MPDA
Master's degree
Parametric Design in Architecture

UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH
School of Professional & Executive Development

Efficiency Bracing in Elastic Gridshell

Wang Zening

Abstract

Gridshell is a new structure that is light, flexible, economic, easy to construction and has high strength, all of these elements point to a word "less", which we can understand it as a high efficient form, however, it is not enough. As a new type of structure, we have to create it though efficient means beside high efficient form. Bracing selected strategy is one of the means. In simply terms, the generation of efficient form by efficient means. "NEW" has a lot of dimensions, environmental element is that we have to consider in addition to being different from traditional architecture. As a result, we must emphasize on the high strength here due to the fact that reusability play an important role. The material properties give it high strength, and the form of structural organization is crucial. Bracing selected strategy is one of form of structural organization.

Keywords: Efficiency, Chebychev, Elastic gridshell, Bracing.

1. Introduction

This research will combine with real case that is GFRP (Glass Fiber Reinforced Plastic) circle gridshell to explore how to select efficient bracing. This thesis is divided two parts. The first part is GFRP circle gridshell that is to offer an ability to design form-active structure; the second part is research of bracing optimization, which offers a method that is to research

1.1 Overview

We start this thesis by defining the context and concepts of gridshell and software technology which are two important and basic parts for subsequent research. Because gridshell is main body of this thesis and software is tool of this research. GFRP circle gridshell is a design that is lighter, faster, stronger, and bracing research will be attached to this design. Then we propose two rounds to continue bracing research, we will be described in detail in Chapter 4.

1.2 Definition

1.2.1. Elastic gridshell

Gridshell was created by Frei Otto who is a German architect, he designed Mannheim Multihalle that is a wooden shell in 1975, which let the world knows about this structure. Elastic gridshell is an unrestrained structure with double curvature. "It based on two principles: one is inversion, another the deformation of an initially planar grid of bars into a double curvature shape followed by stiffening."(Frei Otto). It is easy to construction, just lay out grid in the floor and push parts of boundary inward that will form gridshell structure that "transmitted through compression and tension". In the end, it can cross large span, but uses little materials.

In this case, we summarized some advantages beside we mentioned before, for example, large span with little materials; planar initial geometry, standard connection node, standard profiles and so on, however, we found a series of drawbacks, such as, it has risk of failure in unstable one or more nodes; It needs post erection bracing, because it is an unrestrained, mechanism to take form, more importantly is bracing problem, connecting bracing is very slow, it can not accurate bracing location and so on. In the next chapter, we start to our main topic that is bracing research.

1.2.2. Chebychev net

Actually, Chebychev is a mathematical concept, but it used in other field widely, for example, chebychev net, "it is a coordinate system on the surface obtained through the pure shearing of each planar domain." Modelisation by Chebyshev nets $\varphi : \Omega \subset R2 \rightarrow M \subset R3$, from a domain D in 2D with its orthogonal coordinate system (u , v) to a smooth surface in 3D, key property is $|\partial u\varphi|=|\partial v\varphi|=1$. Local existence on any surface, "Physically, this condition corresponds to inextensibility of the rods along the two initially perpendicular parameter directions."

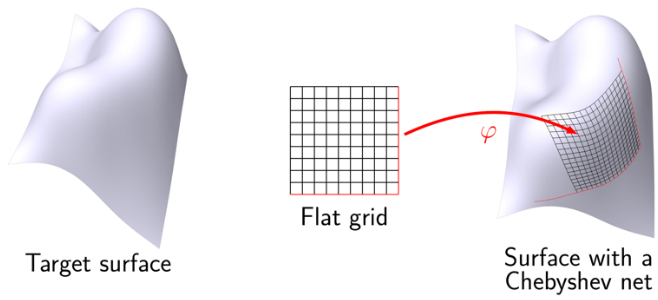


Figure 1: Chebychev net principle (by Yannick Masson)

1.3 Research aim

The aim of this research is to find a new method to study bracing with GFRP gridshell relate to the design of elastic gridshell structure with the Kangaroo and analysis with K2e environment.

Based on this purpose, on the one hand, we have to improve the workflow in order to be more convenient, efficient and logic to achieve this research, on the another hand, this research can provide a reference to engineers, which is a method to analysis bending-active structure within the K2e environment with real circumstances.

1.4 Research status

Most part of gridshell research is based on the timber gridshell since Frei Otto created his first dome made of slender timber during the German building exhibition in Essen in 1962. After that, he created two gridshells under the light cable net roof the Montreal Pavilion in 1967, which is also made by wood. He subsequently designed the bending-active structure, Mannheim Multihalle that is most important work in the gridshell field designed in 1975, it is longer span, double layer grid, the material laid out flat, then lifted up gradually, and curved itself, steel cable spanned diagonally reinforce its strength. Numerous of gridshell he designed to cover courtyards, meeting areas and receptions in the world.

Wood has its limitations. With development of materials technology, increasingly number of low cost, high strength and environmental material was appeared, and under his influence, thousands of engineers and archives followed Frei Otto's ideas and designs. A lot of glazed lattice gridshell buildings. For example, the canopy of the courtyard of the Museum of Hamburg History in 1989. The canopy covers the British Museum courtyard in London in 2000 and the Kogod courtyard at the Smithsonian Institution in Washington D.C in 2008. It can be said that he developed this technology with the help of one person. In this moment, it only improves the analytical techniques and materials.

1.5 Thesis structure

Chapter 1: Introducing basic concepts and identify research direction.

Chapter 2: Introducing whole design process

Chapter 3: Combining the previous design to continue efficient bracing research.

Chapter 4: Concluding this research and discussing the limitations and future work.

2. GFRP gridshell design

The purpose of this chapter is to describe design process in order to demonstrate the capabilities of developed analysis and select final gridshell shape.

2.1. Brief

The aim of GFRP (Glass Fiber Reinforced Polymer) gridshell design is for research of lighter, faster and stronger building. This building is similar to pavilion, at this level, we have to design an interesting, creative and beautiful space and shape, in the end, build it outdoor front of dormitory in Universitat Politècnica de Catalunya of Vallès. It has to fit within a footprint 6m*6m.

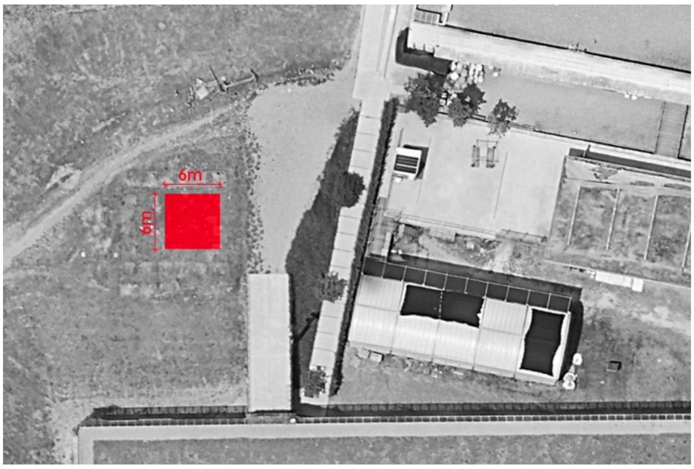


Figure 2: Site (by Google map)

2.2. Design inspiration

This idea of GFRP gridshell design comes from the concept of Chen–Gackstatter minimal surface, three points put down and three points pick up. We were thinking, if we chose GFRP rods to combine this minimal surface concept and use common technique that is lay out at grid in plan and then push parts of boundary inwards to create the spatial shape and to do this research, what will happened?

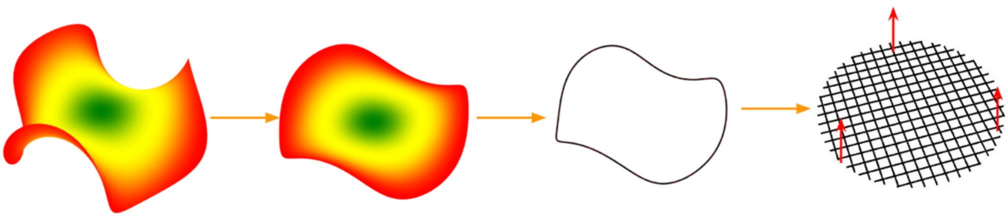


Figure 3: Inspiration process

2.3. Final work description

Final work as figure 4 shows that. Grid distance is 65mm, highest height is 2.95m, max width is 5.7m. Of course, material is 20mm diameter GFRP rods. It has a lot of advantages. For example, high strength, lightweight, seamless construction, resistant to salt water and environment. Compared with timber, it is often used in elastic gridshell structure. Considered to the K2e analysis, GFRP Young's modulus is 40000MPa, GFRP Density is 1900 kg/m3, GFRP strength is 900MPa.

Figure 4: Construction process

Figure 5: Final work (photo by Andres Flajszer)

3. Efficient bracing analysis

This chapter is main topic in the research. We separated this charter into two parts to research. The first part is bracing density optimization, it is simply to say that is layout bracing at grid scientifically and logically; the second part is bracing direction optimization. It means that use octopus that is grasshopper plug-in to decide bracing direction automatically, at the same time, The ultimate goal is to complete optimization if rod length and less displacement.

3.1. Bracing density optimization

3.1.1. Bracing structure system

Actually, there are many ways to bracing, such as membrane, cable and so on. But we just use that add third layer rods to bracing in this research. Because that main structure is gridshell, third layer bracing is best way to "lock" each planar. We use two types of elements bracing, which are along the one direction diagonal and two direction diagonal in order to compare restrain effect(figure6).

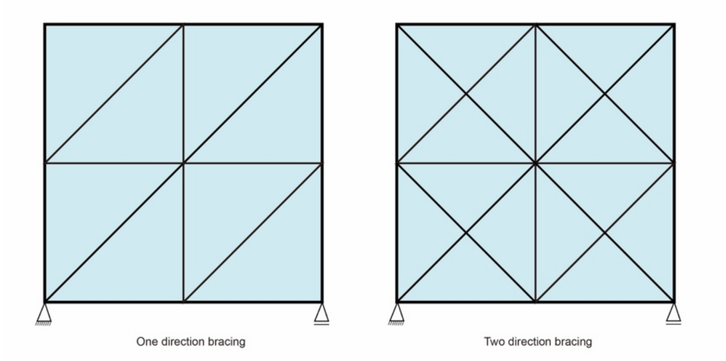


Figure 6: Bracing direction

3.1.2. Layout bracing method

As we know, more bracing will better to control deformation. If we suppose that use diameter 20mm rod to cover bracing at all of grid, it means coverage is 100%, and add a little bit wind load, it will produce displacement that is value to measure bracing effect. For example, displacement is 50mm, if we change rod diameter to 30mm, maybe we just use bracing to cover 30% gridshell will achieve same displacement effect with 20mm diameter rod. But we have to prove this hypothesis.

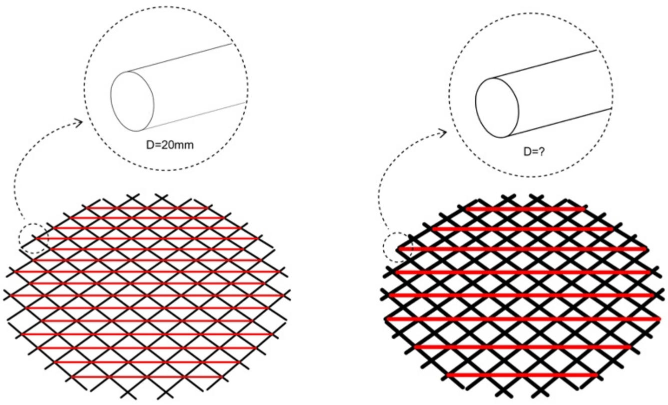


Figure 7: Bracing layout

Mass100%=Mass?%

Mass=pi*r2*L

We have to emphasis on Mass100%=Mass?% in the figure, which means that compare the displacement effect under the different rod diameter and bracing coverage. We use formula of cylindrical volume to represent Max value. L means length of bracing.

3.1.3. Pareto curve

If we want to know how to select optimal bracing coverage, we have to know Pareto curve. Like figure shows, generally, we categorize Pareto curve into three parts—power cluster area, balance cluster area and performance cluster, but in this case, in order to more intuitively explain the meaning of each region， we call them big change area, balance area and very small change area. It means that degree of change of displacement when add wind load. The optimal solution in the balance area where the two axes tend to 0. But how to measure balance area, actually, it is high curvature area. I will explain it in the example.

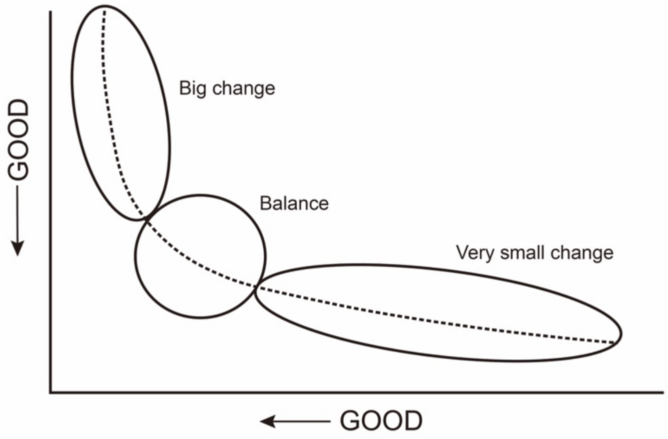


Figure 8: Pareto curve

3.1.4. Sample model bracing analysis

We hope that our research results can be applied to more gridshell structure. We used three representative model samples to research. Which is spherical Chebyshev gridshell, 3-point circle chebychev gridshell and enneper gridshell. Spherical chebychev has constrained boundary, enneper gridshell is very open shape and 3-point circle gridshell is somewhere in between. The coverage of bracing we layout on these three models is also different. For example, relatively, spherical chebychev gridshell has less usage than others, enneper gridshell has larger usage. In the beginning, we assume that bracing converge is almost 25%, 30% and 40% of three sample models after optimizing rod diameter, which will achieve same displacement effect using 100% bracing coverage and 20mm rod diameter. The next job, we will follow principle that I mentioned and start to make experiment and analysis to prove this hypothesis.

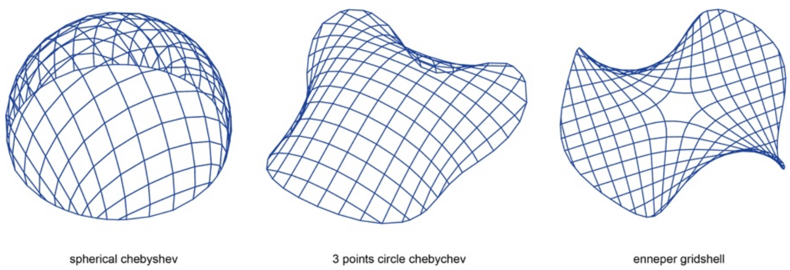


Figure 9: Three sample model shapes

3.1.4.1. Spherical chebychev gridshell

Firstly, we layout bracing on the grid along one direction and two direction diagonal (figure10).

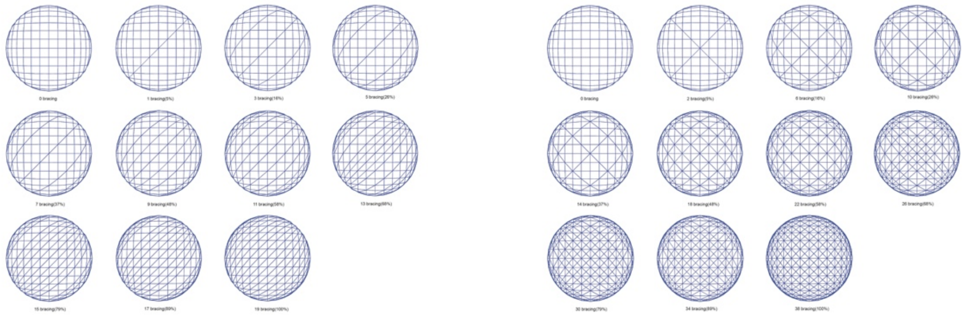
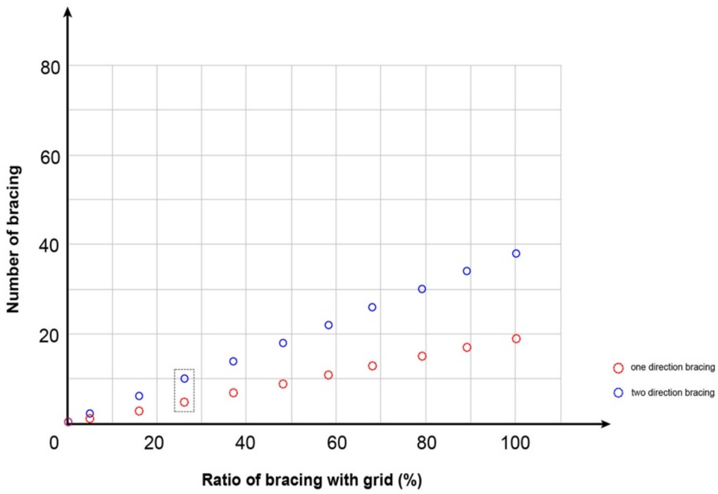
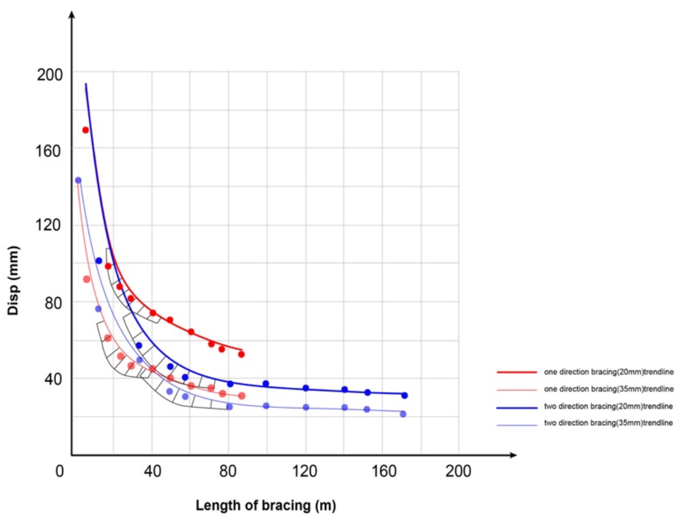


Figure 10: Spherical chebychev bracing layout



Graph 1: Coverage with number bracing



Graph 2: Balance area with length of bracing with disp

And we have to know bracing coverage in the one and two direction, which is ratio of number of bracing covers grid (graph1).

As I mentioned before, high curvature area is balance area. We add wind speed(18km/h) and it will produce displacement under the different bracing number, we collected data and make the graph to measure high curvature area(graph2).

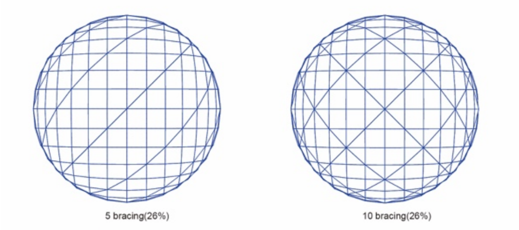
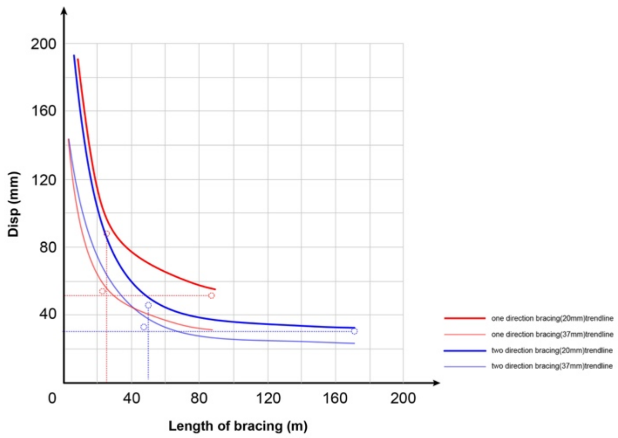


Figure 11: Spherical chebychev optimal bracing



Graph 3: Optimal option with Length of bracing with disp

Look at graph 3. Highest curvature represents a point where is optimal option. Red solid curve is one direction bracing that 20mm diameter rod displacement trend-line and transparent curve is one direction bracing that is 37mm diameter rod displacement trend-line. Blue curve represents two direction bracing that is 20mm and 37mm displacement trend-line. For example, we focus on blue solid curve. we can see that the optimal option is 10 bracing, coverage is 26% and length of bracing is 49m(figure12). Of course, the last point is best option, because coverage is 100%, minimal displacement is 35mm but longest length of bracing is 171m, it will cost more materials and much money, it is not efficient. According to formula mass = $\pi r^2 x L$. We can calculate volume of 20mm rod bracing and 100% coverage:

$$mass100\% = (3.14x10^2)/1000 \text{ x } 171 = 54m^3$$

And we know optimal option is 10 bracing that length is 49m. So we reverse this formula to calculate R that is to prove our hypothesis that if we replace rod diameter to D, whether displacement is same with 20mm rod grid or no.

$$D = \sqrt{(mass100\%/L / \pi)} \text{ x1000}$$

$$= \sqrt{(54 \div 49 \div 3.14)} \text{ x1000} = 37mm$$

Then we replace 37m rod diameter to make experiment again. We get the transparent blue trend-line. Now compare two curves, we can see that displacement is 35mm under the situation of the 20mm rod diameter with mass100%, and displacement is 33mm if we change rod diameter to 37mm. It means that we just use 10 bracing with 37mm rod diameter, the displacement is similar to using 38 bracing with 20mm rod diameter. Result is:

Disp2(20mm)=35mm ≈ Disp2(37mm)=33mm

mass100%=mass26%

And we use same method to analysis one direction bracing, we got the same result that shows in the graph 3.

3.1.4.2. 3-point circle chebychev gridshell

Actually, the analysis method is same as spherical chebychev gridshell, firstly, layout bracing on the grid along one direction and two direction(figure13).

And we draw the graph 4 bracing coverage with number of bracing according to bracing layout.

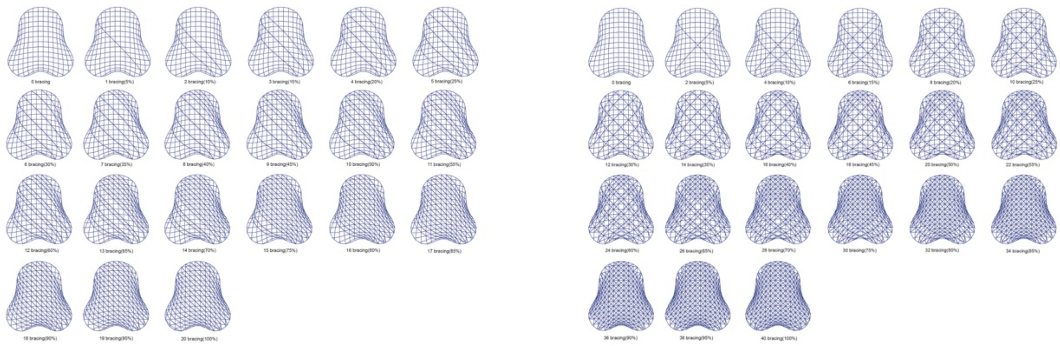
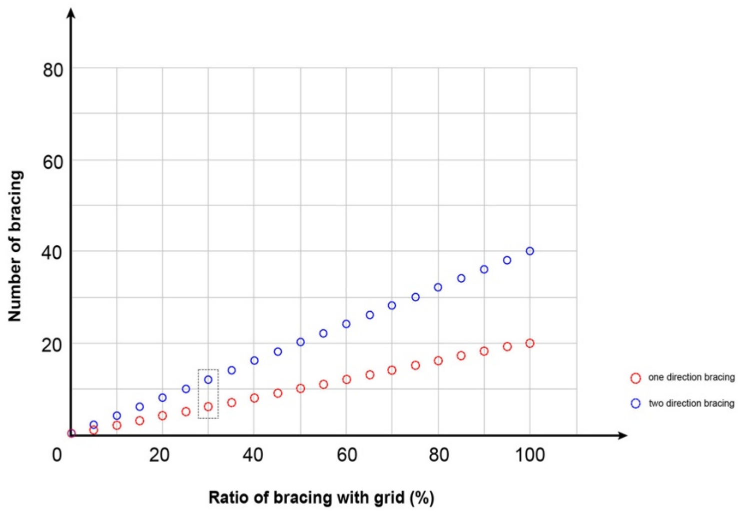
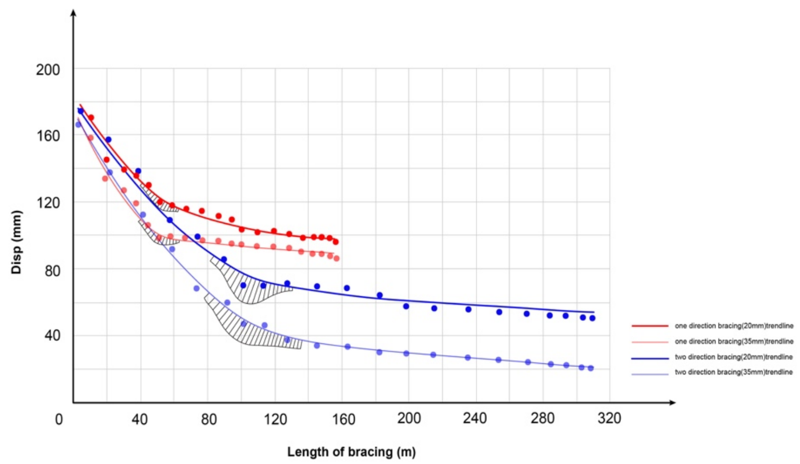


Figure 12: 3-point circle chebychev bracing layout



Graph 4: Coverage with number bracing

And add same wind speed(18km/h) to get the data of displacement and high curvature area that is balance area(graph5).



Graph 5: Balance area with length of bracing with disp

Go further to say, highest curvature point is optimal option. It is 6 bracing in one direction and12 bracing along two directions, coverage is 30%(figure14).

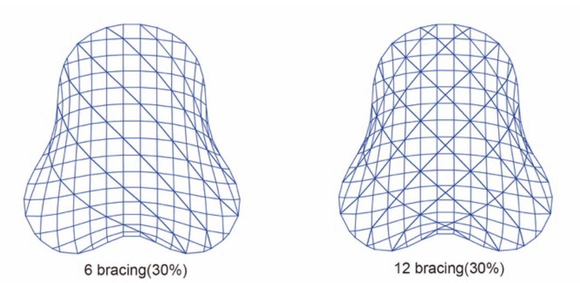
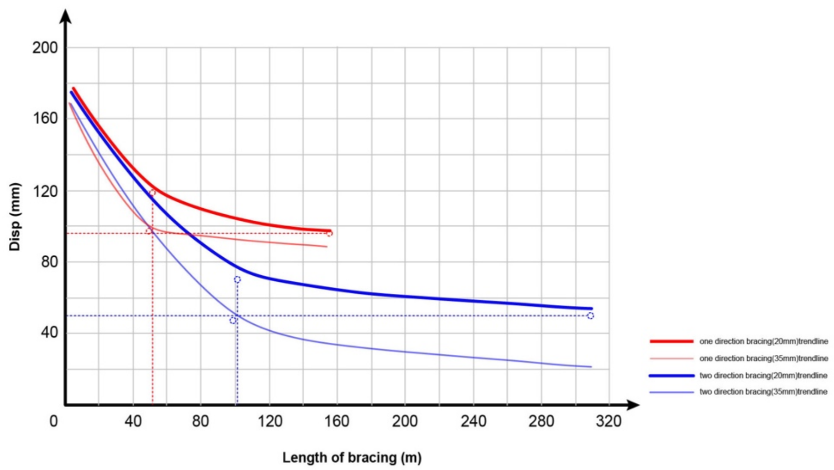


Figure 13: Optimal option



Graph 6: Optimal option with Length of bracing with disp

In the 3-point circle chebychev gridshell, we just look at solid blue curve , which 20mm rod diameter and length of bracing in 100% coverage is 309m trend-line. We can calculate volume of 20mm rod bracing and 100% coverage:

$$mass100\%= (3.14 x 10^2)/1000 \text{ x } 309 = 97m^3$$

And optimal option is 12 bracing that length is 101m. So we replace rod radius to D is:

$$\begin{aligned} D &= \sqrt{(mass100\%/L/\pi)} \text{ x}1000 \\ &= \sqrt{(97 \div 101 \div 3.14)} \text{ x}1000 \\ &= 35mm \end{aligned}$$

So we got the final result is:

$$\begin{gathered} Disp2(20mm)=50mm \approx Disp2(35mm)=48mm \\ mass100\%=mass30\% \end{gathered}$$

In the 3-point circle chebychev gridshell, the displacement of using12 bracing with 35mm rod diameter is similar to displacement of 20mm rod diameter gridshell with 40 bracing. The result of one bracing direction is same as two directions, it shows in graph 6.

3.1.4.3. Enneper gridshell

Enneper gridshell comes from enneper surface, it is a very open shape, by some means, it has few support points. For this reason, it needs more bracing(figure15). Firstly, layout bracing on the grid.

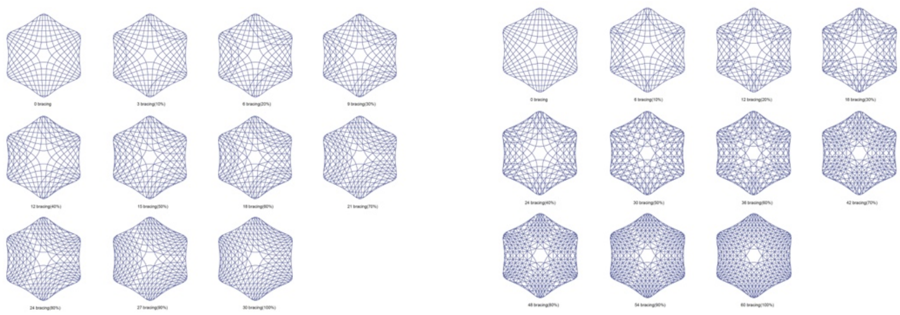
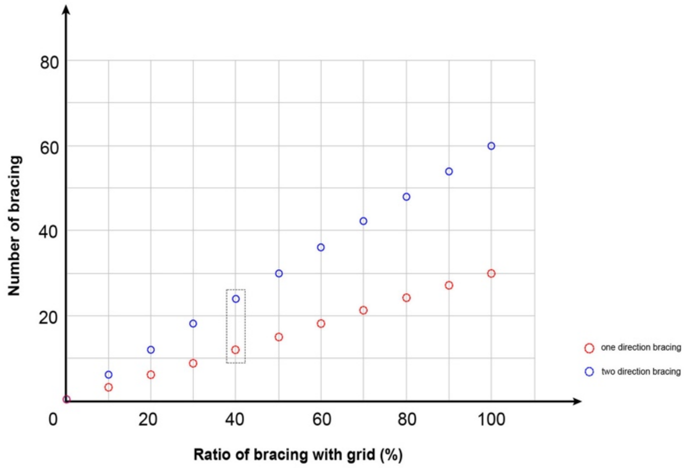
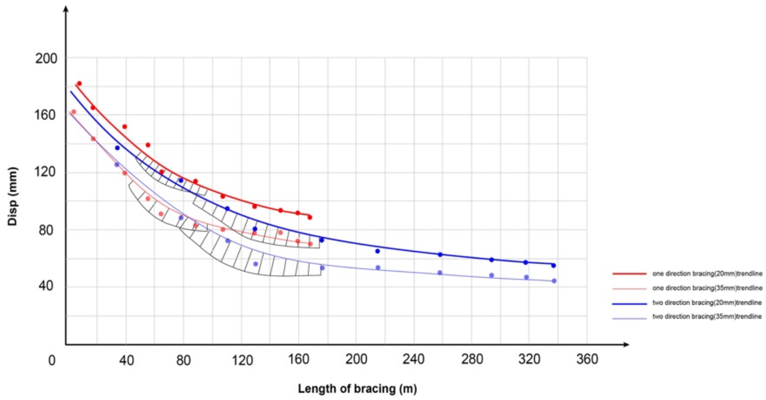


Figure 14: Enneper gridshell bracing layout

And we draw the graph bracing coverage with number of bracing according to bracing layout(graph7).



Graph 7: Coverage with number bracing



Graph 8: Balance area with length of bracing with disp

And we can select optimal option in the high curvature area(graph9). It has 12 bracing in the one direction and 24 bracing in the two direction. Bracing Coverage is 40%(figure15).

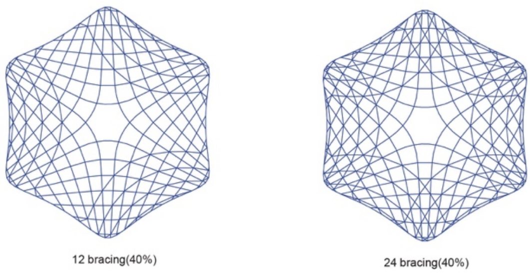
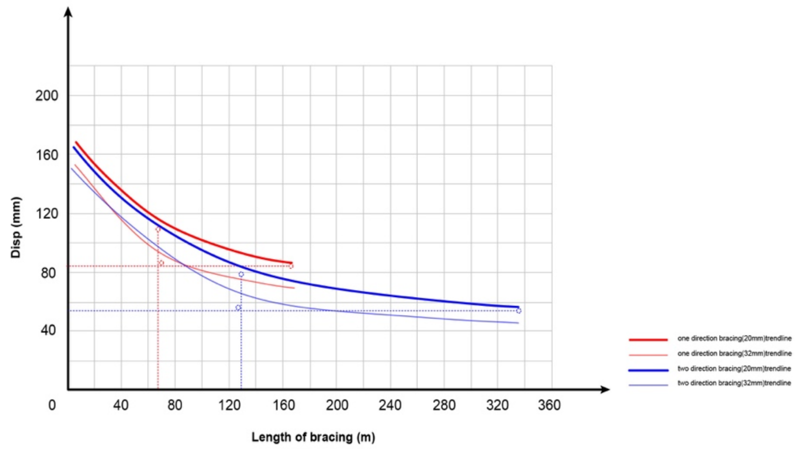


Figure 15: Optimal option



Graph 9: Optimal option with Length of bracing with disp

We still focus on blue solid curve. In the enneper gridshell, optimal option is 24 bracing, length of bracing is 129m. Best option is 60 bracing and length is 337m.

$$mass100\% = (3.14 \text{x} 10^2)/1000 \text{ x } 339 = 106m^3$$

And we replace rod radius to D is:

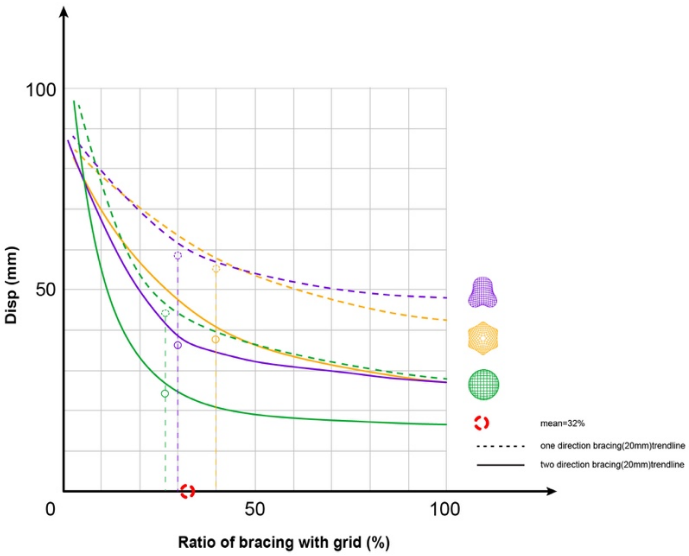
$$D = \sqrt{(mass100\%/L/\pi)} \text{ x}1000$$
$$= \sqrt{(106 \div 129 \div 3.14)} \text{ x}1000$$
$$= 32mm$$

So we got the final result is:

$$Disp2(20mm) = 58mm \approx Disp2(32mm) = 56mm$$
$$mass100\% = mass40\%$$

In enneper gridshell, the displacement of using 24 bracing with 32mm rod diameter is similar to displacement of 20mm rod diameter gridshell with 60 bracing in the two direction. The result of one bracing direction is same as two directions.

Finally, we combine three models displacement trend-line in the one graph10.The spherical chebychec gridshell bracing coverage is 26%, 3-point circle chebychev gridshell bracing coverage is 30% and enneper gridshell bracing coverage is 40%. The bracing coverage mean value is 32%(graph10).



Graph 10: Three optimal options with Length of bracing with disp

3.2. Bracing direction optimization

3.2.1. Manually layout bracing

Let us back to our design. first of all, we want to introduce a bad method that we did before, which used karamba analysis and observed force flow(figure16) in the shell to connect bracing. Actually, force flow curve is complicated and almost cover all of shell. It has thousands of ways to layout bracing.

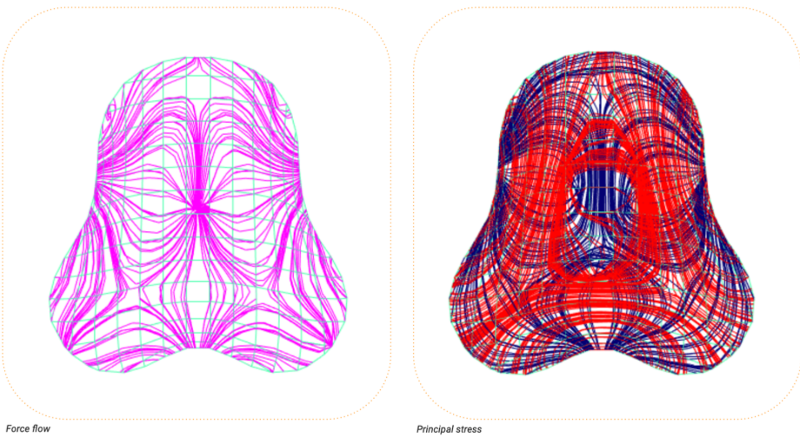


Figure 16: Force flow curve

These 6 bracing(figure18) are picked in the 35 bracing proposals. It is low efficiency, and you never know where is optimal option in these force flow curve.

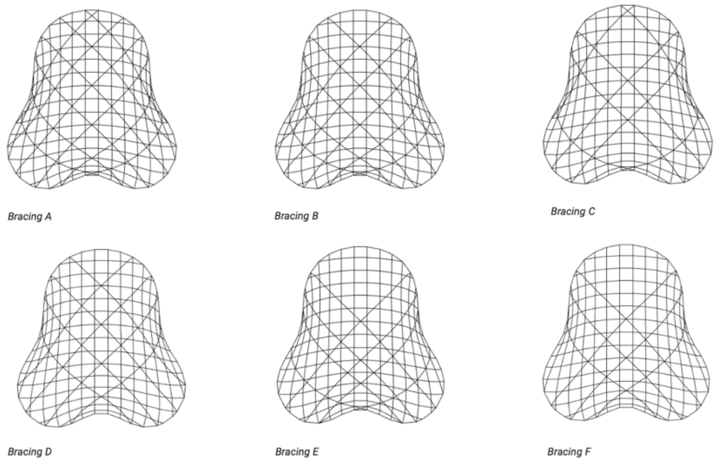


Figure 17: Manually layout bracing

3.2.2. Octopus optimization description

Our goal is very simple and clear, which is to optimize rod length and displacement until to less rod length and less displacement. As we know in the bracing density optimization. Optimal option is 6 bracing in the one direction and 12 bracing in the two direction. We just need write a script(figure19) in the grasshopper to fix these bracing in the right location, less rod length and displacement just two fitness that is show in the figure. The rest thing is hand over to octopus to optimization automatically.

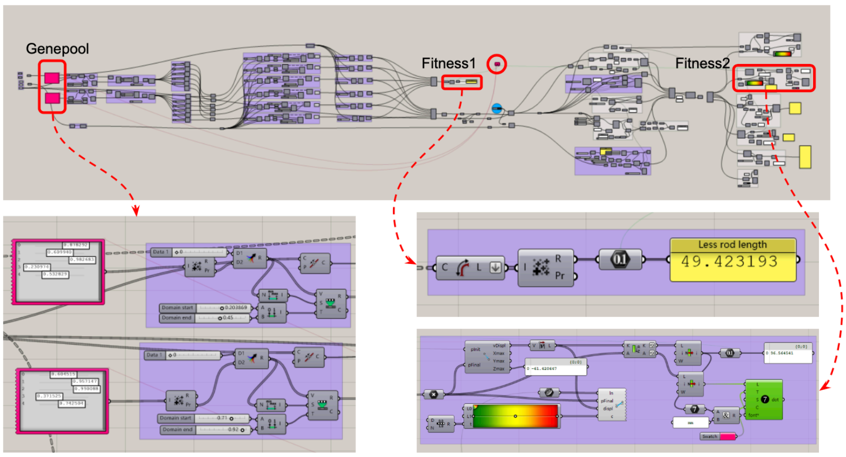


Figure 18: Octopus script

3.2.3. Octopus optimization result

Obviously, for the one bracing direction, we can see the optimal option coordinate system of Octopus according to Pareto curve. Less rod length is 49m and displacement is 83mm(figure19 left). For two bracing direction, it has two optimal options that show in the figure. First option that less rod length is 95m, displacement is 57mm; second option that less rod length is 96m, displacement is 51mm(figure19 right).

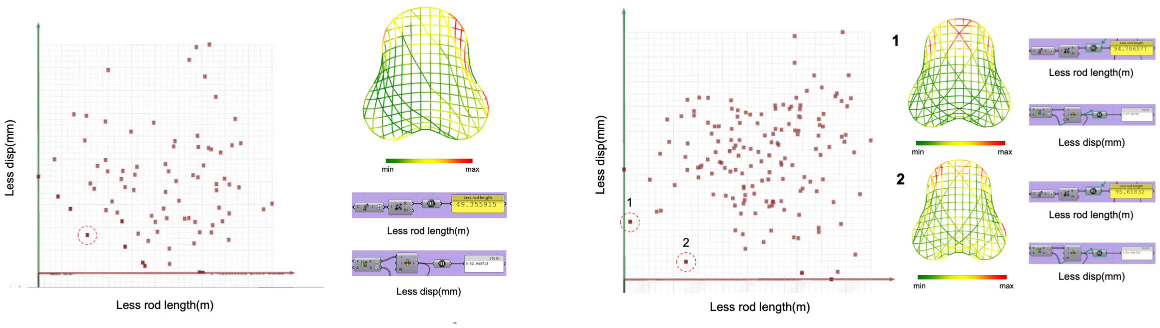


Figure 19: Octopus optimization result

4. Conclusions

4.1. Research Contributions

The research of circle gridshell we designed is not studied in the history.

1. this is first time use three points circle gridshell that we designed as a research carrier;

2. combination of the three types of gridshell provides a reference for bracing research;

3.we created a new workflow to how to select bracing and new method that is how to find high efficiency bracing, which is never used in the specific case in the reality.

4.2. Research Conclusions

To sum up, we get the three main conclusions.

1.an optimized layout provides less fabrication and assembly costs in equal mass value and similar performance;

2.two direction bracing is always better than one direction bracing;

3.the last one is that more constrained at the boundary, more intense change in displacement.

4.3. Research shortages

Because my personal ability is limited, the thesis has three main shortages.

1.he model sample selected in the thesis should be as diverse as possible;

2.bracing direction optimization should improve GH program to make sure bracing is smooth;

3.the third one, We should compare best option after octopus and standard mode bracing and pick some random area candidates to know how much is the benefit of optimization.

5. Acknowledgements

Thank you to my MPDA supervisor Sastre, Ramon for teaching us in this year, this is not an easy task for an elder, I learned the value of persistence in your action.

Thank you to my MPDA supervisor Soriano Botella, Enrique for giving me careful and patiently guidance, more importantly, with your encouragement, I gained more confidence.

Thank you to my MPDA supervisor Bertomeu Farnós, Gerard, you are always a man who is gentle and peaceable. Because your quality, I felt free and relax to study in your class.

Thank you to my MPDA supervisor Tornabell Teixidor, Pep for giving a us a spirit, which is a state between serious and free, I think it is very important in architecture design.

Thank you to my MPDA supervisor Rynne, Alan for giving me selfless help in the class.

Thank you to my all MPDA classmates, we come from different country, we have different culture and background, but we get along very well, time is always flying, maybe it is hard to see each other again, but this experience with you will be a precious treasure in my life.

References

[1] Lionel du Peloux, "ELASTIC GRIDSHELL," PHD thesis 20 December 2017.
[2] Changyeob Baek, Andrew O. Sageman-Furnas, Mohammad K. Jawed, and Pedro M. Reis, "Form finding in elastic gridshells, "20 November, 2017.
[3] Elisa Lafuente Hernández, Christoph Gengnagel, "A new hybrid - Elastic gridshells braced by membranes," Conference Paper, June 2014.
[4] Cecilie Søs Brandt-Olsen, "Calibrated modelling of form-active structure," Master's thesis in Architectural Engineering, June 2016.
[5] Junya Michanan, "Understanding the Power-Performance Tradeoff through Pareto Analysis of Live Performance Data," Conference Paper, November 2014.
[6] Romain Mesnil, "Stability of elastic gridshells," June 2013.
[7] Irene Meissner, Eberhard Möller, "FREI OTTO," edition detail,2015.
[8] Yannick Masson, "Existence and construction of Chebychev nets with singularities and application to gridshells," 2017.