffold being joined with swivel couplers

Once the structure is placed in position, a compression effort is generated making the entire previously fixed pattern bend and create what we know as a dome, this is achieved by applying the same amount of force at each end of the structure and towards the center. Once there we proceed to fix all the ends to the boundary (circle made with the same fiberglass bars).

It will be necessary once having in position the entire structure to ensure the swivel couplers with more force to fix the structure 100% avoiding axial displacements, here is the phase in which you can perform tests of point loads and compare them with the previous analyzes performed by K2E

Figure 103: Bended structure being stressed by a punctual force in Z

10. Conclusion

Initial geometry

Establishing an initial geometric criterion to be able to parametrize with a sequence of variables later, allowed us to create an algorithm on a defined topology, evaluating maximum and minimum ranges of geometric configuration, as well as multiple options for subsequent evaluations.

Dynamic relaxation and form finding

The dynamic relaxation applied to a defined topology allowed us to reach the final form through simulation, in this part we can understand how the simulation of the different parametric options, gives us a variability in structural behaviors, this suggested us which options would have the need of additional elements or also, a different structural configuration of the elements that compose it. In this way we make a combination of geometric and physical variables achieving a dynamic control of parameterized options for a subsequent evaluation of stress calculation and dimension of materials in hybrid structures.

Structural analysis

In the analysis of different frames, options A B C and D were evaluated considering option D as the most stable, by adding cables and membrane we transform structure D into a hybrid structure of 3 elements. In the evaluation we considered important to analyze how optimal this hybrid structure was, if all the elements were directly involved as a coupled system (sharing efforts) to make the system more stable. We decided to apply 2 criteria on which we would make a new analysis, the first was to decrease the diameter of the rods that are bending and reduce the amount of structure to give more participation to the cables and the membrane.

Statement

To conclude, the optimization of the hybrid structure studied for the case of a dome, it is limited to the configuration of its geometry and the initial stiffness, because of its rods, which achieve even more stability when fixed to the perimeter ring in the ground that defines the boundary.

The first strategy changes the diameter of the rods and the second reduces the number of rods in the grid in order to destabilize the structure. Despite this, the result of both strategies causes a minimum impact as a hybrid performance, in both evaluations. So, the membrane and cables participate but not contribute much in the stiffness. However, they provide a functional solution as a habitable space.

11. Further research

We thought that the dome shape and the ring where all the rods and cables were fixed to form the membrane took all the effort that could be contributed by the elements involved. On this, eliminating the rigid ring and replacing it with cables or a membrane is the option of which if we have parametric development to be evaluated in a subsequent investigation.

Reference

[1] Engel, H., “Structure Systems”, 1999

[2] https://en.wikipedia.org/wiki/Tensile_structure

[3] https://www.alibaba.com/showroom/types-of-scaffolding-steel-joints.html

2014.

[4] Ashby, M. F., “Materials selection in mechanical design”, 2005.

[5] Knippers, J. “From Model Thinking to Process Design”, 2013.

[6] Brand C., “Lecture on k2 engineering”, Universidad Politécnica de Catalunya, 2019

[7] Daniel Piker, Lecture on k2 engineering, Universidad Politécnica de Catalunya, 2019

[8] PNAS, January 2, 2018 115 (1) 75-80; first published December 18, 2017 https://doi.org/10.1073/pnas.1713841115 Edited by David A. Weitz, Harvard University, Cambridge, MA, and approved November 20, 2017 (received for review August 4, 2017)

[9] https://kadk.dk/en/case/hybrid-tower

[10] http://www.str-ucture.com/en/what/research-and-development/reference/bending-active-membrane-roofing-marrakech-itke-university-of-stuttgart-2011/

[11] https://icd.uni-stuttgart.de/?p=7799

[12] https://www.researchgate.net/publication/321062605_Bending-active_Sandwich_Shells_Studio_One_Research_Pavilion_2017

[13] Lienhard J. “Bending-Active Structures”, Universität Stuttgart, 2014

[14] Gengnagel C., Alpermann H., Lafuente E., “Active Bending in Hybrid Structures “, Jan., 2014.

[15] https://www.researchgate.net/figure/Development-of-bending-active-structures_fig2_261596411

[16] https://issuu.com/bilgeturgut/docs/ching_2014_building_structures_illu

[17] http://jdsac.com/wp-content/uploads/jdsalasc/books/sistemas_de_estructuras.pdf

[18] https://www.feandalucia.ccoo.es/docu/p5sd5274.pdf

[19] https://www.udk-berlin.de/studium/architektur/fachgebiete-der-architektur/ konstruktives-entwerfen-und-tragwerksplanung/forschung/a-new-hybrid/

[20] https://www.researchgate.net/publication/320256221_Torsion_as_a_design_driver_in_plate-bending-active_tensile_structures

[21] https://experienciapei.wordpress.com/2014/11/07/arquitectura-vernacula-beduinos/

[22] https://www.pinterest.com/pin/551409548118418971/?lp=true