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The Roskilde Domes 2011 and 2012

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Summary: This paper describes the structural design of two plywood domes with geodesic geometry for the Roskilde Festival in 2011 and 2012.

Keywords: *Plywood dome, Conceptual structural design, temporary structure.*

1. INTRODUCTION

In the spring 2011 the architect Kristoffer Tejlgaard contacted me and asked if I could help him design a dome for the Roskilde Festival. The idea was that he and some of his friends would build a sculptural piece of architecture from simple standard plywood plates that could be taken down and reused next year.

Kristoffer Tejlgaard took his master in architecture from the School of Architecture at the Royal Academy of Fine Arts in Copenhagen. During his study he met Ture Wester and became interested in the geometry of geodesics.

At the end of April, eight weeks before the festival opened, the architectural concept for the dome was presented to me, see Fig. 1.

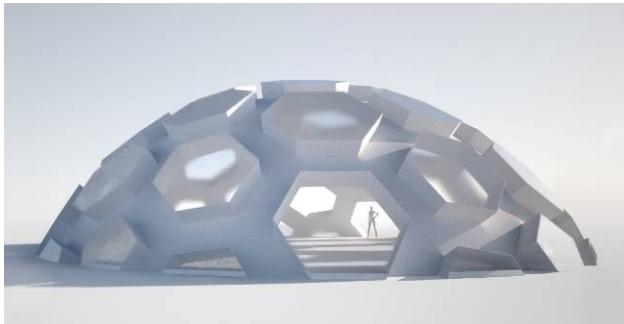


Fig.1. Rendering of Roskilde Dome 2011. Exterior.

The basic ingredients in this project were: geodesic geometry, standard plywood plates, a cnc-cutter and a wish for lightness and grace.

The project had a very short time schedule and a limited budget. But also it had the great advantage that the architect was very interested in the practical execution of the project and that he had a group of skilled people to help him build the dome.

Furthermore the Roskilde Festival had large indoor areas suitable for prefabrication of the dome elements.

2. BACKGROUND

The Roskilde Festival is a Danish music festival that has taken place since 1971. It is managed by a non-profit organization and in 2012 it had around 90.000 guests and 30.000 volunteers.

The campgrounds are opened five days before the concert days starts. In that period different activities take place and each year the festival want to present something new.

Kristoffer was an almost unknown architect who had done some smaller projects in the sub cultural area of art performances, sculptures, wall paintings, scrap architecture etc. Now he wanted to make a visible project. His first proposal for the Roskilde Festival was a dome with a diameter of 12.6m, but after some time they turned back and asked him for a project and a budget on a much bigger dome.

3. THE ROSKILDE DOME 2011

The 2011 dome had the following data:

Inner diameter at ground level: 17.1m

Outer diameter at ground level: 18.5m

Inner radius of sphere: 11.3m

Outer radius of sphere: 11.9m

Inner height: 3.8m

Outer height: 4.4m

The dome was placed in “Art city” at the festival and the architectural idea was that it should provide space for art performances, spontaneous activities or just relaxing.

4. STRUCTURAL CONCEPT

The structure is a geodesic dome with a frequency 4 Class II hexagonation, which means that the overall geometry is a spherical cap. The dome was quite flat and supported all around the edge, so the basic structural concept was clear. But since the shell structure was broken up, a number of structural models for the elements were developed. The final structural model had three levels:

4.1. Level 1. The dome shell structure

At this level the structure is considered as a dome shaped membrane shell. In order to be geometrically and statically determinate the edge just has to be supported in one direction in each point except for three points, where it has to be supported in two directions. In this case the edges are supported vertically in all points and horizontally in a number of anchor points, see below. To take the horizontal thrust a ring beam had to be introduced.

4.2. Level 2. The plate shell subdivision

Although the shell surface consists of a grid with either pentagonal or hexagonal holes, called openings, it was chosen to consider it as a plate shell structure at the second level, because this would ensure the spatial stability of the shell surface.

This meant that the elements around each opening should be considered as a planar frame having substantial rigidity in the tangent plane of the dome. Even though the system lines in each of these frames were contained in a plane none of the symmetry planes of the beam elements in such a frame were contained in this plane. This meant that the beam elements and the connections had to have bending capacity around both local axes.

While the architect had planned to make the shell surface of two plywood plates on top of each other, the beam elements were from this point considered as plywood box girders.

Already from the start it was realized that the side panels around the openings would not contribute to the strength of the structure. They are just polygonal conical tubes supported on the shell surface.

4.3. Level 3. The grid shell structure

This level was used for the structural analysis, calculation of dimensions and documentation of the load bearing capacity. Buckling was a primary concern. The local buckling load and the global buckling load for the spherical shell were considered to be the same. The local buckling capacity was then estimated to be satisfactory if:

1. the bending capacity in a tripod consisting of three elements connected at the top were sufficient to carry the self weight of the three elements plus the design load of the wind pressure on the tripod, and if
2. the deformations from normal forces in a hexagonal frame and the six connected elements under full design load was so small, that the load bearing capacity was practically unaffected.

Also local buckling in the individual plywood plates in the beam element was evaluated at this level.

5. STRUCTURAL DESIGN OF THE 2011 DOME

5.1. Loads

At an early stage it was agreed that the dome would be guarded throughout the whole festival to ensure that nobody climbed or damaged the structure. This meant that the loads were reduced to be self weight and wind load. For the wind load the seasonal factor was taken into consideration, which reduced the load to 70% compared to a standard full year load.

5.2. Design of the beam elements

From the beginning the whole structure were designed so that the beam elements could be made from standard plywood plates with dimensions length x width = 2440mm x 1220mm. Also the whole project was based on the condition that the elements could be prefabricated and just had to be connected on site.

Both the inside and the outside of the beam elements were curved. This meant that they when assembled created an almost perfect spherical shape, in sharp contrast to the pointy polygons formed by the panels around the openings. But it also made the design of connections much easier, see below.

As soon as it was realized that the beam elements had to be considered as plywood box girders the calculation of the necessary dimensions began. At the same time an intense dialogue between Kristoffer, the architect, and I, the engineer, began regarding the detailed design and practical construction of the beam elements - or just the elements, as they were called from now on - and the connections.

Through this dialogue which to a large degree consisted of exchange of hand sketches, we found that the side panels should be separated from the element. It didn't just make sense from a production aspect since elements would be much easier to handle, stack and transport. It also made sense from a structural aspect as already mentioned. And then it made construction much simpler because the elements could be mounted and the whole shell structure completed, before the side panels were added.

Although it might seem as just one of many decisions in a typical engineering design project, this decision is interesting from a conceptual point of view. It was based on the realization that since these two parts had separate functions they could also be physically separated. In this way the structural concept and the construction concept became aligned.

Preliminary calculations showed that in order to utilize the full strength of the plywood panels of the elements and to avoid local buckling the upper and lower surface had to be stiffened by ribs. The maximum distance between the ribs was around 600mm.

The cnc-cutter was considered a bottle neck in the productions of the elements, so at first three ribs were planned to span across the element, because then they could be cut out by a regular saw, see Fig 2.

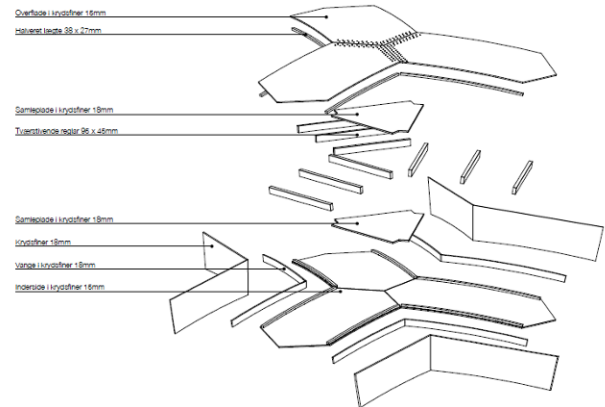


Fig. 2. Construction principle for elements and connections.

Since the elements had to be curved it had been decided that the sides should be cnc-cutted and made out of 24mm plywood. It was agreed upon that the assembly process and the precision of the final curvature of the elements would be improved, if the three ribs could be replaced by a single curved rib, similar to the sides, in the middle of the element. But this would overload the cnc-cutter.

The top and the bottom of the sides had different curvature because they both had the center of curvature in the center of the sphere. Then the proposal came up that if they could have the same curvature the cutting time for the ribs could be reduced to almost half. In this way the beam elements ended up as being stressed skin elements with curved cnc-cut webs.

5.3. Ring beam

The ring beam was designed at a late stage and just built out of wood boards and steel bands. The connections between the wood boards had practically no bending strength why it structurally was considered as a chain rather than a beam. The primary design concern was to find geometry in the vertical section plane that would ensure that the reactions from the shell, the steel bands and the ground met in one point, and that the connections between these elements would work in simple compression, see Fig 3.

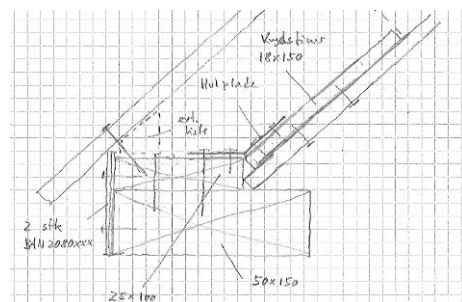


Fig. 3. Engineers sketch of ring beam section.

5.3.1. Connections

The architectural demands to the connection between the elements were simply that they hardly should be visible. The curved surface of the elements gave a smooth transition. So it was decided to make the connections as lap joints with separate connection plates on the inside of the upper and lower flanges and screws as connectors.

The critical design load for the connections showed to be the bending capacity which were determined by the buckling considerations. When different options had been evaluated we decided for just one row of screws. This then determined the thickness upper and lower flanges of the elements.

6. PRODUCTION AND CONSTRUCTION 2011



Fig. 4. Cut out plywood parts ready for assembly.



Fig. 8. Ring beam under construction.



Fig. 5. Test assembling of the first three prefabricated elements.



Fig. 9. Preassembly of connection plates on an edge element.



Fig. 6. Ring beam detail before elements are mounted.



Fig. 10. Detail of the screwed connection between elements.



Fig. 7. Ring beam with two edge elements. At the top between the elements the connection plates are seen.



Fig. 11. The last element in place.



Fig. 12. Completion of shell structure before side panels is added.



Fig. 13. Side panels ready for assembly



Fig. 14. The 2011 dome at the festival.



Fig. 15. Opening covered with plastic film.

7. THE ROSKILDE DOME 2012

Instead of just reusing the dome from 2011 Kristoffer Tejlgaard early in 2012 proposed the Roskilde Festival a new dome that would be bigger and higher. It should be a landmark, see Fig 16.

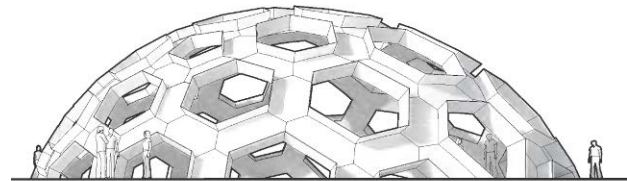


Fig. 16. Roskilde Dome 2011 above, and 2012 below.

The proposal meant that the elements from 2011 were reused and a similar number of new elements were produced, so that the total surface area was doubled. Roskilde Festival accepted the proposal.

The 2012 dome had the following data:

Inner diameter at ground level: 21.2m

Outer diameter at ground level: 22.4m

Inner radius of sphere: 11.3m

Outer radius of Sphere: 11.9m

Inner height: 7.2m

Outer height: 7.8m

8. STRUCTURAL CONCEPT

In general the structural concept was unchanged, but the edge ring at the 2011 dome had proved to be a poor solution. It was difficult to build, it had to be built on site and it could not be disassembled and reused.

The solution was to provide the edge elements with foot plates and pin them to the ground with tent stakes.

In this way the edge elements could be prefabricated and reused just as the rest of the elements. From a structural point of view the ground now not just served as a platform, but became an integrated part of the structural concept. The ground became edge beam and anchoring for uplift at the same time.

The solution was in a way obvious since most of the structures at the Roskilde Festival are tents, anchored to the ground with tent stakes. From an engineering design process perspective it is an example of the well known experience that sometimes the best solution to a complicated problem is simply to get rid of it.

9. CONSTRUCTION

The 2012 construction process was improved in two ways:

1. The ground was carefully leveled with a thin layer of gravel before construction started. In 2011 no leveling were done and the edge ring showed to be poorly surveyed. This caused serious problems when the last elements were to be assembled. The shell surface had to be manipulated by hydraulic jacks in order to make the elements meet precisely at the connections, see Fig. 17.
2. Scaffolding in two levels was built to ease construction and assembly of the dome, see Fig. 18.



Fig. 17. Manipulation of shell surface by hydraulic jacks in 2011.



Fig. 21. Shell structure completed.



Fig. 18. Scaffolding for the 2012 dome.



Fig. 22. The 2012 dome at the festival



Fig. 19. Assembly of the 2012 dome.



Fig. 23. Edge element anchored with tent stakes.



Fig. 20. Prefabricated edge element



Fig. 24. Inside the 2012 dome at the festival.

10. DISCUSSION

This project is unusual. As a structural engineer it has been a challenge to work fast and on a low budget with an unusual structure like this. New structural models had to be created and they had to be simple and at the same time relatively precise.

In a way a design project like this is straightforward. It is nothing but architecture and structure. No installations or insulation to disturb the pure form. But this fact also makes the design vulnerable. If the concept whether it is the architectural or the structural concept, is not clear, it will be fully exposed.

The close cooperation with Kristoffer Teglgard and his crew worked extremely well. It felt both personally and professionally motivating and rewarding. Our common interest for and experience with technical and constructional aspects meant that our discussions could cover the whole range from architecture over structure to practical building technique, and I believe that we because of this found some very good solutions.

Temporary structures may make the structural engineer consider if the design loads and/or safety factors could be included as structural design parameters. Especially under these - I guess quite common - conditions: compressed time schedule, low budget and high ambitions.

In 2012 it was agreed upon with the Roskilde Festival only to install tent stakes for a wind speed up to 14m/s. If higher wind speeds were warned either the plastic covering of the openings had to be removed or additional stakes had to be installed. When the dome is going to be rebuilt in 2013, the number of tent stakes might be doubled.

11. CONCLUSION

This dome project seems to be a success. The Roskilde Festival is planning to rebuild the 2012 dome in 2013. It was a good decision to make the dome bigger in 2012. Thanks to that many more guests at the festival went to see or meet in the dome.

The project has given the architect and the engineer new projects and the cooperation is continued.

12. REFERENCES

- [1] Building The Dome – YouTube
- [2] Plywood Dome 2012 – YouTube
- [3] The Dome in Art City - YouTube

