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Transformable Bending Active Structures

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Abstract

In this short research, inspired by the principles of elastic gridshells, we chose to study and enhance the potentials of building elastic gridshells. Elastic gridshells comprise an initially planar network of elastic elements that are actuated into forms characterized of double curvature. Elastic gridhsell structures can be used either as parts of a bigger building (for example, as roofs) or as a building itself. Some of the characteristics that establish the aforementioned as an ever-growing field, today more eagerly than in the past decades, is the efficiency in assembly, transportation, the variety of design forms that can be shaped into and, when studied properly, the financial and ecological efficiency.

Our goal is to make use of the techniques of erecting elastic gridshells from a planar network, and come up with at least two stable forms deriving from the same planar network of elements and also, have the ability to transform from one form to another. Thus, by utilizing the same elements we could produce variable building structures able to adjust to different purposes and needs. Moreover, we seek for the minimization of the effort and money needed to swift in between these two stable states.

Keywords: Gridhsell, bending active, multistability, transformability, transformable structures, GFRP, bracing, optimization, form finding, chebyshev

1.Hypothesis

Our hypothesis implies that from a single planar network of elements, we can obtain multi-stable erected geometrical forms, while utilizing the principles of a chebyshev gridshell. Multiple forms, which serve different purposes while demanding the minimum energy and material wastage possible for the transition.
The different geometries are obtained by exploring the possibilities of modifying the number and location of supports.

2. Purpose of Research

Two terms are considered important to back up our case.

"Multi-stability" and *"Transformability"*.

In a dynamical system, multi-stability means the system has two or more stable equilibrium states, giving it the ability to rest in either of these states.

Transformability, describes the ability of a system to transform and adjust to different conditions.[0]

Gridshells that use bending active, are by fact, structures that are efficient because of their characteristic to transform, from an initially planar network configuration to a 3D form in space. We use the term multi – stable structures, as we seek to obtain geometries, that apart from a flat configuration and an erected geometrical form can achieve at least one more stable state, which will ensure that the potential structure could be adaptive to different conditions.

Nowadays, gridshell structures when designed as autonomous buildings and not as parts of a bigger structure, due to their aforementioned efficiency, usually can host short term events or public gestures, mostly in open public spaces. Starting from that, we believe these structures could serve that purpose multiple times, considered the materials' lifespan, while their form could change, based for example, on the weather and climate conditions or needs concerning the privacy of a particular use.
In winter time, or for a more private event we could create a pavilion more introverted, which when shifting between seasons, or accordingly more public events could transform to a more open form.

By achieving that, we do not only design a form able to adjust to different conditions, while minimizing the assembly difficulty, but we consider that as a more sustainable approach.

3. Introduction

This thesis explores a method to apply the aforementioned hypothesis on a GFRP (Glass Fiber Reinforced Plastic) elastic gridhsell and furthermore the optimization regarding an efficient bracing pattern and detailing. To test the correctness of our hypothesis, we present our initial experiment, which proves that such an idea could be feasible and also an efficient solution when a transformable gridshell is needed or desired.

3.1. Definitions

3.1.1. Elastic Gridshell

An elastic gridshell is a free form structure, usually doubly curved which is retrieved by the deformation of a regular, initially flat structural grid. The stresses on these structures are mainly transmitted through compression and tension. The concept was firstly introduced by the German architect Frei Otto, who designed the Mannheim Multihale in 1975, introducing the concept to the world. Gridshell structures, with the invention of new materials, have become an ever - growing concept in today's architectural world. [1]

3.1.2. Chebyshev net

Chebyshev nets are coordinate systems on surfaces obtained by pure shearing of a planar domain.[2]

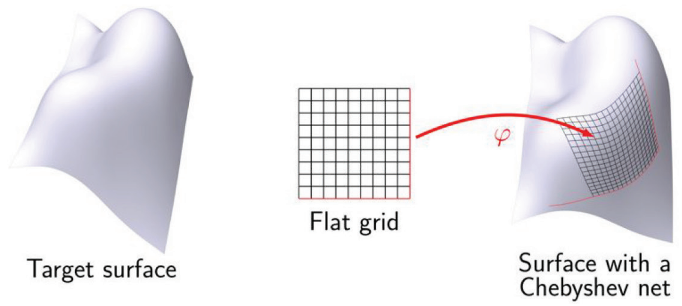


Figure 1: Chebyshev net principle (diagram by Y. Masson)

3.2. Initial Experiment

Before proceeding to an optimization process and to a more detailed research and code, we set up a simulation to check if our initial hypothesis could be further investigated.

After creating an initial octagonal flat base net, we parametrically selected two sets of vertices which would be the supports of our first pair of structures, an open - form structure and a closed - form structure.

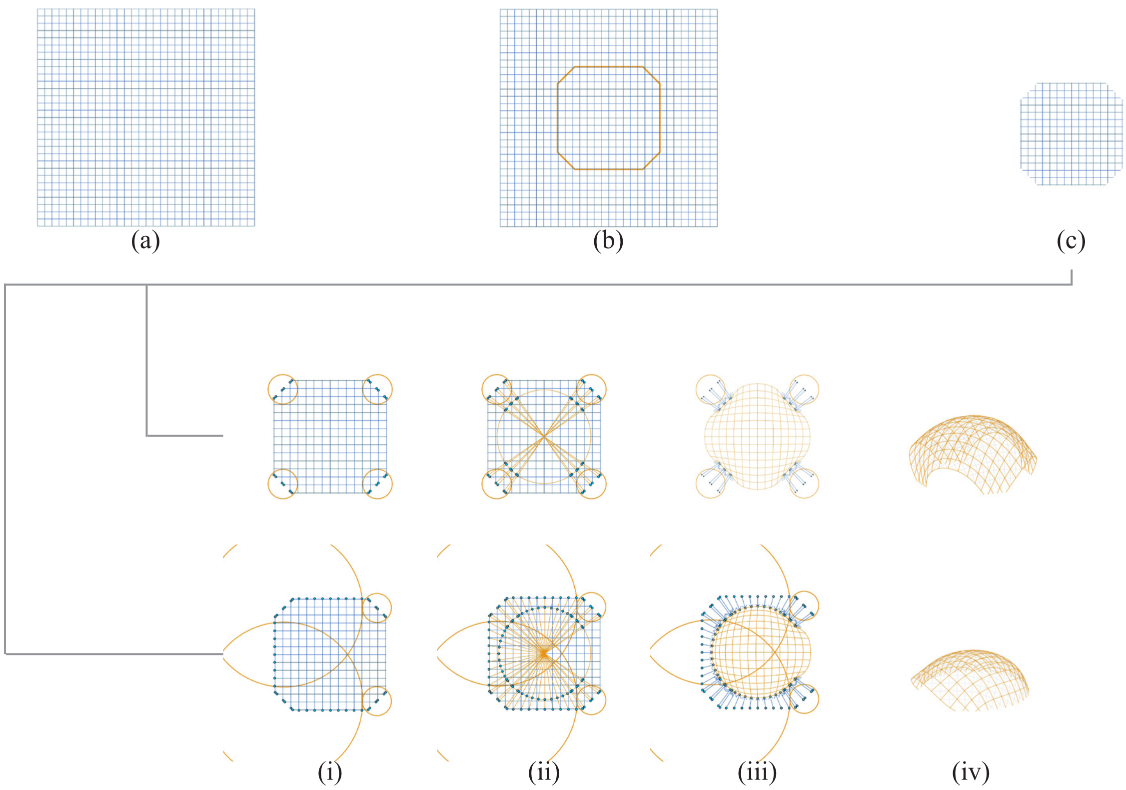


Figure 2 : (a) Original square flat net, (b) Trimming polygone, (c) Resulting octagonal flat base net.
(i) Selection of supports, (ii) Selection of target supports, (iii) Generation of resulting 3D net, (iv) 3D form

3.3. Objectives

As presented above, two stable 3D geometries can be retrieved from one single planar network.

Although, when it comes to the physical model, the different needs of each of these two structures could define that proposal as not feasible and economical. For that reason, we decide on some objectives, which will play a critical role in the feasibility of the original idea.

Since in our study we use gridshells that answer to the attributes of a chebyshev net, we have ensured that the number and the physical characteristics (length) of the elements we are using, for the base net, as long as their joint locations, are exactly the same between the two stable forms.

The differences between the two structures concern the material used for the efficient bracing of the structure, the number and the location of the supports and the energy needed to dislocate and swift between those two stable stages and last but not least, the patterning of the membrane, covering the structures.

As a start, we choose to focus on optimizing the variety range of bracing. More specifically, following the decision of the location of the needed bracing coverage that would help the structures behave well, we aim to minimize the number of different elements needed between the two forms.

3.4. Transformable GFRP Gridshell

3.4.1. Selection of base flat structural grid net

As the first step of our research, we had to define the base net (Planar network of elements) from which the multistable form would erect.

While experimenting with flat nets of different shapes to generate different forms we selected four locations of supports accordingly to each geometry's symmetry and the potential stability of the erected form. Initially, our experimentation began with circular and hexagonal nets retrieved by the suitable trimming of a starting rectangular net. Through a comparison of the resulting erected forms, we selected the most suitable shape of the flat net for further exploration.

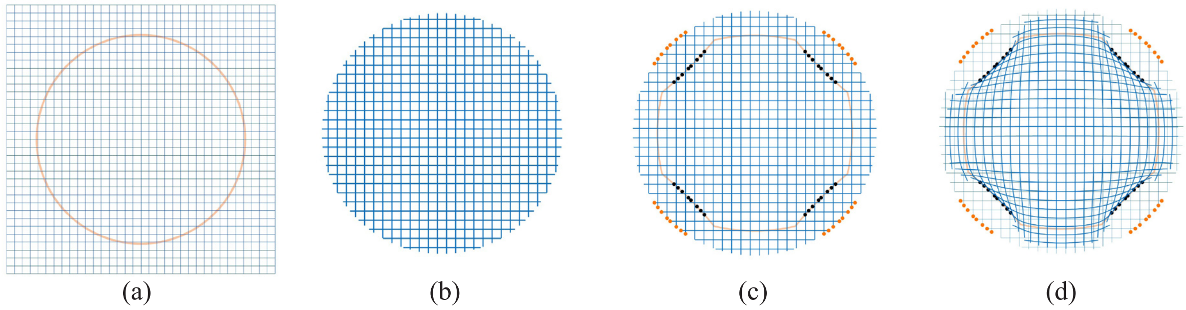
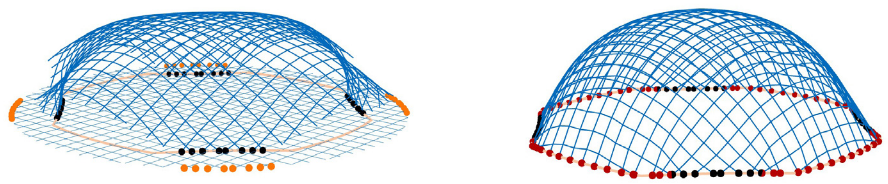
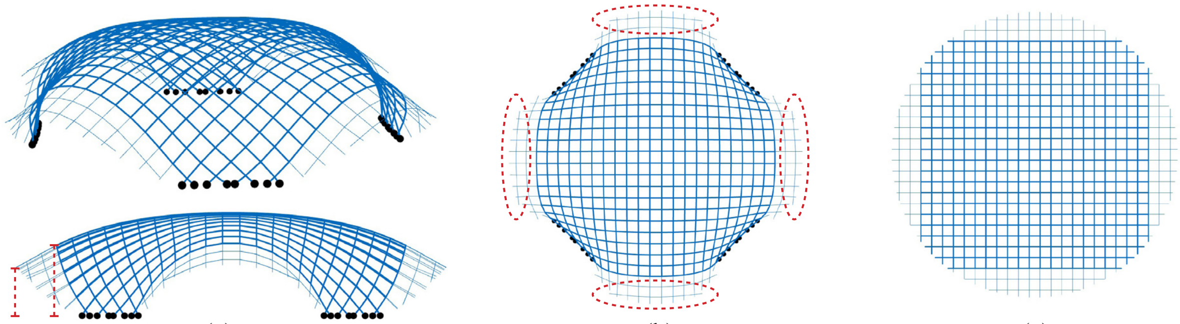


Figure 3 : (a) Original square net and trimming geometry. (b) Generated circular net. (c) Selection of 4 location of supports. By pulling these points toward a target geoemtry, the supports of the erected form are created. (d) Resulting form



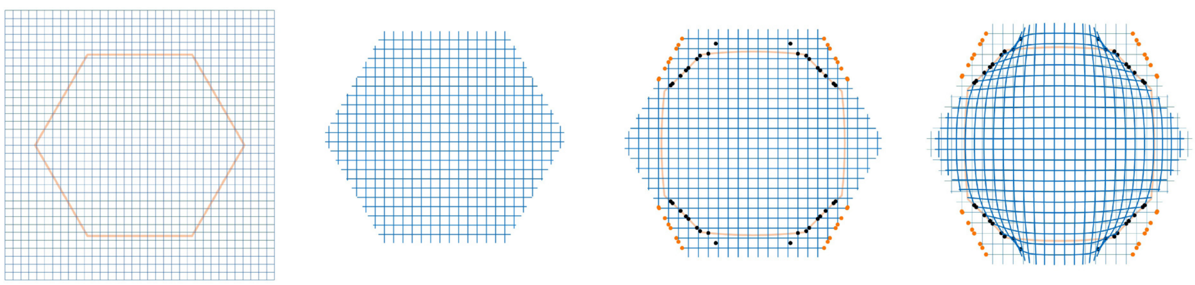
(a) (b)

Figure 4 : (a) Open form. (b) Close form- Generated from flat circular net



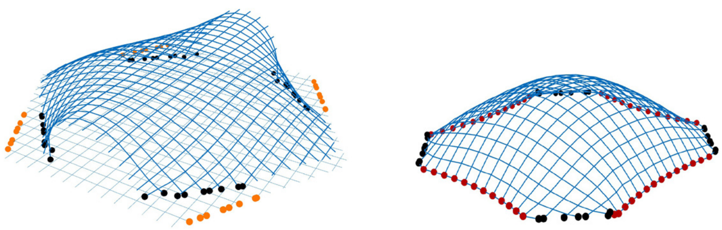
(a) (b) (c)

Figure 5 : (a), (b) Trimmimg the excess net to create larger openings for open form
(c) Result: Trimmed flat net by removing the excess net



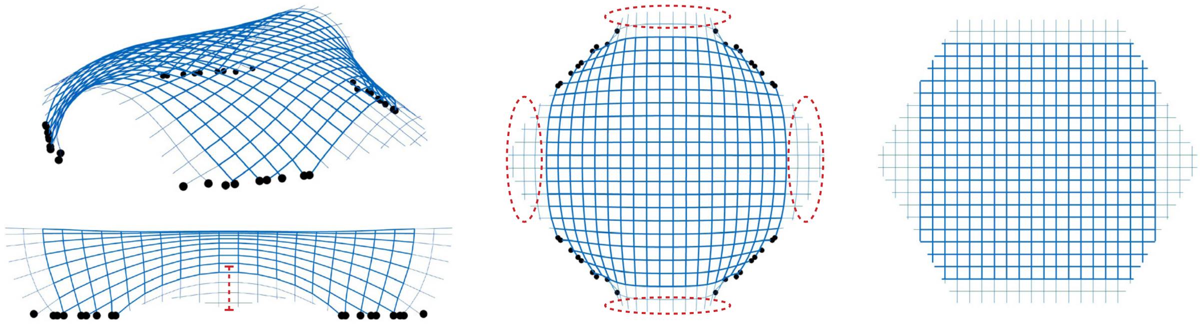
(a) (b) (c) (d)

Figure 6 : (a) Original square net and trimming geometry. (b) Generated hexagonal net. (c) Selection of 4 location of supports. By pulling these points toward a target geoemtry, the supports of the erected form are created. (d) Resulting form



(a) (b)

Figure 7 : (a) Open form. (b)Close form - Generated from flat circular net



(a) (b) (c)

Figure 8: (a) , (b) Trimmimg the excess net to create larger openings for open form, eleminating number of unwanted supports, excluding bars with excessive curvature.
(c) Resulting trimmed flat net.

When analyzing the different erected forms generated from both the circular and the hexagonal planar network, we observed that the trimming process was essential to achieve the ideal heights of openings - entrances, and for the elements to have a permissible radius of curvature for the efficiency, feasibility and constructability of the forms.

The trimming process of the excess nets, in both the circular and hexagonal cases, resulted in an octagonal shaped planar network. Through that procedure, our team decided to continue the research and the experimentation with a series of different octagonal nets.

3.4.2. Basic Workflow

After the above procedure, we initiated our workflow from the beginning. The first step of our work was to define a base octagonal-shaped planar network, starting from a base square network having a definite size for cells. Our previous experiments, as mentioned, proved that an octagonal-shaped planar network is ideal to provide multiple stable forms. Thus, the experimental chebyshev nets of our research would be within the bounds of an octagon, and a parametric code was built to easily control and test nets with different ratios and different measurements. The final value of the octagon's edge ratio (the chamfer value of the original square grid) is a value dependent on the objectives that we set as fitness in the optimization process.

After trimming the original square net with the octagonal shape it was decided that two different approaches of the octagonal-shaped planar network should be tested. One, where are no free vertices on the edges of the network (the net is exactly within the bounds of the octagonal shape, it is marked as (a) enclosed net) and a second one where four of the free edges, will have their vertices naked (It is marked as (b) naked net).

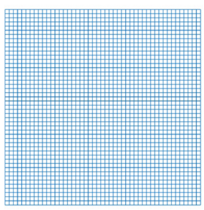


Figure 9 : Base Square Net

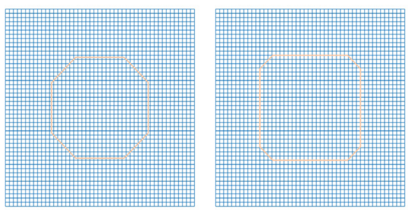


Figure 10 : Possible trimming geometries

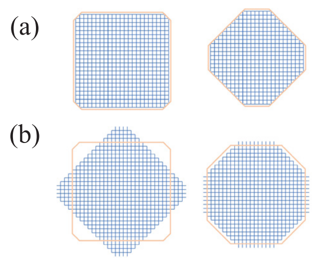


Figure 11 : (a) Enclosed Net.
(b) Naked Net

In the workflow, an open-form design is first created, later based on controlling certain parameters of that form the closed-form design is retrieved. To achieve that it is essential to select the vertices of the base planar network which will be the supports of the erected structure. The topology of that base planar network was decided after taking into consideration the stability of the possible erected form. Thus, the coincident vertices, which are the endpoints of the according edges and which shape a free angle, are treated as supports. The remaining naked coincident vertices form a straight edge line, in case (a) which is considered to enhance the stability of the erected form as it could behave as an edge beam, and in the option (b) they remain as naked vertices on the air.

The number of supports increases or decreases accordingly to the values that determine the shape of the chamfer of the octagonal trim. Support vertices are defined in the code, as included points inside the formed circles.

To erect the planar network to a three-dimensional form, the selected supports have to be pushed inwards. That requires a decision of where these points are going to be pulled to. Our first approach was creating the new target supports inside the design space of the planar network, but the result was not as expected, due to the fact that the constraint of the pre-decided new supports was too strict. Alternatively, we created a desired, parametrically controlled target geometry, on which the support points could slide along to find the optimal position, in order to retrieve a more balanced form.

Both the shape of that geometry and the distance between the geometry and the original supports are controlled. Both of these parameters have a great effect on the geometry of the - later simulated form.

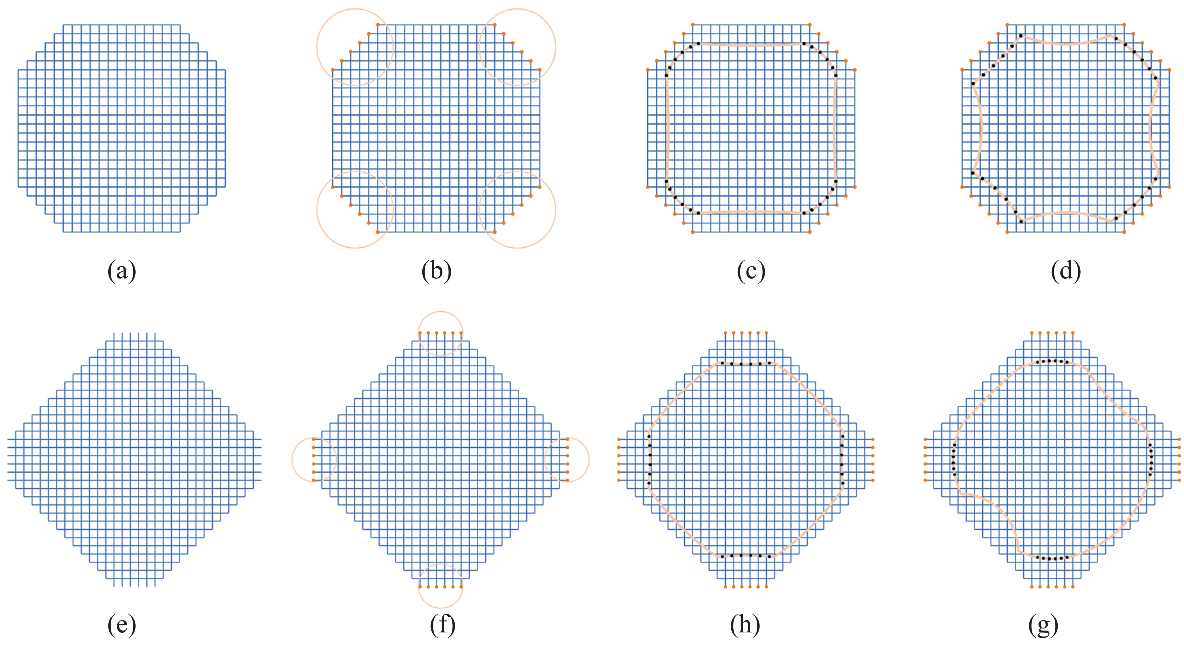


Figure 12 :(a),(e) Octagonal base net. (b),(f)Support points. (c)(g) Target geometry. (d),(h)Possible modification of target geoemtry.

After deciding on the base planar network, the number of supports and the target geometry for these supports, to achieve the erection of the network, we implement a dynamic relaxation method, with the help of Kangaroo2- a live physics engine for interactive simulation, form-finding and optimization.

For kangaroo2 to simulate as expected, we have to force the program to follow some restrictions as follows:-
1. we demand the original polylines of the planar network, to start behaving as bending rods, to achieve the desired transformation.
2. The original lengths of the individual segments of the network are preserved to ensure that the network, even after the erection remains a chebyshev.
3. The end points of the network which will be the supports of the structure, to be pulled towards the desired geometry and all of them to remain on the same plane.
4. Preserve the central symmetry of the form.

Once the erected open - from is retrieved, we have to run a second simulation with kangaroo2, using the results of the first one, to create the closed-form, by pulling the endpoints which are in the air, towards and preferably on the aforementioned target geometry, while we keep the constraints mentioned above.

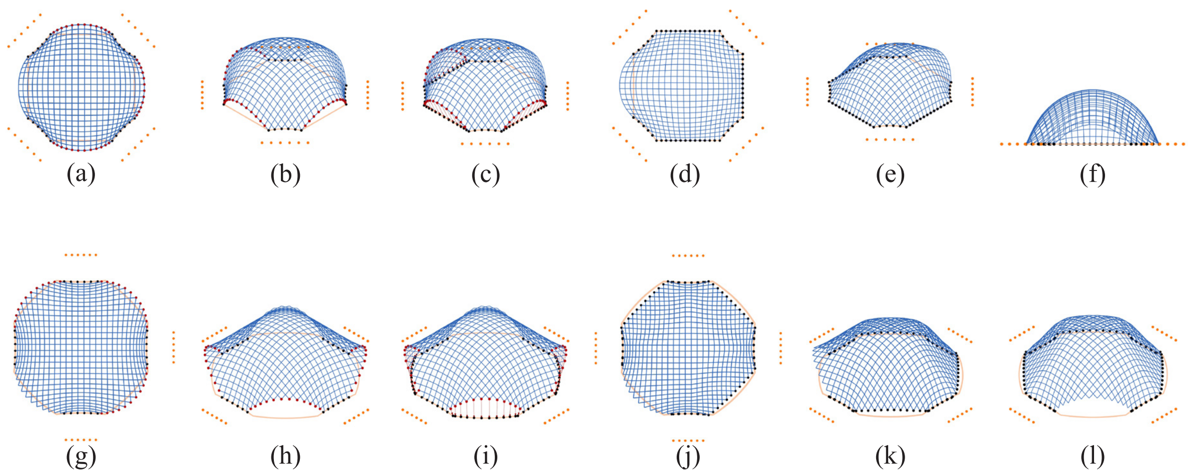


Figure 13 :(a),(g) Open form - top view. (b),(h) Support points - perspective view. (c)(i) Movement vectors for the free points. (d),(j)Close form - top view. (e),(k),(f),(l) Close form - perspective view

An important observation was made while comparing the results of the network (a) and the network(b). The edge beam in network (a) which was performing as an element to increase the stability of the pen form structure, was an over-constraint, for pulling down the free points to create the closed-form.

For the net elements of the closed form to have a smooth curvature, the edge beam ended up either a kinked curve or a curve with length seriously minimized compared to the original, consequently, resulting to a modified net, which was not either a chebyshev net, or identical to the initial planar network. As a result, we decided to abort the approach (a), and our research continued focusing on the network (b).

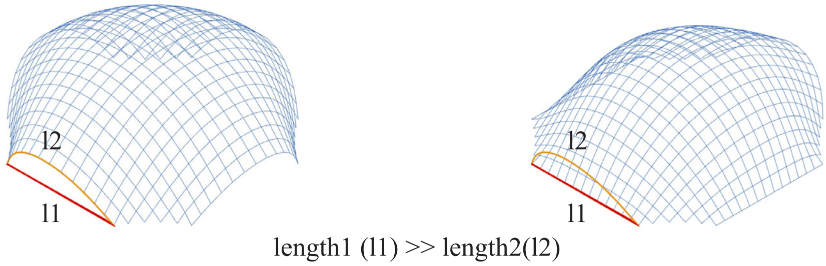


Figure 14 :Over-constraint resulting in modification of the original net, and consequently error.

The next step was to run the optimization process which would help to define the exact values of the parameters to retrieve the optimal form. As one of the aims of the research is to minimize the different bracing elements needed between the open and the closed from, a step before the optimization, was to define the pattern of bracing, which would increase the stability of the two forms.

The trials on bracing included three different patterns of pre-tensioned cable, used as bracing, and an option consisting of elements of GFRP. A comparison of these solutions, based on how different the elements needed for the two forms were, led us conclude that using one of the cable - option - bracings (d), would enable a great minimization of the different bracing elements between the two forms.

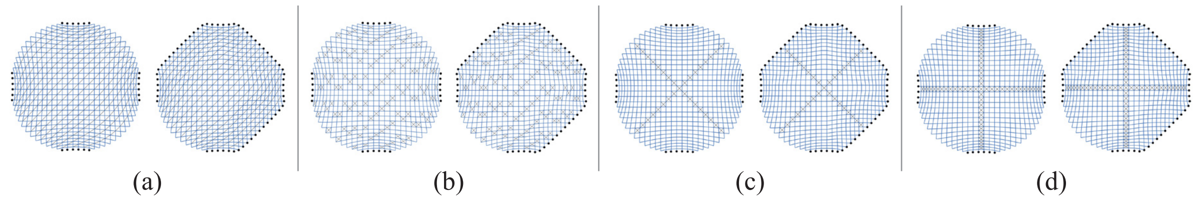


Figure 15 :(a)Continuous GFRP bracing in one direction. (b)Cable bracing, triangulation of the nets' rhombuses. (c). Continuous central cable bracing in both direction and trialngulation of the crossing rhombuses. (d) Beam - effect central cable bracing in both directions.

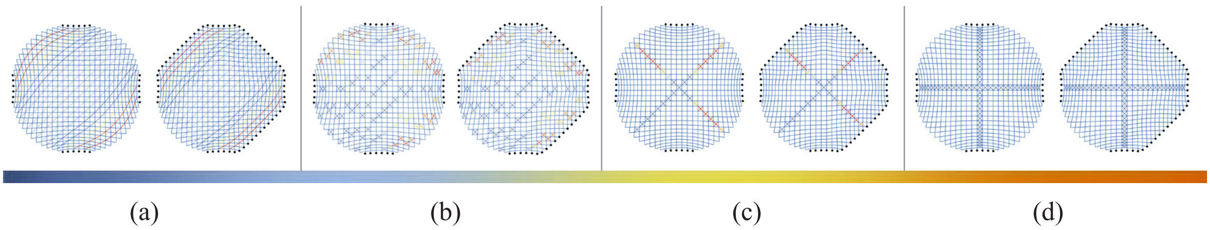


Figure 16:(a),(b),(c),(d) Comparison of bracing length between the open and close from in pairs.

In these diagrams, bracing lines are coloured based on how different their lengths are when comparing the open and closed form patterns of each pair. Based on the gradient, it is observed that bracings of option (d) have identical lengths.

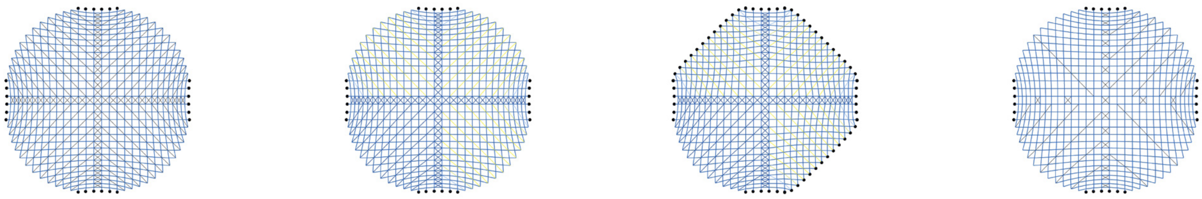
Before erecting the open-form nework, the cross-bracings in the middle of the form were locked on the x and y axis accordingly ,while they could freely move along the z axis, to ensure the symmetry. After the erection of the form, these bracings were locked in their position to ensure that after retrieving the closed form, the length and the location of these would be the same. Thus, we minimized the difference of the middle cross bracings to zero

Furthermore, as in network (b), in the open - form, the points on the air, are free vertices, not held in place by an edge beam, it was considered essential to place extra bracings which would amplify the stability of the structure.

When transforming from the open form to the closed one, a slight modification on the length of these bracings is observed, minor to the one observed when applying the other bracing patterns. That difference on the lengths, is controlled with the help of the structural details. Thus the modification of the bracings needed when a shift from the open to the closed from takes place, is handled without having to introduce and replace any elements.

All structural details, are gonna be presented in the next section of the research.

Once again, the number of bracing elements used in the structure is parametrically controlled, and will be decided after a second optimization process, to ensure the minimum displacement of the structure with the minimum possible bracing length needed.



(a) (b) (c) (d)

Figure 17 :(a)Reinforced bracing option (d). (b),(c) Comparison of bracing lengths between close/open form.
(d) Parametrically controlled bracing coverage.

Before presenting the final results of the form-finding optimization, we should introduce a more thorough description of the values / objectives (which we will call fitness) of that process.

In our optimization, the aim is to maximize three different values.

•*The Comfort Area*. We describe as comfort area the space underneath the structure with a height larger than 2.4m, to ensure the pleasant movement of the users within the boundaries of our structure.

•*The Minimum Radius of Curvature.* In differential geometry, the radius of curvature, R, is the reciprocal of the curvature. For a curve, it equals the radius of the circular arc which best approximates the curve at that point. In our case, if we think of the GFRP rods as curves, the smaller the radius of curvature is, the more the initial stress on the element. The minimum curvature of radius, also affects the diameter of our rod, as the smaller the radius, the smaller the diameter of the rod, and thus the lower the stiffness of the structure. [3]

•The Form Deviation. A value that we defined as the design difference between the close and the open form. Aim of this research is to ensure the ability to retrieve two different designs from one single net, with the less material waste and effort possible. But for that research to be beneficial, these two forms have to differ a lot.

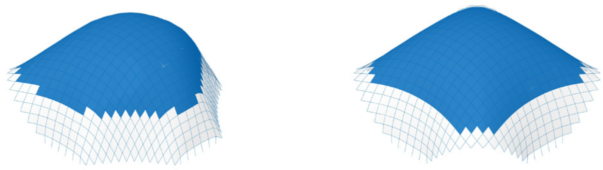


Figure 18 : Fitness 1. Comfort Area in a pair of Open - Close Forms

Figure 19 : Fitness 2. Radius of Curvature

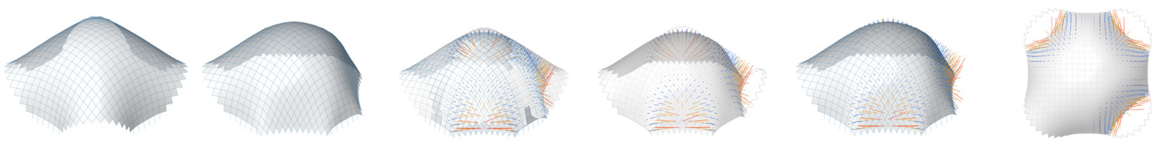


Figure 20 : Fitness3. Form Deviation

Fitness 1 : Select the points (Pt_{ca}) from planar netwrok that should control the area described as comfort area. We ensure the $Pt_{ca}(z) > 2.4$ m. We found the mass addition of all the z values of these points and we maximize that number.

$$z_{(sum)} = Pt_{ca}(z) > 2.4 \text{ m} \qquad (1)$$

$$\text{Fitness 1} = \Sigma(z_{(sum)})$$

Fitness 2 : Find the minimum curvature radius. Set a minimum acceptable value equal to 2 m and we subtract the minimum radius value. Our aim is to minimize thar result, which would mean, that the form's minimum radius will approximate the value of 2m.

$$\text{Fitness 2} = |2 - r_{min}| \qquad (2)$$

Fitness 3 : Find the distance of the centroids(Pt_a)of the open form mesh, from the centroids (Pt_b) of the close form mesh. Find the mass addition of these distances and the aim is to maximize that value.

$$d = \sqrt{(x_a - x_b)^2 + (y_a - y_b)^2 + (z_a - z_b)^2} \qquad (3)$$

$$\text{Fitness 3} = \Sigma(d)$$

For both the optimization processes, a grasshopper plug-in, ‘Octopus’ is used.

Octopus was originally made for Multi-Objective Evolutionary Optimization. It allows the search for many goals at once, producing a range of optimized trade-off solutions between the extremes of each goal. It is used and works similar to David Rutten’s Galapagos, but introduces **the Pareto-Principle for Multiple Goals.**

For octopus to perform, we create some numbers (form mathematical expressions which will be displayed below) as fitness inputs, and our parameters to be changed as genome inputs. As mentioned above, the parameters to be controlled are the chamfer value of the net (number of supports), the morphology of the target geometry on which the supports will be pulled, and the distance of the initial and the latter supports.

After the optimization process was completed, we gathered some of the best results and compared them to continue to the optimization of the bracing elements.

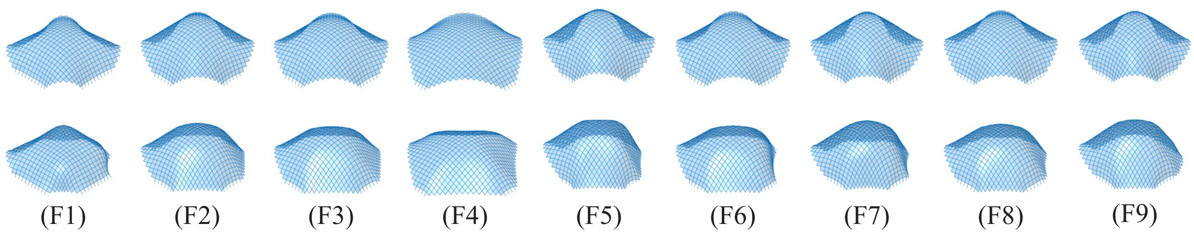


Figure 21 : Solutions extracted from the optimization.

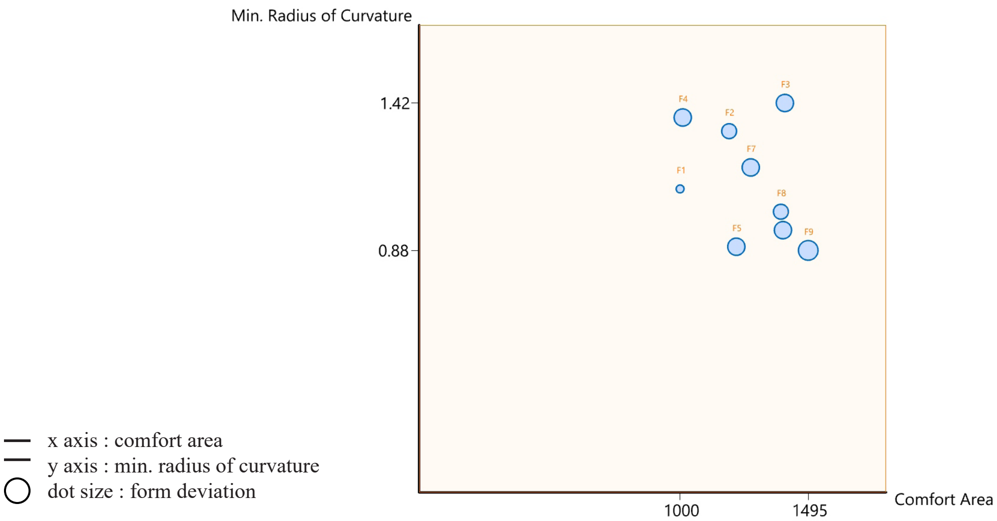


Figure 22 : Solutions’ Comparison Graph.

Once our final testing pair of forms was decided (F3), we organized a structural analysis to decide the material and the bracing coverage, and check the performance of these forms under certain loads.

To achieve that, we used K2Engineering, a plug-in, by Cecilie Brandt - Olsen, which contains a set of customized Kangaroo 2 grasshopper components with the scope of calibrating several goals concerning structural properties.

After taking into consideration the characteristics of the chosen form, the gridshells to be simulated will be one - layer gridshell structures, with GFRP rods, of diameter 40mm, as basic elements, and pre-tensioned cable of the diameter of 5mm, as bracing material.

In the second optimization process our goal is to minimize two values :

- The displacement of the structure when selfweight and windload are applied

- The total length of bracing material needed to ensure the stiffness of the structure.

Again we create some numbers (form mathematical expressions which will be displayed below) as fitness inputs, and our parameters to be changed as genome inputs are the different percentage of bracing applied on the structure.

The optimization was first applied to the open form. Once we gathered the results of the optimization applied, first on the open-form, we compared and decided on a bracing pattern

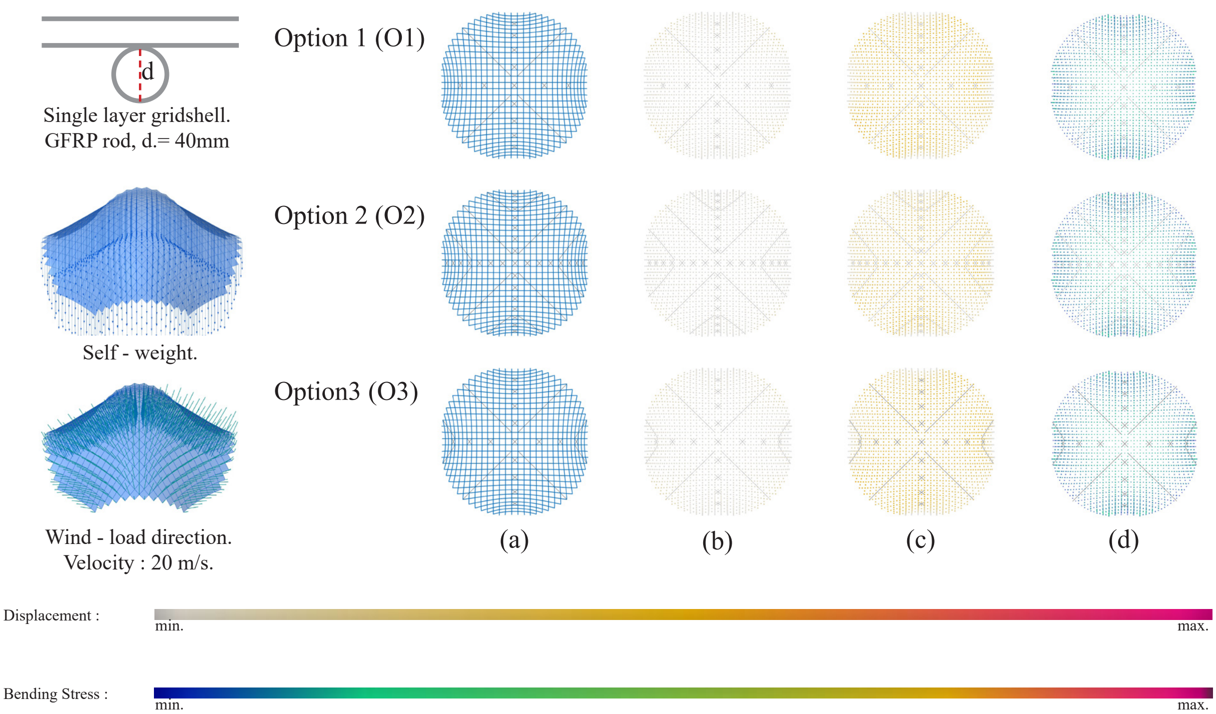


Figure 23 : Solutions extracted from the optimization. (a)Bracing Pattern. (b) Displacement under self-weight. (c)Displacement under self-weight and wind-load. (d) Structures bending stress under self-weight and wind-load.

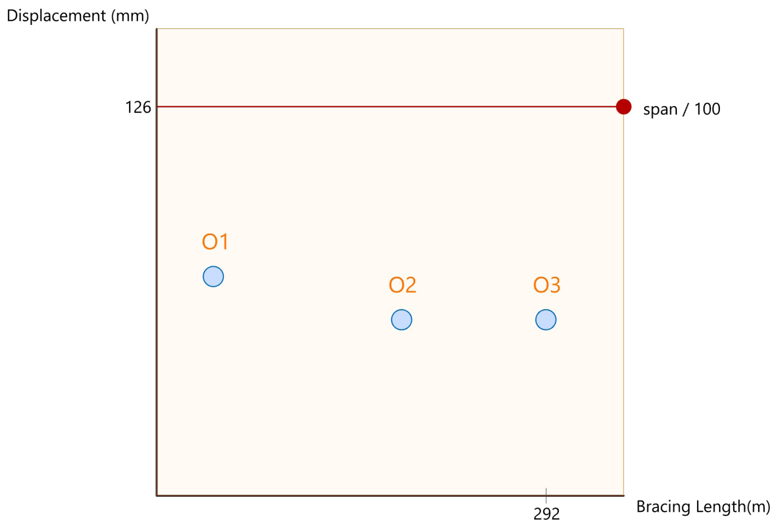
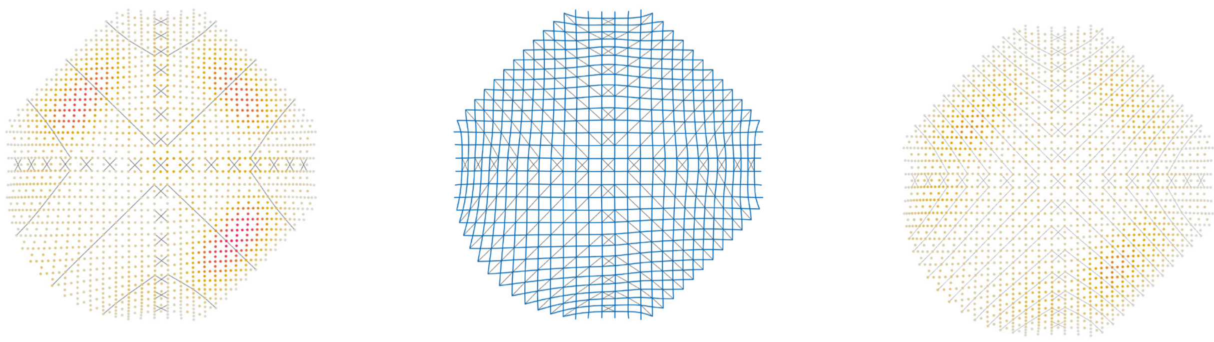


Figure 24 : Comparison Graph.

We decided to apply bracing Option 2. As described, the same bracing pattern will be used to the close form structure. d

After running the needed simulations to ensure the adequacy of the chosen pattern for the closed - form, we realized that due to the geometry of the form, some extra bracing should be applied and based on the designing needs, we performed the needed modifications.

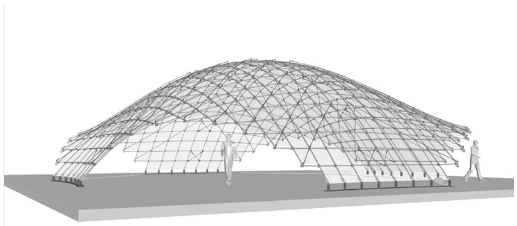


(a) (b) (c)

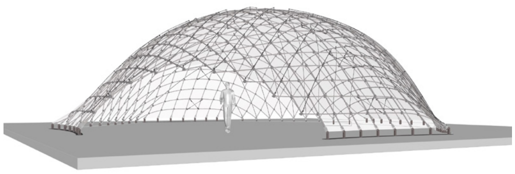
Figure 25 : Close Form - Bracing Check. (a) Displacement under self-weight and wind-load, bracing O2. (b) Modified bracing pattern O2. (c) Displacement under self-weight and wind-load, modified bracing O2.

3.4.3. Structural Details

After concluding on both the pair of the open and closed form and an efficient pattern and percentage of bracing, we will present the structural details.



(a)



(b)

Figure 26 : (a) Open form. (b) Closed form

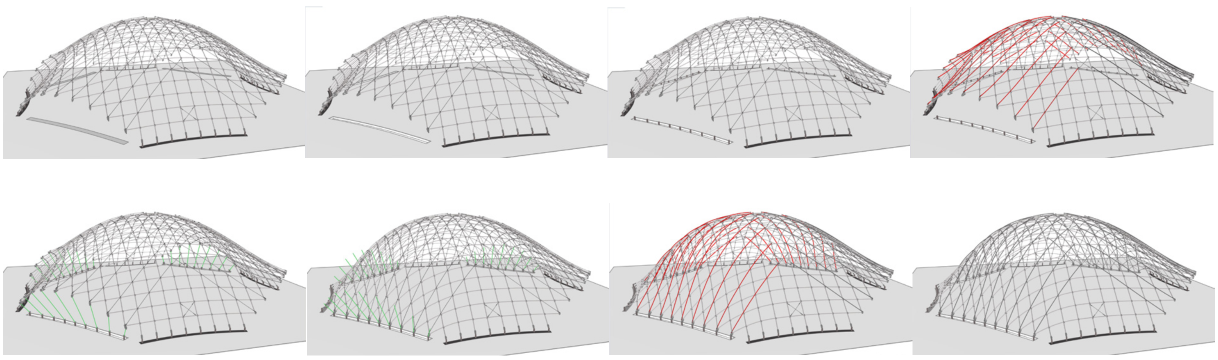
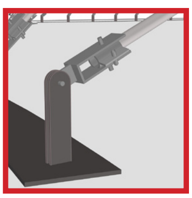


Figure 27 : Steps of transformation process from open to closed form

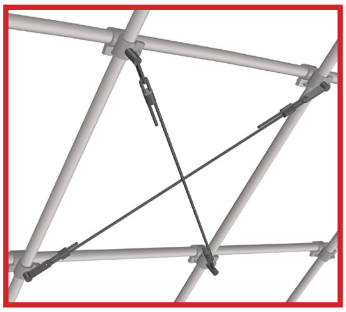


(a)

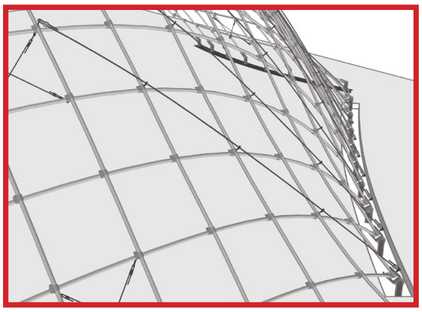
(b)

(c)

Figure 28 : (a) Permanent ground support detailing. (b) Modifying free points - possible supports (open form). (c) Modifying ground supports in closed from.



(a)



(b)

Figure 29 : (a) Permanent stable bracing. (b)Bracing with modified length between the open and close form.

2.4.3. Perspective Illustrations of the two Structures

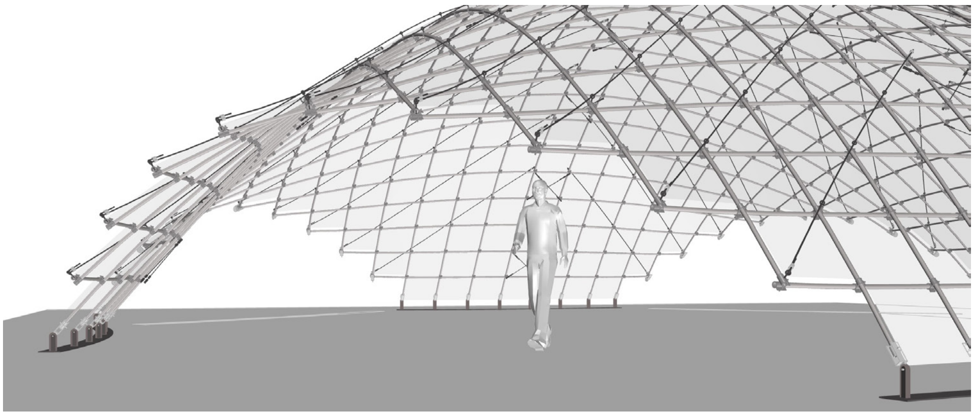


Figure 30 : Perspective Caption of the Open Form Structure.

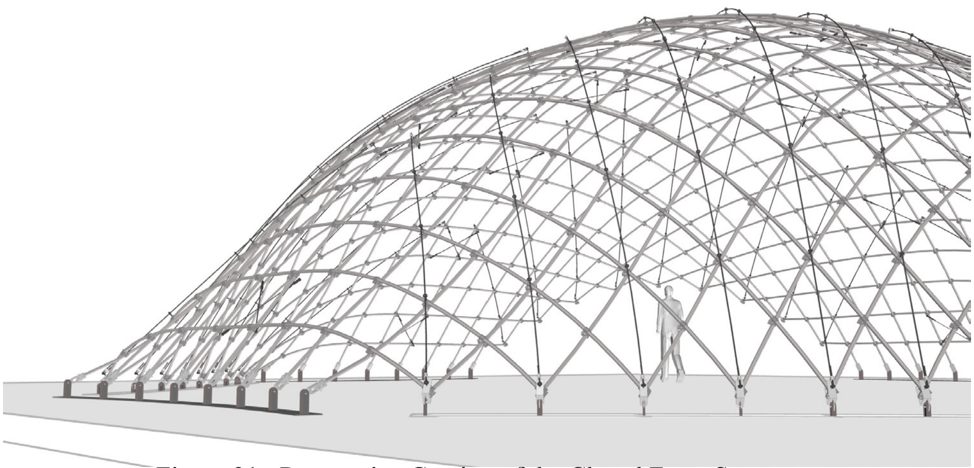
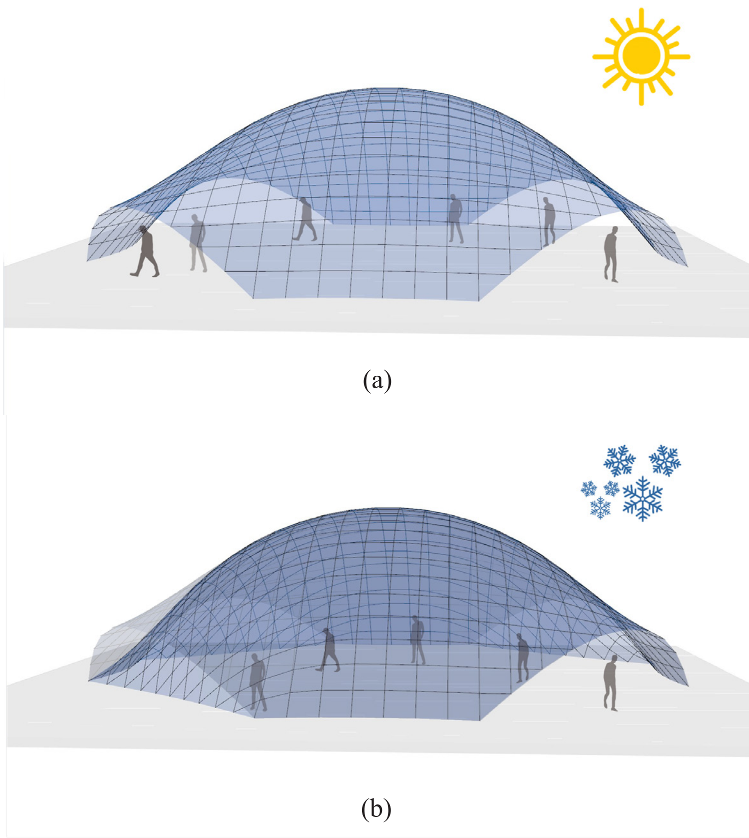


Figure 31 : Perspective Caption of the Closed Form Structure.

4. Conclusions

4.1. Research Conclusions

Starting from an initial inspiration to experiment with multistable forms and kinematic structures we managed to specify the topic of our research into trying to build an efficient code and form-finding process for the creation of forms with two stable erected positions. We managed to implement in our structure a detailing process which would minimize the effort and cost of transformation between the two potential geometries. By locking the location of the supports of the open structure, and exclusively modifying the vertices of the net which are free in the air we aim to make that procedure more simple. Our code is built in a parametric way in order to be able to produce multiple solutions and through the optimization, the user could select the one, most fitted to his needs.
These pair of structures will enable users, not only to swift between designs for aesthetic reasons, but also, have the possibility to transform an already established on-site structure, to a different one, according to his need and the weather conditions.



(a)

(b)

Figure 32 : (a) Summer Open form struccture. (b)Winter Close form structure.

4.2. Further Research

As mentioned above, the aim of this research was the minimization of effort and cost in the procedure of retrieving two or more very different forms from one single flat structural grid net configuration.

Our team would like to further research the possibility to minimize the different membrane elements needed for the two forms.

Furthermore, we would like to experiment with more complicated flat nets, rather than the polygonal (octagonal) ones and research the possibility of achieving multiple different forms rather than two and minimize in these varying solutions all of the above.

Last but not least, since we experimented with GFRP, we would like to research the possibilities of such ideas applied in more natural materials, like wood.

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We would also like to thank our classmates for the knowledge we shared, but mostly for all the moments of laughter, anxiety and coffee breaks.

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We would also like to thank Alan Rynne who was always eager to help us find solutions with a big smile, even during his August vacation!

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