Topology based Construction Process Optimization

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Abstract

In this paper, a complete process from design to construction is presented, aiming for a real scale gridshell, using wood (more specifically plywood), with the design generation being analyzed throughout the different stages. The type of gridshell examined is composed of linear elements (planks) laying on a network of 3 directional pseudo geodesic curves that belong to the surface and the final result is a structurally efficient, lightweight elastic gridshell. Taking under consideration the on-site experiences, the difficulties occurred through the construction phase, the decisions and the artifacts that accelerated the procedure, an evaluation and a critical overview of the steps followed, as well as their efficiency, is approached. In the frame of this case study, research is carried out for optimisation of the construction process in terms of time needed and facilitating its assembly, with the best possible use of auxiliary means. Lastly, the results of different approaches, including the realized one, are compared and evaluated giving an insight on the best performance along the sequence of assembly.

Keywords: 3 directional geodesic gridshell, geodesic gridshell, bending-active, optimization, construction process, optimized assembly, auxiliary means, parametric optimisation

1. Introduction

Gridshells are an evolving topic of research, with many experimental and most of the times temporary installations taking part for material, behavior and standing duration, capability tests. All these experiments and the interest regarding these structures, have created a sector in architectural design with slender elements, with many aspects yet to be explored and new projects can constitute a contribution in understanding deeper the needs and their behavior and expand the use and the potentials.

As mentioned beforehand, the case examined in this study belongs to elastic geodesic gridshells, where actively bent initially flat planks are following a network of geodesic curves, so that the final system (gridshell) is generated.

1.1 Definition

1.1.1 Geodesic curves

A geodesic curve on any surface is defined by a shortest path from one point to another. A characteristic of the geodesics is that they share the same normal vector with the surface at every point. Therefore the structural elements following the geodesics of the surface have the ability to be unrolled straight. [1]

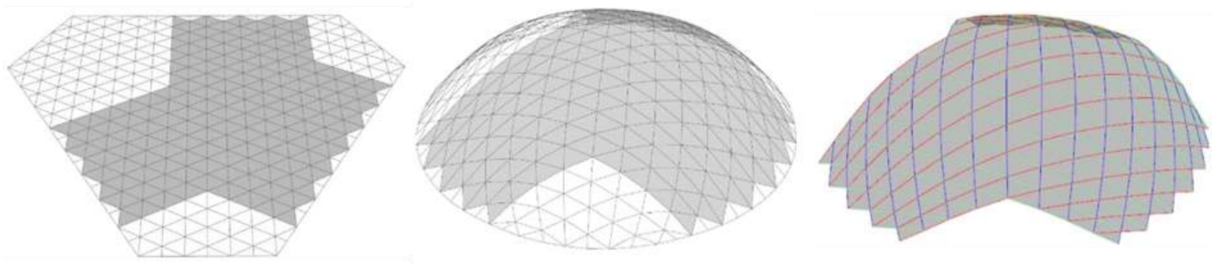
The advantages of these structures is that planar elements can be used for the construction, and after their assembly they result in a strong form which occurs from the inherited double curvature of the final shape. The overall structure remains lightweight while being able to bear multiple loads of its weight.

The vanishing geodesic curvature ensures the component to be developable and straight, which benefits and eases the fabrication and reduces the construction cost. For the active-bending structure, mainly the normal curvature and torsion will be taken care of and that frees the limit in the width of the component.

1.2 Form Finding

For this project, the target shape had to be a dome form, pavilion wise form an outdoor installation of 70 to 100 m2 which should cover the safety rules and give shelter to outdoor activities.

The process followed to generate the shape was the transmutation of a flat grid composed of a 3 directional curve network, with the use of a Grasshopper plug-in: Kangaroo, to a 3D dome-like mesh, composed of a geodesic grid. A decisive and important factor in the selection of the final shape was the capability allowed for the elements to be bent along its geodesic curves. [2]



Figures 1a, 1b, 1c. Form finding from an initially flat configuration.

1.3 Analysis

After comparing the different layering options in terms of mass and displacement, the case that was opted for was a balance between these two parameters and it is composed of a single layer with doubled only the boundary beams for extra support and an additional layer of more narrow planks in the unique direction, that can be seen as the skeleton (ribs) of the membrane.

One difficulty while conducting the structure analysis was that, due to the bending effect, the structure could result in large deformation, which would be inaccurate if only the linear analysis applied.

Kiwi3D is a plugin based on Grasshopper3D, which allows performing isometric-based finite element analysis (IGA) based on NURBS parameterization. It was developed by Chair for structural analysis, TU Munich and str-ucture GmbH in Stuttgart, Germany. We opted for this plugin to do the structure analysis for its provision of user-friendly settings with the non-linear analysis configuration and automated pre-stress definitions.

Assembling the structural model requires deep consideration. One is the joint axes on the nodes, the rotational axis must be perpendicular to the proposed surface while the other degree of freedom needs to be locked. The other important part is the axis of the beam cross-section, incorrect settings will lead to inaccurate results.

The loads that were taken into consideration were: self weight, snow load and wind load. The wind load and snow load are roughly approximated from surface loads into point loads acting on nodes by opting for some components in the K2E plugin (MeshVertexArea, MeshWindLoad, MeshSnowLoad).

2. Final work

The final project and its 6-day construction took place in Alp, in Catalonia, close to the municipal gymnasium covering an area of approximately 75 m^2. The material used was plywood of 15 mm thickness and 130 mm was the width of the planks.

Figure 2. The site.

Figure 3. The gym complex across the street.

2.1 Fabrication & Assembly

The geodesic property of the beams allowed the generation of them by unrolling the 3D designed planks. Their total length was composed of individual pieces of maximum 2.50m (maximum material sheet dimension) that were joined with shear blocks. The joints were placed taking into consideration the location of holes (for the nodes).

Although the fabrication of the elements required a direct procedure, real construction difficulties were less easy to estimate.

Since the beginning of the construction, the absence of auxiliary means created the necessity for workers supporting the planks and cutting short the manpower, until the improvised on-site placement of scaffolding elements achieved a self standing configuration.

Subsequently, among the first steps of the assembly (approximately for the first 18 planks) the displacement events weren't controlled and manual force was needed to relocate them correctly.

Finally, the last serious inconsistency was faced during the last steps of assembly and mainly closer to the supports, when the structure's stiffness and the accumulated displacements led to extremely demanding effort in order to force the nodes' holes to coincide and be able to fix them.

2.2 Realized project

Figures. Construction process.

Figures. Final gridshell. (photos by Andres Flajszer)

3. State of the art

In the last several years many architects, engineers and constructors have worked on the implementation of the properties of geodesic curves into various structures.

Mina no mori, 2015, Japan, Toyo Ito

Designed by the well-known architect Toyo Ito, “Mina no mori” (the forest for everyone) is a new media center with an area of roughly 7,500 m² in Gifu, Japan. The roof structure is made of 3 directional laminated pinewood and probably one of the biggest 3 directional geodesic grid shells in the world. The structure is assembled by multi-layer pinewood planks to attain the necessary profile height.

Jukbuin pavilion, 2012, Spain, CODA [5]

The Jukbuin pavilion is an experimental pavilion utilizing the “kagome” pattern into the active bending structure. In the construction process, the whole structure will be erected from flat ground by controlling the foundation position. The cells’ dimension is unified, which results in global curvature as zero. Thus, it reduces the stability which a double-curved surface can provide.

Almond pavilion, 2012, Spain, CODA [3]

The Almond pavilion is a 2 axis geodesic pavilion characterized by removing the boundary constraint of the geometry so that it contains some mechanical features during the construction process. The structure can be flattened into a plane and be convenient to transfer and erect on site with pre-fabrication and assembly. [7] It merely permits low curvature deviation locally so that the length between the nodes has less difference so that it can avoid bending in the tangent direction of the planks.

Research Pavilion MPDA 2021, Spain, MPDA students

This newly built research pavilion has one direction crossing the surface as the main structural axis. The designer also selected this direction to enhance it with ribbed options. As long as the planks of that direction have been assembled, simple bracing from another direction will stabilize the structure immediately.

Concerning the construction process of the research pavilion in Alp , which not only has the more equalized load distribution among the 3 axes, but also with high curvature on top of the pavilion, the complexity of the equilibrium is difficult to predict. It is also inevitable to select the long span planks and assemble them one after another because of the geometrical topology. The pursuit of a better sequence of assembly is worthwhile.



Figures. 4. Mina No Mori Figure 5.Jjukbuin pavilion Figure 6. Almond pavilion

Figure. 7. 3 axis research pavilion MPDA 2021

Figure 8. Construction process

4. Construction process optimization approach

In this chapter, the main scope of the research is introduced, which is the exploration of the tools that can facilitate and therefore optimize the construction process of the 3 way geodesic gridshell studied. The goal of this research is the implementation of a process sequence of evaluating the geometry based characteristics of the gridshell. That will provide us with the information needed to indicate the combinations of assembly sequences which will perform in the best way possible, as far as the displacement and the utilization are concerned.

4.1 Hypothesis

With an assumption that the time consumed, as well as the extensively demanding power needed (normally, tangentially or binormally) on the planks in order to align and fix the nodes, can both be reduced or at least be more predicted and controlled, our objective is to gain control over the construction and improve the assembly process.

To achieve this objective, the proposal is to find an optimized sequence by taking into consideration the displacement and utilization, while assessing the influence of the angle defect, the standard deviation of segment length and the completion of the vertex valence that the elements of the system are subjected to. Thus, our hypothesis is oriented towards the sequence of assembly, targeting to facilitate the construction process.

Complementing this anticipated improvement, the planned in advance sequence and placement of auxiliary means such as temporary bracing and scaffolding, will also help to decrease consumption of time and physical effort during the construction process.

4.2 Methodology

The single layer gridshell has 53 planks in total, with 17 planks in direction A, B and 19 planks in direction C. A full iteration of all the possible combinations would be unachievable since the total amount of 53 planks would have $\prod_{n=1}^{53} C(n,1) = 4.2749e+69$ amount of combinations. Thus, some geometrical and topological properties need to be researched and found in order to constrain the searching scope of the combinations.

We started the research by simulating different types of load conditions on a simple active bending beam in a 2D environment. As the following figure (Figure 9) shows, with a single point load being applied, the worst case emerges where the load point is positioned at a high curvature area. However, if it’s on top and middle of the beam, the deflection is minimal.

Furthermore, a pair of point loads was tested with the same force value. The deflections are slight in symmetrical cases, regardless of where the position of the point load is, in comparison to the asymmetric cases. The case with the maximum deflection and utilization remains to be an asymmetric load pair in a high curvature area.

Similarly, the same behavior is observed in 3D simulation, where the simulation is more complicated than the 2D cases. The equilibrium of every beam that constitutes the structure system needs to be considered. Additionally, we should also care about the torsion on the beams. The various choices of combinations in the structure system consist of a wide range of scope. Under these conditions, we tend to focus on the geometric topological properties.

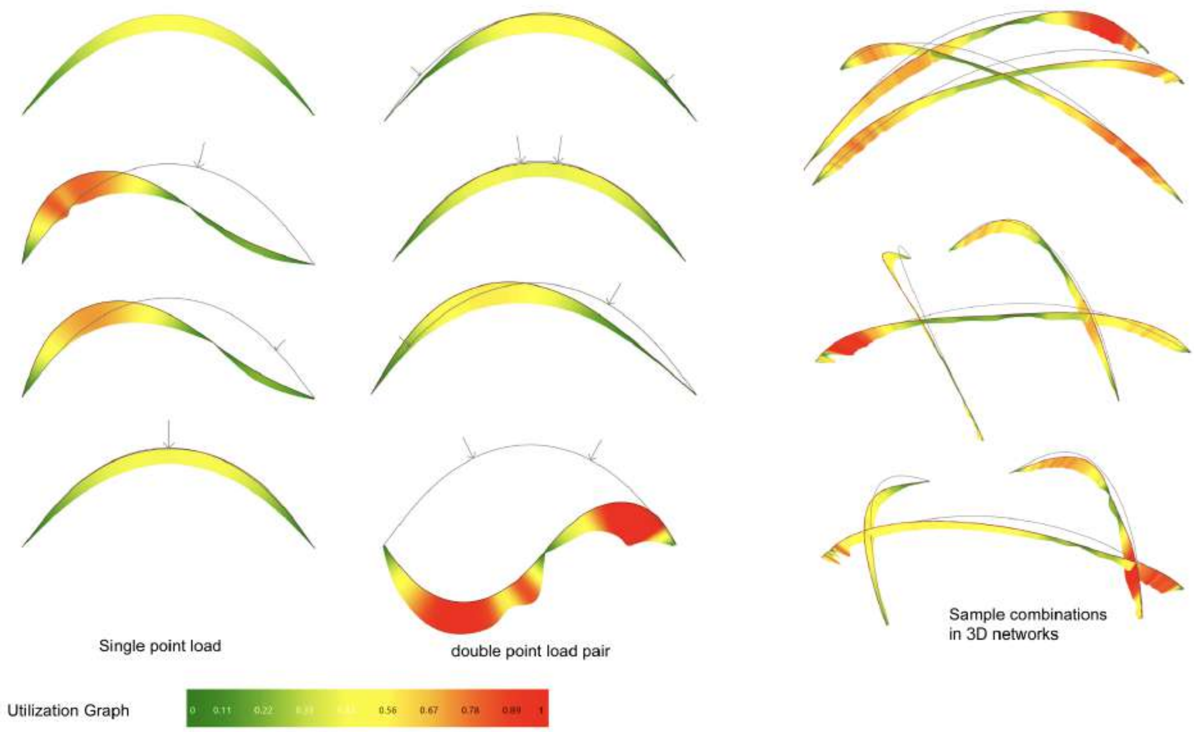


Figure 9. 2D and 3D mock up simulation

4.3 Assembly sequence

4.3.1 Strategy

For the documentation of the structure's behavior along its assembly, six sample cases were determined, where for each of them the assembly sequence was different, but for all of them the planks were assembled in 12 steps (5 planks are the first and second step and 4 planks for all the rest steps). This way the comparisons made afterwards consider the same number of planks assembled differently and therefore creating different geometry topologies and generating more or less ideal structural analysis results.

4.3.2 Illustration of cases

For the assembly steps of all the cases with the corresponding utilization and displacements see **Appendix A.**

- **Case A – Sequential selection of planks' placement** [Figure 11]

For this case, the planks were selected based on their physical sequence starting from the first direction (layer A), then continuing with the symmetrical direction (layer B) and finishing with the unique direction (layer C).

- **Case B – Three directions (Theoretical approach)**

During this assembly the layering of the three directions is not taken into consideration and therefore the difficulty occurring on the vertices is the necessity for temporary assembly and reassembly of nodes, a fact that increases the construction time. Thus, although this case is of high performance, it is characterized as theoretical.

- **Case C – On site sequence (As built)**

Case C is the sequence of assembly followed in the realized project in Alp. In this case as in Case B, planks of the third layer were implemented before the completion of the 2 symmetrical prior layers in order to provide the structure with more stiffness by creating triangles on the grid (valence 6 vertices). Difficulties due to displacement and delay due to disassembly of temporarily fixed nodes were faced.

- **Case D – Alternative / Symmetrical**

In this case, the planks of the two identical directions are assembled symmetrically and once they are completed, the third and unique direction follows.

- **Case E – Custom approach 1 and** - **Case F – Custom approach 2**

For both of these custom-sequence cases the symmetrical directions are assembled prior to the third layer.

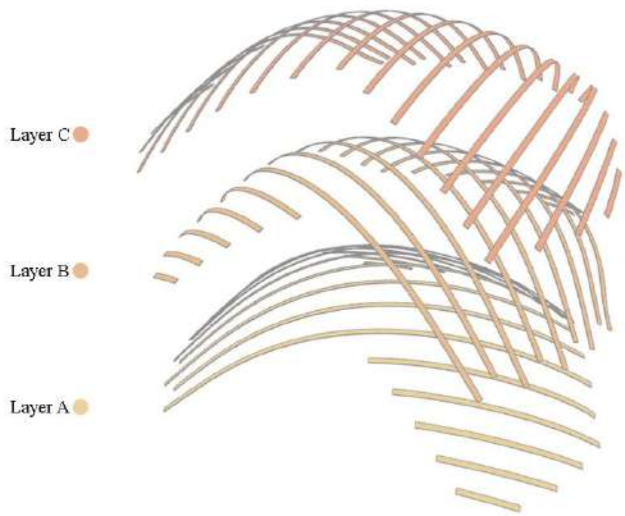


Figure 10. Layer sequence of the 3 directions.

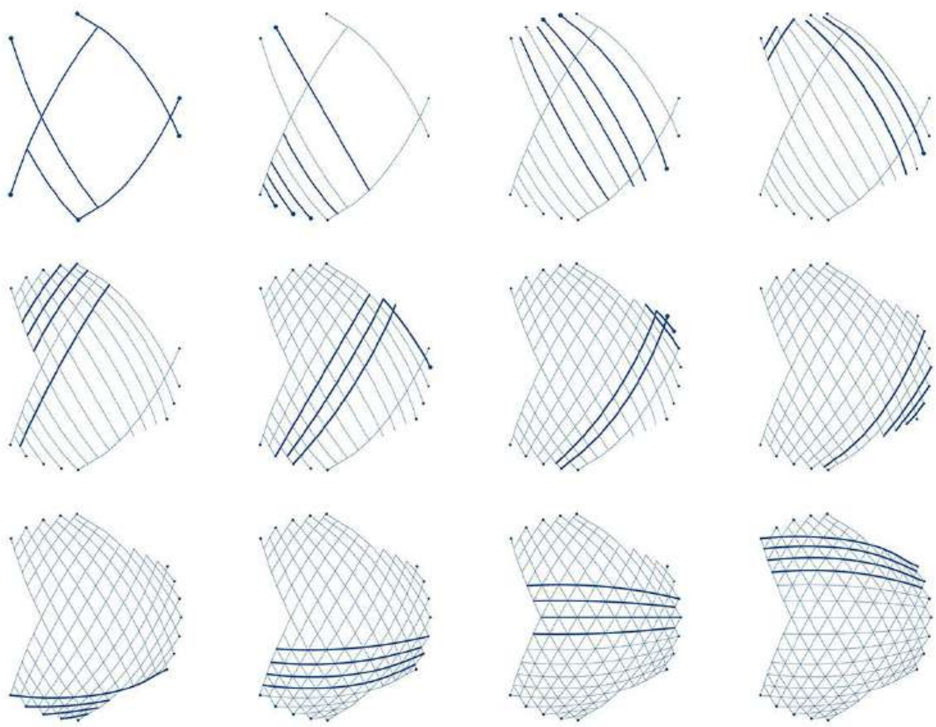


Figure 11. Assembly steps of case A.

4.3.3 Comparison and Assessment of cases

By reviewing all the cases and sequences as discrete samples, the maximum deflection and topological metric properties can be evaluated and the way that the stiffness of the structure is influenced by these metrics can be observed. This research will include the scope of the total discrete curvature, the standard deviation of the length of segment and the percentage of full valence of the nodes.

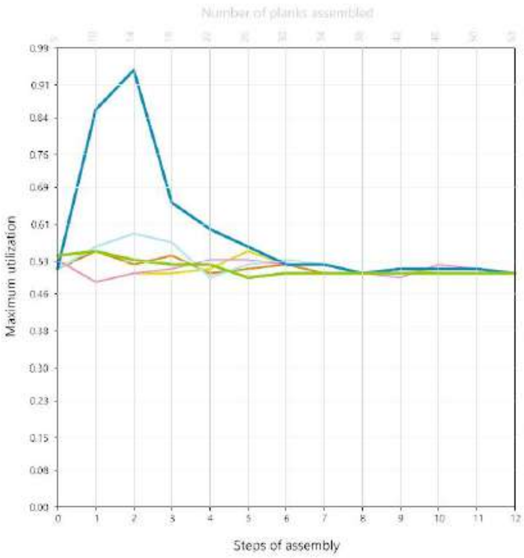


Figure 12. Comparison of maximum utilization of sample cases.

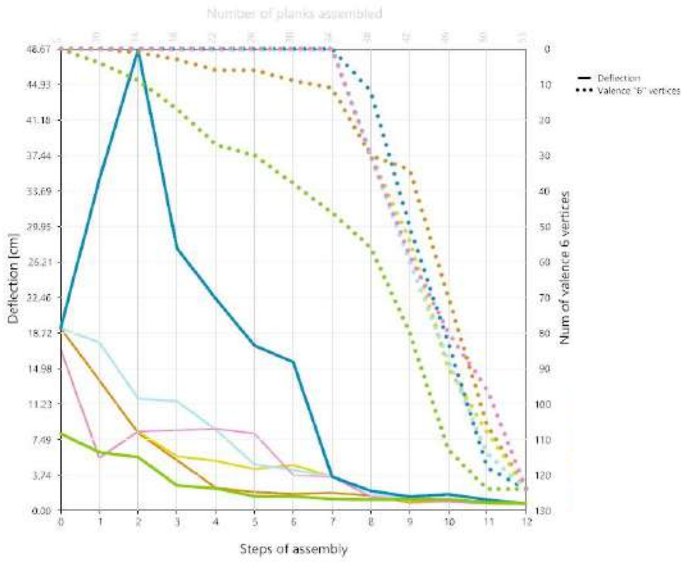


Figure 13. Comparison of deflection performance along with 6-valence vertices.

Firstly, the utilization along the assembly steps for all the cases was recorded and as presented in the graph [Figure 12], only the first case, in which no specific sequence strategy was implemented, is subjected to high utilization values. Another simultaneous illustration of the deflection results and the presence of 6-valence vertices, which means triangulation of the grid and therefore stiffness addition is presented on the graph [Figure 13]. Nonetheless, although the cases that all three directions were implemented for the assembly have low deflection values, 2 directional assemblies perform well.

The data were recorded during every assembly step and are considered as a data set. By applying linear and non-linear regression with these datasets, some relations between stiffness and topology occur. Lunchbox ML is the plugin we opted for to reach the goals. LunchBoxML introduces several generalized supervised and unsupervised learning tools for visual programming including regression analysis, neural networks, and mixture models.

A linear performance is represented between the maximum deflection and the standard deviation of the length between nodes (segment's length) [Figure 14]. In general, the more equalized the structure is, the less deflection it has. For different sequence variations, we can verify that the slope indicates the aid of the third direction and the slope of the line is decreased.

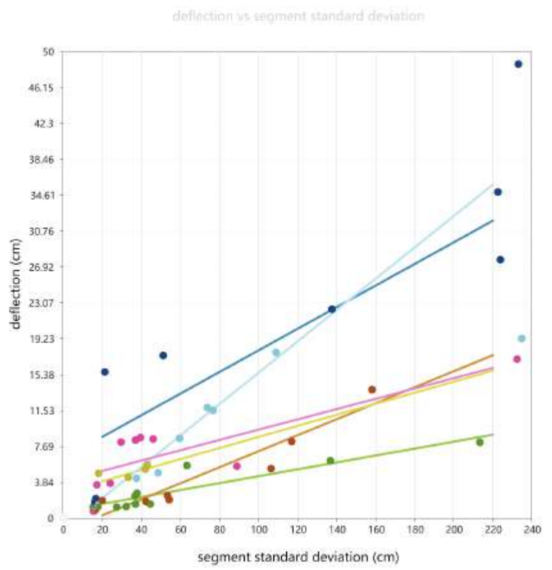


Figure 14. Deflection and segment standard deviation relation.

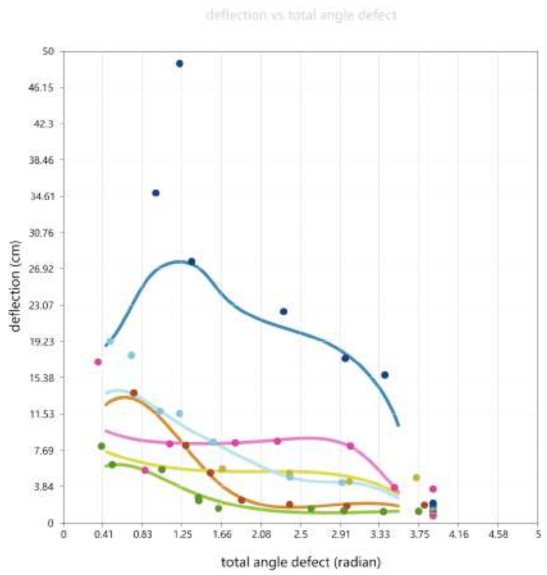


Figure 15. Deflection and angle defect relation.

The average trend between deflection and percentage of the full valence is displayed in the graph [Figure 16]. Despite the amount of cases pointed at Y axis, while the two directional assemblies lead to incomplete nodes in the beginning, a drastic drop of the deflection appears as soon as the valences of 6 (complete nodes) emerge (triangles are formed on the grid). Around approximately 8% of valence-6 nodes can help to stabilize the structure into a favorable condition, as the inflection point indicates on the non-linear regression curve.

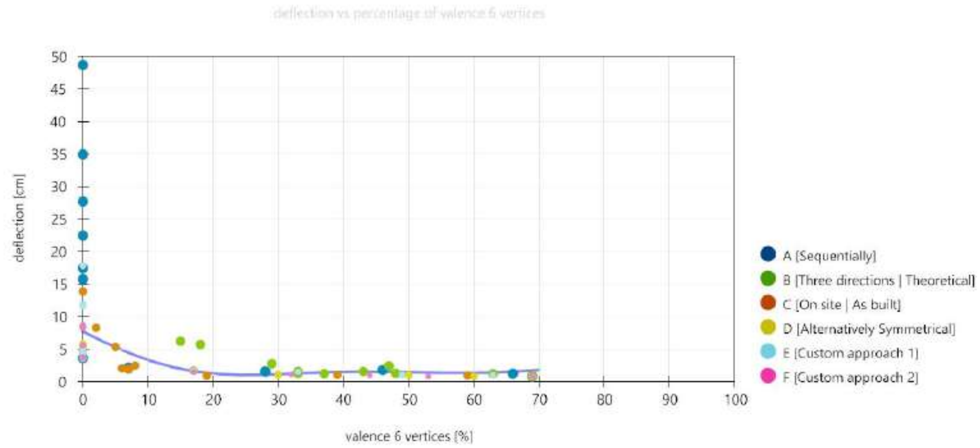


Figure 16. Average trend relation between deflection and percentage of the full valence vertices.

Inverse relations are noted between the stability of the structure and curvature of the form. Ordinarily, the more angle defects on the nodes, the less displacement the structure will get. For all the regression curves of each case the inflection points are situated at around 1.66, which can also constitute an indicator for the choice of assembly [Figure 15].

Among the case studies researched, case B and case C, which involve the third direction in the beginning of the process, display the best performance with the assistance of more than 8% of complete joint nodes. Apart from these, between the assembly cases that complete the two directions in the first place, Case D is the best case as the least length standard deviation of the plank's segments is marked and the essential global curvature is reached expeditiously. The evaluation of the labor of reassembling the nodes of the planks when crossing the existing third direction is hard to predict. On the other hand, the large deflection can be avoided with the use of auxiliary means such as temporary scaffolding and bracing.

Eventually, Case D is selected as the relative optimal option for this project.

4.4 Auxiliary means

While assembling the gridshell in Alp, there were about 15 people involved among which more than half of them were only there holding the beams providing support (as seen in the construction images) replacing the much required auxiliary means. This was cutting the manpower in half and it took a lot of effort to keep holding it during the whole process. Therefore, in order to make the assembly process easy, use of auxiliary means (temporary scaffolding and bracing) was a suggestion.

4.4.1 The Algorithm

Going ahead with the idea of using auxiliary means, we assumed that locating the crucial positions where either horizontal or vertical support is required can make a huge impact on the deflection of the beams. To check this assumption, we formed an algorithm to locate these positions and checked the impact with Kiwi.

To begin with this process, we performed an initial kiwi test and used the displacement results to know areas with maximum vertical and horizontal deflection. With this information, we created point groups and obtained the average location for vertical and horizontal scaffolding. As seen in the next figure [Figure 17] the green points resemble all the points with maximum deflection, and the circles loosely represent point groups, and the black points are locations for nodes.

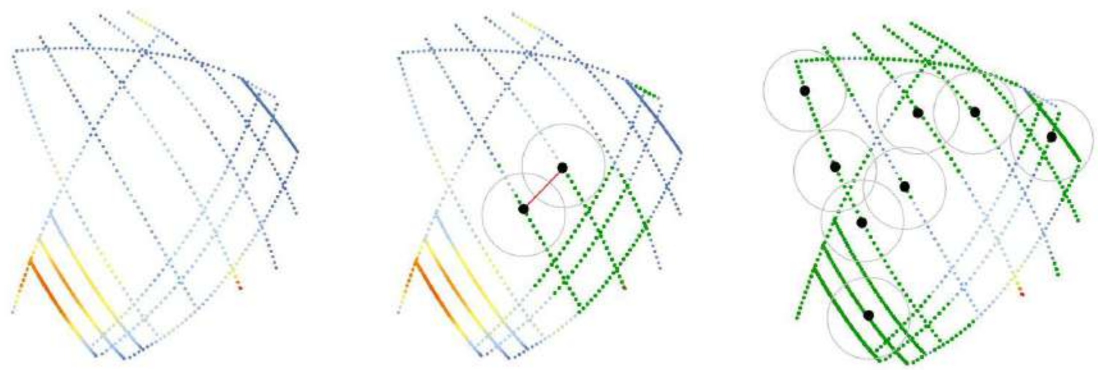


Figure 17. a.) No deflection, b.) maximum horizontal deflection and bracing location, c.) maximum vertical displacement and scaffolding location

Furthermore, while designing the scaffolding, we kept in mind to use maximum 8 supports and made sure they are all longer than 0.5m for ease of assembly. On the other hand, for bracing, we made sure all the connections are shorter than 0.8m but we did not restrict the number of supports to oppose the scissor effect as much as possible.

4.4.2 Testing the Algorithm

To test the above mentioned algorithm, we used it on the first 4 steps of case B and C before using it to optimize case D. In the figures below, the results from case B and C are represented.

While running the algorithm for every step, it was noticed that the position for scaffolding and bracing was changing with each step but in general, maximum vertical displacement was noticed close to the openings whereas maximum horizontal displacement was noticed in the center.

For the results from the optimisation process of Case B, C and D see Appendix B.

As seen in the results (See Figure 18), the location and use of auxiliary means made a huge impact on the maximum deflection of each step. With this successful attempt of optimisation of auxiliary means, we performed the same exercise on case D for getting the final optimized assembly process.

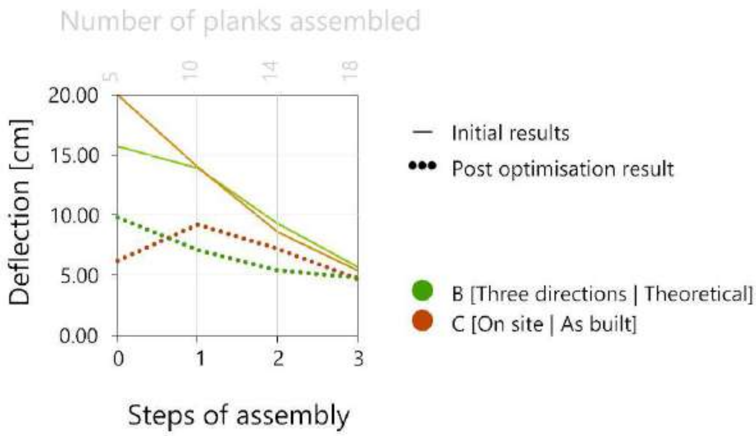


Figure 18. Change in deflection pre and post the optimisation algorithm

4.4.3 Optimisation of Case D

With the tests we ran on Case B and C with the designed algorithm, it was established that the algorithm was giving much better results and that the use of auxiliary means is helping a lot with the ease of assembly. Therefore, we decided to use this algorithm to optimize Case D which was determined to be an optimal option for the assembly.

The final construction process obtained after optimization displayed drastic changes in the displacement and utilization in each step (see figure 19). The maximum displacement for Case D reduced as low as 2cm giving a fair competition to the results from case B and C which include the use of direction C from the initial steps.

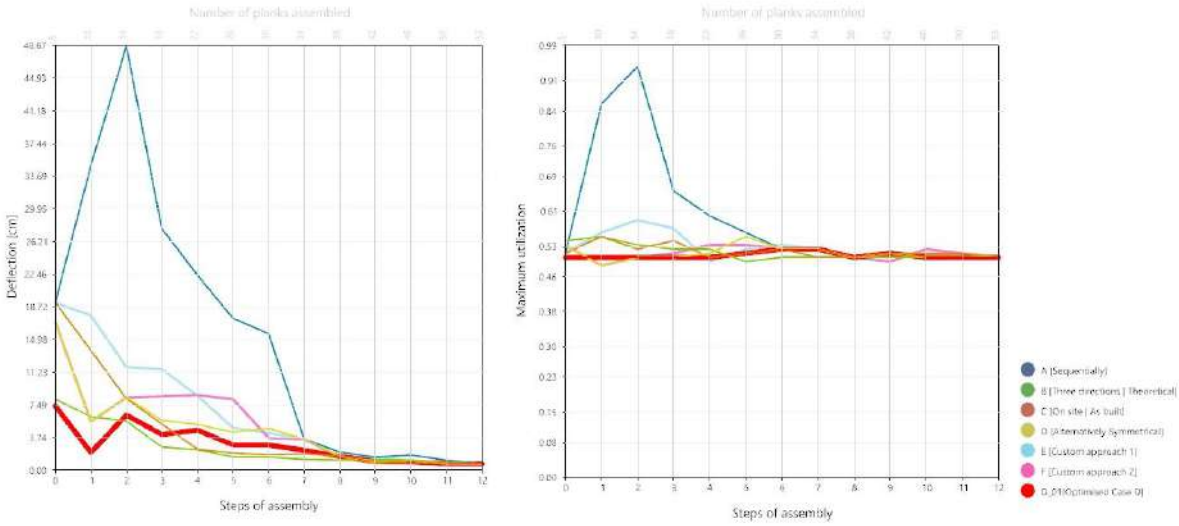


Figure 19(a,b). Change in deflection and utilization pre and post the optimisation respectively

5. Conclusions

The three geometrical topological factors studied above (vertices' valence, total angle defect and standard deviation of the segments' length) can be adopted as the dominant factors for the stability of a 3 directional geodesic gridshell during the construction process. They can be utilized as the guidelines for the decision-making of the construction sequences of one project.

Approximately a percentage of around 8% of the "full valence" vertices assembled (with all 3 directions of planks assembled), by introducing a small amount of the third-direction planks, contributes to a significant decrease of displacement. As full valence suggests more triangulation and thus provided more stiffness.

The length between the nodes should be more equalized, as the standard deviation of the length has a linear relation with the displacement. Therefore, extremely asymmetrical situations should be avoided.

The bending behavior helps to stabilize the structure as well. Since, with a total angle defect more than 1.66 in radian, the cases always perform better, the sooner this value is reached, the earlier the structure's stiffness is achieved.

6. Further research

Indeed, the implementation of the topological characteristics as a factor that combined with the structure's utilization can determine and contribute to a theoretically improved process of the gridshell construction, with less effort required, as the pre-estimated supplementary and temporary use of cables, rods and scaffoldings can transform the procedure.

Time and human efforts were not deeply considered in the research as it's imprecise to quantify and estimate them, such as the displacement effect which requires the human forces to resist back, etc.

Auxiliary means during the construction process are always recommended to enhance the stability of the structure.

Even though introducing the third direction reduces a huge amount of the displacement, it’s still a trade-off between simple assembly with the nodes and the resistance with scissor effect.

So the scope of further optimization of the construction process can be the implementation of an algorithm that will combine the topology while opting for the planks that will result in lower displacement, keeping utilization in an acceptable range.

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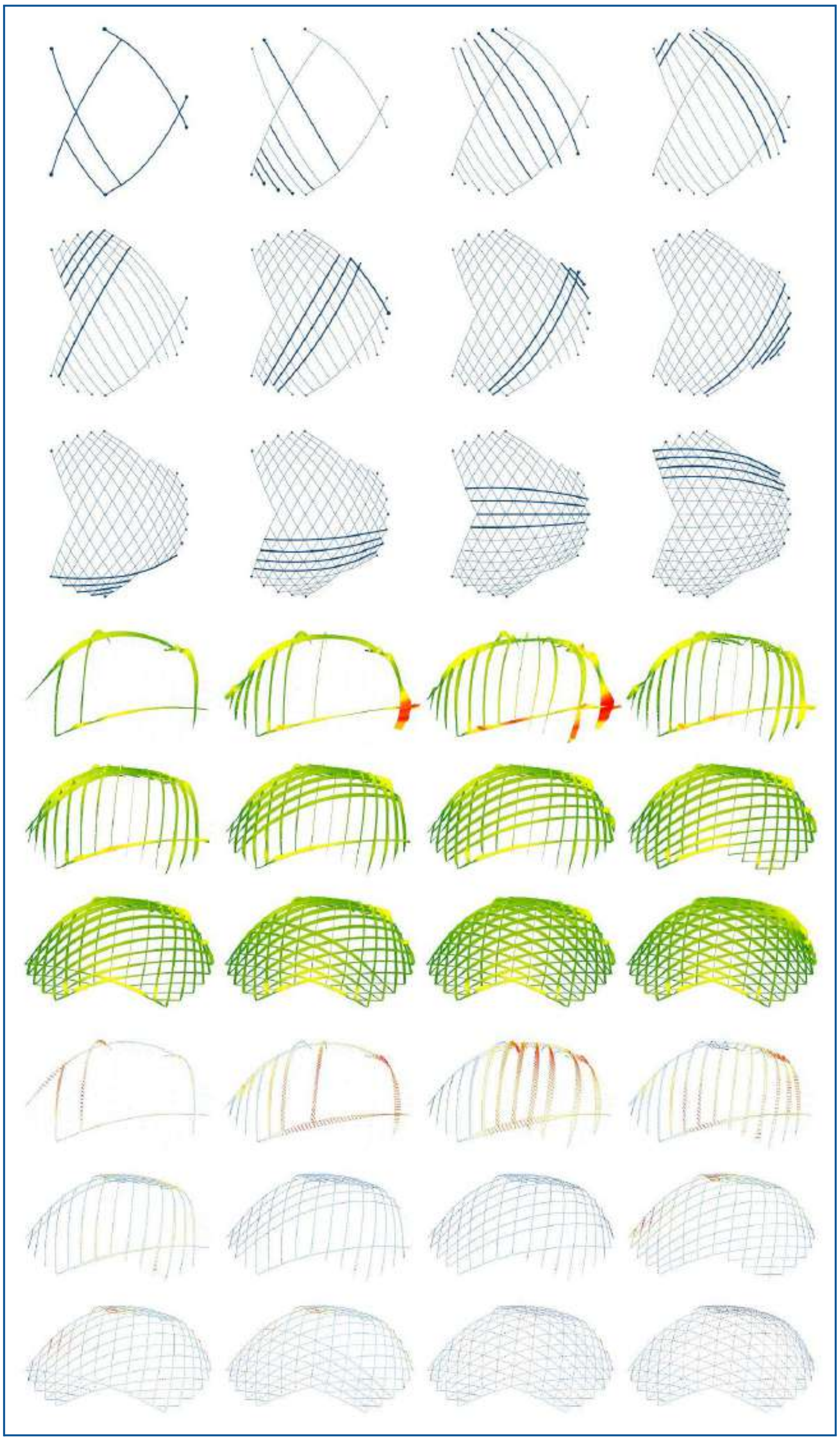
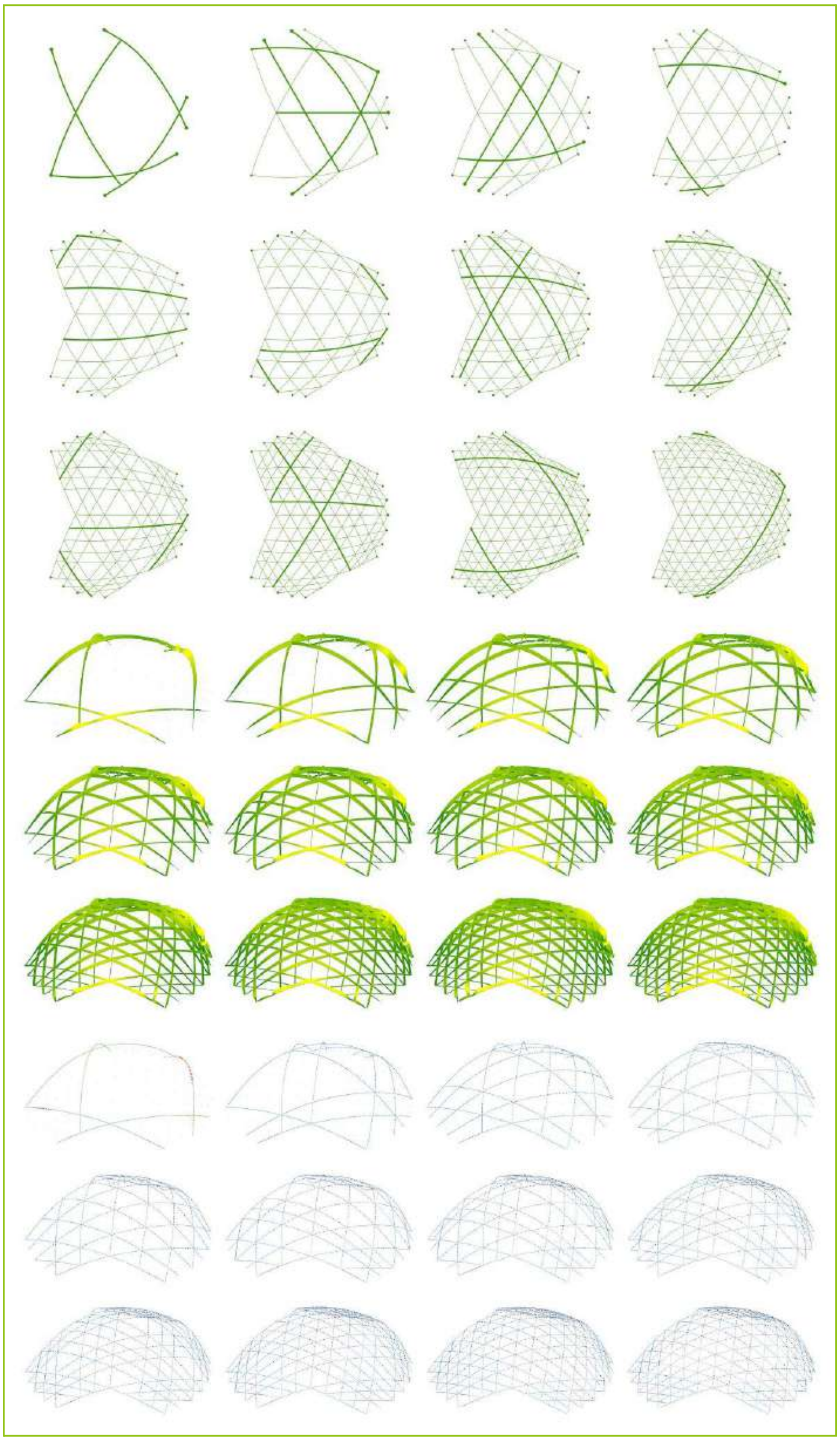
Appendix A

In the following figures are illustrated the steps, the utilization and the displacement graphs of the sample cases along the assembly process.

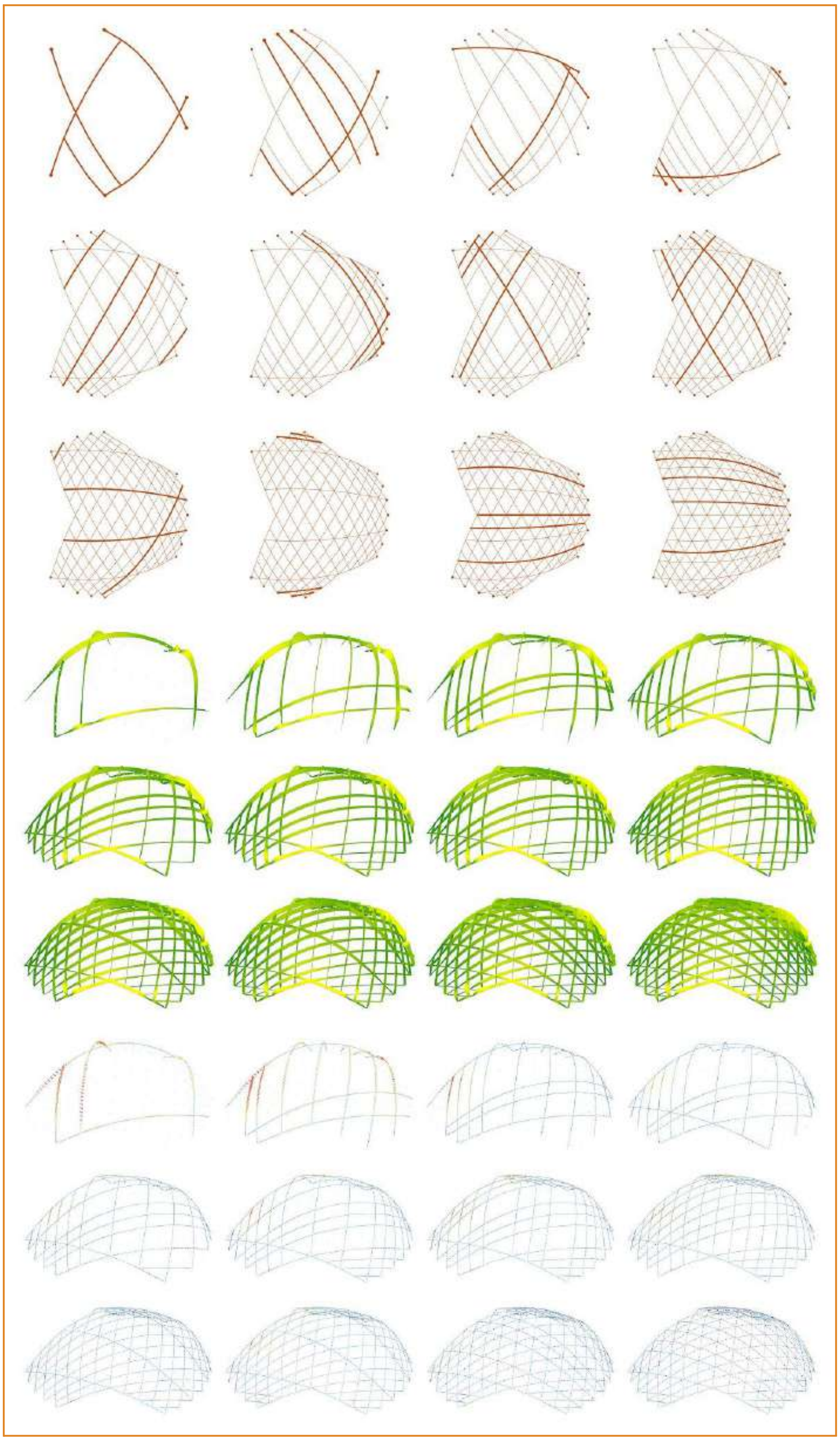
- **Case A – Sequential selection of planks' placement**



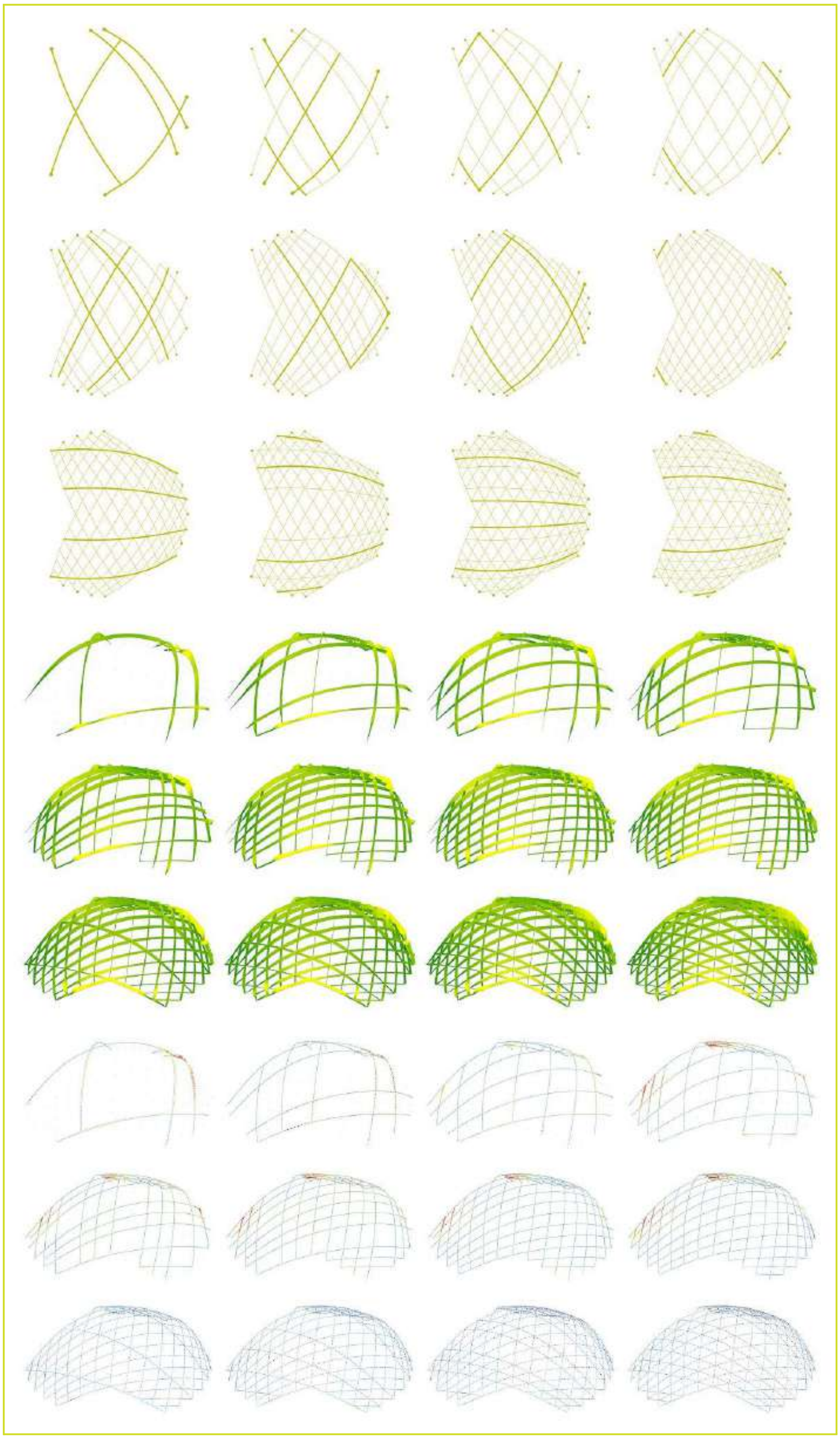
- **Case B – Three directions (Theoretical approach)**



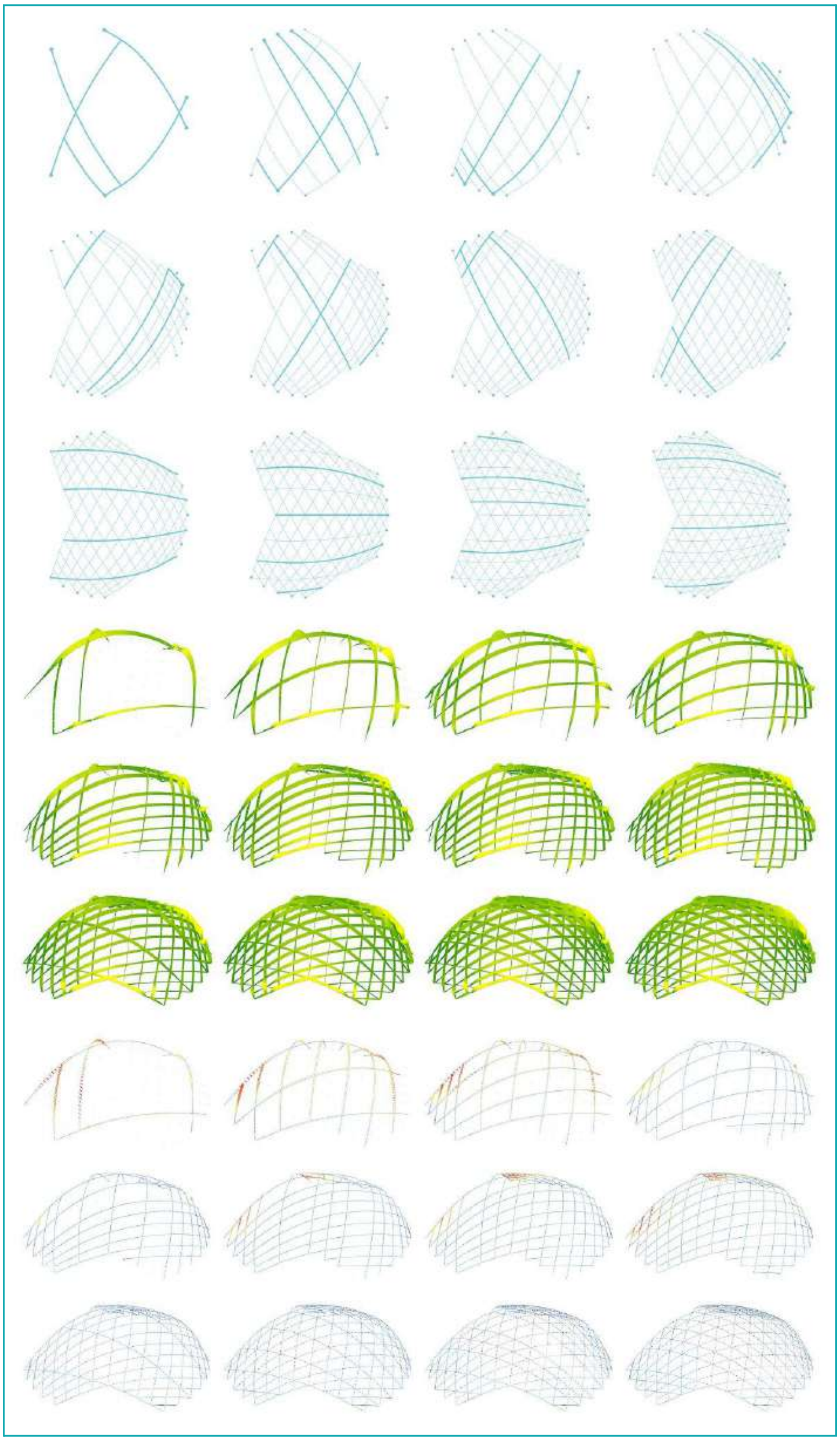
- **Case C – On site sequence (As built)**



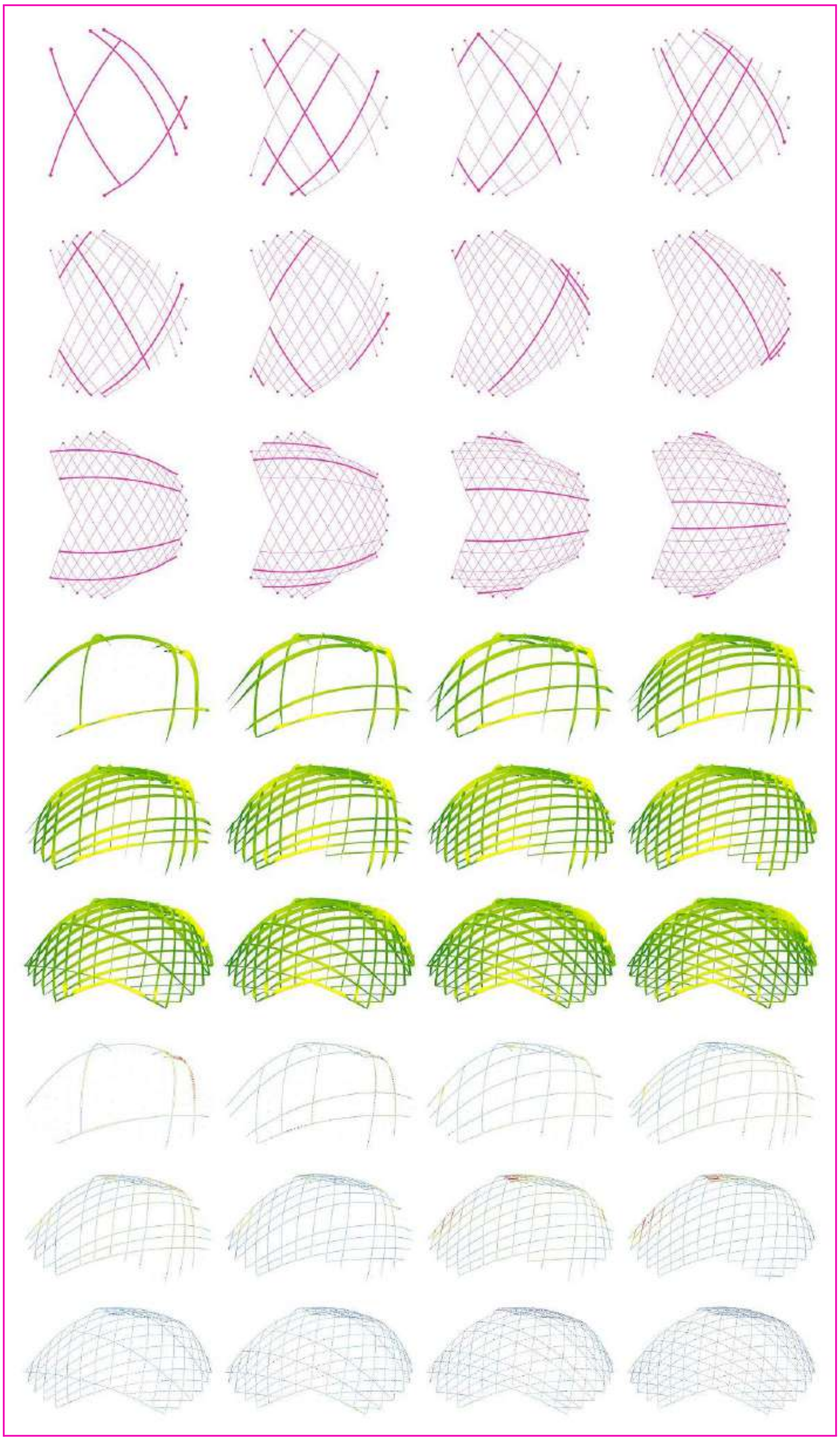
- **Case D – Alternative / Symmetrical**



Case E – Custom approach 1

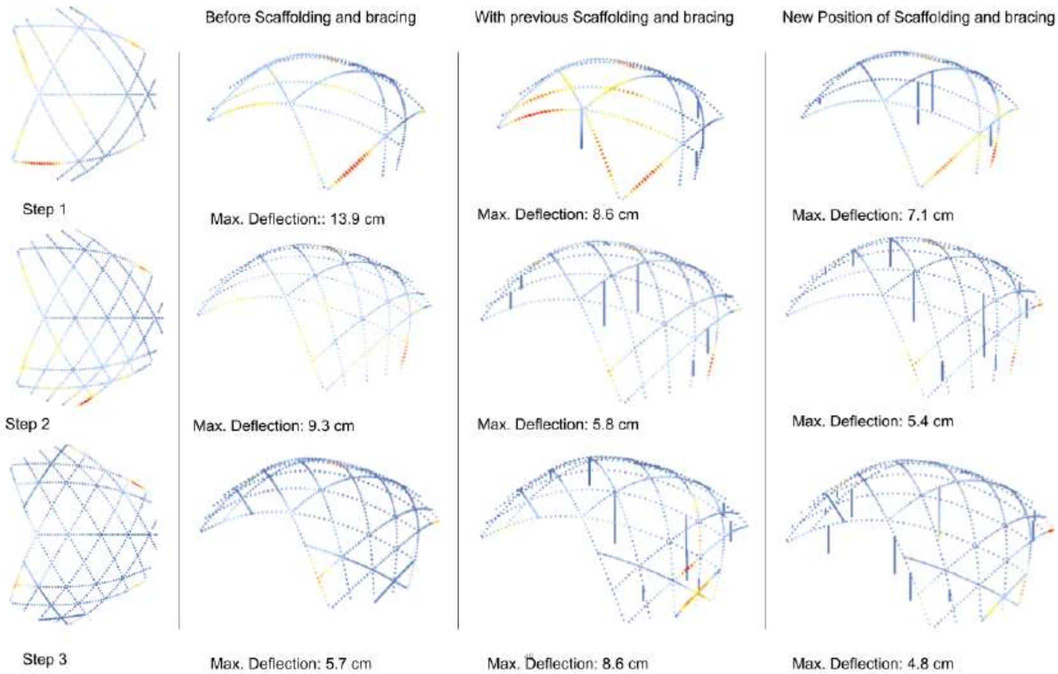


- **Case F – Custom approach 2**

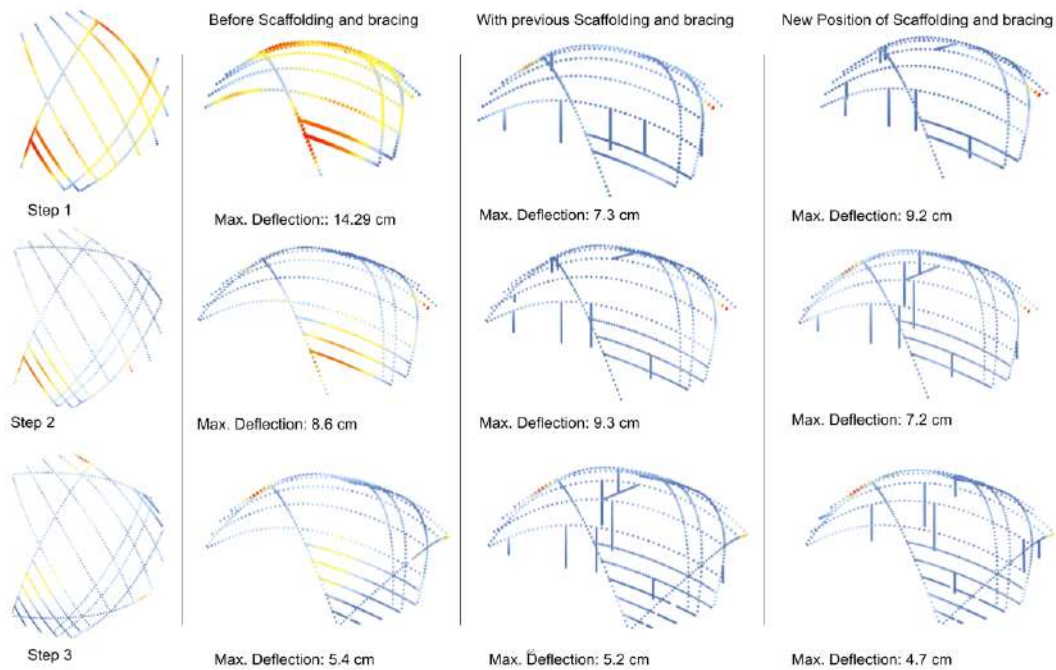


Appendix B

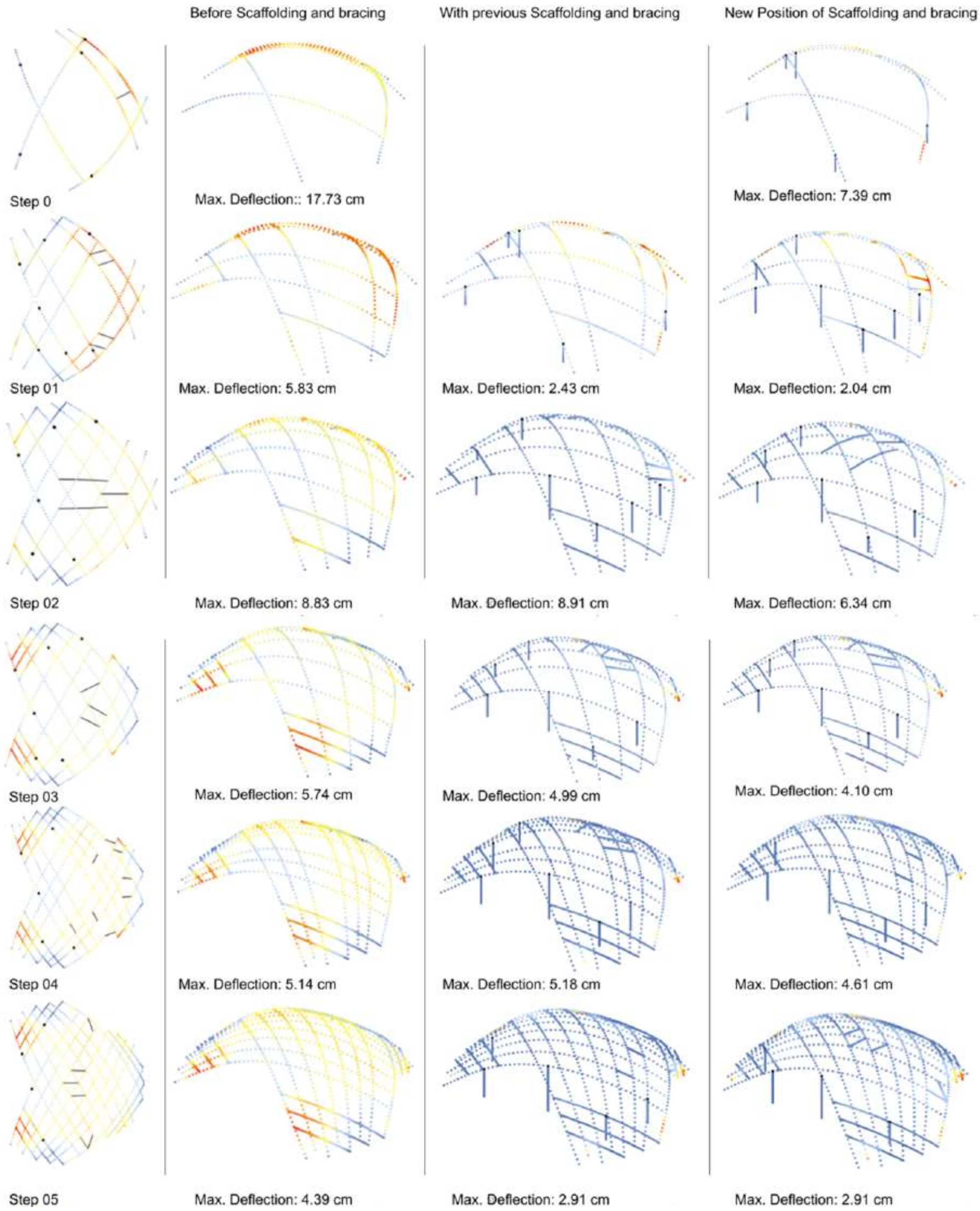
Case B:

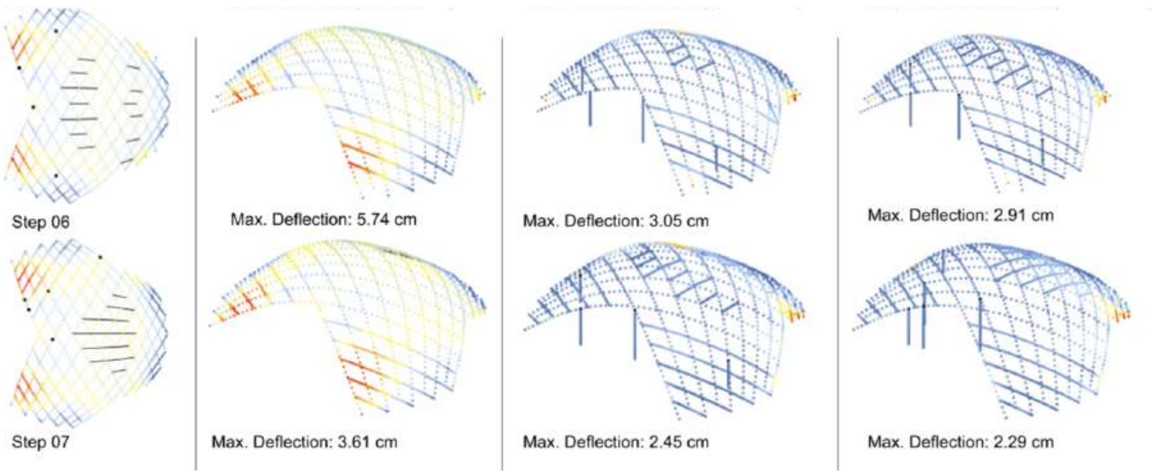


Case C:



Case D:


Before Scaffolding and bracing
With previous Scaffolding and bracing
New Position of Scaffolding and bracing
Step 0
Max. Deflection:: 17.73 cm
Max. Deflection: 7.39 cm
Step 01
Max. Deflection: 5.83 cm
Max. Deflection: 2.43 cm
Max. Deflection: 2.04 cm
Step 02
Max. Deflection: 8.83 cm
Max. Deflection: 8.91 cm
Max. Deflection: 6.34 cm
Step 03
Max. Deflection: 5.74 cm
Max. Deflection: 4.99 cm
Max. Deflection: 4.10 cm
Step 04
Max. Deflection: 5.14 cm
Max. Deflection: 5.18 cm
Max. Deflection: 4.61 cm
Step 05
Max. Deflection: 4.39 cm
Max. Deflection: 2.91 cm
Max. Deflection: 2.91 cm


Step 06
Max. Deflection: 5.74 cm
Max. Deflection: 3.05 cm
Max. Deflection: 2.91 cm
Step 07
Max. Deflection: 3.61 cm
Max. Deflection: 2.45 cm
Max. Deflection: 2.29 cm