The Roskilde Domes 2011 and 2012

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

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

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

Fig. 8. Ring beam under construction.

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

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

Fig. 11. The last element in place.
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.](image)

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. Ground leveling.](image)
Fig. 17. Manipulation of shell surface by hydraulic jacks in 2011.

Fig. 18. Scaffolding for the 2012 dome.

Fig. 19. Assembly of the 2012 dome.

Fig. 20. Prefabricated edge element

Fig. 21. Shell structure completed.

Fig. 22. The 2012 dome at the festival

Fig. 23. Edge element anchored with tent stakes.

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 Teglgaard 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
[3] The Dome in Art City - YouTube