Origami Funicular Shell

Applying an origami structure design to a funicular shell

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0_Abstract

This thesis is an exploration through how to design a funicular shell with an origami structure. It goes from the basic vault simulation to how an origami Miura Ori design is applied on it and its structural behavior. In every step of the process, a structural analysis is done to compare the results of every design, as the point of it, it to find the best design strategy and at the end, if having an origami design in a funicular shell is an optimal design: easier to build, less material, thinner materials.

The exploration has three different phases: going for basic strategies to achieve the design, so the problems in every step can be detected; trying different strategies to find the optimal shape of a funicular shell, changing the initial 2D Mesh and the constrains; and applying folding patterns like origami Miura Ori or Yoshimura, and if they can be optimized structurally or to be with equal length.

In the first part of the thesis, the basic strategies, it can be seen how the funicular shell has some irregularities that later for the origami design produce some problems. It is also noted that fold designs make sense structurally. This first steps, though they don't give any final results, is very important to see what things should be explored: how to simulate a good funicular shell design and that it is worth it to apply folding designs to the vaults.

In the second part, there is an exploration on how to simulate the design of the vault: what is the difference of the vault if it is simulated from a high resolution mesh or a low one; how using the same strategy and parameters, the tessellation of the first 2D mesh makes the vault to have different shapes; and finally, there are some strategies to fix problems like fixing the perimeter or to have a vault without creases.

In the third and final part, the folding designs are applied. Starting with a curved fold design that could be unfolded, and then with two origami patterns: a basic regular Yoshimura design that proved to be the most efficient, and a basic Miura design. After that, there are two proposed approaches to optimize the Miura Ori design trying to create it from the values obtained in the structural analysis of the vault, and another trying to make it with the same width, as a fisrt step to make it unfoldable.

06

1_Introduction

This exploration tries to be the combination of some topics explored in class during the master through some case studies. These main topics would be Funicular Shells and Origami architecture. Both topics were studied in class, but they could have been explored more deeply and corrected to achieve some better goals. They were two topics that left some unanswered questions…

So the purpose of this work is to get an efficient design combining these technics, and try to see how they combine together and if it's a good idea to do so.

1.1_ Hypothesis and Objectives

The proposed design to reach is a funicular shell with an origami structure. While they seem two very different topics, they seem to be complementary.

On the one hand, the main characteristic of a folded origami structure is getting inertia with the creases, the higher, the more inertia it has. If we fold a rectangle sheet of paper just using parallel creases, but folding one extreme more than the other, we get one side of the design more compressed, with less length and more inertia, and another side that covers more distance but with less inertia; it would be like making a paper fan.

On the other hand, we have a funicular shell, a vault designed to work perfect under pure compression. Their purpose is to cover long distance with few supports and with the thinnest design. Usually, the forces that go to a support come from an area of the vault bigger than the support area, so it takes the weight of the entire vault and deliver it to few points; therefore as the vault reaches lower points, it needs more inertia or area in its section.

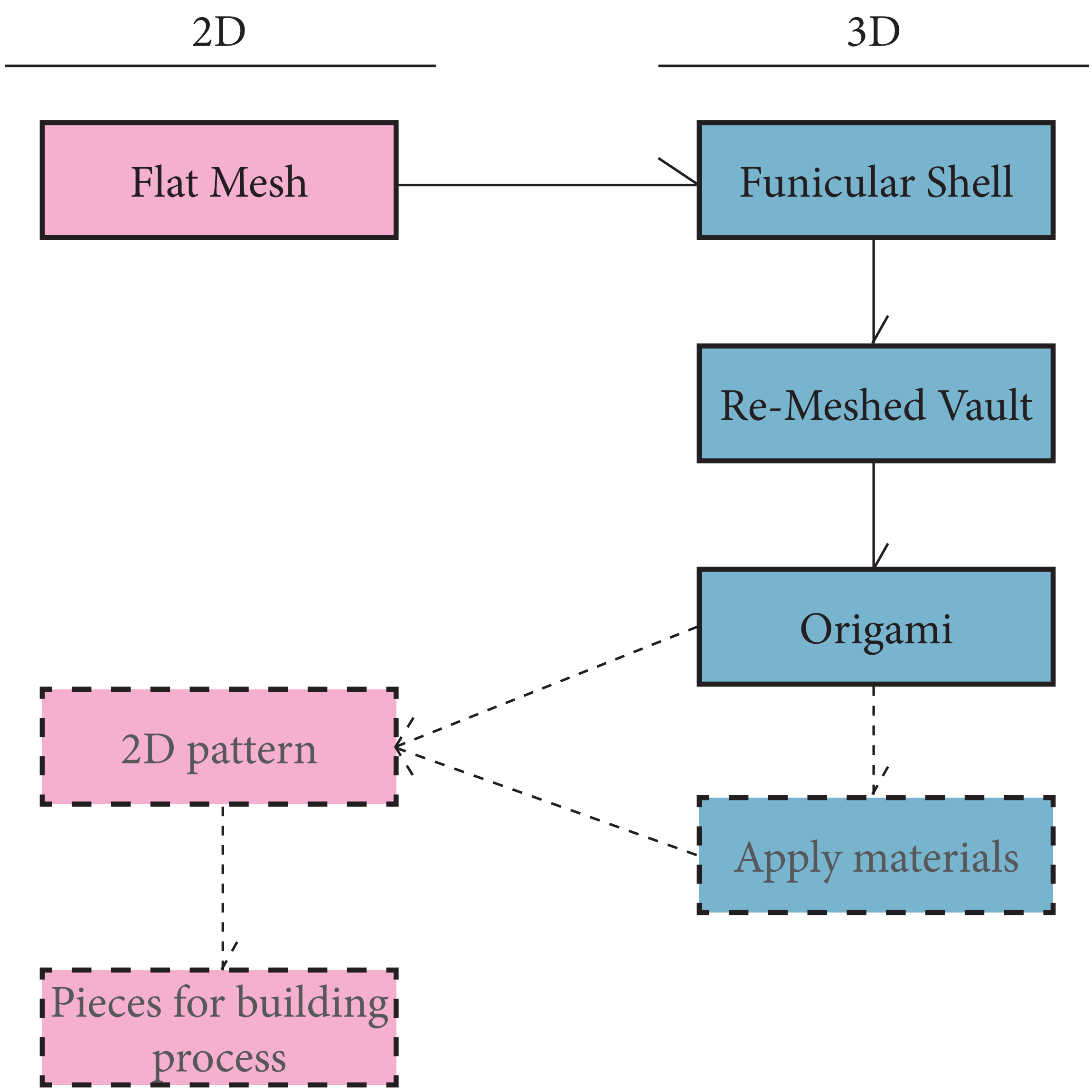
Consequently, trying to combine these two designs makes sense on the paper, as like in the paper fan, the vault would get almost flat creases on its highest parts and high creases on the supports where it needs more inertia.

Apart from just getting this funicular shell with an origami structure, in this process all the unanswered questions on the topics will be explored, like which is the best way to prepare a mesh to go through this form finding process?, which origami process is more structurally efficient? Can it come from a rectangle, just one uncut sheet folded?

1.2_ Proposed design process

For this design it has been proposed a specific process from the start. It has two main parts: first reaching the funicular shell shape and second looking for an origami pattern.

For the first part, the process goes from 2D to 3D; and the second part, the other way around, from the 3D, the 2D pattern is found.



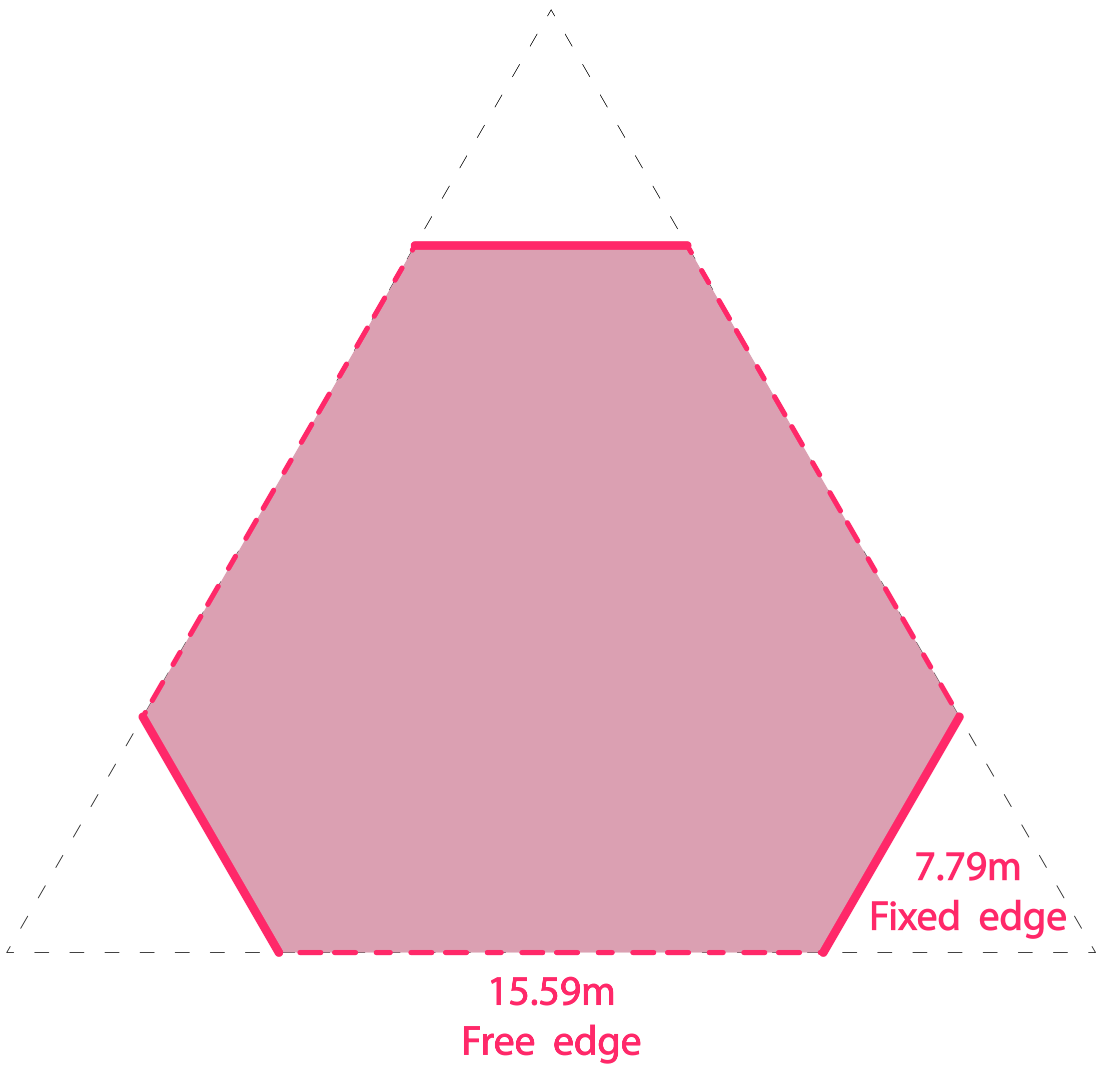
In this work, the process arribes and tests just the first part, from 2D to 3D. Comapring ll the results and trying to proves if an origami design is an efficient desgin for a funicular shell.

1.3_ Proposed conditions of the experiments

To have a results that can be compared and then choose which solution works better, all the designs come from the same initial 2D shape, so they should reach a specific form.

As this is a first exploration, it will be done with a regular known shape: an equilateral triangle with cuts on the vertices that will be the supports. This way, the final shape it's ensured to be symmetrical and divisible in known points.

This way, the proposed design processes should be at least applicable to any regular polygon. And at some point, with adjustments, it should work for any kind of funicular mesh with specific conditions. Therefore, it's a process that studies an easy regular generic case to try to get an universal definition, rather than go for a difficult irregular case study that may just get a definition that just works on itself.

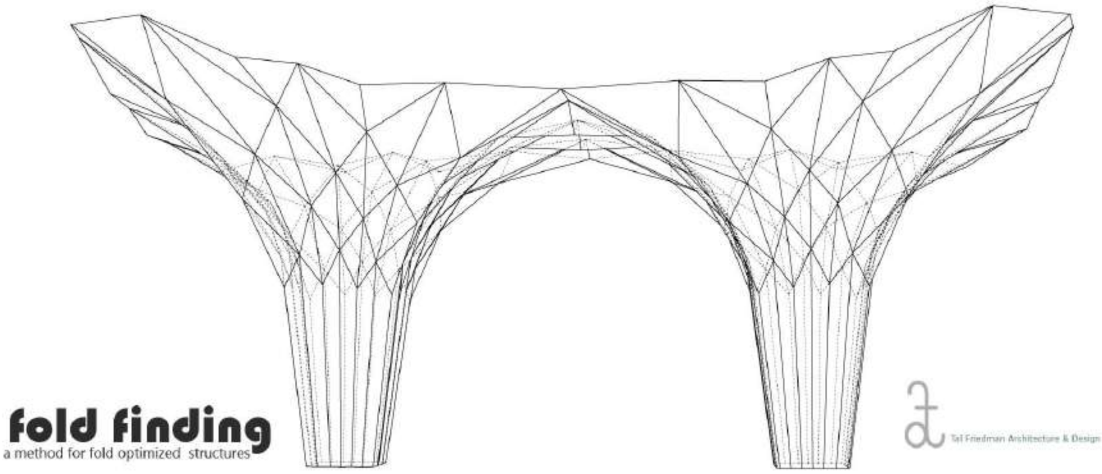


2_State of the art

2.1_Folding Architecture: Tal Friedman - Fold Finding

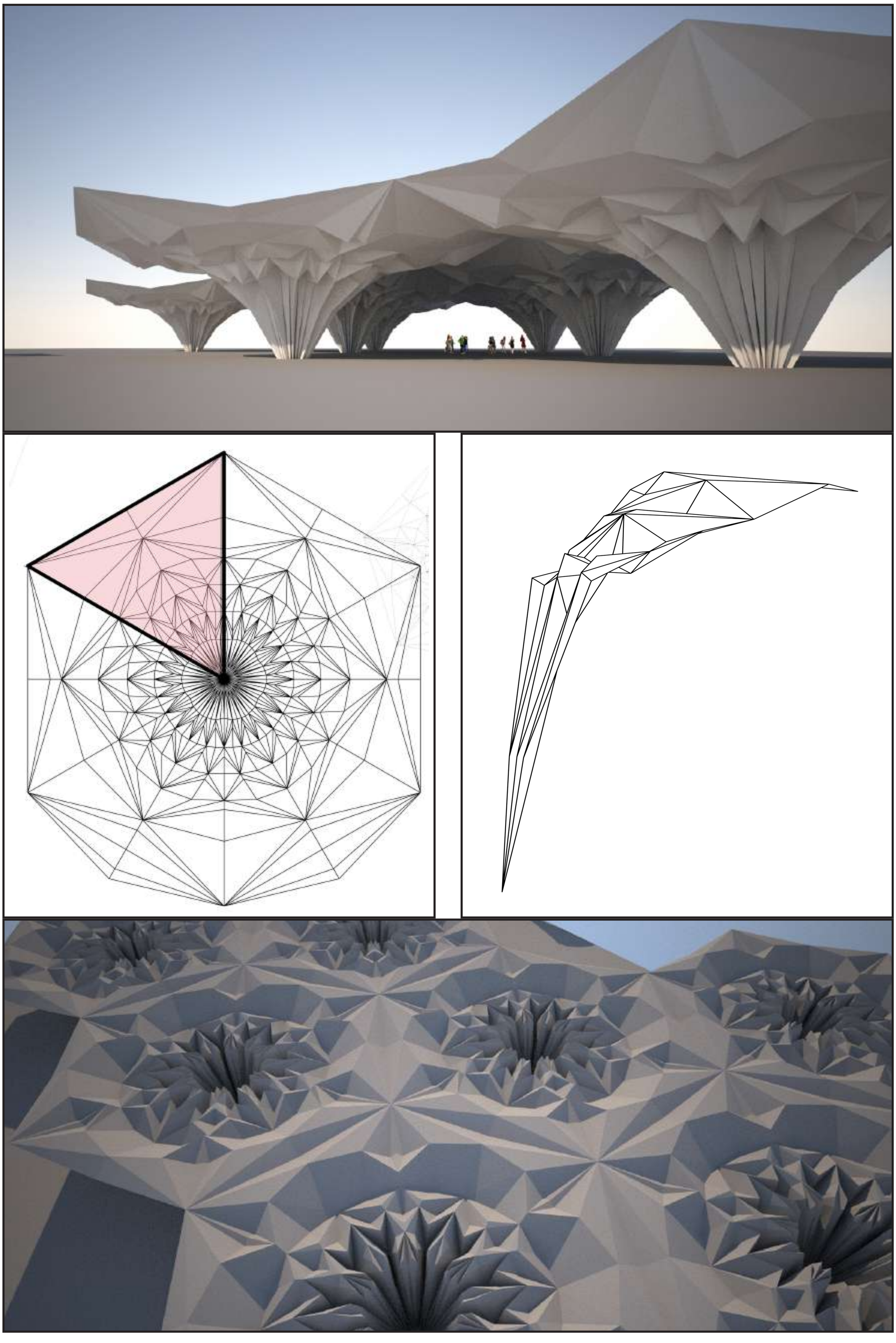
2.1.1_Origami Pavillion

Tal Friedman utilizes origami techniques to create fold finding pavilion
architect tal friedman's 'fold finding' pavilion is a self-supporting folded architectural work that utilizes traditional origami techniques (both aesthetic and structural) to avoid the need of any sub-structure. composed in its entirety using only eight 4mm thick alucobond panels, friedman created algorithms necessary to take advantage of the material's innate surface rigidity. the result is an ultra thin shell, from which nothing can be added or subtracted, that uses surface tension as its structural foundation.
Each 'flower' is made of four unique sections. each of these, are composed of 12/20 interconnected surfaces. when fully assembled, the pavilion serves as a proof of concept, illustrating the possibilities of folded structures in full-scale architectural design. the method may have further applications in fields such as: deployable structures, shading systems, public or private architecture, and more.


fold finding
a method for fold optimized structures
Tal Friedman Architecture & Design

2.1.2_ Exploring light folded structures possibilities

This is his master thesis in computational design construction at the Detmold univesity of applied sciences.



2.2_ Funicular Shells

Foster's Pavilion in Venice. This Pavilion is a prototype though to be next to another in a chain, so it's a form finding proces with the perimeter fixed. Another thing, it is its light and easy to build base, and as it is a module for a bigger building, the modul can be used again, for all the other modules.

2.3_ Origami Architecture

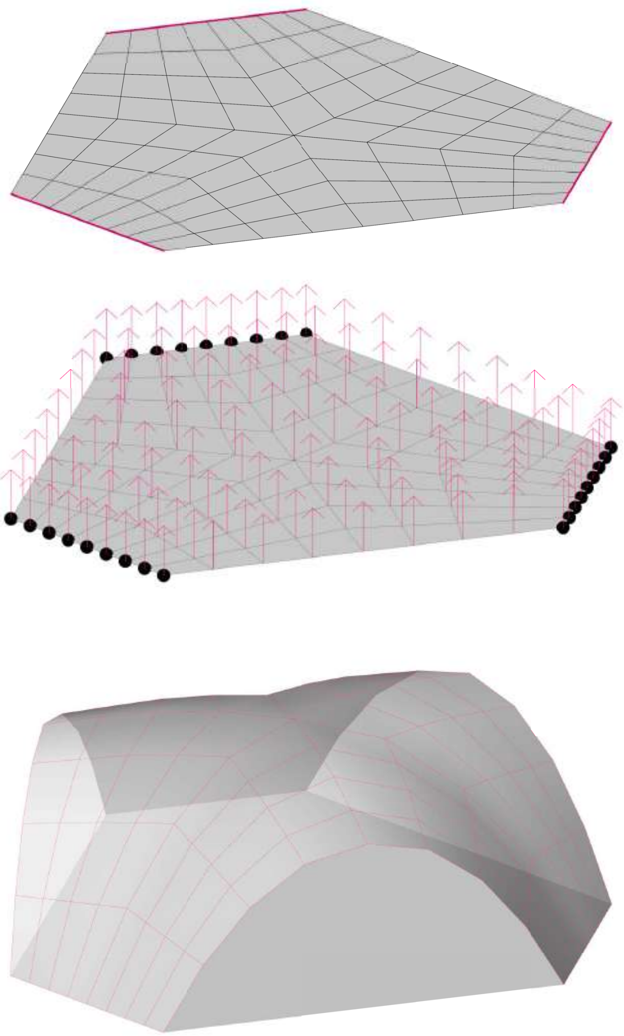
Manuel Bouzas Cavada, Manuel Bouzas Barcala and Clara Álvarez García's Self-standing Pavilion with wood panels inspired by origami design.

3_First hypothesis design

As all the topics applied on this design have been studied in class, my first approach is to see what I would get applying directly the last results I got in the previous case studies.

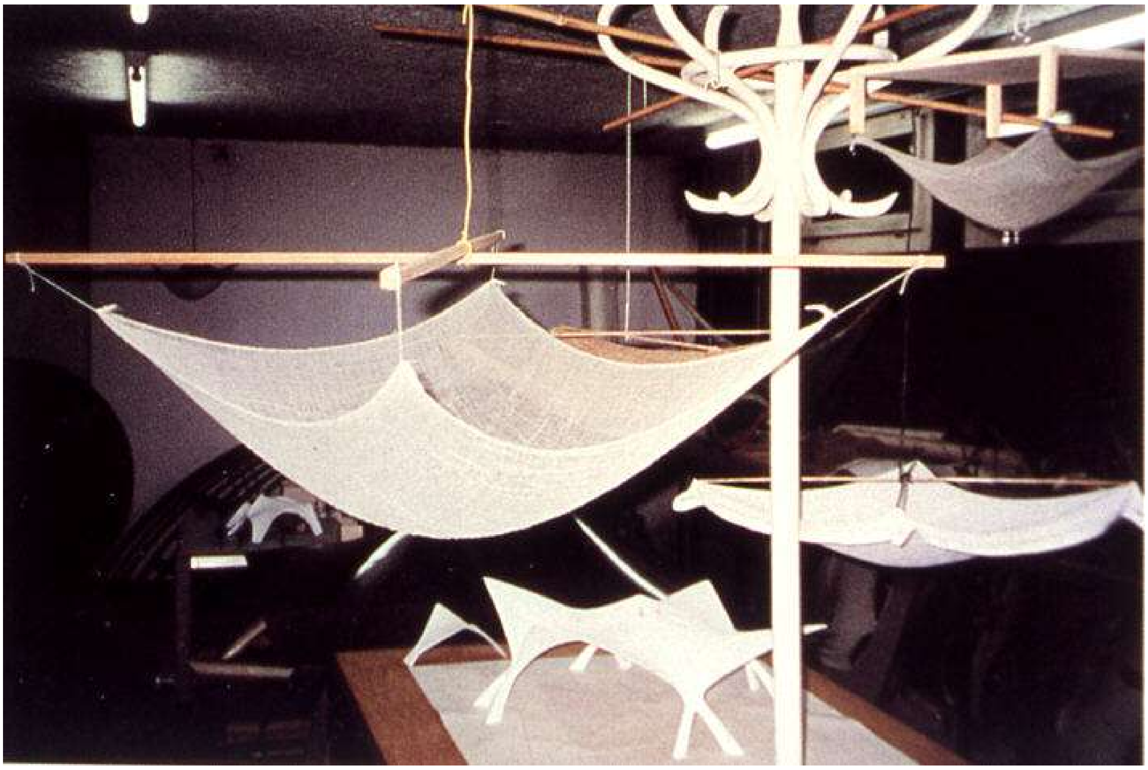
This approach is also useful to find out all the troubles or strategies that should be improved.

3.1_ Funicular Shell Form Finding (FSFF)



The form finding process of a funicular shell with grasshopper-Kangaroo2 seems pretty logical and easy. It is based on making a 2D mesh inside a desired perimeter and applying just vertical forces while fixing the support points and the lengths of the mesh's edges.

This simulation conditions are copied from the previous analog experiments realized on looking for the funicular shell form: the hanging models.

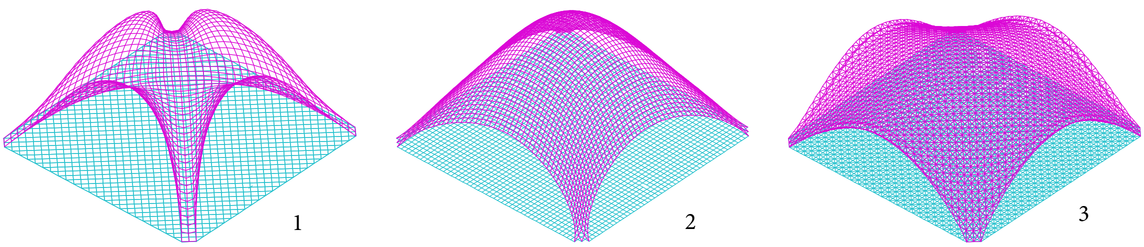


See "Mesh Table 01_Triangular Mesh"

3.1.1_ FSFF Meshing problems

Through some case studies of simulating funicular shells, it was discovered that the final shape was very different depending on the initial 2D mesh tessellation while having the same fixed support points and the same initial perimeter.

At the end of the studio, we decided that the triangular tessellation was the right one for the 2D mesh. Therefore, this is the mesh applied in this first approach.

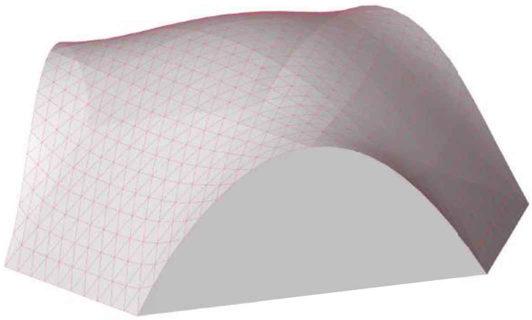


3.2_ Re-Meshing the Funicular Shell with geodesic lines

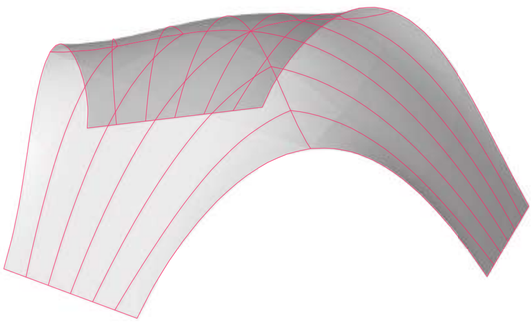
To apply the origami patterns studied in class (Miura Ori and Yoshimura), not any tessellation of the mesh is valid. In this case, we have a triangular mesh of too many too small triangles to apply any origami definition that we got in the previous study cases. So a new tessellation of the mesh must be done, it needs to be a quad mesh with edges parallels to the edges of the supports.

To make a quad Mesh, the vault is divided in three symmetrical parts from its center. Then the new shapes are 3 identical meshes with 5 perimeter edges: the edge of the vault's base, two lateral edges and 2 at the two that will be considered as one; or as this new form is symmetrical itself, it can be split in two parts, creating two 4-edges polygon, a distorted rectangle, that can be re-meshed in well oriented quads for the origami definition.

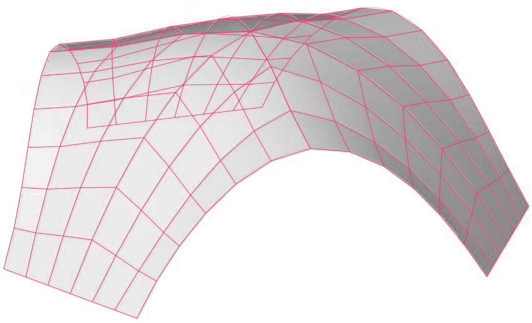
The creation of the new quad mesh is done with geodesic lines that go from the top edge to the base edge; those would be the long edges parallel to the lateral ones. Then, all this new geodesic lines are paired to create ruled surfaces which will have a proper UV to be meshed as quads.



High resolution triangular Mesh



Ruled Surfaces through pairs of geodesic curves

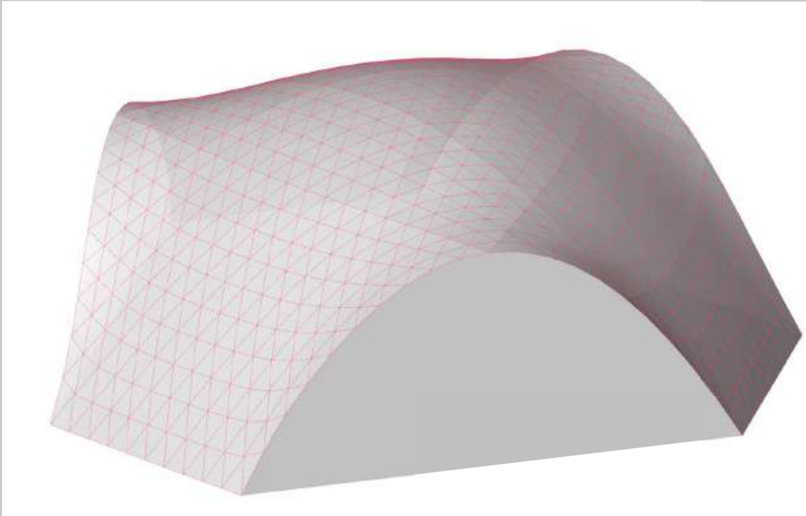


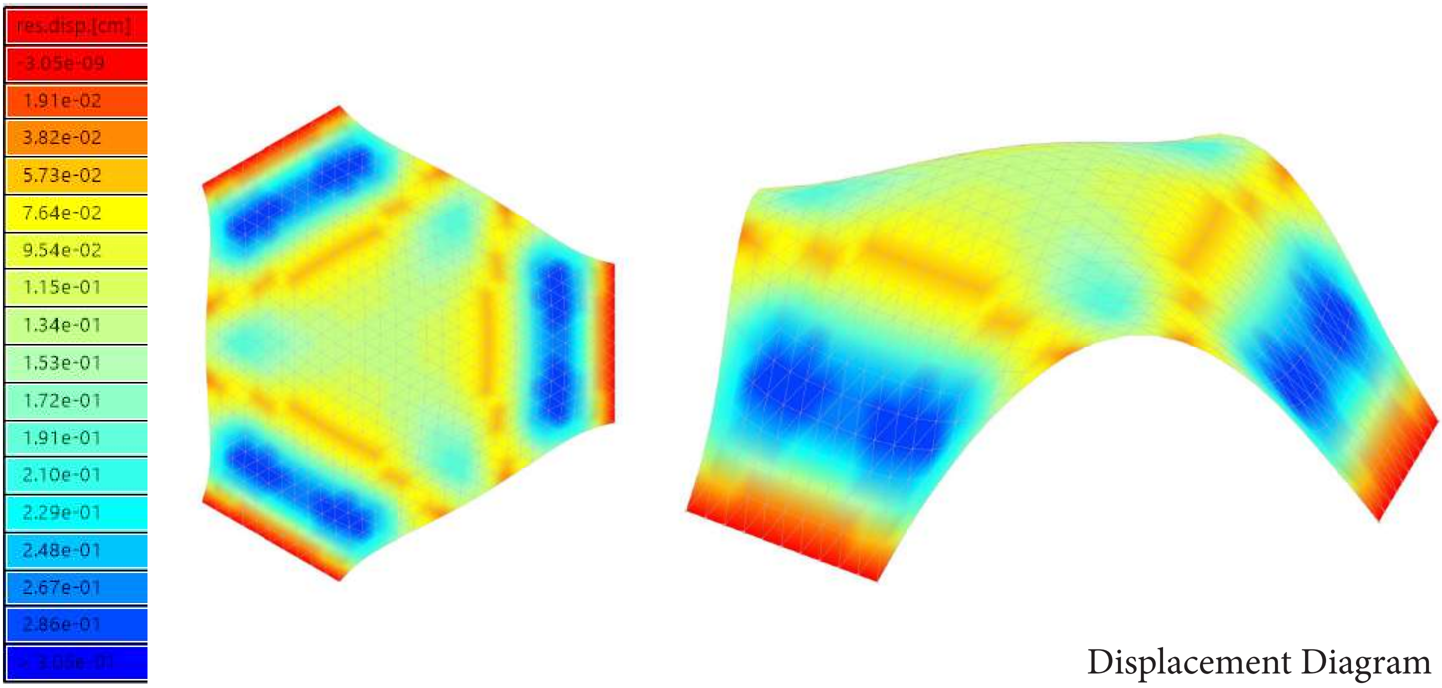
Quad Mesh from the ruled surfaces

MESH TABLE: 01_Triangular Mesh

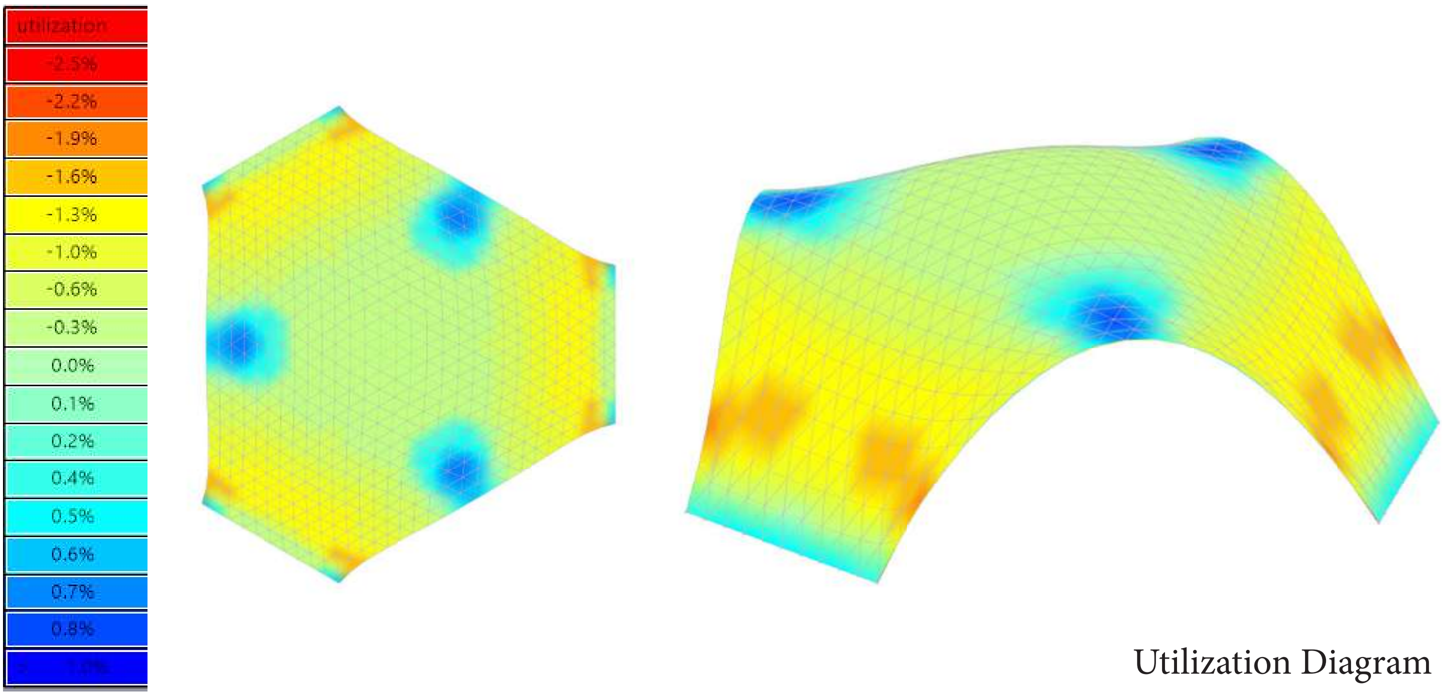
Properties

Area: *430.86m2*
Faces: *1300*
Vertices: *1092*
Edges: *1995*
Perimetral Edges: *90*
Supports: *33*
Max. Height: *8.633m*
Thickness: *3cm*
Forces: *Gravity*

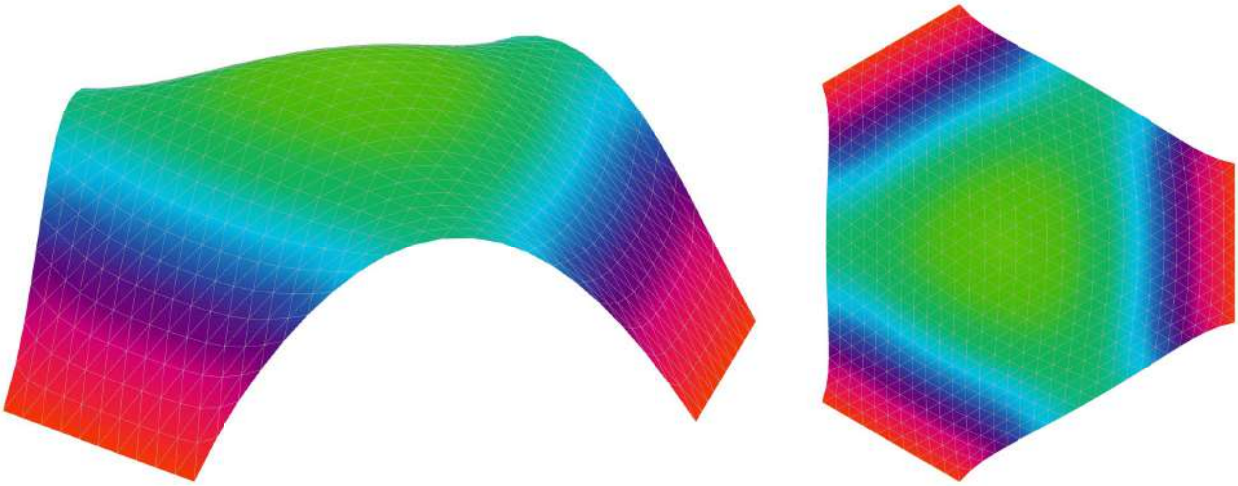




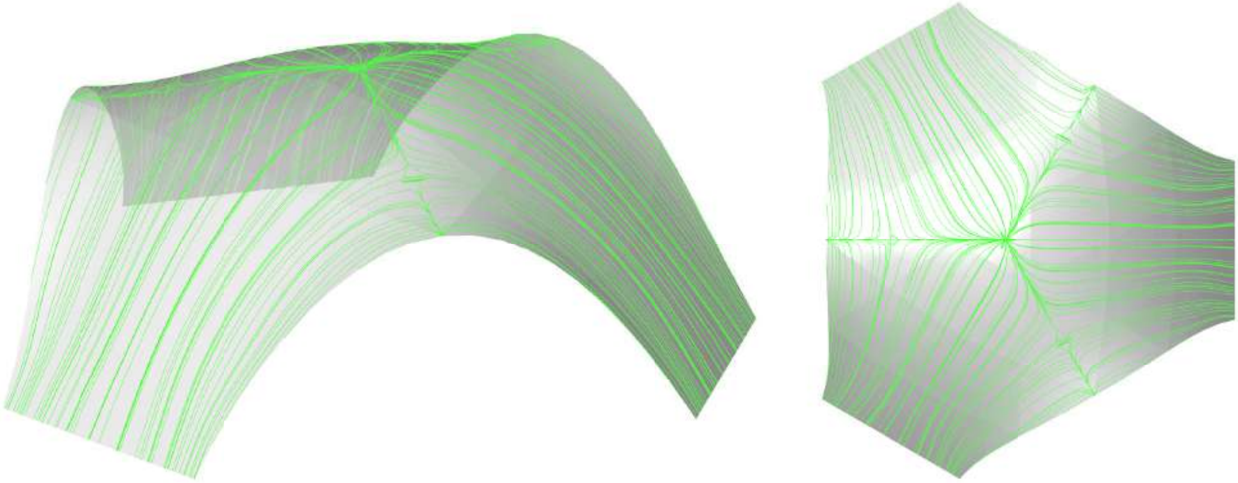
Displacement Diagram



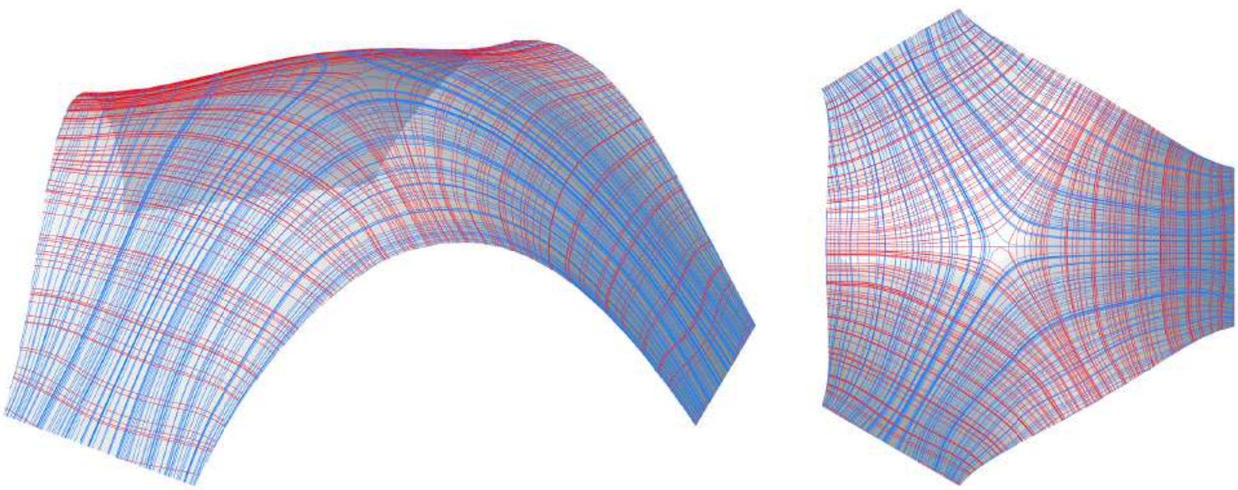
Utilization Diagram



Height Diagram



Force Flow Diagram



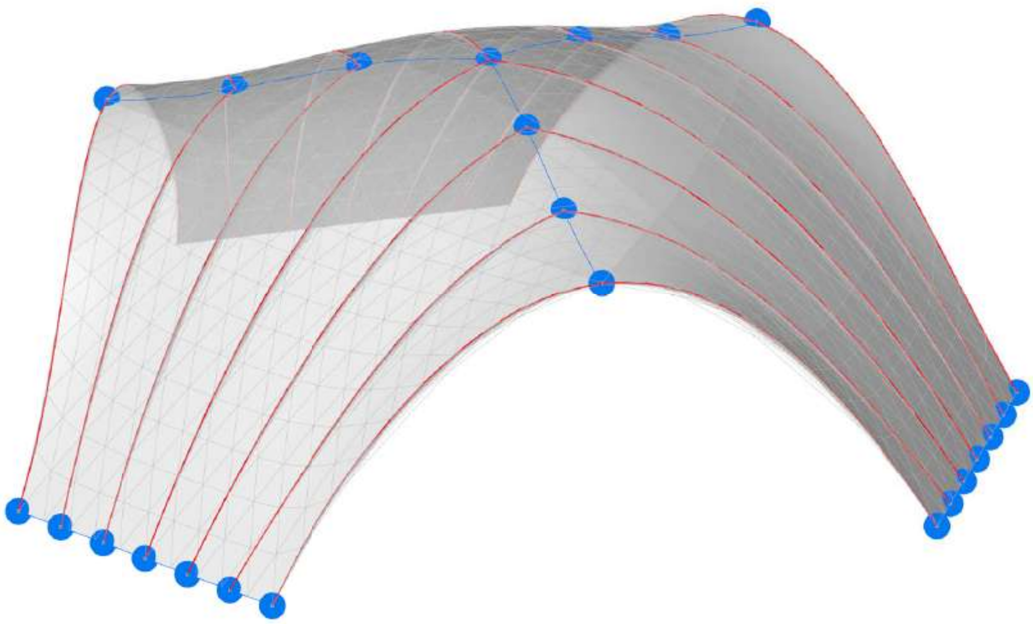
Principal Strees Lines Diagram

3.2.1_ Geodesic line on a mesh

There is no command to create geodesic lines on a Mesh, so an algorithm made in python during the master was used.

This algorithm consists on creating a line from the start point to the end, take the middle point of it and look for the nearest point in the mesh. Then make a polyline again outside the mesh with the star/end points and the middle points found, so the resolution of the polyline is increased. After that, the process is repeated again, using just the start/end and the new found points in this new step. This process is iterated as many times as desired, the more iterations, the more resolution it will have. However this algorithm tends to accumulate a lot of points on the extremes, so it has a filter that makes the lines have a minimal length, so at some point the resolution stops increasing, but it gets more precision.

*This command may have a problem or not be efficient for certain Meshes, but in this case study should work just fine.



Geodesic lines on the mesh going from the top curves to the support curves.

3.3_ Structural Analysis f the re-meshed Funicular Shell

At this point, before going any further, it is performed a structural analysis or the original kangaroo triangular-mesh shell with the new quad-mesh made from the geodesic lines.

The triangular mesh, as it was the simulated one for the form finding process, was a high resolution mesh (2512 faces) with edges between 0.46-0.87m , so it has a more accurate vault shape than the new re-meshed vault that is a simplification of the other (108 quad faces and an averaged edges of 1.77m). Therefore, the first mesh has a better behavior, but the objective is to prove that both have similar results, so that the simplification didn't change the structural results.

The structural analyses show some interesting results, if we introduce the new mesh as designed, the results are pretty similar to the original mesh, but if for the analysis we subdivide the new mesh to analyze more points, then some weird results appear.

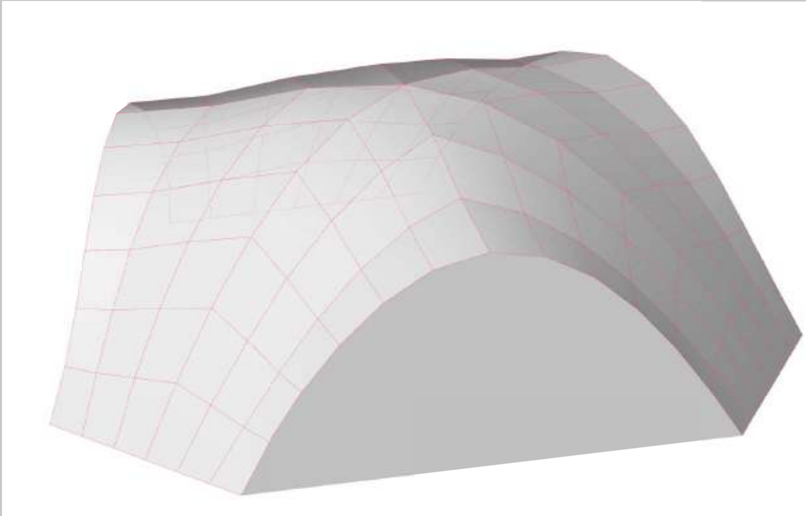
What's more, this analysis is also useful to see what the stresses are and the cross-sections needed, so then it could be compared to the results of the analysis of the vault once it has an origami design. We can see in the results what was first anticipated, the nearer to the support the panels are, the thicker they need to be.

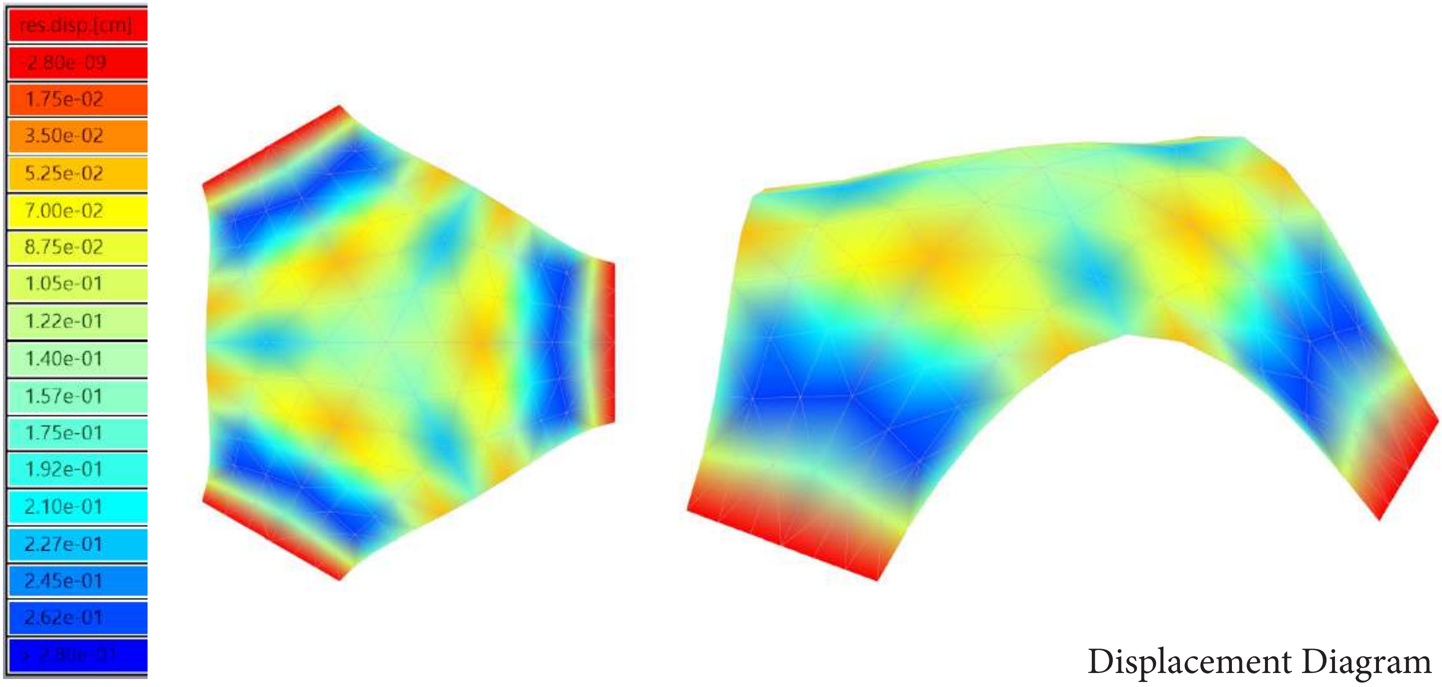
See "Mesh Table 02_Quad Mesh from ruled surface"

Mesh Table: 02_Quad Mesh from ruled surface

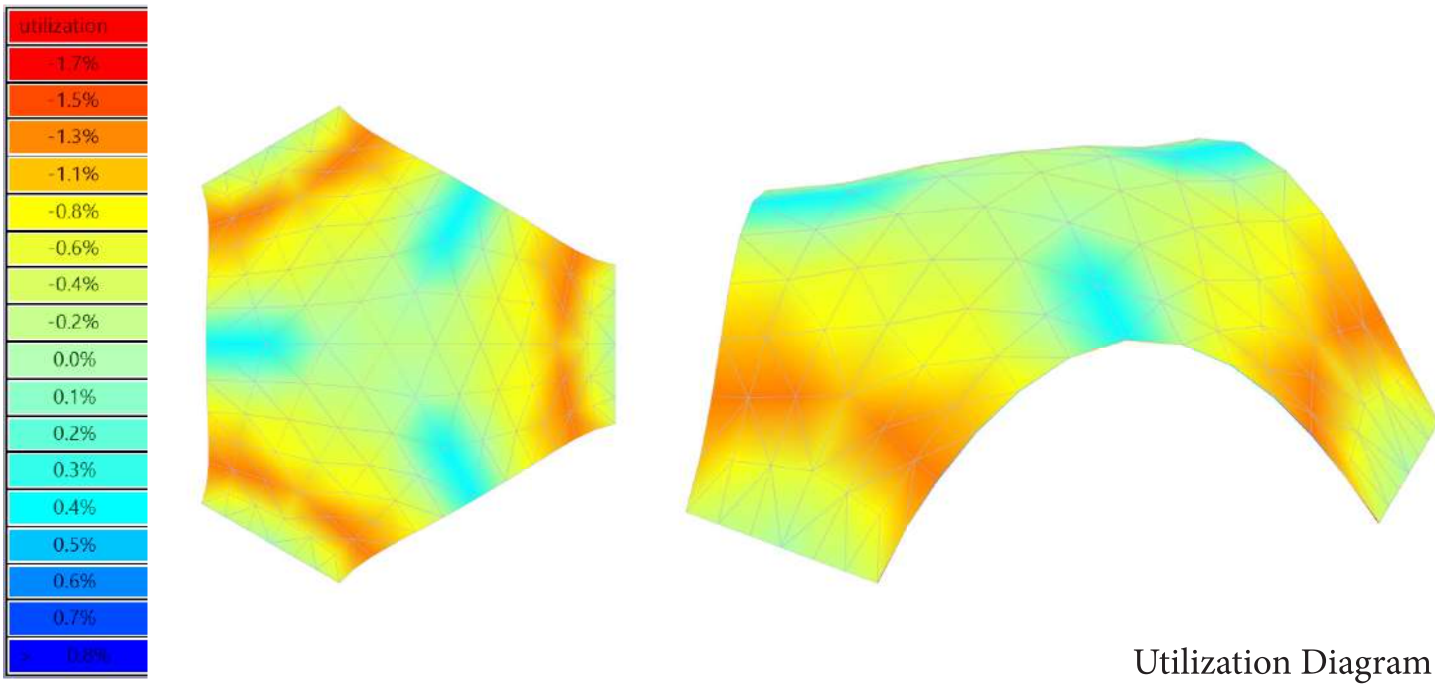
Properties

Area: *430.455m2*
Faces: *108*
Vertices: *252*
Edges: *250*
Perimetral Edges: *54*
Supports: *21*
Max. Height: *8.633m*
Thickness: *3cm*
Forces: *Gravity*

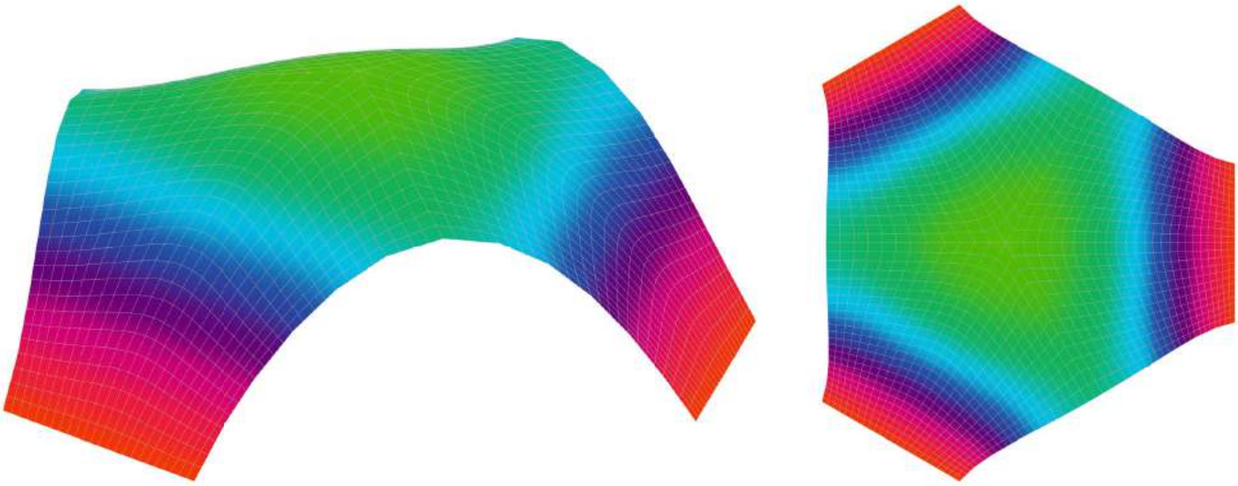




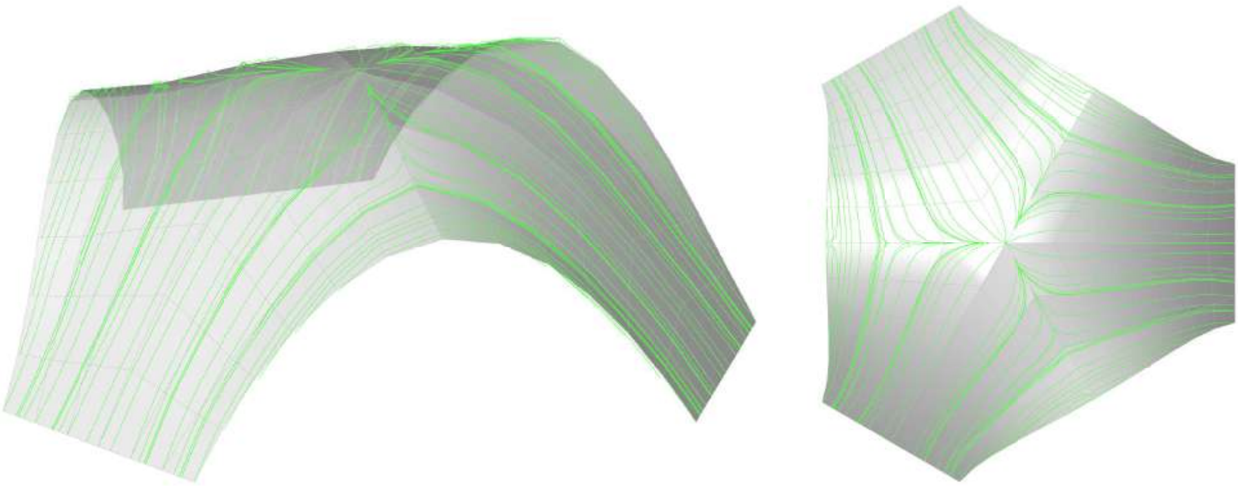
Displacement Diagram



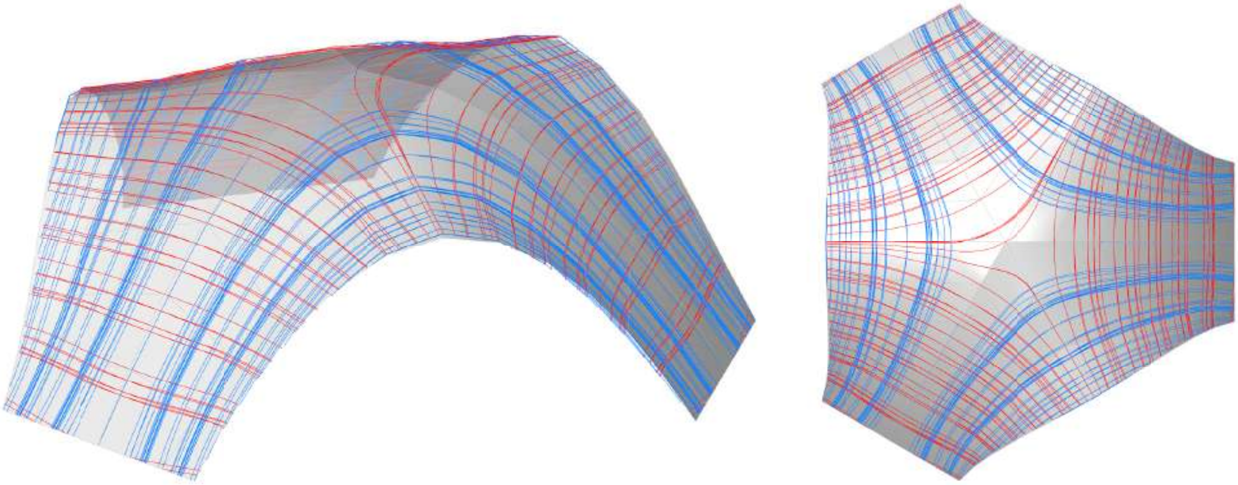
Utilization Diagram



Height Diagram



Force Flow Diagram



Principal Strees Lines Diagram

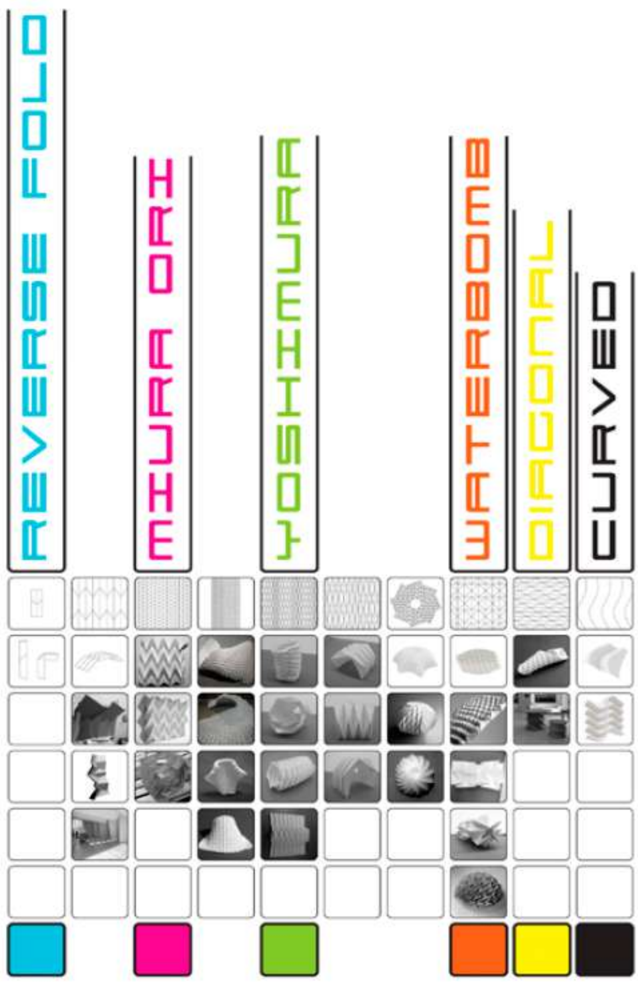
3.4_Origami

During the master, two origami patterns have been explored and ended up with a definition that worked as a cut origami design, an origami that can't be unfolded in one piece, but cut in some tires. This two origami patterns were the Miura Ori and Yoshimura. Nevertheless, the definition was though to work on closed surfaces, no on meshes, so it had to be re-defined.

The process is to create the pattern from the final form you want to achieve: the funicular shell. Then unfold it to have the 2D pattern.

As this is the first design hypothesis, the goal now is to adapt the definition to a Mesh and see how it works out, if it's possible to create a Miura Ori or a Yoshimura Pattern, and then, to make an structural analysis and see if it works better than the previous quad Mesh.

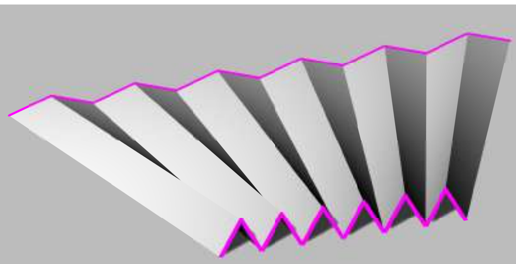
Nevertheless, one of the goals I said in the introduction is to make the design coming from a flat 2D rectangle. And although, it was not achieved in the origami definitions, in this state, it was applied and tested if the "paper fan effect" was worth it, meaning that it would help to have less thickness.



Variation of folding types (table from *"Digital Origami: Modeling planar folding structures Dave Lee, Brian Leounis"*) *See "Mesh Table 03_Folded Quad Mesh"*

3.4.1_Does it make sense to fold from a rectangle?

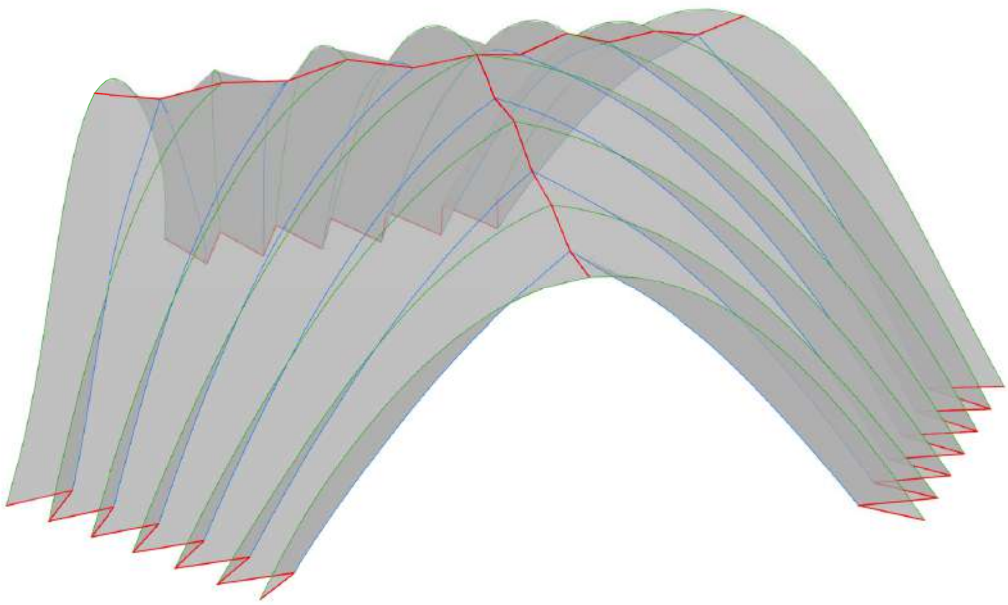
As right now it's just a test, it won't be tested as an origami definition, but on a folded structure. The idea is that between the geodesic lines put the same amount of material as it had come from a rectangle. So all the quads from the quad mesh must have the edges, which are parallel to the ground, with the same length.



The paper-fan effect: Both magenta lines have the same length

To do that, the geodesic lines are paired with the one next to them creating strips. Those lines are divided in X segments (all the same number) and in the perpendicular plane circles are created with the radius half the size of the max distance between the points of every strip. Where the two circles collide, is the point that if you make a polyline with it and the points of the center of the circle, all the polylines of the strip have the same length. Therefore, taking this new middle points and making a polyline, new curves between the geodesics are obtained that can be used to create new surfaces and finally a mesh were all the edges parallel to the ground have the same length.

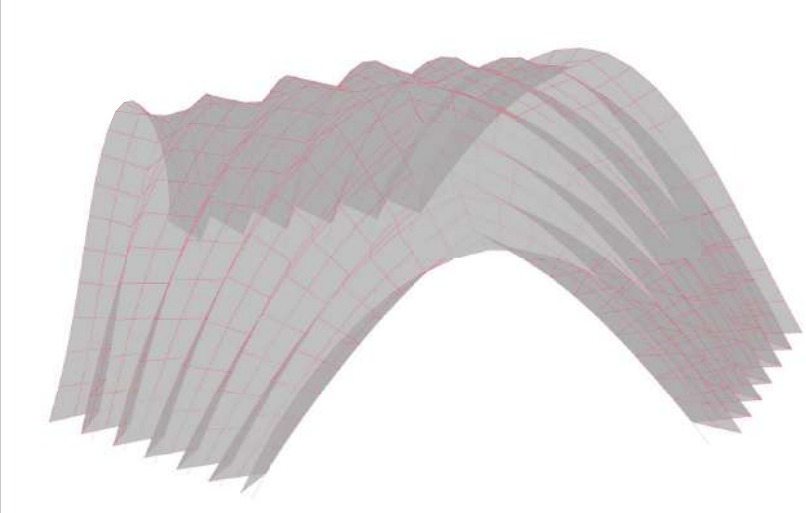
Finally, this mesh has the same analysis as the quad-mesh applied on it, so we can compare the results. It can be observed that imposing the same stress constrains and given the same thickness possibilities, and using the same material, the folded mesh, works better and can be less thick.

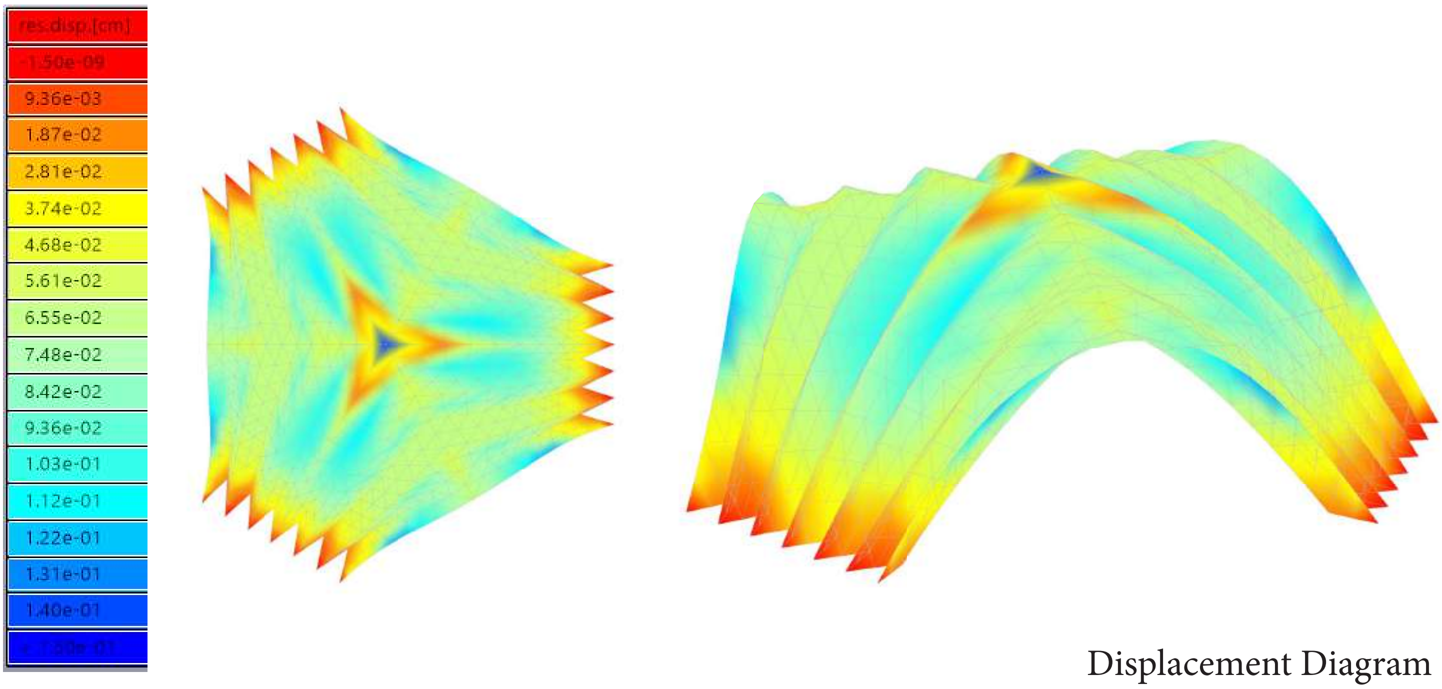


MESH TABLE: 03_Folded Quad Mesh

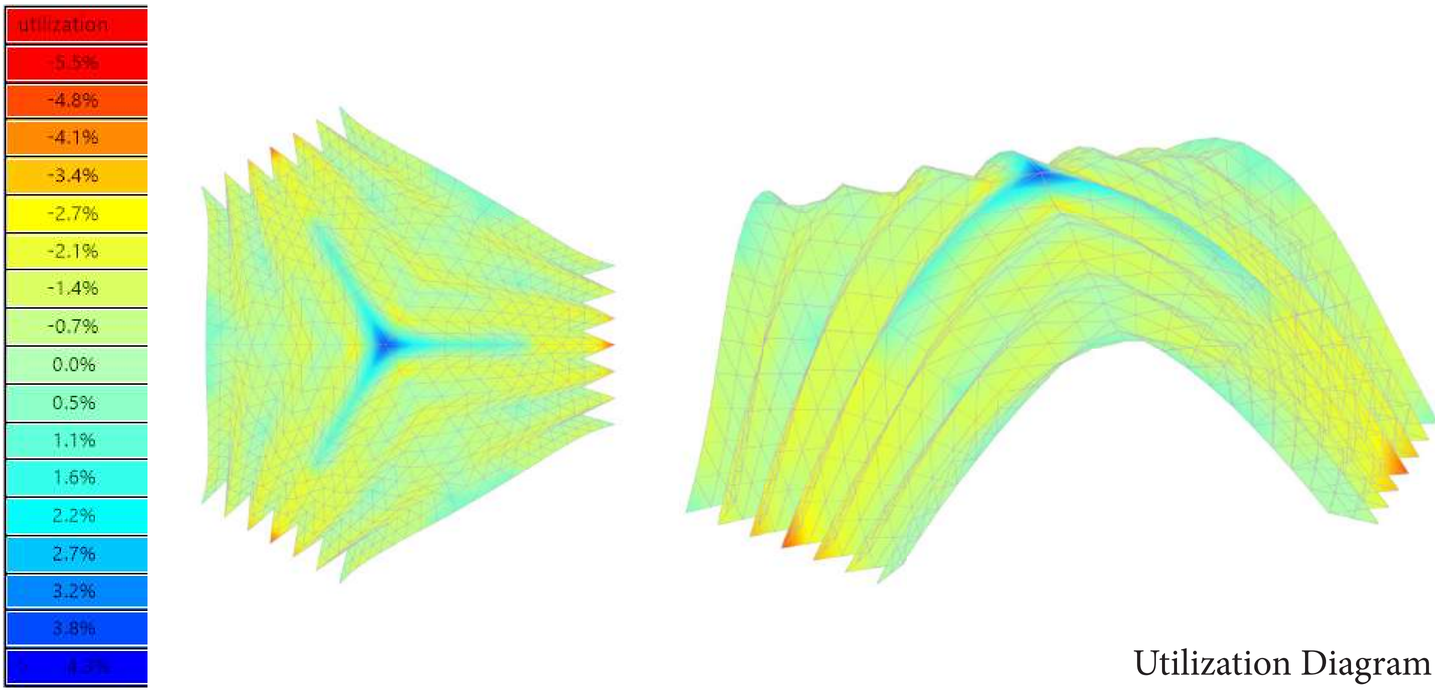
Properties

Area: *626.531m2*
Faces: *720*
Vertices: *790*
Edges: *1512*
Perimetral Edges: *96*
Supports: *21*
Max. Height: *8.633m*
Thickness: *3cm*
Forces: *Gravity*

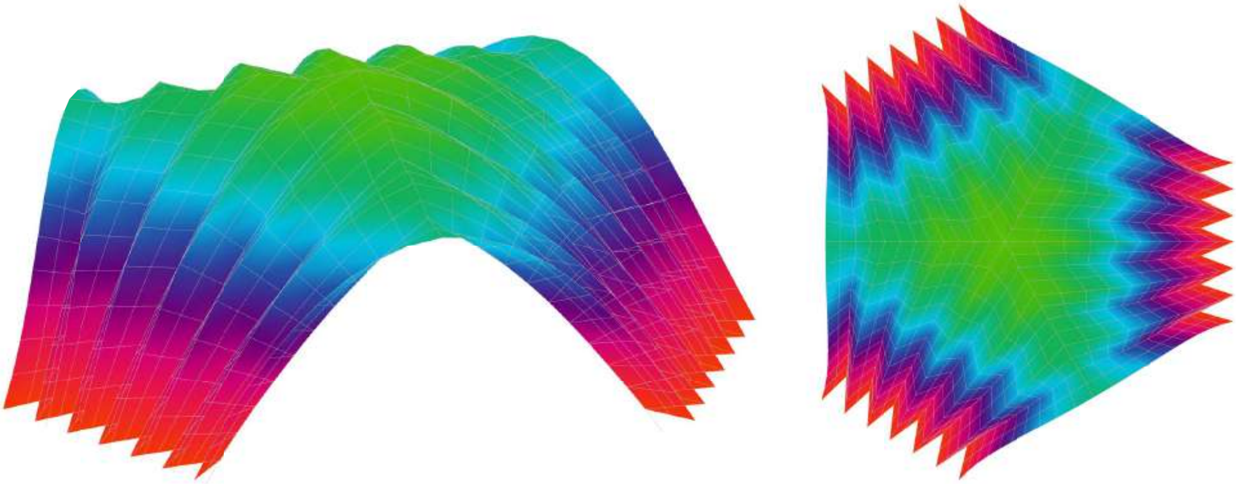




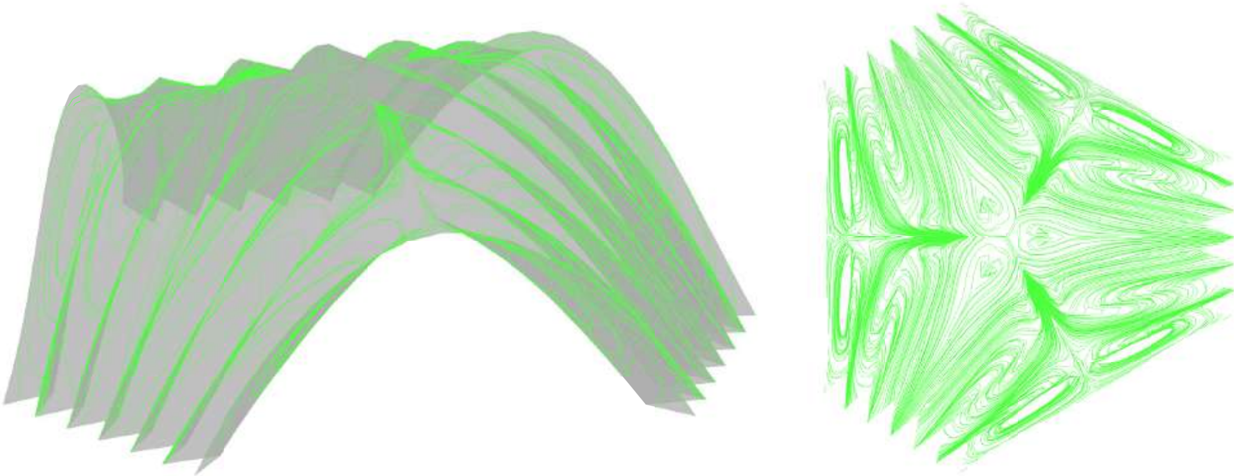
Displacement Diagram



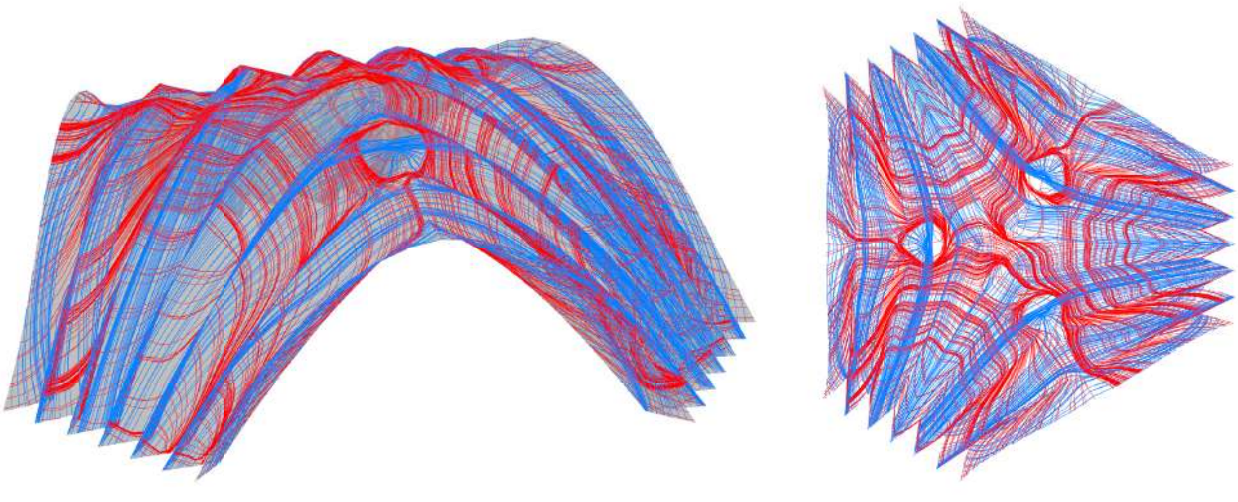
Utilization Diagram



Height Diagram

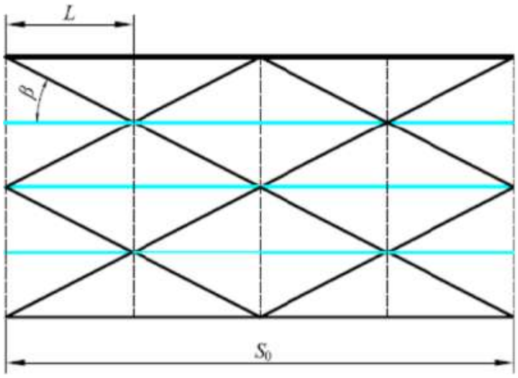


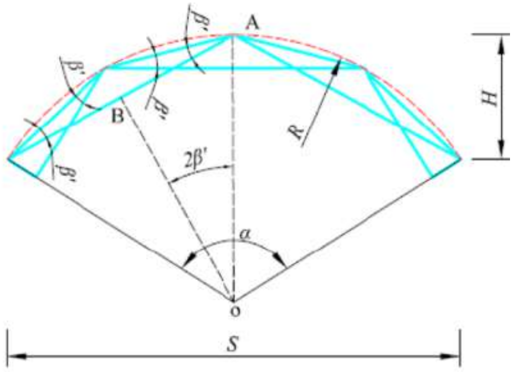
Force Flow Diagram



Principal Strees Lines Diagram

3.4.2_Yoshimura Pattern

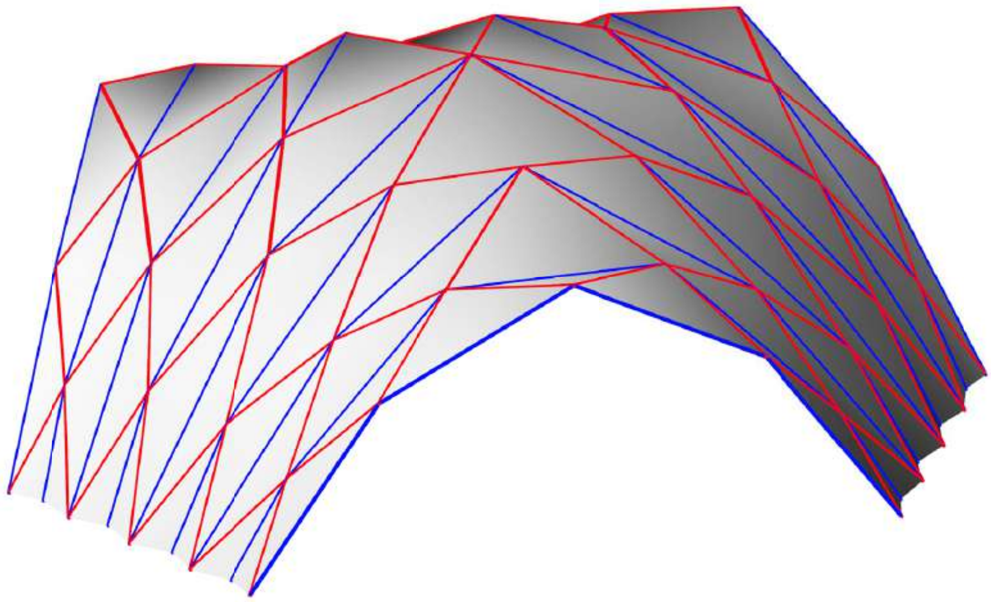




Yoshimura Pattern

Yoshimura design

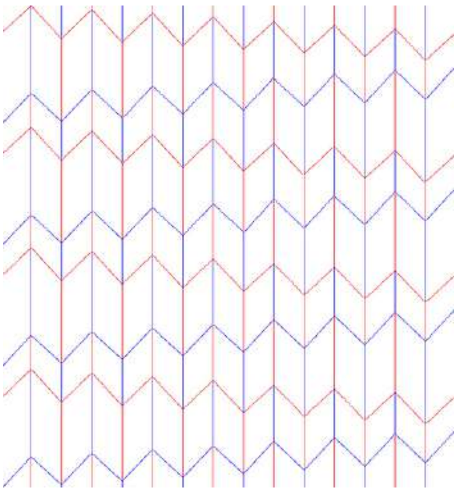
The strategy to create a Yoshimura pattern is to take the geodesic lines and divide them all in the same number of points. Then with those curves sort from one side to the other of the mesh, the odd ones must have the odd or even points culled and the even curves, has to eliminate the others opposite ones (even or odds). Then rebuild the curve with just the remaining points whit a 1 degree polyline. Then every vertices of this polylines must be joined to the tow closest points of the neighbor lines.



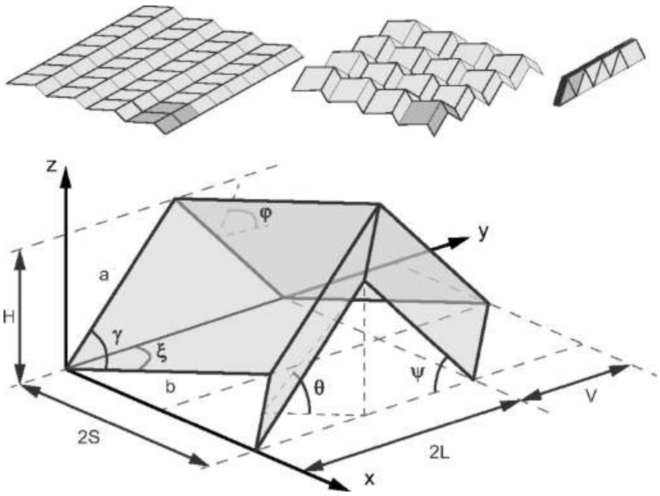
Miura Ori Pattern: red-mountains blue-valleys

See "Mesh Table 04_Yoshimura Funicular Shell"

3.4.3_Miura Ori Pattern

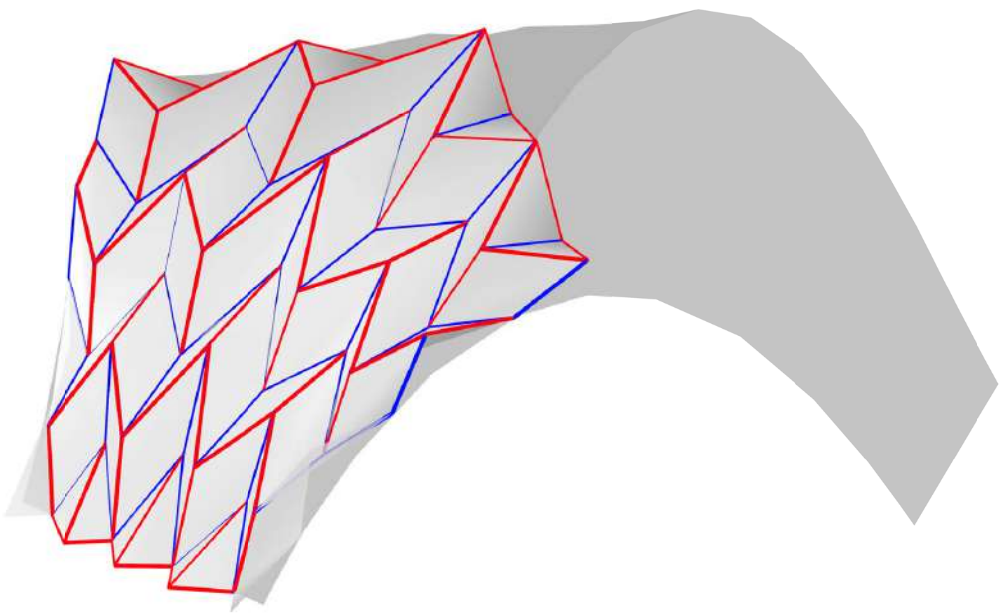


Miura Ori Pattern



Miura Ori design and folding

The strategy to create a Miura Ori pattern is to go from a 3D Mesh (shell), make it a quad mesh as it has already been done. Then, offset the points of the mesh that will be the vertices on the origami design. After that, chosing U or V curves, with the points in order through this lines, you take one original poit and one offseted, so when you join them just with the lines of the Miura pattern, the result is a Miura-like design.



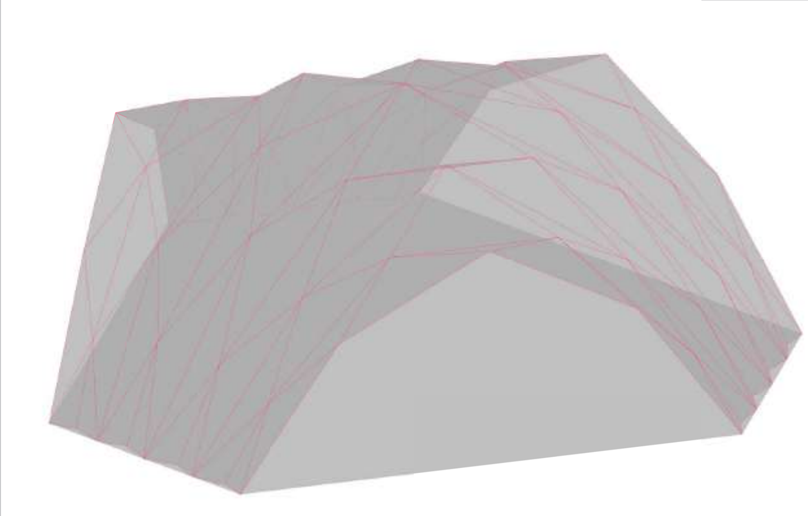
Miura Ori Pattern: red-mountains blue-valleys

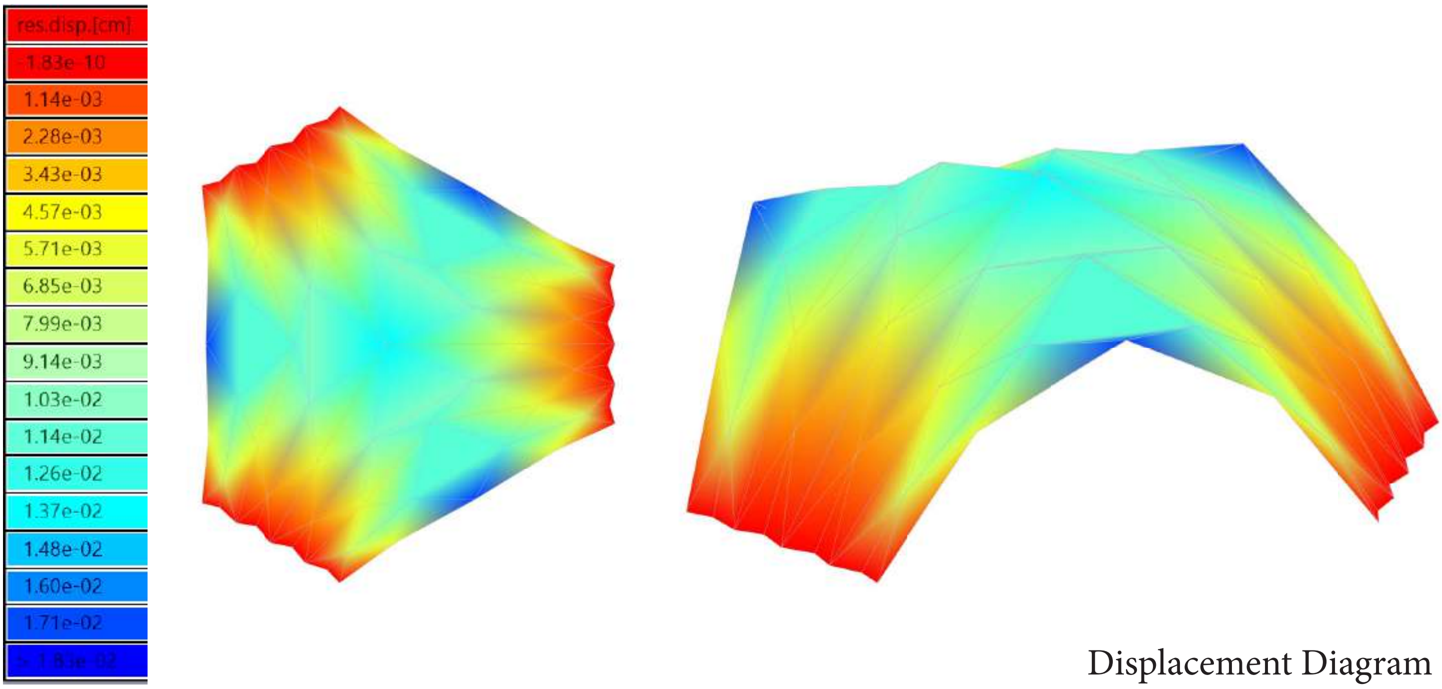
See "Mesh Table 05_Miura Ori Funicular Shell"

Mesh Table: 04_Yoshimura

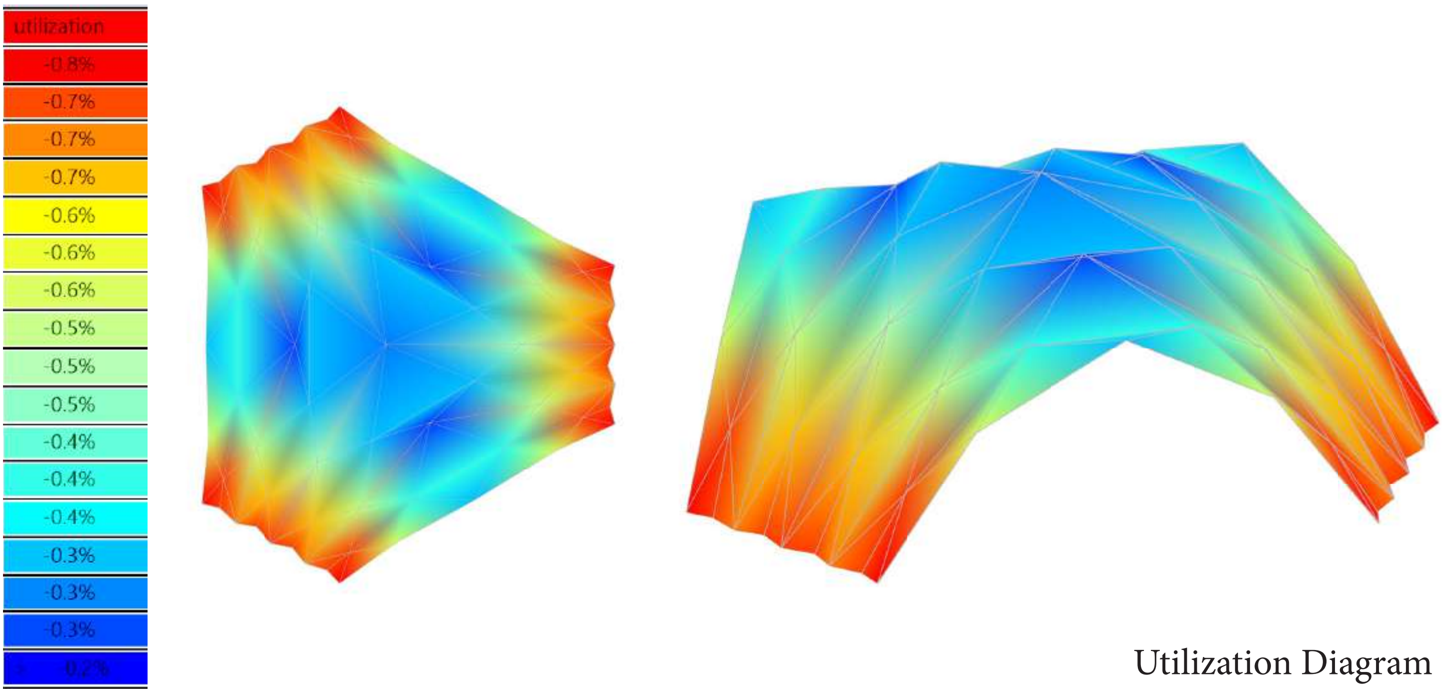
Properties

Area: *626.531m2*
Faces: *720*
Vertices: *790*
Edges: *1512*
Perimetral Edges: *96*
Supports: *21*
Max. Height: *8.633m*
Thickness: *3cm*
Forces: *Gravity*

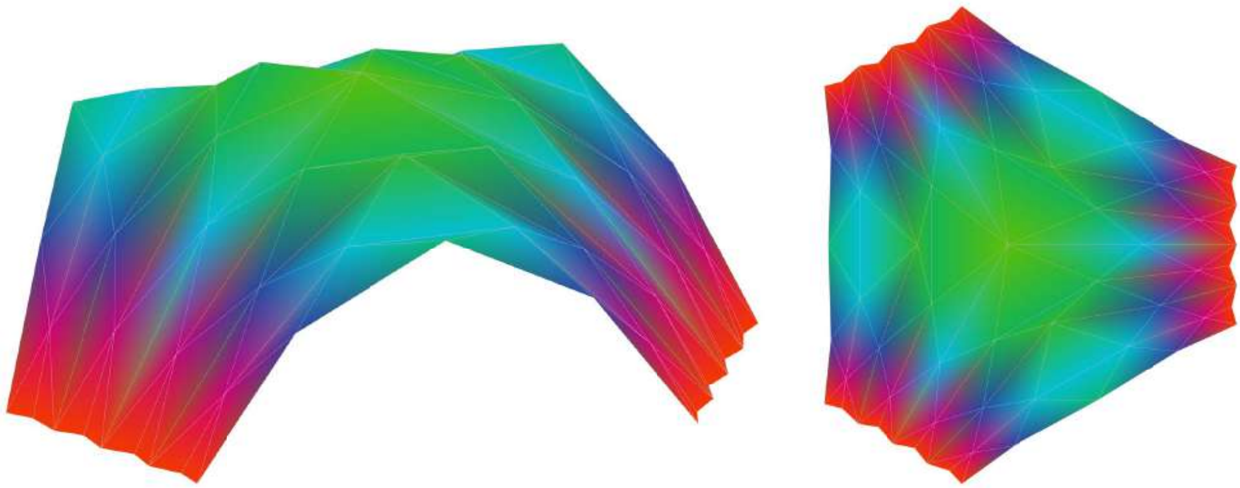




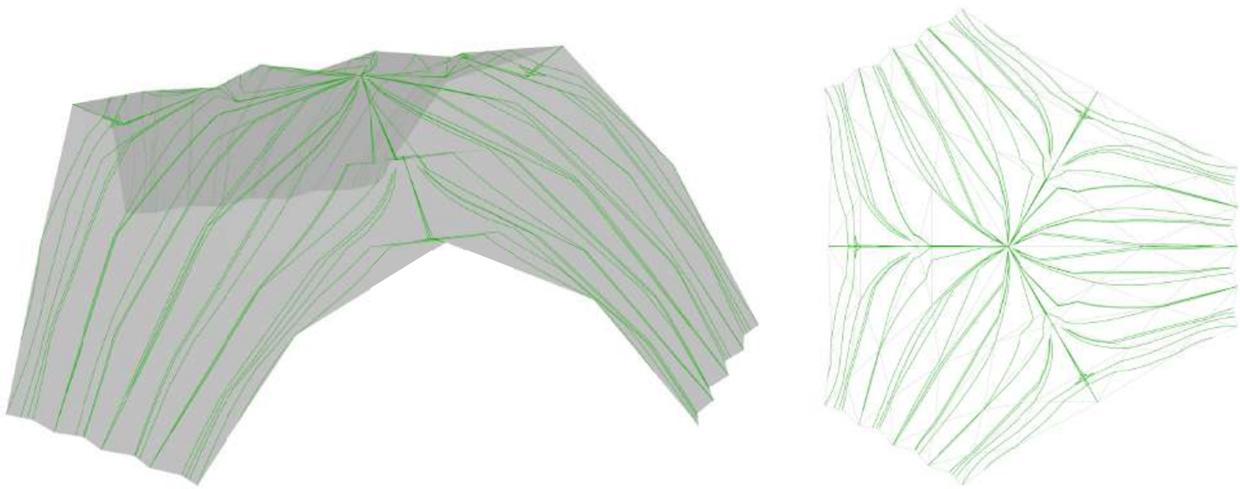
Displacement Diagram



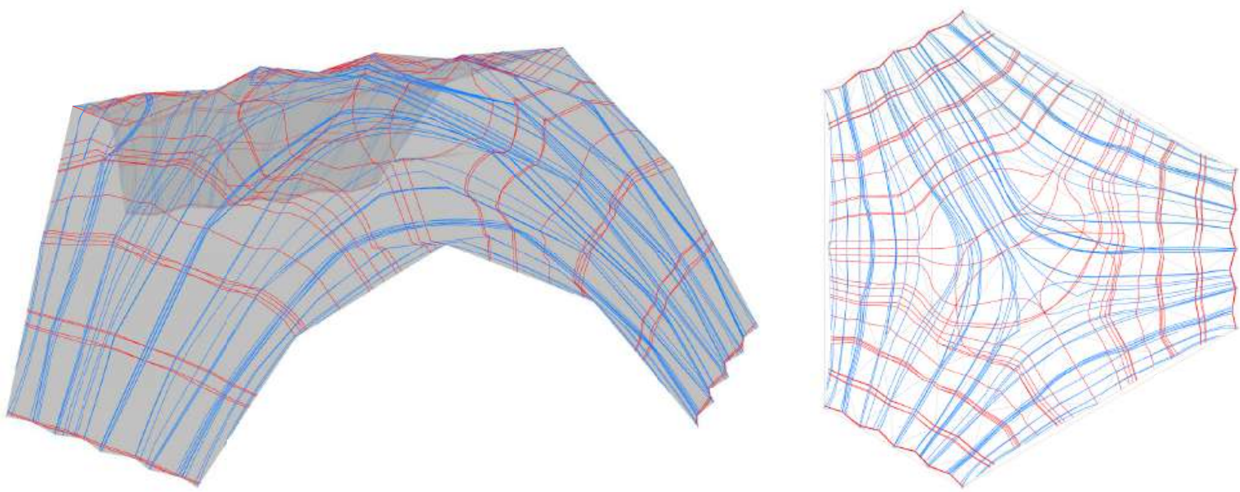
Utilization Diagram



Height Diagram



Force Flow Diagram



Principal Strees Lines Diagram

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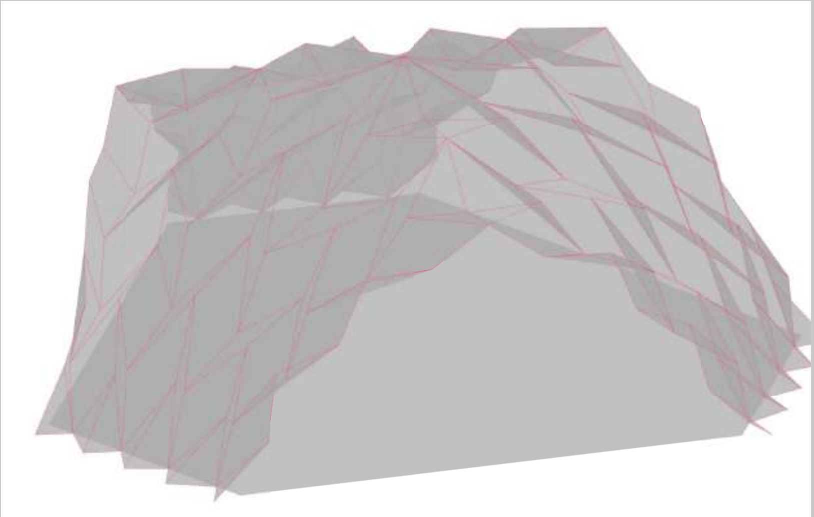
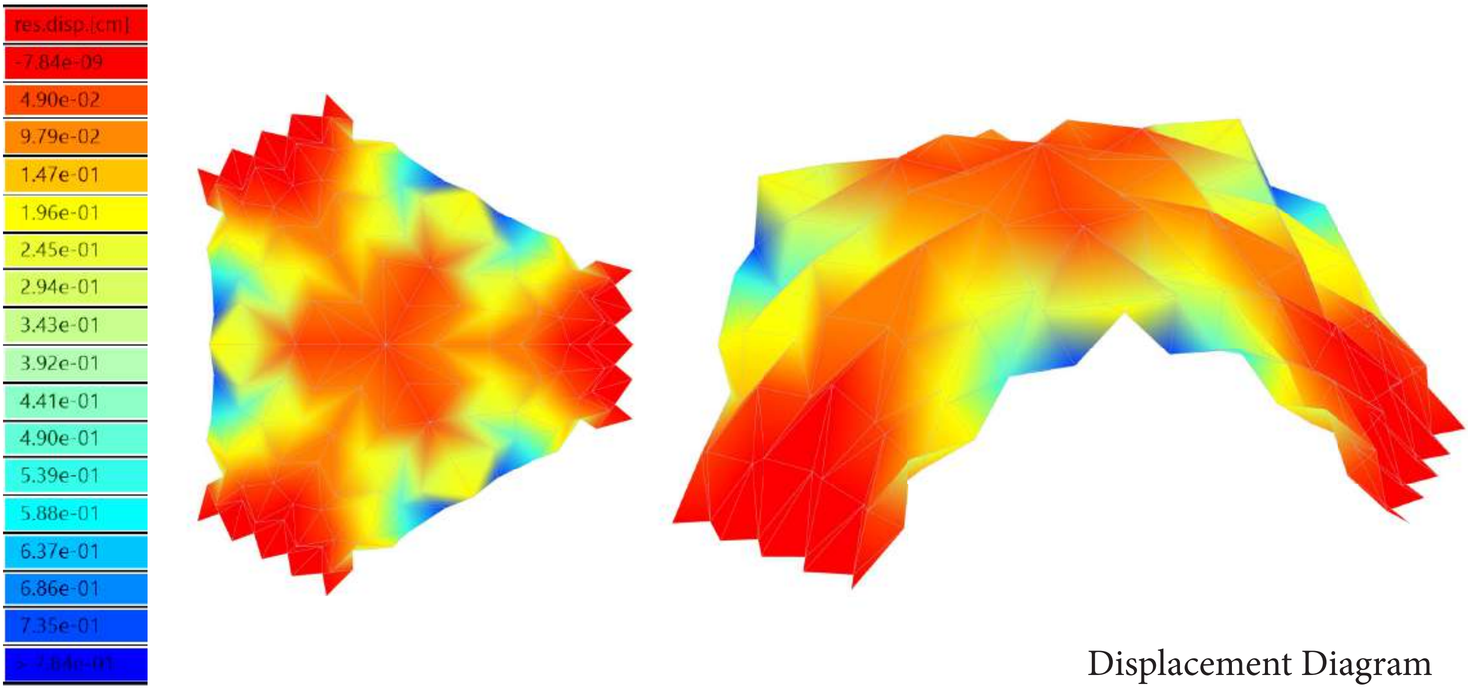
Mesh Table: 05_Miura Ori

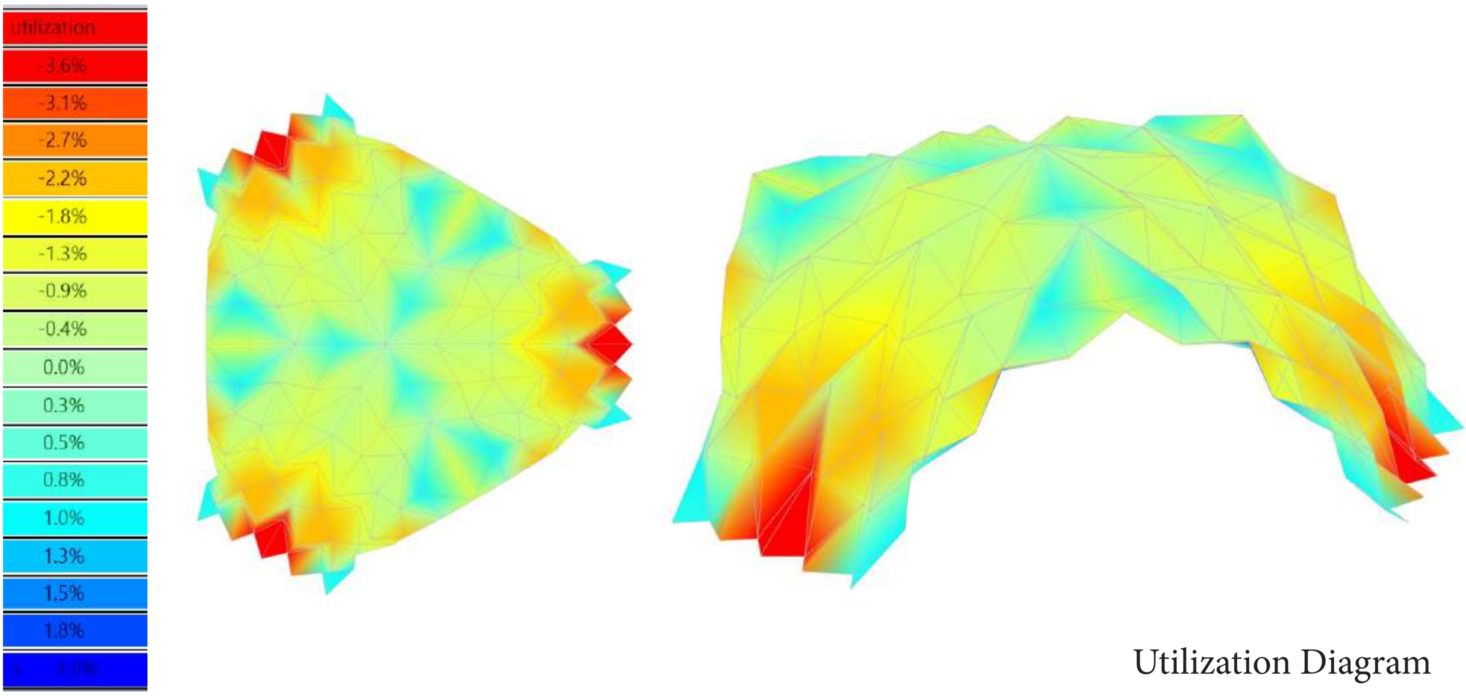


Properties

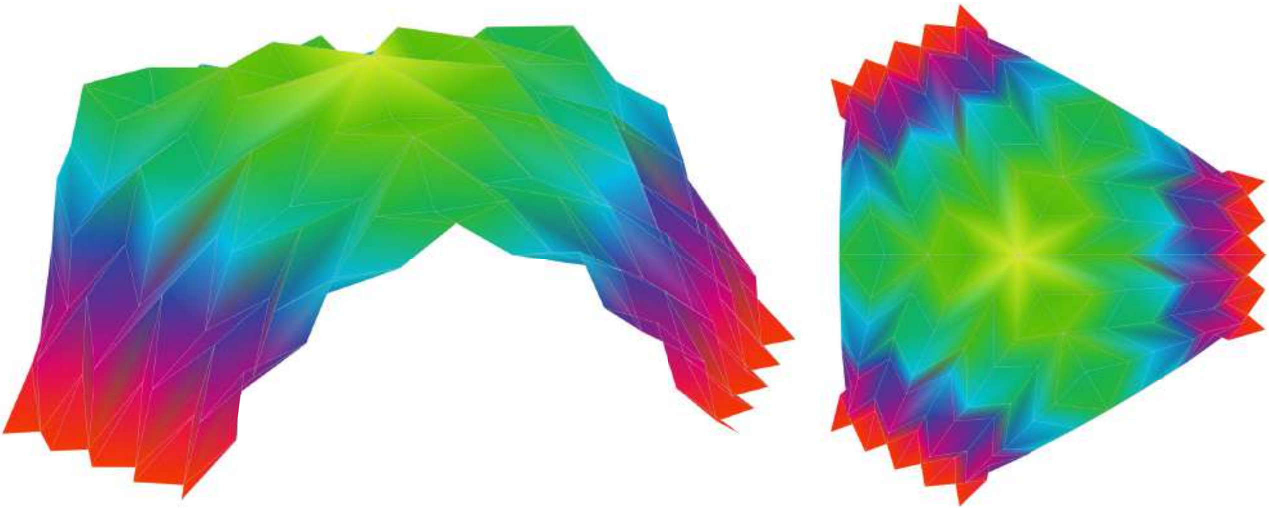
Area: *626.531m2*
Faces: *720*
Vertices: *790*
Edges: *1512*
Perimetral Edges: *96*
Supports: *21*
Max. Height: *8.633m*
Thickness: *3cm*
Forces: *Gravity*



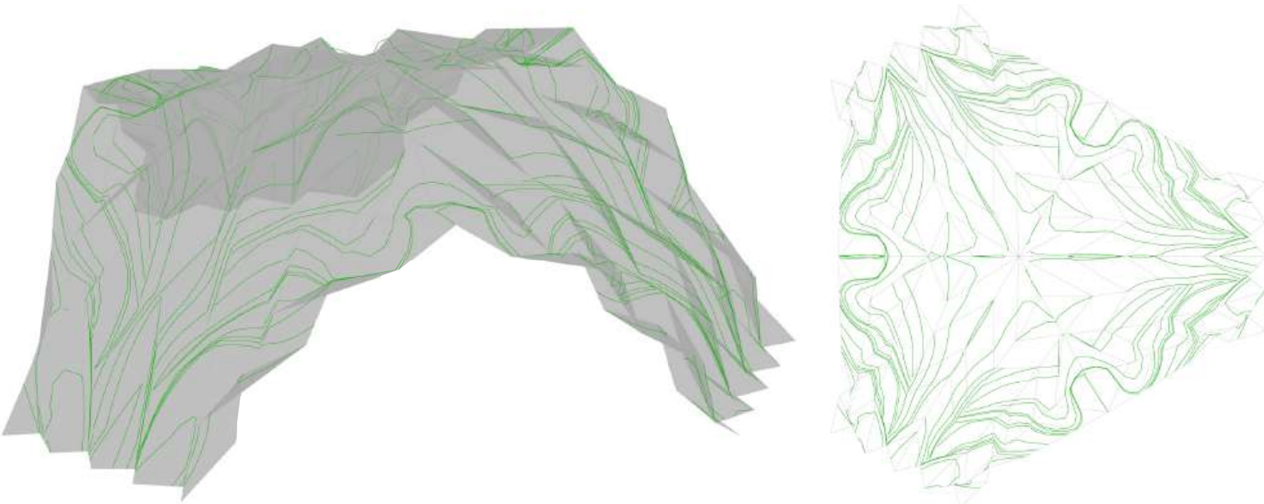
Displacement Diagram



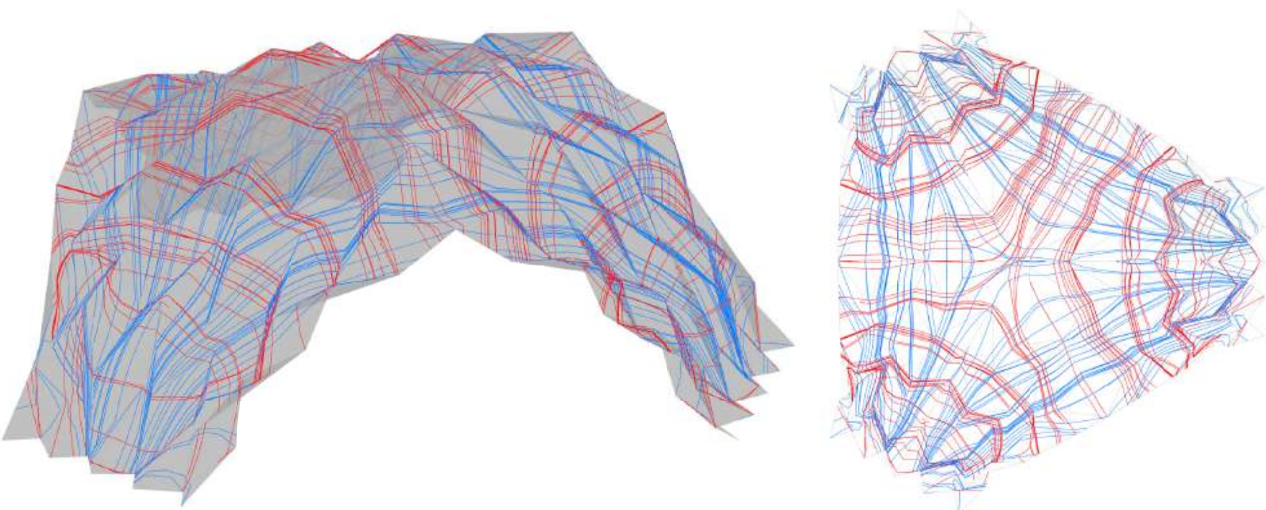
Utilization Diagram



Height Diagram



Force Flow Diagram



Principal Strees Lines Diagram

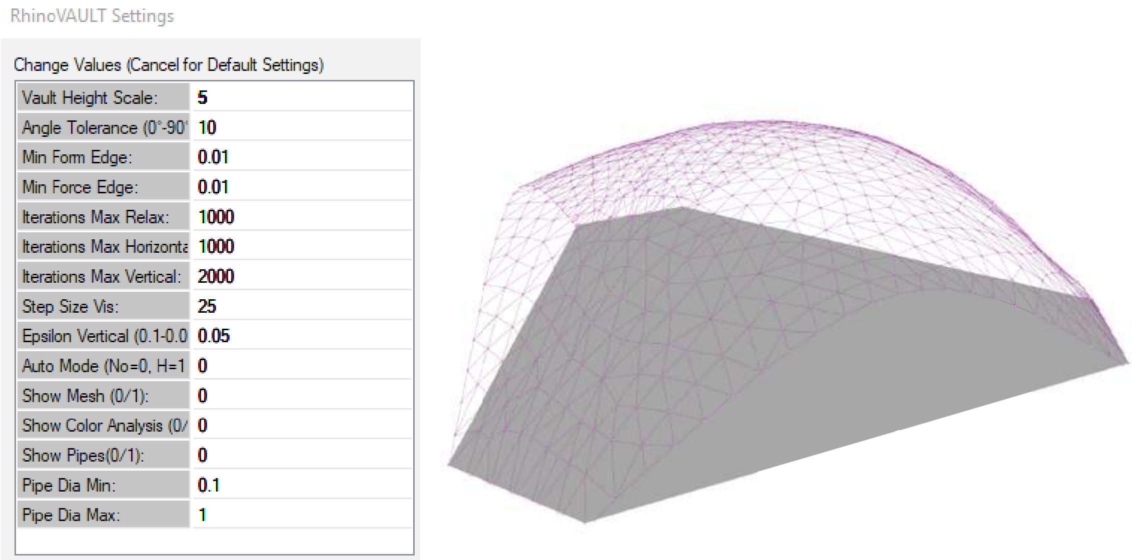
4_Design Process
Funicular Shell Form Finding (FSFF)

As seen in the introduction and in "first hypothesis design", the first step of the design once the perimeter is decided is to simulate a way to get a funicular Shell shape through a form finding process.

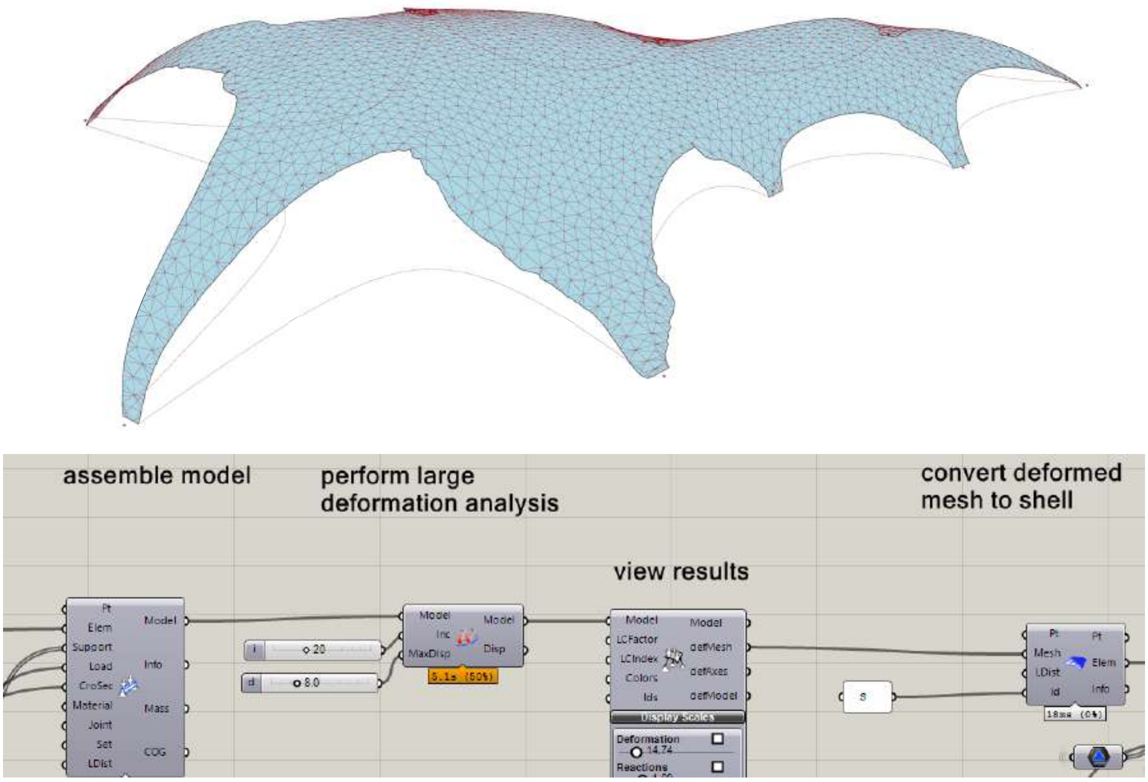
Firstly, a strategy form the form finding must be set. As explained before, the basic strategy is to create a Mesh in proposed shape, whose edges will have the constrain to keep their length, the nodes that will be the supports will be in a fixed position and all the nodes will have a vertical load applied on them to simulate the gravity. This would be the strategy used with the plugin Kangaroo in Grasshopper, there are others plugins that can do it like Karamba (it will be used to calculate and test the structures) and RhinoVault (creates Vaults from surfaces).

This part of the study is based on how to simulate Funicular Shell with form finding in Kangaroo, so to know the best results and chose; it will be done comparing their structural analysis. The better ones will be the ones that work better at pure compression, as a funicular shell should work, and that have a smooth mesh, as seen during previous explorations, sometimes this strategy in kangaroo creates some undesired creases.

4.1_ Strategy of the FSFF: Grasshopper-Kangaroo / Grasshopper-Karamba / RhinoVault



RhinoVAULT example of process and result



Karamba example of process and result

4.2_ Mesh resolution

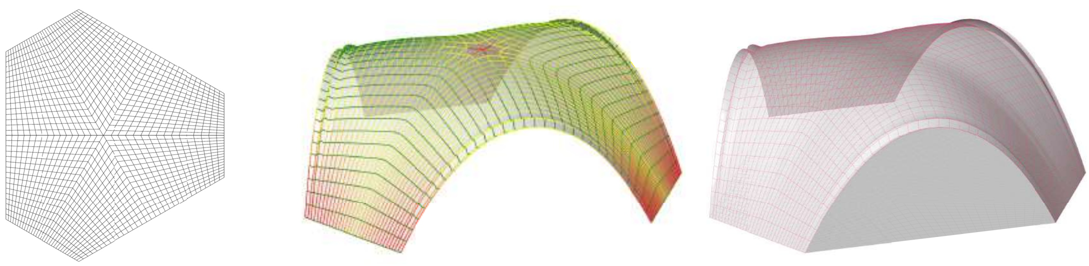
The more subdivisions, resolution, the mesh has, the better shape it will the Vault have. As the only points where the mesh can have curvature is in the nodes, more subdivisions mean more nodes, so more curvature. The lines are always straight lines. However, the nodes must be increased in a regular way according to the mesh tessellation or as seen before (tessellation matters), the subdivision can change the resulting vault.

Another thing observed is that when testing the shell with a structural analysis, this one has to be made with the exact resulting mesh. If the mesh is subdivided after the form finding process, the diagrams shows not desired results such as spirals in the force flow diagram or the deformation could change. A shell mesh with low resolution can have good structural results if you just analyses it with the nodes used in the form finding process, when you analyses new points created after the form finding, these are created in faces that are created from edges of the mesh, not calculated nodes. Therefore, we would get the analysis of those faces of the mesh rather than the general behavior of the shell.

2D Mesh | FSFF process | Final Mesh

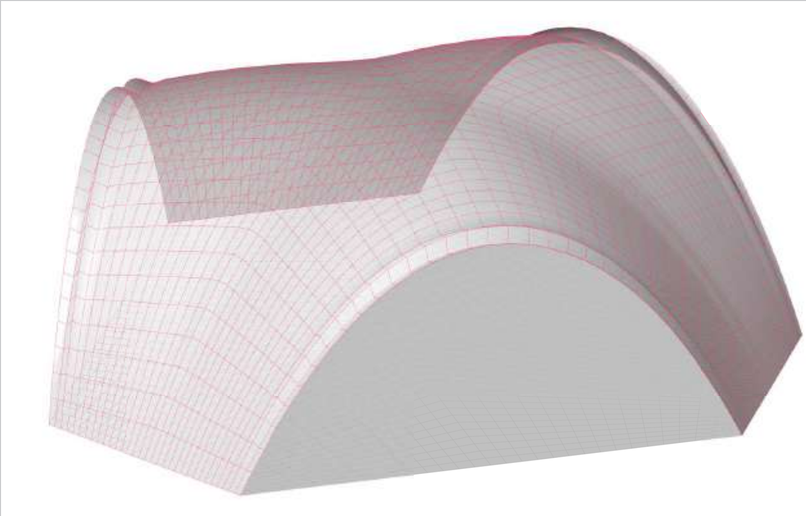
"Mesh Table 11_Low resolution Quad Mesh"

"Mesh Table 12_High-Low resolution Quad Mesh"



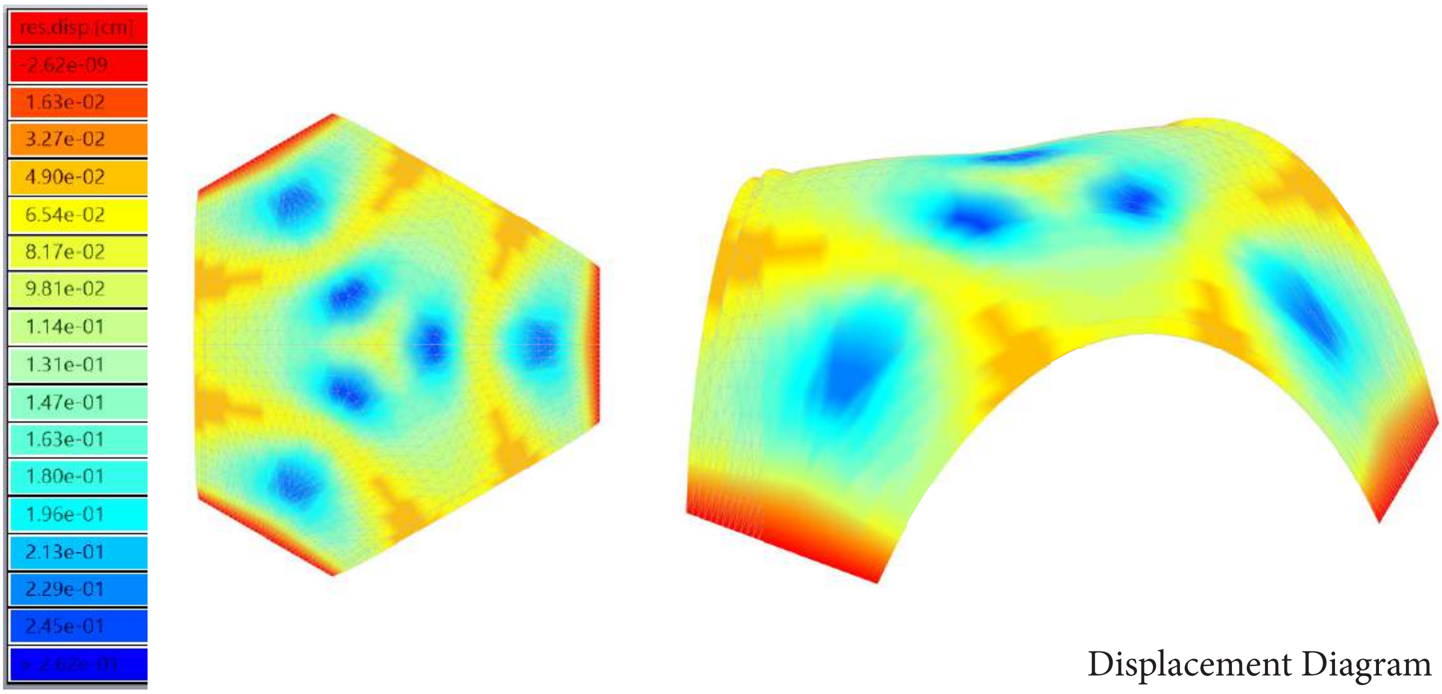
"Mesh Table 10_High resolution Quad Mesh"

Mesh Table: 10_High resolution Quad Mesh

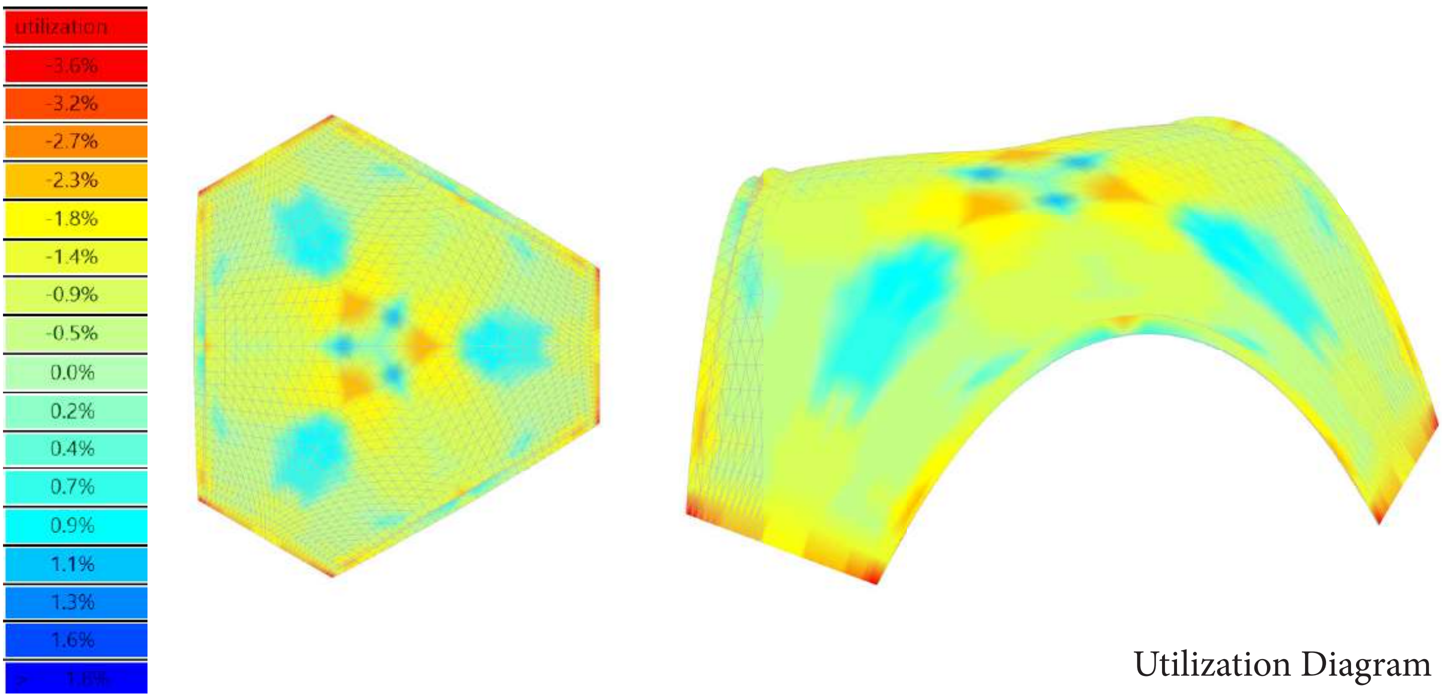


Properties

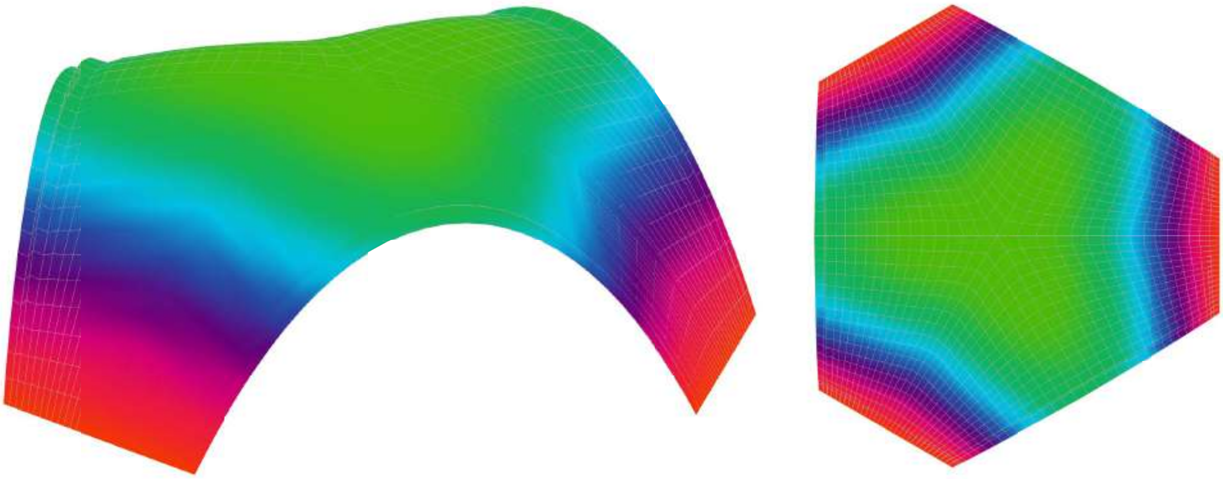
Area: *479.083m2*
Faces: *1536*
Vertices: *1633*
Edges: *3168*
Perimetral Edges: *192*
Supports: *99*
Max. Height: *8.486m*
Thickness: *3cm*
Forces: *Gravity*



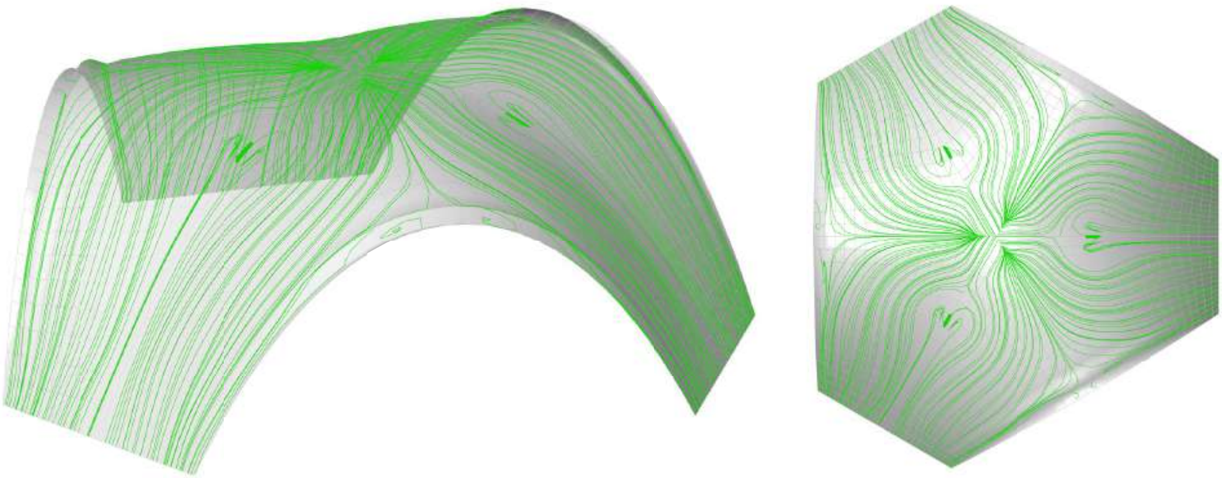
Displacement Diagram



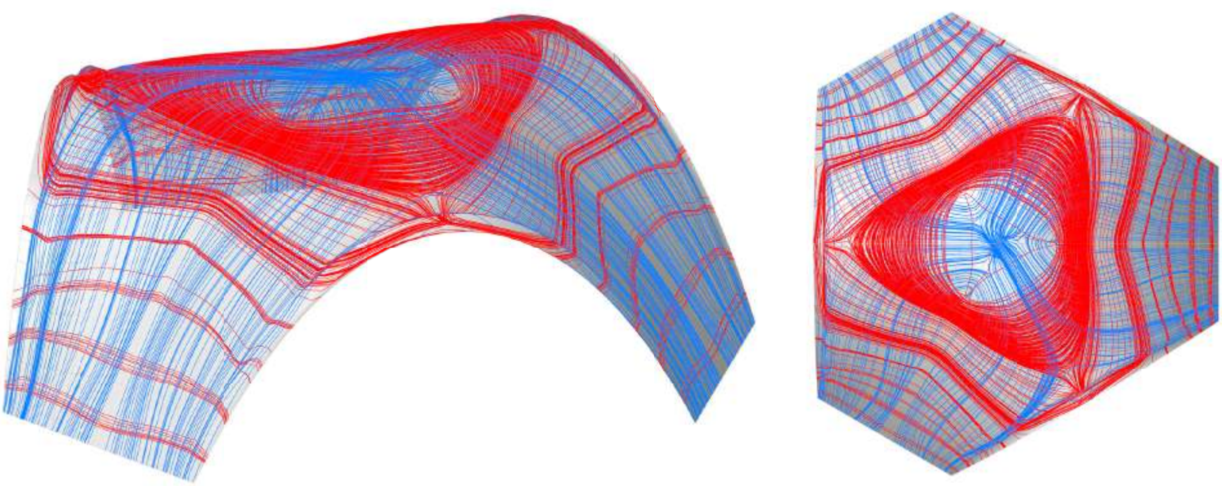
Utilization Diagram



Height Diagram



Force Flow Diagram



Principal Strees Lines Diagram

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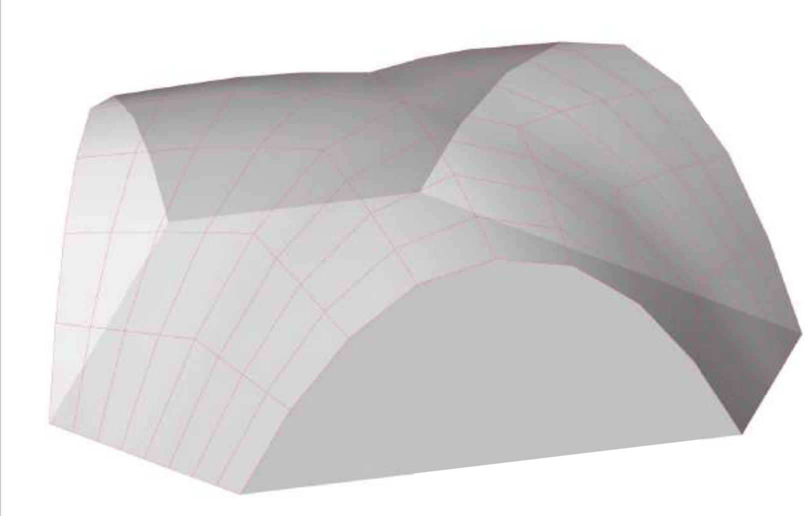
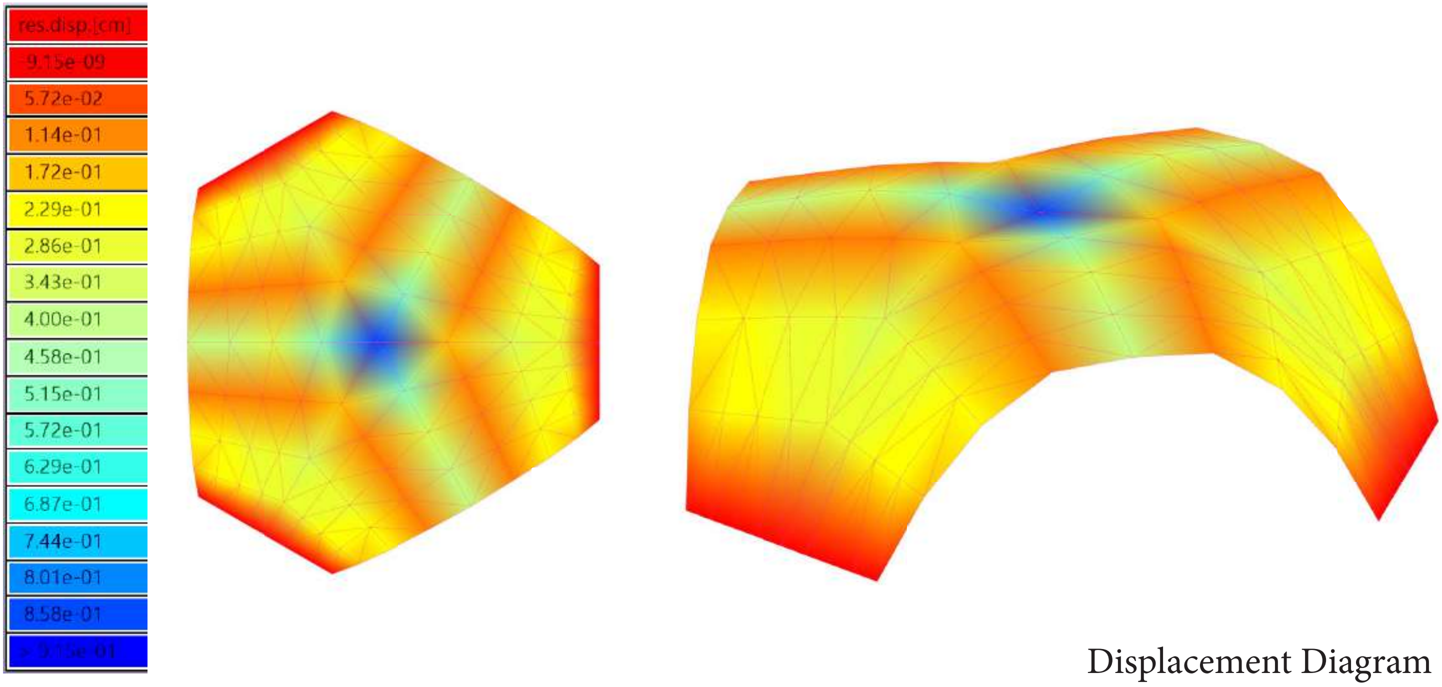
MESH TABLE: 11_Low resolution Quad Mesh

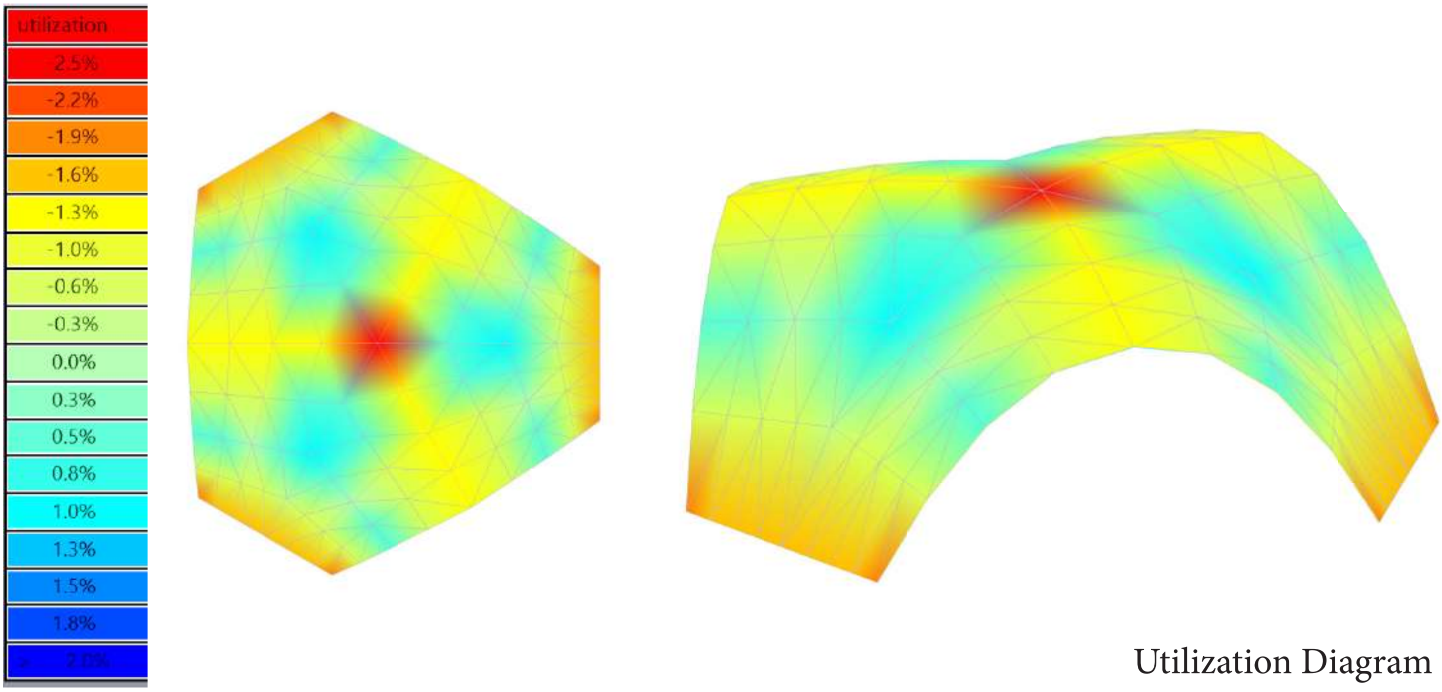


Properties

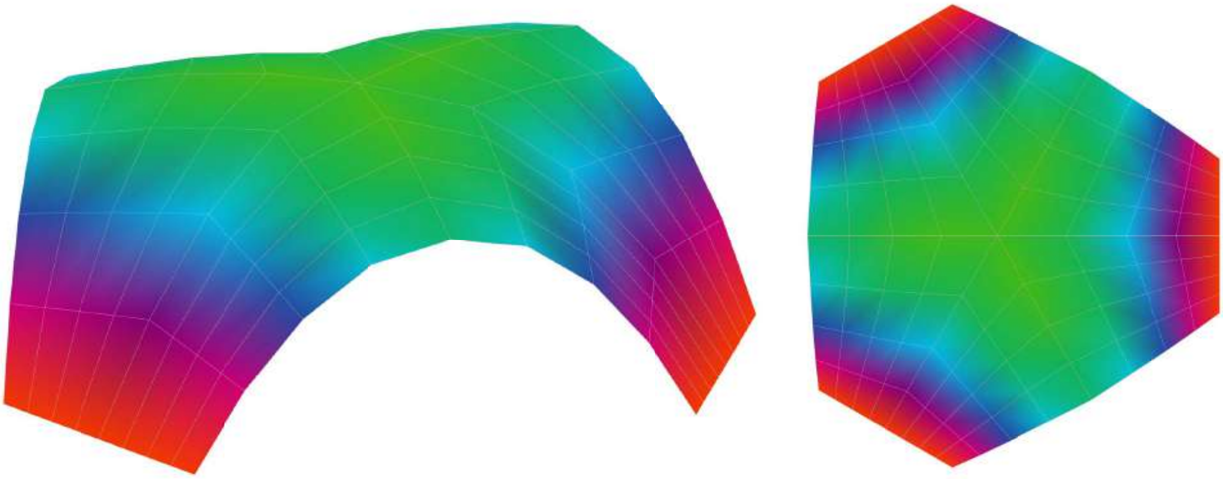
Area: *466.81m2*
Faces: *96*
Vertices: *121*
Edges: *216*
Perimetral Edges: *48*
Supports: *27*
Max. Height: *8.053m*
Thickness: *3cm*
Forces: *Gravity*



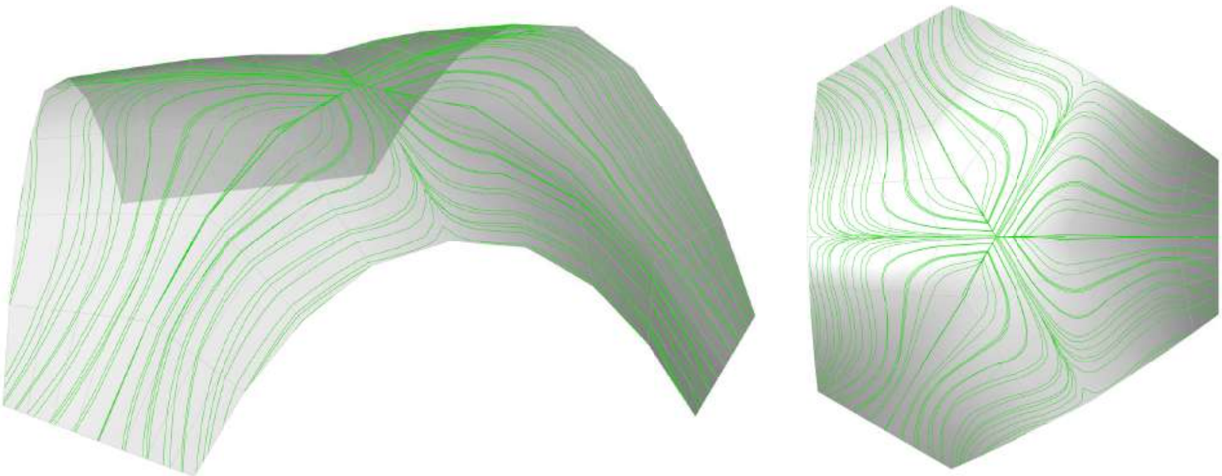
Displacement Diagram



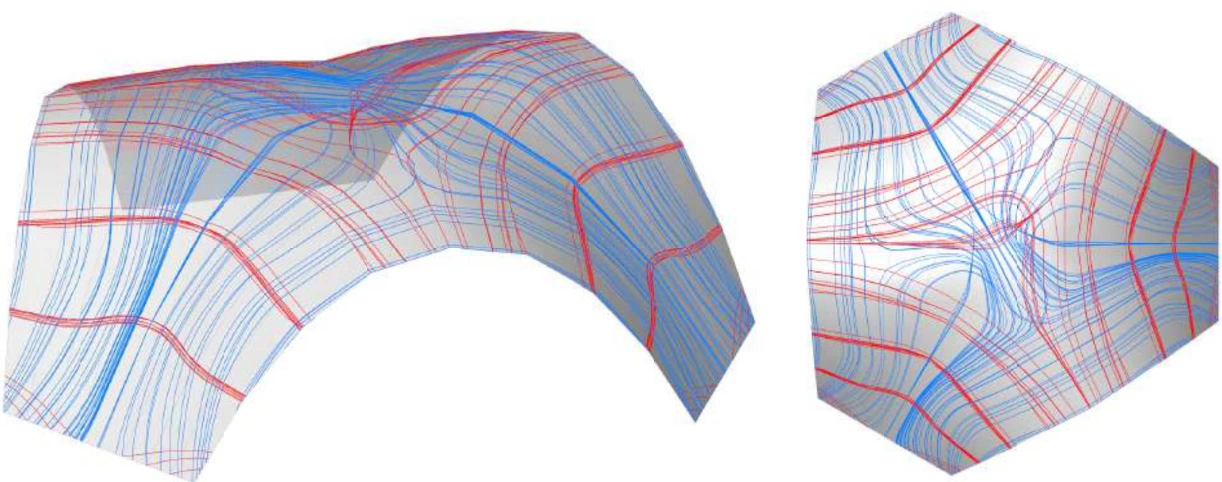
Utilization Diagram



Height Diagram

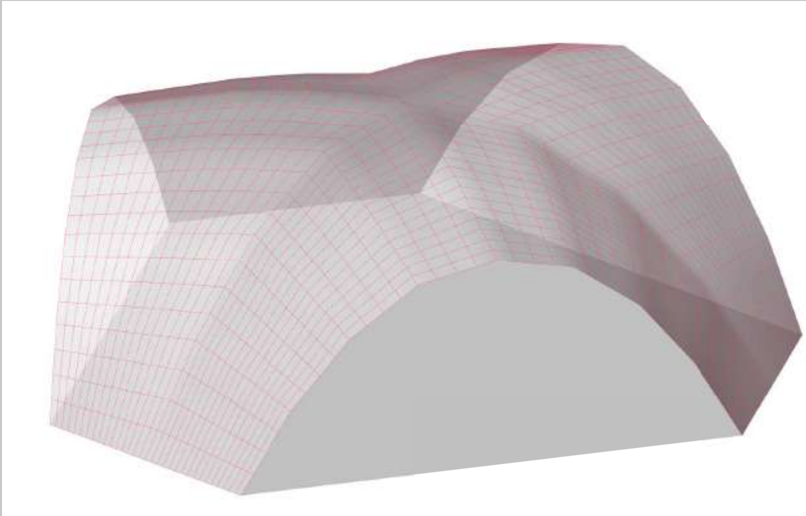


Force Flow Diagram



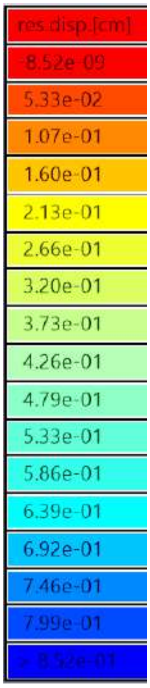
Principal Strees Lines Diagram

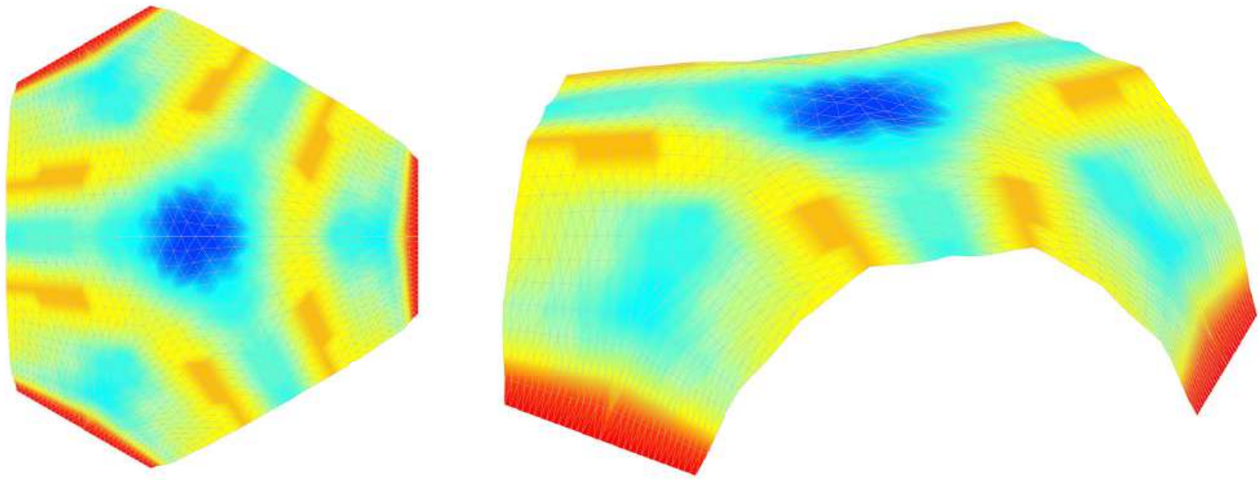
Mesh Table: 12_High-Low resolution Quad Mesh



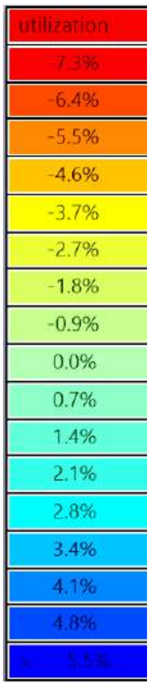
Properties

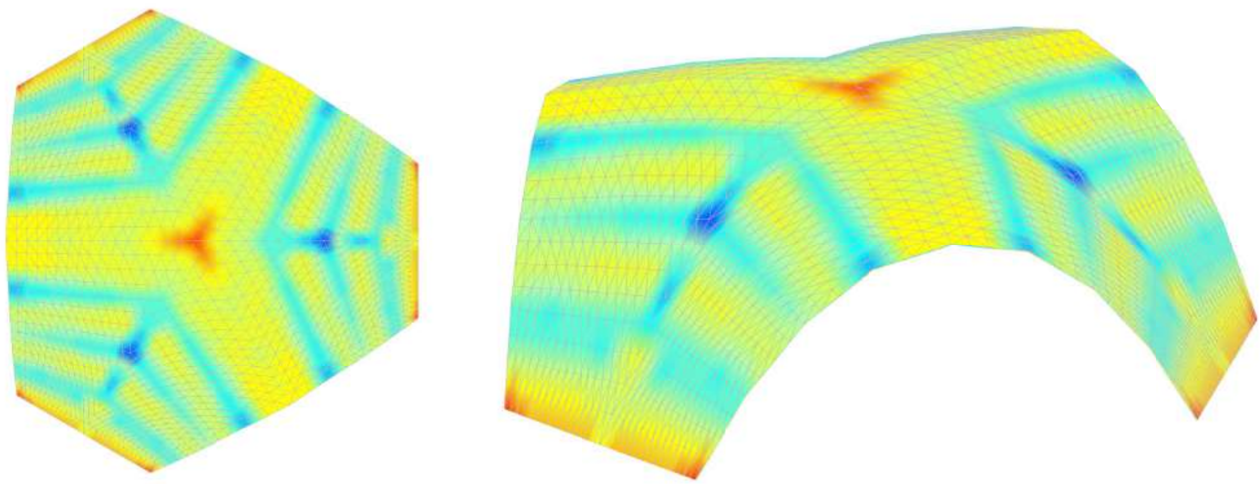
Area: *466.59m2*
Faces: *1536*
Vertices: *1633*
Edges: *3168*
Perimetral Edges: *192*
Supports: *99*
Max. Height: *8.053m*
Thickness: *3cm*
Forces: *Gravity*



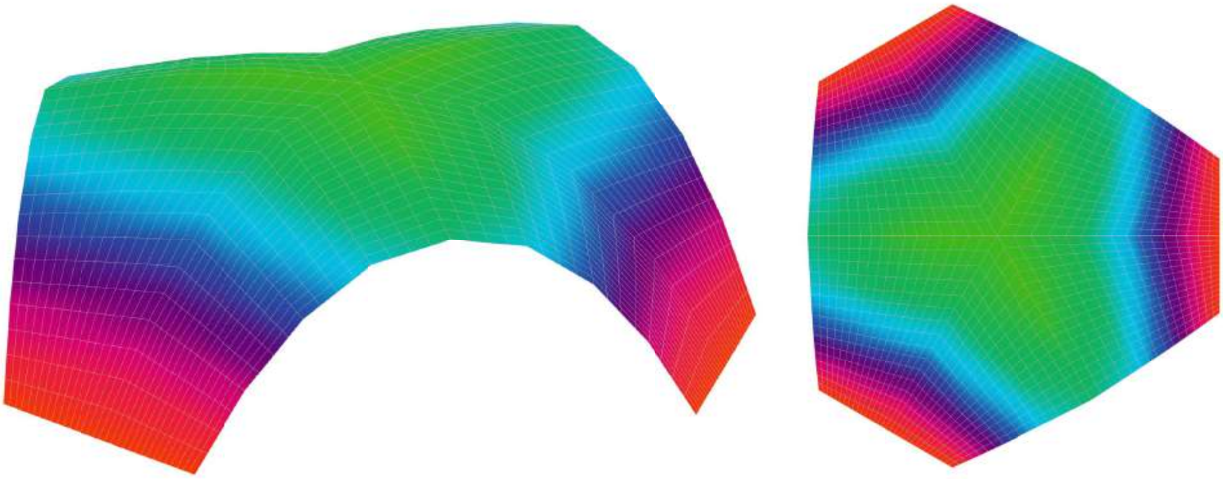


Displacement Diagram

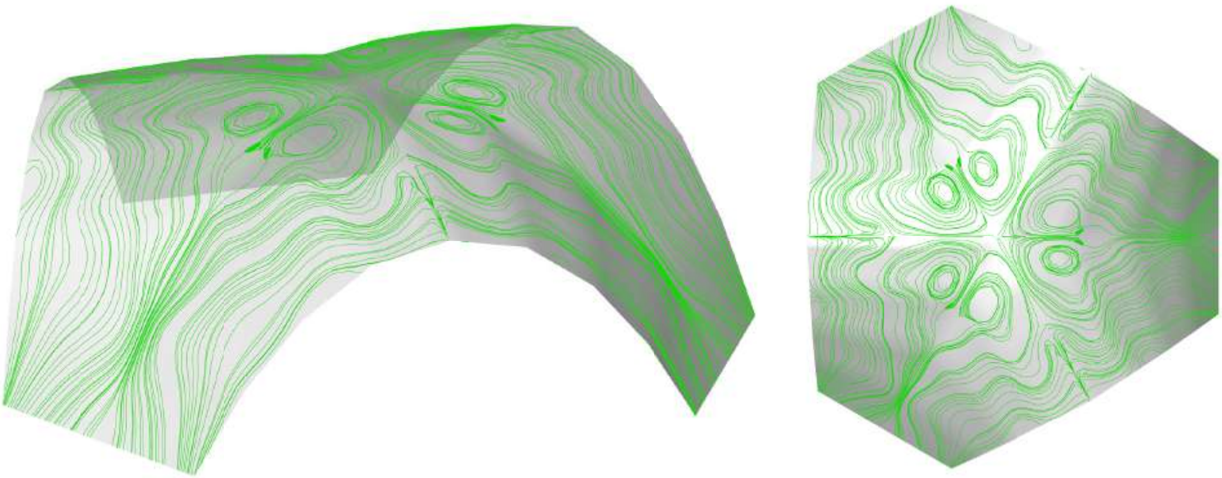




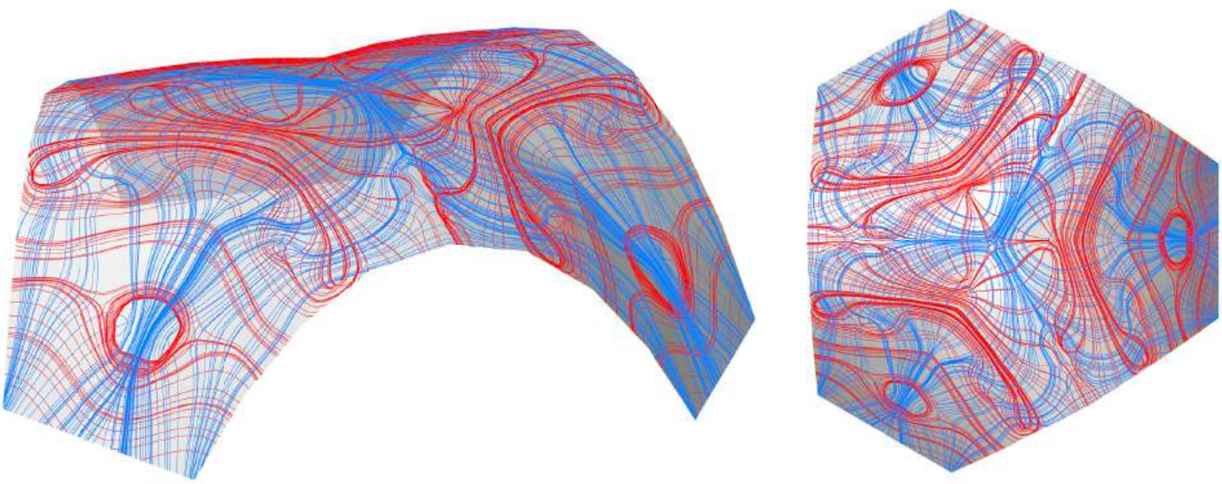
Utilization Diagram



Height Diagram



Force Flow Diagram



Principal Strees Lines Diagram

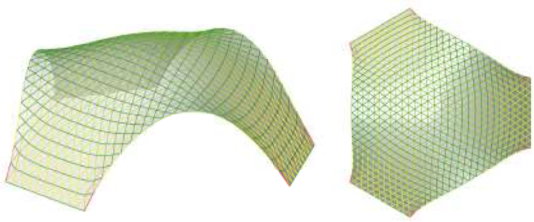
4.3_Planar Mesh: Best mesh tessellation

Tessellation matter, depending how the mesh is created the result is different, it is not just about the resolution; it is about how to distribute the nodes in the mesh, which must be the direction of the edges.

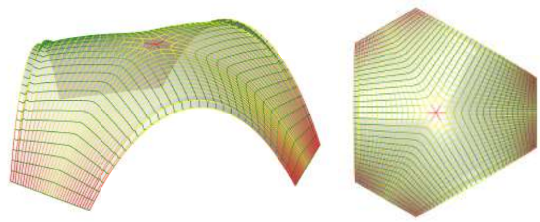
As seen before in those 3 different meshing test every tessellation gives you a different result. So as said before, knowing what result is wanted, some meshes have been created to see which one gives us the best result. All with similar loads, strength and

The tessellations tested would be: an equilateral triangular mesh, triangular mesh from a brep allowing manifold edges (karamba component), a mesh from a radial grid, two deluanay meshes from random distributed points, a quad mesh from a square grid, a distorted quad-mesh following the directions that will be needed for the later tessellation for the origami.

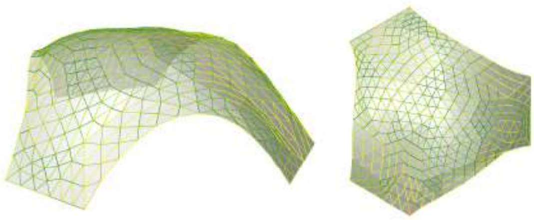
See:



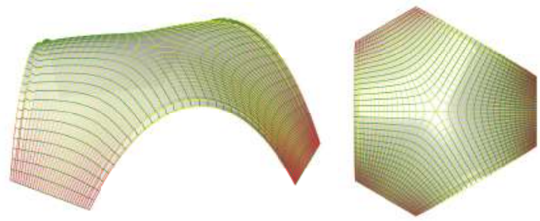
"Mesh Table 01_Triangular Mesh"



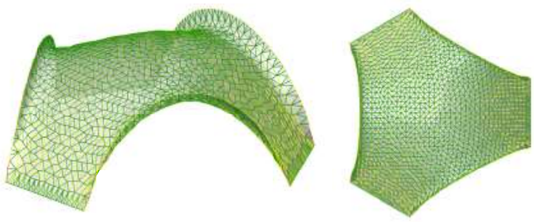
"Mesh Table 10_High resolution Quad Mesh"



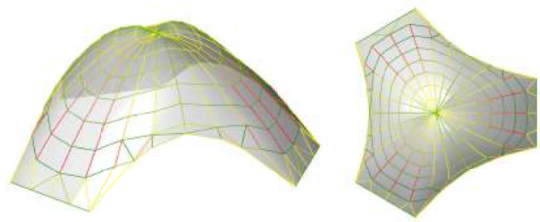
"Mesh Table 20_Random points Mesh"



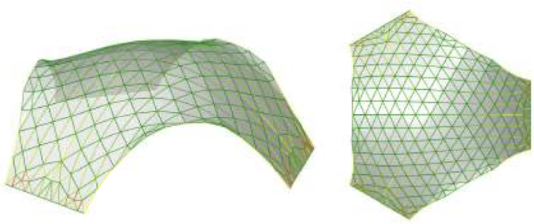
"Mesh Table 21_Catmull-Clark Mesh"



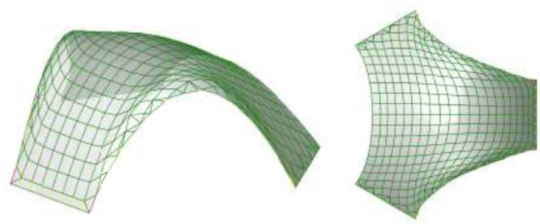
"Mesh Table 22_Brep to Mesh (0.5m edge)"



"Mesh Table 23_Radial Mesh"



"Mesh Table 24_Rotated triangle Mesh"

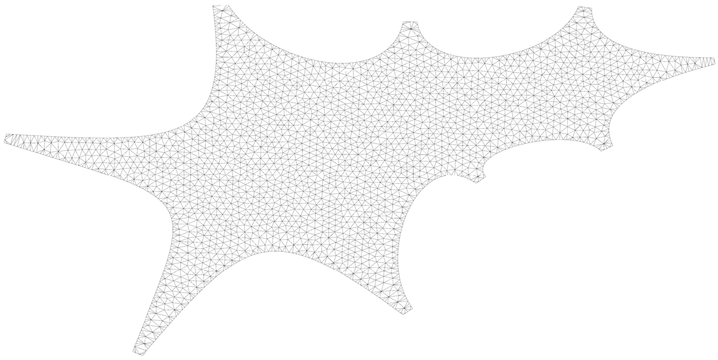


"Mesh Table 25_Squares Quad Mesh"

4.3.1_ Other tessellations (karamba / RhinoVault)

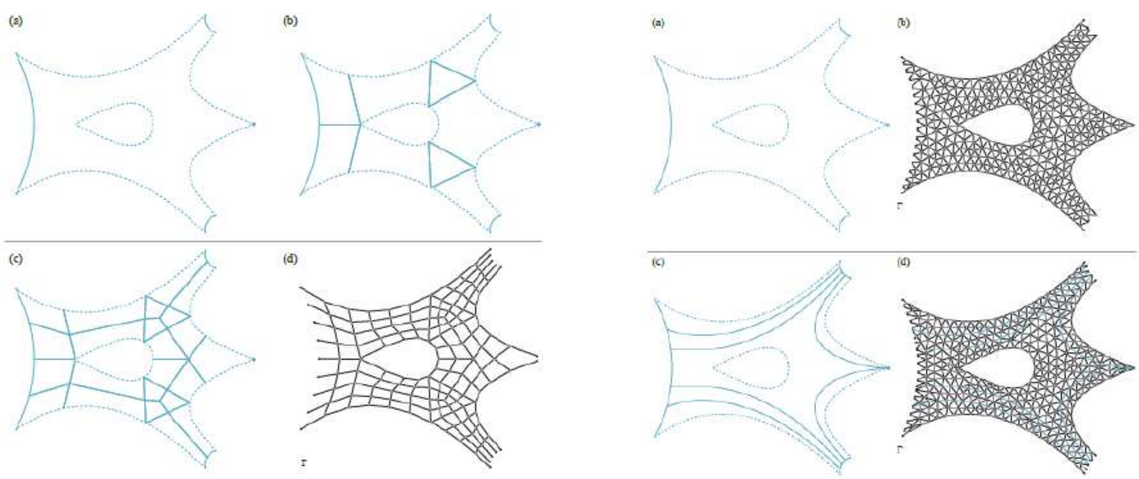
Plugins like karamba or rhinoVault propose different methods to create the mesh for the form finding.

Karamba's proposed method doesn't take care about how to mesh, they introduce a bred to the algorithm and with their component "brep to mesh", they set the mesh resolution desired, the edge refinement factor and the smoothness. This component doesn't tessellates with any clear structure.



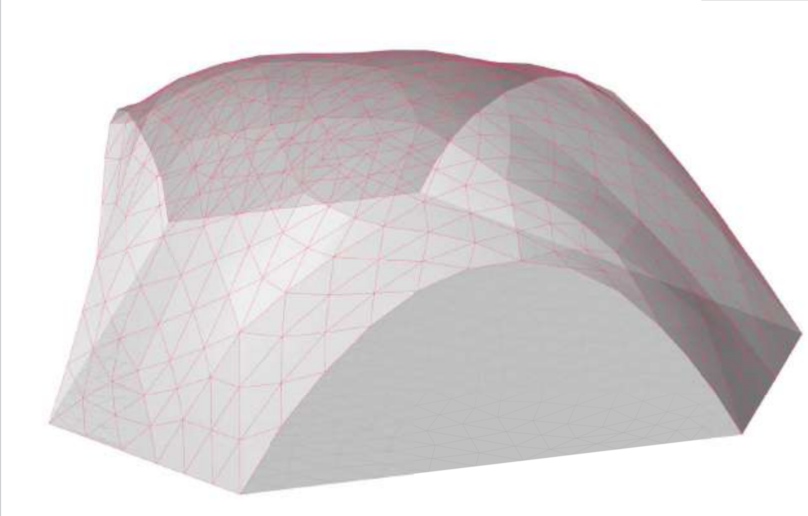
2D Mesh of the Karamba FSFF example

On the other hand, for RhinoVault, Ripperman propose 2 ways of making the mesh: quad-mesh and triangular mesh. However, they are two intentioned ways of creating the mesh, the automatic tessellations doesn't work; the best way are creating them with guidelines. For the quad-mesh, the edges must be drawn according to an anticipated "force flow", using guidelines and taking into account which edges have the supports, the shape must be subdivided by the user in triangular, quadrilateral or pentagonal patches; and then subdivide the patches to have exclusively quadrilateral patches. To have a better approximation of the equilibrium of the shell, there must be a good agreement between the nodes and the centroid. For the triangular mesh, they propose two ways: triangulating the quad-mesh, or a Delaunay mesh constrined first by the boundaries that have supports and those that doesn't, then adding a constrain including edges along defined load path.



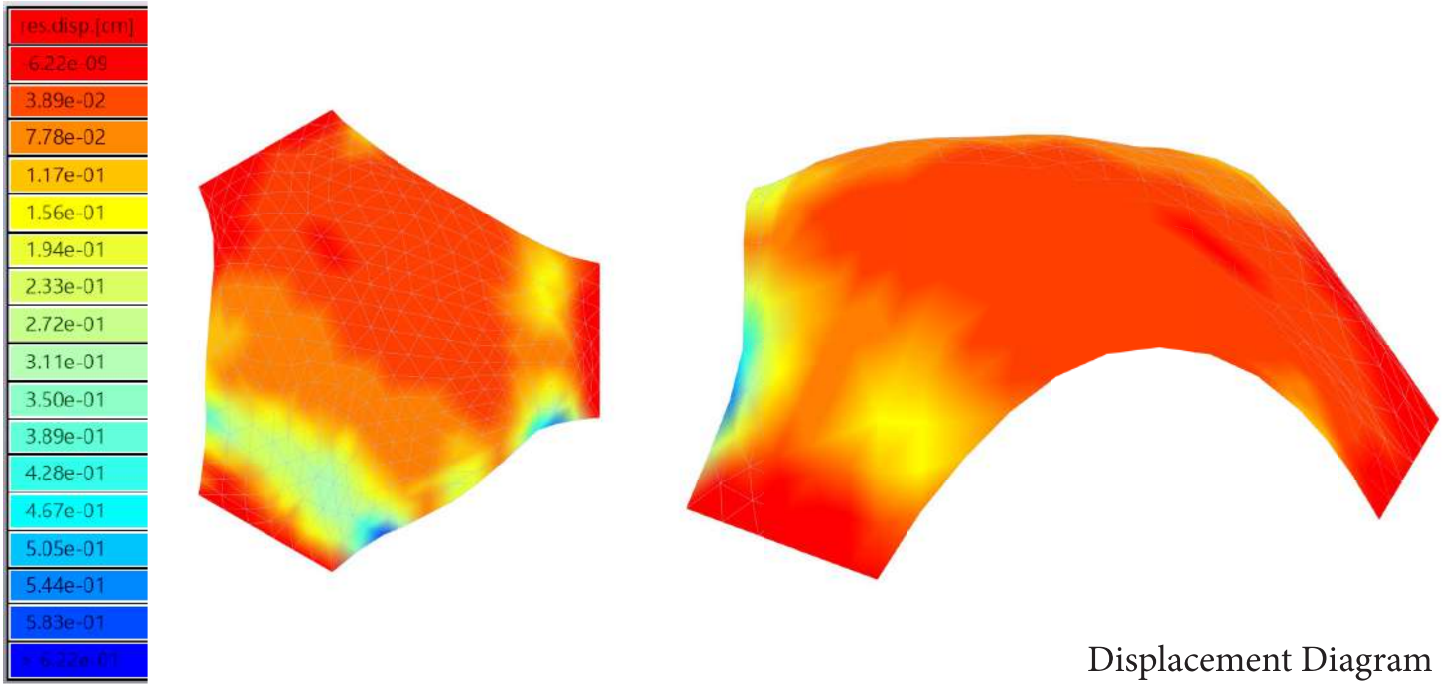
Rhinovault Quad Mesh and triangular mesh (images from the Phd: *"Funicular Shell Design _Matthias Rippman"*)

MESH TABLE: 20_Random points Mesh

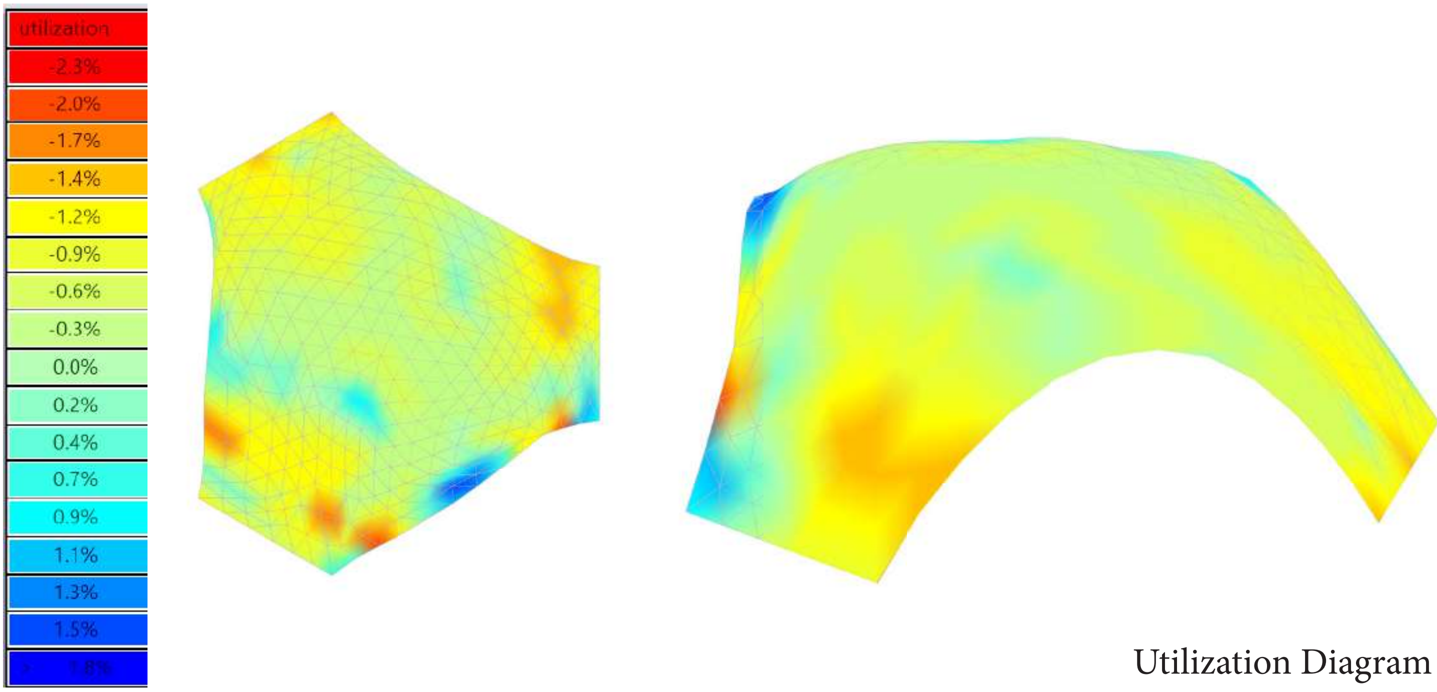


Properties

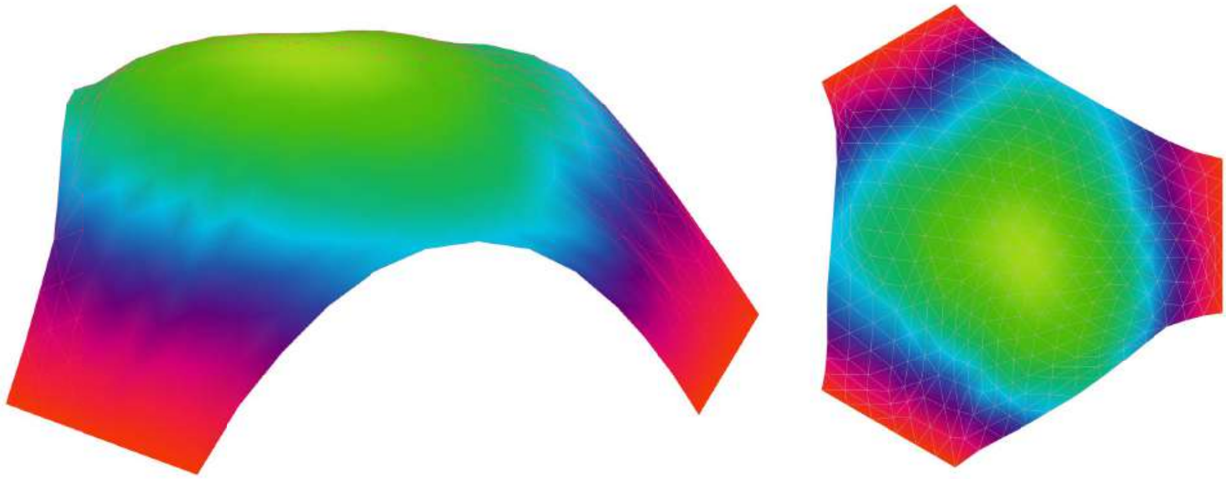
- Area: *438.535m2*
- Faces: *630*
- Vertices: *700*
- Edges: *972*
- Perimetral Edges: *54*
- Supports: *21*
- Max. Height: *9.071m*
- Thickness: *3cm*
- Forces: *Gravity*



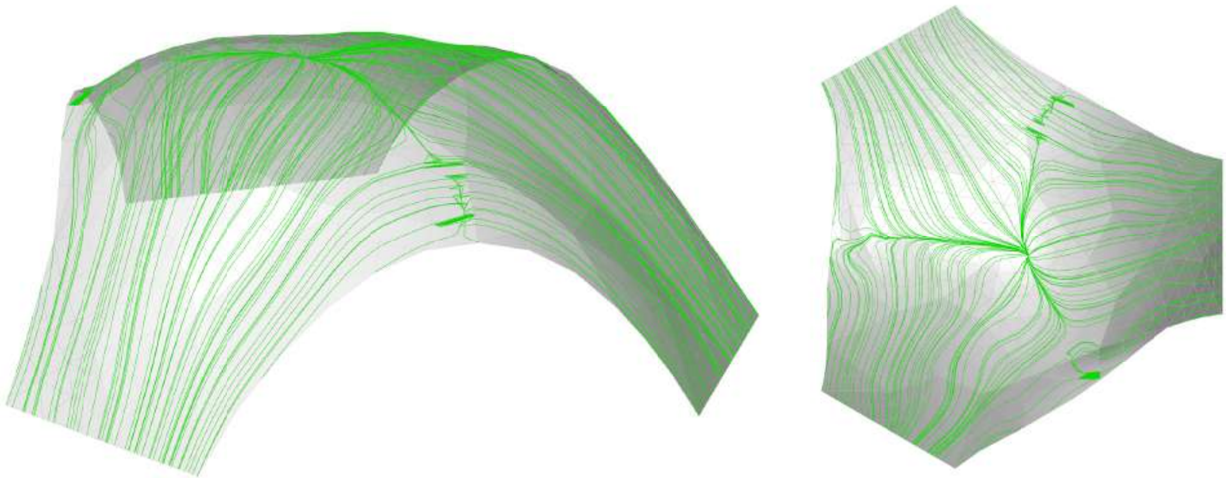
Displacement Diagram



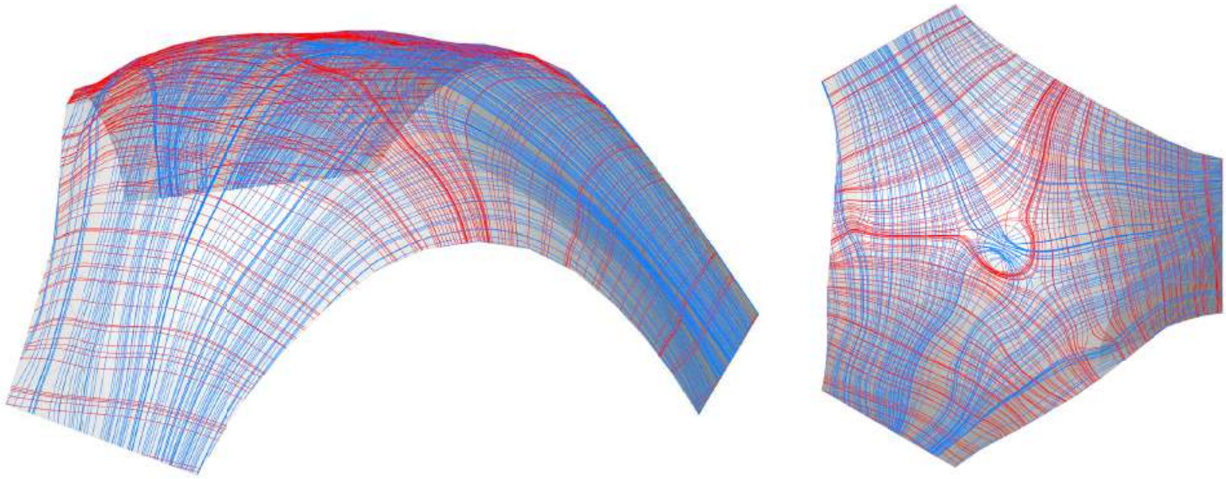
Utilization Diagram



Height Diagram

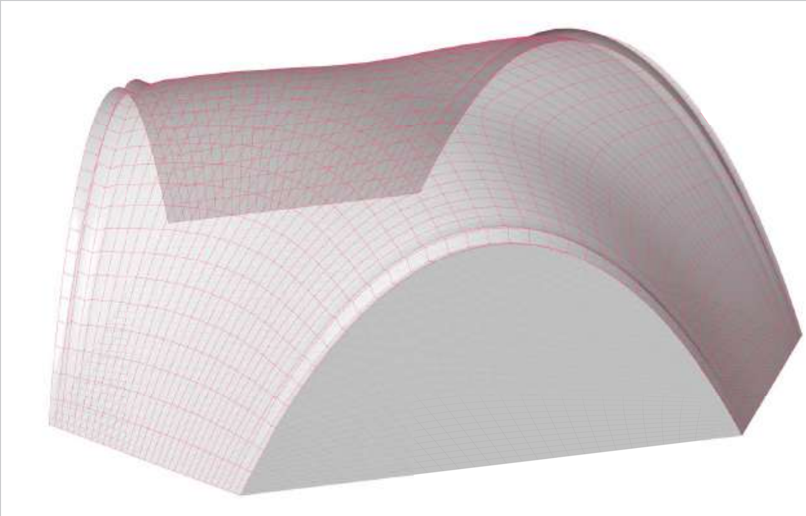


Force Flow Diagram



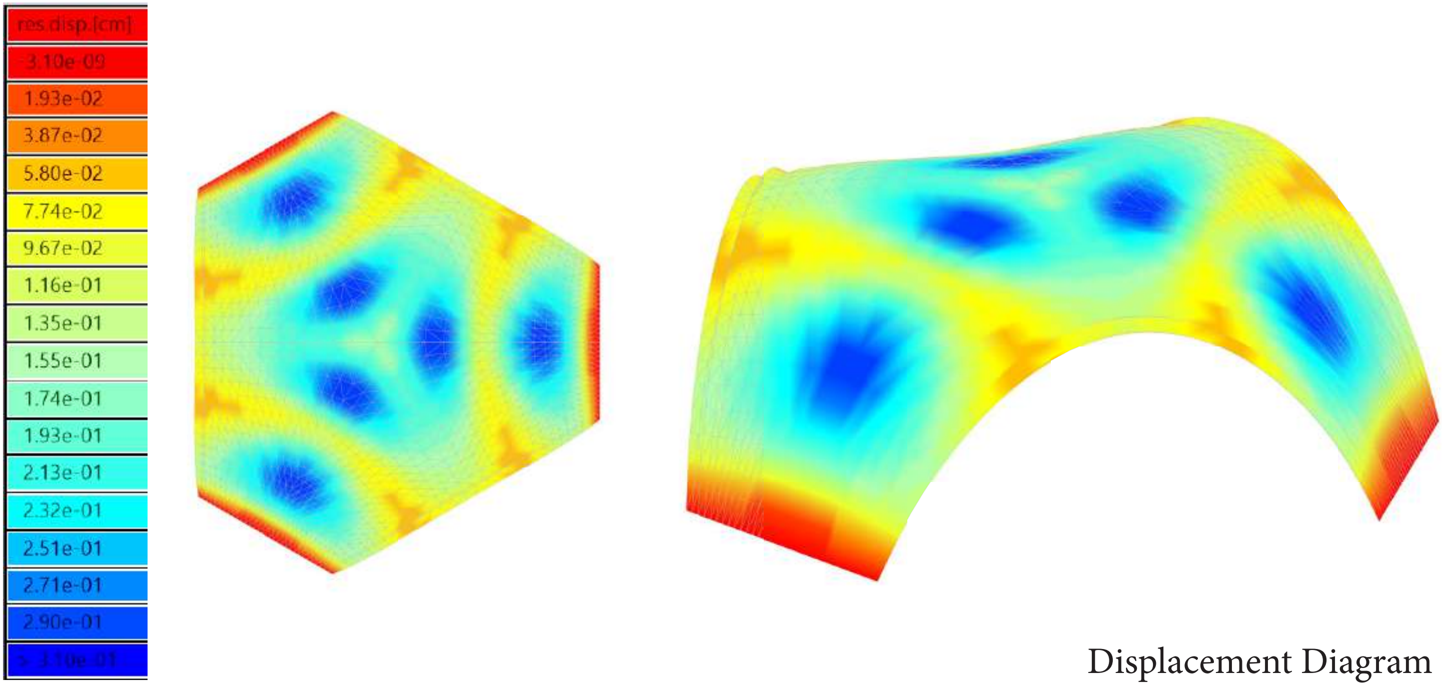
Principal Strees Lines Diagram

Mesh Table: 21_Catmull-Clark subdivision Mesh

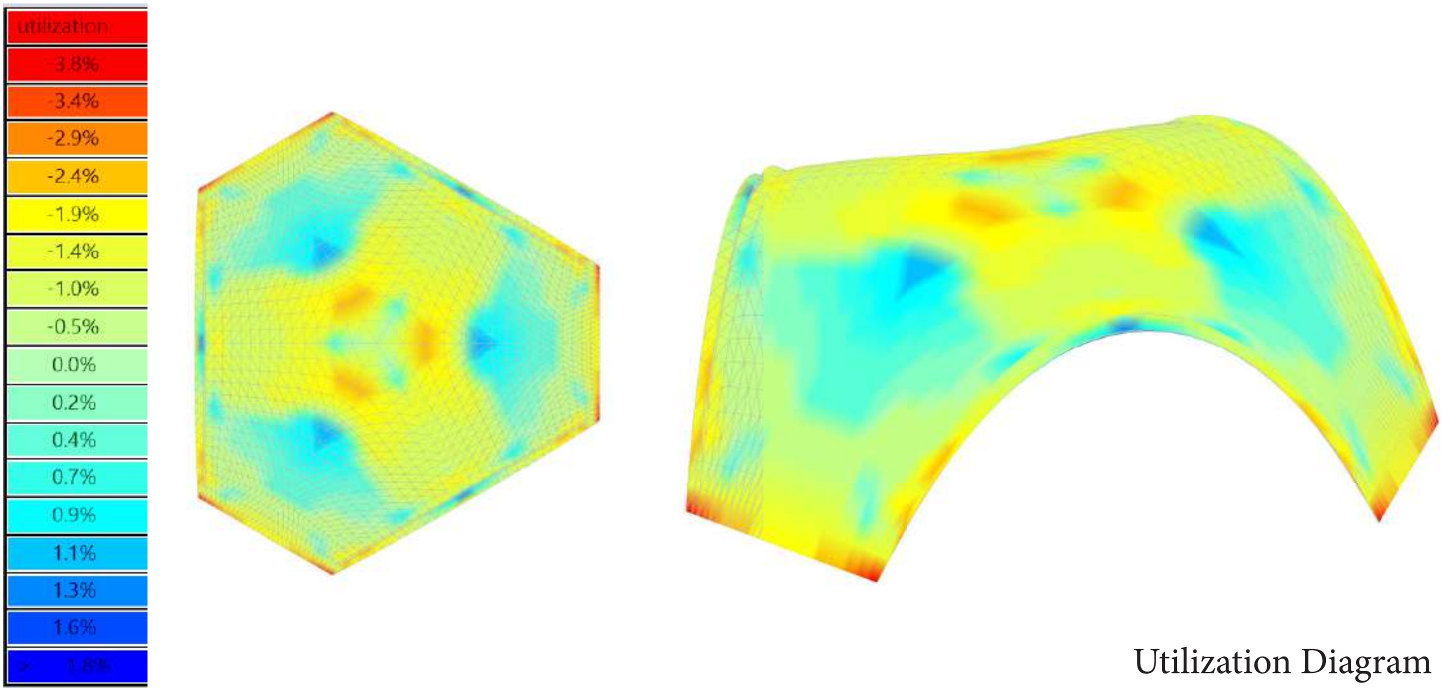


Properties

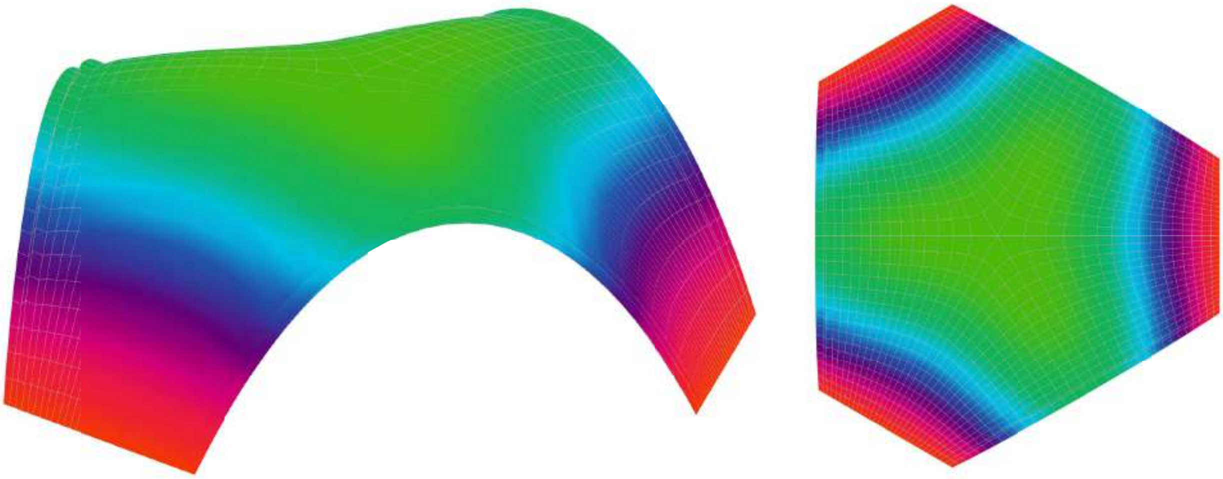
Area: *474.5588m2*
Faces: *1536*
Vertices: *1633*
Edges: *3168*
Perimetral Edges: *192*
Supports: *99*
Max. Height: *8.277m*
Thickness: *3cm*
Forces: *Gravity*



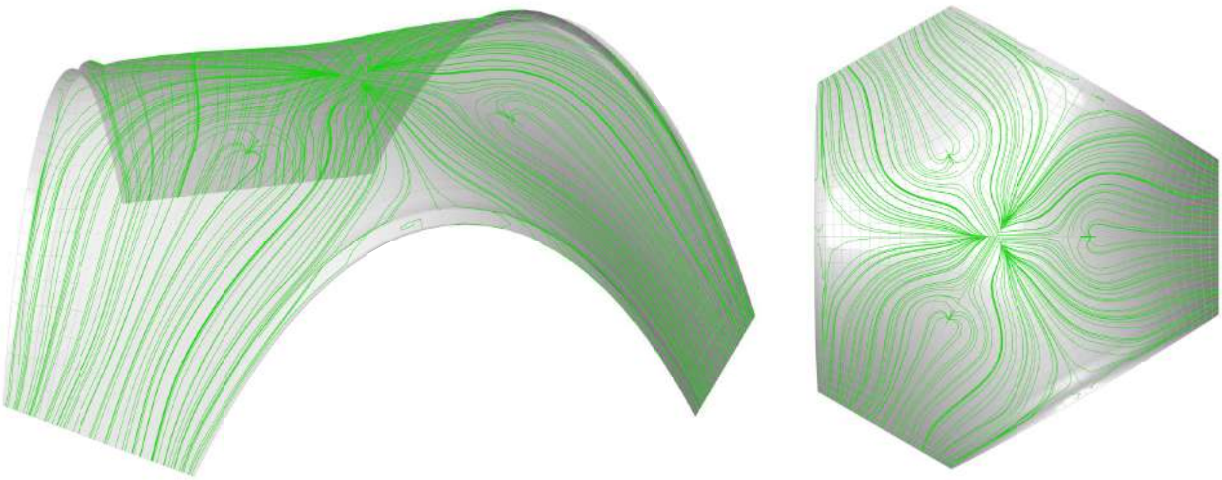
Displacement Diagram



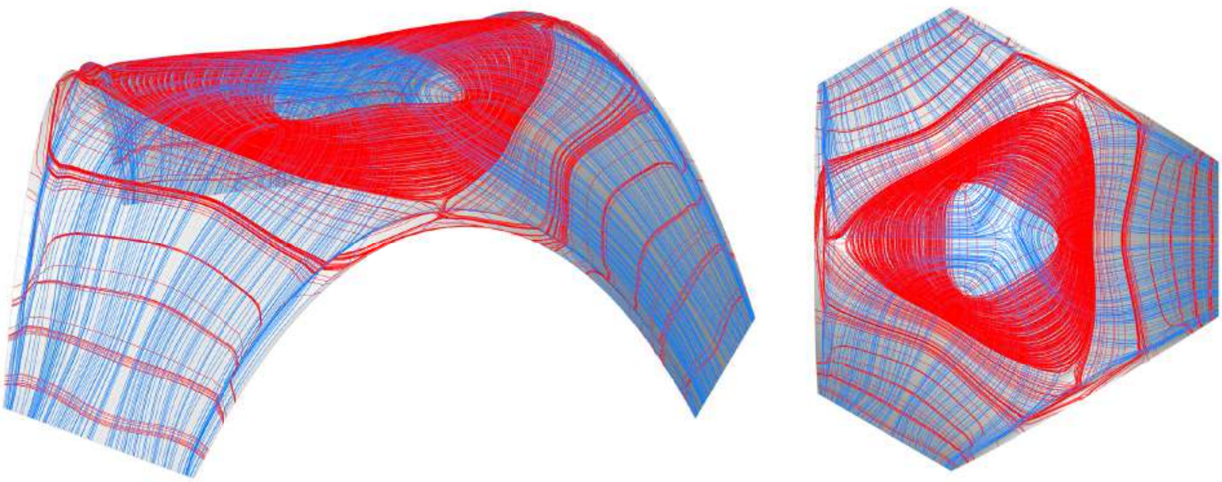
Utilization Diagram



Height Diagram

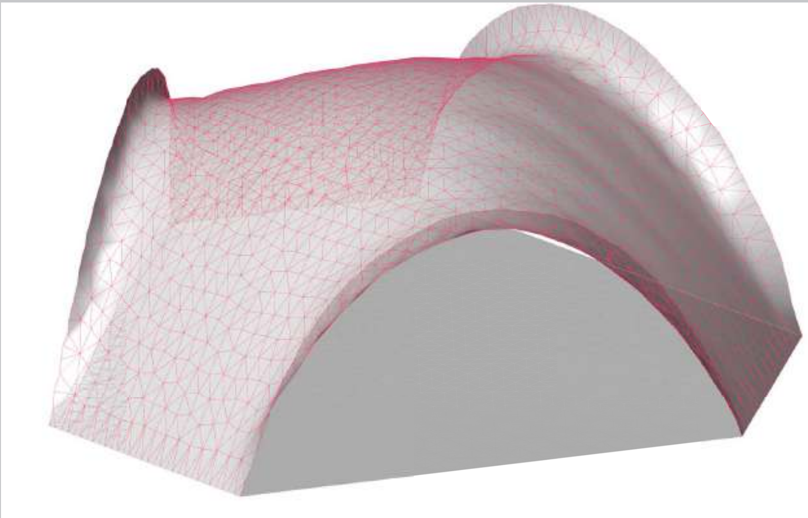


Force Flow Diagram



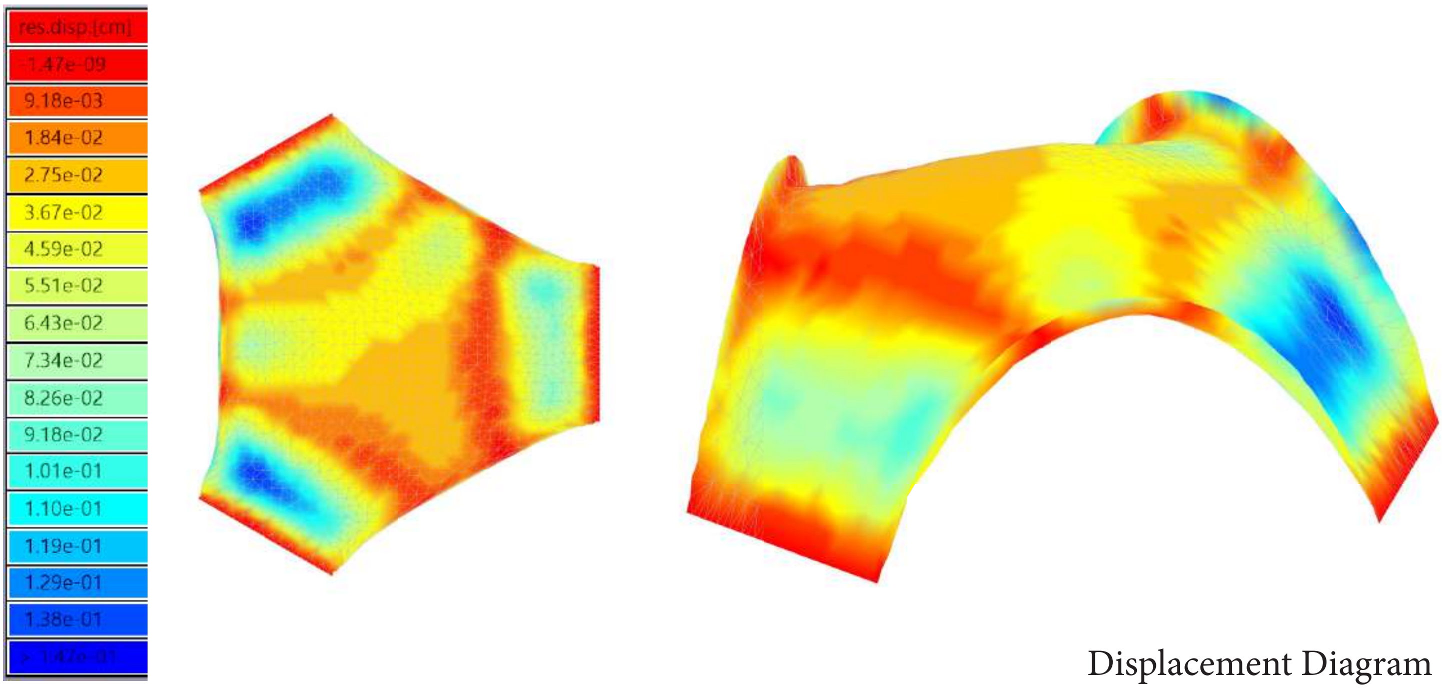
Principal Strees Lines Diagram

Mesh Table: 22_Brep to Mesh (0.5m edge)

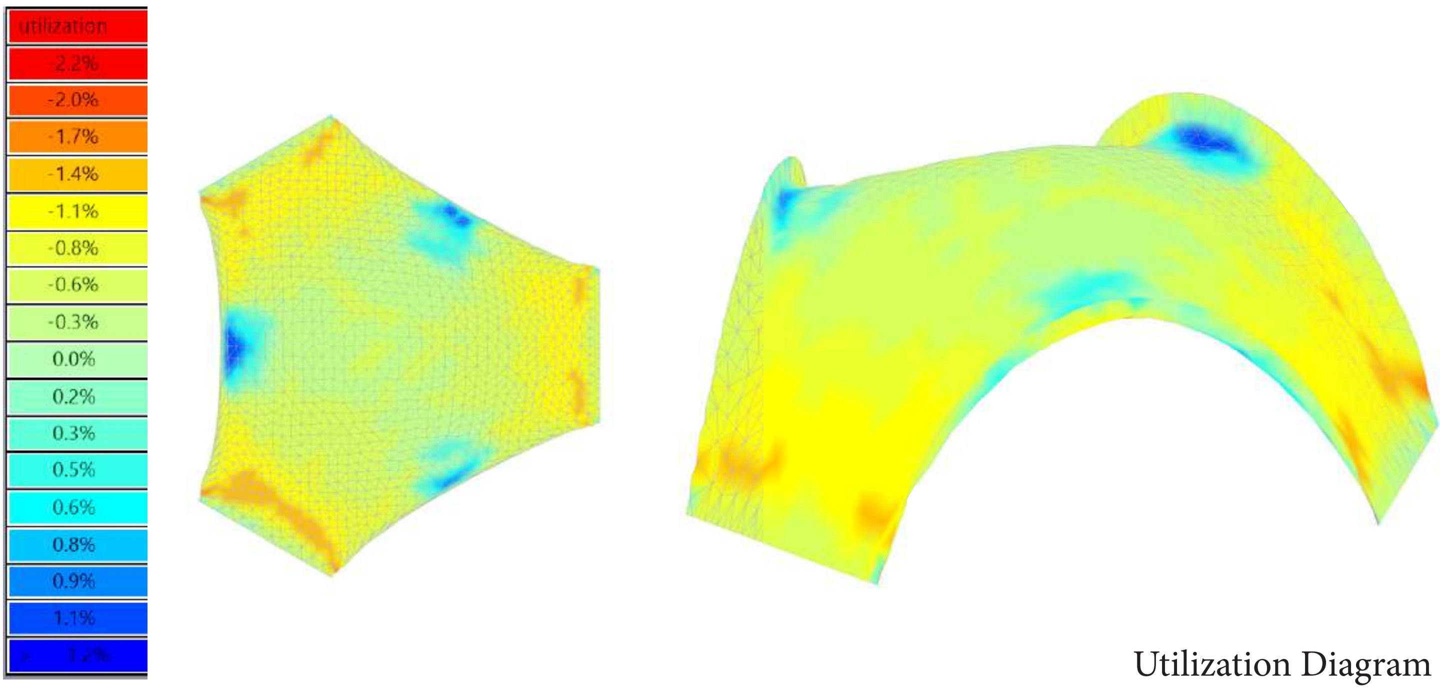


Properties

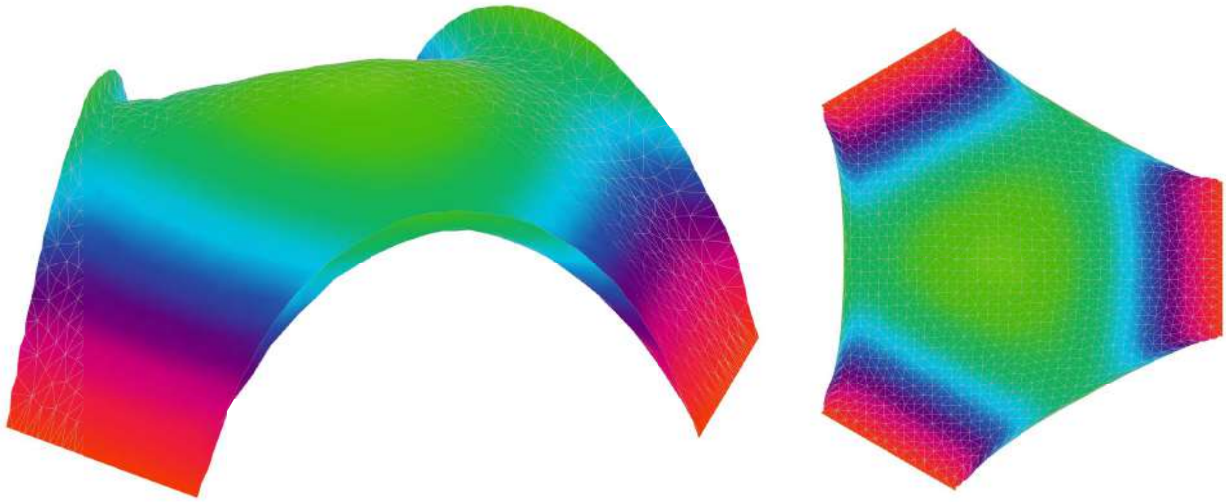
- Area: *440.15m2*
- Faces: *2761*
- Vertices: *1521*
- Edges: *4281*
- Perimetral Edges: *279*
- Supports: *96*
- Max. Height: *8.699m*
- Thickness: *3cm*
- Forces: *Gravity*



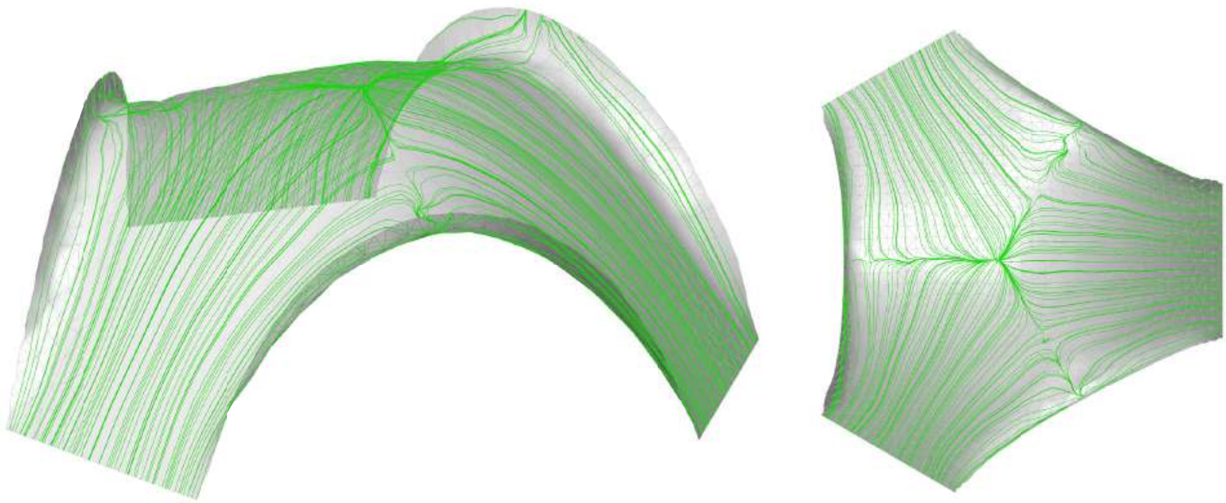
Displacement Diagram



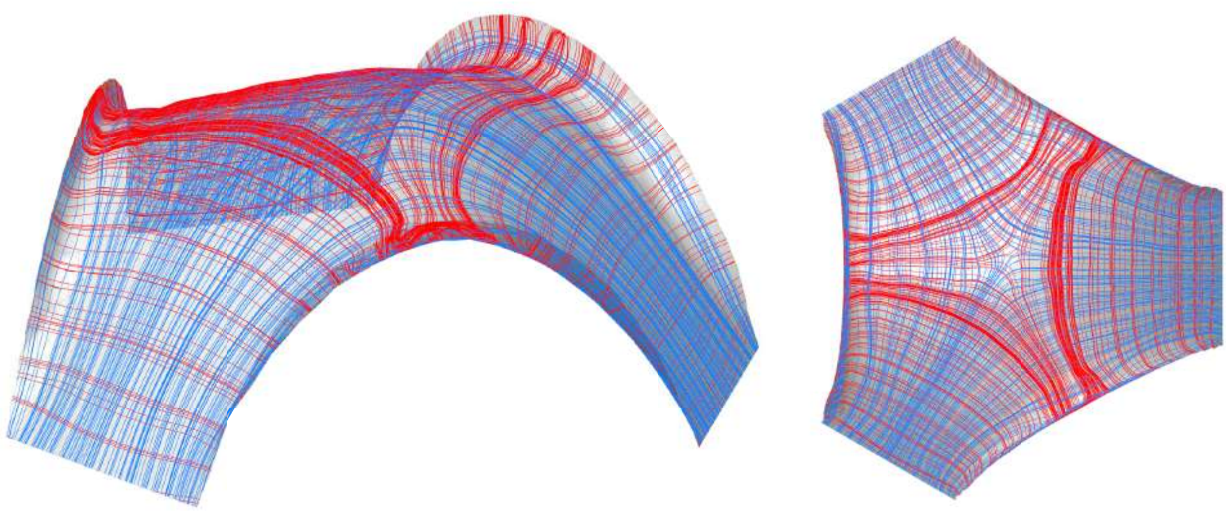
Utilization Diagram



Height Diagram

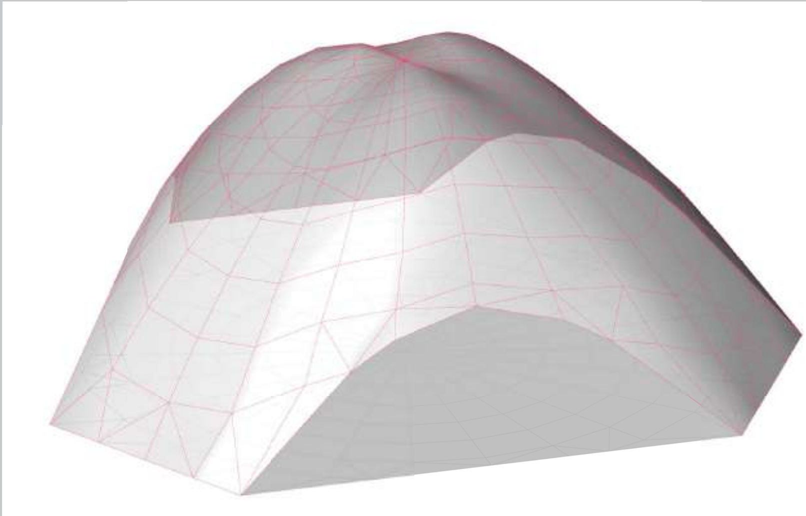


Force Flow Diagram



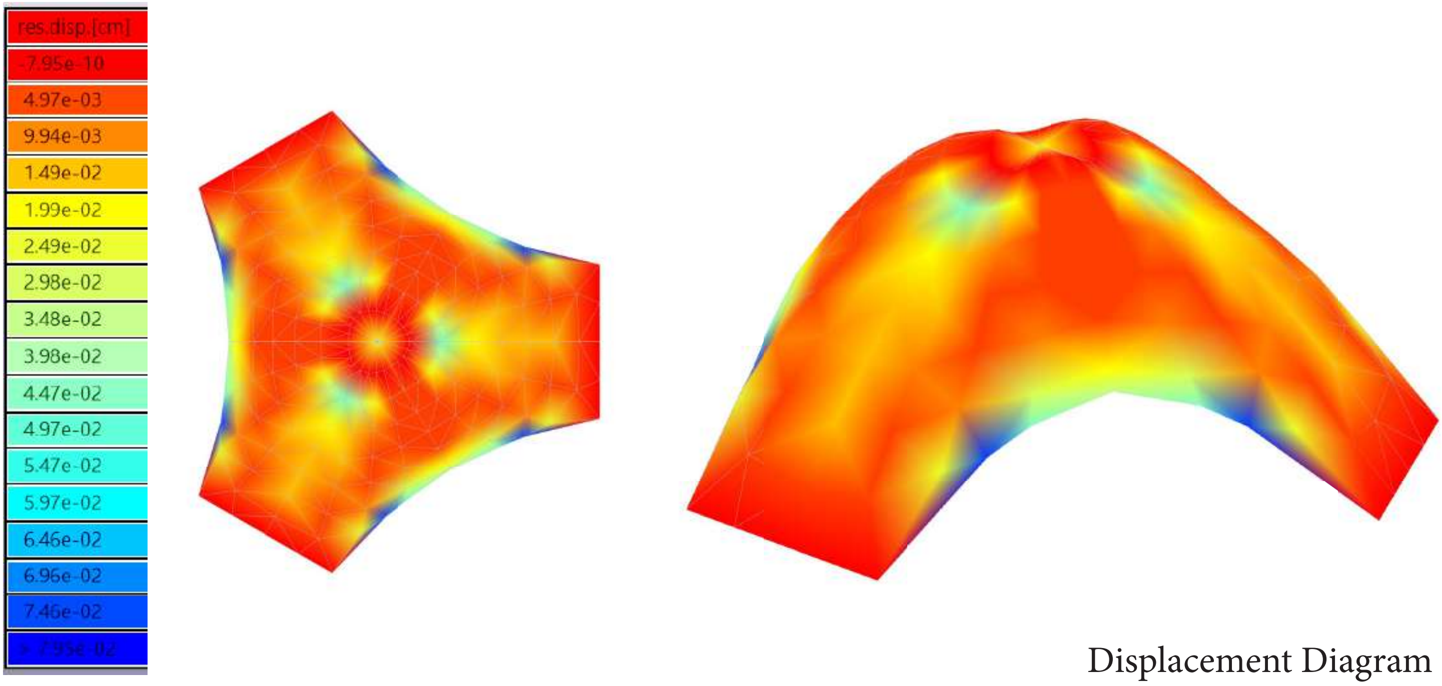
Principal Strees Lines Diagram

Mesh Table: 23_Radial Mesh

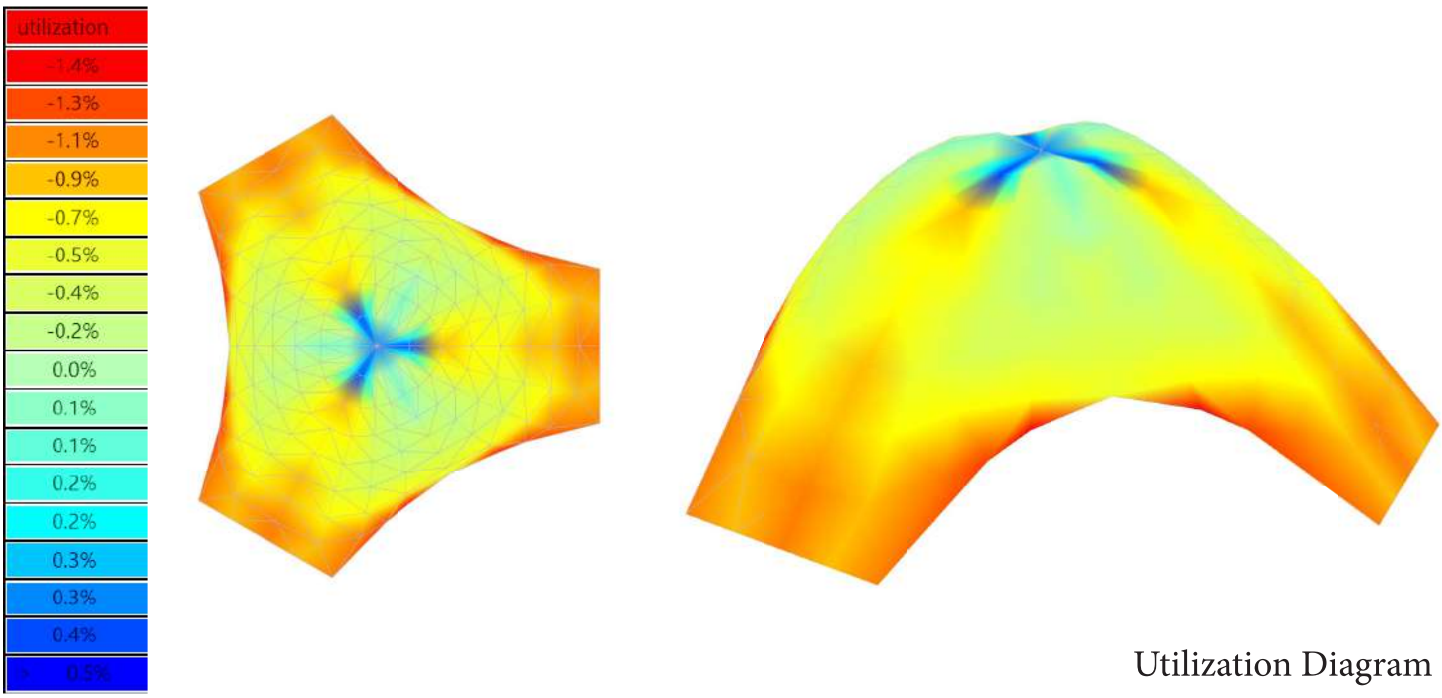


Properties

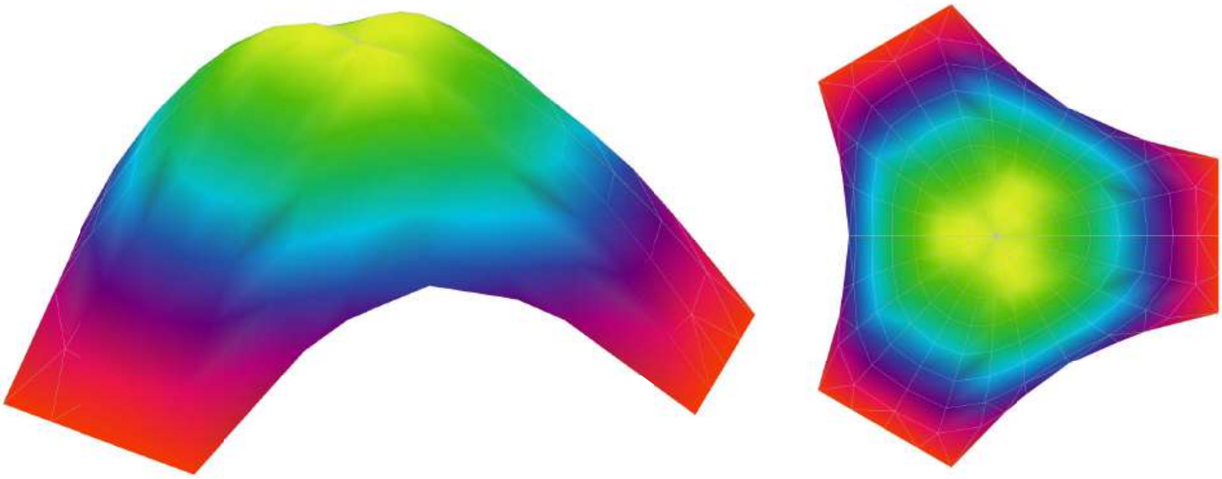
Area: *442.24m2*
Faces: *216*
Vertices: *190*
Edges: *405*
Perimetral Edges: *30*
Supports: *15*
Max. Height: *9.74m*
Thickness: *3cm*
Forces: *Gravity*



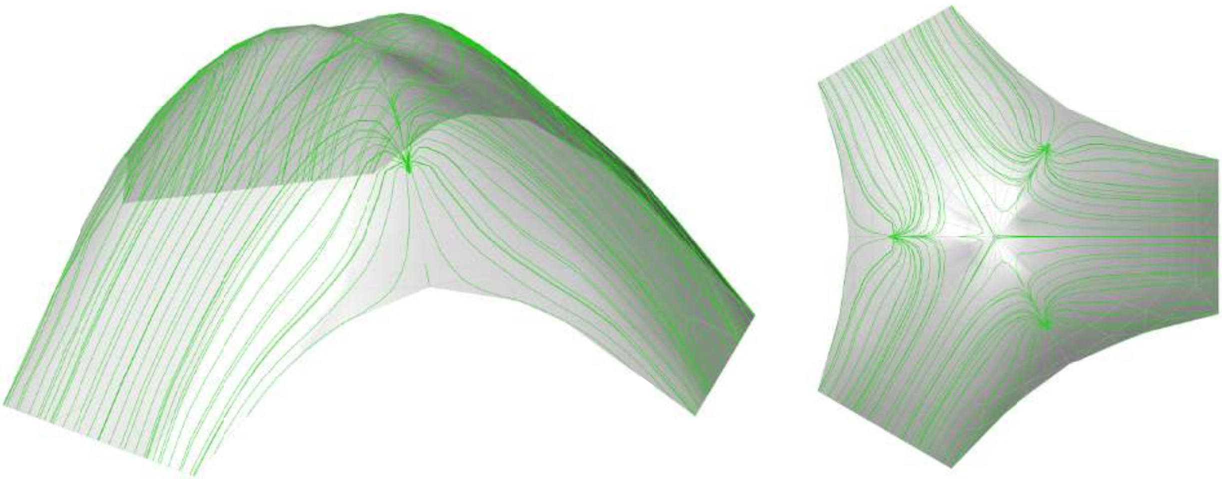
Displacement Diagram



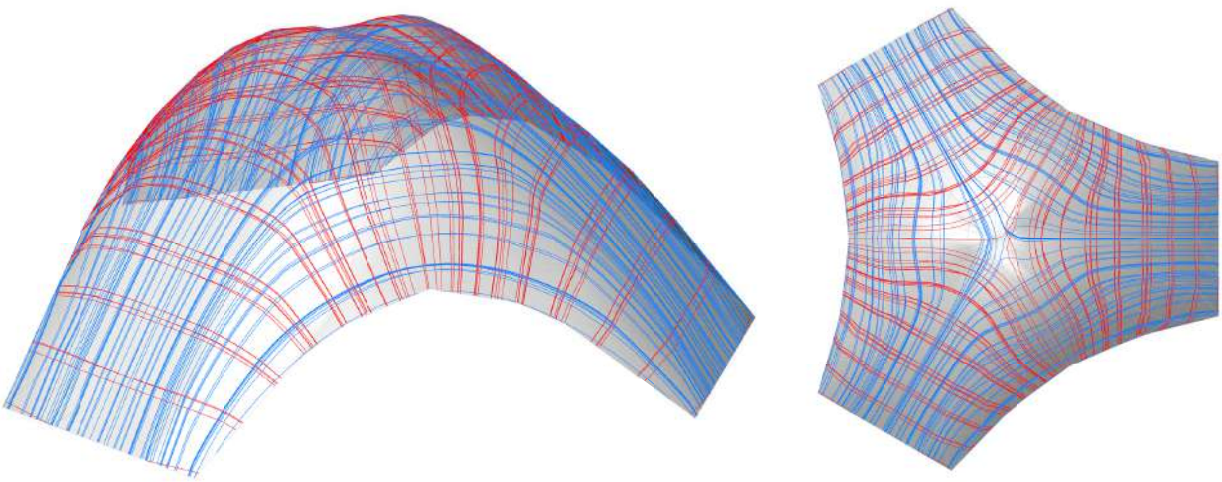
Utilization Diagram



Height Diagram



Force Flow Diagram

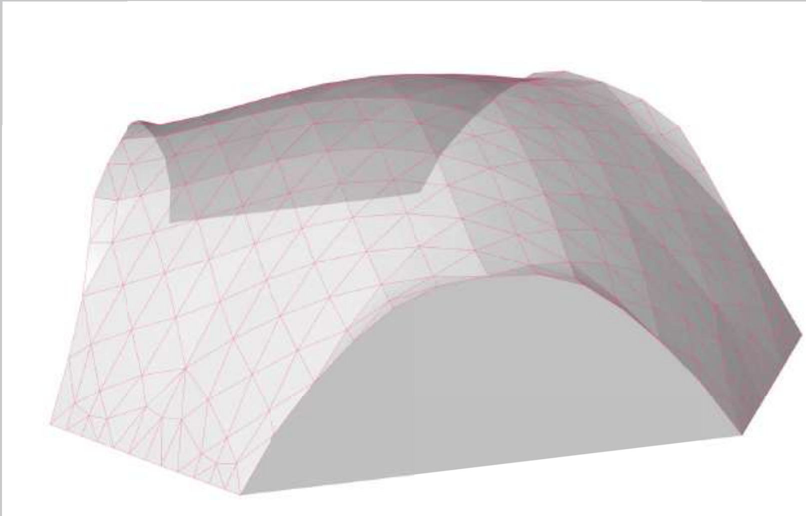


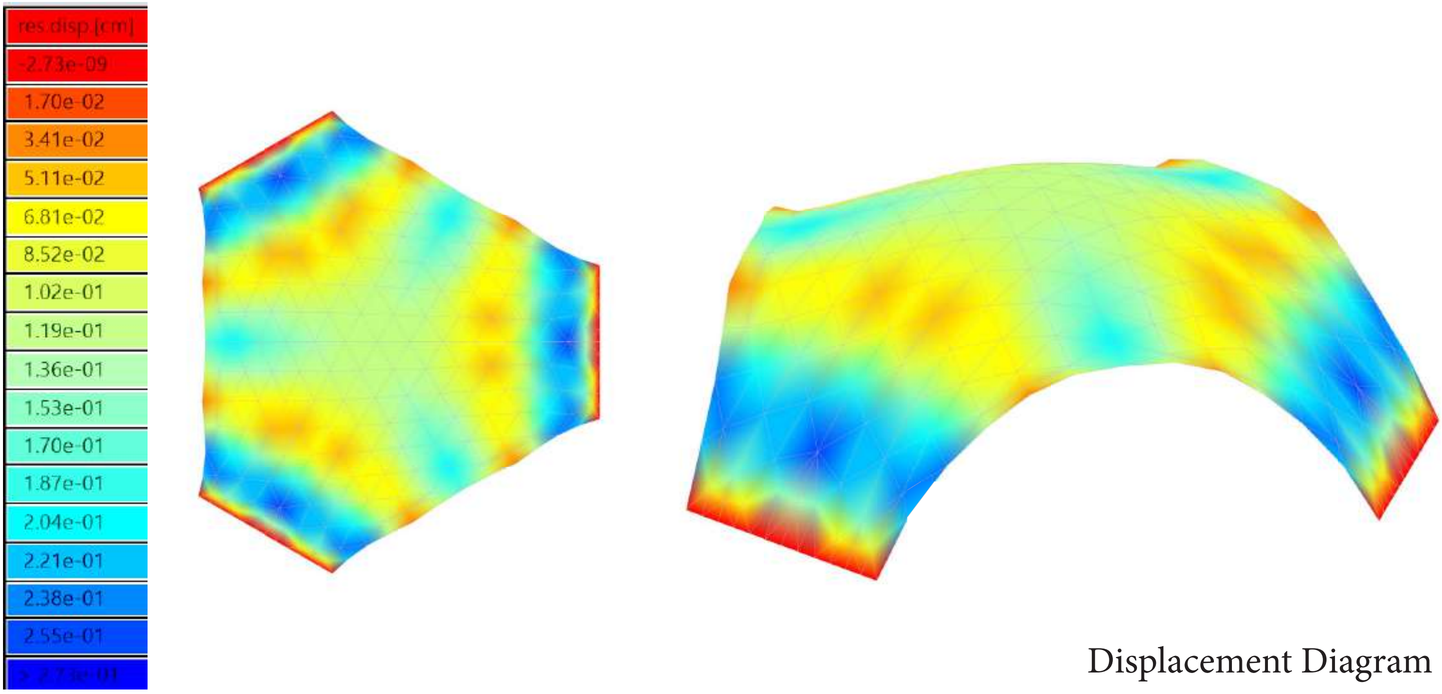
Principal Strees Lines Diagram

Mesh Table: 24_Rotated triangle Mesh

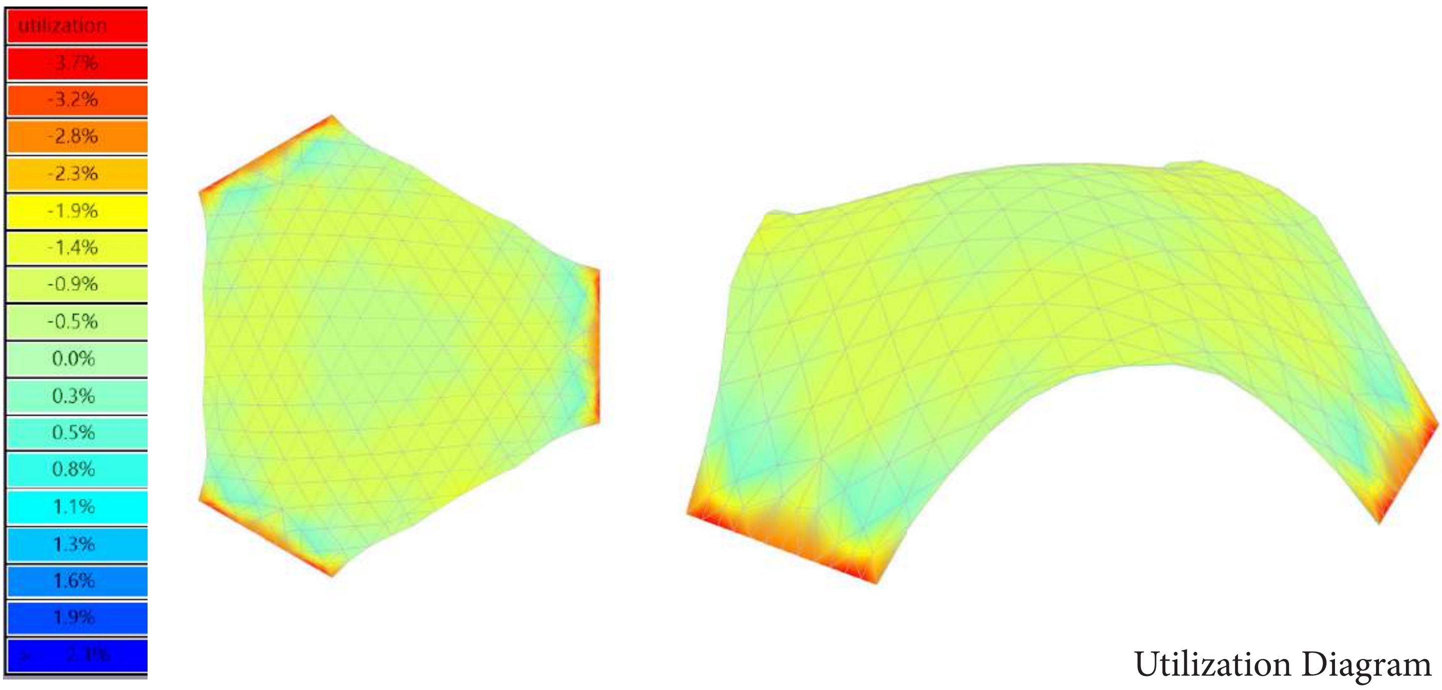
Properties

Area: *418.405m2*
Faces: *456*
Vertices: *684*
Edges: *720*
Perimetral Edges: *72*
Supports: *39*
Max. Height: *8.18m*
Thickness: *3cm*
Forces: *Gravity*

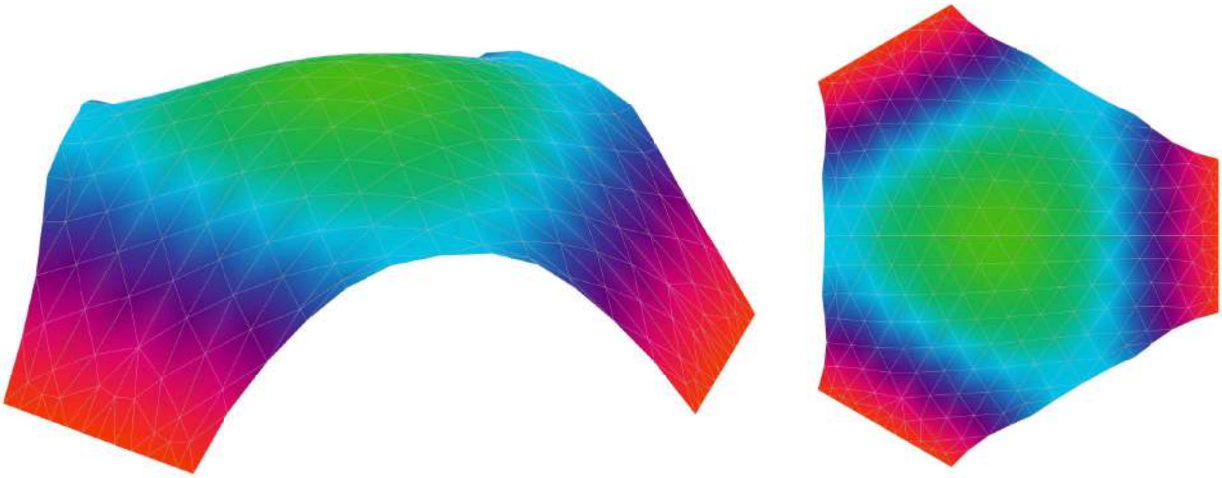




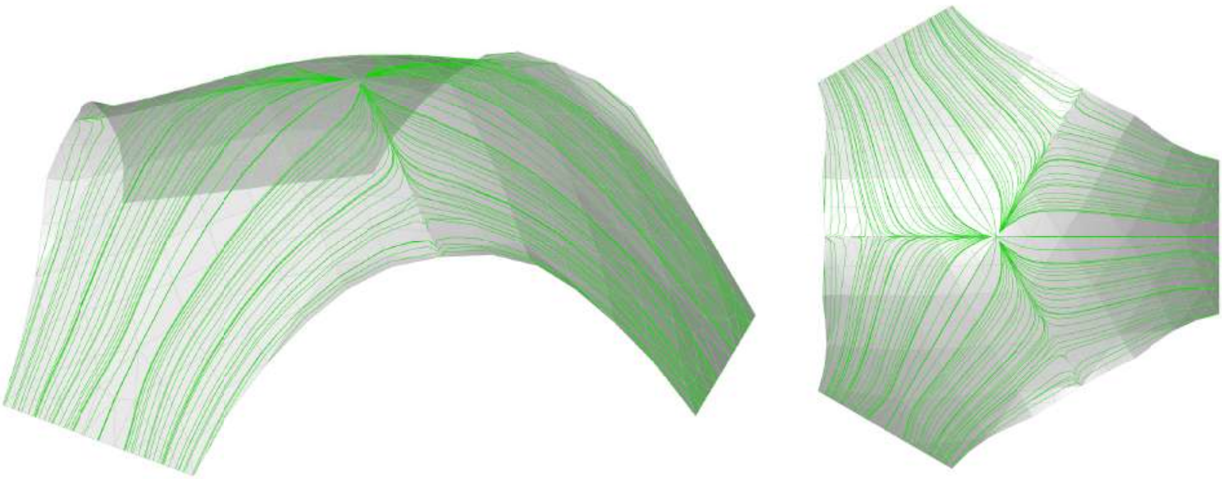
Displacement Diagram



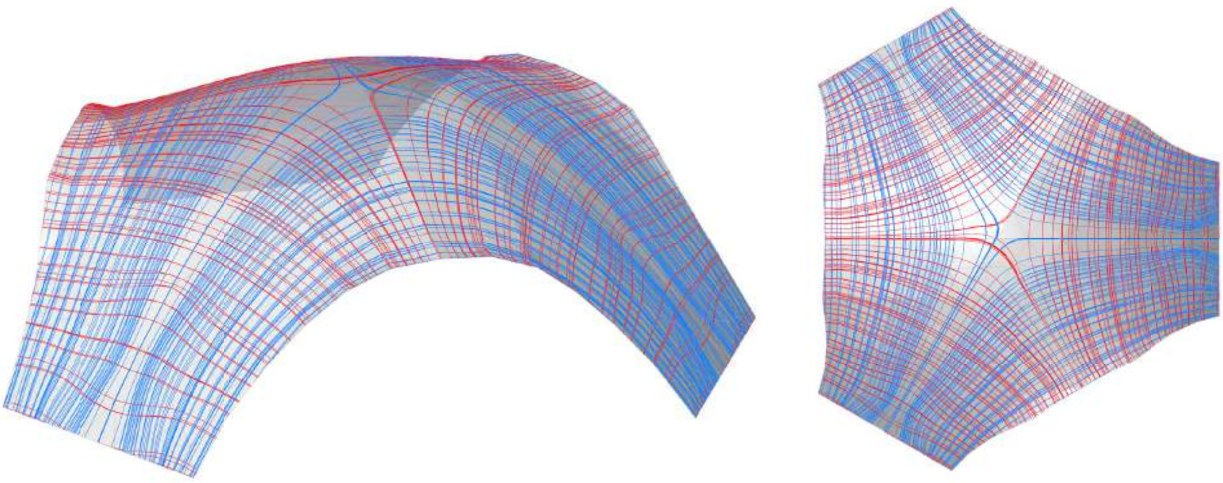
Utilization Diagram



Height Diagram

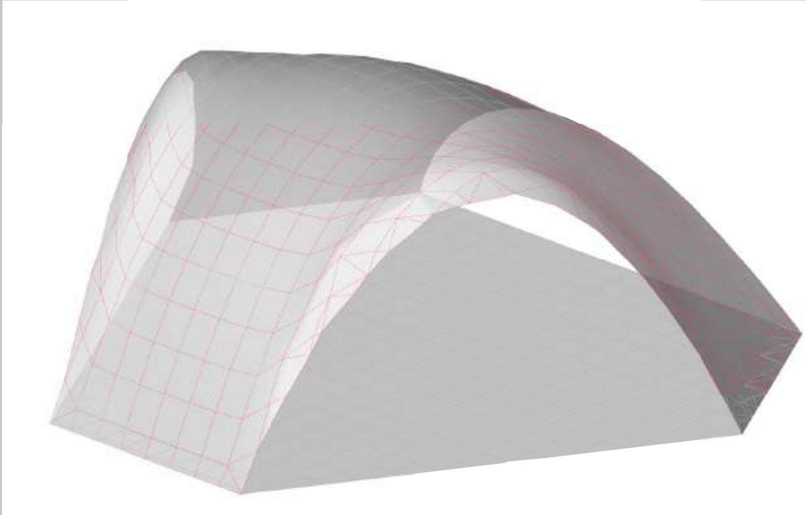


Force Flow Diagram



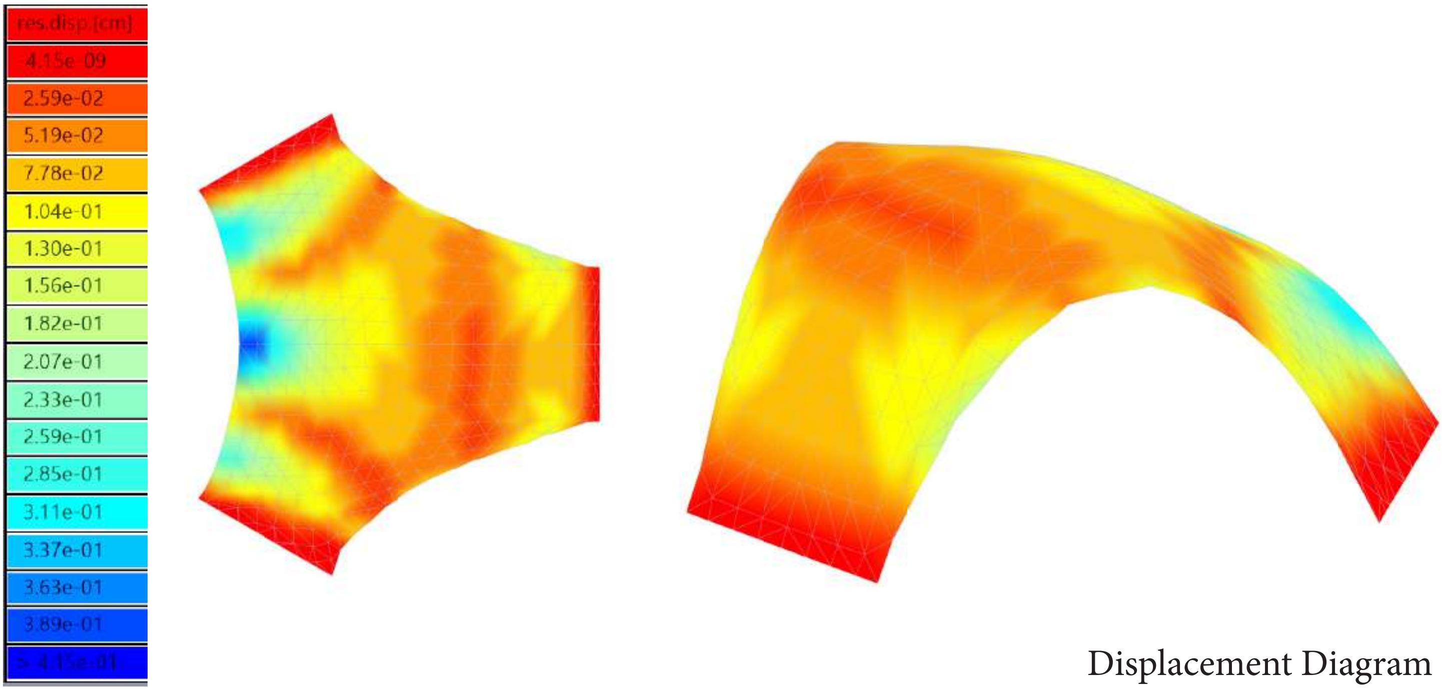
Principal Strees Lines Diagram

Mesh Table: 25_Squares Quad Mesh

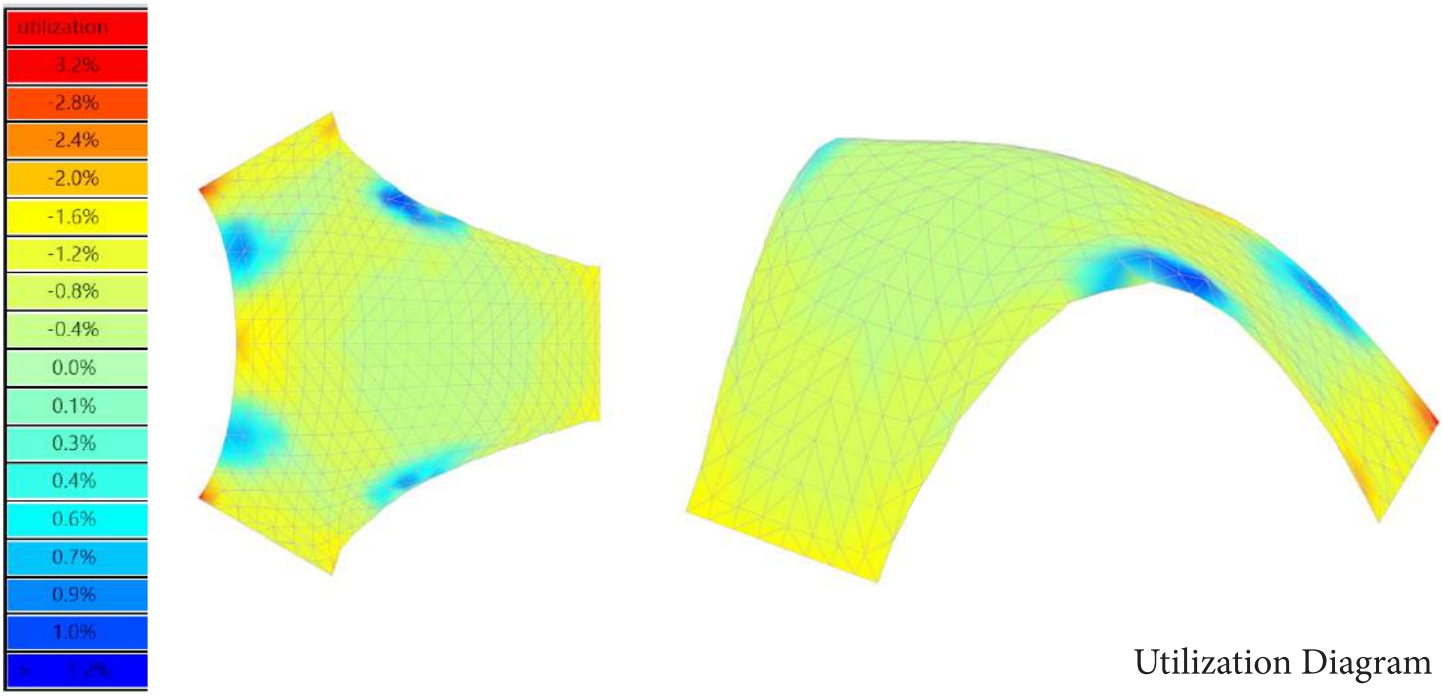


Properties

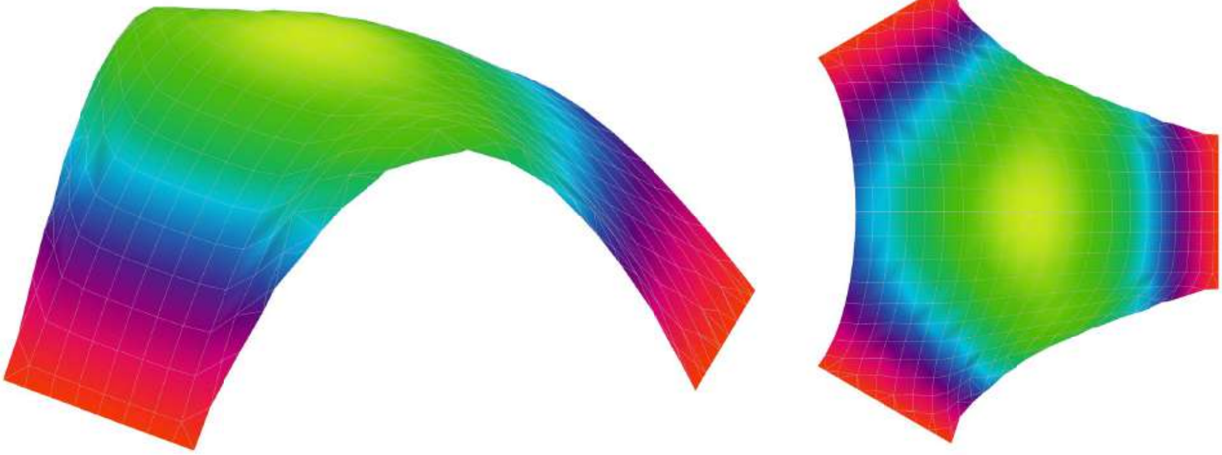
Area: *392.601m2*
Faces: *424*
Vertices: *420*
Edges: *843*
Perimetral Edges: *86*
Supports: *39*
Max. Height: *9.337m*
Thickness: *3cm*
Forces: *Gravity*



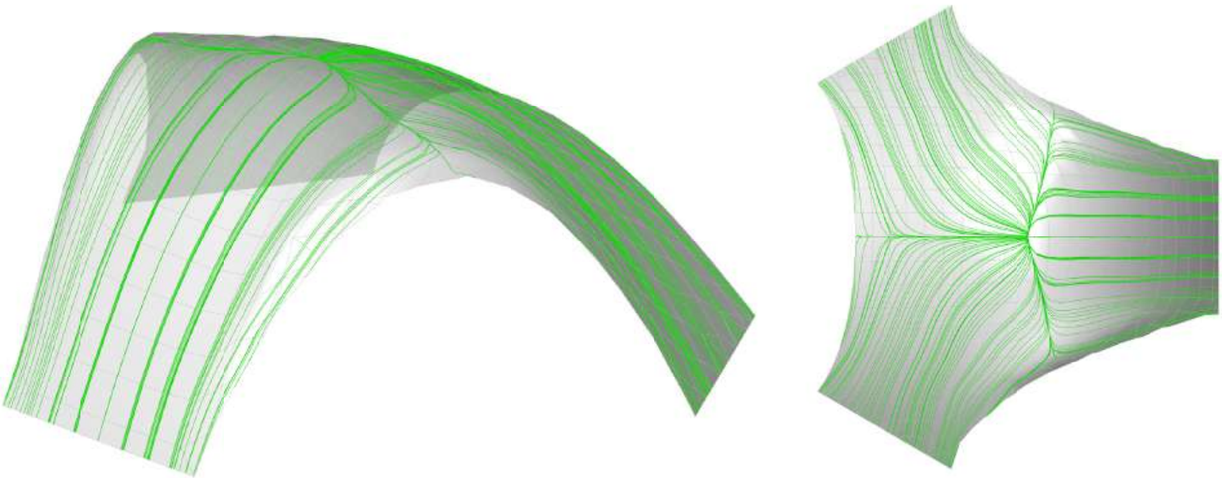
Displacement Diagram



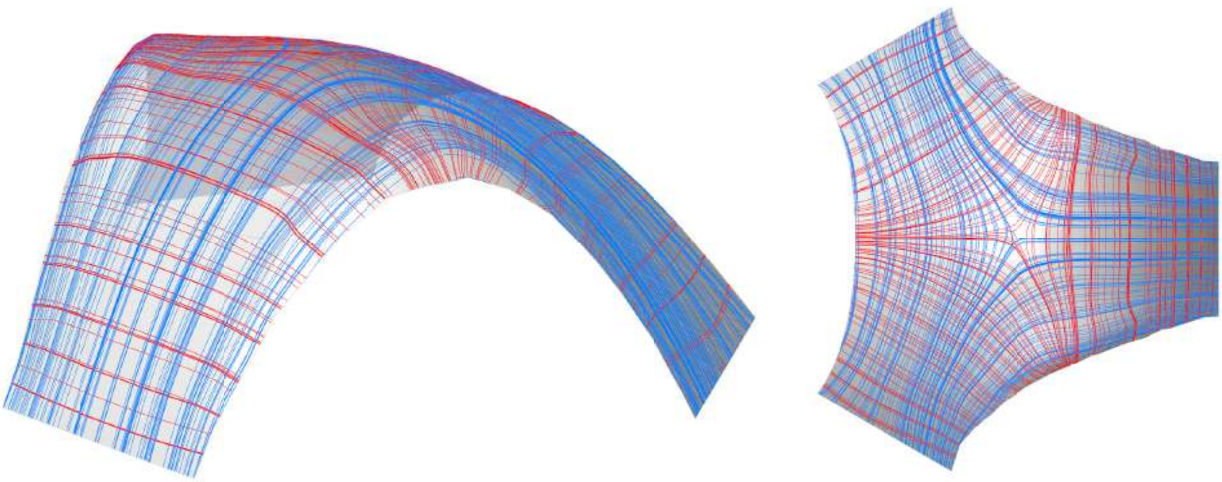
Utilization Diagram



Height Diagram



Force Flow Diagram

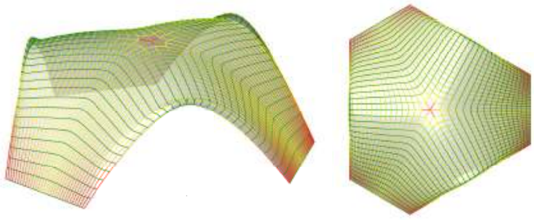


Principal Strees Lines Diagram

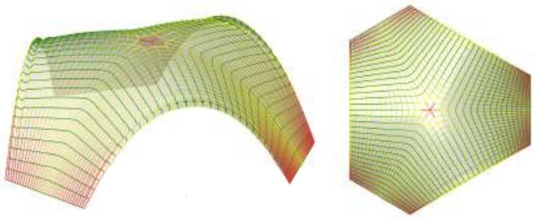
4.4_Strategy II: fixing the perimeter

Seeing the results, it can be observed that after the form finding process, the shape changes its perimeter, sometimes it's interesting when designing in plant to keep the projected perimeter or when you want to use the shell as a module in an array design. What's more, some papers suggest that the perimeter must be fixed in the form finding process to get a better result.

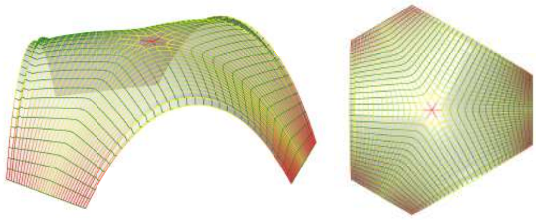
So here let's see the results of fixing the perimeter: first fixing the xy coordinates of the naked nodes, then allowing them to move along the line in the perimeter they are.



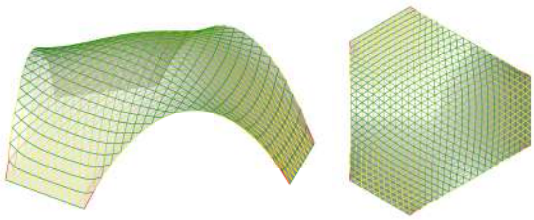
"Mesh Table 30_Perimerter XY fixed - Quad Mesh"



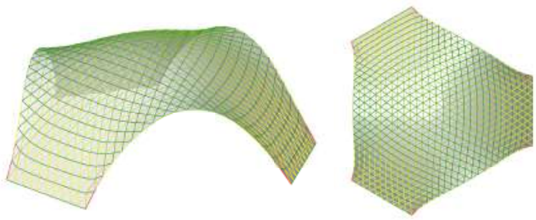
"Mesh Table 31_Perimerter fixed - Quad Mesh"



"Mesh Table 10_High resolution Quad Mesh"



"Mesh Table 32_Perimerter fixed - Triangle



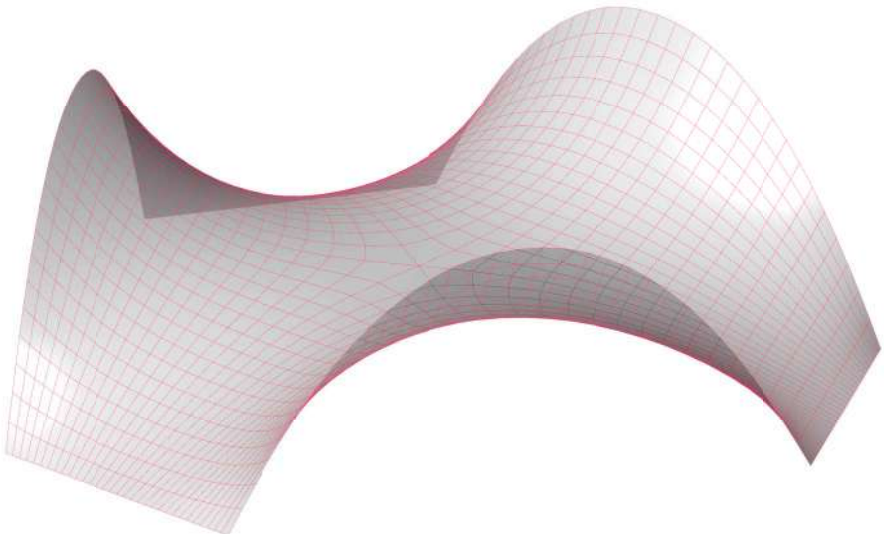
"Mesh Table 01_Triangular Mesh"

4.5_Post-strategy: “Minimal Surface Regulariza-tion(MSR)”

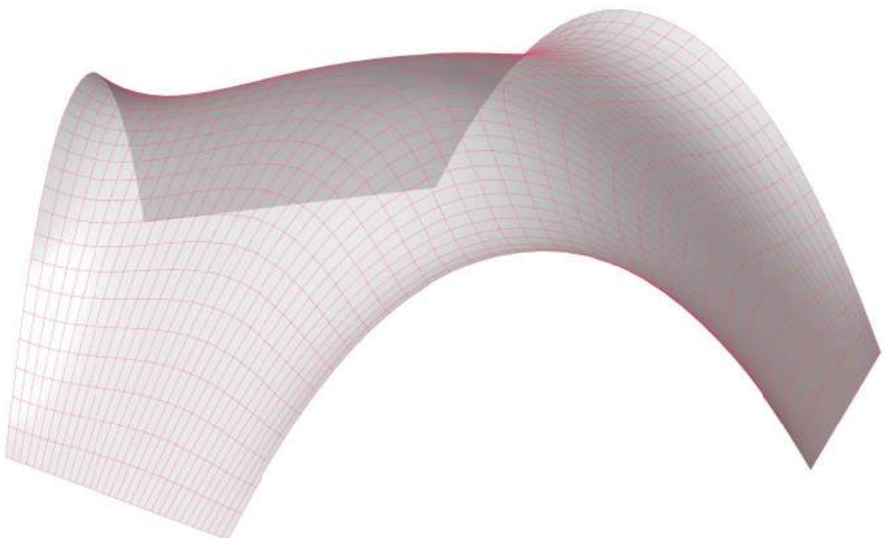
Another issue regarding this form finding process is the creation of some creases when the desired shape is a smooth vault. Usually the creation of the creases means that there need to be more thickness or inertia, but as the structural process will be where it will be decided or in the post design, the origami, the creases in the abstract vault design should be avoided.

In some papers, they suggest that once the form finding is made, a second process must be done: a minimal surface regularization. Another post process applied can be the smooth command of Kangaroo2.

Fixing the perimeter of the Funicular Shell, a Minimal Surface strategy is applied (edges with 0 length), as it deforms too much, the same process is made but fixing the highest node.

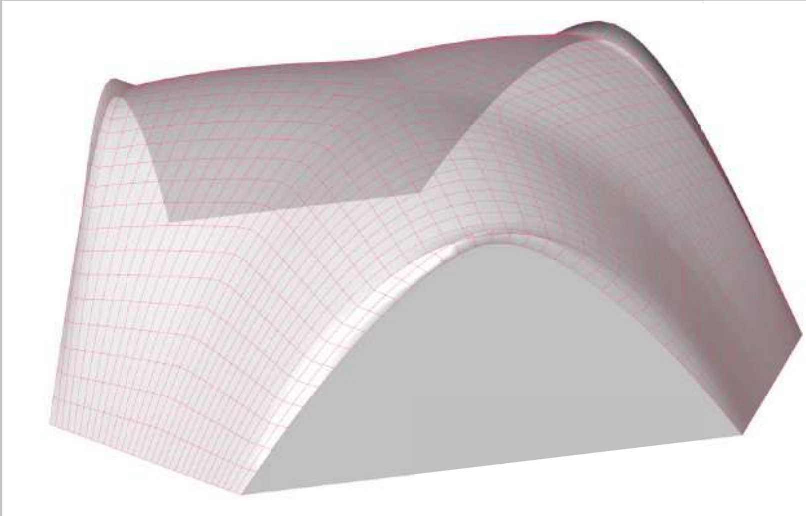


Fixing the perimeter of the Funicular Shell + MSR



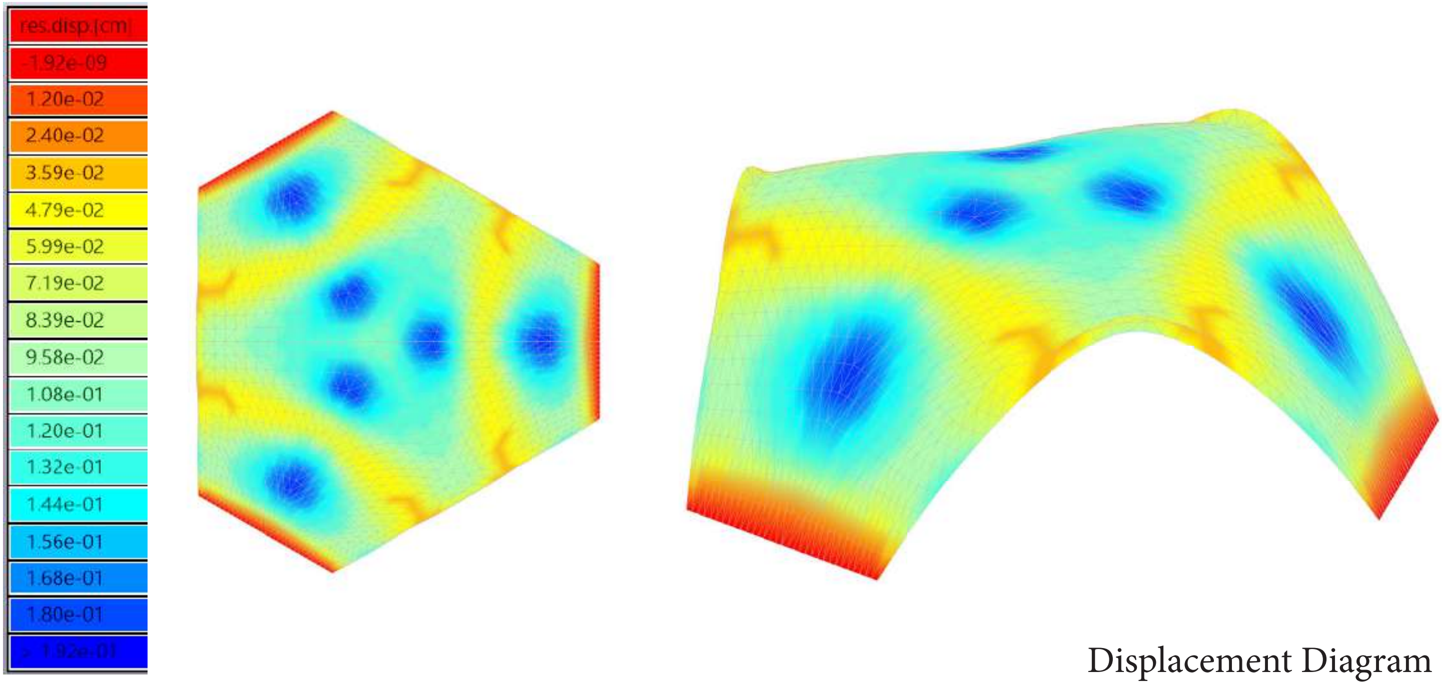
Fixing the perimeter of the Funicular Shell and the highest node + MSR

Mesh Table: 30_Perimerter XY fixed - Quad Mesh

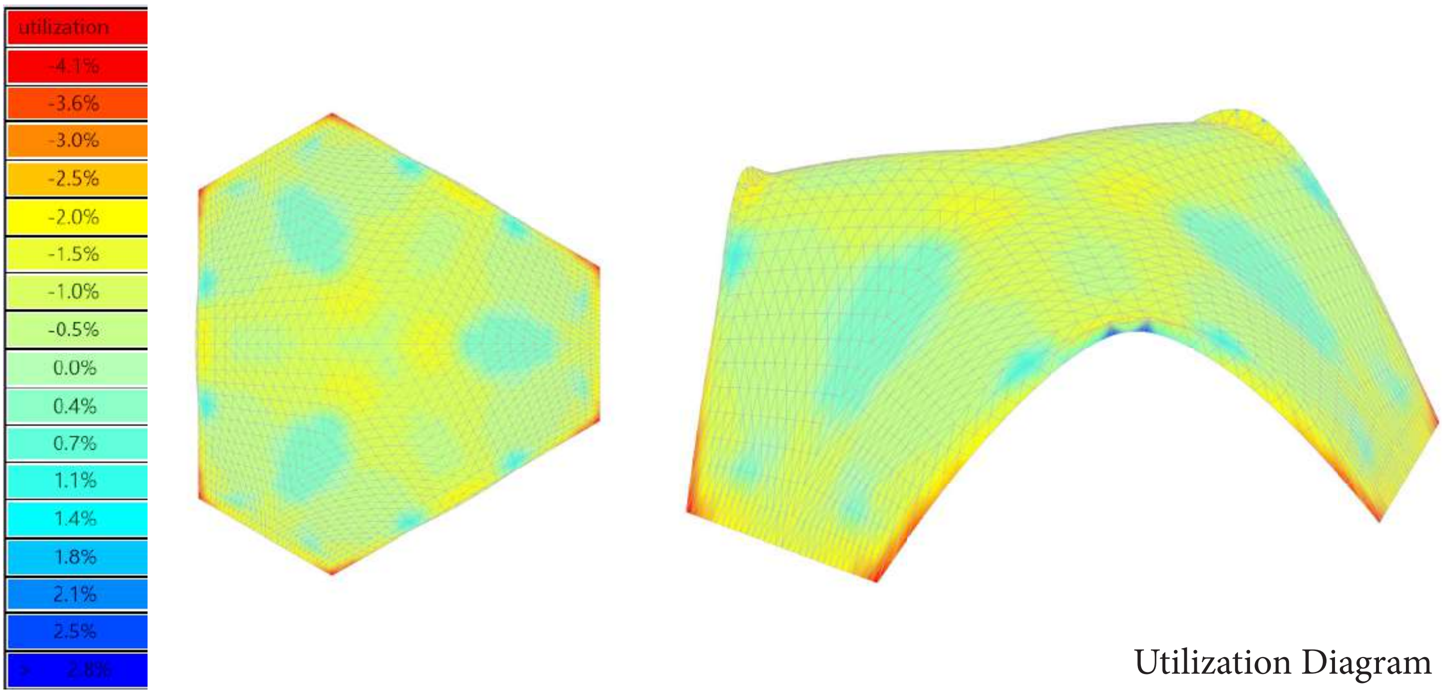


Properties

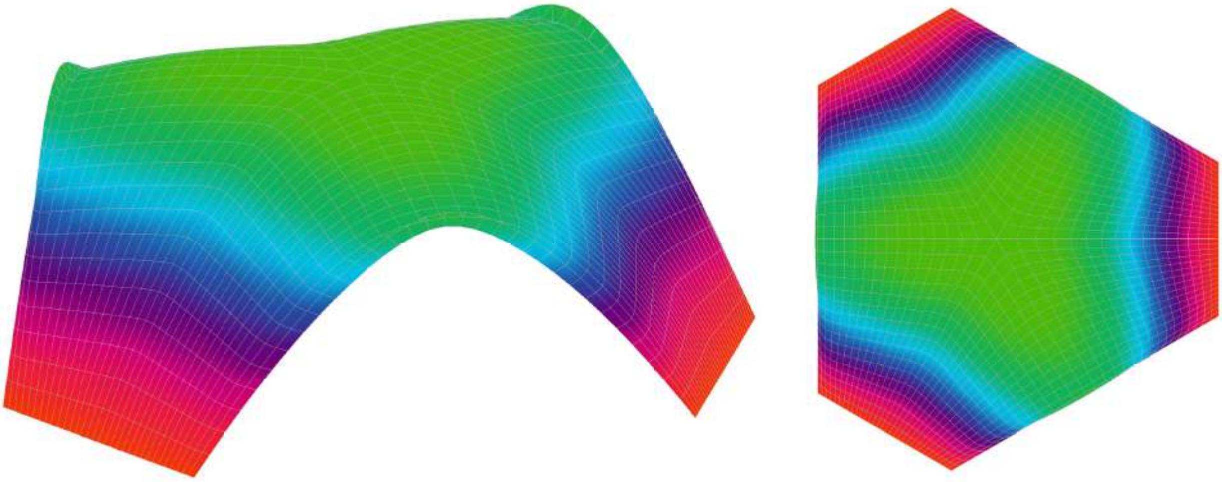
Area: *480.943m2*
Faces: *1536*
Vertices: *1633*
Edges: *3168*
Perimetral Edges: *192*
Supports: *99*
Max. Height: *8.479m*
Thickness: *3cm*
Forces: *Gravity*



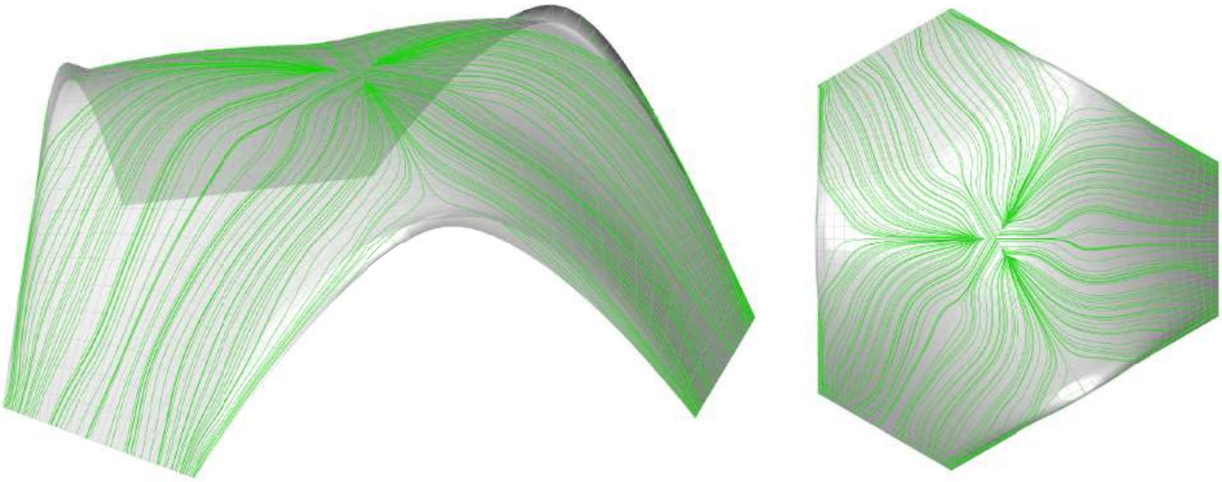
Displacement Diagram



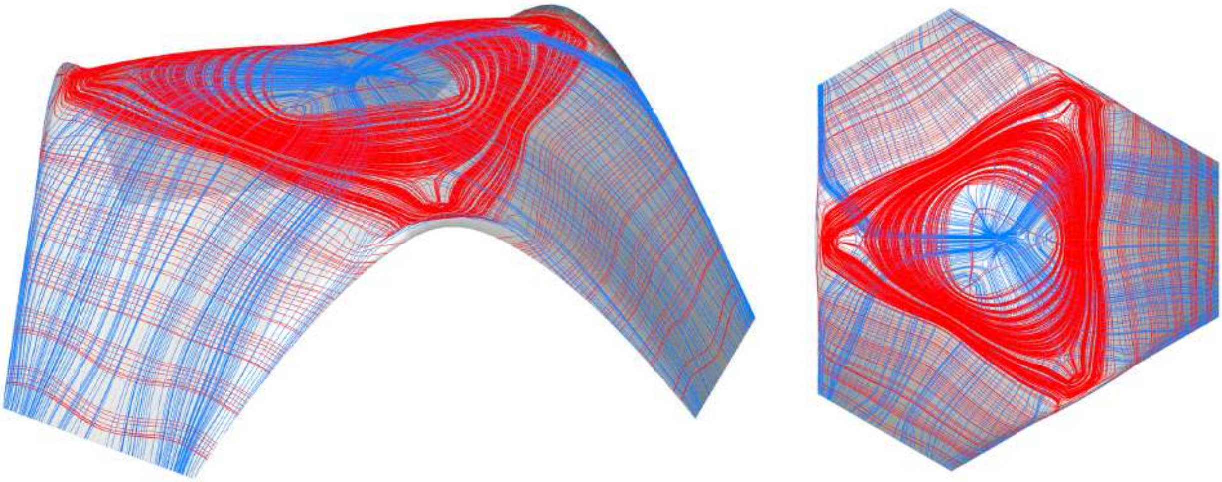
Utilization Diagram



Height Diagram

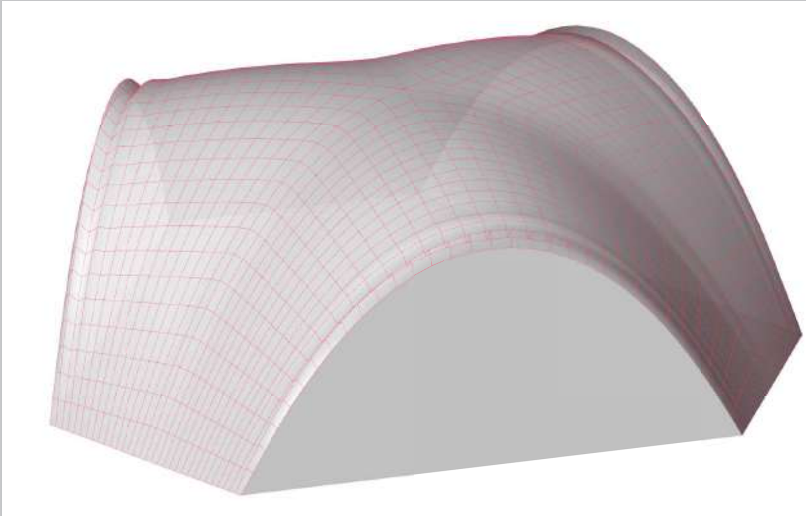


Force Flow Diagram



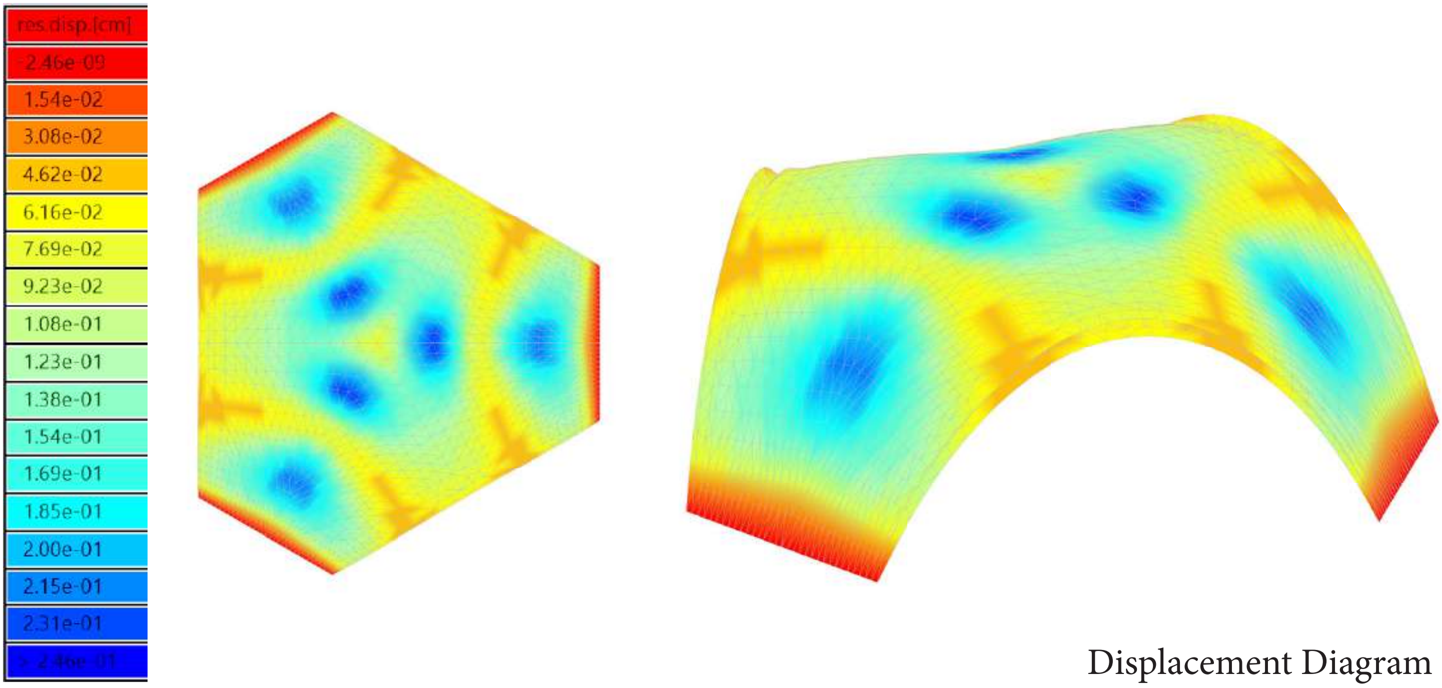
Principal Strees Lines Diagram

Mesh Table: 31_Perimerter fixed - Quad Mesh

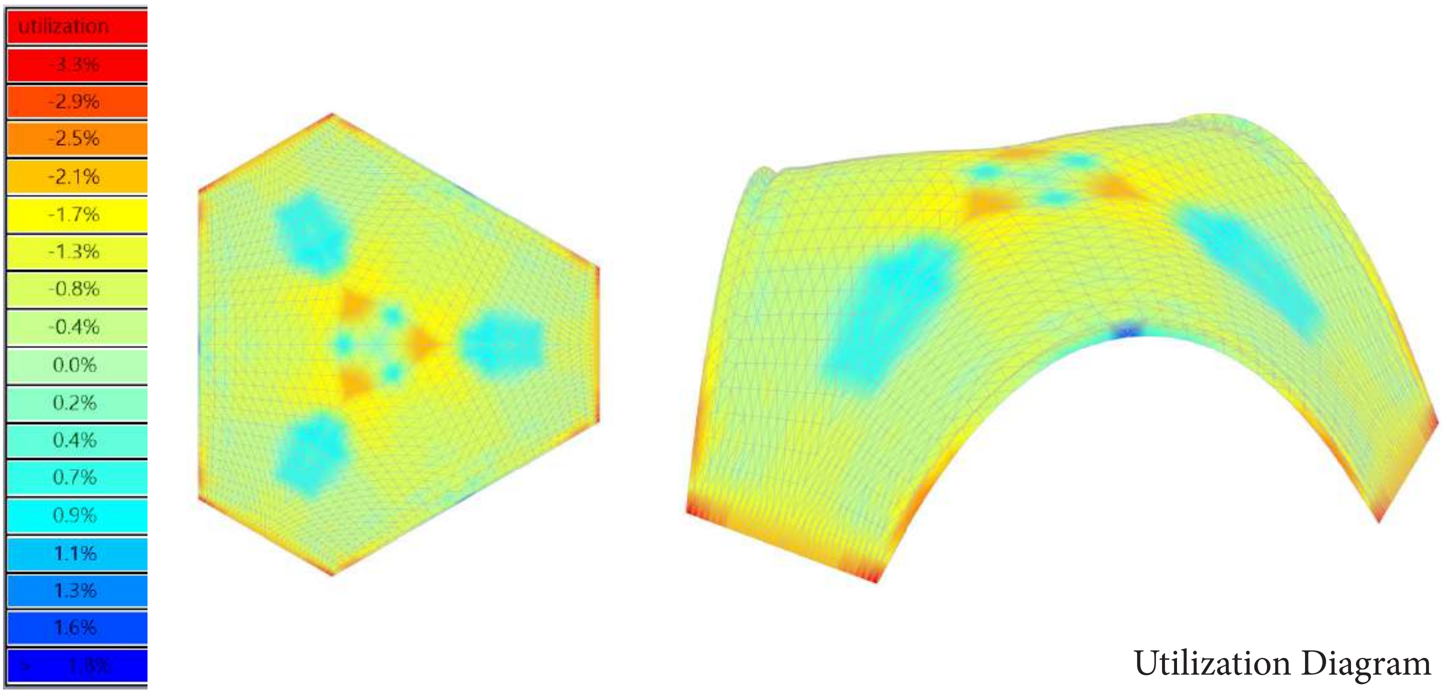


Properties

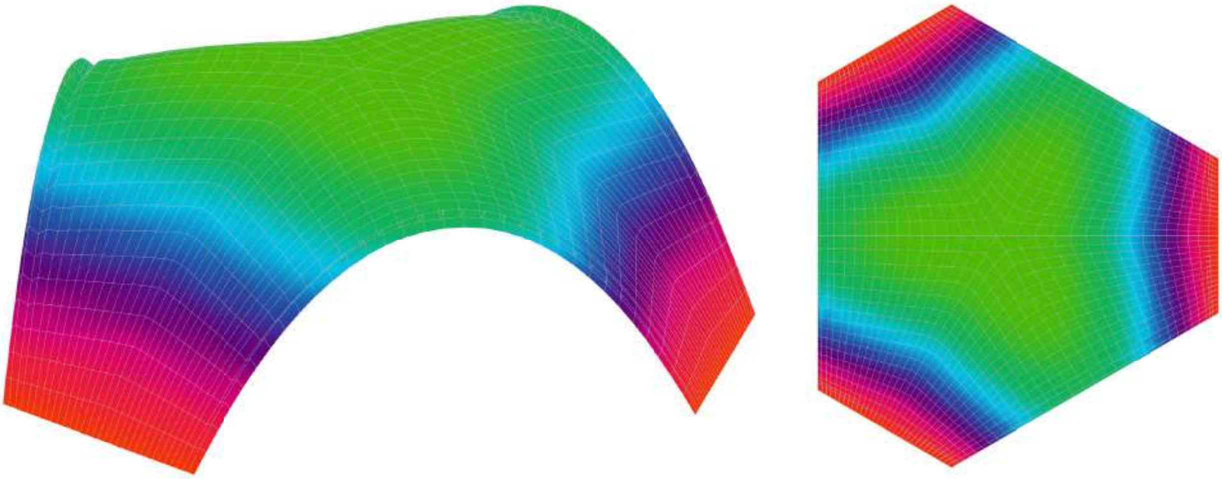
Area: *478.091m2*
Faces: *1536*
Vertices: *1633*
Edges: *3168*
Perimetral Edges: *192*
Supports: *99*
Max. Height: *8.487m*
Thickness: *3cm*
Forces: *Gravity*



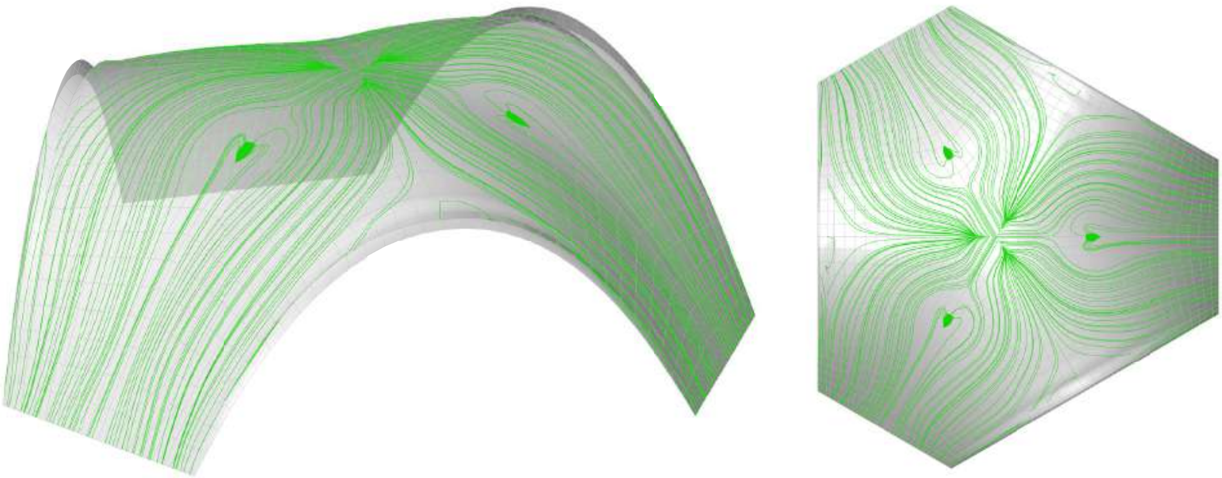
Displacement Diagram



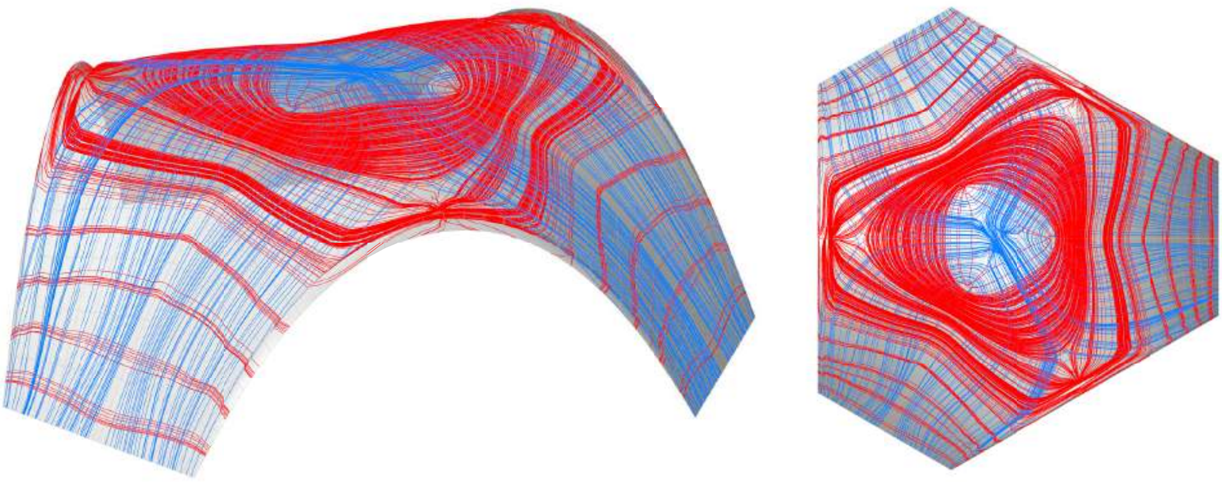
Utilization Diagram



Height Diagram

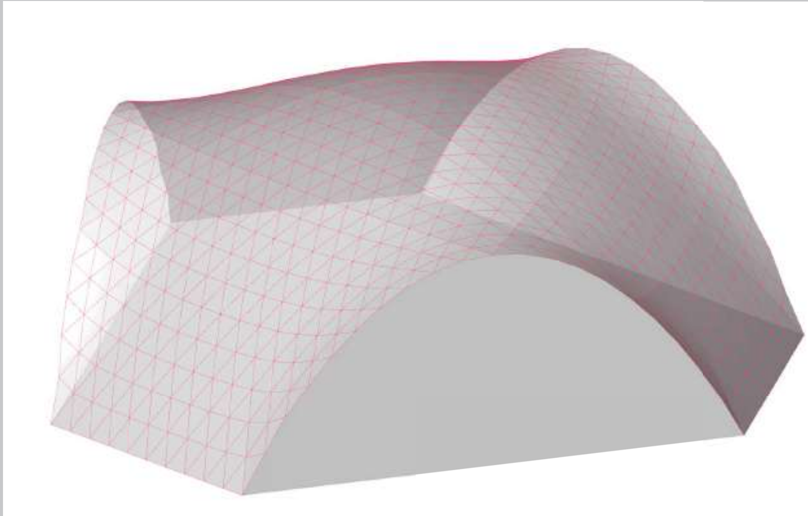


Force Flow Diagram



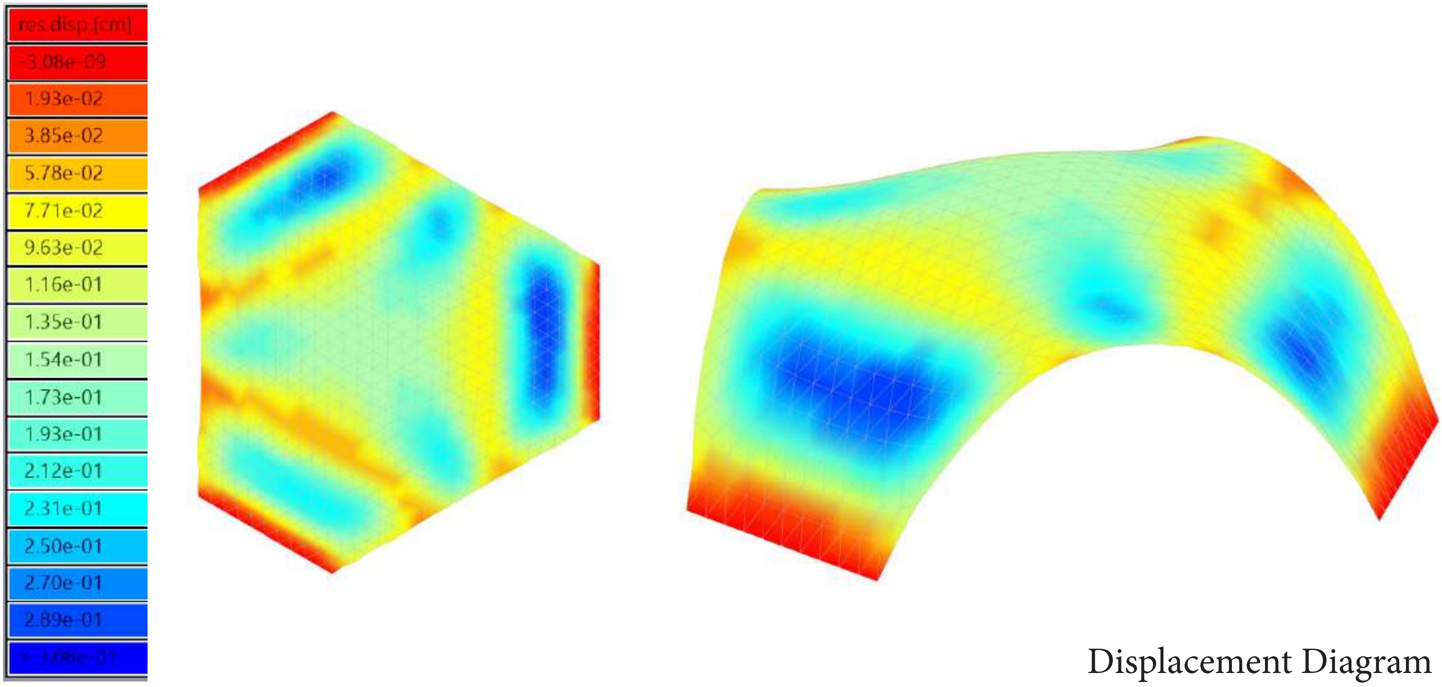
Principal Strees Lines Diagram

Mesh Table: 32_Perimerter fixed - Triangle Mesh

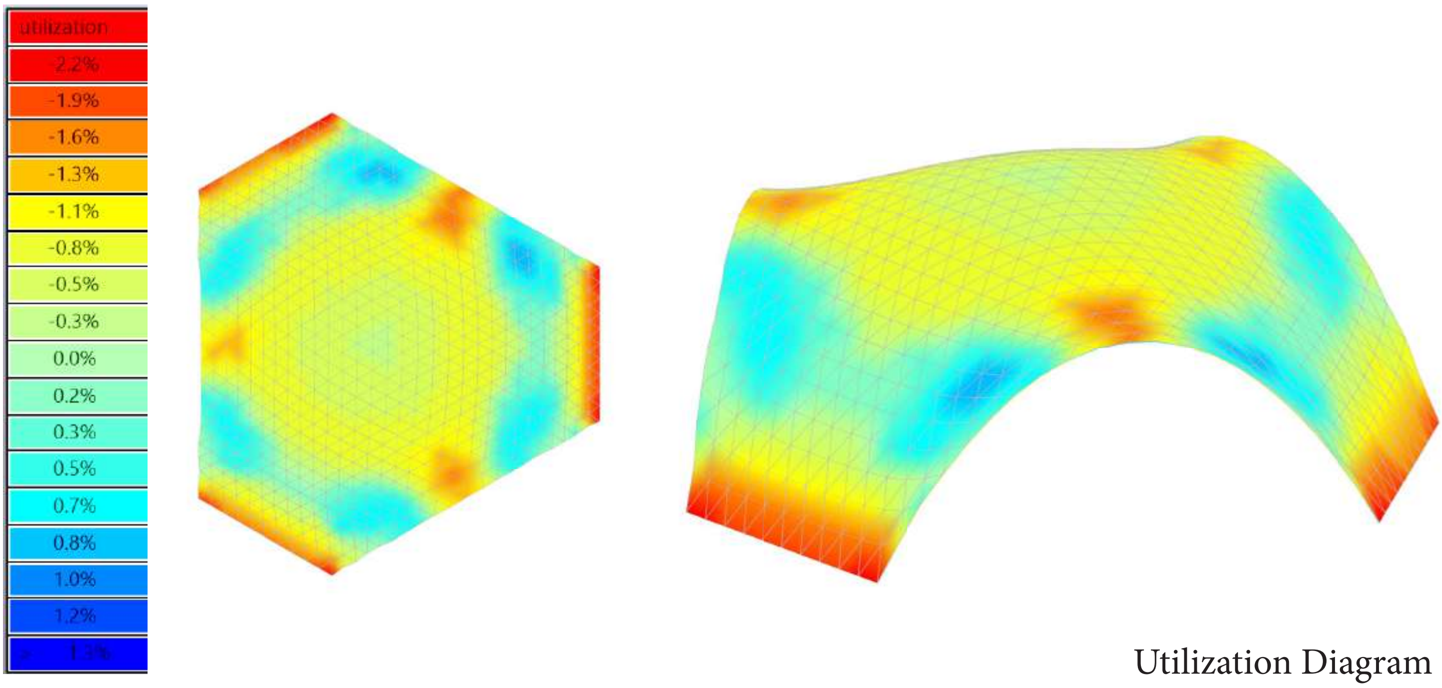


Properties

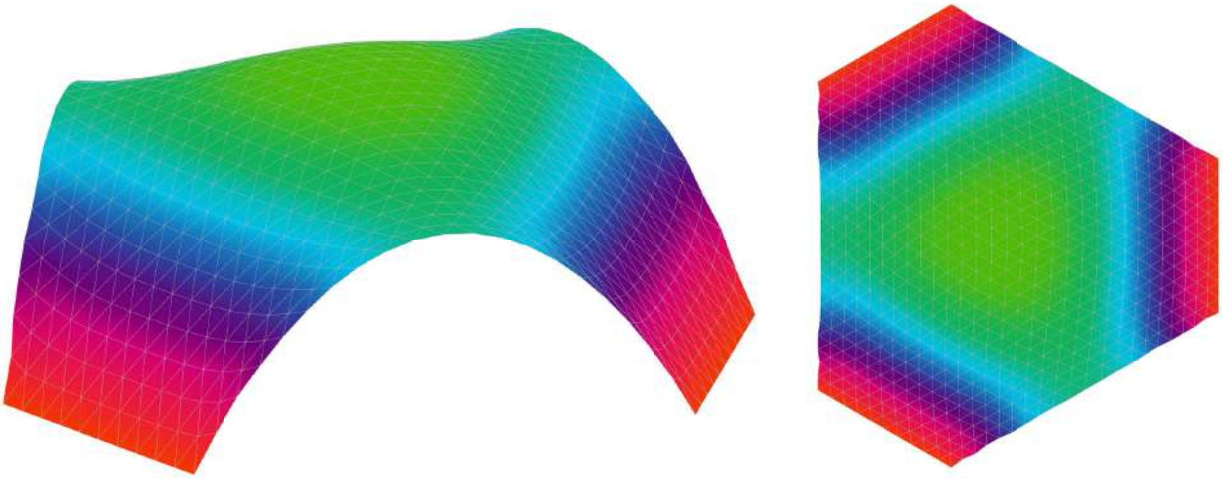
Area: *442.093m2*
Faces: *1300*
Vertices: *1092*
Edges: *1995*
Perimetral Edges: *90*
Supports: *33*
Max. Height: *8.517m*
Thickness: *3cm*
Forces: *Gravity*



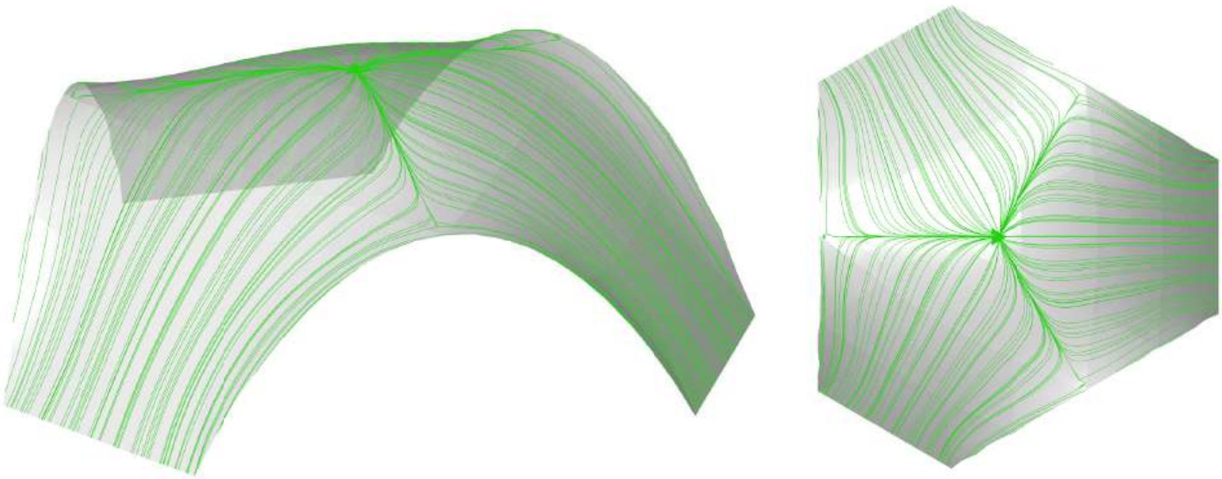
Displacement Diagram



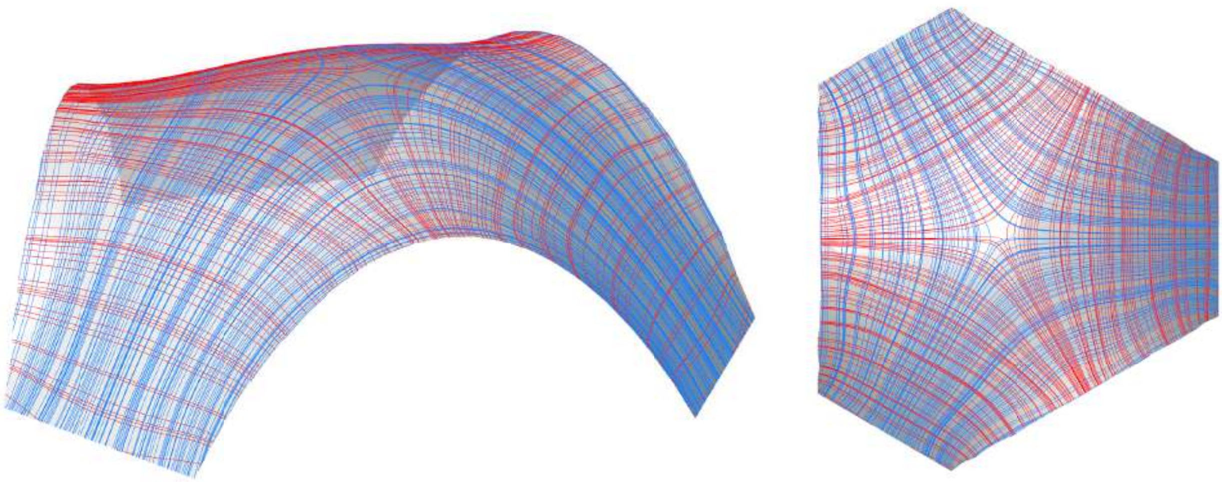
Utilization Diagram



Height Diagram



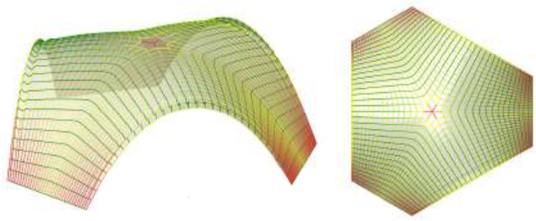
Force Flow Diagram



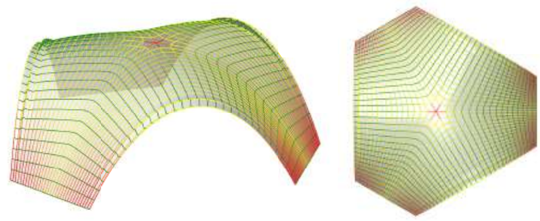
Principal Strees Lines Diagram

4.6_Strategy III: FSFF while applying Minimal Surface Regularizaion

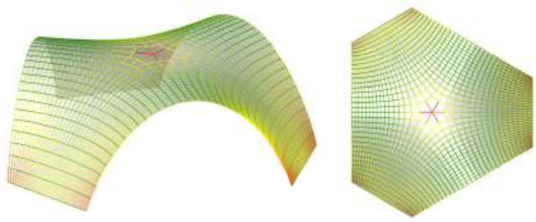
The creases created on the mesh are always in the edges of the same direction, so maybe if we do the form finding process fixing the perimeter, keeping the length of the edges is not a necessary constrain, so it could not be there or the constrain may be to keep the length in 0 like a minimal surface. This new constrains could be for all the edges or just de ones that creates the creases.



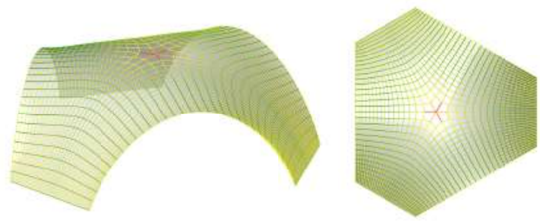
"Mesh Table 31_Perimerter fixed - Quad Mesh"



"Mesh Table 10_High resolution Quad Mesh"



"Mesh Table 33_UV-Length 0 - Quad Mesh"



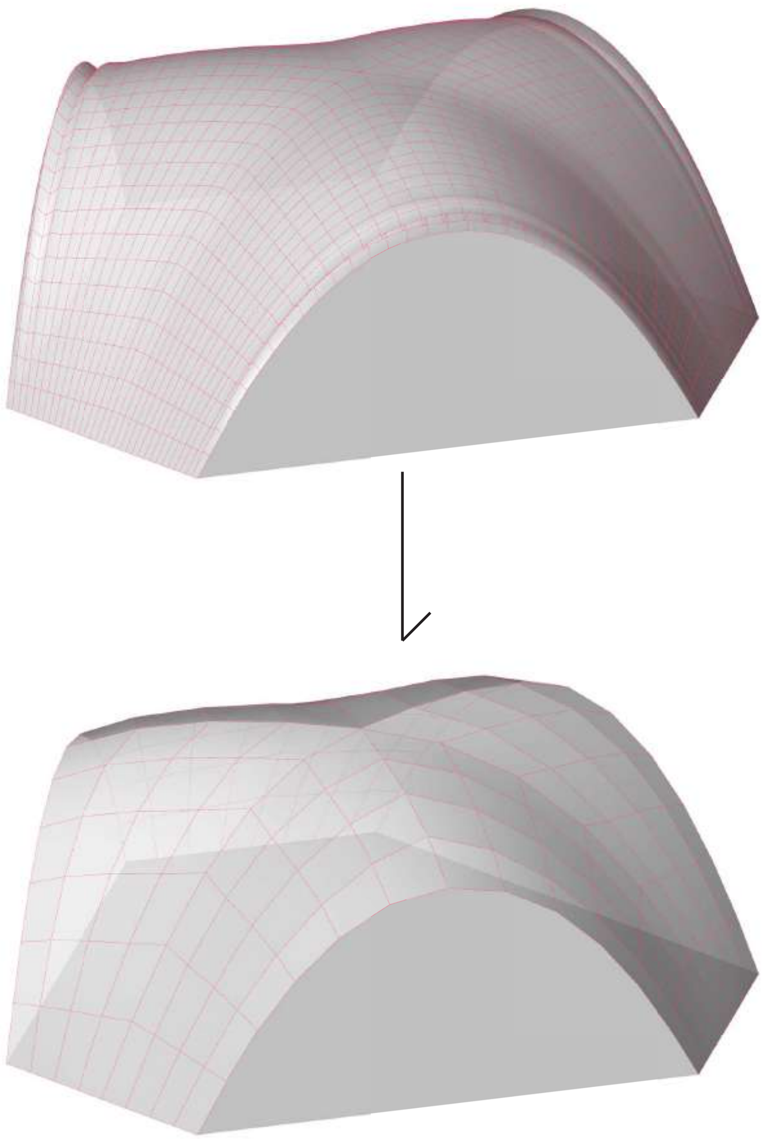
"Mesh Table 34_U-Length 0 - Quad Mesh"

4.7_Re-meshing the vault

As seen in "first hypothesis design", to apply an origami definition we need regular quad-mesh, therefore now that we have a funicular shell that works as it should, it is time to re-mesh it. Using this vault as a mesh to create the guide lines to create the quad-mesh or surface where the origami definition will be applied.

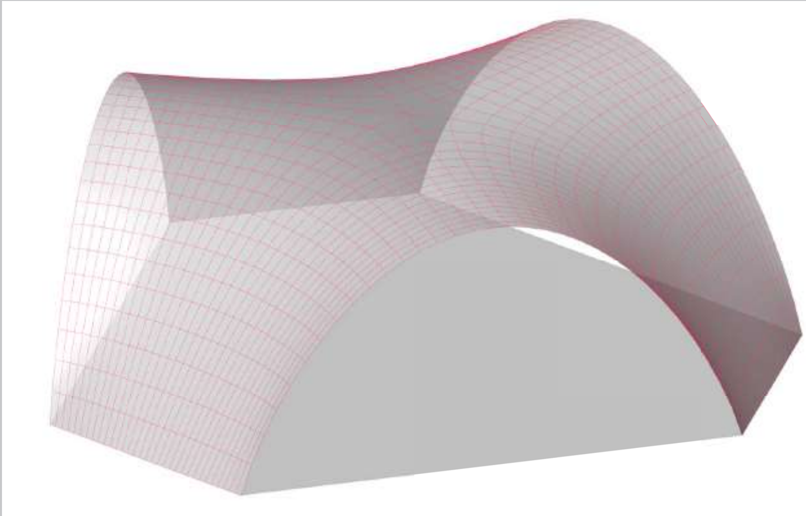
This quad-mesh needs to be able to be developed in quad strips, for a good performance of the origami, and even better if they are planar quads. What's more, for an origami pattern like Miura Ori, an offset of the mesh needs to be created and geodesic lines' normal are perpendicular to the mesh so the offset of the mesh can be created from offsetting the geodesic lines.

Therefore, creating this new guidelines from geodesic lines is the best option.



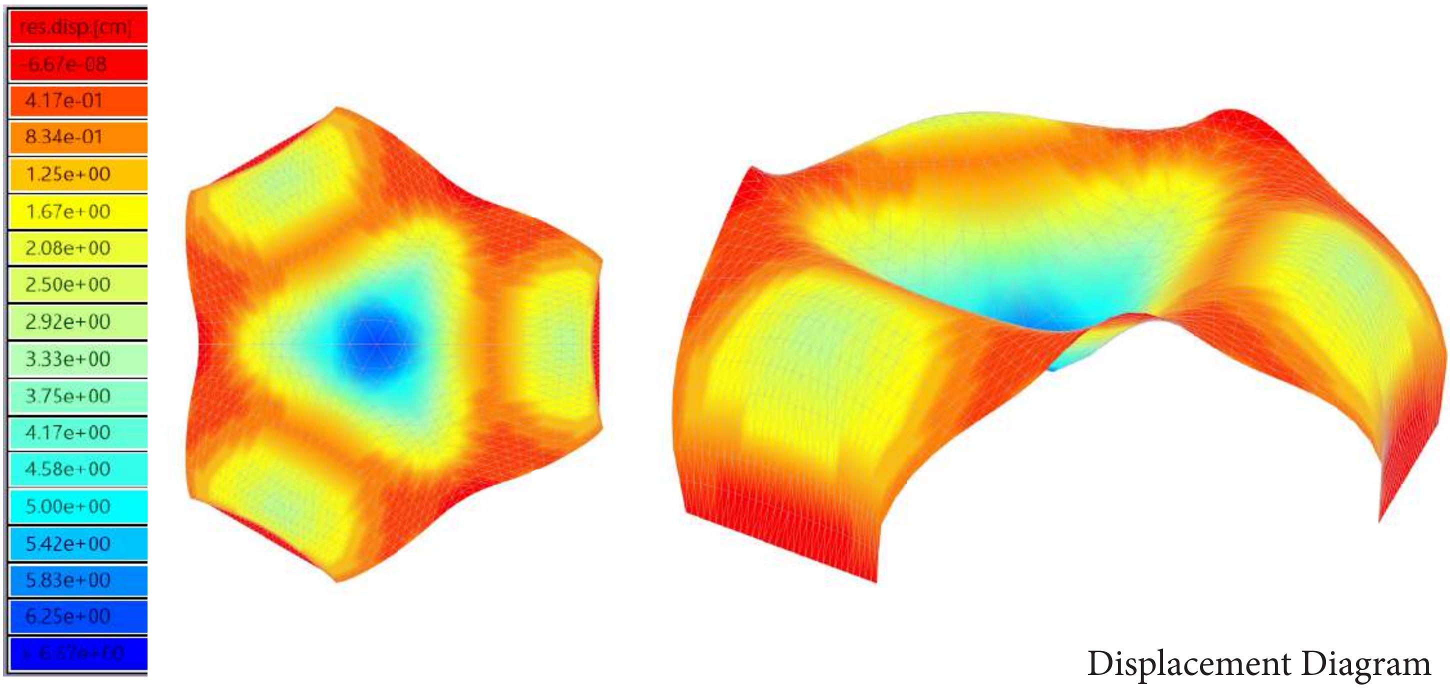
See "Mesh Table 40_Quad Mesh from geodesics (QMFG)"

Mesh Table: 33_UV-Length 0 - Quad Mesh

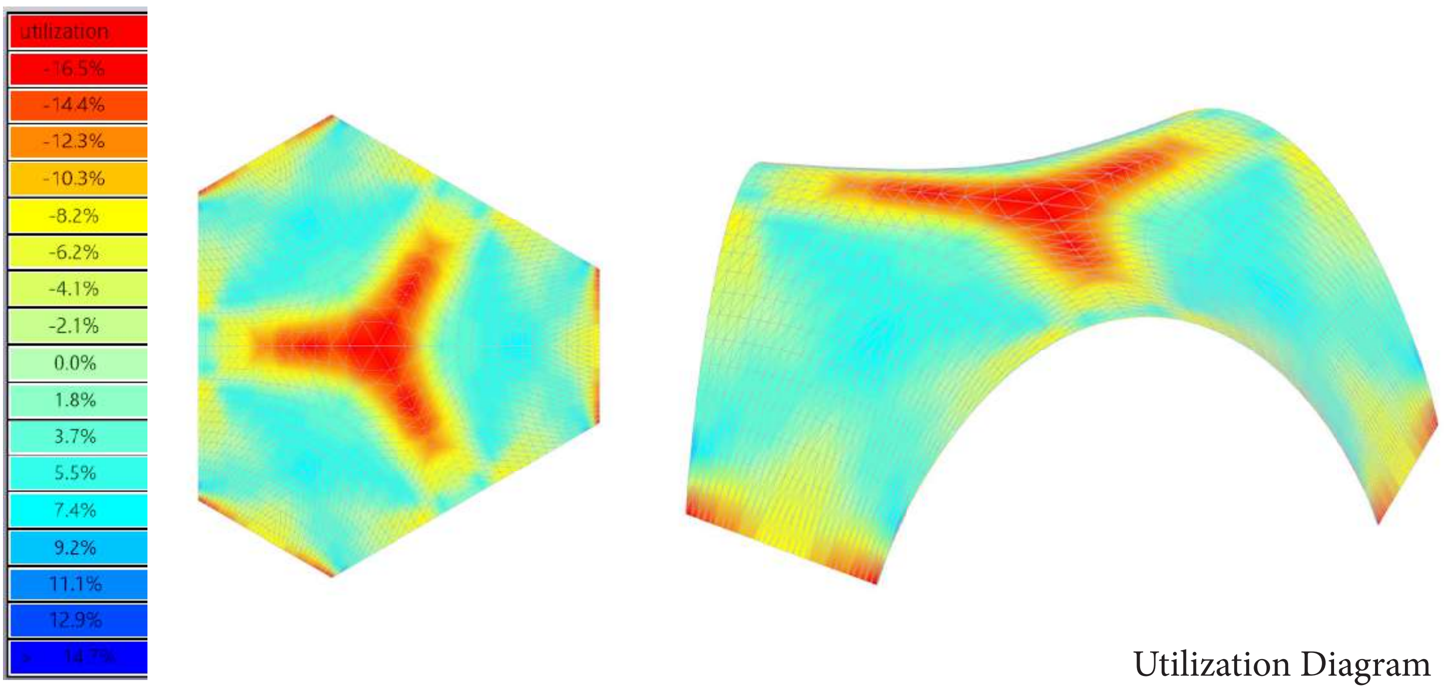


Properties

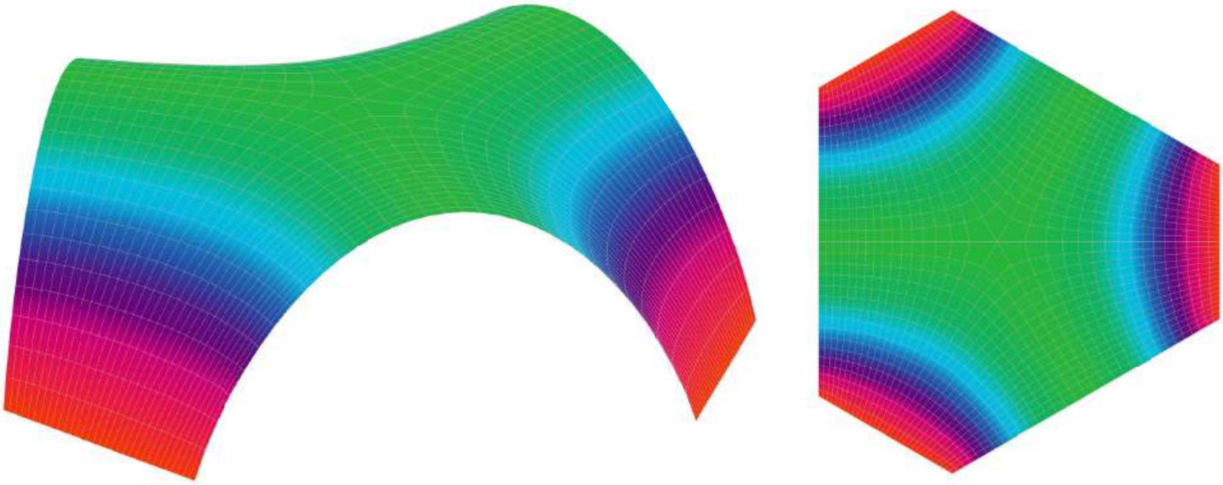
Area: *444.773m2*
Faces: *1536*
Vertices: *1633*
Edges: *3168*
Perimetral Edges: *192*
Supports: *99*
Max. Height: *7.701m*
Thickness: *3cm*
Forces: *Gravity*



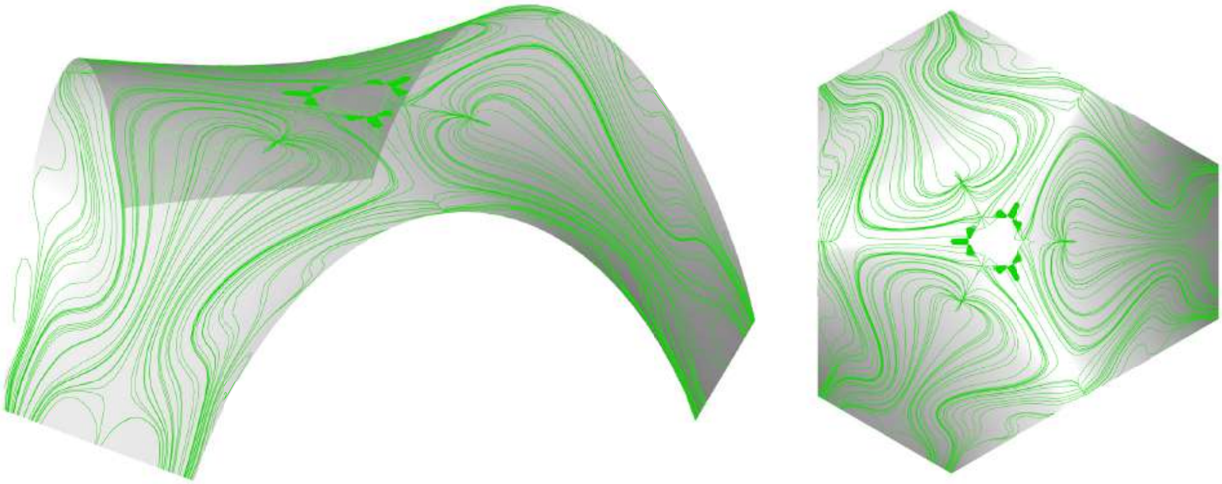
Displacement Diagram



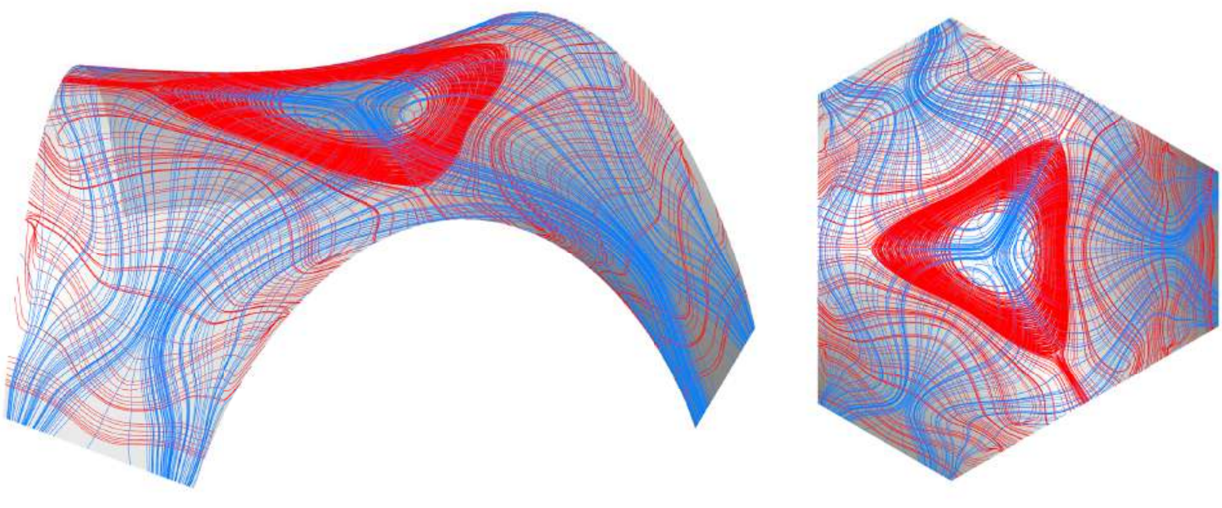
Utilization Diagram



Height Diagram



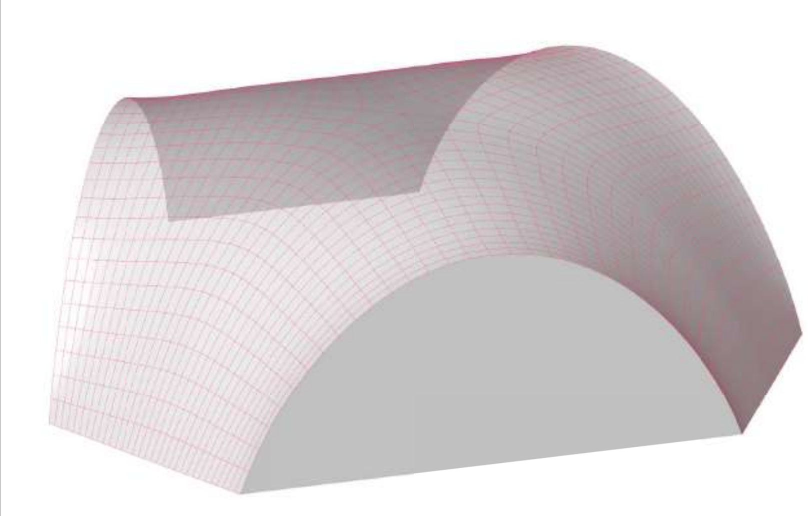
Force Flow Diagram



Principal Strees Lines Diagram

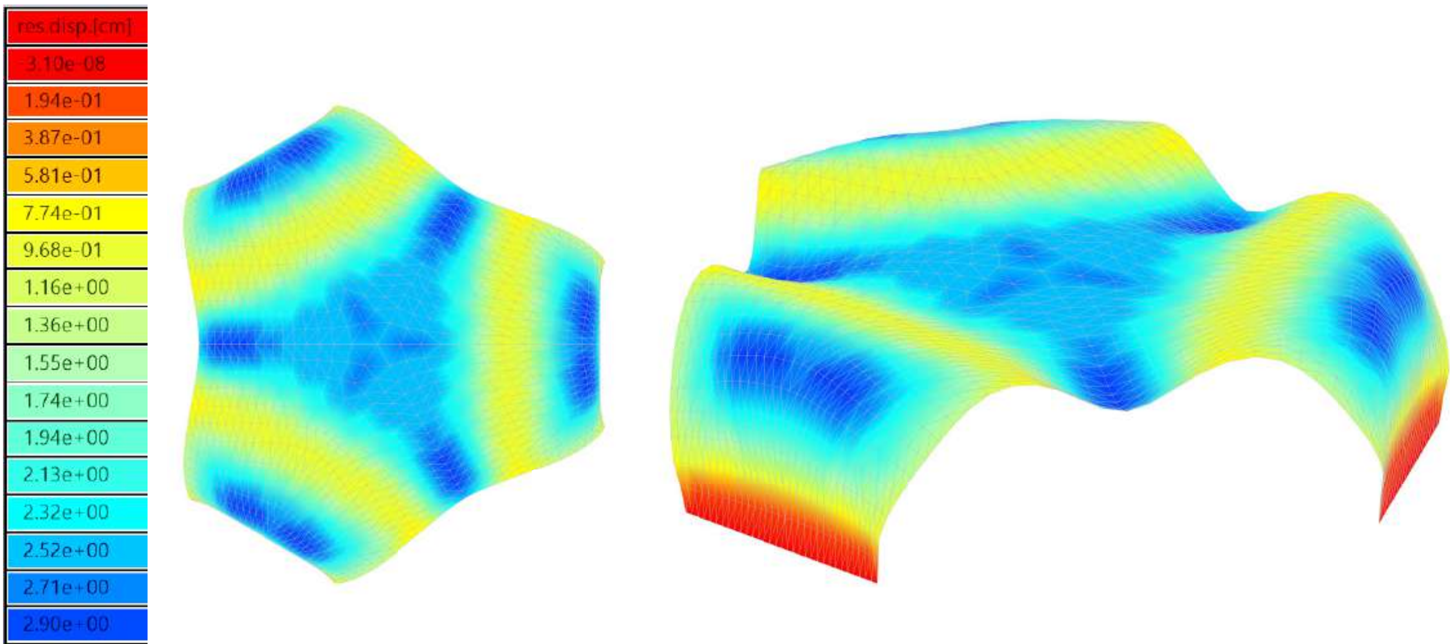
MPDA BarcelonaTech
Master's degree
Parametric Design in Architecture
UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH
School of Professional & Executive Development

Mesh Table: 34_U-Length 0 - Quad Mesh

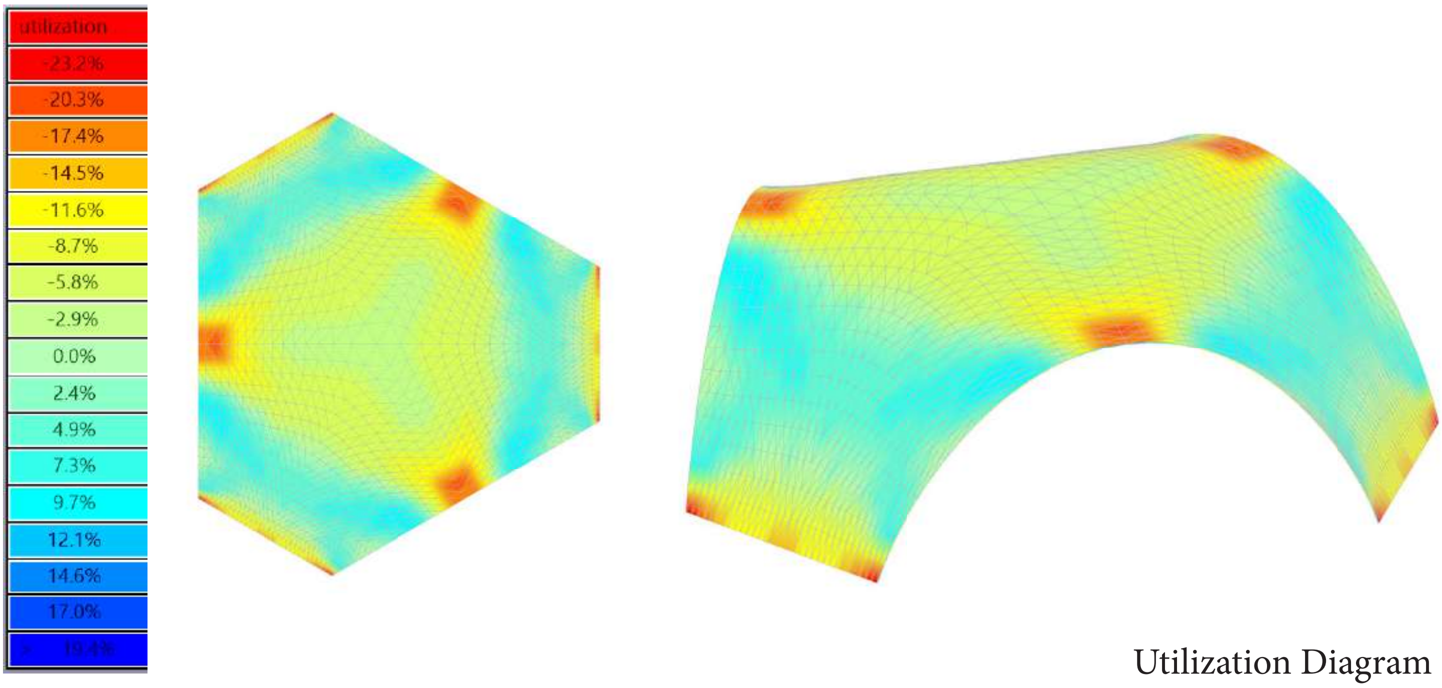


Properties

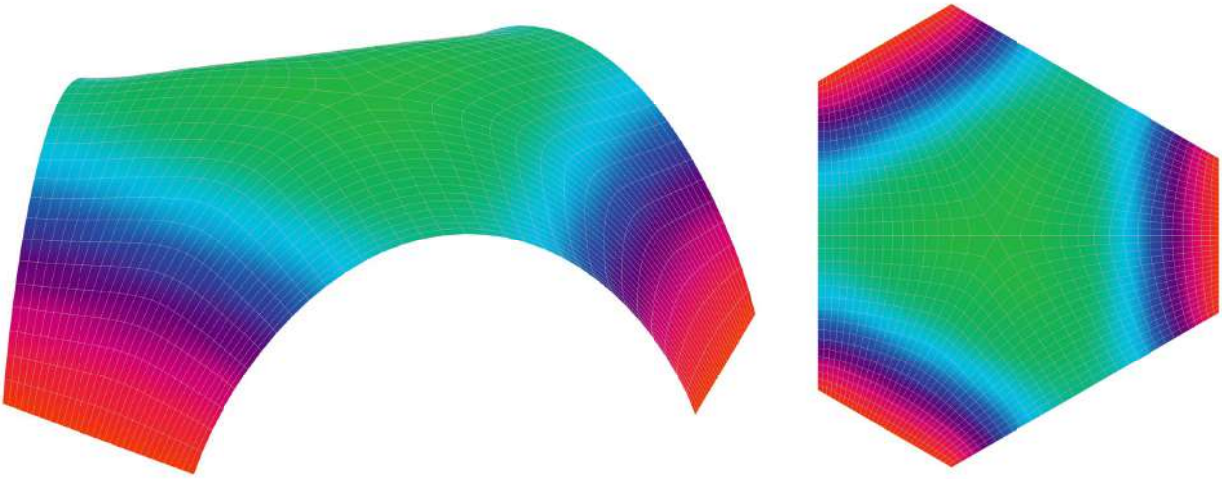
Area: *439.008m2*
Faces: *1536*
Vertices: *1633*
Edges: *3168*
Perimetral Edges: *192*
Supports: *99*
Max. Height: *7.65m*
Thickness: *3cm*
Forces: *Gravity*



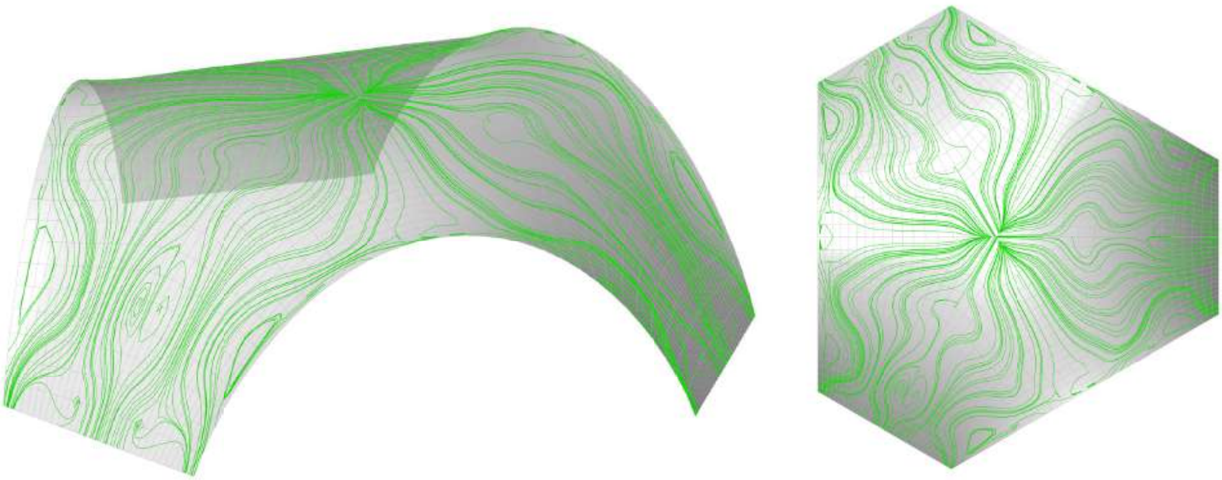
Displacement Diagram



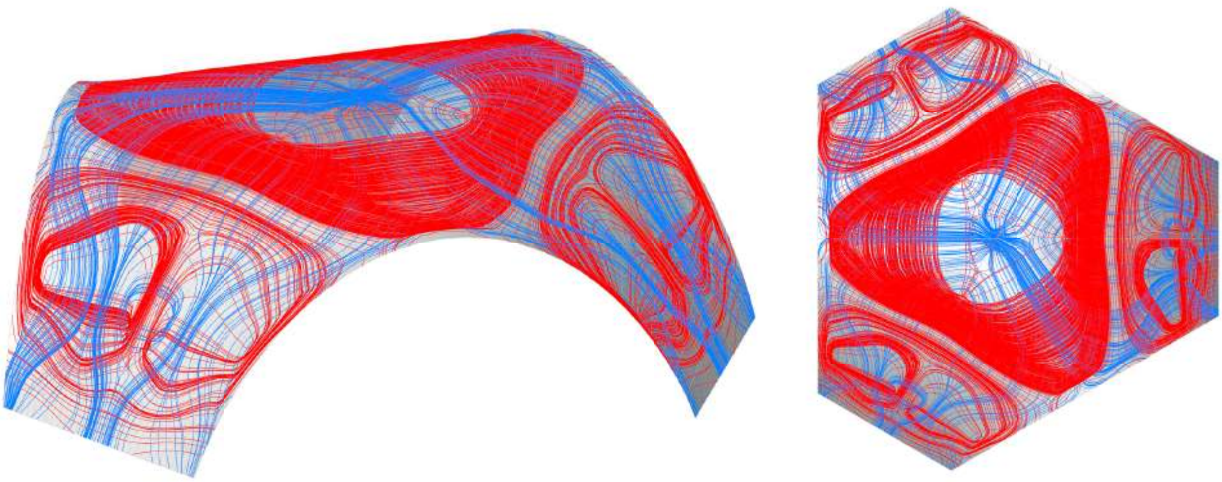
Utilization Diagram



Height Diagram



Force Flow Diagram

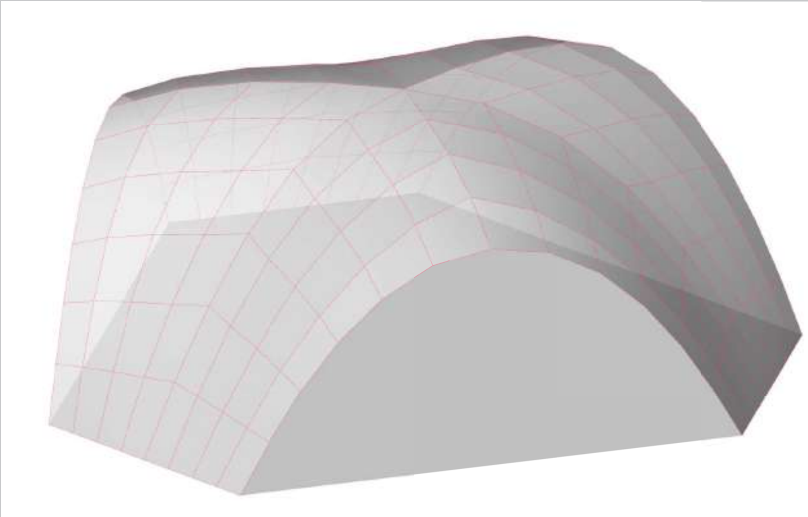


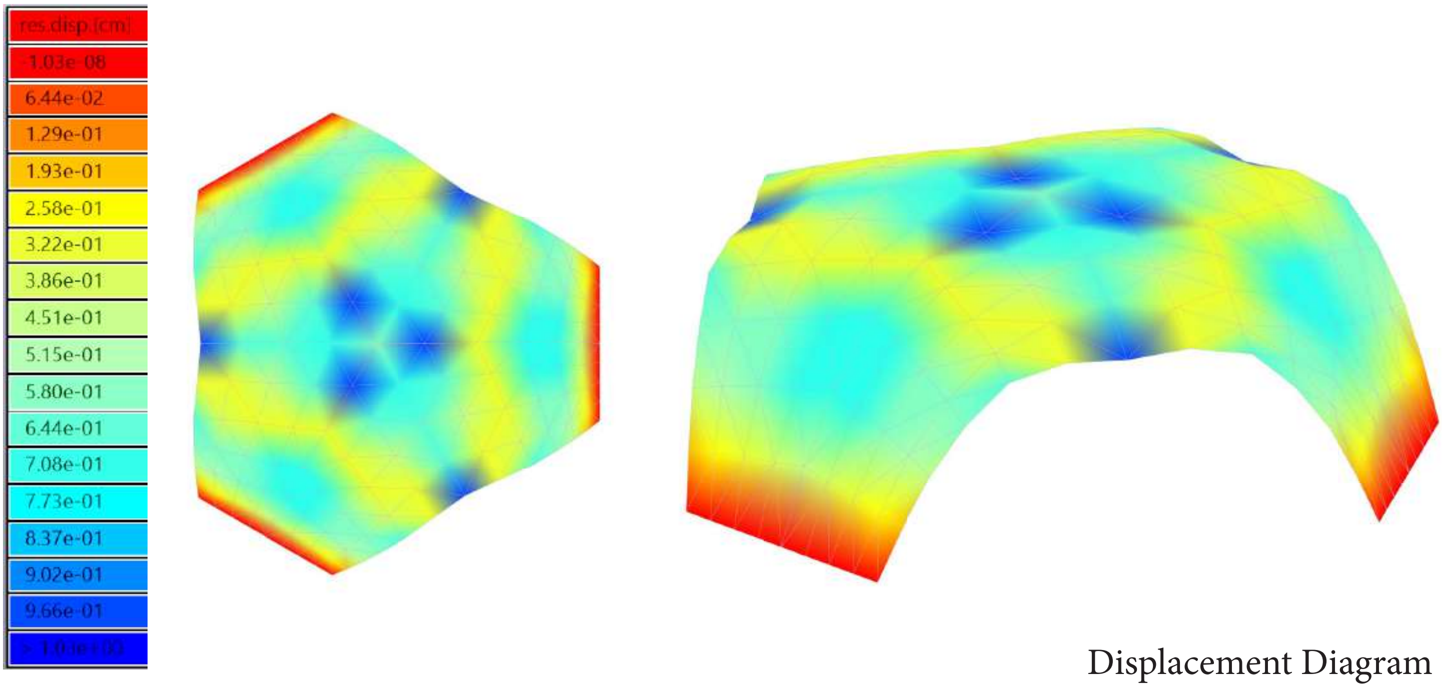
Principal Strees Lines Diagram

Mesh Table: 40_Quad Mesh from geodesics (QMFG)

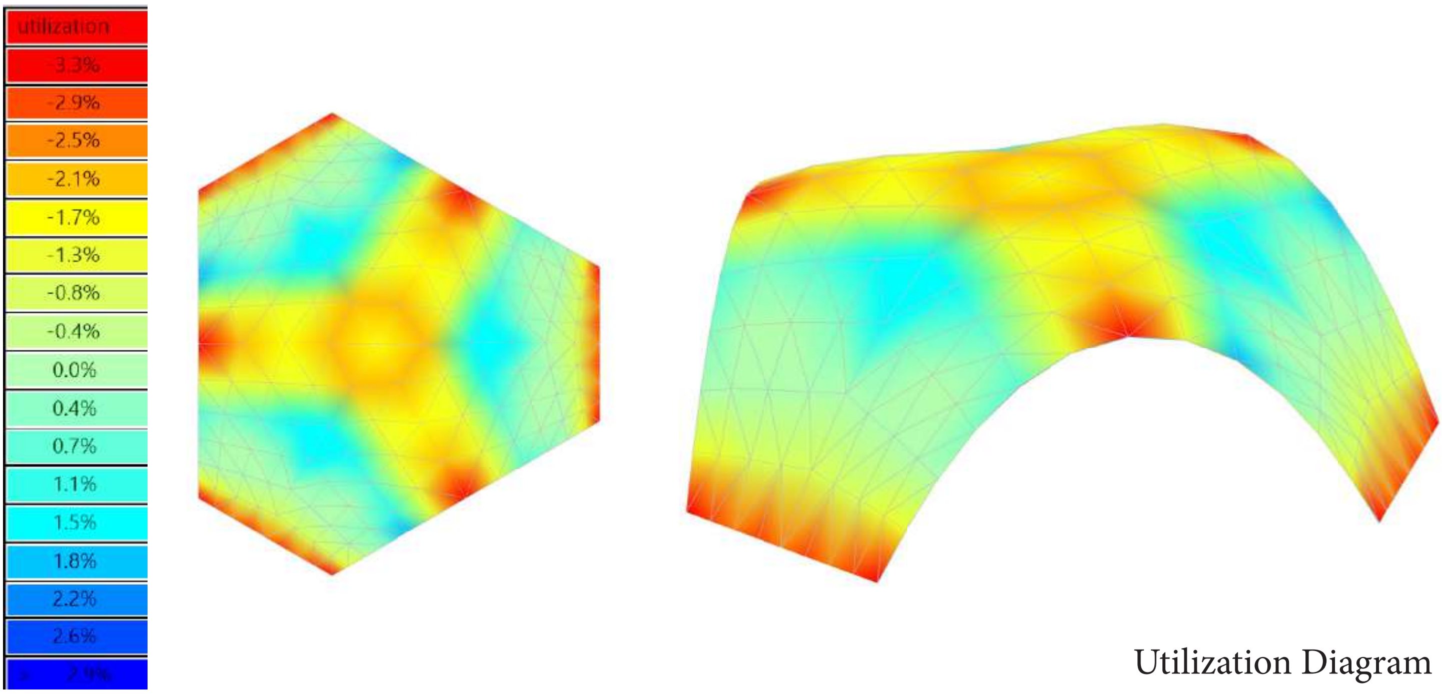
Properties

Area: *457.439m2*
Faces: *144*
Vertices: *336*
Edges: *328*
Perimetral Edges: *60*
Supports: *27*
Max. Height: *8.48m*
Thickness: *3cm*
Forces: *Gravity*

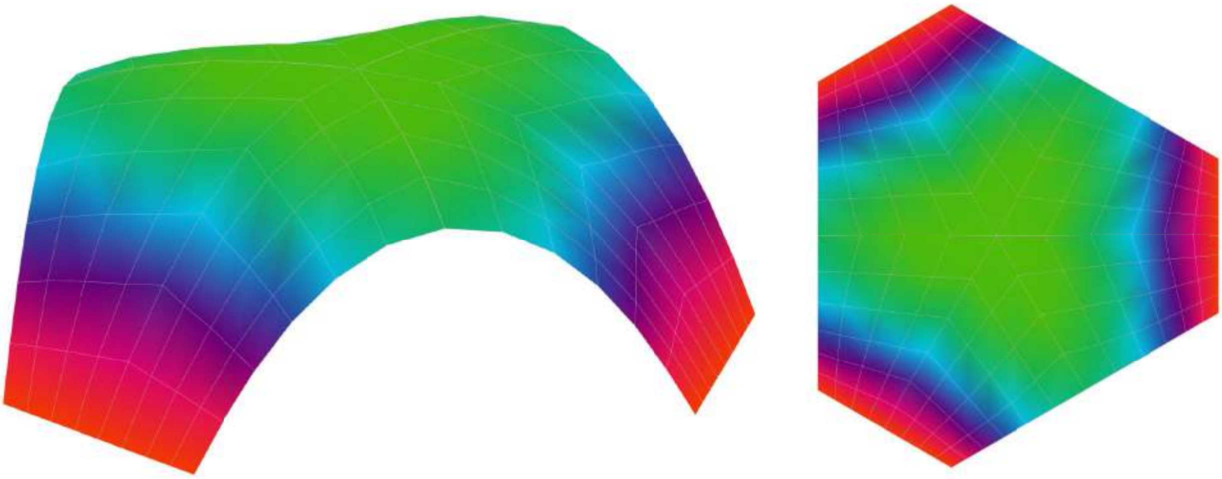




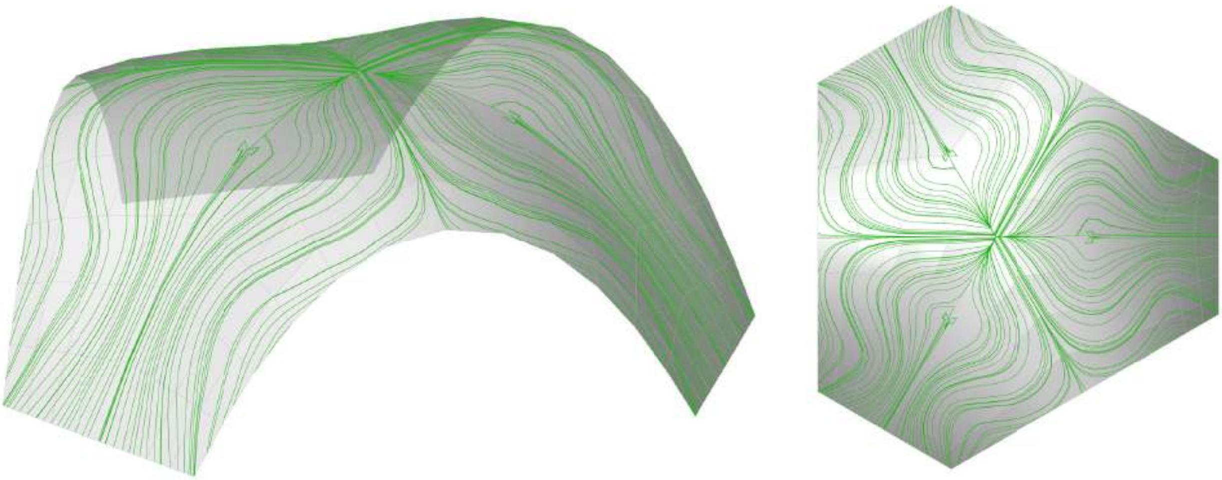
Displacement Diagram



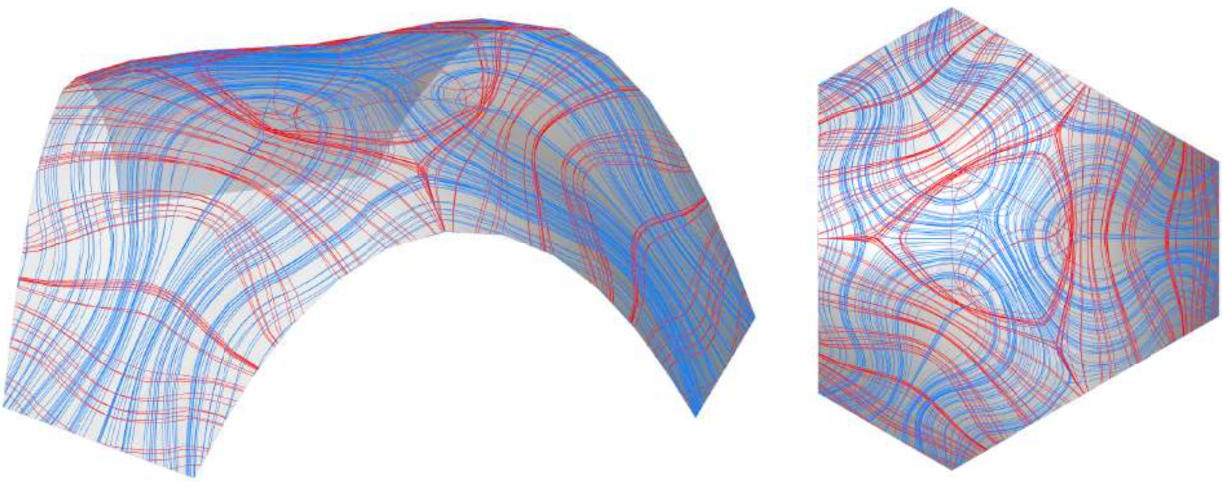
Utilization Diagram



Height Diagram



Force Flow Diagram



Principal Strees Lines Diagram

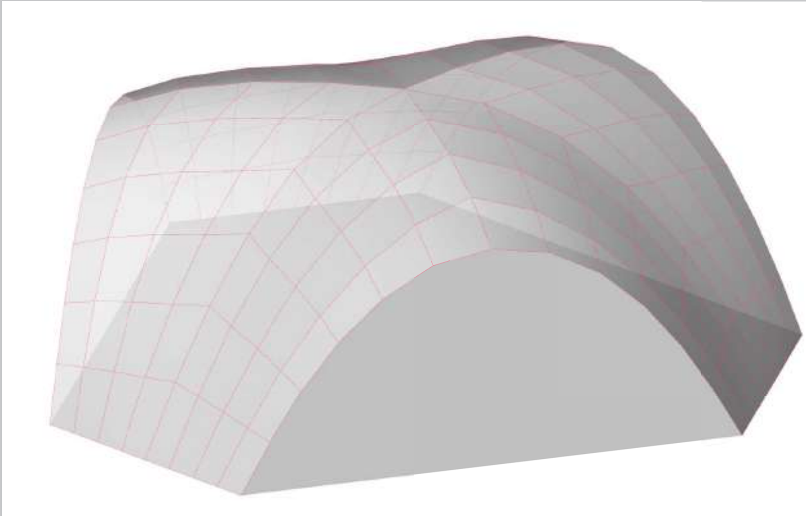
5_Design Process
Origami Structures

Firts of all, the origami definitions of the "firts hypothesis desgin" are applied to he new mesh (40_Quad Mesh from geodesics): folded design, Yoshimura and Miura Ori.

For this comparison, we chose the quad mesh optimazed with certain conditions (see table) as a reference. This new Shell tables have to load hypothesis: Gravity / Gravity+100KN wind in X direction.
This way we can see that the origami desingns improve the design of the vault structurally and makes it more stable in wind loads.

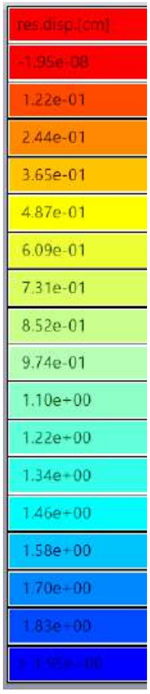
See "Shell Table 01_Optimazed - 40 QMFG "
"Shell Table 02_Optimazed - 40 QMFG"
"Shell Table 03_Folded & Optimazed - 40 QMFG"
"Shell Table 04_Folded & Optimazed - 40 QMFG"
"Shell Table 05_Yoshimura - 40 QMFG"
"Shell Table 06_Yoshimura - 40 QMFG"
"Shell Table 07_Miura ori - 40 QMFG"
"Shell Table 08_Miura ori - 40 QMFG"

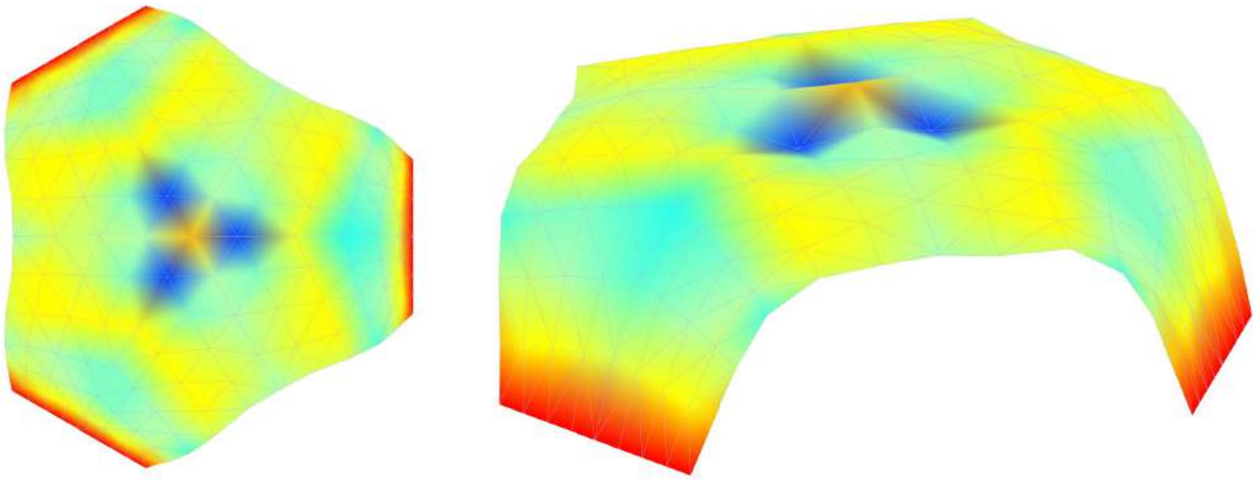
SHELL TABLE: **01_Optimazed - 40 QMFG**



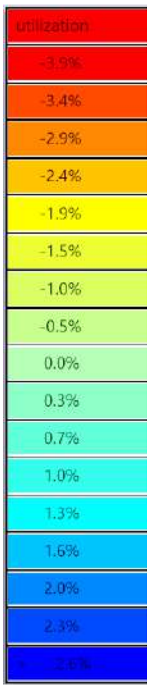
Properties

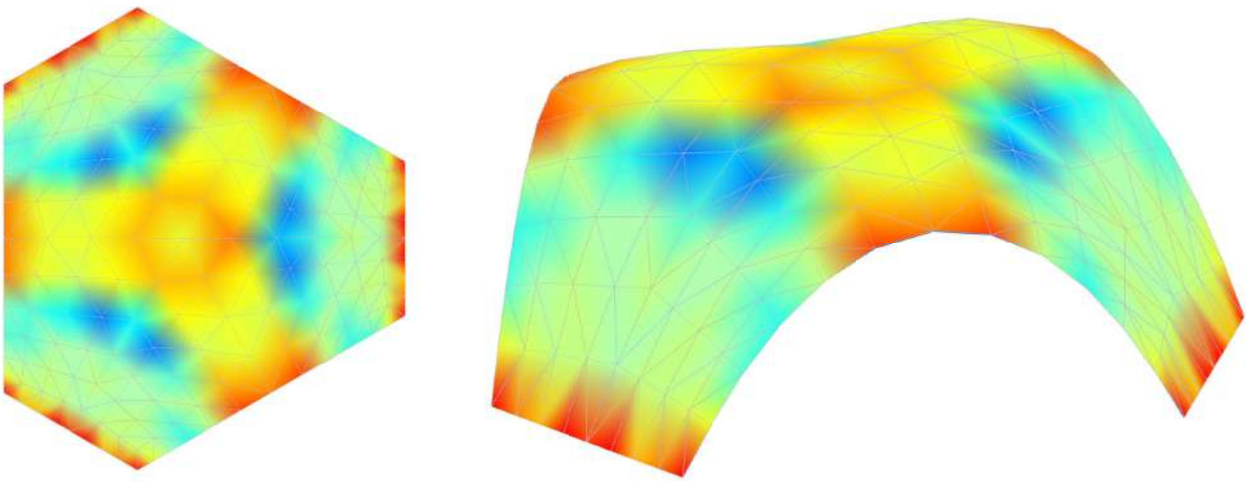
Area: *457.439m2*
Faces: *144*
Vertices: *336*
Edges: *328*
Perimetral Edges: *60*
Supports: *27*
Optimization: *4% utiliation*
Thickness: *optimazed 1-4.5cm*
Forces: *Gravity*



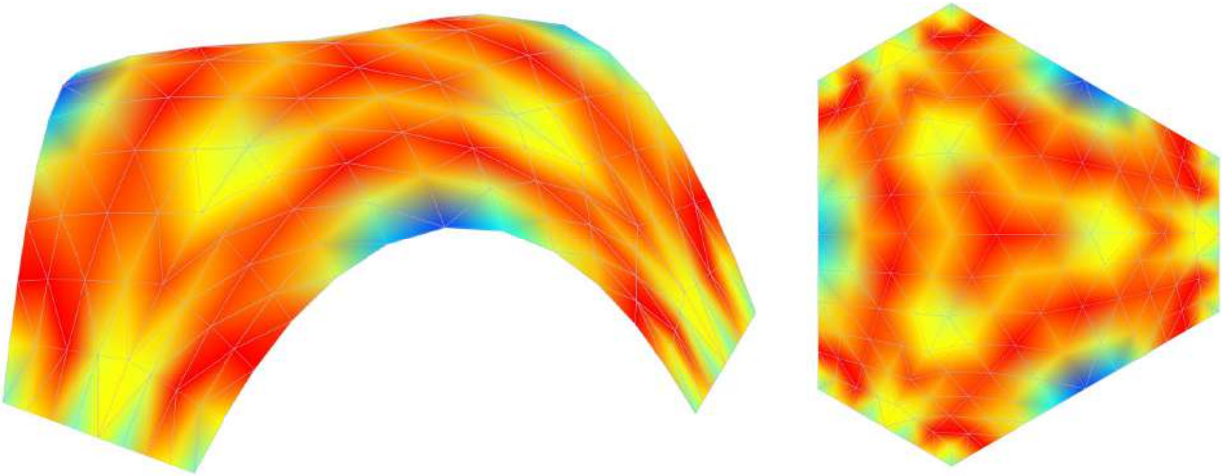


Displacement Diagram

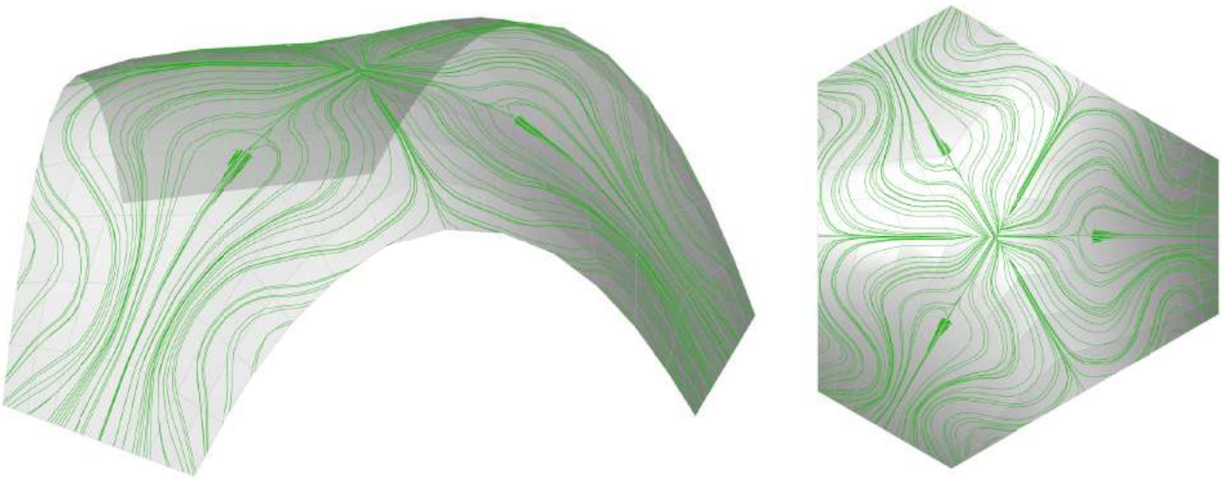




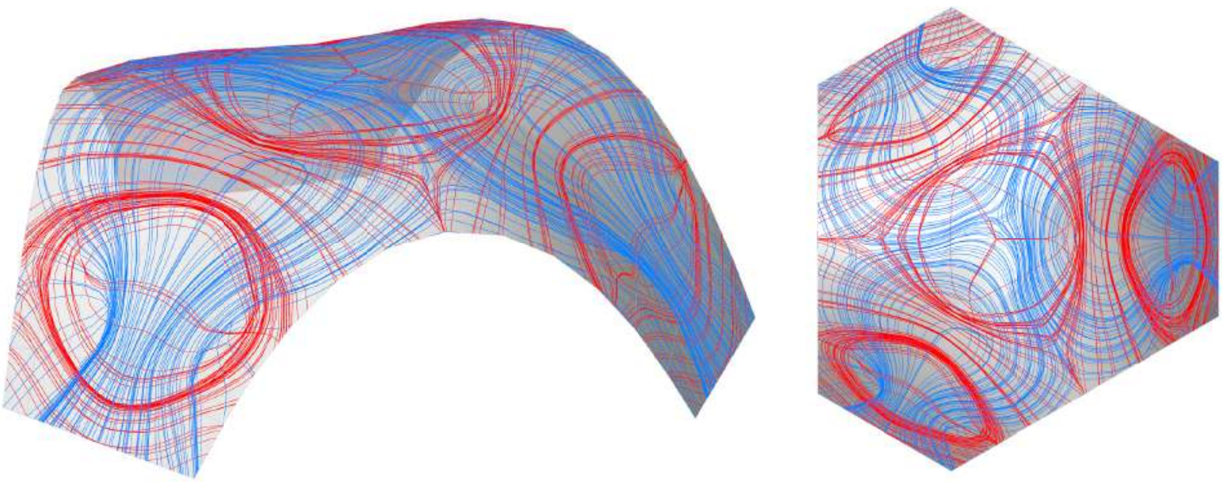
Utilization Diagram



Thickness Diagram



Force Flow Diagram

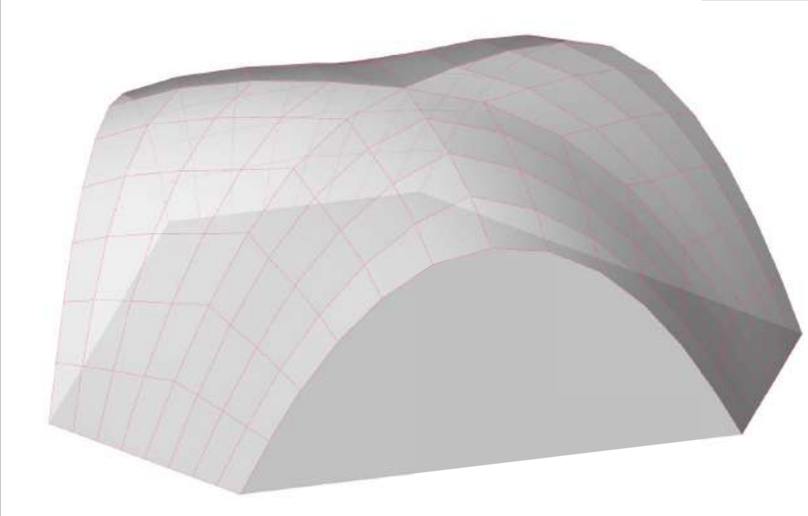


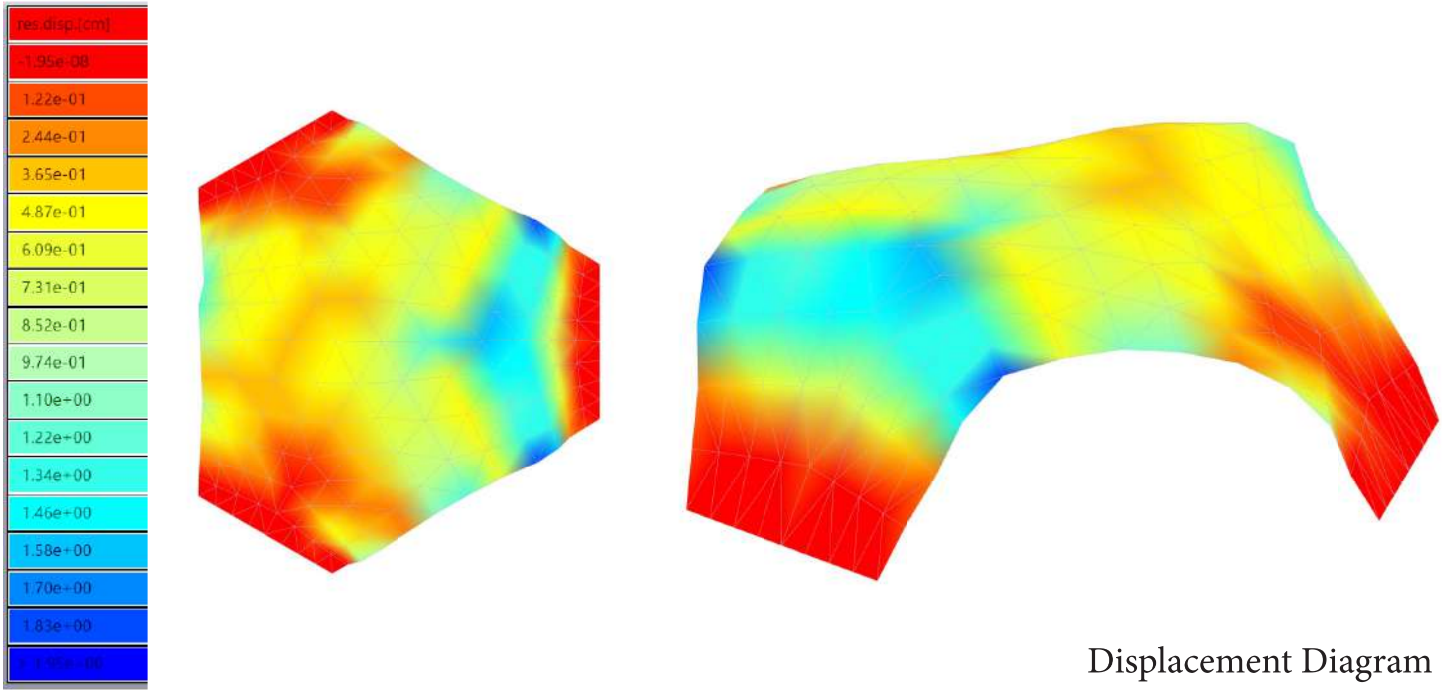
Principal Strees Lines Diagram

SHELL TABLE: 02_Optimazed - 40 QMFG

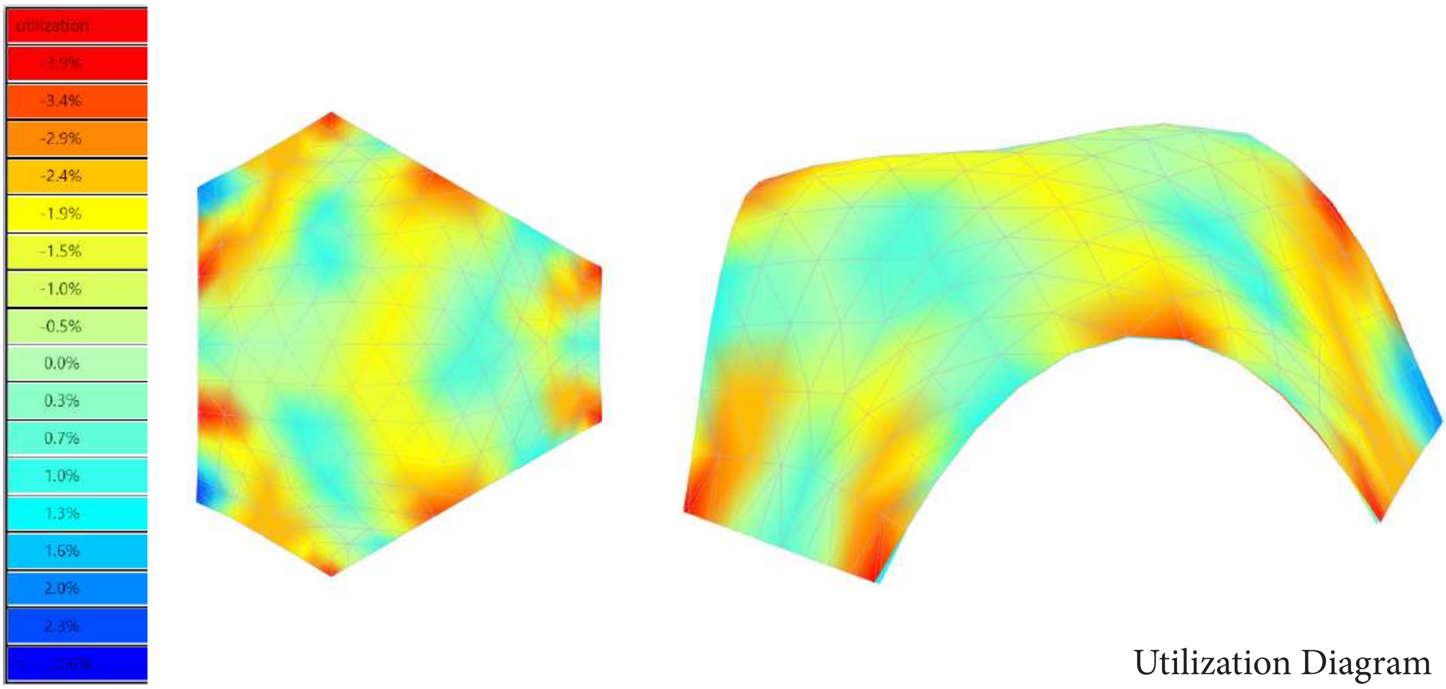
Properties

Area: *457.439m2*
Faces: *144*
Vertices: *336*
Edges: *328*
Perimetral Edges: *60*
Supports: *27*
Optimization: *4% utiliation*
Thickness: *optimazed 1-46.5cm*
Forces: *Gravity + 100KN wind (X)*

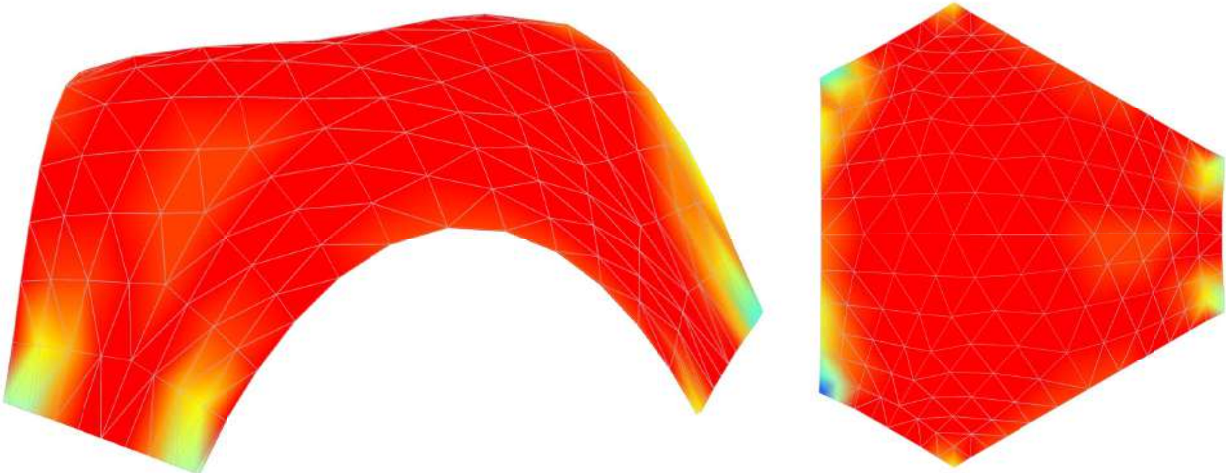




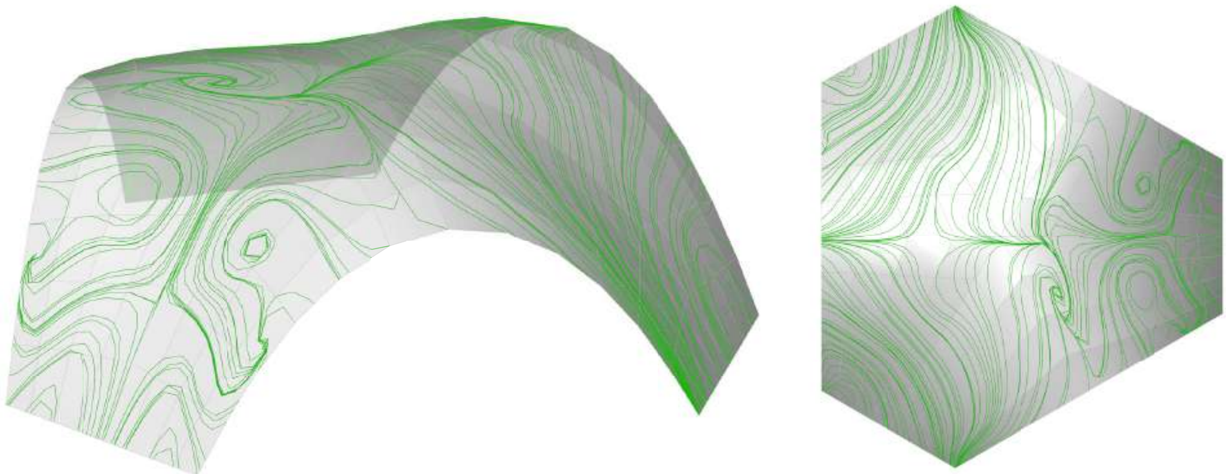
Displacement Diagram



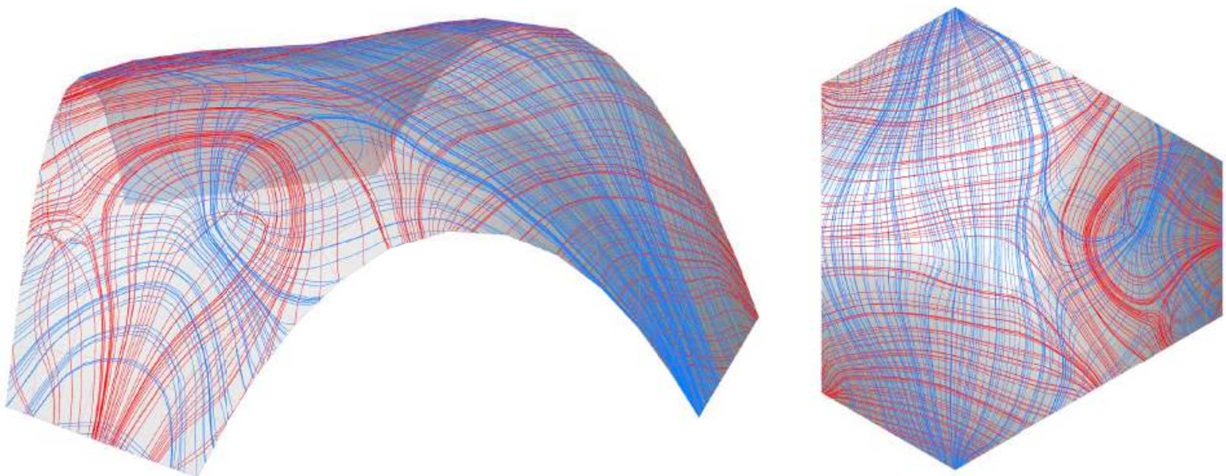
Utilization Diagram



Thickness Diagram *1 - 3.84 - 6.69 cm (red-orange)*

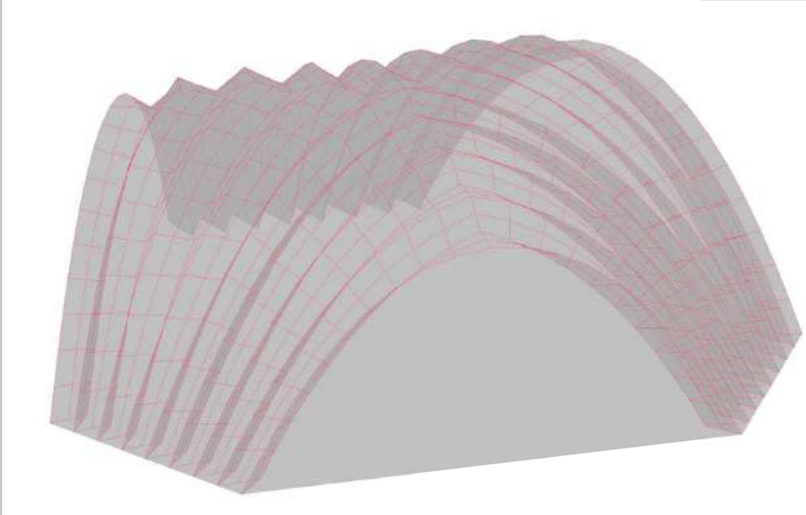


Force Flow Diagram



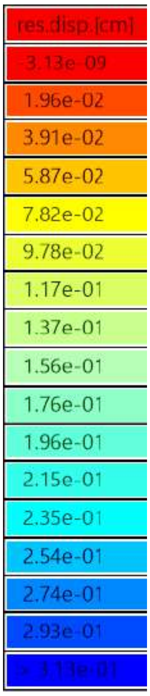
Principal Strees Lines Diagram

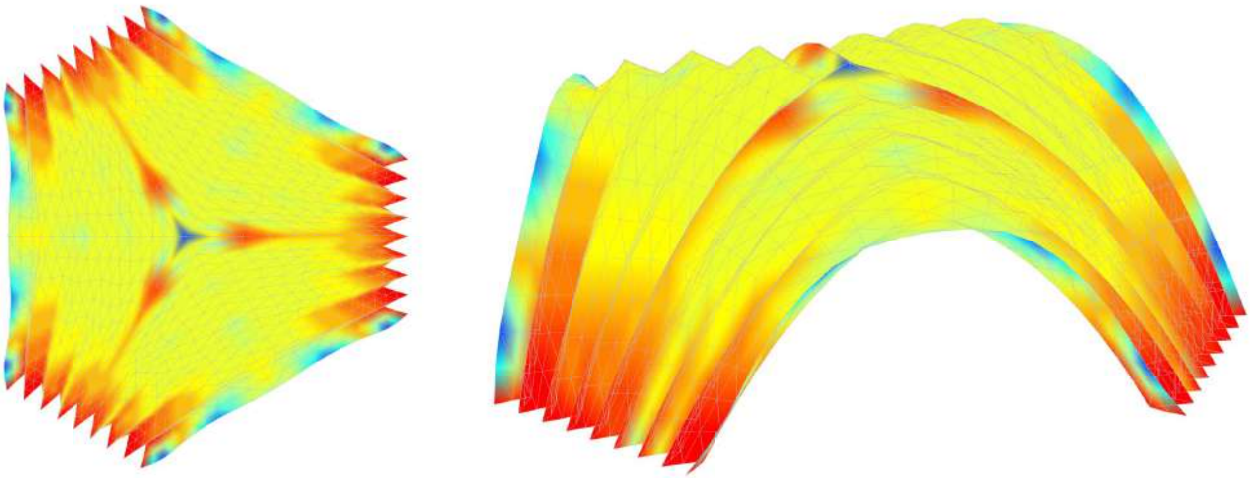
Shell Table: 03_Folded & Optimazed - 40 QMFG



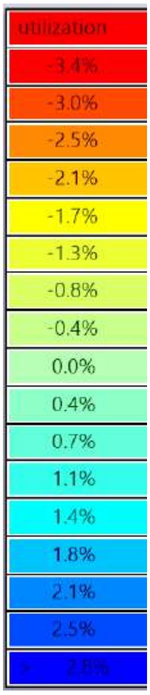
Properties

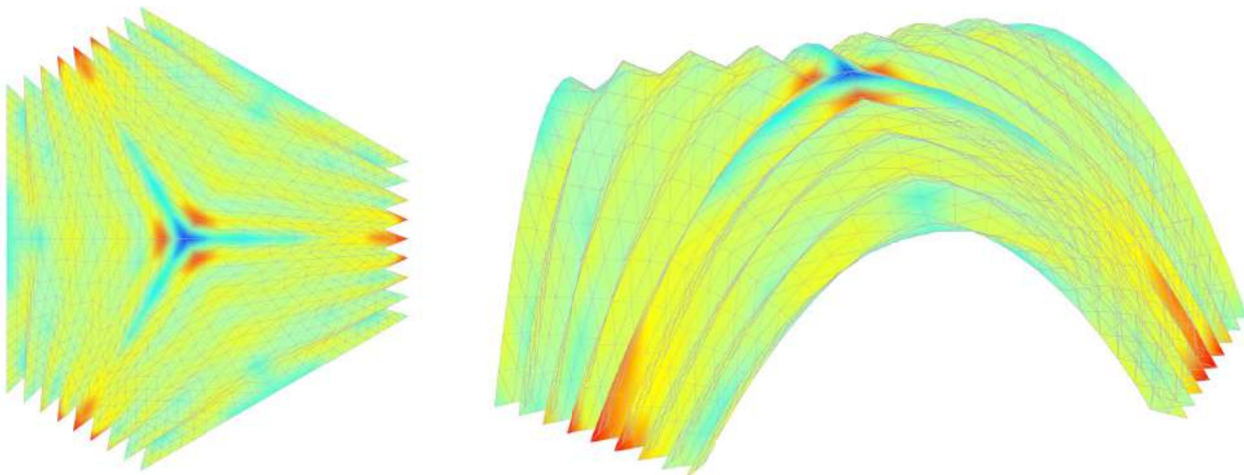
Area: *691.609m2*
Faces: *960*
Vertices: *1039*
Edges: *1998*
Perimetral Edges: *156*
Supports: *27*
Optimization: *4% utiliation*
Thickness: *optimazed 1-2cm*
Forces: *Gravity*



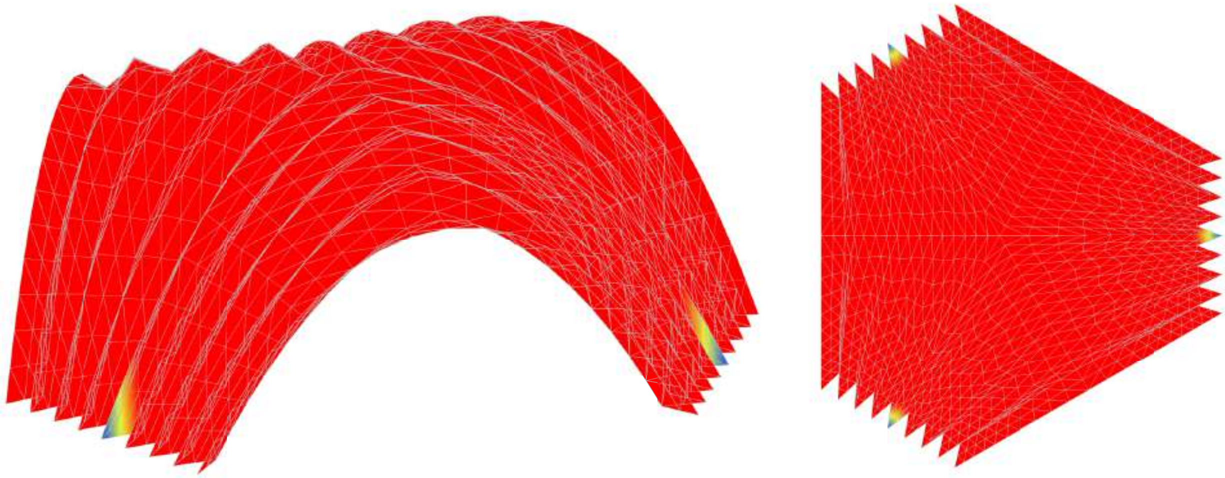


Displacement Diagram

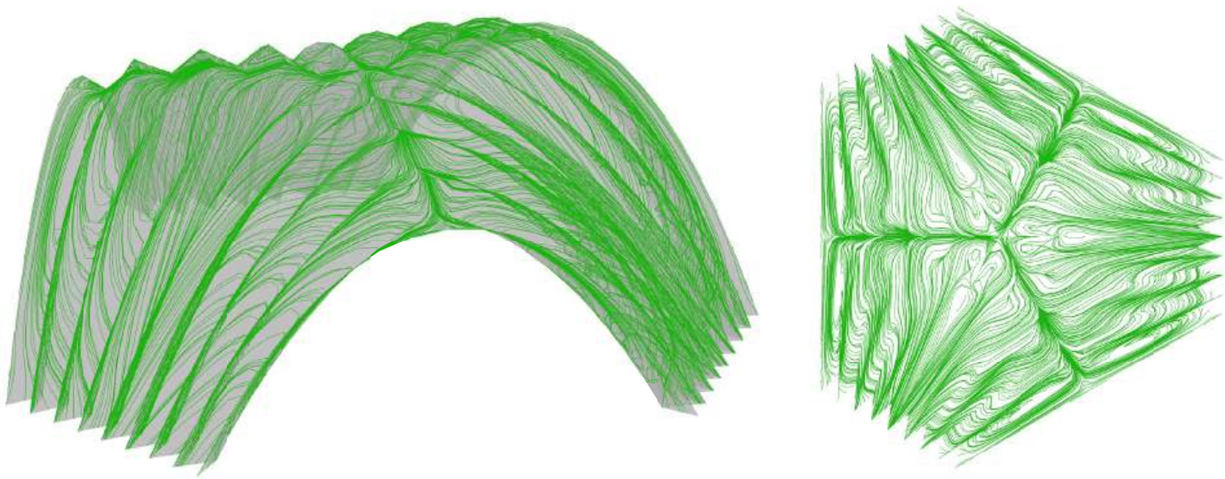




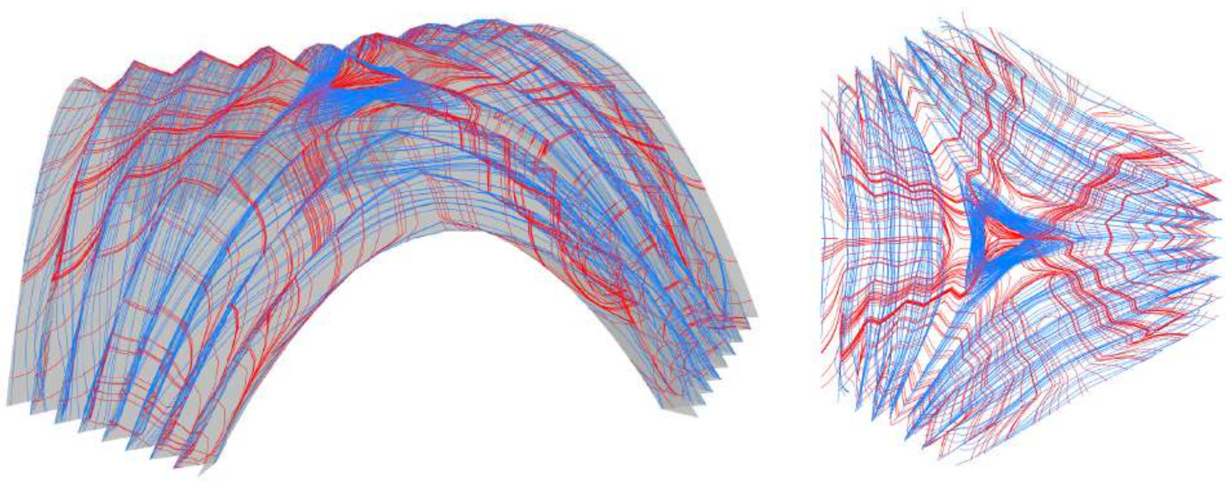
Utilization Diagram



Thickness Diagram



Force Flow Diagram

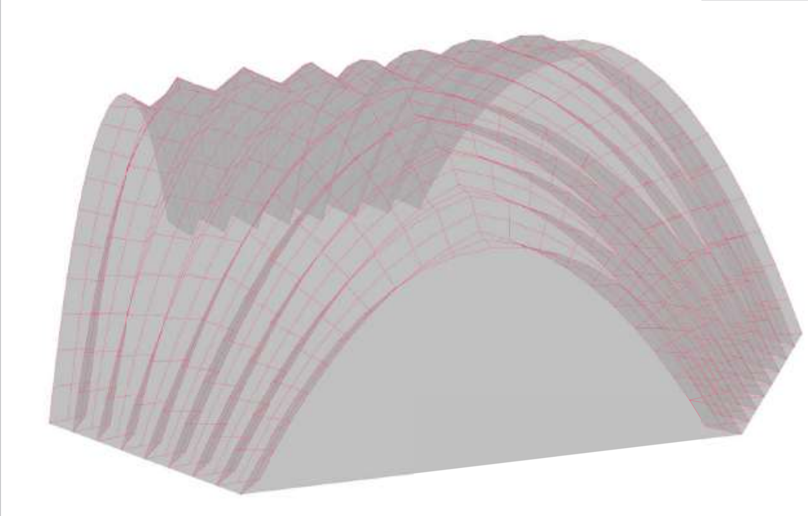


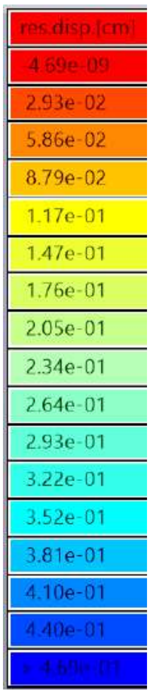
Principal Strees Lines Diagram

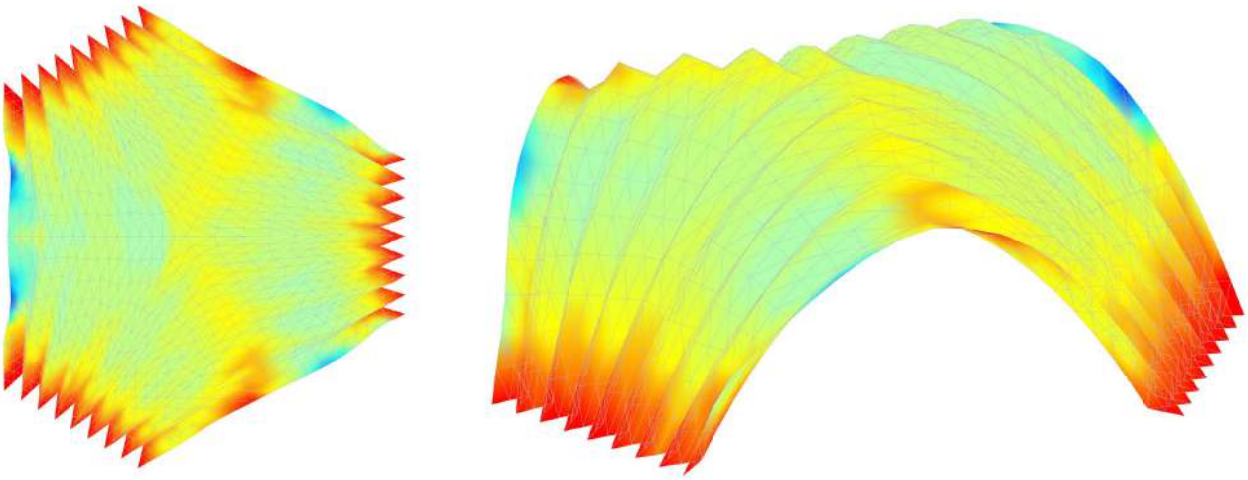
Shell Table: 04_Folded & Optimazed - 40 QMFG

Properties

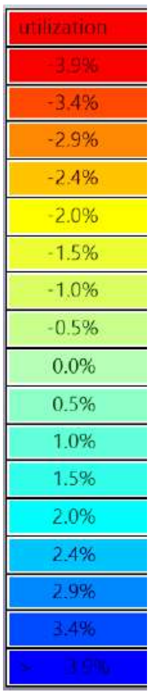
Area: *691.609m2*
Faces: *960*
Vertices: *1039*
Edges: *1998*
Perimetral Edges: *156*
Supports: *27*
Optimization: *4% utiliation*
Thickness: *optimazed 1-14.1cm*
Forces: *Gravity + 100KN wind (X)*

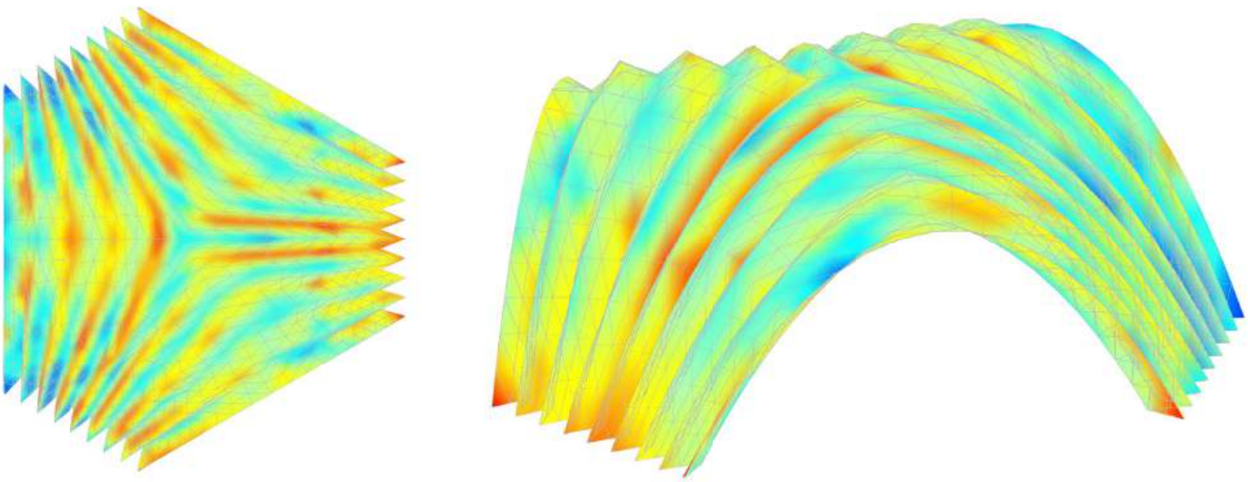




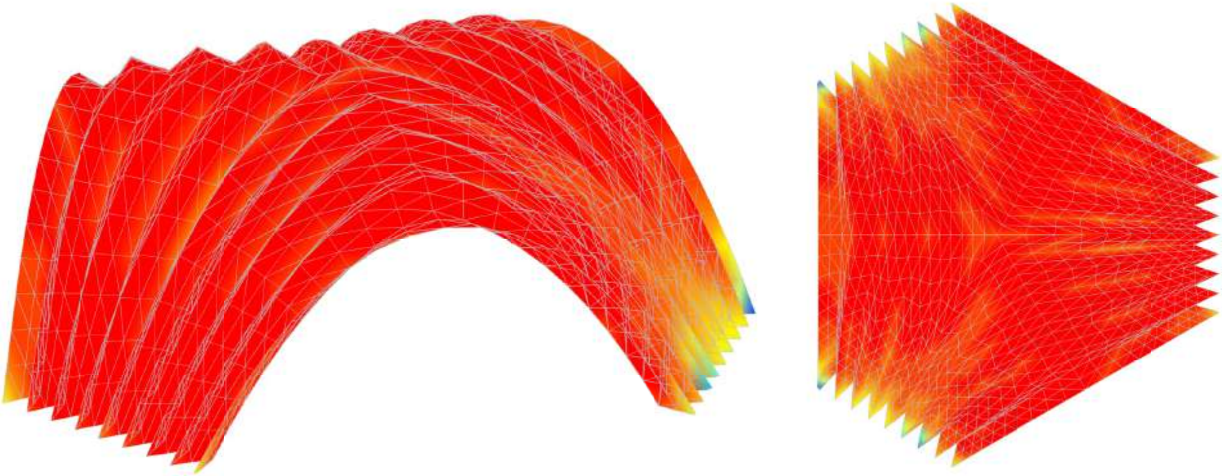


Displacement Diagram

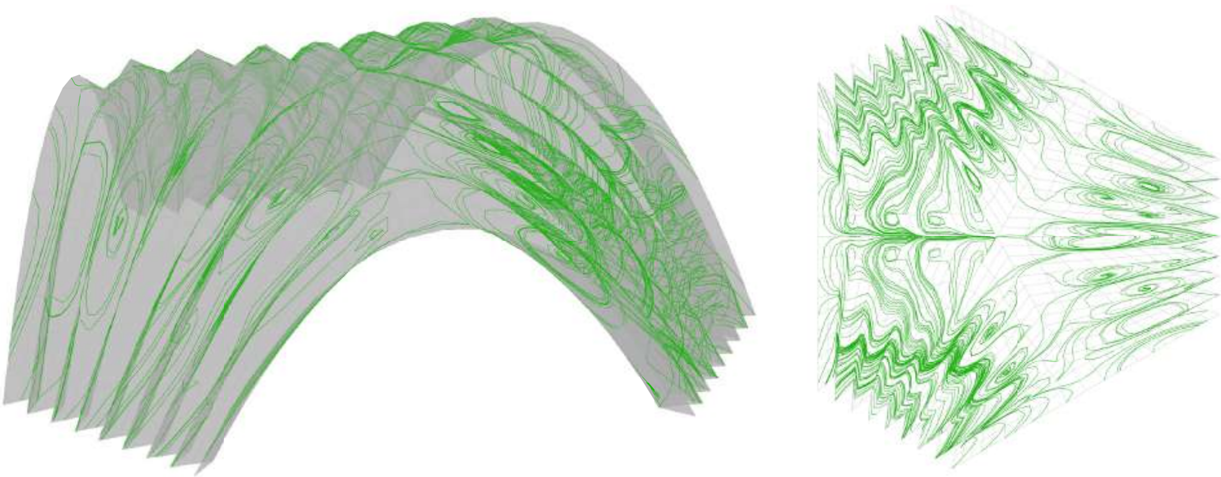




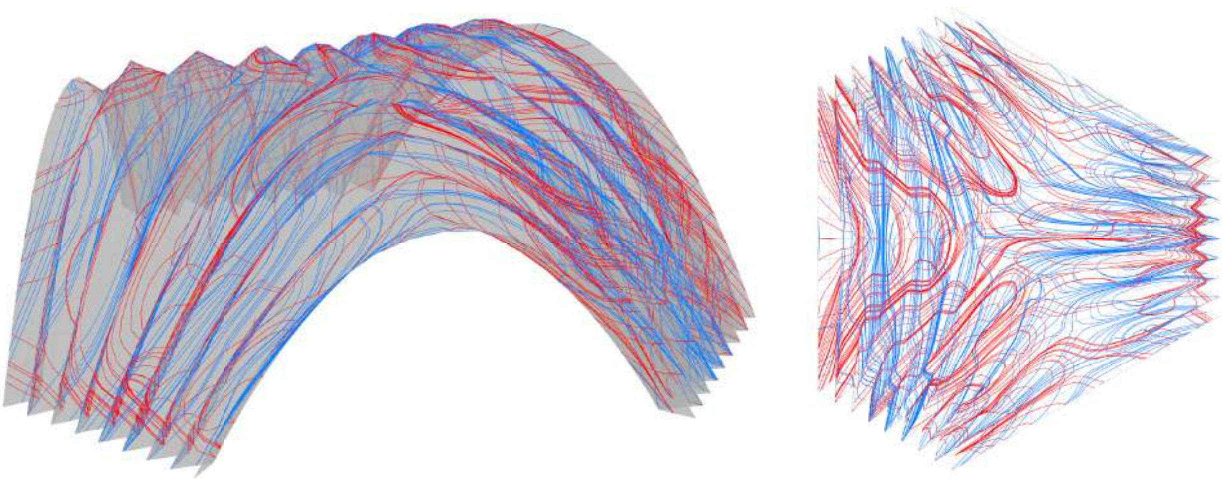
Utilization Diagram



Thickness Diagram *1 - 1.88 - 2.75 cm (red-orange)*

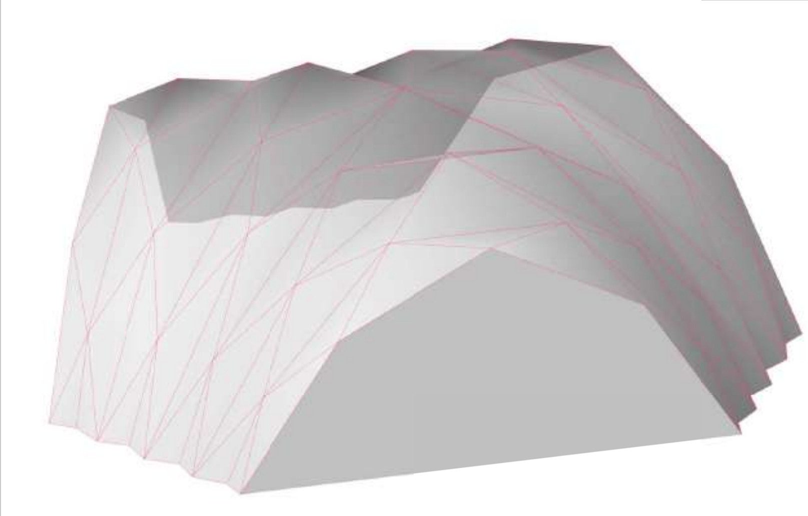


Force Flow Diagram



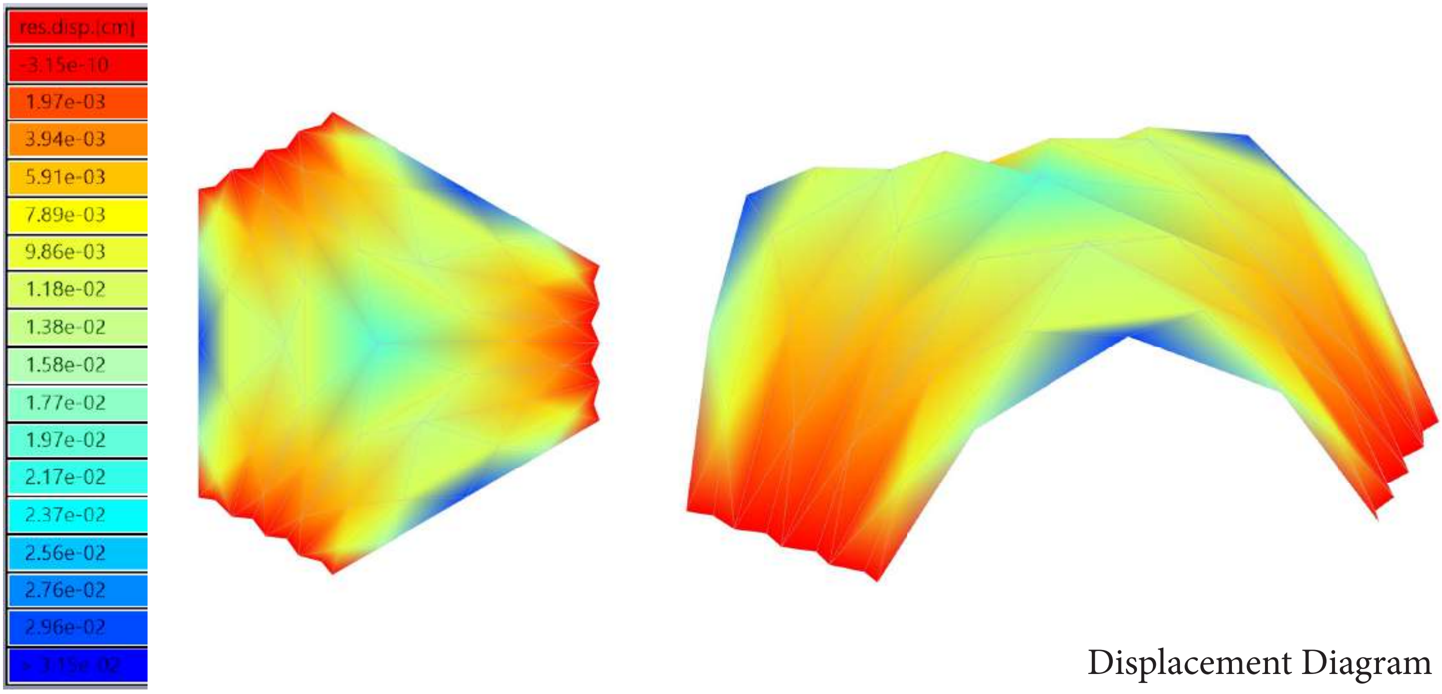
Principal Strees Lines Diagram

Shell Table: 05_Yoshimura - 40 QMFG

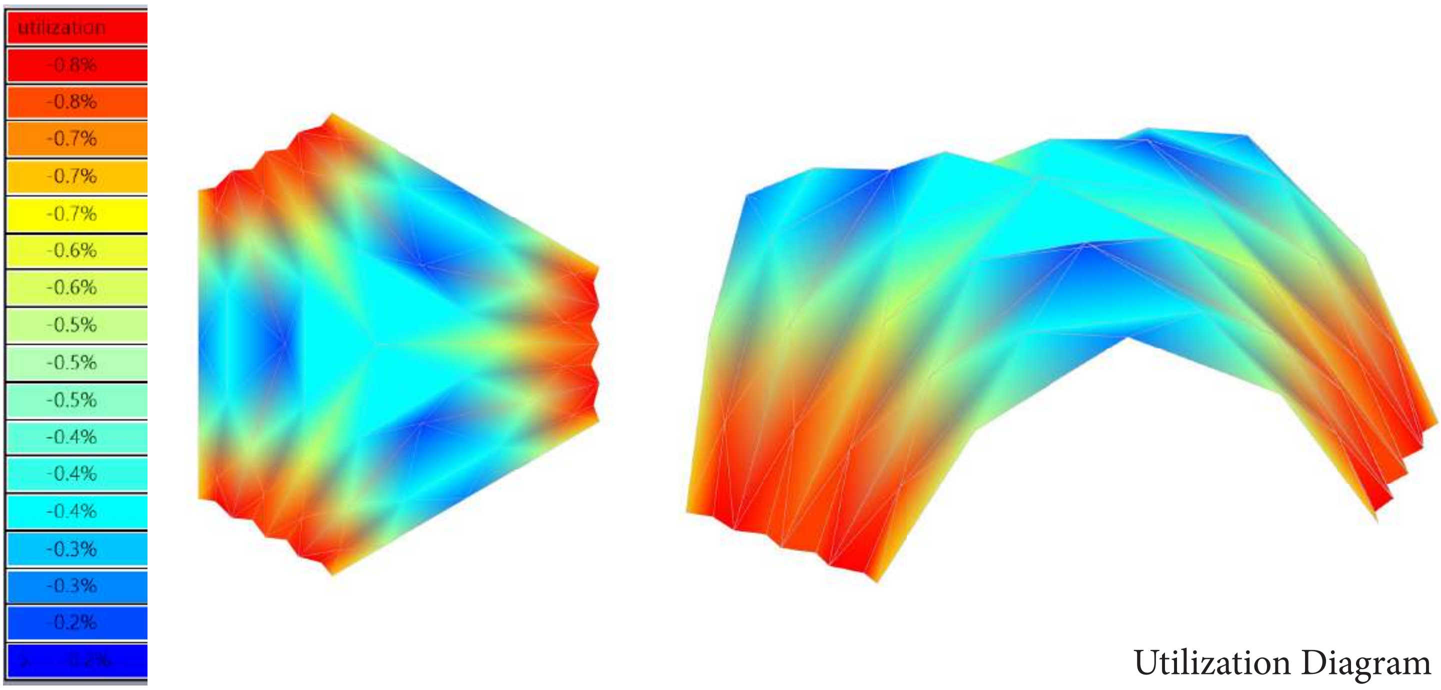


Properties

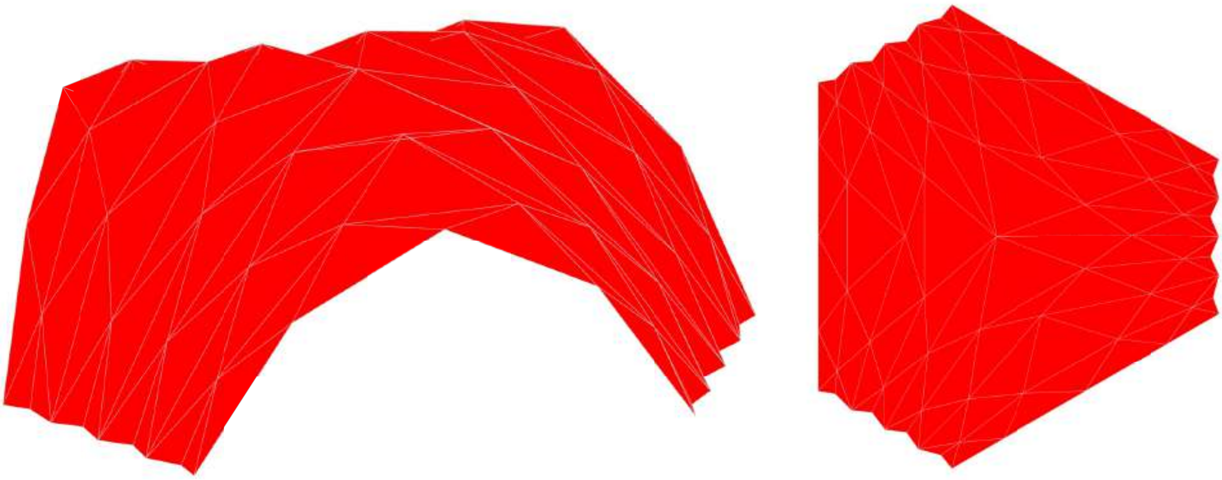
Area: *473.115m2*
Faces: *108*
Vertices: *73*
Edges: *180*
Perimetral Edges: *36*
Supports: *27*
Optimization: *4% utiliation*
Thickness: *optimazed 1cm*
Forces: *Gravity*



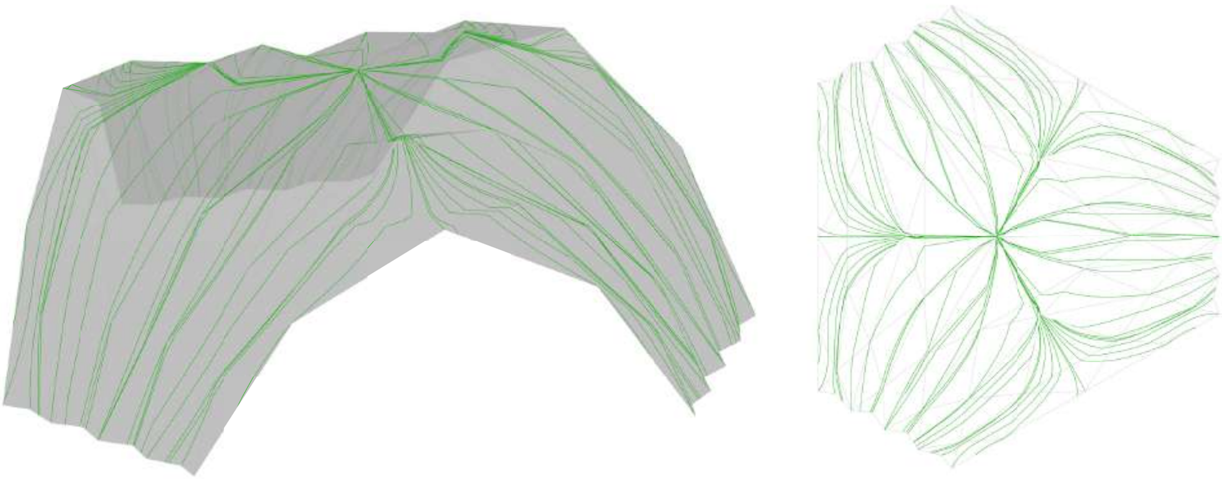
Displacement Diagram



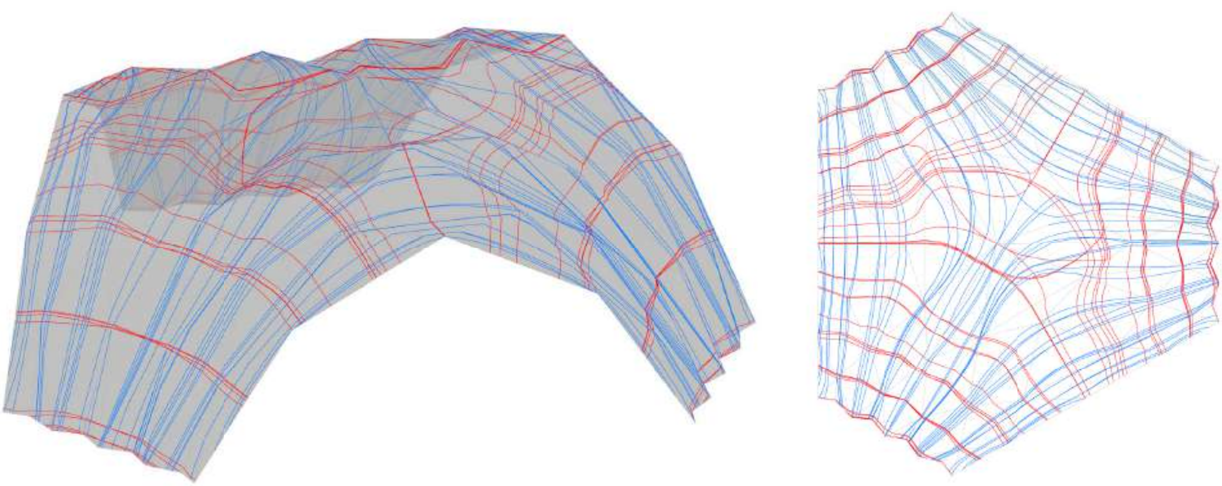
Utilization Diagram



Thickness Diagram



Force Flow Diagram

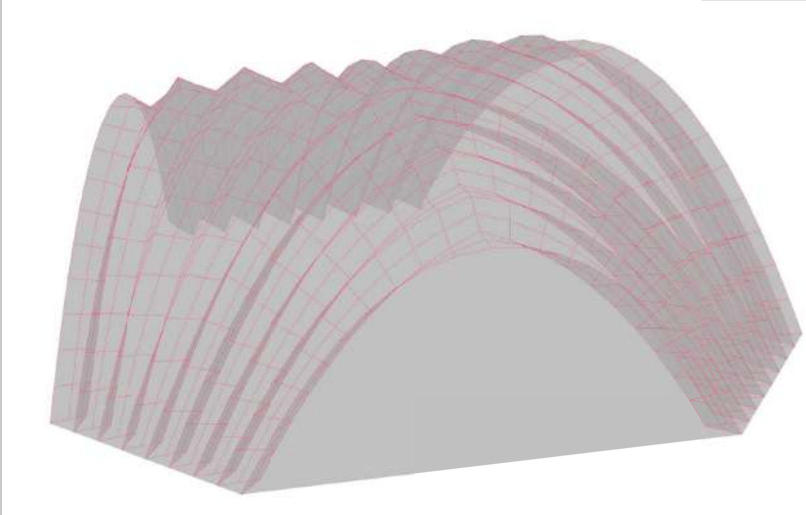


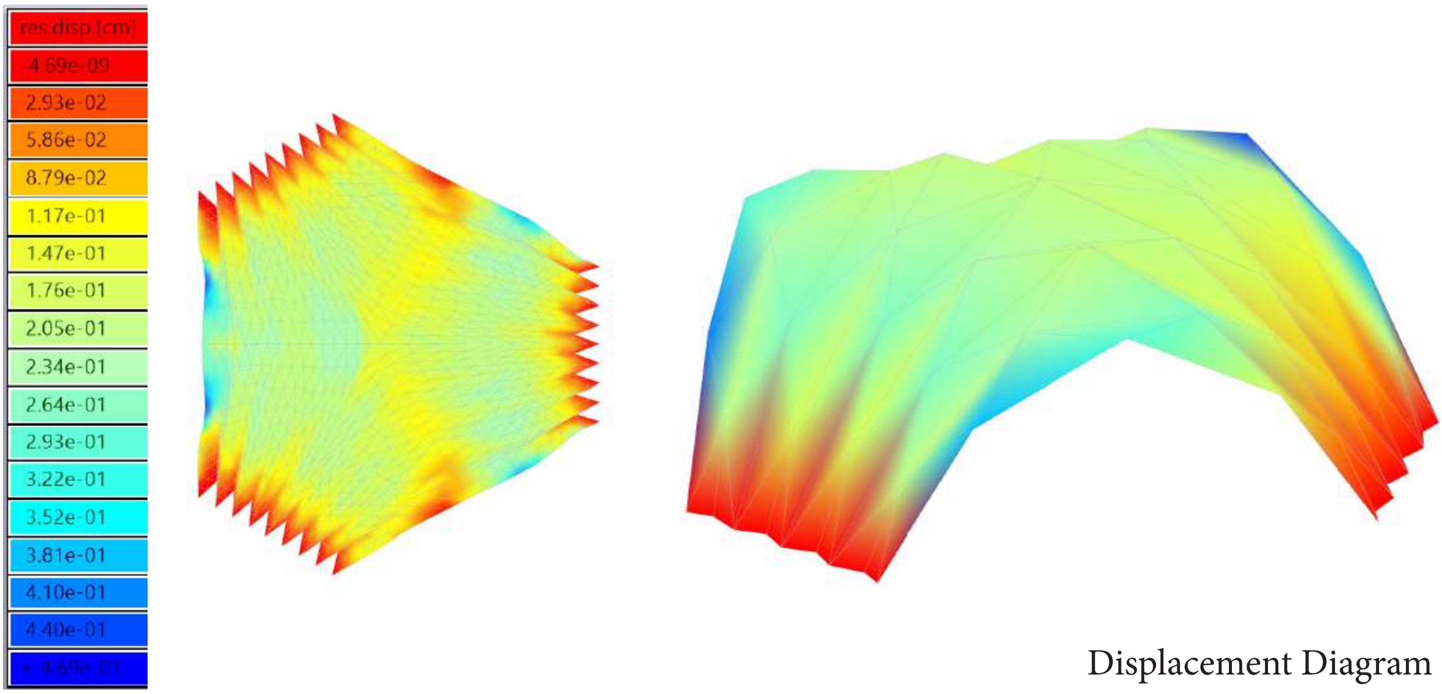
Principal Strees Lines Diagram

Shell Table: 06_Yoshimura - 40 QMFG

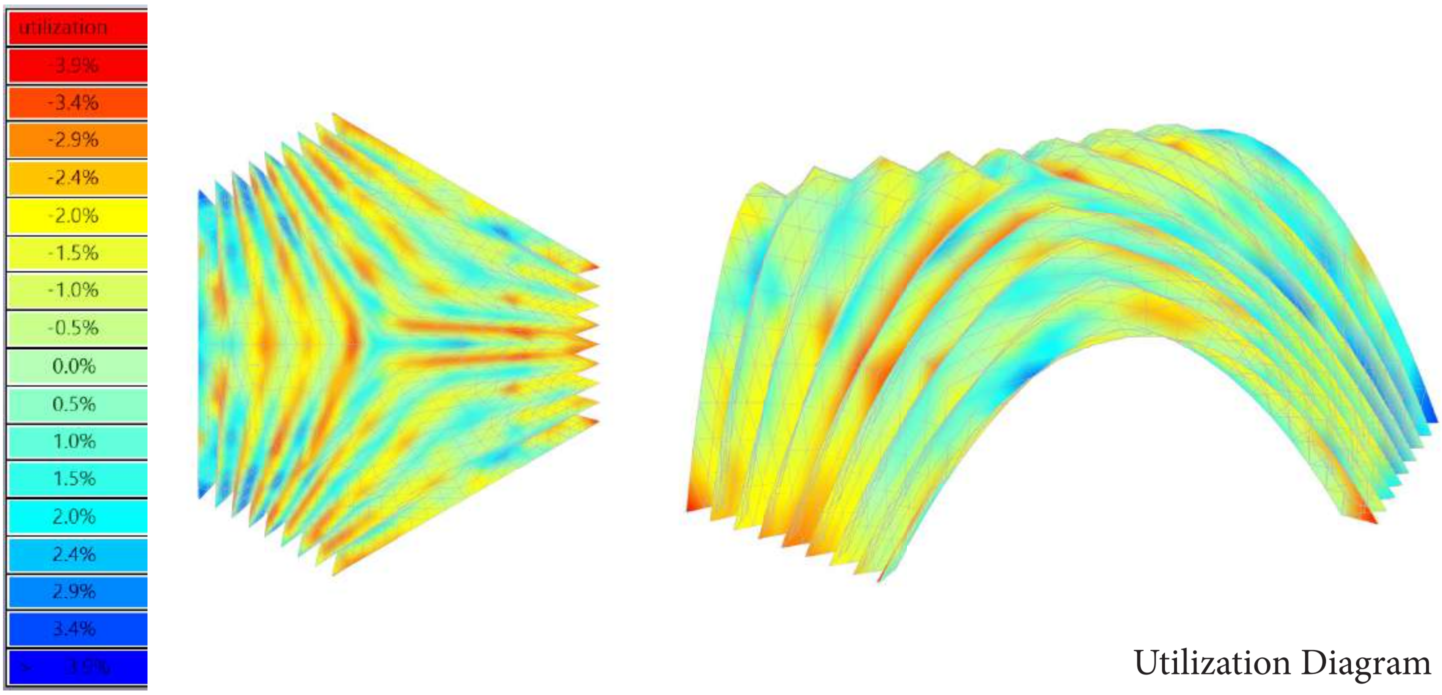
Properties

Area: *473.115m2*
Faces: *108*
Vertices: *73*
Edges: *180*
Perimetral Edges: *36*
Supports: *27*
Optimization: *4% utiliation*
Thickness: *optimazed 1- 4cm*
Forces: *Gravity + 100KN wind (X)*

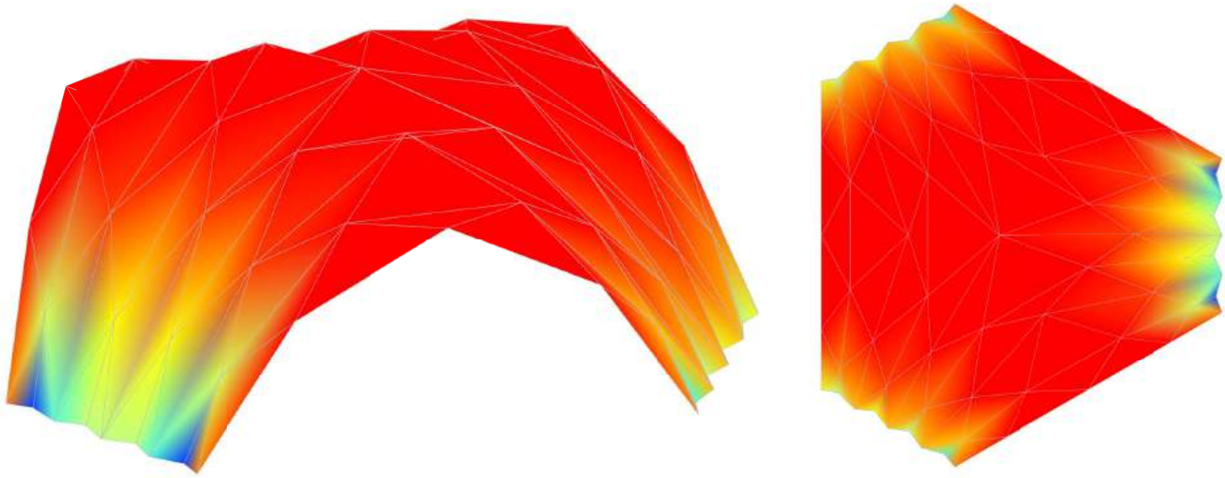




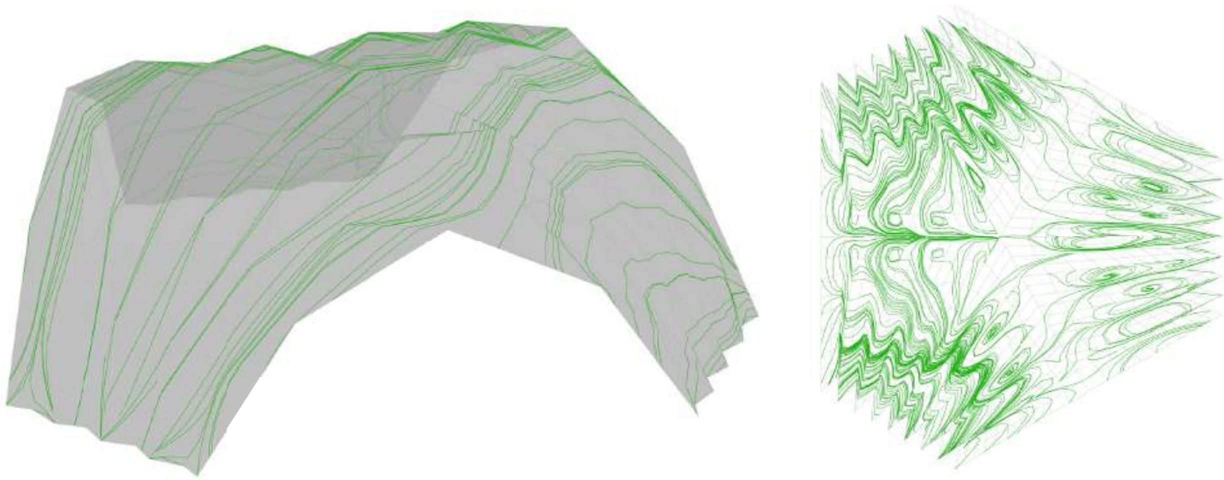
Displacement Diagram



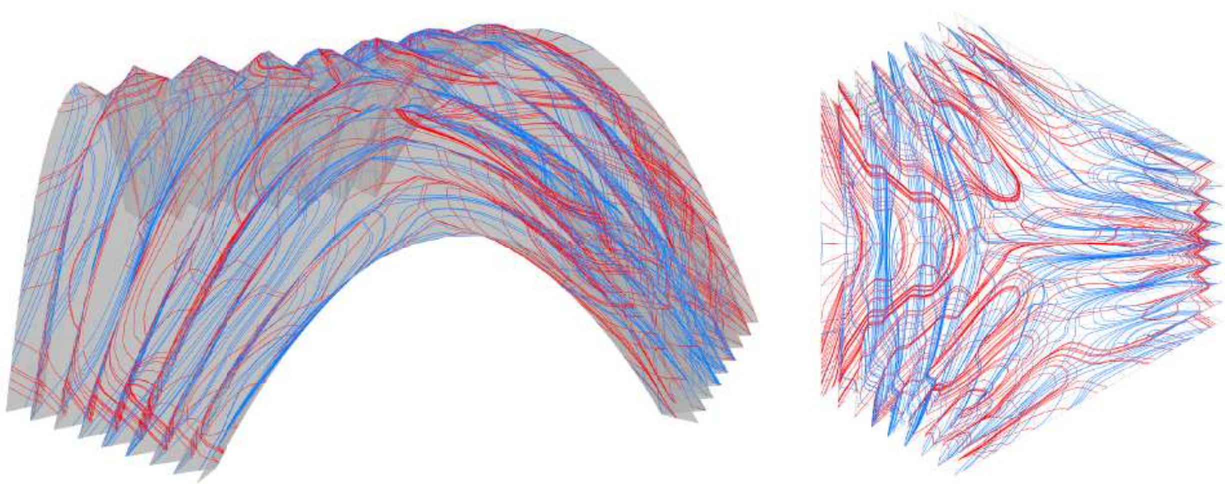
Utilization Diagram



Thickness Diagram

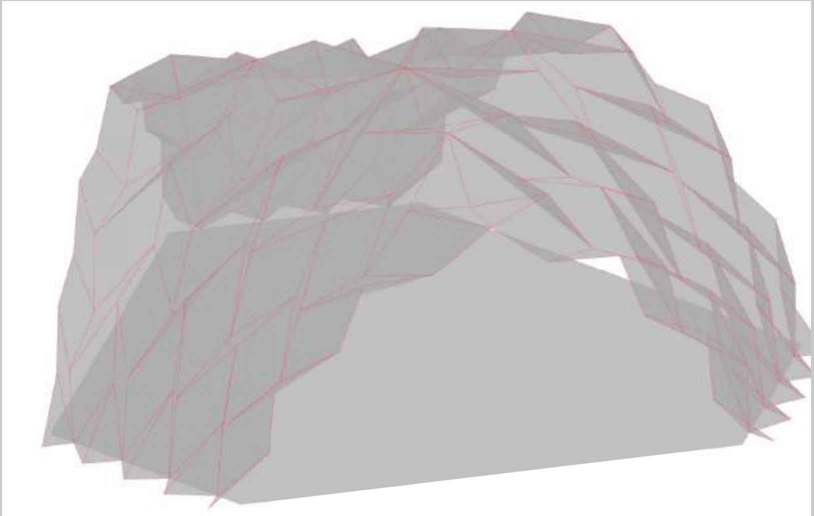


Force Flow Diagram



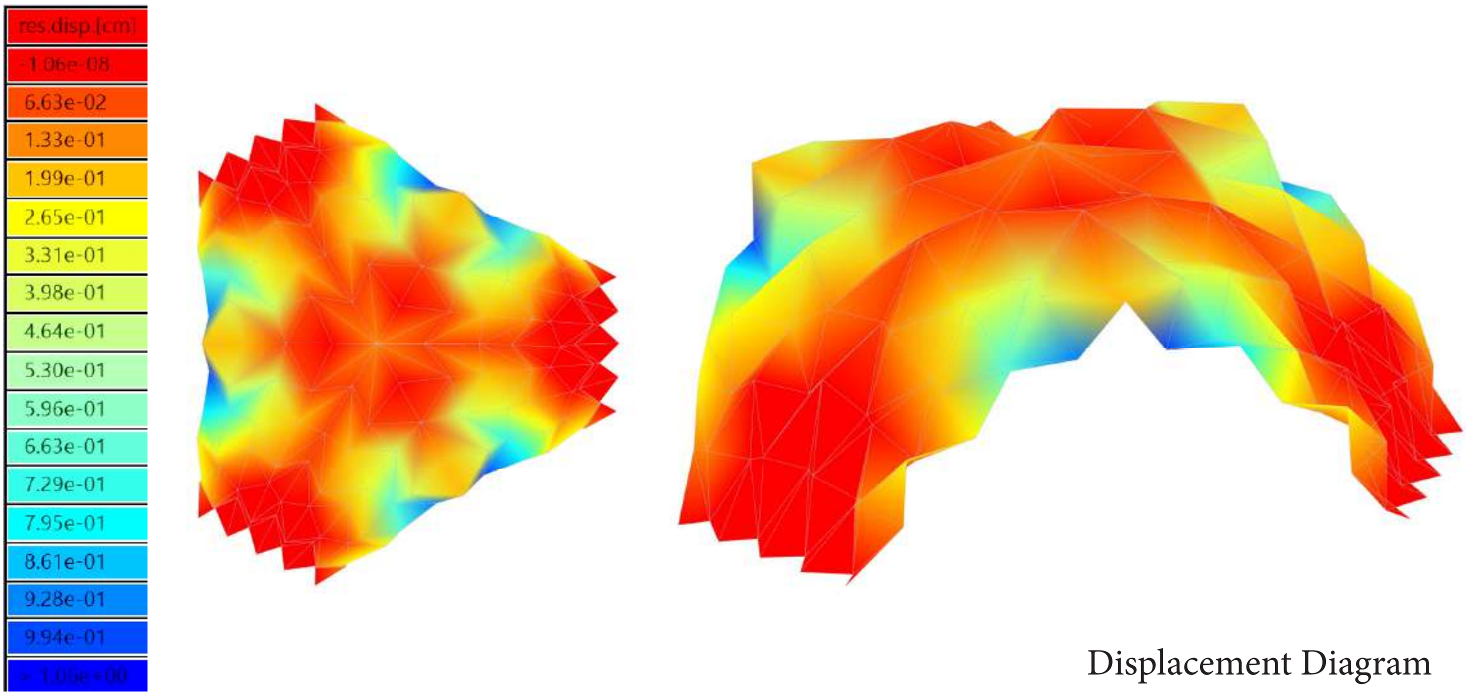
Principal Strees Lines Diagram

Shell Table: 07_Miura ori - 40 QMFG

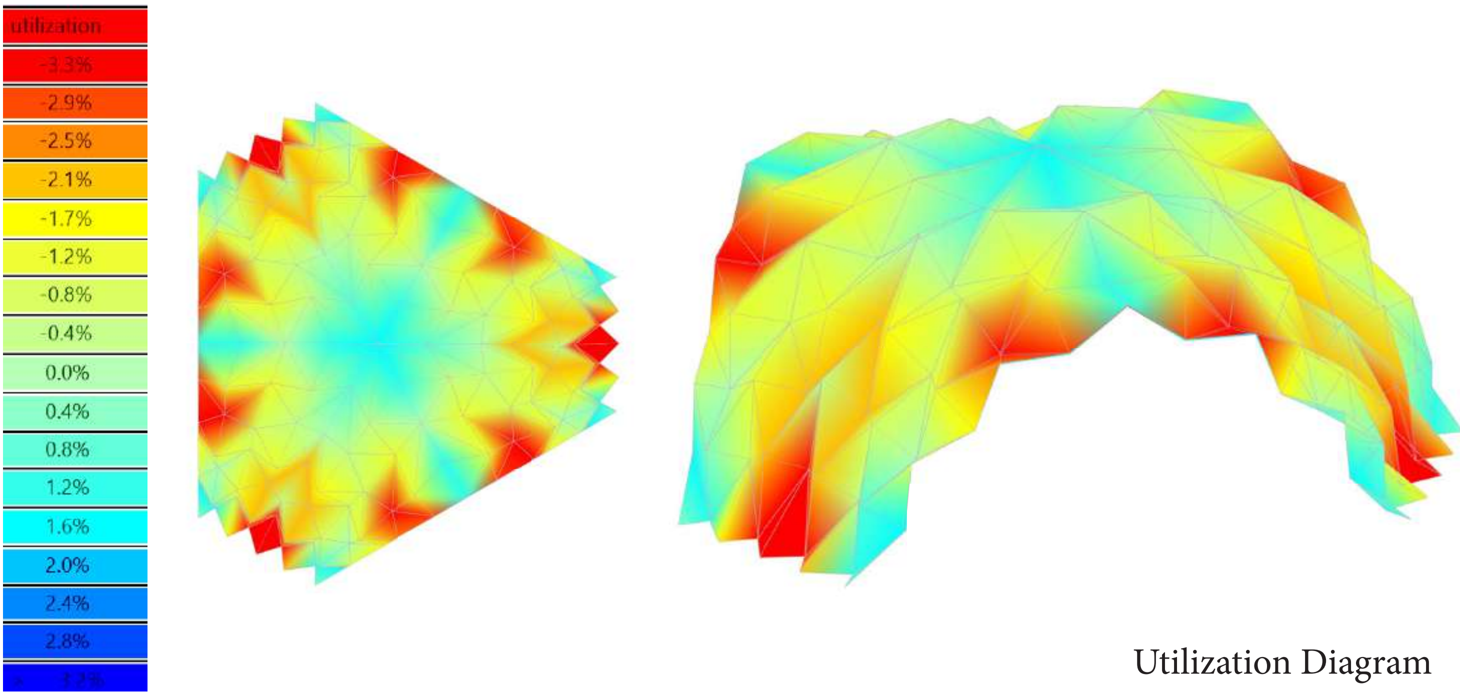


Properties

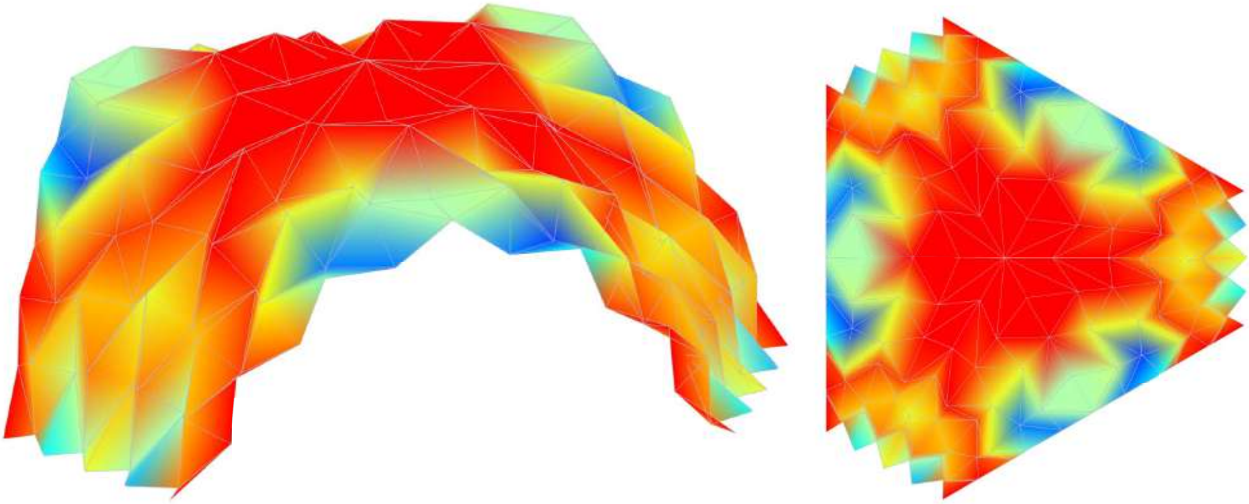
Area: *614.404m2*
Faces: *168*
Vertices: *175*
Edges: *342*
Perimetral Edges: *60*
Supports: *27*
Optimization: *4% utiliation*
Thickness: *optimazed 1-6.5cm*
Forces: *Gravity + 100KN wind (X)*



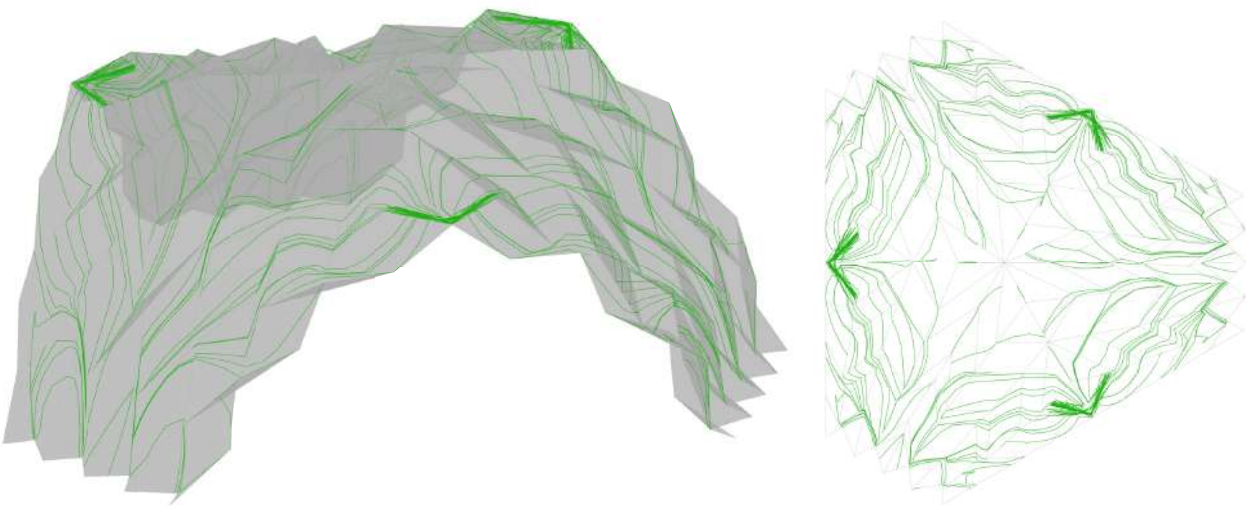
Displacement Diagram



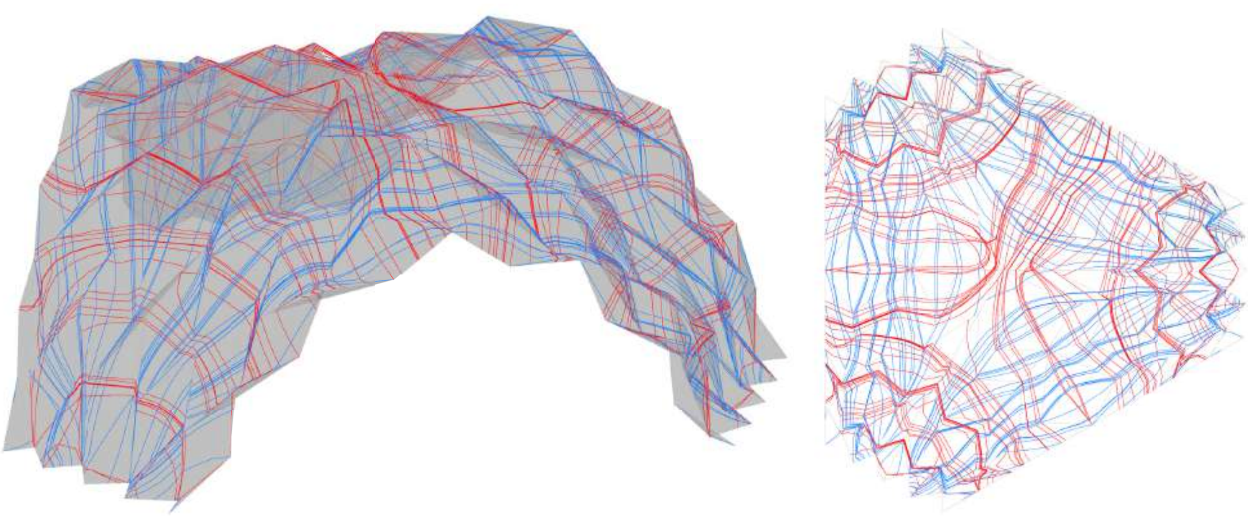
Utilization Diagram



Thickness Diagram *1 - 1.35- 1.7 cm (red-orange)*

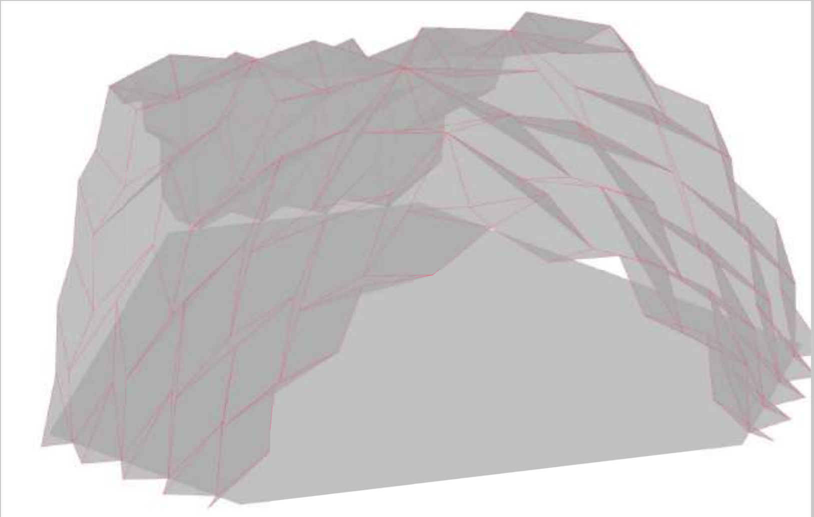


Force Flow Diagram



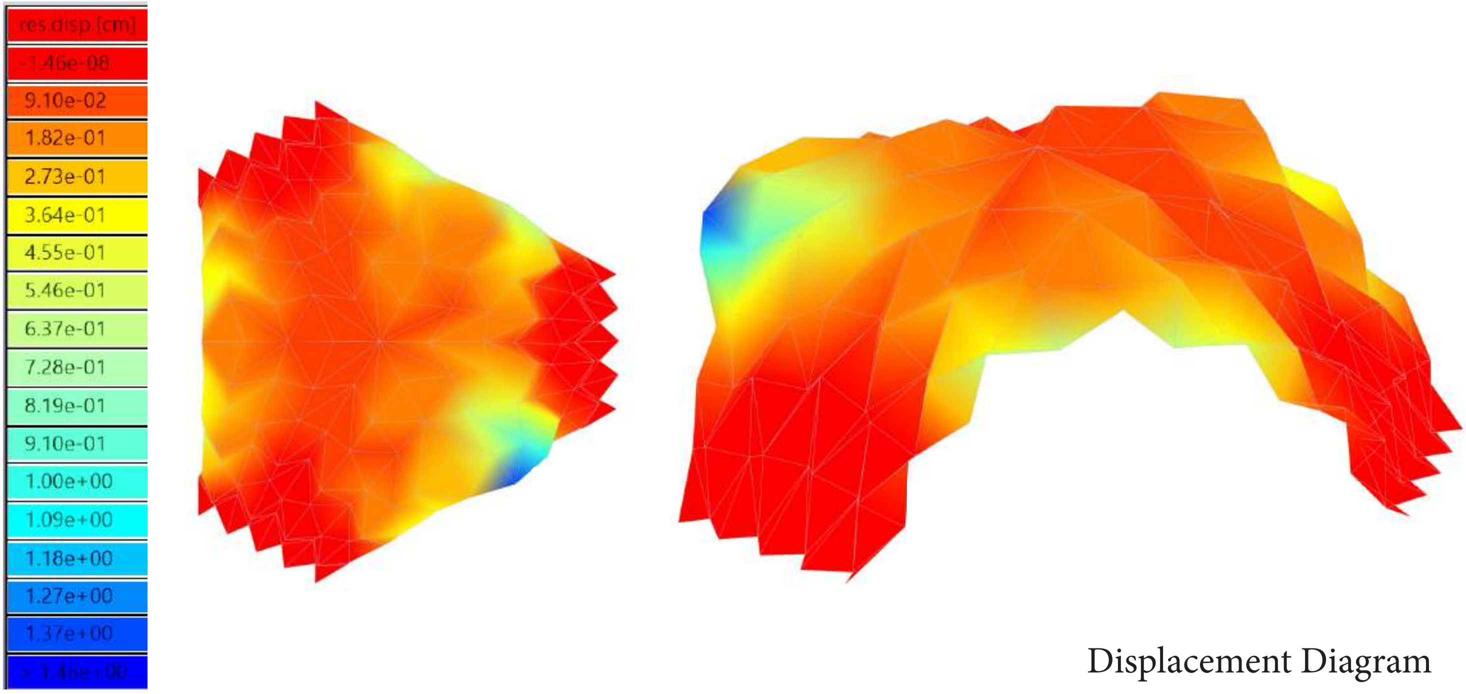
Principal Strees Lines Diagram

Shell Table: 08_Miura ori - 40 QMFG

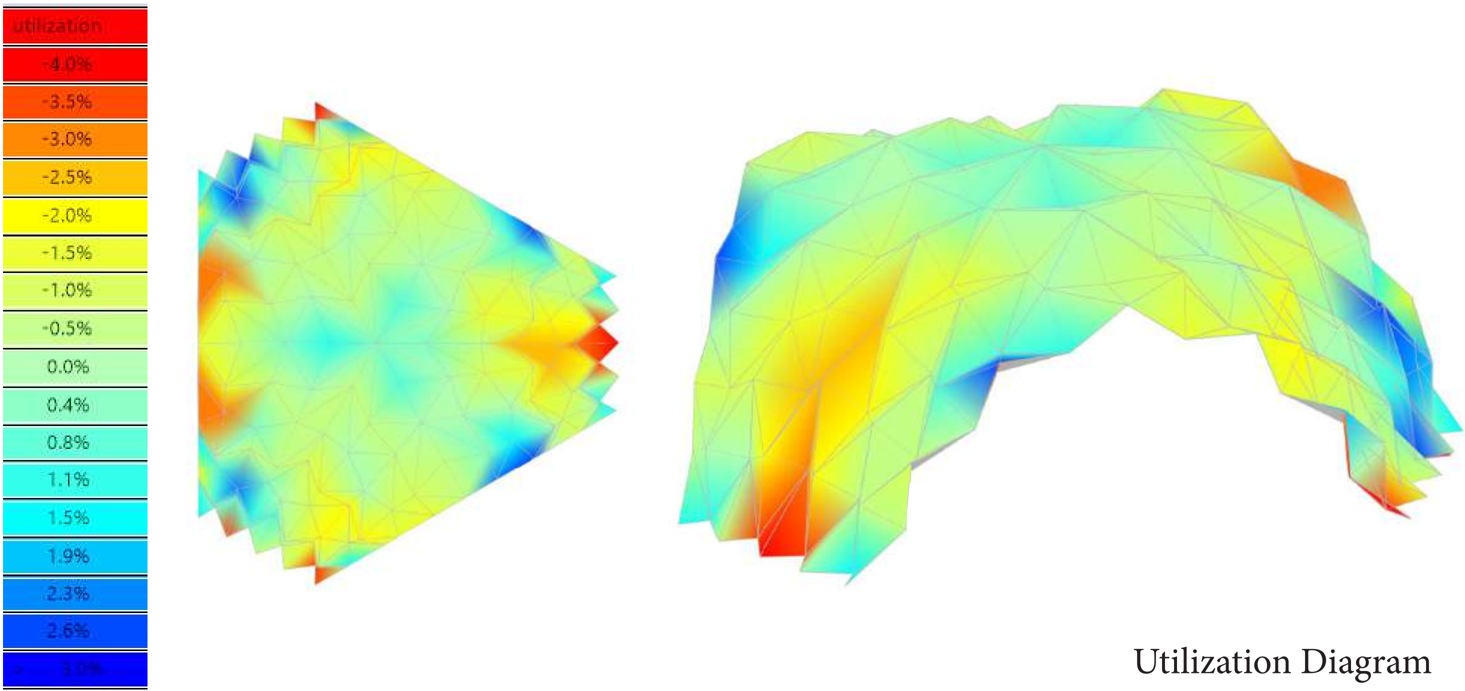


Properties

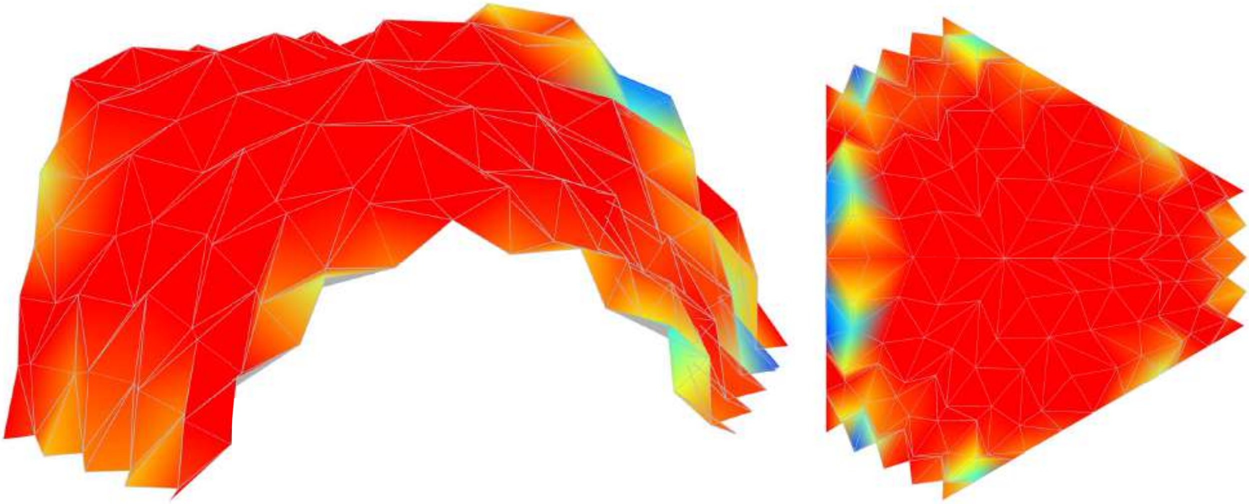
Area: *614.404m2*
Faces: *168*
Vertices: *175*
Edges: *342*
Perimetral Edges: *60*
Supports: *27*
Optimization: *4% utiliation*
Thickness: *optimazed 1-17cm*
Forces: *Gravity + 100KN wind (X)*



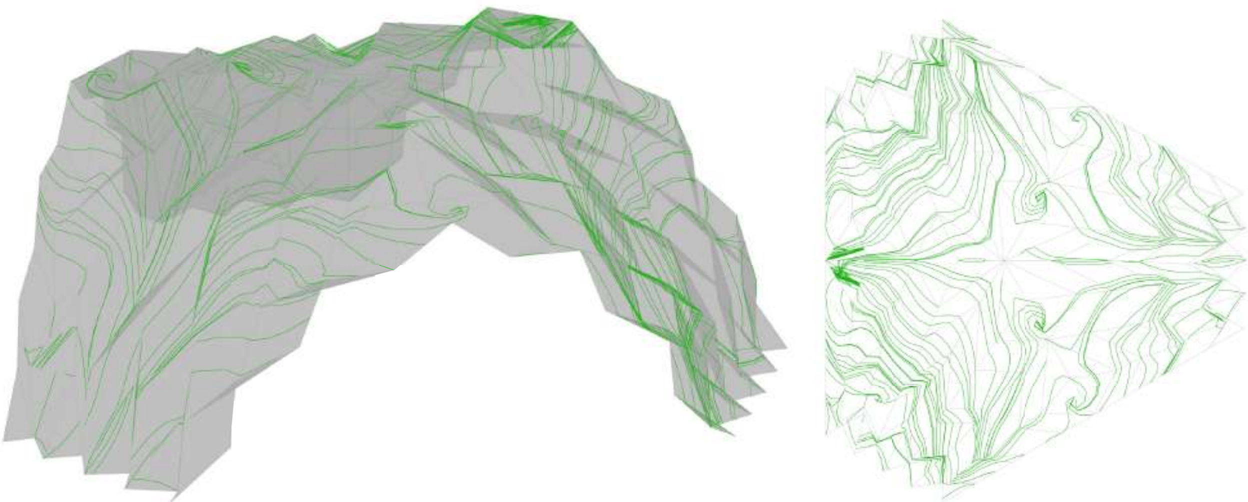
Displacement Diagram



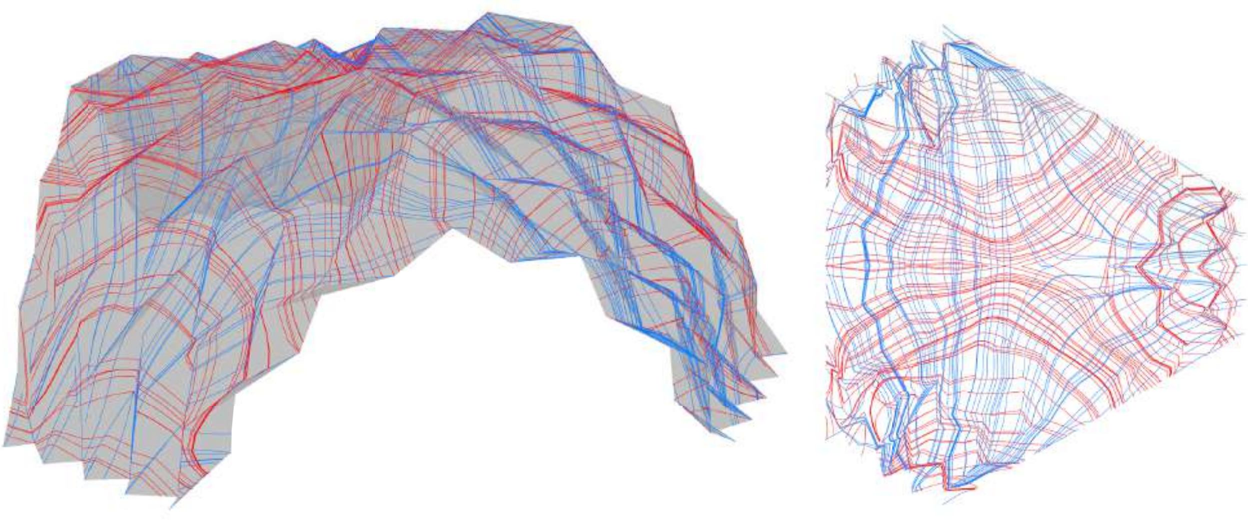
Utilization Diagram



Thickness Diagram *1 - 2- 3 cm (red-orange)*



Force Flow Diagram



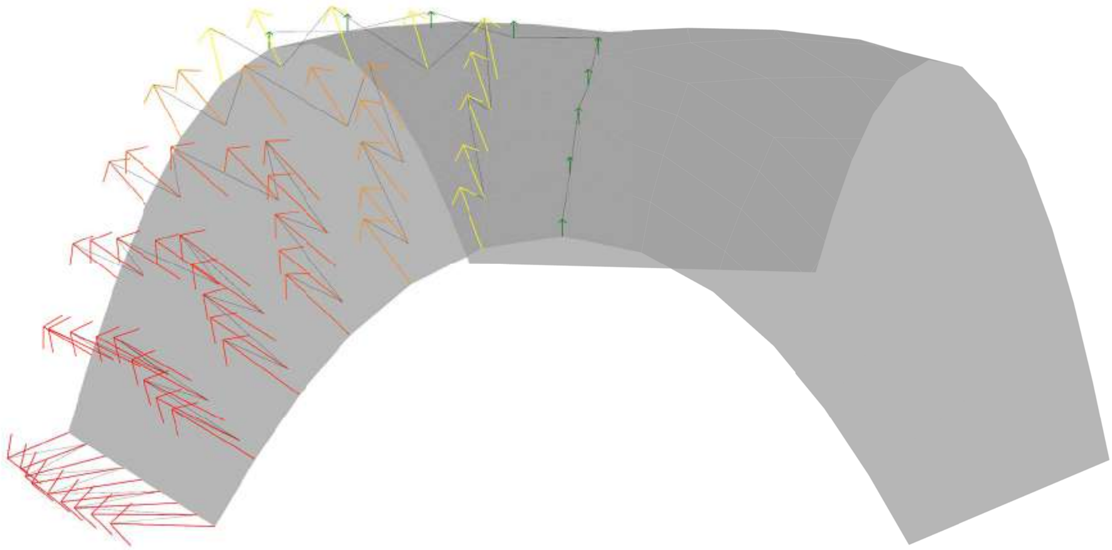
Principal Strees Lines Diagram

5.1_Miura Ori regularized

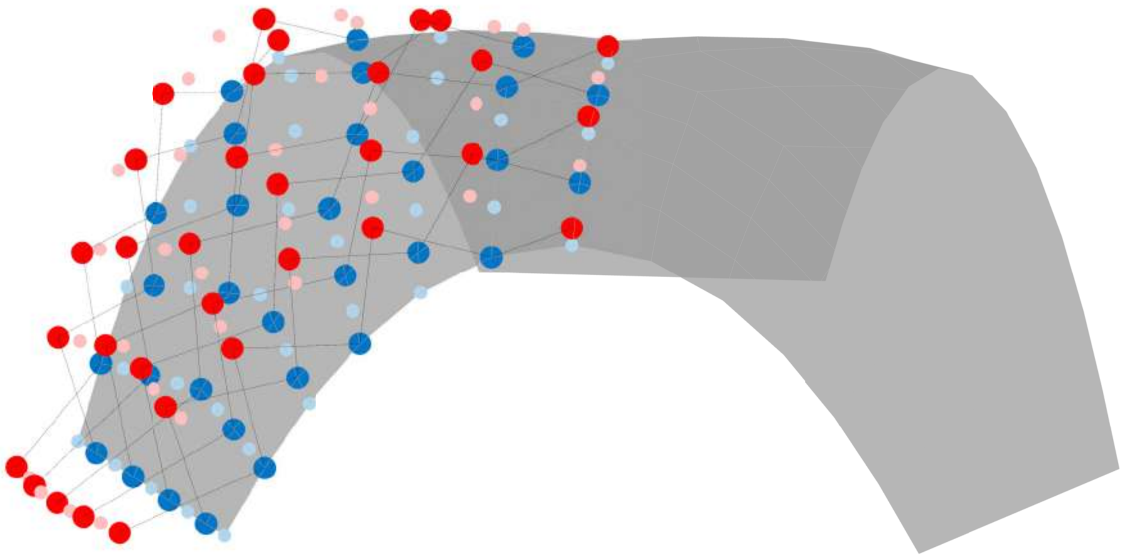
One goal, exposed on the introduction, was to create an origami definition that can be unfolded to a single 2D piece, if possible a rectangle, and one that actually made sense.

Inthis design, it's just achieved that the width of the quads, are the same. The strategy to do it, is to offset the nodes of the mesh in a perpendicular direction the distance that makes them regular by brute force (galapagos).

So, this design doesn't get the final goal, but a first step (the vertical lines of the pattern should be straight or paralell).



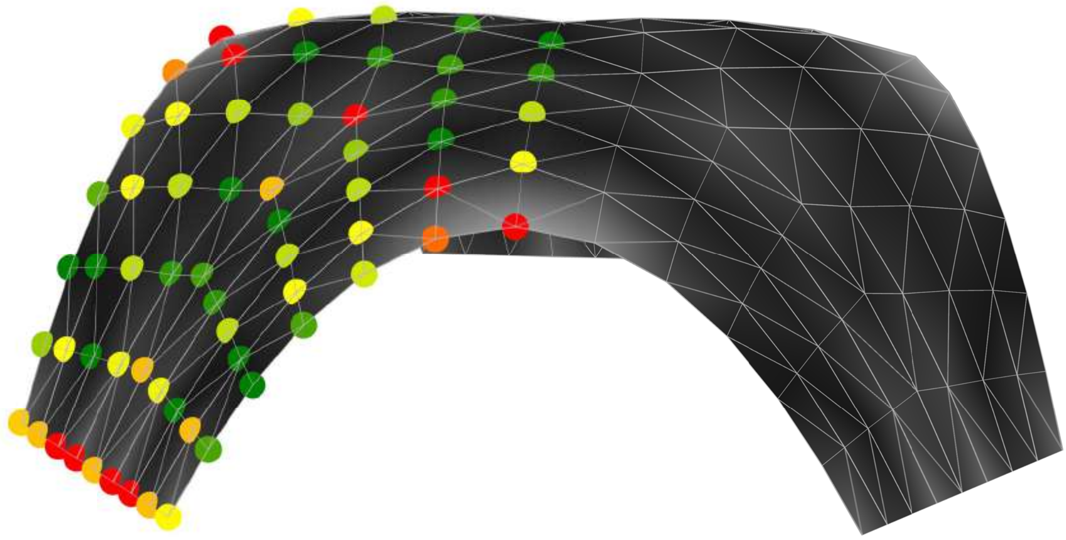
Offsetting the points to reach the same length of every polyline



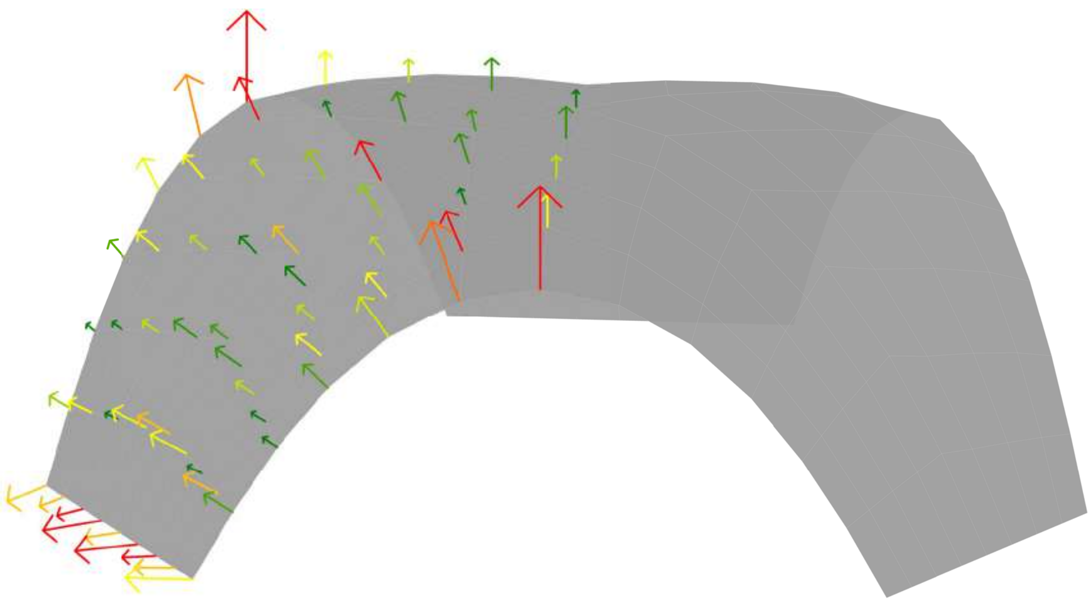
Chosing the points to create the pattern

5.2_Miura Ori Optimized

Another kind of origami design can be made where the thickness of the fold is proportional as the stress that the vault has there.
For this design, the geodesic Qaud mesh has been optimazed to know the optimal thickness of the vault. Karamba gives a color value from 0-1 (greyscale) for every point analyzd in the mesh, then every value is remaped to 0.4-1.4m or 0.4-2.4m, this values are used to offset this points. Therefore, this Miura design has the thickness proportional to the thickness desired by the funicular shell design.



Remaping the values of each point from the values of the structual analysis

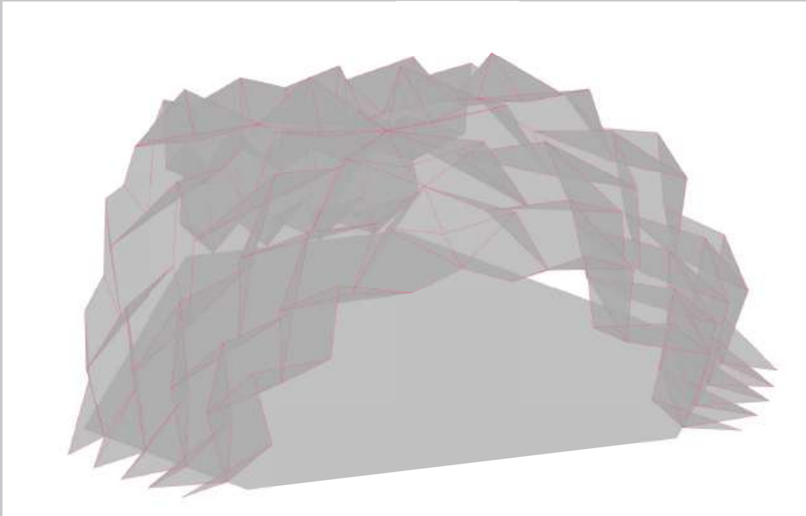


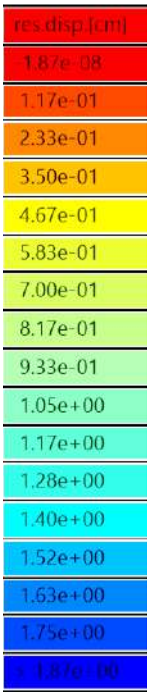
Offsetting the points with the remaped values from the colored mesh of Karamba

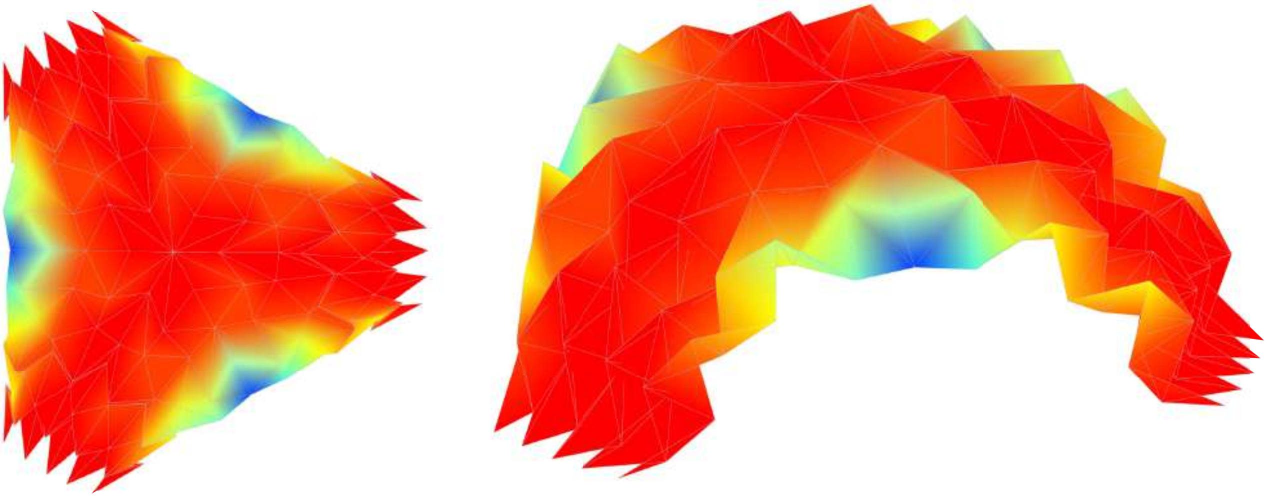
Shell Table: 10_Miura ori - regularized

Properties

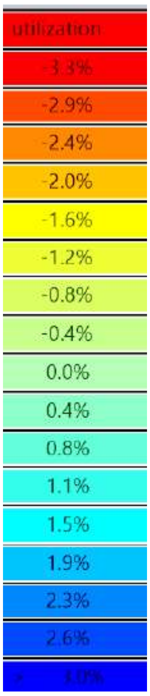
Area: *878.497m2*
Faces: *168*
Vertices: *175*
Edges: *342*
Perimetral Edges: *60*
Supports: *27*
Optimization: *4% utiliation*
Thickness: *optimazed 1-8.2cm*
Forces: *Gravity*

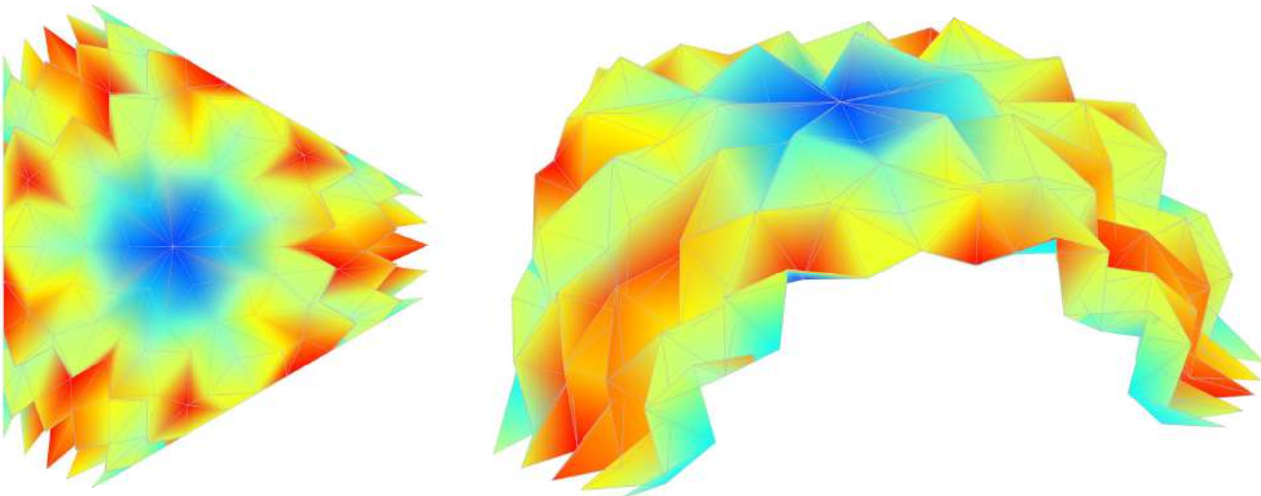




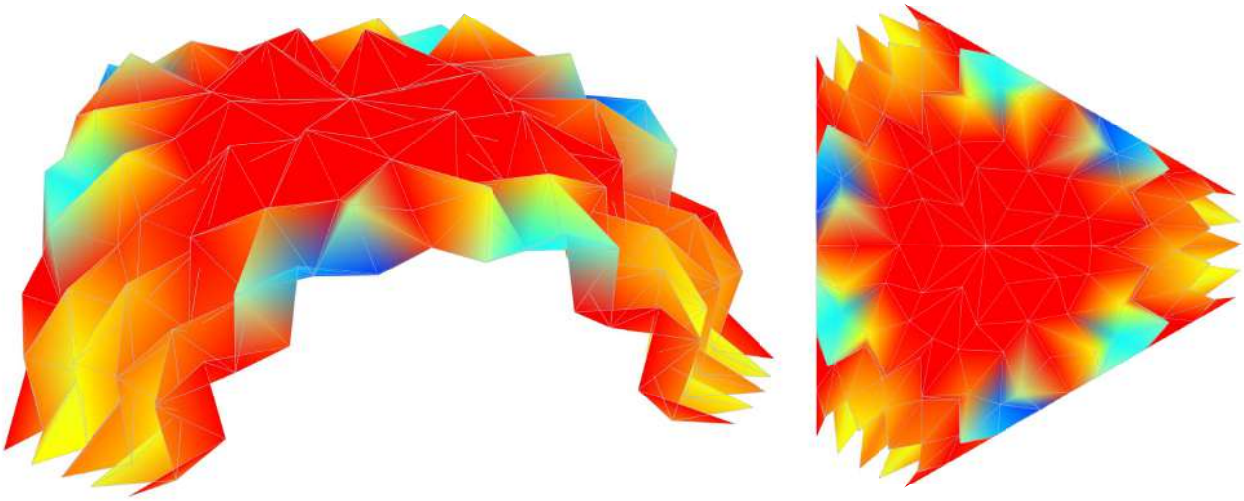


Displacement Diagram

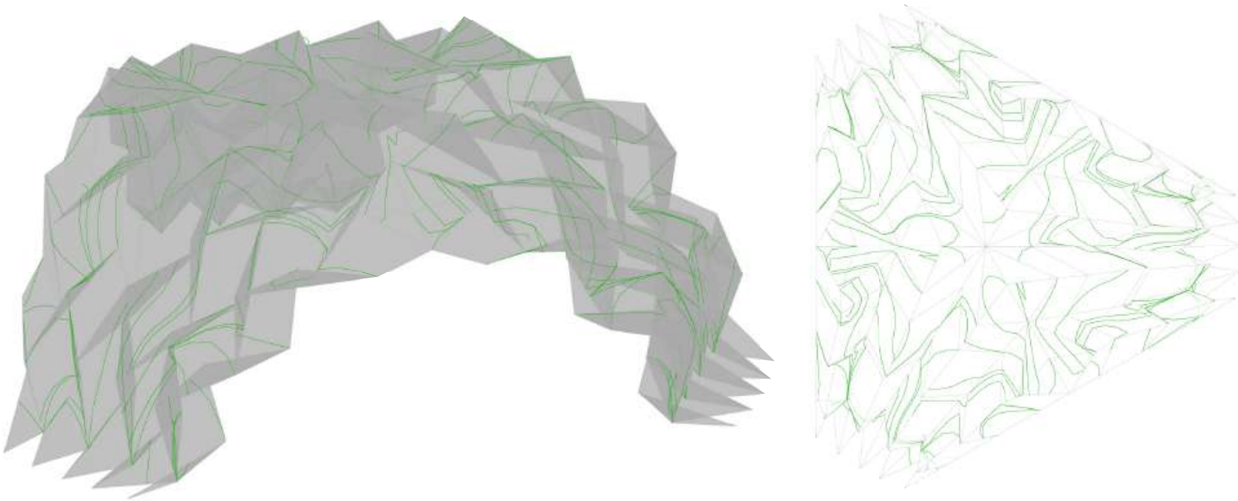




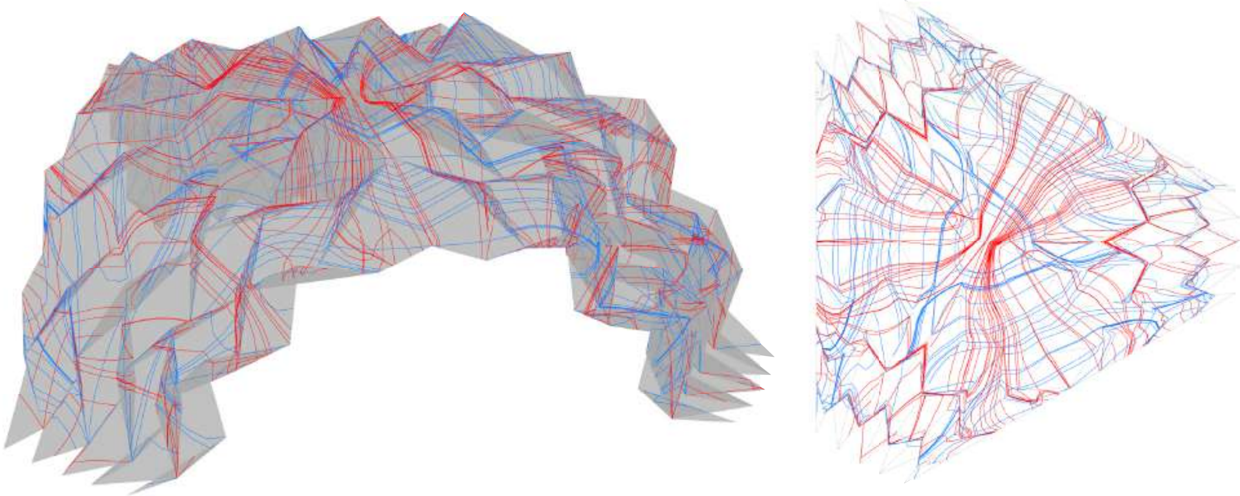
Utilization Diagram



Thickness Diagram *1 - 1.5- 2 cm (red-orange)*

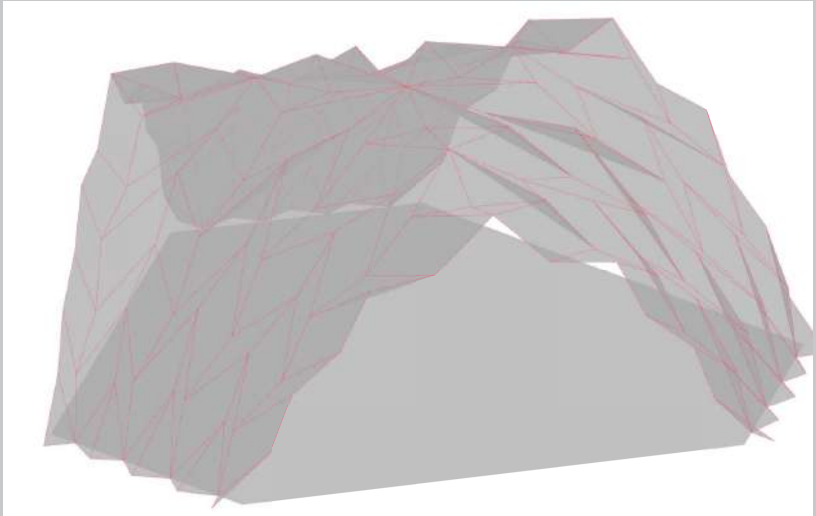


Force Flow Diagram



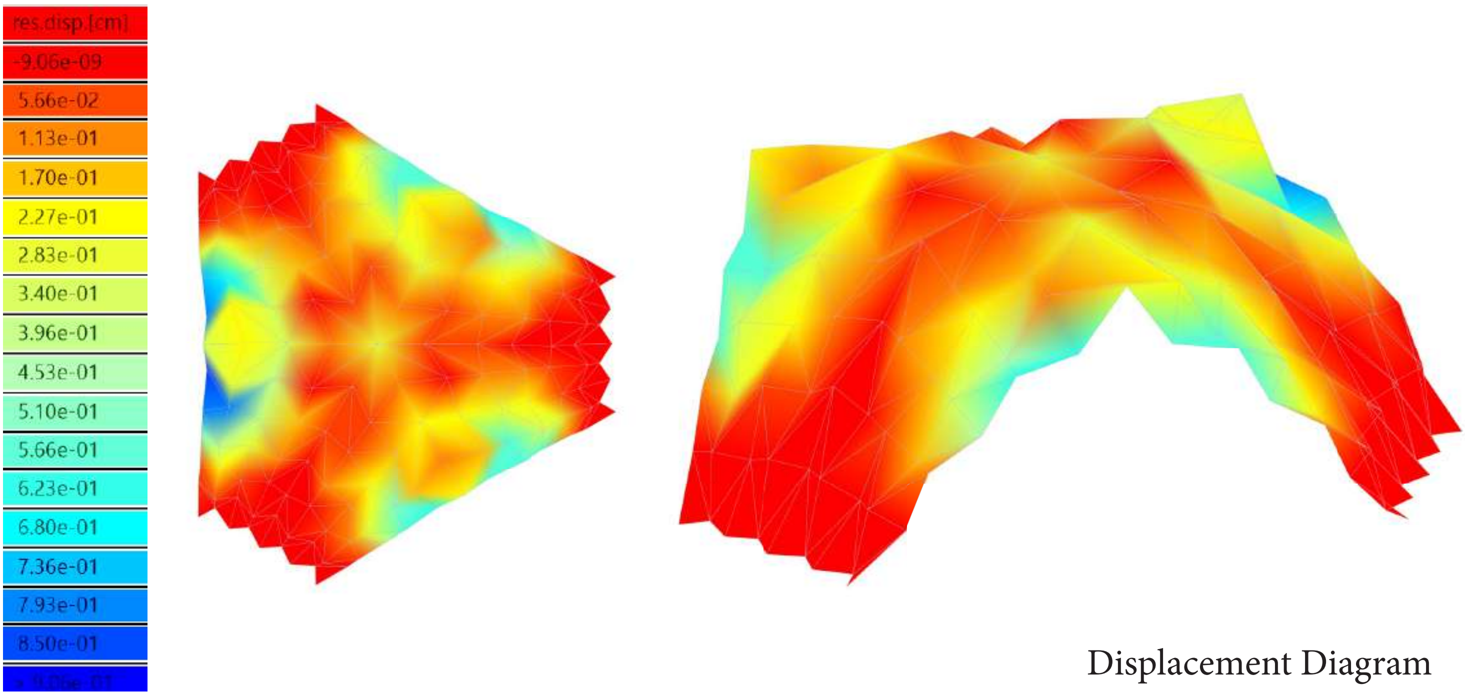
Principal Strees Lines Diagram

Shell Table: 11_Miura ori - optimized I (0.4-1.4)

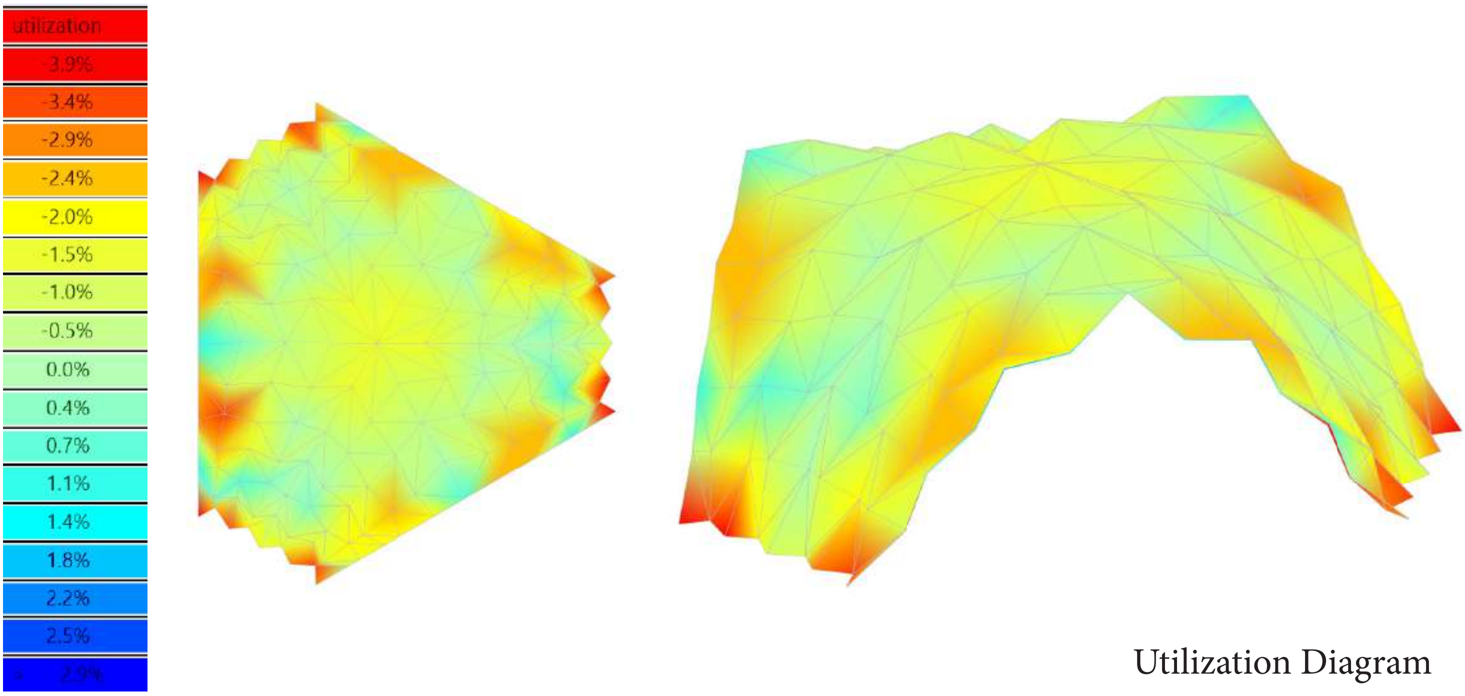


Properties

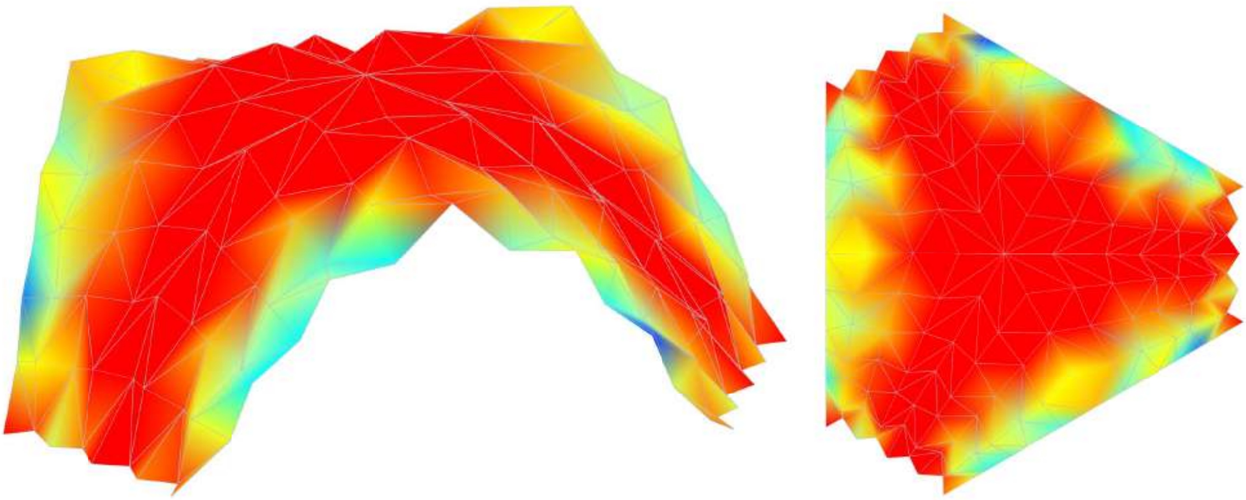
Area: *564.133m2*
Faces: *168*
Vertices: *175*
Edges: *342*
Perimetral Edges: *60*
Supports: *27*
Optimization: *4% utiliation*
Thickness: *optimazed 1-7.9cm*
Forces: *Gravity*



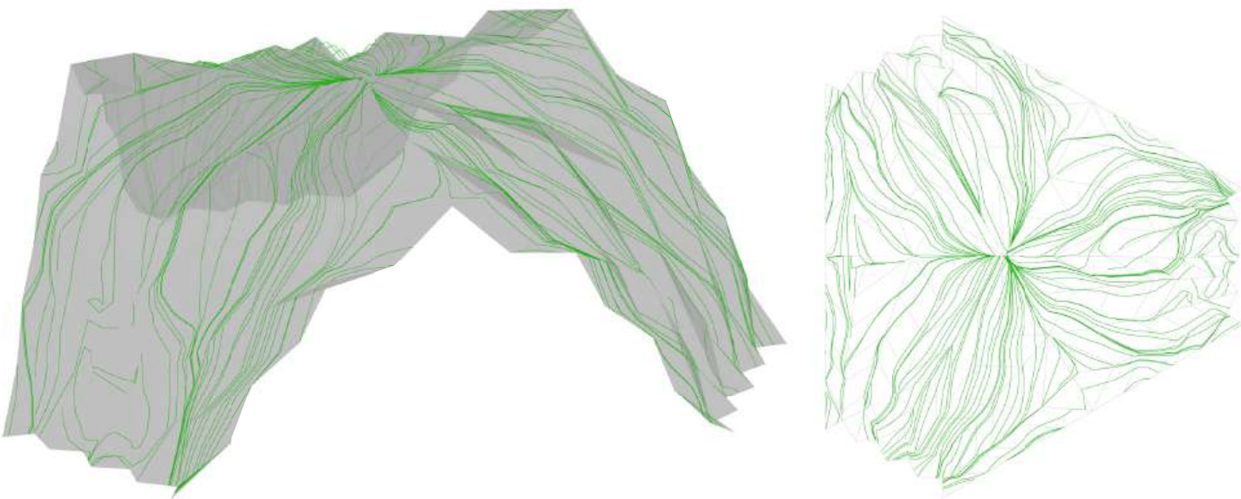
Displacement Diagram



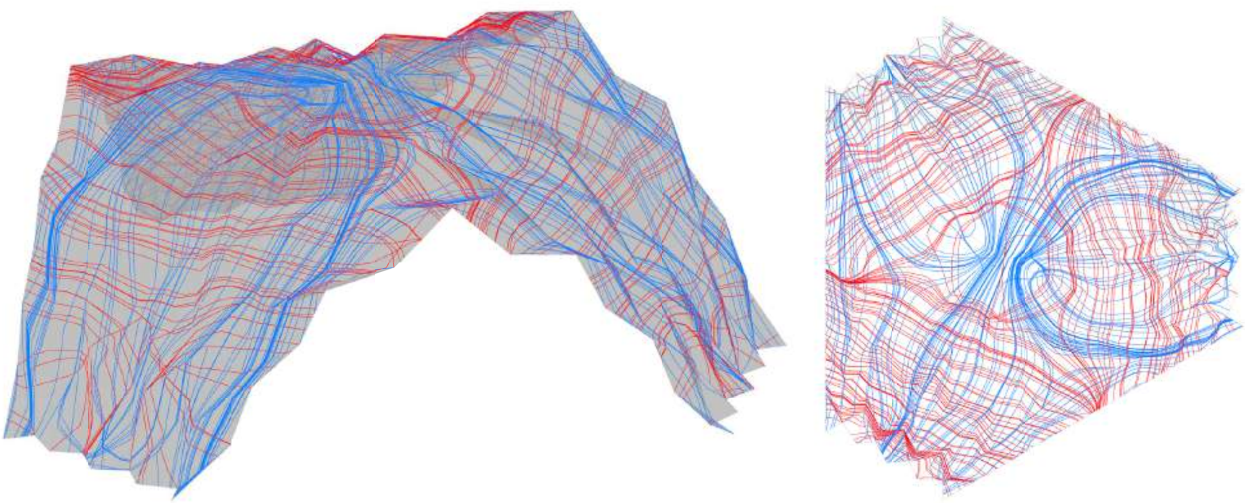
Utilization Diagram



Thickness Diagram *1 - 1.5- 2 cm (red-orange)*

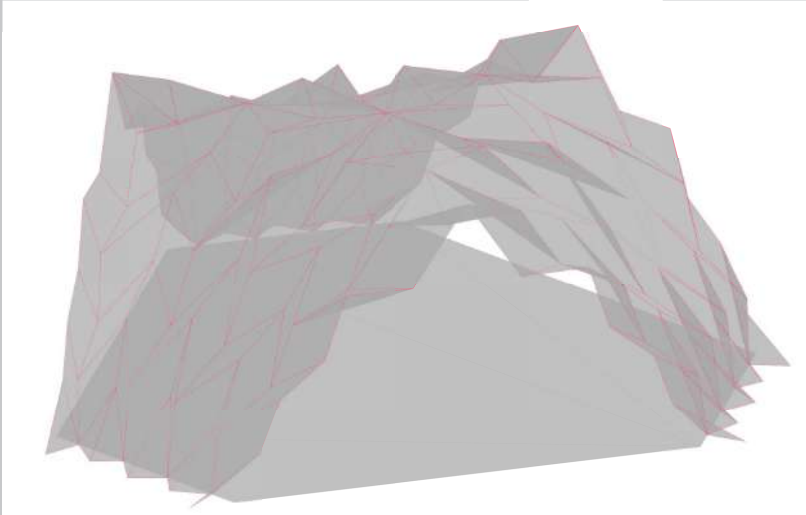


Force Flow Diagram



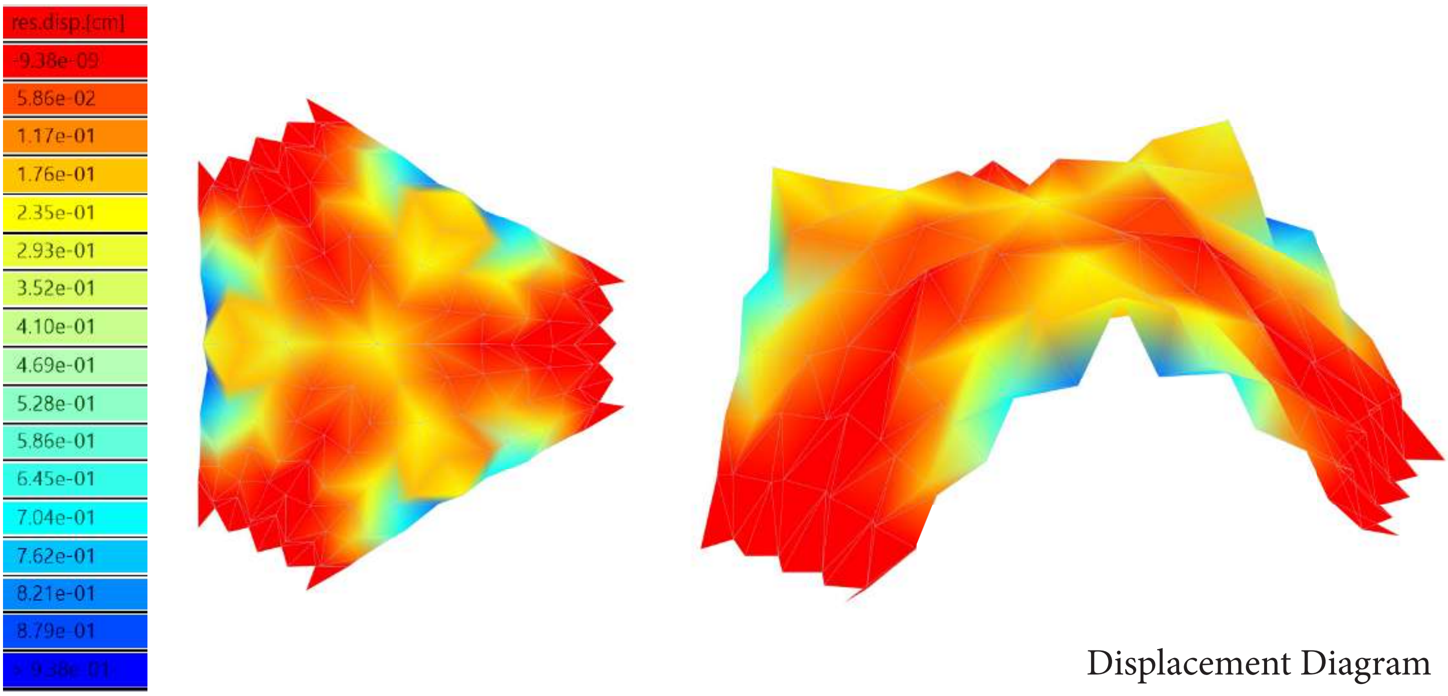
Principal Strees Lines Diagram

Shell Table: 12_Miura ori - optimized II (0.4-2.4)

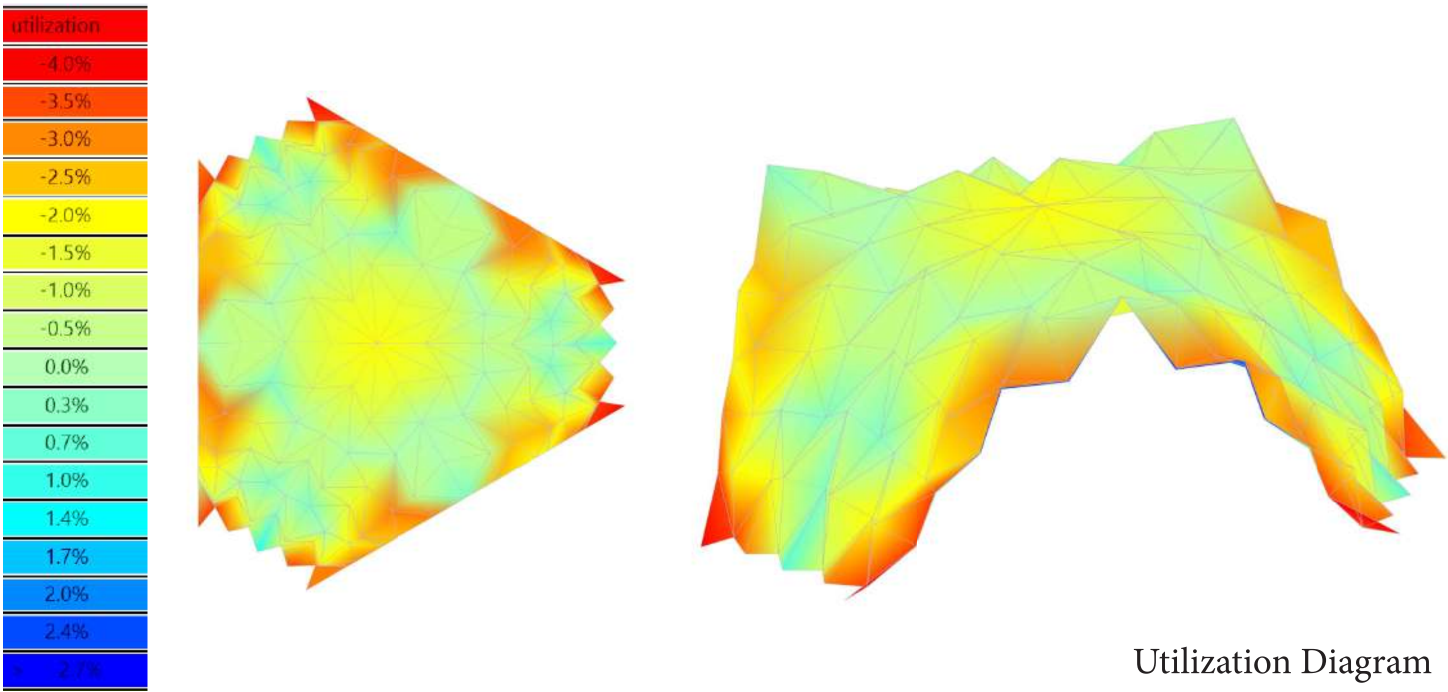


Properties

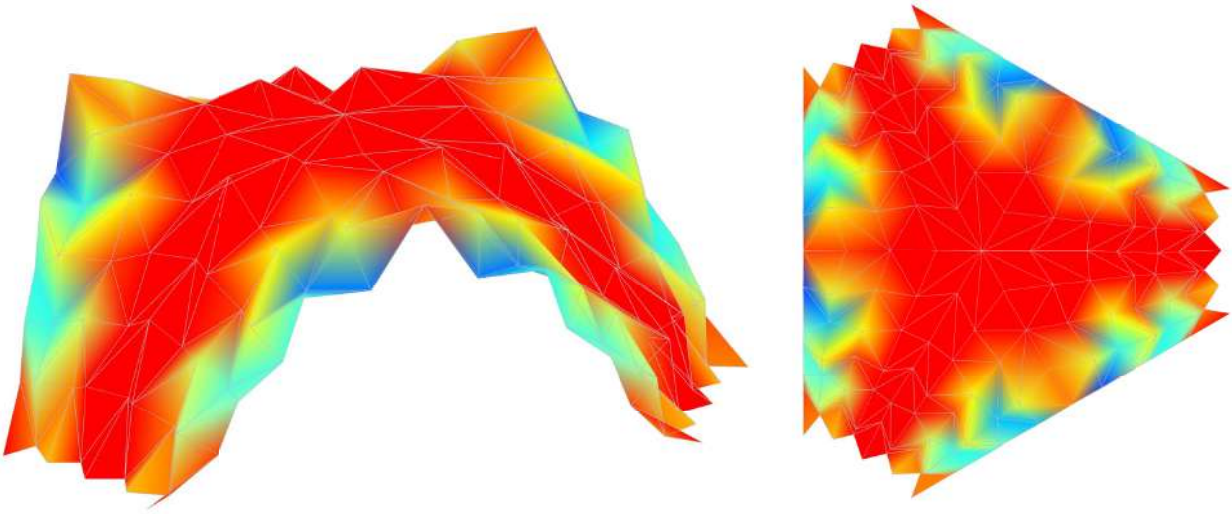
Area: *564.133m2*
Faces: *168*
Vertices: *175*
Edges: *342*
Perimetral Edges: *60*
Supports: *27*
Optimization: *4% utiliation*
Thickness: *optimazed 1-8.2m*
Forces: *Gravity*



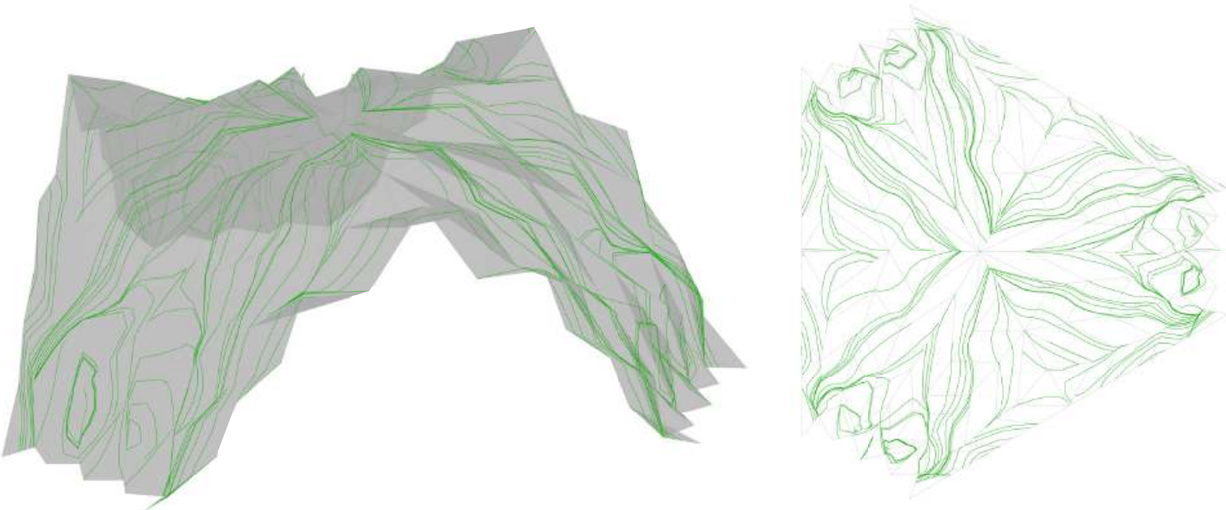
Displacement Diagram



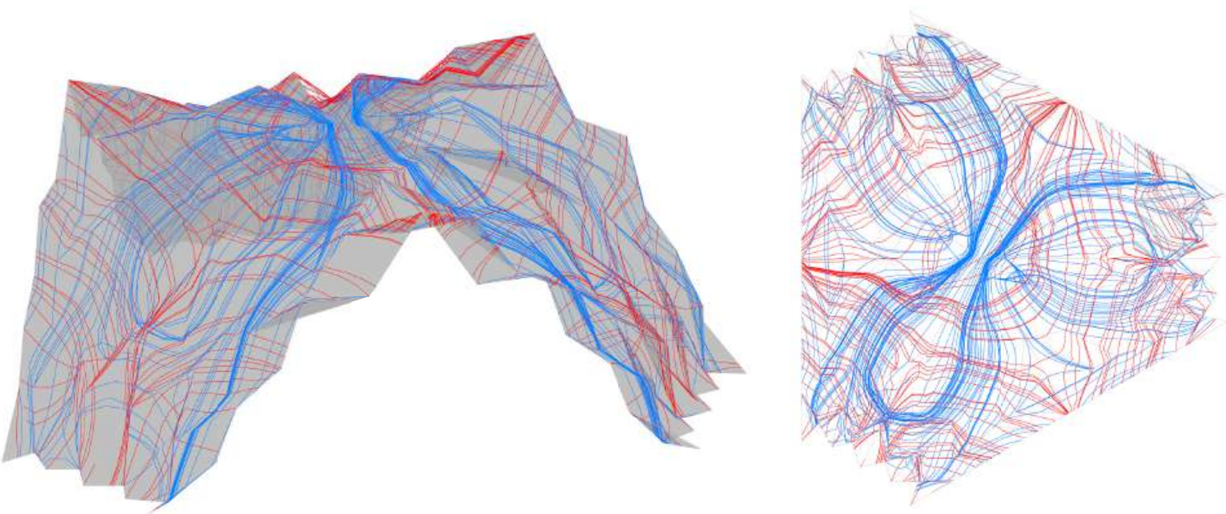
Utilization Diagram



Thickness Diagram *1 - 1.5- 2 cm (red-orange)*

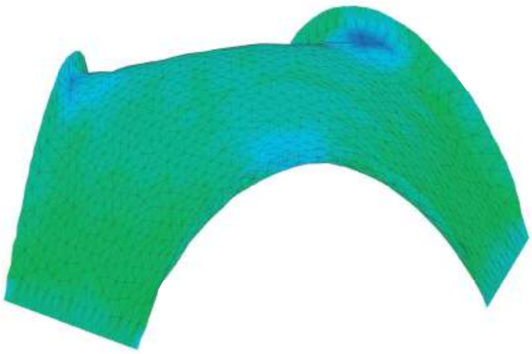


Force Flow Diagram

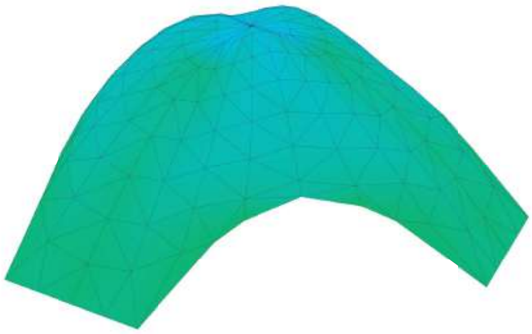


Principal Strees Lines Diagram

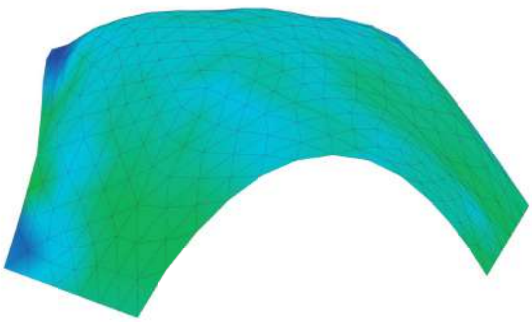
6_ Shell Meshes
Utilization comparison



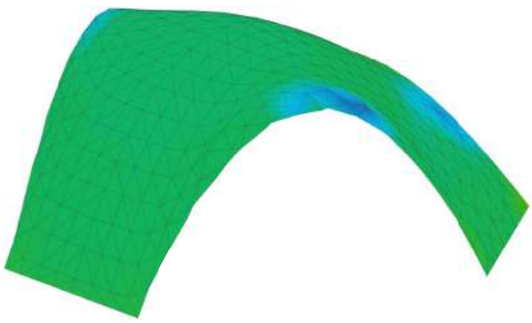
Brep to Mesh



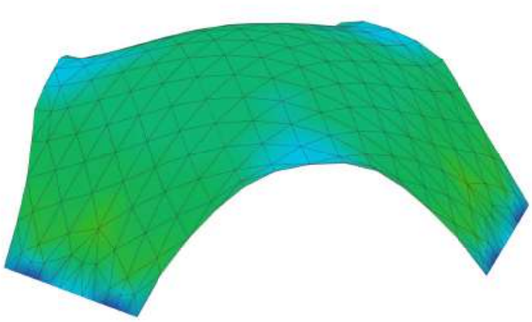
Radial Mesh



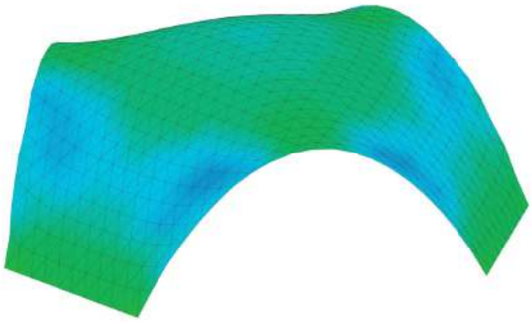
Random Mesh



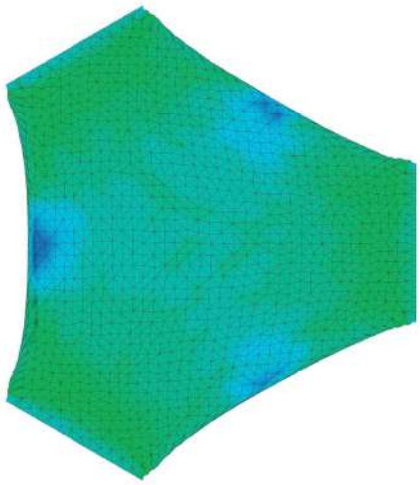
Squares Mesh



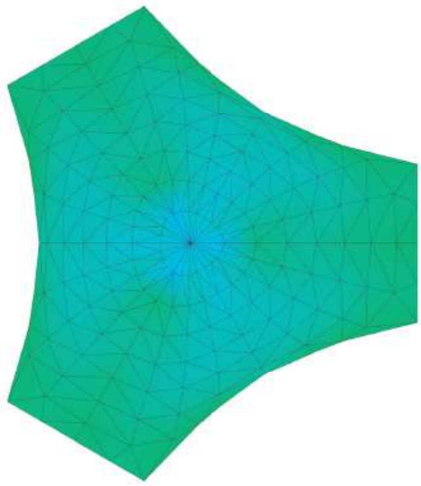
Unoriented triangles Mesh



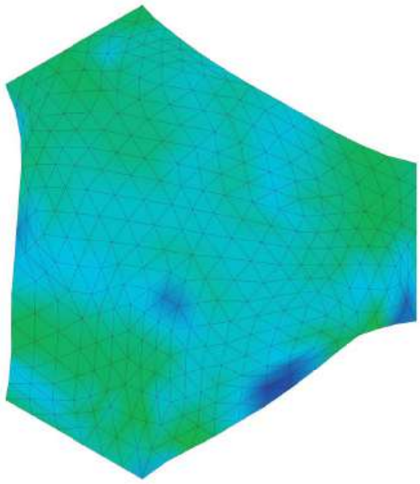
Triangles Mesh



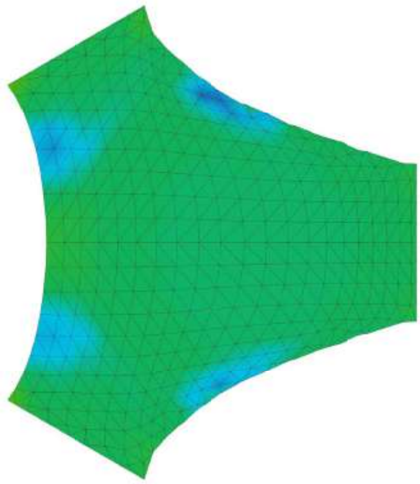
Brep to Mesh



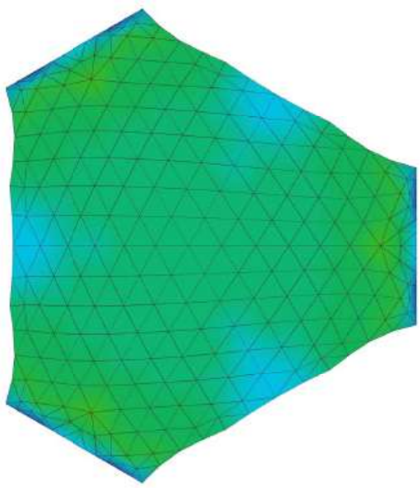
Radial Mesh



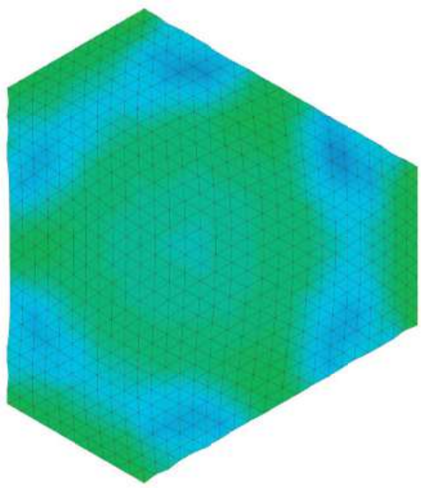
Random Mesh



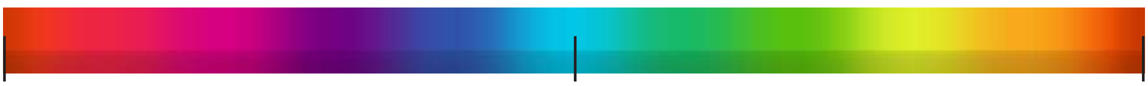
Squares Mesh



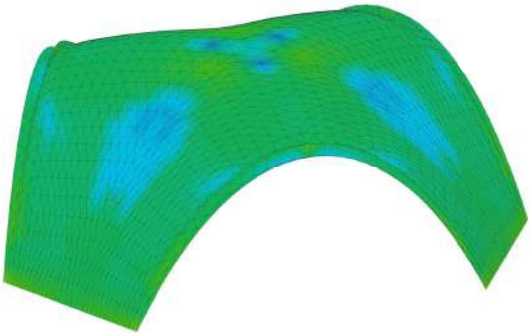
Unoriented triangles Mesh



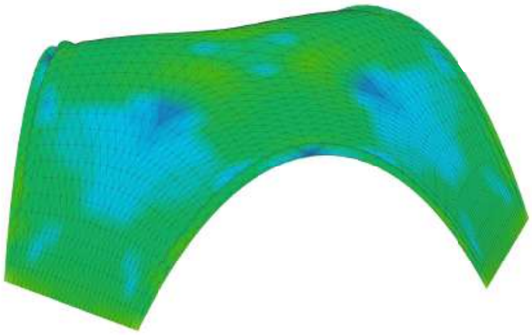
Triangles Mesh



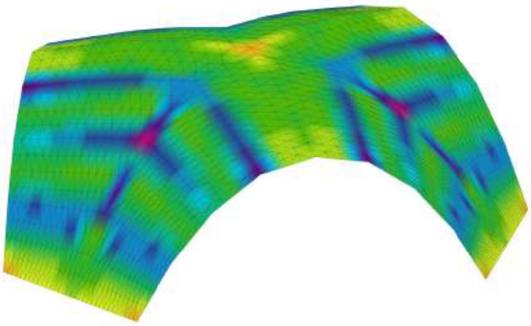
6_ Shell Meshes
Utilization comparison



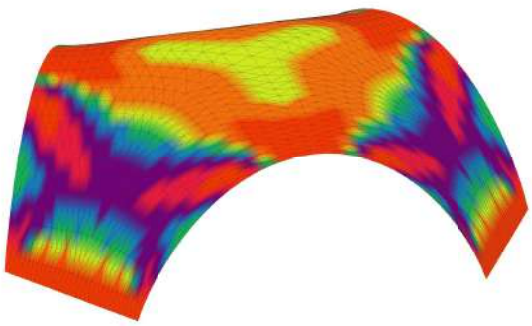
Equidistant Quads Mesh



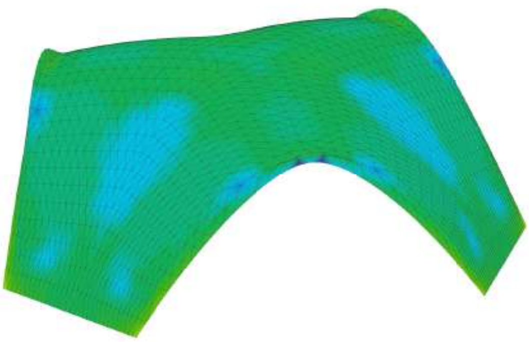
Catmull-Clark Mesh



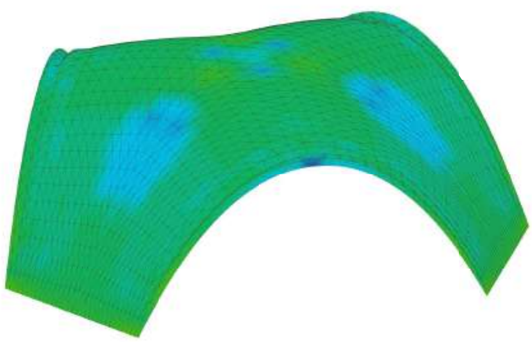
Low-high Eq. Quads Mesh



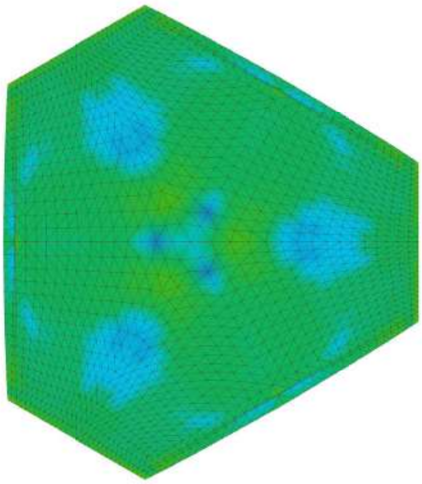
U-length=0 Mesh



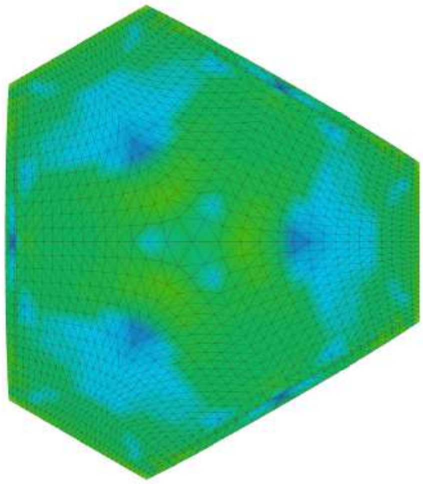
Perimeter XY fixed Eq. Quads Mesh



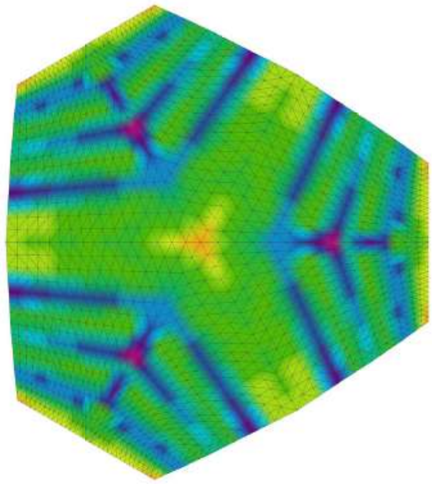
Perimeter fixed Eq. Quads Mesh



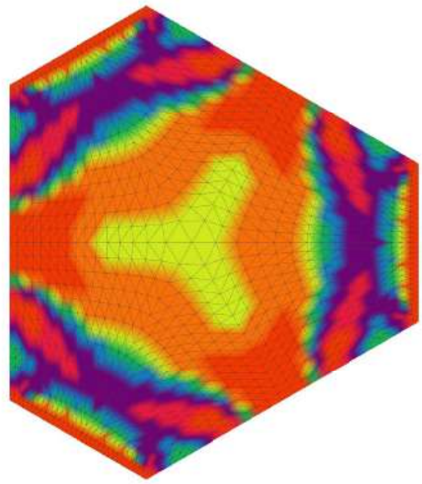
Equidistant Quads Mesh



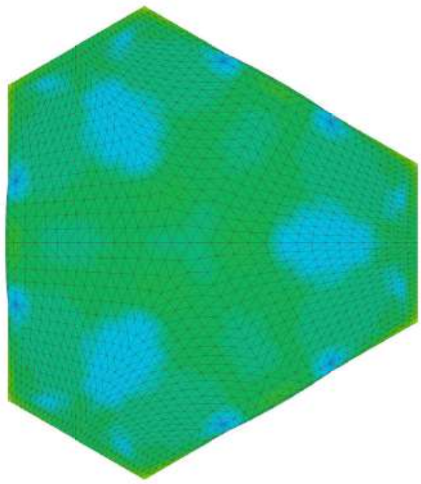
Catmull-Clark Mesh



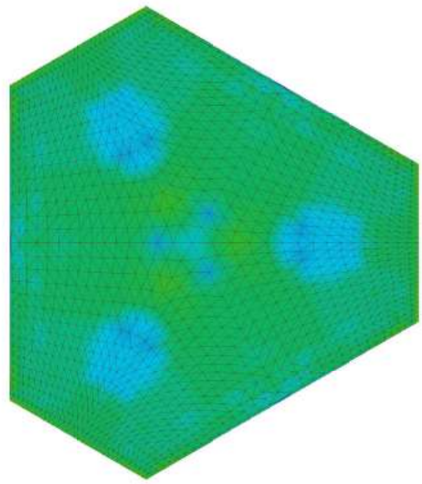
Low-high Eq. Quads Mesh



U-length=0 Mesh



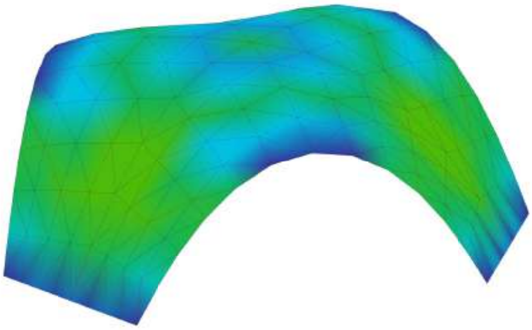
Perimeter XY fixed Eq. Quads Mesh



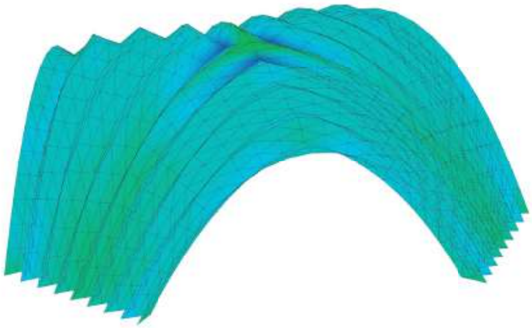
Perimeter fixed Eq. Quads Mesh

8% 0% -8%

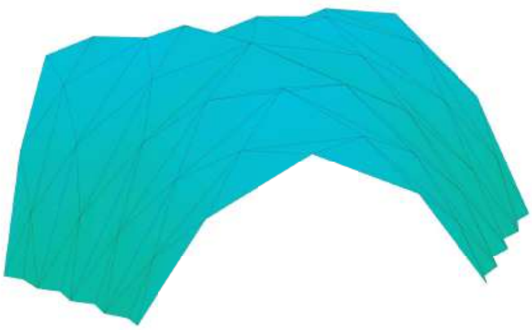
7_Folded Meshes
Utilization comparison



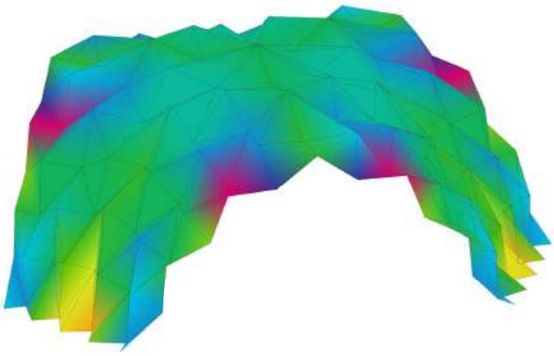
Geodesic Mesh



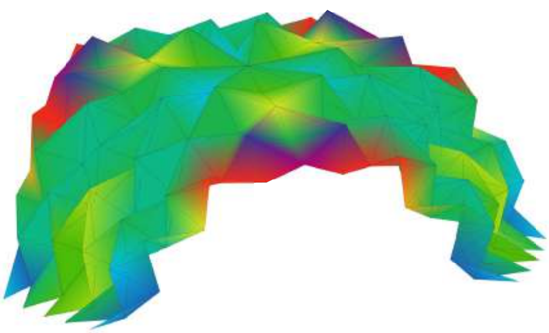
Folded Mesh



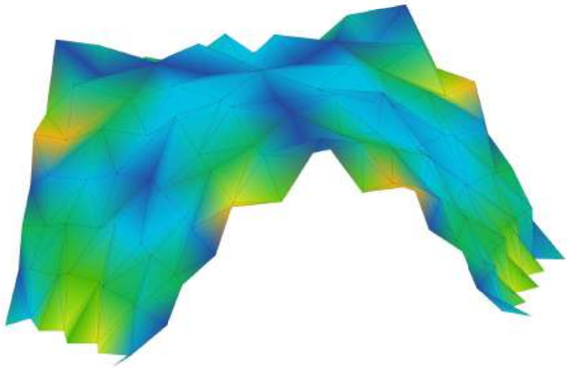
Yoshimura Mesh



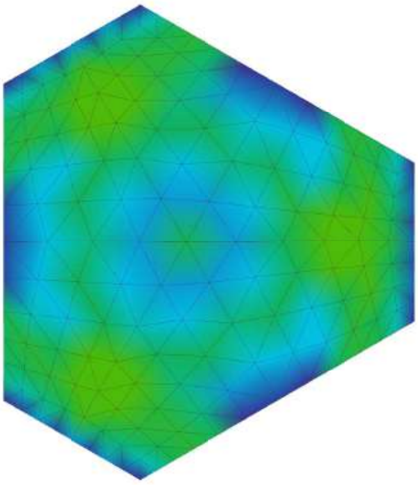
Basic Miura Ori Mesh



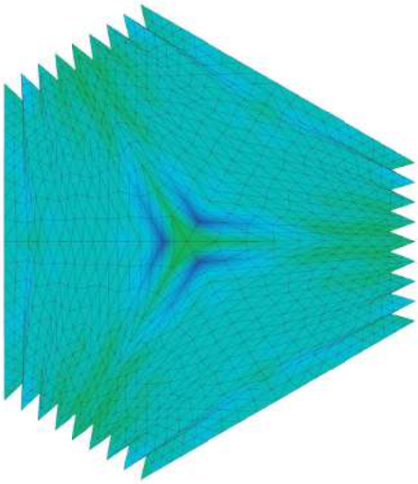
Regularized Miura Ori Mesh



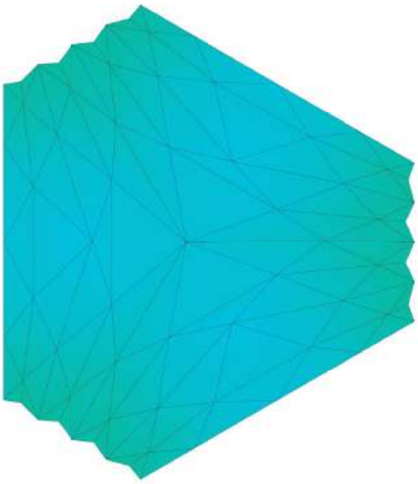
Optimized Miura Ori Mesh



Geodesic Mesh



Folded Mesh



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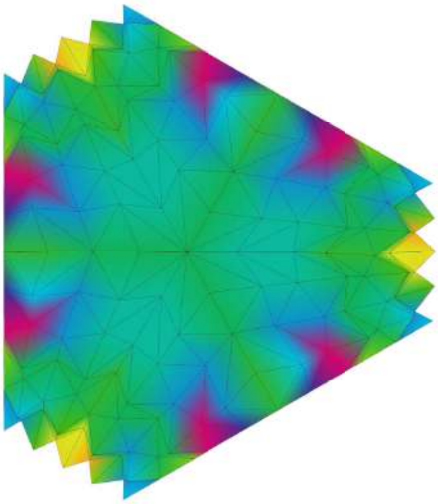

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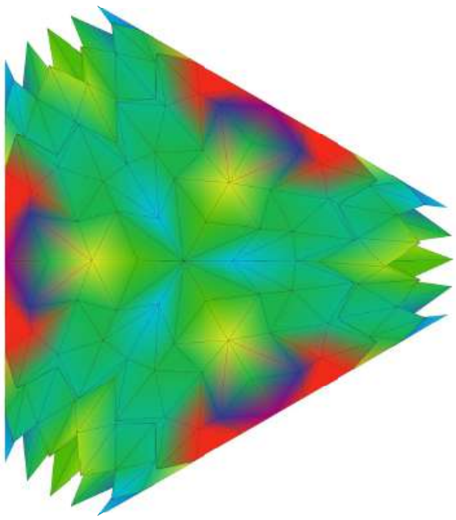

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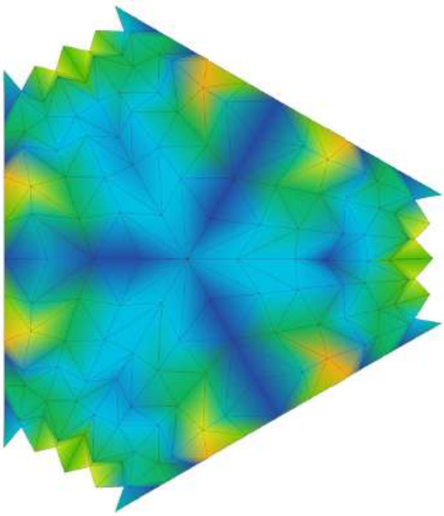
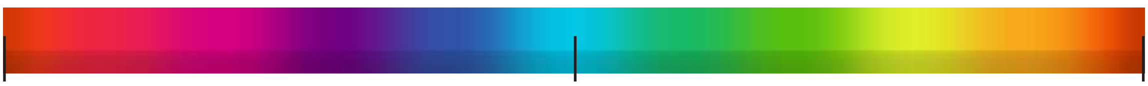


Folded Mesh



8% 0% -8%

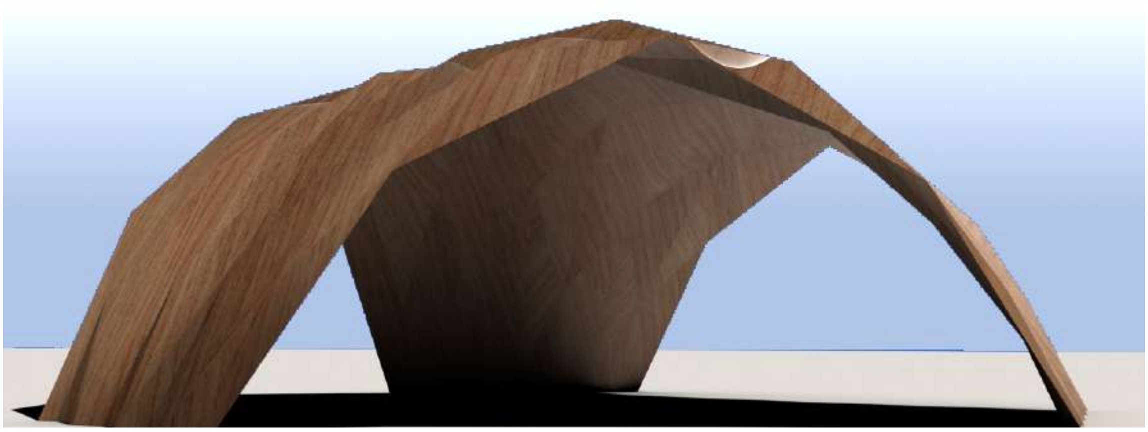
7_Folded Meshes - Utilization Comparison

8_Conclusions

In conclusion, it has been proven that an origami Yoshimura design is a good solution to design a funicular shell, not only it stands against gravity, but it increases its resistance to wind too.

Funicular Shells are unique designs; every shape gets a different form, even the same perimeter gets different form depending on the materials, so every part of the shell is unique and has a two-curved design as a base for aformal materials or as a prefab pieces to be assembled. Therefore, every part of the funicular shell requires a lot of effort to be built or need a special base that will never be used again. The Origami design apart from being better structurally, the Yoshimura design, is based on thin flat triangular panels, so from wood or steel sheets, triangles can just be cut and assembled, easy and fast, without effort or wasting material, even as a base, then the panels can be re-used or cut again.

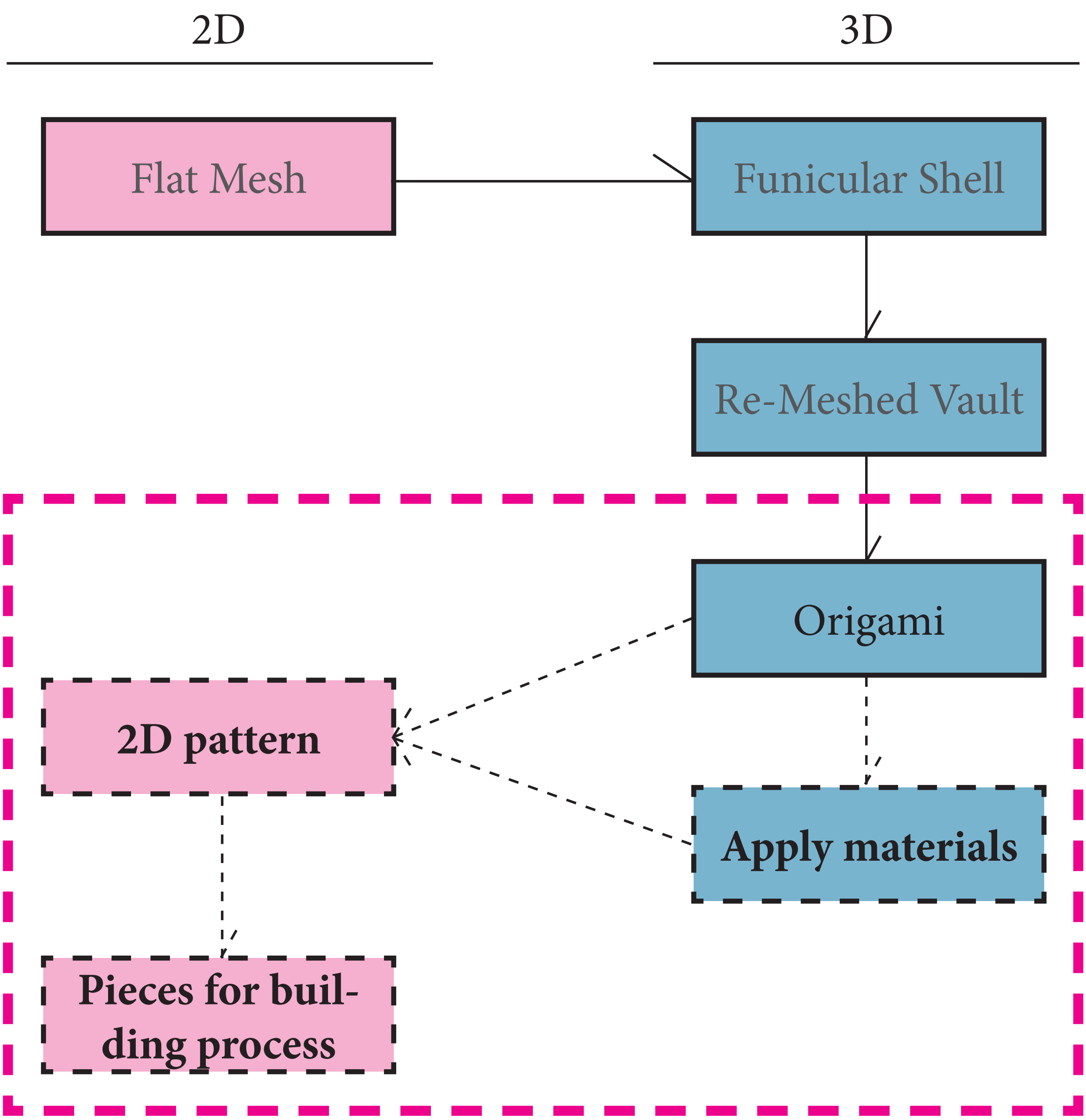
Other topics on this work: the tessellation of the mesh used for the form finding process matters, depending on the mesh and if it needs to keep the perimeter like it is in 2D, the funicular shell will behave one way or another structurally. The better solutions are the meshes that try to get to the centroid and be the more uniform or equal distributed, if it can be following an anticipated force flow. Secondly, the more resolution the mesh has, the better shape it will get, but it may create creases or show the problems it has, while a low resolution mesh has so few edges that the "problems" don't appear. Thirdly, all the creases or problems that appear in the FSFF are better to be solved when re-meshing the shell with the constructions constrains that trying to fix it changing the design.



9_Further research

In the introduction, there is a diagram of the next steps to go on with this work, so they are the further research of this design: making the simulation more real applying materials and joints, create the 2D pattern and preparing a strategy to build it.

Moreover, further research should also focus on the optimization on the origami pattern: can it be flat? Unfold it?; or can the Yoshimura design be optimized? As it has been proven to be the best pattern.



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