PRELIMINARY STRUCTURAL DESIGN OF A DEMOUNTABLE STADIUM

based on the architectural design of Zwarts & Jansma Architects
PRELIMINARY STRUCTURAL DESIGN OF A DEMOUNTABLE STADIUM
BASED ON THE ARCHITECTURAL DESIGN OF ZWARTS & JANSMA ARCHITECTS

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Rotterdam, December 2011
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Summary

During this master thesis, research is done on the structural feasibility of a demountable football stadium.

To avoid derelict stadiums after one-off events such as the World Cup or Olympic Games, a solution is found in the application of a demountable stadium that can be relocated once a year.

The goal of the research is to present a preliminary structural design of a demountable and transportable (football) stadium based on the flying shell concept of Zwarts & Jansma Architects.

Based on ideal lines of sight and a limited viewing distance to the centre of the field a distinctive stadium results with an undulating upper edge. The applicability of shell action to create an efficient structural system to the stadium is researched with the help of the method of graphic statics. The 2D results of this study are placed in a 3D context to examine the usefulness to the stadium.

Based on these results, four configurations are examined with the help of a computer model to check hypotheses and to gain further insight to allow the design of a final model. A final model is chosen on the basis of behaviour under loading, functionality, ease of assembly and appearance. This final model is tested on ultimate limit situations and serviceability limit state situations. Dynamic behaviour happened to be a critical issue that needed further research. Adjustments to the final model are made to improve the dynamic behaviour of the stadium.

In addition to structural behaviour, research is done on the assembly, demountability and transportability of the stadium. Transportation limitations cause the stadium to consist of many small elements that are designed to create maximum uniformity. The order of assembly is based on direct stability, together with shell and ring action providing stiffness during assembly. This is achieved by erecting the stadium layer by layer.

The structural system is based on the principle of shell action. Within this principle, double curvature is a very important criterion to ensure structural stiffness. Results of the models that are investigated showed a lack of structural stiffness resulting in a low natural frequency of the total structure. This has major consequences regarding the grandstand structure, as the load spectrum of dynamic crowd loads lies within the response frequency of the grandstand. Either natural frequencies should be increased, or severe measures should be taken regarding the increase of damping capacity, monitoring oscillations in the stadium or design for a dynamic amplification, to rectify this.

In order to increase the natural frequency of the stadium the stiffness needs to be increased. The most efficient way to do so with regards to shell action is to increase (double) curvature. Tangential curvature is based on ‘C’ values and preferably should not be altered. Radial curvature is almost absent and needs to be increased.

In the situation where natural frequency will not be increased, damping capacity should be increased dramatically by means of the application of dampers at connections or integrated into preassembled elements. The response of the stadium should be monitored and measures taken whenever predefined movements are exceeded.

Regarding finance, recurring and non-recurring costs are taken into account. The structural system should be proven to be feasible before financial implications are investigated in more detail.
This report is a result of the graduation project of the master Building Engineering, specialisation Structural Design at the Technical University of Delft.

Almost 7.5 years ago, after travelling for eight months through Australia and New Zealand, my study time in Delft started. During my Bachelor’s degree in Industrial Design Engineering I learned a lot about design qualities, production methods and the basics of engineering.

Looking for a bigger challenge regarding technical engineering I changed studies after obtaining my Bachelor’s. Civil Engineering brought me the technical challenge that I was looking for, and I was able to combine my design skills with technical issues. This combination has fascinated me ever since, and during the search for a graduation subject I was especially interested in combining engineering with challenging (structural) design.

The ideal opportunity on such a subject was offered by Corsmit together with Zwarts & Jansma Architects with the structural design of a demountable football stadium as a follow-up study on the research done by Anne den Hollander.

During this graduation project I was really helped by the ability of generating lots of ideas within a short time, followed by elaboration on a technical level, using the combination of skills from my two studies. I really enjoyed being an important factor between the wishes of the architect and structural boundaries prescribed by laws of nature.

This research was both a motivating as well as a challenging project and I hope reading this will be as inspiring to you as creating it was to me.

Myrte Loosjes

The Hague, December 6th, 2011
Acknowledgements

This master thesis is developed with the help of a lot of intelligent, inspiring and encouraging people who I would like to thank.

First of all I would like to thank my graduation committee for guiding me through the entire process. I would like to thank prof. R. Nijsse for his useful comments and the enthusiasm he showed during all meetings.

Secondly I thank Janko Arts, who helped me out when I was in trouble by placing things in the right perspective and sharing his technical experience with me. He really had an answer to anything.

Rob Torsing showed me the wonderful world of architects in some of its facets. Working with him was both inspiring and instructive for which I would like to thank him.

I would like to thank Karel Terwel for thoroughly reading my report over and over again, providing me with a lot of useful advices and helping me out during hard times. His encouragement made me achieve a maximum performance.

Without the extensive knowledge of Andrew Borgart, this report would never have been created the way it is now. Thanks to Andrew I became familiar with the theory of graphic statics and learned to work with and understand shell structures.

Raphaël Steenbergen shared his knowledge on dynamic aspects with me and brought this design to a higher level on this topic, for which I am very grateful.

Although I learned a lot on 3D modelling during this research, the extended research and form finding of the right structural shape had never happened without the help of Jack Bakker, who provided me a lot of 3D models with a continued enthusiasm about the behavior of each model and possible improvements.

Finance being of huge importance to the feasibility of any building project, these aspects could not lag behind in this design either. Nardo Hoogendijk and Kees van Rooijen helped me out on this topic during a very instructive consult at their office, for which I would like to thank them.

Furthermore I would like to say thanks to my colleagues at Corsmit for sharing their knowledge, showing interest in my findings and last but not least showing me the ins and outs of solving cryptograms.

I would like to thank my family for encouraging me during my study time and especially my parents for making this all possible.

The fact that this is a (hopefully) easily readable report has everything to do with the thorough reading and criticizing of some of my friends; Roos, Rhoanne and Jeroen. Thank you for checking my English texts and comments on the structure of the report.

Karen en Marleen, thank you for accepting me being unsociable every now and then and for still encouraging me during these times.

For all who supported me but is not mentioned here; thank you!
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Introduction

First of all the subject of this research will be explained in detail. The idea and relevance of the ideal stadium by Zwarts & Jansma will be examined, and its properties will be explained. The stadium will be placed in context with the help of past events and future measures.

In addition to this the objective of the research will be elaborated upon, and a research question is posed.
Problem Definition

Before the start of this Master Thesis, the problem definition will be clearly defined. The problem definition with the research question functions as a guide throughout the whole project. To clearly mark the scope of the project project boundaries will be defined.

1.1 PROJECT OBJECTIVE
The century where words like ‘green’ and ‘sustainable’ are of high value is struggling with the consequences of building large venues which are only useful within a very short period of time and become desolate places afterwards. This is especially the case with returning events like the World Cup and the Olympic Games, which are hosted by different countries every time. The additional wish to prevail yourself as an excellent guest country plays a major role in the outcome of such events. The competition to ‘win’ the Games is tough and has higher standards every time.

To respond to the needs and wishes of today, reuse becomes very valuable. This research explores the possibilities of a portable stadium which could be used several times at different locations. To have any chance of success, the image of the stadium becomes very important. A permanent, solid and distinctive look is therefore essential.

Zwarts & Jansma Architects, known from several stadium design projects in the past, enters the market with a design for a stadium that will be able to travel around the world by taking it down, transporting it and reassembling it at a different locations repeatedly. This research is based on this idea as a starting point, and examines the structural aspects and feasibility of this stadium.

Objective
The final product shows the viability and presents a preliminary structural design of a demountable stadium (grandstand, roof and foundation) based on the architectural design of Zwarts & Jansma, in which transportability is taken into account.

To achieve this, several questions are posed to embody the research and specify research issues.

Subject
A preliminary structural design of a demountable and transportable (football) stadium based on the flying-shell concept of Zwarts & Jansma Architects (figure 001).

Research question
How can the design proposed by Zwarts & Jansma Architects be translated into a structural design in a way that it is technically (and financially) feasible within the idea of a demountable stadium?

Sub questions
What are the possibilities of a demountable shell structure within the design of the architect?

How is the connection between the different (shell) modules achieved in a way that they act together like a shell?

What are the most efficient and quick ways to (dis) assemble a shell structure and transport it?

In which way will stability be provided during assembly, preferably without the need for a temporary structure?
1.2 PROJECT BOUNDARIES

During this project, the focus lies on the structural design of the stadium, taking into account the assembly and deconstruction as well as the transportability. It is inevitable to examine some issues to a lesser extent due to the short period of time. This is why project boundaries are defined from the start to avoid straying from the topic and remain focused.

The following topics are not taken into account during this research:

- Functional spaces (changing rooms, social areas, shops, media areas, toilets, etc) are not taken into account within the structural design. Most of these facilities will be housed in tents surrounding the stadium and will not be part of the structure.
- Costs are taken into account in a very limited way. Costs of the stadium are calculated to gain a little insight, but no complete business plan will be provided.
- The pitch is not part of the project.
- Lighting and installations will not be taken into account in detail.
- Because the focus lies on a structural feasibility study, cladding and finishing will not be taken into account.
Lotus Stadium

The Lotus Stadium, an idea by Zwarts & Jansma Architects, is a design for a demountable stadium. The design of this ‘ideal’ stadium is based on optimal lines of sight, limited distance to the centre of the field and a rapid construction process.

2.1 THE IDEA
Nothing is as annoying as looking at the back of someone’s head all time during a football game. To avoid this matter one should adopt ideal lines of sight and maximum viewing distances to the field. Once the design is adjusted to these measurements, one can speak of an ‘ideal’ stadium on these points. The stature of the stadium is parametrically determined by these factors, and consequently approaches the shape of an upside-down shell. Not only are the lines of sight innovative, but the rapid construction time is also of major importance. A suggested construction process of the Lotus stadium is depicted in figure 005.

2.2 DISTINCTIVE PROPERTIES

Lines of sight
The ideal line of sight for a spectator is measured by a so-called C-factor (Figure 002, 003). The higher the seat, the steeper the slope of the grandstand will become. Applying the optimal ‘C’ value of 120mm for all spectators will lead to a parabolic section of the grandstand. Nowadays grandstands only have one or two different angles.

Compared to most of the current stadiums, the shape of the Lotus Stadium differs. This is due to the viewing distance and optimal sightlines, which are deciding factors in the design of this stadium. The optimum viewing distance is 150 metres from the far corners, which means an assumed optimum viewing distance of 90 metres from the centre of the field. Applied to the stadium, this leads to a round shape (looked from above) with the highest stands at the long side of the field and the lowest stand in the corners (Zwarts & Jansma Architecten 2006). (figure 004 and 007) The term sightline refers to a spectator’s ability to see a critical point on the playing field over the head of the spectator below and is measured by the ‘C’ value. The most optimum viewing standard is a ‘C’ value of 120mm. To achieve this value across the whole stand, the section of the stand will have a parabolic shape (Zwarts & Jansma Architecten 2006). Because the ‘C’ value being most unfavourable in the corner locations, this location is used to determine the (parabolic) slope of the grandstand that is adopted around the entire stadium by sweeping this slope around the pitch. This causes the ‘C’ values to be at least 120mm for every seat.

002 Definition ‘C’ value (FSIF 2004)
The parabolic shape of the grandstand is calculated precisely with the help of Excel (figure 009). Because the ‘C’ value in this design is leading for the shape of the grandstand, the riser height (the slope N) becomes a variable of C (John 2007:132).

\[
C = \frac{((D(N+R))/((D+T)) - R}{(R+C)^{(D+T)}/D) - R
\]

The curvature of the grandstand is a very important measure, because it is necessary to provide for the double curvature needed for shell action. The contribution of the curvature due to the parabolic shape to realise shell action is examined in chapter 9, in which the forces acting in the ‘shell’ will be explained.

**Distance to the field**

Another parameter within stadium design is the viewing distance to the field. As mentioned previously, the optimum viewing distance in the case of a football stadium is 150 metres from the far corners. This leads to an assumed optimum viewing distance of 90 metres from the centre of the field. In terms of these rules, the ideal stadium will have a circular shape (viewed from above) with a higher grandstand along the edges of the field and a lower grandstand at the corners (undulation of grandstand) (Nixdorf 2008). This principle responds to the preferred position of the spectators. Furthermore, the round shape corresponds to a typical football aspect; the wave.

The limited radius of 90 metres from the centre of the pitch determines the capacity of the stadium.

**Grandstand**

The grandstand is lifted from the ground, which makes the stadium accessible from each side. This also creates space for shops, toilets and other facilities. As a starting point, these facilities will be situated in tents surrounding the stadium.

**Construction**

A remarkable aspect of the desired stadium, is the rapid construction time. According to the draft of Zwarts & Jansma Architects, the parabolic shape consists of triangular elements in two different shapes; one shape for the corners and a different shape along the edges. The elements will be connected to the foundations with a universal joint, and lifted with the help of a cable running around the upper boundary of the stadium (figure 005, 006 and 008).

2.3 SHELL ACTION

The idea of the stadium is based on a ring support at the top of the grandstand. By creating tension in this ring, all individual elements (modules) of the stadium will be pushed together, and ideally they will act like a shell (figure 006). Shell action depends on the double curvature present in the stadium, in this case, provided by the parabolic shape in tangential direction, and of course the radial curvature around the pitch. The possibility of shell action in this stadium will be elaborated during the conceptual design phase.
After a brief elaboration of the idea behind the design, the view from the architect Zwarts & Jansma will be explained in this part. Questions like ‘In what perspective should we place this project?’, ‘Is there a market for this idea?’ and ‘Where does the idea came from?’ will be answered.

3.1 PROJECT
This project is initially a follow-up project on the study of Anne den Hollander. From Zwarts & Jansma Architects there is the need to design the ideal stadium in a structural way. To enter the market of world stadiums, the architect came up with this controversial idea. The structure of the stadium has a mathematical approach, parametrically following from the numerical values of lines of sight and viewing distances. These factors result in a stadium resembling a shell, and together with the portability, make this project distinctive.

3.2 PERSPECTIVE
To place this subject in perspective we have to look at the approach to current large events. For example London’s successful bid for the Olympic 2012 Games was based on its commitment to a sustainable legacy; maintaining and reusing the buildings for athletic and community use after the event. There is huge emphasis placed on green issues; with this in mind, a demand is created for the re-use of large venues after the events they were built for.

Abandoned stadiums or the need to demolish them, play a major role in the view towards stadiums. High costs and debts for the guest countries is the second greatest problem for these once-in-a-year events. To respond to these issues a more ‘green’ approach is necessary, in which a portable stadium is an excellent idea.

Points of attention
To sell this product to the market, several aspects need attention.

- The portable stadium should have a permanent look and should not look like a temporary structure.
- The image of the structure should in some way be adaptable to several requirements from different parties.
- The structure should look robust and make visitors feel comfortable and safe.

3.3 GOAL
In general terms, following from the previous points, the portable stadium should be able to meet the following demands:

- Minimise economic disasters, such as empty stadiums left after events.
- The demountable stadium should reduce the building costs by repeated use.
- The stadium will provide flexibility within the organisation.
- The ecological footprint will be reduced by reuse of material.
4

Context

To place this project in a context, several relevant projects will be discussed in order to learn from these events, and try to understand if it is possible to respond to new market trends with the demountable Lotus stadium.

4.1 PAST EVENTS
There are many examples from the past from which we can deduce that stadiums, built for a special event, can lead to undesirable situations afterwards. For example the Summer Olympics 2004, held in Athens, where the Olympic Park is an unpleasantly barren and discouraging surrounding nowadays, turning the main stadium into an iconic landmark for contemporary Athens (Hersh 2008). Also the Stadiums in South-Africa, guest country of the Word Cup 2010, are all empty now. These ‘monuments of African imperialism of the FIFA’ (Remmen 2010) show how distressing the problems are. Not only do stadiums become ‘white elephants’, but this situation is also increasing the guest-country’s expenses.

This problem asks for a solution. Several measures have been taken from different parties to allow the stadiums be of some worth after they have been built for specific use during an event. For example in South-Korea and Japan, who hosted the World Cup 2002, the government sought ways to use the stadiums after the Cup. New professional soccer teams have started and will continue to utilize the stadiums afterwards (Hyon-kohn 2002). An organised soccer league will continue to attract retailers and other facilities to set up near this area and therefore attract more revenue.

Another solution to avoid stadiums becoming redundant is to adapt the stadium to multiple purposes. An example of such a multi-purpose stadium is the Toronto Skydome from 1989. This stadium can be adapted by movable seating which responds to various uses. The stadium can accommodate from 10,000 up to 68,000 people (John 2007) (figure 010).

Seen from the past, there are several measures to be taken to keep the stadiums of value, for example:
- Find a new destination for the stadium
- Apply multi-purpose stadium

4.2 FUTURE MEASURES
Increasing measures are taken to avoid or solve the problems of abandoned stadiums. Expansion of existing stadiums is a relatively cheap way to make a stadium meet requirements for a big event and at the same time avoid dereliction. A similar solution is investigated for the expansion of the Olympic Stadium in Amsterdam, by providing a customized solution in the form of an expansion unit providing a total capacity of 40,000 to 60,000 seats (Architectenweb 2009) (figure 011). Here they attempted to make this temporary structure reusable.

011 Temporary expansion of Olympic Stadium in Amsterdam (2 options)

In London the authorities in question are very aware of the possible consequences of hosting the Olympic Games 2012. In the first instance the Olympic Stadium is made of layers from which many are temporary (figure 012). An extra ring which will accommodate an additional 55,000 individuals is made of lightweight steel and concrete in a way that it is demountable. After the Games, the permanent part with a capacity of 25,000
seats remains (OlympicGames2012London 2011). Secondly the basketball Arena for the Summer Games 2012 in London is intended to be dismantled and sold. This stadium, with a capacity of 12,000 will be taken apart and sold to Brazil. After reassembling the stadium at location it will be used during the Games in Brazil in 2016. This venue will be one of the largest temporary structures built for any Olympic competition (figure 013). It is especially designed to be deconstructed and relocated after the Games (Gibson 2011).

Qatar, host of the World Cup 2022, is also very ambitious concerning the reusability of stadiums. They planned to donate a part of the stadium to developing countries. To avoid the fact that the stadiums, especially built for the World Cup, become superfluous after the event, they decided to give them away. To do so, part of the grandstand will be built in special modules which can be easily transported and rebuilt. The reassembly will be at the expense of the organisation committee in partnership with the FIFA (Bruijn 2010).

Summarised this comes to the following measurements to deal with the temporality of one-off events:
- Expansion of current stadium
- Temporary parts of structure
- Reuse of parts of structure
- Portable stadiums
- New destination/function
- Demolition

To get insight in the ways to solve a problem, figure 014 visualises the solutions mentioned in this part and categorises them. Some ways are more effective than others. It is always better to prevent something from happening than to solve a problem afterwards.
schema in figure 014, a demountable stadium is applicable everywhere and does not need adapting to an existing situation.

4.3 READING GUIDE
This report contains the research of the structural feasibility of a demountable football stadium. The outline of this report is clarified here.

As a starting point of the research, the idea of the Lotus stadium as a demountable stadium is explained and placed in context in the ‘Introduction’.

The ‘Analysis’ deals with the list of demands and preferences that are applicable to the stadium, together with a few reference projects of relevance to this research.

The theory of graphic statics is applied to investigate the possibilities of shell action in the structure. First this is analysed in 2D, after which a 3D evaluation follows. This is all part of the ‘Conceptual design’.

Following from the research on graphic statics, some conclusions are drawn regarding the structural behaviour of the stadium. The ‘Optimisation’ part deals with the issues arising from shell action and provides optimisation solutions for these topics. Optimisation when shell action is retained, optimisation regarding bending within the structure, and a combination of these two, are treated with the help of computer modelling with the program Oasys GSA.

Findings in modelling are brought together in one final model that is calculated regarding strength, stiffness, stability and dynamic behaviour. Adjustments are made during this process, and the adjusted model is further examined regarding demountability. The folding principle and assembly are explained, and transportation is mentioned. This is all part of the ‘Structural design’. In the end, benefits of the stadium are elaborated with regard to finance; including non-recurring and recurring costs.

Reverting to the list of demands and preferences the final product is assessed on its feasibility and qualities. Besides conclusions on the research, recommendations are made regarding issues that are not solved within this research or issues that need further research.

The report is logically divided into sections, each having their own colour. Page numbers correspond to these section colours to allow easy navigation through this report.
Analysis

The design process consists of different phases. The analysis phase is of major importance to understanding the subject and defining project boundaries. The stadium is analysed with regard to its specialties and placed in context by looking at reference projects. A list of demands and preferences will be drawn from findings and research.

This list will be of help as a guide throughout the design process and eases decision making between several alternatives. Demands eliminate alternatives, while preferences test alternatives on quality.

The analysis phase functions as a starting point for the synthesis phase.
5

List of Demands and Preferences

The list of requirements is a product oriented elaboration of the objective of a product development project. Statements about the objective come in different forms, which lead to different criteria within the list of requirements. Criteria are qualitative or quantitative and can be either a demand or a desire.

The final design should meet every demand. Preferences subsequently qualify alternative designs.

5.1 SAFETY AND COMFORT

To prevent undesired vibrations that can cause resonance in the structure, the natural frequency of the stadium should be at least 5 Hz by rule. This increases to 7 Hz by desire (NEN 2002b).

In serviceability limit state the maximum sag due to the variable load is limited to 0.003*l. For the cantilevered structure an increased sag of 0.006*l is permitted (NEN 2002a).

Fire protection between 90 and 120 minutes is obligatory.

During evacuation everybody should be able to leave an open air stadium within 12 minutes. For a covered stadium this time is reduced to 6 minutes (Torsing 2011).

The steepness of the grandstand should not exceed 34 degrees (Nixdorf 2008).

To provide for optimal sightlines throughout the entire stadium, a ‘C’ value of 120mm should be achieved (NEN 2002).

Spectators should always have a clear, unrestricted view of the whole of the football playing area, this prohibits obstructions in view.

Gangways in seated accommodation should be at least 1.2m wide (Nixdorf 2008).

Based on an optimal viewing distance of 150m from the far corners, an assumed optimum viewing distance of 90 metres from the centre of the field should be adopted.

Roof

The main function of the roof is to provide shelter for the spectators and simultaneously limit the shading on the pitch. Demands following from this statement are:

(1) When a partial roof is applied, the first 5 rows should lie in the area formed by a triangle, making an angle of 15 to 30 degrees with a vertical line.

(2) Spectators in the highest seats should be able to see points within a range of 12 to 18 metres above the centre point. Because of the ideal character of the stadium, this amounts to 18 metres.

(3) The cantilevered roof should not be too large because otherwise it causes shading of the grass. As long as there is a possibility of using natural grass this plays a role and should be paid attention to.
5.2 FUNCTIONALITY

Demands
The dimensions of the field are determined by the Union of European Football Associations (UEFA) and are described in the next two requirements.

(1) The dimensions of the inner edge are dictated by the dimensions of the field (68*105m²), a border around the field of 7.5m and a safety barrier. Within these limitations, the seats should start as close to the field as possible.

(2) The dimensions of the outer edge in this particular stadium are not determined by the required capacity, but by the maximum acceptable distance from the field to the outer seats, and the preferred viewing locations (maximum radius 90m).

No element should be heavier than 40 tons; this is the maximum weight that can be transported by a standard truck in Europe.

All elements could be lifted by crane. Based on a flight of 12m, 20 tons can be lifted with a TK120 hydraulic mobile crane (Kuiphuis Kraanverhuur 2011).

Change of location should be possible within 8 months. Within this time maintenance is included.

Wishes
Between the separate elements there should preferably be as much uniformity as possible.

Preferably the stadium is usable for other functions besides football. Flexibility of the stadium contributes to multiple function use (co-habitation).

The roof should limit shading on the pitch.

Maintenance should not be necessary during use and will be performed during the moving time of 8 months.

In and around the stadium there should be enough space to accommodate the facilities that should be present.

Stadium placement should be possible within at least 60% of locations in Europe.

NOTE: these elements are not taken into account within this research.
5.3 STRUCTURAL ASPECTS

Elements should be designed to withstand forces during transport that are different from loads during use/assembly. It is desired that there is a handle attached to lift the elements.

Connections should be designed for repeated use. An important issue herein is fatigue.

The structure should be able to bear the loads; Dead load (Weight of stadium (↓)), Variable load (Imposed load (↓ + →) (↓ = 4.0 kN/m² (NEN 2002b: table 6.2); → = 6%*4.0 = 0.24 kN/m² (Hollander 2010)), Wind (→ + ↓ + ↑)).

Preferably a temporary and transportable foundation (raft foundation) is used. Weak soils will prescribe a pile foundation.

Preferably all elements should fit in a truck without guidance (4.0*3.50*18 m³) and be lighter than 40,000 kg.

The stadium should be designed to conform to requirements in the EuroCode Principles of the structural design, Eurocode1 1 and 4; loads on structures.

The stadium should meet requirements imposed by football organisations (UEFA, FIFA).

5.4 FINANCIAL ASPECTS

Preferably the demountable stadium should be more economic than permanent stadiums after using it five times.

The portable stadium will be designed for a life span of at least 15 years.

5.5 SUSTAINABILITY

Preferably the stadium is made of sustainable material concerning production/origin, manufacturing, transport, reuse and life span.

5.6 APPEARANCE

The stadium should have the look of a permanent stadium.

The stadium should meet the flying shell image as proposed by Zwarts & Jansma Architects.

The appearance should be attractive to visitors.

The appearance should be adaptable to different (club-) styles to a certain level.
Materials

Appendix ‘material’ consists of a study between several materials. From this analysis the most favourable materials for every part of the structure are mentioned here.

6.1 MATERIAL TYPES
There are a lot of factors that play a role in choosing the right material for the different functions and elements in the stadium. These aspects can be divided into groups (Romeijn 2006).

Safety and comfort:
Fire safety
When situated in outdoor conditions, no requirements are given concerning the fire safety. In the case of a roof that can be closed this is different. Especially for steel structures, the lack of fire resistance is a very important issue.
Natural frequency
The natural frequency in case of the grandstand is very important. Vibrations due to enthusiastic spectators could give an unsafe feeling to the visitors and could also damage the building.

Functionality:
Connections
The (dis)assembly plays a very dominant role in the design. Connections are therefore a major part of the whole structure. The material should not be too sensitive to fatigue and should be easy to connect.

Conservation
Maintenance
The stadium ideally should not require a lot of maintenance. Especially during the operation time of four months maintenance is unwanted.
Storage
The storage does not impose restrictions to the choice of material.

Structural aspects:
Weight
Because the concept of transportability, the mass of the material in use becomes very important. This is especially essential during transportation and handling of the elements at the building site.
Transportability
This aspect is mainly to do with the weight of the elements. The lighter the elements, the easier the transport will be.
Natural frequency
See ‘safety and comfort’

Financial aspect:
Material costs
The portable stadium should be more economically viable, than other permanent stadiums. Reducing the costs will sooner lead to a more beneficial design. But, the material costs are non-recurring and will be a one-off investment. When choosing a high quality, expensive material this might be preferred over other cheaper materials that need more frequent replacement or maintenance.

Looking at the aspects mentioned above, every part of the structure prescribes a different ideal material to use. Suitability of the most common materials to be applied to the stadium is listed in section 6.2. Sometimes, to fulfill two different properties, the application of the most ideal materials will lead to contradictory materials. In such a case one should look at different aspects to base the choice on, for example, the image or uniformity.

6.2 SUITABILITY OF MATERIALS
Summarised, table 1 leads to the following appropriate materials for the different structural elements.

Load bearing structure
Concrete, steel
Grandstand
Concrete, steel, timber, aluminum, composites
Cladding
Steel, aluminum, different kind of membranes
Roof structure
Timber, aluminum, steel, membrane (ETFE, PTFE, PVC-coated)
Foundation
Concrete, steel (piles)
Table 1  Material properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>Low cost, Flexibility, Durability, Fire resistance, High strength, Natural frequency (damping)</td>
<td>High weight, Production and transport energy intensive, Weak in tension</td>
</tr>
<tr>
<td></td>
<td>Suitable for: load bearing structure, grandstand, foundation</td>
<td></td>
</tr>
<tr>
<td>Steel (high strength)</td>
<td>Relatively low cost, High strength to weight ratio, Speed of construction, Equally strong in tension and compression</td>
<td>Low fire resistance (needs protection), Low thermal mass, Prone to corrosion</td>
</tr>
<tr>
<td></td>
<td>Suitable for: load bearing structure, grandstand, cladding, foundation (piles)</td>
<td></td>
</tr>
<tr>
<td>Timber</td>
<td>Strong in tension and compression, Sustainable (Cradle 2 cradle)</td>
<td>Properties non-linear and very variable, Can be weak in bending, Difficult to achieve demountable connections</td>
</tr>
<tr>
<td></td>
<td>Suitable for: grandstand, cladding, roof, foundation (piles)</td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>Lightweight, Ductile, Easily machined, cast and extruded, Good strength to weight ratio</td>
<td>Soft, 1/3 of E-modulus of steel, Ductile, Relatively expensive</td>
</tr>
<tr>
<td></td>
<td>Suitable for: grandstand, cladding, roof</td>
<td></td>
</tr>
<tr>
<td>Plastic/composites</td>
<td>Extremely good strength to weight ratios</td>
<td>Fail in brittle manner when overloaded, Very expensive, Low E-moduli, Time dependent behaviour</td>
</tr>
<tr>
<td></td>
<td>Suitable for: grandstand?</td>
<td></td>
</tr>
<tr>
<td>Membrane - PVC coated polyester fabric (Nixdorf 2008: 227)</td>
<td>Relatively cheap, Easy to handle, Life span of about 15 years</td>
<td>Fabric tends to sag with time, Surface becomes sticky with age, Requires frequent cleaning</td>
</tr>
<tr>
<td>Membrane - Teflon-coated glass fiber fabric (PTFE-coated glass fiber fabric)</td>
<td>Long life span, To some degree self-cleaning</td>
<td>Expensive, Tendency to produce toxic fumes in a fire</td>
</tr>
<tr>
<td></td>
<td>Suitable for: cladding, roof</td>
<td></td>
</tr>
</tbody>
</table>
Reference projects

Learning from other projects aids understanding of the context of the problem. Projects that are helpful in this case are portable structures and stadium structures. There are also some examples of portable stadiums.

7.1 PORTABLE STRUCTURES

To make a structure portable, it should be possible to divide the structure into transportable elements. There are several ways to expand an object. These ways will be examined and the applicability for a portable stadium is mentioned. The projects shown are mostly not intended as reference projects, but to demonstrate the principles as mentioned. Within the range of portable structures, the following variants are defined: tent structures, scaffolding structures, inflatable structures, telescopic structures and foldable structures.

Important factors for assessing different methods regarding the applicability for the stadium are: constructability, transportability, durability, use for large spans, use for a cantilevered structure, robustness and easiness to connect.

Tent structures

A tent structure is an easy erectable and easy collapsible structure (figure 015). The tent principle itself is very useful for the roof of a portable stadium. Large spans are possible. The Olympic stadium in Munich is a good example of a tent structure used for a stadium roof (figure 016).

In terms of transportability and portable structures, the tent is a good example of careful consideration of resource use, in a way that allows the components to be disassembled for relocation, replacement and maintenance. Tents typically use separate compressive frames and tensile membranes to create a stable structure that can be easily and quickly taken apart by the user. The light weight of the materials and the size of the components are important features of the design (Crowther 2005).

Scaffolding structures

Scaffolding is a quick way to build very diverse structures. Scaffolding structures are almost always column based, which makes this method less useful to a cantilevered structure. In addition, although scaffolding is useful for portable structures, it will always have a temporary character, which is not wanted in the design of the stadium. Scaffolding however can be used as a secondary structure. The connection principle might also be useful. It is not subject to wear. An example of a scaffolding structure is given in figure 017.
Inflatable structures
Inflation of a structure is a quick and easy way to erect a building (figure 018). Pneumatic structures are also an example of air-supported structures which can be of permanent nature (figure 021). This kind of structure is not very suitable to the grandstand, however it could be of use for the roof when a closed roof is applied.

Telescopic structures
The telescope principle is useful in a lot of different ways (figures 019 and 020). Combined with the scaffolding principle a lot of shapes are easily erected.

Foldable structures
Folding is possible in a lot of ways. Folding can take place in a linear way, or a radial way (like an umbrella). An example is shown in figure 022.
7.2 STADIUM STRUCTURES
Stadium structures vary in shape a lot. The undulating shape of the grandstand, following from ideal lines of sight, is present in other stadiums as well. A few examples show this similarity (figures 023-027). Cables are often a structural material used in roof structures of a stadium. A few examples are shown in figures 028-033. Different membranes are used to cover a (cable) roof structure. These pictures show mostly lightweight roof structures that are not of structural value to the total structure.

023 Green Point stadium, Kaapstad, 2010, 66.000sts
024 Durban Stadium, Durban, 2006, 70.000sts
025 Aviva Stadium, Dublin, 2010, 50.000sts
026 Sydney Football Stadium, Sydney, 2004, 41.200sts
027 Zentralstadion, Leibzig, WK2006, 44.300sts
028 Estadio Municipal de Braga, Portugal, UEFA Euro 2004

029 Velodrome, London, Olympic Games 2012, 6,000sts

030 Lusail Iconic Stadium, Qatar, FIFA World Cup 2022, 86,000 sts

031 Foshan’s Century Lotus Sports Centre, Asian Games, 36,000sts

032 Commerzbank Arena, Frankfurt, FIFA World Cup 2006, 48,000sts

033 Soccer City Stadium, Johannesburg, 1987, 88,500sts
From the following pictures (figures 034-038) a variety in roofshapes and -structures is presented. Very often steel structures are used, but concrete is also a material especially suitable for dome structures (figure 037).

The main function of the roof is to provide shelter to the spectators. A roof structure therefore leads most of the time to large cantilever structures because the demand of providing a non obstructed view for spectators prohibits the use of (structural) columns.
7.3 TEMPORARY STADIUM STRUCTURES

The interim stadium of the B.C. Lions in Vancouver is built while the permanent stadium undergoes renovations (figure 039). This stadium, built by Nussli, has a capacity of 27,500 seats and was erected within three months by 50 assemblers. A total of 2,500 tons of structural material is transported by 160 40-foot containers (=12m) (Nussli 2011).

For the Swiss Wrestling and Alpine Festival of 2010 a temporary arena was built in Frauwenfeld (Figure 040). This stadium is also built by Nussli and has a capacity of 47,500 seats. Total assembly time amounted to seven weeks (Nussli 2011).

In Dusseldorf the Fortuna stadium housed the Eurovision Song Contest of 2011. This mobile stadium has a capacity of 20,000 seats again built by Nussli. The total costs of this project amounted to 2.8 million euros and was assembled within eight weeks (Nussli 2011).

For the Royal Military Tattoo in Edinburgh a temporary grandstand was erected (figure 041). Another structure by Nussli with a capacity of 8,700. A group of 40 assemblers built this grandstand in seven weeks, using 700 tons of steel. The grandstand is temporary, while the foundation is a permanent one (Nussli 2011).
Conceptual design

Using a two dimensional method to examine the forces in the structure of the stadium (the grandstand and the roof), the most suitable shape of the stadium will be searched for. This will be based on the shell action in the structure, and taking into consideration the magnitude of hoop and ring forces.

The methodology used to do this is called graphic statics. Through this graphic method, forces are put into relation to the shape of the structure and the consequences of adjustments to the shape are examined. This two dimensional research will be put in a 3D context afterwards.

With the gained knowledge and based on the conclusions of this chapter, the next part of this report will start with optimisation possibilities on the design.
8

Introduction

The stadium as designed by Zwarts & Jansma is initially designed as a shell structure. Apart from the look of a shell, the stadium should preferably also act like a shell. The possibilities and a short theoretical explanation of shell action are included in this chapter.

8.1 SHELL ACTION
The figures in chapter two show some models of the Lotus Stadium. These pictures show one tension cable along the upper boundary of the whole grandstand. The idea is to create shell action within the grandstand of the stadium. To explain the effect of one cable compared to the effect of cables at every certain height, a figure is used to explain each situation.

The difference between the design as it is now and the preferred situation is explained with the help of figures 042 and 043.

The situation in figure 042 represents a design in which only a cable along the boundary is present. At the upper ring a cable is present to keep the elements up. The lower parts of the grandstand are subjected to bending and a large bending moment occurs at the connection with the foundation. This is explained in chapter 11.2.

Figure 043 shows the situation when the structure works as a shell. The structure shows equilibrium between hoop forces and vertical forces. No bending moments are present in the shell, which makes a hinged connection at the foot of the structure possible. Note that compression forces in the elements are omitted to enhance clarity of the picture.

8.2 METHODOLOGY
To examine the structural possibilities of the original design as proposed by Zwarts & Jansma Architects, a research will be done on the forces in the structure. The method used to do so, graphic statics, is used to determine the shell action. During this procedure the actual design will be compared to several alternatives regarding the shape. This procedure assumes the presence of hoop forces as shown in figure 043.

After the determination of hoop and ring forces and the influence of a difference in shape on these forces, a choice of a structural system will be made. This contains the load bearing structure of the grandstand as well as the roof structure.

On the basis of the research on the forces, bottlenecks are summarised in a conclusion and within every issue solutions are proposed based on several optimisation principles. These optimisations may contain adjustments to the original design. The ambition is a structural system that acts in the most efficient way within the design boundaries.

During the whole process, the design will be checked on the list of demands and preferences presented in
the analysis phase. Specific criteria to test different alternatives on their quality are added in paragraph 10.4.

8.3 THEORY
Graphic statics is a graphic method to visualise the relationship between structural form and forces and to analyse the line of thrust within a shell structure. In a two dimensional way, forces in 3D are elaborated. The external forces on the structure are plotted to a scale of length to force on a load line. Working from the load line, the forces in the members of the structure are determined by scaling the lengths of lines constructed parallel to the members. This procedure results in a force polygon (figure 044). The horizontal distance between the load line and the intersection of the diagonal line with the horizontal line gives the horizontal thrust in the system (Greenwold 2001; Pahlavan 2010).

Compression forces are represented in blue while tension forces are represented in red (figure 045). The horizontal thrust represents the necessary horizontal force (hoop force) to let the thrust line coincide with the centre line of the section. As long as the line of thrust coincides with the centre line, the entire section is in compression and no bending forces are present; the structure works as a shell.

Horizontal thrust is realised by ring forces and result in tension or compression in the surface of the shell. This is visualised in figures 044 c and d.
In a section through the dome all forces are visualised (a). The numbers 1 till 6 represent vertical forces resulting from the mass of the structure. The slope per element has different colours. These colours correspond to the colours used in the forces polygon (b). To create equilibrium, horizontal forces are needed. These hoop forces depend from the slope of the dome. From above the hoop forces are represented in (c), with the numbering still corresponding to the different elements. This force polygon is closed in radial direction by the presence of ring forces (d).

Example of a force polygon of a dome structure

The shape of the section of the dome as presented is subjected to bending at the top and because of the curve this changes to tension at the bottom. By varying the curve, the forces in the dome will change.

8.4 PURPOSE

With the help of graphic statics, the forces in the shell structure of the stadium are determined. Different configurations are analysed to make a considered choice regarding the shape of the stadium that suits the shell action best. Also the roof will be taken into account during this process.

Providing shell action means that no bending moments are present in the structure, which is advantageous for several reasons. First of all, fixed connections are more complicated than hinged connections and less easy to realise on site, which is unfavourable since the stadium needs to be demountable. Secondly, elements designed to transfer compression and tension forces have smaller dimensions than elements designed to transfer bending moments. This lowers material costs, decreases weight and therefore has a positive influence on the transport.

Conditions

To function as a shell, all elements should be connected together along the entire section. At locations where this connection is missing, bending will occur.
From the theory of Graphic Statics, the forces in the section of the stadium will be investigated in 2D. The ideal shape of the stadium regarding the shell forces will be analysed by means of force polygons.

9.1 IDEAL SHAPE
The shape of the stadium as designed by Zwarts & Jansma Architects is based on ideal lines of sight and a limited distance to the centre of the field. In this part, the ideal shape of the grandstand is searched for, based on ideal spread of the forces in the shell. Factors that affect the flow of forces are elaborated.

Starting point for the research is the original design. This shape originates from sweeping the ideal shape based on ‘C’ values around a curve surrounding the pitch (figure 047). Figure 046 shows some basic dimensions in the stadium plan.

The shape using ‘C’ values is calculated within the corner of the structure, because of this location being the most unfavourable situation. Adopting the same slope all around the stadium prevents undulating row heights. Using the corner slope as a standard means that at other locations, the lines of sight are even more advantageous.

Grandstand
Regarding the grandstand, several shape configurations are determined to analyse the effect of adjustments on the forces in the shell compared to the original design (figure 048).

The load bearing structure in the figures is displayed in grey. The grandstand itself (the seating elements) is not part of this structure, although we assume all forces acting on the load bearing structure. The section as shown in the figures is a section along the long edge of the stadium. Sections at different locations, for example the corner section, are determined as well. These are included in the appendices (appendix A2.2).

The second configuration shows a load bearing structure with an opposite curvature compared to the grandstand (figure 049).

The third configuration is a combination of the previous two configurations (figure 050). The load bearing structure partly follows the shape of the grandstand, but has an opposite curvature at the bottom of the grandstand. Configuration 4 has a more hollow shape (figure 051) and configuration 5 shows an S-shape (figure 052).
Roof

When the roof structure is a structural part of the stadium this influences the forces in the grandstand structure. By analyzing different roof configurations, reaction forces from the roof on the grandstand are determined. The main distinction is the choice between a concave or a convex roof. The support from the grandstand is schematised as a roller in the figures (figure 053-055).
9.2 FORCE ANALYSIS

To analyse the shell forces (=hoop and ring) with the help of a force polygon, a section of the grandstand is examined in detail. The whole stadium is divided into 24 tangential elements (figure 056). Each of these elements is subdivided into ten radial parts (figure 057).

Within these calculations, no attention has been paid to wind forces yet. Also the horizontal component of 6% of the public load is not taken into account; these horizontal forces affect the force polygon in a limited way.

For now only the dead weight and public loading are taken into account.

To calculate the vertical force used for drawing the force polygon, the dead weight and public load are multiplied by the area of the segment.

Dead weight estimation (pg)\(^1\)
- Grandstand elements: 1.5 kN/m\(^2\)
- Finishing: 0.5 kN/m\(^2\)
- Load bearing structure: 2.5 kN/m\(^2\) + Total: 4.5 kN/m\(^2\)

Public load (pq) 4.0 kN/m\(^2\)

Adding safety factors, the calculation value will be achieved. The governing calculation value will be used to perform the following calculations with and compose force polygons.

(1) \(F_d = 1.2 \times pg + 1.5 \times pq^2\)
(2) \(F_d = 1.35 \times pg\)

(1) \(F_d = 4.5 \times 1.2 + 1.5 \times 4.0 = 11.4\) kN/m\(^2\)
(2) \(F_d = 1.35 \times 4.5 = 6.1\) kN/m\(^2\)

\(F_d\) (1) results in the governing value and will be used for further calculation.

Table 2 shows an overview of the governing vertical forces as will be applied to the section.

<table>
<thead>
<tr>
<th>Segment</th>
<th>([r1])</th>
<th>([r2])</th>
<th>([m2])</th>
<th>([kN/m2])</th>
<th>(F_v) [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>90.0</td>
<td>85.2</td>
<td>110</td>
<td>11.4</td>
<td>1255</td>
</tr>
<tr>
<td>2</td>
<td>85.2</td>
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<td>104</td>
<td>11.4</td>
<td>1186</td>
</tr>
<tr>
<td>3</td>
<td>80.4</td>
<td>75.6</td>
<td>98</td>
<td>11.4</td>
<td>1117</td>
</tr>
<tr>
<td>4</td>
<td>75.6</td>
<td>70.8</td>
<td>92</td>
<td>11.4</td>
<td>1049</td>
</tr>
<tr>
<td>5</td>
<td>70.8</td>
<td>66.0</td>
<td>86</td>
<td>11.4</td>
<td>980</td>
</tr>
<tr>
<td>6</td>
<td>66.0</td>
<td>61.2</td>
<td>80</td>
<td>11.4</td>
<td>911</td>
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<td>842</td>
</tr>
<tr>
<td>8</td>
<td>56.4</td>
<td>51.6</td>
<td>68</td>
<td>11.4</td>
<td>774</td>
</tr>
<tr>
<td>9</td>
<td>51.6</td>
<td>46.8</td>
<td>62</td>
<td>11.4</td>
<td>705</td>
</tr>
<tr>
<td>10</td>
<td>46.8</td>
<td>42.0</td>
<td>56</td>
<td>11.4</td>
<td>636</td>
</tr>
</tbody>
</table>

\(^1\) These load combinations are according to NEN 6702 standards. The same load combinations according Eurocode prescribes: 1.35*pg + 1.5*ψ*pq.

\(^2\) Grandstand elements, based on:
- Seating Floor elements
- Finishing, based on:
- Steel sheeting
- Load bearing structure, based on:
- Steel elements (main elements)
- Secondary elements (girders)
9.3 FORCE POLYGONS

**Current situation**
The original idea of the demountable stadium is based on small tangential elements held together with one cable at the top of the stadium. This cable at the top of the stadium takes up the hoop forces. The hoop forces at lower parts, in figure 058 represented as element ‘2’ till ‘10’, are not taken up by ring forces, which results in a line of thrust which is not in line with the centre line of the structure.

In an ideal shell structure, ring forces are present to ensure force polygons in which the compression force (diagonal in the force polygon) equals the slope of the section of the structure, so the entire section is in compression. No bending moments occur in such a situation. By eliminating ring forces, which is the case in the current situation, the line of thrust (compression line) is no longer in line with the section, which causes bending moments.

This means a lot of bending is present in the stadium structure and the structure does not act like a shell. The line of thrust and corresponding bending is visualised in figure 058 in green. The aberrant line of thrust is represented in purple.

The numbering of the vertical line in the force polygon corresponds to the numbering of the grandstand elements (Fv). Note that reaction forces resulting from the roof structure are not applied to the grandstand section yet.

![Diagram showing bending in grandstand when applying horizontal ring forces at the top only](image)

*Arrows in the right and left picture correspond to one another. The left picture shows the forces acting on the structure. The right picture shows the force polygon of this section. Vertical forces Fv, horizontal hoop forces and diagonal compression forces are visualised.*
The assumption is made that for the first calculation the forces \( F_v \), as calculated before, do not directly act on the load bearing structure when this structure differs from the grandstand shape. When more insight is gained in the behaviour of the shape in relation to the shell action, this issue will be dealt with. For now we assume an additional structure is present to lead the forces to the load bearing structure.

To provide for shell action, hoop forces need to be taken up for every element, which means ring forces must be present within every element. The force polygons determine the needed ring forces at the ten different parts along the section for every configuration.

**Configuration 1**
Configuration 1 represents the shape of the original architectural design. As can be seen from the force polygon of this configuration (figure 059), the structure is subjected to tension only. Due to the gentle slope of the grandstand, a large cantilever arises. This results in hoop forces more than twice the size as the vertical forces caused by the dead weight and public loading. The ratio between vertical and horizontal (hoop) forces is presented with the \( x \)'s along the axes of the force polygon and this ratio in this case is 2.2.
Configuration 2
Applying an opposite and bigger curvature results in large tension forces at the top of the grandstand and small compression forces at the bottom (figure 060). The slope of the middle part of the section almost coincides with the line of thrust, which results in the fact that no hoop forces are present here.

Compared to the original shape the total horizontal forces equal the total vertical forces. This is a more favourable situation for the magnitude of forces. To optimize the forces in this configuration, the lower part can be easily adjusted to eliminate the compression forces, by applying a more gentle slope.

Configuration 3
The third section configuration is depicted in figure 061. The force polygon it shows that the lower part of the structure follows the line of thrust, which eliminates horizontal (hoop) forces. Tension forces are present at the top of the structure. The curvature at the lower part has a very positive influence on the forces in the structure because the natural line of thrust is approached.

The sum of the hoop forces is even smaller than the sum of the total vertical forces, which means smaller ring forces and therefore a more efficient structure compared to configuration 1 and 2.
Configuration 4 and 5
The force polygons of configuration 4 and 5 are included in appendix A2.1. These configurations are both less favourable compared to other configurations.

Roof
The vertical forces acting on the roof are calculated in the same way as was done for the grandstand. Wind forces are taken into account at a later stage, so only dead weight is present in these calculations. For these calculations, the starting point is a roof covering about 2/3 of the seats\(^1\). For the roof elements characters A till F are used.

Dead weight estimation (pg)
- Roof covering: 0.5 kN/m\(^2\)
- Load bearing structure: 1.2 kN/m\(^2\)\(^2\)
- Total: 1.7 kN/m\(^2\)

Public load (pq) 0.0 kN/m\(^2\)

Because of the assumption that the roof and grandstand structure work together as one structure, the load combination that was used for the grandstand is used for the roof.

\[
F_d = 1.2 \times pg + 1.5 \times pq = 1.2 \times 1.7 = 2.04 \text{ kN/m}^2
\]

Table 3 shows the governing vertical forces that apply to the roof structure.

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<th>roof</th>
<th>[r1]</th>
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<th>[m2]</th>
<th>[kN/m2]</th>
<th>Fv</th>
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<td>110</td>
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</tbody>
</table>

\(^1\) Later on in the research this value is adjusted to total covering to provide enough shelter according the demands.

\(^2\) Load bearing structure: 1.2 kN/m\(^2\)
As a starting point a steel grid is used including covering and installation (lighting, screens, speakers)
A convex shape of the roof causes large tension and compression forces at the top part, where the direction of the slope changes (figure 062). The bending moment to take up the forces from the left part hanging down is created within the thickness of the roof structure. Because of the small thickness, tension and compression forces become enormous. Note that the hoop force present at element F acts on the top part of the grandstand. This influence is elaborated in section 9.7.
Configuration 2
A representation of a concave roof is shown in figure 064. With this shape large compression and tension forces occur at the lowest point. This has to do with the bending moment as explained at configuration 1. The discontinuous line shows that the occurring forces are too large to show (figure 063).
**Configuration 3**

This configuration has reasonable compression forces at the top part and small tension forces in element B (figure 065). Lower elements are in line with the natural line of thrust; no hoop forces are needed. Forces are transferred via compression through the section.

This forces polygon shows that a section of the roof that does not approach zero, avoids extreme compression forces.

065  Force polygon roof configuration 3
9.4 HOOP AND RING FORCES

**Hoop forces**

From the previous force polygons, a lot of information is gained. First of all, the hoop forces that are directly visible within the forces polygon are determined. The hoop forces will be used to evaluate the magnitude of the ring forces. Because the force polygons are a scaled representation of the real forces in the shell, the hoop forces can be read from the horizontal line. This same force can be calculated mathematically, which is done in the tables later on.

**Ring forces**

With the help of the curvature of the grandstand, the ring forces can be constructed using the hoop forces (figure 066). Because there is a very small curvature in the grandstand, especially along the long edges, the ring forces become very large.

Because of the special shape of the grandstand, the curvature at every element is the same, although it looks like the curvature becomes bigger at the outer ring (figure 067).

Curvature of grandstand along long edge: 282.7 metre
Angle of ring forces (assuming 24 elements): 5°
Fring: $(\frac{1}{2} \times F_{\text{hoop}}) / \sin(2.5°)$
Notes
Before interpreting the values in the tables presenting the ring forces, attention should be paid to the following; initially ring forces are calculated assuming a horizontal transfer of the forces along the boundary of the stadium. However, in reality, the upper boundary of the stadium has an undulating shape, which makes horizontal transfer of ring forces impossible. This issue is dealt with in chapter 10.

Area of steel
From the ring forces, the needed area of steel (=structural material) is calculated. For the calculation of the area of steel ($A_{steel}$), a yield strength of 355 N/mm$^2$ (S355) is used. Initially this is represented as if it is one bar of steel, regardless of the diameter of the bar. In the case of the final model, this will be specified in connection types and amount of structural elements to take up these forces (chapter 16 'Demountability'). Forces in the grandstand structure are listed in table 4-6. The calculated area of steel needed to take up the ring forces is graphically represented in figure 068. Tension forces are coloured in red, while compression forces are shown in blue. The bars are drawn on scale to give a more clear impression and to allow quick comparison.

Forces in the roof structure are listed in tables 7-9.

### Table 4 forces of grandstand configuration 1

<table>
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<tr>
<th>element nr</th>
<th>Fv [kN]</th>
<th>slope [°]</th>
<th>Fhoop [kN]</th>
<th>Fring [kN]</th>
<th>$A_{steel}$ [mm$^2$]</th>
<th>$Ø$ [mm]</th>
<th>compression [kN]</th>
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<th>Fhoop [kN]</th>
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### Table 6 Forces of grandstand configuration 3

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Compression

The pressure in the structure equals the length of the diagonal in the force polygon. Compression forces add up along the height of the structure. A visualisation of these compression forces is given in figure 069 (configuration 4 and 5 are again included in the appendices (appendix A2.1).

Both figure 068 and 069 do not take into account additional reaction forces resulting from the roof structure.

Roof

A graphical representation of the amount of steel needed to take up the ring forces in the roof structure is included in the appendices (appendix A1.2).

### Table 7 Forces of roof configuration 1

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### Table 9 Forces of roof configuration 3

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068 Value of ring forces; area of steel (configurations 1 to 3)

069 Compression in tangential elements (configurations 1 to 3)
9.5 REMARKS

**Grandstand**
Comparing the forces in the different shapes of the grandstand shows that creating an opposite curvature at the foot of the grandstand, has a positive influence on the forces in the structure. Creating a line of thrust that lies in the section eliminates hoop forces. The structure is only loaded in plane, transferring vertical and horizontal forces to the foundation.

**Roof**
Avoiding high or low points in the structure of the roof eliminates large compression and tension forces due to a bending moment that has to be taken up. This makes configuration 3 the most efficient structure. The steeper the roof, the smaller the compression force at the canilevered part will be. However, a steeper roof provides less protection against rain and sunlight. The same holds for a roof that goes down completely, but this is not desired regarding the spectators’ view and atmosphere in the stadium.

9.6 COOPERATION GRANDSTAND - ROOF
Till now, reaction forces from the roof structure were not applied to the grandstand. The influence of the reaction forces on the forces in the grandstand is investigated. A combination of the roof structure with the load bearing structure of the grandstand, leads to a combined force polygon. The roof structure causes reaction forces on the grandstand, which shows in the force polygon. To look at the influence of the reaction forces a combined force polygon of grandstand configuration 3 with roof configuration 3 is presented in figure 070. The influence of roof configuration 1 and 2, both with horizontal forces acting on the grandstand, is included in the appendices (Ax).

Table 10 shows values of resulting hoop and ring forces.

![Force polygon cooperation roof with grandstand](image-url)
Calculations before were all based on dead weight and public loading only. The real structure will be subject to dynamic wind loading, which will cause different behaviour and magnitude of forces. Horizontal forces can have a negative influence on the magnitude of ring forces. Pressure and suction due to wind loading will be taken into account in further calculations.

Besides wind loading, a horizontal factor of 6% of the public load will be applied to the grandstand. This takes into account the horizontal forces acting on the structure due to movements of spectators.

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Table 10 Forces in grandstand due to cooperation grandstand and roof
Besides additional forces, an additional structure is needed to transfer the forces acting on the grandstand to the load bearing substructure (figure 071). In red, the aberrant part of the grandstand is visualised that needs additional support. To realise this connection in a way the structure works as calculated, forces need to be transferred evenly along the load bearing structure. Whenever this additional structure cannot be realised, the lower part of the forces of the aberrant part are directly transferred to the foundation, while the upper part will result in a concentrated vertical force in the force polygon, which results in an locally enlarged horizontal (hoop) force here (figures 072 and 073).

The reaction forces on the grandstand resulting from a roof structure are not taken into account here. A reaction force due to a roof structure has the same effect on the hoop forces, namely a local increase of the horizontal force due to the enlarged vertical load at that location.

To eliminate bending in the load bearing structure when no additional structure is applied, the slope of the load bearing structure slightly differs from the original slope (figure 073).
3D approach

Graphic statics is a 2D method to investigate forces in a shell structure. A 2D representation may differ from reality to a certain scale, because the structure of the Lotus stadium is asymmetric. This chapter deals with 3D consequences of the 2D calculation.

10.1 3D BEHAVIOUR

With the calculation of the forces, no attention is yet paid to the 3D shape of the stadium. Because the undulating upper boundary, the ring forces cannot be transferred horizontally and need to be taken up by diagonal forces, following the outer boundary of the stadium.

Ring forces cannot be taken up in the horizontal plane, because of the shape of the structure. To take up these forces, the ‘ring’ must be in the plane of the undulating upper shape of the stadium. The most extreme point is in the plane of the section of the grandstand. To visualise this graphically, a side view of the stadium is given to explain this (figure 074).

The biggest problem arises at the top element (element 1), where the hoop forces (and therefore the ring forces) are the biggest, and the transfer direction of the ring force approaches the slope of the grandstand itself. This results in extremely large ring and compression forces due to an inefficient transfer of these forces. Force polygons that show equilibrium in both situation are shown in figure 076.

From figure 075 shows along which slope the ring forces are transferred. From element 2 onwards, the slope of the ring force approaches the horizontal line more and more, which means more optimal ring, and therefore compression forces, arise along the section of the grandstand.
A hand calculation as performed in figure 077 shows different views of the direction of the forces and how the angle of the ring force contributes to enlarged compression forces in the section. The 3D shape of the stadium has a lot of consequences on the forces in the structure. Conclusions on this topic are presented in the next section together with some criteria to judge different alternatives on.

![Diagram of stadium forces](image)

**077 Hand calculation of ring forces acting non-horizontal**
10.2 CONCLUSIONS
From the research done, several conclusions can be drawn regarding the battle between optimal ‘C’ values versus shell action. Conclusions regarding optimal shell action are listed whereafter optimisations are suggested in the next part.

The former calculations did not take into account the 3D shape of the stadium. The application of the ‘C’ value causes an undulating shape of the stadium, which causes a difference in height along the grandstand. In turn, the ring forces in the highest part along the long edge of the stadium can therefore not be transferred horizontally in the current design. Without changing the situation, the ring forces have to be transferred along the upper boundary and have a downwards slope. This deviation of the horizontal transfer of forces causes huge ring forces due to a less efficient transfer of (hoop) forces. The increase of the ring forces leads to an increase of the compression forces in the grandstand section as well.

From the different configurations it can be seen that difference in curvature of the load bearing structure has consequences on the forces in the section. Difference in curvature causes difference in forces. An opposite curvature at the top results in large tension forces while an opposite curvature at the bottom reduces or even eliminates the hoop forces. The more the curvature differs, the more the magnitude of the hoop forces varies along the section. Strong curvature at the bottom can cause compression forces. The original structure causes the most equally divided forces along the section. The original shape has a very unfavourable ratio of horizontal hoop forces to vertical forces, namely more than twice as big. Overall, the steeper the slope of the grandstand, the smaller the ratio of horizontal forces to vertical forces.

Difference in the shape of the load bearing structure compared to the shape of the grandstand (resulting from ‘C’ values) has consequences on the look of the stadium that differs from the original look. Another consequence from a difference in shape of the load bearing structure and the grandstand is the need to transfer the forces from the grandstand to the load bearing structure to create shell action as calculated.

Forces from the roof structure act as a reaction force on the load bearing structure of the grandstand. Ring forces in the upper ring of the grandstand are influenced by the reaction forces from the roof structure. The total vertical force, Fv, from the roof acts as a vertical component on the grandstand. Horizontal forces from the roof increase or decrease the hoop forces of the top element of the grandstand.

Within the corners of the stadium the situation is most optimal. First of all the ring forces can be transferred horizontally because the corner elements have the lowest height. Moreover the curvature for transferring the ring forces is a lot bigger. The bigger curvature causes smaller ring forces to take up the same hoop forces. Because of the limited height the compression forces are also smaller.

Over all, the ring forces in the structure are large. These large tension forces may lead to excessive deformations which needs to be investigated.
10.3 CRITERIA

During the process of finding the optimal shape of the grandstand regarding the hoop and ring forces, consequences arose that are of influence on different areas of interest. To judge on this specific topic, criteria are set up besides the general list of demands and preferences, as listed previously in chapter 5.

 Forces

As mentioned, the prior research was based on finding alternatives that are very efficient regarding the forces in the structure. A choice on this criterion alone will not lead to a well balanced choice; this is why several other selection criteria are defined. Within the criterion the two different forces are weight load and wind load. These types of forces result in very different kind of behaviour of the structure.

[choice: smallest forces/equally divided forces]

 Assembly

Looking at the assembly, elements are preferably of the same size or shape. This simplifies the assembly process and therefore accelerates the assembly time. Uniformity within elements is preferred.

[choice: uniformity/most efficient]

 Additional structure

Aberration of the original shape causes the forces from the seating elements need to be transferred to the load bearing structure, which means a secondary structure to achieve this. The acceptance of this plays a role in the decision-making process.

[choice: absence/presence of additional structure]

 Dynamic behaviour

Graphic statics examines the static behaviour of a shell structure. A structure behaves different under dynamic loading. Dynamic loading might prescribe a different structure more optimal than following from graphic statics. Equivalence of elements might play a role in this criterion and might be determinative for the behaviour of the structure under dynamic loading.

When determining the behaviour under dynamic loading, the focus lies on weight loading, in this case a jumping crowd on the grandstand which will be governing.

[choice: equivalence of elements and forces/accepting less optimal dynamic behaviour(?)]

 Architectural design

An adjustment to the structure might have negative consequences on the look of the stadium. This criterion has to be discussed with the architect, on behalf of acceptability of adjustments.

[choice: possible deviation from original design – what is acceptable?]
Optimisation possibilities are elaborated in this section. Based on the research done in the previous section, with the help of the suggested optimisations, 3D models will be used to perform calculations with.

The end of this section presents a final design as a starting point for the structural design. This design will be based on all conclusions and points of attention encountered throughout the optimisation research.
Optimisation

Optimisations on several issues are investigated based on the conclusions drawn in the previous chapter. Because of the impossibility to transfer the ring forces of the higher grandstand parts horizontally, shell action is difficult to realise. Possibilities to provide shell action play a major role during optimisation.

Regarding the optimisation options for the shape of the Lotus Stadium a dividence in three is made. The most important issue is wether the structure will work as a shell or wether it will transfer the forces mainly by bending. A third alternative is a combination between shell action and bending forces (figure 078).

To provide shell action the most efficient way to transport the ring forces is in a horizontal way.
11.1 SHELL ACTION
The optimal way to transfer the upper ring forces is to transfer them horizontally. The possibility to transfer ring forces along the undulating boundary of the stadium was examined in chapter 10 and proven to be inefficient due to resulting large ring and compression forces to be able to achieve equilibrium and still avoid bending moments in the section. Former calculations were all based on horizontal transfer of ring forces. Several ways to actually transfer these forces in a horizontal manner are explained in this section.

Optimisation I
Apply cables at every height by adjusting the lower grandstand parts to the same height of the highest point along the long edge by following the slope of the grandstand till equal height is reached around the whole stadium. What this looks like from above is depicted in figure 080. A 3D impression is shown with figure 079.

Ring forces are transferred horizontally. Lower grandstand structures are adjusted till an equal height is reached all around the stadium, following the slope prescribed by the 'C' values. The forces that need to be transferred are visualised in figure 081. The difference in height along the grandstand is marked by level lines. Locations of the 'cables' as calculated are marked red. The word 'cable' means a force unit that needs to be transferred; this is possible by

A cable or by different structural elements. By sweeping the slope of the grandstand around the field, the 90 m boundary is exceeded due to the rectangular shape of the field and the sweeping curve around it (figure 079).

Special attention should be paid to the tangential elements perpendicular to the ring forces. Because the grandstand weight is absent here, the force polygon is no longer in equivalence, assuming the same hoop forces.

An additional structure should be added to increase the vertical weight (Fv) to solve this problem. One of the options is to enlarge the capacity and expand the seating area. These additional seats will have less optimal viewing distances compared to the seats within a radius of 90 metres.
inwards. Counter-pressure is needed to keep the structure in place.

Because the edge is loaded in its weakest axis and therefore will deform largely, this is a very ineffective way to transfer the forces, the gentle curvature.

Because of the sudden change of the slope of the grandstand at the locations where the structure goes straight up to stay within the 90 metre boundary, the force polygon is largely influenced. Together with this effect, bending moments occur in this edge to withstand out of plance forces due to horizontal ring forces.

This needs further investigation. Additional mass needs to be added to avoid the ring forces that are guided through the section here tend to pull the structure

Optimisation II
A second option is to apply cables at every height staying within the boundary of 90 metres from the centre point. To retain the special circular look of the stadium the additional structure (or cables) is placed within the radius of 90 metres. This caused a large difference between the corner section and the section of the long edge. This is presented in figure 082. A 3D representation of what this looks like is shown in figure 083. Note that horizontal cables are not shown in this picture.

Optimisation II
A second option is to apply cables at every height staying within the boundary of 90 metres from the centre point. To retain the special circular look of the stadium the additional structure (or cables) is placed within the radius of 90 metres. This caused a large difference between the corner section and the section of the long edge. This is presented in figure 082. A 3D representation of what this looks like is shown in figure 083. Note that horizontal cables are not shown in this picture.

The forces that need to be transferred as calculated are calculated for the specific section along the long edge of the stadium. When transferring these forces along different angles, the difference in force should be taken into account. When the stadium is equally leveled, at the highest point along the long edge of the stadium, the upper ring force has an exact circular shape. Lower ring forces will more and more approach the curve as drawn around the field. This means less optimal forces due to

The forces that need to be transferred as calculated are calculated for the specific section along the long edge of the stadium. When transferring these forces along different angles, the difference in force should be taken into account. When the stadium is equally leveled, at the highest point along the long edge of the stadium, the upper ring force has an exact circular shape. Lower ring forces will more and more approach the curve as drawn around the field. This means less optimal forces due to
Optimisation III
Guide the ring forces of the upper elements through the roof structure at the corners and along the short edge by adjusting them to the height of the highest point along the long edge of the grandstand (figure 084 and 085). To be able to guide the upper ring force of the highest elements through the stadium, this is done by guiding this force through the roof structure along the other sections. This means that the roof structure needs to be of equal height with the highest point. The results for the different sections is visualised in figure 084 in which three sections are placed side to side.

Another solution might be to find a situation where the forces acting due to shell action and ring forces from the long edge have a positive influence onto each other by canceling each other out. It might be possible to create equilibrium between the needed compression forces in the roof with the tension in the ring forces originating from the long edge.

The cables used to transfer the forces are of use to provide a roof structure. These cables are absent at the grandstand along the long edge, which means an additional roof structure at this location. This creates an asymmetric structure which is unwanted by the architect.

The ring forces that are guided through the roof structure are of influence on the shell action in the roof as calculated before. Because the cables to take up the ring forces are very suitable to apply a cable roof combined with membrane, this might be a solution.

084 Ring forces through roof structure in different sections

085 Top view of cables running through the roof structure
Optimisation IV

Apply cables at the highest points spanning from one side of the stadium to the other side (figure 087). This optimisation is based on the fact that the ring forces needed at the highest elements (the difference between the highest point along the long edge minus the highest point along the short edge) will be transferred from one side of the stadium to the other side of the stadium. Figure 086 shows a section of the stadium presenting the cables in red.

The sudden change in direction of the ring force has influence on the behaviour of the structure. An important property of shell action is the presence of ring forces going round the structure. In this case the ring force will not go round but it will create a shortcut and is directly being transferred to the other side. Note that this in only the case for the upper ring forces; lower ring forces will be present in the section and go round the stadium in a horizontal way, ensuring the line of thrust being in line with the section, eliminating bending moments.

Forces are in equilibrium as long as the force polygons are closed. Horizontal (hoop) forces, ring forces and the compression force in the tangential elements are in equilibrium with each other. The angle of the tangential elements compared to the curvature (the direction of the ring forces) determines the direction of the hoop forces.

Hoop (and compression) forces are most effective when perpendicular to the ring forces. First option is to place all tangential elements directed to the centre of the field, while a more obvious way to arrange them is perpendicular to the curvature. The knowledge of the direction of the tangential elements is not only important for determination of the forces but is also defining the location of structural elements.

Within this solution a lot of variations are possible for placement of the cables.
11.2 NO SHELL ACTION/PARTIAL BENDING
The stadium shape as it is designed with the undulating upper boundary is not very suitable to the application of shell action. Because of the undulating shape, ring forces cannot be transferred horizontally which is a condition for optimal shell action. When an adjustment to the look of the stadium is unwanted, automatical bending occurs in the structure because of the absence of hoop forces.

Optimisation V
Hoop forces are not taken up by ring forces, so bending occurs in the structure. The lower parts of the stadium structure will be dimensioned to take up bending moments from parts of the grandstand that are not able to transfer ring forces horizontally (figure 088).

The parts of the grandstand above the corner level are all subjected to bending, because no hoop forces are present. Assuming that below the corner level shell action is activated again, the bending moment is the biggest at the corner level. A force polygon of this situation shows clearly the consequences of this situation. The bending moment is very large and needs to be taken up by the thickness of the structure. Assuming a thickness of 3 metres (grandstand and load bearing structure are 3 metres apart) still enormous dimensions are the result. Allowing bending leads to a very inefficient structure regarding the transfer of forces and the used material.

11.3 SUBOPTIMISATIONS
Within the proposed optimisations, sub optimisations are possible regarding several issues. To limit the magnitude of the hoop and ring forces, several measures can be taken. The solutions can be applied next to the main optimisations I till V.

(1) Apply a more optimal shape that partly follows the line of thrust so a part of the hoop forces is eliminated and a more material-efficient structure arises.
Referring to the research done in chapter 9 (graphic statics), an aberrant load bearing structure eliminates some of the hoop forces by following the line of thrust. This measure needs an additional structure as illustrated in section 9.7.

(2) Aberrant load bearing structure without a connection to the grandstand. Forces are transferred differently and an adjusted force polygon arises.
This topic is a variant of optimisation (1) and is also mentioned in section 9.7. The force polygon does not show a lot of difference compared to the calculations where a connection was assumed. This is favourable because this means that an additional structure is superfluous since it does not outweigh the advantages of the transfer of forces.

088 Bending in upper part of the grandstand
The figure at the left shows the forces on the section of the stadium. At the right, the forces polygon is created.
(3) Optimize reaction forces from the roof structure to limit the increase of hoop force of the upper elements of the grandstand

Applying a lightweight cable roof combined with membrane will limit reaction forces on the grandstand structure. The horizontal thrust needed in the upper elements depends on the reaction force from the roof structure. The bigger this force, the larger the horizontal thrust needed. By applying a lightweight cable roof covered with membrane, this force is relatively small. The application of a cable roof means that the roof structure does not work as a shell structure because cables are only suitable to be loaded in tension. Some of the optimizations mentioned earlier are highly favourable to combine with a cable roof, because these optimizations are based on the presence of cables in the area of the roof.

(4) Adjust the roof structure in a way that reaction forces have a positive influence on the forces in the grandstand.

The shape of the structure influences the magnitude of the forces in the roof. Roof shape with configuration 3 (9.3) has compression in the upper ring and (small) tension forces in the lower rings. Through smart combination of the roof structure with the grandstand structure, reaction forces from the roof structure can have a positive influence on the force in the upper element of the grandstand structure (appendix A1.1). This effect is of importance to the operation of optimization III, however it is difficult to calculate in a two-dimensional way due to the complex (undulating) shape.

(5) Increase the slope of the grandstand

Increasing the slope of the grandstand limits the ratio of vertical forces to horizontal hoop forces (figure 089) and becomes a more efficient structure due to the decrease of ring forces. Regarding the increase of the grandstand slope, the maximum slope of 34 degrees should be kept in mind. The benefit of this measure is small because a maximum increase of 2 degrees is feasible (the slope currently being 32 degrees).

Within this optimization another option is increasing the load bearing structure without changing the slope of the seating elements. There is no limit on the maximum slope of the load bearing structure, however a large change in slope undermines the “flying shell” appearance. Besides the appearance an additional structure for the right transfer of forces is needed along the total height, which eliminates the advantages.

(6) Increase curvature in radial direction

Increasing the curvature in radial direction, creates more efficient transfer of forces, because smaller ring forces are needed to create hoop forces for ensuring a line of thrust in line with the section of the structure. Increasing the radial curvature without changing the upper boundary, causes an increased slope of the grandstand. The consequences are mentioned at suboptimisation(5).

When an increase of the steepness is not wanted, consequently the amount of seats decreases and the undulating upper boundary becomes less.
11.4 CONCLUSION
The added surface of optimisation I can be used for facilities. When combined with solution II, the facilities are placed onto the additional surface to provide the needed mass for equilibrium, while the rim is used as architectural wall to divide the facilities or VIP rooms behind it from the regular seating area.
Optimisation III stays the closest to the original design regarding appearance. A very important issue regarding the design is the geometry and the pattern of the structural elements. The grandstands act together as a shell; this is also wanted for the roof structure. The solution in alternative III provides transfer of ring forces through the roof but this only creates two parts of the roof above the short edges and the corner areas. The roof part above the long edge of the grandstand will need compression elements to avoid the structure from folding together by means of the tension in the ring forces in perpendicular direction. This compression is to be realised by pressure arcs, which does result in a continuous round going structure. This continuity, realised by shell action regarding the grandstand, is a criterion for the roof structure as well; this means some adjustments need to be made. The roof should have the appearance of a lid onto the grandstand; the grandstand together with the roof will have the appearance of an oyster with the undulating boundary halfway.
Using a cable roof, shell action is not the most obvious way to transfer the forces, because cables act in tension only. Assuming a cable roof, a geometrical pattern in the structure has to be realised to convince the architect of the worth. The structure will be clearly visible throughout the stadium, which is why this is wanted to be a very natural geometrical shape that finds a logical explanation from the transfer of forces in a structure. The structural elements will not be covered to keep them out of sight. The load bearing structure is the connection of the seating, without extended secondary structures needed.
The concept of allowing bending is not appreciated by the architect, because the ineffective transfer of forces and the wanted appearance of a shell.
An increase regarding the slope of the grandstand might have a bigger margin than the 2 degrees as calculated. The maximum steepness of the gangways of a grandstand amount to 38 degrees. This means an increase of the steepness by 6 degrees. Because the slightly parabolic shape the feeling when you look down from the grandstand is less frightening than when looking down from a straight angle.
Regarding the curvature, the basis might get a more optimized curvature. Based on two curvatures (R and r) a rounded shape will be created around the grandstand, leading to a bigger curvature of the structure which will lead to smaller ring forces. Increasing the curvature will eventually eliminate the difference in height between the short edge of the structure and the corner elements. This influences the appearance (the undulating upper boundary) enormously.
For further modelling, it is chosen to use the original shape of the grandstand. Ring forces are influenced by adjusting the shape of the section through the grandstand, however, equally devided ring forces as present in the current design are possible to be taken up. Focus lies on an efficient transfer of the upper ring forces to minimise bending in the structure and lead to an efficient design within the architectural boundaries.
For modelling purposes, first of all we compare a model without a roof with a few models with different roof types. The three roof types to be modelled are in line with the research as carried out in this section. A convex shell roof will be modelled as well as a conclave membrane roof making use of the principle of transferring forces by means of cables (in a minimal surface shape). In the end a combination between these two is modelled; providing horizontal transfer of the upper ring forces by means of an additional edge, combined with a minimal surface roof connected to this edge. All roof types provide an opening in the roof to avoid shading on the pitch. This eliminates cables spanning from one side to the other, because compression occurs in the roof structure and buckling will become a problem.
12 Modelling

Because of the complex shape of the Lotus Stadium the studies in 2D need to be checked by a 3D model. Because the transfer of forces in 3D cannot be predicted accurate, this chapter deals with the modelling of the stadium in a computer.

12.1 LOAD CASES
Different load cases are to be applied to the stadium structure. A division in two is made between dead load (G) and live load (Q). Dead loads, taking into account the mass of the load bearing structure as well as the secondary structure and seating elements. Live loads, taking into account the wind loads and public load.

Dead load
Load bearing structure
For the calculation of the load bearing structure the area of steel as calculated in section 9 ‘2D approach’ is used in a grid of 12*6 metres. Using an area of steel of Ø300 mm, this approaches 1,5 kN/m². Note that the load bearing structure is inserted in a calculation program and the mass is generated by the program itself. Secondary structures and seating elements have to be taken into account as additional loading.

Secondary structure
The secondary structure between the mean grid of 12*6 metres will be applied as additional load to perform a calculation in Oasys GSA. Because this will be a lighter structure than the load bearing structure a value of 1,0 kN/m² will be adopted.

Seating elements
Regarding the seating elements several suppliers are investigated to give an estimation of the uniformly distributed load. One of this suppliers, Freedom Enterprises, offers a grandstand with a dead load of 0,25 kN/m² (appendix A4).

Live load
Public load
According to the defined user classes in the EuroCode, the stadium belongs to user class C; areas where people can gather (NEN 2002b: table 6.1). Because of the fixed seating category C2 is applied, which limits the public load to 4,0 kN/m². (Appendix A3.2) The fixed seating prevents gathering of large groups together.

Imposed load on floors, balconies and stairs:
C2: qk = 3,5 – 4,0 kN/m², Qk = 4,0 kN (NEN 2002b: table 6.2)

Snow load
Snow loads are not taken into account during calculations. The stadium will be used during summertime in Europe when snow is very unlikely to occur.

Wind load
The wind load on the stadium depends on the peak velocity pressure, which is composed determined by the mean wind and wind turbulence. To calculate the actual wind pressure on the structure, for factors are applied to take the shape of the building into account.

> Form factor c
Due to the wind flow along a building pressure and suction arises. This is taken into account with form factors. These factors are a mean value of deviating pressure along a façade.

> Peak velocity pressure
Integrating all relevant factors in one formula, the peak velocity pressure takes the following form (appendix A3.3):

\[
q_p(z) = (1+7*1/(ln(z/0.003)))^{*}1,25^{*}(4,6 * \ln (z/0.003))^2
\]

The peak velocity pressure is dependent on the height of the structure. Because the height is smaller than the

090 Distribution of peak velocity pressure along the height
openings, so for the roof this aspect does not play a role. For the façade (= the grandstand) a value for internal pressure should be used. A first approach uses the internal pressure coefficient for open buildings. Depending on the openness of the roof, the internal pressure coefficient is 0.6 to 0.9 times the external pressure coefficient.

Most negative situation results in a cpi of:

\[ \text{cpi} = 0.9 \times \text{cpe} \]

This value will be adopted for further modeling.

Roof structure

The roof structure will be treated as a canopy, taking the circular shape into account. Because of the circular shape, corner values will not exist. A canopy factor \( c \) will be used (referencing the Eurocode appendix A3.4). The factor \( c \) is applied to the peak velocity pressure. The circular shape of the stadium has a positive influence on the external pressure. External pressure coefficients that will be used are depicted in figure 091 and appendix A3.4. Because of the rounded shape of the stadium, the wind moves around the stadium without large disturbances due to sharp edges. At locations where the wind moves away from the structure, whirls occur, which cause under pressure and therefore wind suction. This phenomena is depicted in figure 091, together with the resulting wind pressure and suction. Compared to standards in the Eurocode, different zoning is used. Because of the wind pressure and suction.

along the sides, friction occurs resulting from the wind flowing along the façade of the stadium. Factors that will be used (referring to the characters used in figure 091).

\[ A = 0.7 \]
\[ B = -0.8 \]
\[ E = -0.3 \]

Internal pressure

Internal pressure plays a role in buildings with small openings so for the roof this aspect does not play a role. For the façade (= the grandstand) a value for internal pressure should be used. A first approach uses the internal pressure coefficient for open buildings. Depending on the openness of the roof, the internal pressure coefficient is 0.6 to 0.9 times the external pressure coefficient.

width of the stadium, the pressure is assumed uniformly distributed along the height (figure 090). For the height 'z' a value of 30m will be adopted, which is the highest point of the grandstand.

Net pressure coefficients on the roof:

- upward pressure (wind uplift): 2.0
- downward pressure: 0.7

The factor used plays a role for the roof because the structure is not stiff and is subjected to vibrations.
Study has been done regarding equivalent static wind loads for cantilevered grandstand roofs (Letchford 2001) and research showed a $c_{p,c}$ factor of 5.0. Because this results from Australian research, this value should be converted to Eurocode standard. The factor $C_{p,c}$ as mentioned in this article equals $c_p (1+7I)$ in Eurocode, this means a $c_{p,c}$ factor of 2.5 ($=5.0/(1+7*0.15))$. This factor will be used to calculate wind uplift of the stadium roof. Compared with the canopy-method of the EuroCode, the factor from research is higher so this value will be used in order to calculate the governing load combination.

Because of the dynamic behaviour an amplification by means of a $c_{p,c}$ factor of 1.2 should be applied to achieve the design value of the wind load on the roof.

**Load combinations**

For live loads the combined value, presented as a product of $\psi_0 Q_k$, will be used to check the behaviour in ultimate limit state. One of the live loads will be taken as a leading variable action, while accompanying variable actions are treated instantaneous, using the $\psi$ –factor. Together with a safety factor, different combinations will be checked.

The calculation value of a load $F$ will be formulated as follows in general terms (NEN 2002a: 6.3.1).

\[
F_d = \gamma_f \times F_{rep}
\]

\[
F_{rep} = \psi_0 F_k
\]

- $F_d$ characteristic value of the load
- $F_{rep}$ representative value of the load
- $F_k$ partial load factor, taking unfavourable values of the load compared to the representative load into consideration
- $\psi_0$ safety factors that will be used for different load combinations are included in appendix A3.5.

- $\psi$ –factors

Recommended $\psi$ values for buildings are mentioned below. According to NEN-EN 1991-1-1 the stadium is a category C building (gathering area). This category determines the $\psi$ values.

**Category C**

\[
\psi_0 = 0.7, \psi_1 = 0.7, \psi_2 = 0.6 \text{ (NEN 2002a: table A1.1)}
\]

\[
\psi_0 = 0.25, \psi_1 = 0.7, \psi_2 = 0.6 \text{ (NEN 2002a: NB table A1.1)}
\]

**Wind load**

\[
\psi_0 = 0.6, \psi_1 = 0.3, \psi_2 = 0.0 \text{ (NEN 2002a: NB table A1.1)}
\]

Safety factors that will be used for different load combinations are included in appendix A3.5.
A summary of all loads applied to the stadium is listed in table 11. Because the models are wire frames, evenly distributed loads are converted to a node load using the gridsizes. Due to the shell shape of the stadium, the grid gets wider at the top. This difference is not taken into account, an average grid is taken as a measure.

Table 12 shows different load combinations to ensure the structure is capable to withstand the loads in every condition. The goal of these combinations is to find the governing forces to design for. With the help of the output the total stadium will be dimensioned and profile types will be attributed to different elements.

<table>
<thead>
<tr>
<th>Table 11 Apied loads</th>
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<tr>
<td><strong>Elements</strong></td>
</tr>
<tr>
<td>Grandstand</td>
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<td></td>
</tr>
<tr>
<td>Roof</td>
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</tbody>
</table>

* (secondary structure + finishing + seats)

<table>
<thead>
<tr>
<th>Table 12 Load combinations; the table shows the different combinations of loading to ensure the governing combinations will be calculated for. Within Ultimate Limit State combinations, safety factors are applied. Difference is made between static and dynamic analysis.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Analysis</strong></td>
</tr>
<tr>
<td>Static</td>
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<tr>
<td>Dynamic</td>
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</tbody>
</table>

¹ SLS; Serviceability Limit State  
² ULS; Ultimate Limit State
12.2 PRECONDITIONS 3D MODEL
During modelling, attention should be paid to the requirements to the shape of the stadium. It is chosen for to model the grandstand as originally designed. Forces can be limited with a difference in section but the appearance weighs out the decrease of forces in this case. Regarding the shape of the roof, a few limiting requirements are stated below.

- The roof should limit shading on the pitch. When making use of natural grass, insolation is a very important measure to keep the grass pitch healthy.
- The roof should provide enough shelter to the spectators. One of the main reasons of applying a roof structure is to provide shelter for spectators. Protection against rain is important.
- From all seats a point at 18 metre above the pitch should be visible.

These measures will be of importance for judging different variants on.

12.3 CHOICE FOR MODELLING
From the conclusion drawn in section 11.4 several options showed as good alternatives to investigate in more detail with a 3D model. These models have a variance in roof structure. To investigate the model without the structural help of a roof, the grandstand on itself is modelled seperately.

First of all the grandstand itself with curved ring forces will be investigated (figure 092). The behaviour of this model will show the behaviour of the grandstand when no roof is applied to the stadium. A comparison between the models with a roof to the model without a roof will also gain insight in the possible advantages of a structural roof.

Several different solution possibilities for the roof structure and therefore the transfer of large upper ringforces are applied to investigate the most effective and efficient way to take up the forces in the structure, taking into account the demountable aspect of the stadium. After elaboration of all models a choice should be made regarding the following topics.

- behaviour of structure under loading
- difficulty to assemble
- amount of material used
- functionality (insolation)
- appearance

The models that will be calculated by means of a computer model follow from the optimisation phase and are as follows. It was concluded that hoop forces are taken up by horizontal ring forces as most optimal (chapter 9). The first roof type consists of a shell roof with horizontal elements guided through the roof. (figure 093).

Another solution was found in the possibility to transfer forces in a more direct way with the help of cables spanning to the oculus. This is modelled by means of radial roof elements spanning from the boundary of the stadium towards an inner circle (the opening) in the roof. This creates a minimal surface roof (figure 95).

The last model that will be calculated is a combination between these two variants. A shell edge is put on top of the stadium to create the same height along the total stadium boundary. From this equal level a membrane roof will be created with radial elements spanning towards a central roof circle (figure 95).

Because shell action is the main way to transfer the forces of the grandstand, the grandstand structure is fully braced within every variant. This provides in plane stiffness as well as stability to the structure. The membrane roof is performed with and without braces to compare the difference and structural function of the different elements.
Ring forces curved along the undulating boundary

Shell roof

Minimal surface roof

Combined shell edge with minimal surface roof
I - Grandstand without a roof
As mentioned before the grandstand itself is also modelled as a separate structure to investigate the forces in the structure and judge the structural capabilities of this shape, regarding the previous research on the shell action. This basic model will show the structural differences when applying a (structural) roof to the stadium. A closer look is taken towards the path of the ring forces within the grandstand.

II - Shell roof
Besides the structural functionality other aspects play a role as well. The main function of the roof is to provide shelter for the spectators but simultaneously limit the shading on the pitch. The shell roof causes a relatively large shading area on the pitch because of its height and large structure. The shelter provided by this roof type is not optimal; the grandstand along the long edge is not covered entirely regarding the rule for shelter (list of demands and preferences 5.1 roof(1)). Compared to the small depth of the grandstand in the corners, the roof has a large depth. Regarding assembly this is a very labour intensive type of structure. Structural stiffness is gained when all elements are in place and act together as a shell. This means temporary supports might be needed to support the structure as long as it has not been fully assembled. Although there are some disadvantages, it is chosen for to model this roof type to gain more insight in the structural behaviour of such a shell roof.

III - Minimal surface roof
As a starting point the membrane roof is designed with a surface relaxation method, providing tension in the entire surface, which is ideal for a cable roof combined with a membrane cover. Due to the character of this structure the roof tends to hang between the edges. A large sag causes an obstructed view to the 18m point above the centre point of the pitch. Taking into account both the rules for shelter and lines of sight, this structure is in its nature the most ideal. Regarding the insolation the flatness of the roof has a positive influence.

This type of roof is very suitable for a demountable structure, because the limited amount of elements in the roof. Less elements and a less heavy construction are of positive influence on the (transportation) costs. Within this design several variants arise regarding the grid of the elements in the roof.

IV - Combined roof edge with minimal surface roof
This design combines the two former roof shapes. An edge is added to the grandstand to create equal height around the total stadium. From this edge a minimal surface roof is created as was done with roof design III. This means a good ratio between sufficient shelter and a maximized insolation on the pitch. Because the roof has a more symmetrical shape, more equal forces are likely to show in this structure.

The undulating shape of the grandstand is somewhat flattened by a different method of formfinding. The additional edge on the roof has a conoid shape due to cutting the structure by that shape. This results in a flattened undulation and a more rectangular shape looked from above.

Input
Elements are split in groups; horizontal, vertical, diagonal and roof elements. Till a certain level adjusting to function of element type is possible, this will however not always the most efficient solution. This issue is not taken into account within this subdivision.

Output
To make a quick comparison possible, these four models will only be subjected to dead weight and public load first. After the results are examined, the most optimal model (regarding the topics mentioned before) will be elaborated in more detail.
12.4 MODELLING WITH OASYS GSA

I - Grandstand without a roof

During the research on the behaviour of shell action in the Lotus Stadium (chapter 9), the research was based on the presence of horizontal ring forces and vertical compression elements perpendicular to it. In reality the shape of the stadium does not provide the possibility to transfer these forces in a horizontal way along the boundary of the stadium. Within the 'wings' of the stadium, the shell forces will find their most optimal path, which is along the curved boundary towards the foundation. Perpendicular to this compression elements arise in a fanning pattern.

This would mean that four sub shells arise which will all transfer the forces towards the foundation by tension in radial direction (ring forces) and compression in tangential direction. These four shells are connected in the corners.

The grid will be stiffened by adding braces so a stiff plane arises.

With this model the reality of the curved ring forces is checked to elaborate the shell action without any help or force disturbance of the roof structure.

Input

Within the model different kinds of elements are distinguished. Separate properties are assigned to the tangential members, the radial members (ring members) and the braces. The upper edge of the grandstand is reinforced with a more stiff element. (larger section). Note that profile types are assigned to create a quick view of global forces and might not be the most efficient choice.

<table>
<thead>
<tr>
<th>Tangential elements</th>
<th>RHS 1000, 400, 20, 20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radial elements</td>
<td>C 400</td>
</tr>
<tr>
<td>Braces</td>
<td>C 300</td>
</tr>
<tr>
<td>Grandstand edge</td>
<td>CHS 1200,30</td>
</tr>
</tbody>
</table>

From table 12, load cases 1 and 2 (dead weight and public load) are elaborated. ULS situations include dead weight and public load with safety factors.

Output

Regarding the output, three subjects are determined. First of all the deflected shape of the stadium will be looked at with its displacements due to dead weight and public load. The maximum allowable displacement of the grandstand amounts 300mm (0.006*length of the grandstand (=50m)). Note that additional displacements are of importance, because displacements due to dead weight can be theoretically resolved by making use of a camber.

With the help of the deflected shape the transfer of axial forces and bending moments is explained.
The deformation of the shell structure without roof is depicted in figure 100 and 101. The deformed image (figure 098-099) shows the grandstand that falls backwards due to dead weight and public load. The grandstand cantilevers about 40 metres which is a large length for a shell structure that has not very much curvature.

These large deformations are a logical consequence of the shape of the structure with its large cantilever and small curvature.

max displacement due to dead weight: 3.5m
max displacement due to public load: 3.2m
total displacement (SLS): 6.7m

These displacements are far beyond the maximum allowable displacement of 300mm and is therefore not acceptable.
> Axial force
The axial force in ultimate limit state situation is shown in figure 103. This picture clearly shows the ring forces curved along the surface, and the compression forces perpendicular to it. Forces are largest in the corners, where all forces from the grandstand quadrant are transferred to the foundation. Profile types of choice are not able to take up these forces, but are chosen to allow easy comparison between the four models.

> Bending moments
Because of the undulating upper boundary a bending moment arises (figures 105 and 106). This bending moment is taken up by the upper ring by negative moments along the edges and positive moments in the corner sections. Bending moments in y direction are present along the tangential elements of the grandstand; showing the line of thrust not being completely in the section.
Due to difference in displacement of the grandstand along the edges and the corners, resulting in distortion of the upper edge, a torsional moment arises (figure 104).
II - Shell roof
This model is completely based on shell action. The grandstand is modelled as a shell and the roof is a shell structure with a large opening in it. The grid of the roof is based on possible horizontal transfer of ring forces through these elements. From aside, the radial elements are all in a horizontal plane. For shell action the stiffness in plane is very important. This is why the structure is fully braced to create planar action in which forces can follow the most effective stress trajectories.

Input
For the input of the grandstand elements the function of these elements is highly important. To simplify the process, elements are grouped together assuming the same function within the structure. Radial elements in the grandstand will be loaded in tension due to the ring forces. These elements are modelled with a steel beam with circular solid section (C). Tangential elements in the grandstand are subject to compression forces and therefore will need a bigger moment of inertia to avoid buckling. A hollow section profile will be assigned to these elements. The undulating boundary between grandstand and roof shows large bending moments in both directions so a large moment of inertia is required. A circular hollow section is the most obvious choice. Note that some elements in this grid are subject to large forces so large sections are required. During materialisation phase these sections will be converted to regular sections what might result in a different grid.

Radial  Steel  STD C 400
Tangential  Steel  STD RHS 1000, 400, 20, 20
Braces  Steel  STD C 300
Gr.st. edge  Steel  STD CHS 1200, 30
Roof tangential  Steel  STD CHS 400, 20
Roof radial  Steel  STD C 300
Braces roof  Steel  STD C 200
Ring roof  Steel  STD CHS 1200, 30

Shape
The shape of the stadium is depicted in figure 105 and 106. The following grid and elements are used:
- 48 tangential elements
- Horizontal ring elements
- All elements are beams

The stadium is supported by a foundation, schematised with pin supports at ground level. All connections are rigid connections. In reality the connections will be party hinged.

* A beam element is a two-noded element that models axial, bending and torsional effects. Shear deformations are included when calculating deflections.
Output
First of all the displacements are checked to verify the validity of the values of the forces. For every check two situations are shown. The deformation due to dead weight and the deformation due to public loading. Per item of investigation the same colour scale is used to be able to compare the results due to different load cases.

> Deformation
The deflected shape of the structure is depicted in figure 109 and 110 and is quantified in figure 111 and 112. It can be seen that the grandstand along the long edge moves backwards. The roof structure moves upward and pushes the grandstand along the short edges inside. The whole stadium gets squeezed together at the corners.

The circular oculus gets a bean shape. This contradiction in movements in the roof caused by the movement of the grandstand causes large bending forces along the edge of the opening. The whole structure gets squeezed together from the short edges.

Max displacement due to dead weight; 2.5m
Max displacement due to public load; 1.5m
Total displacement (SLS); 4.0m

Displacements of the roof structure are large, displacements of the grandstand are reduced a lot due to the added stiffness of the roof structure.
> **Axial force**

The axial forces in the structure are shown in figure 113. The horizontal ring forces are clearly present along the long edges of the grandstand and are transferred to the foundation via bracing in the corner structures. Large compression forces arise along the outer boundary of the stadium along the long edges. This is due to the squeezing of the stadium together in this direction. The backwards movement of the grandstand along the long edge of the stadium together causes the squeeze action and also contributes to the tension present along the upper boundary of the grandstand along the short edge.

The way the stadium deforms disturbs the natural compression ring of the roof. Now it can be seen that one side is in compression while the opposite sides are in tension. Within the corners of the roof, the forces are transferred through the braces by compression and tension.

From the visualisation of axial forces in the structure it can be seen that radial tension forces follow the curved shape of the structure rather than going around following a horizontal path.

> **Bending moments**

Opposite displacements occurring in the roof (figure 109) cause large bending moments in the inner ring of the roof (figure 114 and 115). The relative slack edge of the oculus has to withstand the deformations due to loading which causes large bending moments. In general it can be concluded that because the roof is a shell structure itself and has its own natural displacements differing from the displacements of the grandstand, large forces arise because of these opposing forces.
III - Minimal surface roof
This structure has a minimal surface roof. Radial elements in the roof are connected together with a central circle, being the oculus. This roof is based on the shortest way of forces from one side of the stadium to the other side, with an oculus in the middle of the roof. When tensioning a membrane over the edge of the stadium a similar shape is achieved. This shape is achieved with a surface relaxation method. Ideally this roof structure is suitable for a cable roof covered with membrane. The structure is created with tangential elements spanning from the edges to the inner ellipse connecting these elements together.

Input
Section properties:
Radial Steel STD C 300
Tangential Steel STD RHS 1200, 600, 30, 30
Braces Steel STD C 400
Roof tangential Steel STD C 400
Roof braces Steel STD C 400
Roof ring Steel STD CHS 1600, 20

Shape
The shape of the stadium with a minimal surface roof is depicted in figure 116. The same grid is retained and a radial division of 48 parts is applied. The entire structure consists of beam elements. Two variants of the roof grid are depicted in figure 117 and 118. The grid of a bicycle wheel is simulated with figure 118.

Output
The output of variant b is graphically shown in this section. A calculation of configuration a and c is included in the appendices A4.1 and A4.2.
**Variant b - braced roof**

To create more stiffness in plane, braces are added in the roof structure (figure 117). In this way the roof will act like a diaphragm.

> **Deformation**

Due to the braced roof the displacements become more similar to the shell roof. The roof gains more stiffness in plane and deforms with the movements of the grandstand parts.

Max displacement due to dead weight; 1.15m
Max displacement due to public load; 1.25m
Total displacement (SL); 2.40m

In general displacements are decreased compared to previous models. Displacements due to public load are larger compared to displacements due to dead weight. This situation is favourable regarding the possibility of applying a camber.

Displacements of the grandstand are not very much limited by the application of this type of roof.
Axial force
The grandstand side along the long edge shows clearly the horizontal ring forces and vertical compression forces (figure 123). The large grandstands fall backwards and cause tension forces in the inner ring in this direction. These tension forces are guided towards the edge via braces in the roof structure. Guidance of forces towards the foundation happens via braces in the grandstand structure. The roof provides stiffness to the structure and forces are transferred via a lattice frame.

Diaphragm action is visible by the transfer of forces through the roof structure via tension and compression. The grandstand along the short edge is subject to compression forces, because this part is lifted up by the movement of the large grandstand part.

Bending moments
Due to the non-stiffness of the inner ring of the roof, opposing displacements occur, leading to large bending moments.

The braced roof functions as a lattice frame in plane and functions therefore as a diaphragm. The total structure gets a lot more stiffness which can directly be seen when looked at the displacements, which are largely decreased.
IV - Combined shell edge with membrane roof

This model is a combination of the previous two variants. An edge on top of the grandstand will act as a shell. This edge has an equal height so it varies in width along the grandstand.

Input
section properties:
Radial Steel STD C 300
Tangential Steel STD RHS 1000, 400, 20, 20
Braces Steel STD C 300
Roof tangential Steel STD C 400
Roof braces Steel STD C 400
Roof ring Steel STD CHS 1600, 30
Roof edge ring Steel STD CHS 1000, 30

Shape
This type of roof is a combination between the former two. On top of the grandstand a shell shaped edge is placed to create equal height of the roof. From this edge on a minimal surface roof is applied which covers the stadium. Due to the equality of height this roof has a symmetric elliptical shape which should act like a bicycle wheel.

The shell roof needs a lot of material when the roof is performed as an entire shell structure. The membrane roof has a large sag due to the deflection naturally going down. The idea within this combined structure is to lift the membrane roof and minimise the material to be used by providing just a shell edge instead of a total roof.
> Deformation

The deflected shape of this concept is different to the other structures. The roof structure is connected to the edge in its weak direction. This causes relative large deflections of the roof structure. The sag of the roof in this design is not much influenced by the movements of the grandstand. This causes mainly downward movement due to dead weight and public load.

Max displacement due to dead weight; 3.2m
Max displacement due to public load; 1.0m
Total displacement (SLS); 4.2
> Axial force
From figure 131 it can be seen that the roof structure acts like a ring; the outer ring is in compression, while the inner ring is in tension. Forces are transferred through the roof via compression and tension in the braces.

> Bending moments
The amount of bending moments in the structure is similar to what we saw before. Bending moments (myy) are present in the vertical elements of the grandstand (figure 132). Around the oculus in the roof, bending is largest due to dead weight. The structure is very slack and the ring around the oculus has to withstand the movements due to loading. Figure 133 shows bending in z-direction.
12.5 CONCLUSIONS
From the results it can be concluded that adding a roof to the stadium has structural advantages above creating a stand alone grandstand combined with a roof as a structure standing apart.

The three different roofs were examined on different fields, the issues of attention are stated again below.

- behaviour of structure under loading
- difficulty to assemble
- amount of material used
- functionality (insolation/shelter)
- appearance

The models where only tested under dead weight and public loading so this is not reality yet. But before going into more detail, the design with the best future possibilities will be chosen to use for further modelling.

Regarding the forces in the structure differences are observed. The main differences are visible in the way and magnitude of deflection between the different roof types. Because safety is a very important issue, deflection is an important measure to minimise within limits. Limitation of 0,006 * l for the grandstand are not met but the structure with the best behaviour will be modelled and adjusted to meet these requirements.

The deflection of the combined roof differs a lot compared to the other two types. The roof seems to behave like a structure on itself, while the other two roofs are largely influenced by the deflection of the grandstand.

The desired advantages of a shell edge for creating an equal height for the roof structure are not making a large difference. This, together with the knowledge of the stadium shape differing from the original design by the conoid cutting of the roof, makes this roof less appropriate to the wanted qualities.

Regarding assembly the amount and types of elements are of importance even as the shape of the structure and the possibilities of assembly within this shape. The minimal surface roof is based on a minimal surface within the boundaries of the upper edge of the grandstand and the oculus of the roof. The other two types have a larger surface which will mean more elements.

Insolation of the pitch is very important in case of the use of natural grass. Because is is very common to use natural grass, this aspect within functionality should be considered. In advance it was mentioned that the convex roof causes a lot of shading on the pitch.

The main function of the roof is providing shelter to the spectators. A large upward angle of the roof provides less shelter because rain enters the stadium more easily.

In short
The shell roof will be eliminated because of functional reasons. Too much shading occurs at the pitch which will not stimulate growth of the natural grass.

The combined roof has some advantages because of equal height that creates more symmetric loading in the roof structure, but more difficulty regarding assembly does not outweigh these advantages. Regarding functionality (shading and shelter) both the minimal surface roof and the combined roof have the same qualities.

From the above it can be concluded that a minimal surface roof fits the best within the criteria and behaviour under loading. Within this shape, an optimal grid will be developed and the whole structure will be examined in more detail.

Due to the presence of compression in the roof structure, the original idea of applying a tensioned cable roof will not be able to be used.

The minimal surface roof will be used for further research (figure 134).
Structural design

The structural design deals with the calculation of the final model and the development of the stadium on behalf of static behaviour, dynamic behaviour and materialisation of the stadium. A translation will be made from the model in GSA to a real structure.
The previous part examined the structural behaviour of the grandstand itself and three different types of roofs. Based on the results of these models, a final slightly adjusted model will be examined in more detail.

13.1 SHAPE
At the start of modelling a few topics were presented to judge the different models. The bicycle wheel shows good results on deflections and, because of the minimal surface shape a limitation of material is achieved. An alternative on this model shows a different configuration of elements in the roof which has good qualities. By connecting the separate elements at their connections, a grid arises. Element lengths are limited which is favourable for buckling. To create more in plane stiffness, radial elements are added so a triangular grid arises (figures 136 and 137).

A downward curved roof has more favourable forces, because the sideward forces to take up the dead load are smaller (figure 135). On the other hand this causes bad sight on the 18m point above the pitch due to the low roof. To solve this, the total roof is lifted a few metres to create space for the roof to hang down and at the same time provide more space for installations within the extra triangular shape that arises at the back of the grandstands. This solution does not influence the appearance of the total stadium except for a small enlargement.

Because tension and compression are present in the roof structure, creating a cable roof is not an option. Because of the asymmetric shape and height of the grandstand parts, the whole structure gets squeezed together, which causes tension in one side and compression in the opposite sides. The compression might be limited by bringing the roof structure under a lot of tension, to withstand compression forces. However this is a very costly process and labour intensive regarding the demountable aspect of the stadium.

This is the reason why the roof in its final configuration has a grid, so compression elements have limited lengths which prevents them from buckling.
13.2 CALCULATION
For calculation all loads as mentioned in table 11 and all load combinations of table 12 are taken into account. This means large wind uplift will be present on the roof structure. Two different variant will be elaborated regarding deflections; the first using section dimensions with a result to limit deflections. The second to design the most efficient structure regarding stresses in the steel.

Variant 1 - design to limit deflection of the roof
Input (1)
Section dimensions
Radial  Steel  STD C 400
Tangential Steel  STD RHS 3000, 1000, 50, 50
Braces  Steel  STD C 400
Grandst. edge Steel  STD CHS 2000, 40
Roof braces Steel  STD CHS 600, 50
Roof tangential Steel  STD CHS 600, 50
Roof ring Steel  STD CHS 2500, 50
Constr. edge Steel  STD CHS 600, 50

*These are in fact not very realistic dimensions to use in reality, but this gives an indications of the amount of steel needed, without using trusses for input.

Output (2)
> Deflections
As mentioned in the list of demands and preferences the demand regarding deflection of the grandstand is limited to 0.006*l, which equates to 0.006 * 50.0m = 300mm.

The roof structure does not have demands regarding a safe feeling of spectators, but is primarily limited by the sight on the pitch; all spectators should have non-obstructed view on a point 18 metres above the centre of the pitch. The concave shape of the roof gains structural stiffness by adding more curvature (more concave). On the other hand, this shape is limited because of the view of the spectators.
**Variant 2 - design for an efficient structure regarding stresses**

**Input (2)**

- Section dimensions:
  - Radial: Steel STD CHS 300, 25
  - Tangential: Steel STD RHS 2500, 1000, 40, 40
  - Braces: Steel STD CHS 300, 25
  - Grandst. edge: Steel STD CHS 600, 40
  - Roof braces: Steel STD CHS 600, 40
  - Roof tangential: Steel STD CHS 400, 30
  - Roof ring: Steel STD CHS 1000, 50
  - Constr. edge: Steel STD CHS 600, 50

**Output (2)**

> **Deflections**

From figure 141 to 143 it can be seen that wind uplift results in large upward movements of the roof structure, because it behaves very slack. Using the most slender dimensions concerning axial forces to take up, this results in large deflections because the structure in its shape is not very stiff. Stiffness needs to be gained from profile dimensions in this case, which is an inefficient way of designing.

Wind is taken into account to a very severe quantity. The value for wind velocity (29.5 m/s) occurs only once in 50 years. Regarding reference time and return time of extreme wind velocities, reduction on wind loading can be applied to create a more favourable situation (Steenbergen 2011).


**Reduced wind loading**

Depending on the reference period of a building, a correction may be applied to the extreme value of a uniformly distributed variable load. According to the standard NEN 6702 this correction $\psi_t$ amounts 0.83 with the knowledge that wind loading has a $\psi_r$ of 0.6 and using a reference period of 1 year. A reference period of 4 months is not included within this standard, but will logically result in a larger reduction factor $\psi_t$ (NEN 6702:2001; table 4).

The fundamental value of wind velocity as used (29.5 m/s) is based on a return time of 50 years. Comparing this with a return time of ten years (the extreme value occurring once in ten years) a reduction in wind velocity is achieved. Looking at the wind velocity in Groningen, based on a return time of ten years the wind velocity amounts 25.3 compared to a value of 28.4 returning once in 50 years (Wieringa et al. 1983). This is a reduction of almost 11%. The reduction of basic wind velocity is included in the Eurocode with the factor $c_{\text{prob}}$. The 10 minute mean wind velocity with a probability of exceeding $p$, is achieved by multiplying the basic wind velocity with the probability factor $c_{\text{prob}}$. $c_{\text{prob}}$ is calculated with formula (1).

$$c_{\text{prob}} = \left( \frac{1-K^* \ln (-\ln(1-p))}{1-K^* \ln (-\ln(0.98))} \right)^n \tag{1}$$

$K = \text{shape parameter}; 0.2$

$n = \text{exponent}; 0.5$

$p = \text{probability of exceedance a year (1/return time)}$

Applied to several return times, reduced basic wind velocities are listed in table 13. This table shows a wind velocity of 20.2 m/s has a probability of exceedence once a year.

Besides the above mentioned issues, the stadium will be used during match seasons (during summertimes). The occurrence of severe storms in The Netherlands is more likely to occur from August to April, rather than during summer months (KNMI 2007).

Summarised, a reduction is possible by reducing the used value due to reference period and seasonal factors. On the other hand a correction can be applied in fundamental load combinations.

With the above measures, a basic wind velocity of 20 m/s will be used for further design. This is a rather optimistic value to use because the chance of exceedence during use is present, but, the roof will be designed in way the covering membrane can be rolled up so the wind loading decreases enormously. Because this value is in the formula for calculating the peak velocity pressure to the second power, this will have a large influence on the total wind load acting on the stadium.

**Mean wind**

$v_b = 20.0 \text{ m/s}$

$v_m(z) = 0.156 \times \ln \left( \frac{z}{0.003} \right) \times 1.0 \times 20.0$

$v_m(z) = 3.12 \times \ln(z/0.003)$

$v_m(30) = 28.7 \text{ m/s}$

**Peak velocity pressure**

$q_p(z) = (1+7I_v(z)) \times \frac{1}{2} \times \rho \times v_m^2(z)$

$I_v(30) = 0.1$

$\rho = 1.25 \text{ kg/m}$

$v_m(30) = 28.7 \text{ m/s}$

$q_p(30) = (1+7*0.1) \times \frac{1}{2} \times 1.25 \times 28.7^2$

$q_p(30) = 0.88 \text{ kN/m}^2$

---

$^1$ Although this stadium is of temporary nature, and will be used repeatedly for a period of four months, it should be questioned if a reference period less than 15 years can be applied.

---

**Table 13** Calculation of cprob for different return times

<table>
<thead>
<tr>
<th>return time</th>
<th>50</th>
<th>20</th>
<th>15</th>
<th>10</th>
<th>5</th>
<th>2</th>
<th>1.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>probability (p)</td>
<td>0.02</td>
<td>0.05</td>
<td>0.07</td>
<td>0.1</td>
<td>0.2</td>
<td>0.5</td>
<td>0.9</td>
</tr>
<tr>
<td>$c_{\text{prob}}$</td>
<td>1</td>
<td>0.95</td>
<td>0.93</td>
<td>0.90</td>
<td>0.85</td>
<td>0.78</td>
<td>0.68</td>
</tr>
<tr>
<td>$v_b \text{ reduced}$</td>
<td>29.5</td>
<td>27.9</td>
<td>27.3</td>
<td>26.6</td>
<td>25.2</td>
<td>22.9</td>
<td>20.2</td>
</tr>
</tbody>
</table>
Output due to reduced wind loading

Axial force

The total structure is modelled in steel. As a starting point S355 will be used, so stresses with a maximum of 355N/mm² are allowed to create the most efficient structure regarding material.

The governing load combination in ultimate limit state is reached when the public load is taken instantaneous and the wind with a maximum safety factor of 1.5 (reduction is taken into account by lowering the basic wind velocity, so the safety factor will be 1.5 as used before). Axial forces from this combination are depicted in figures 144 to 146.

Prior to elaboration of all forces in the model, first of all the dynamic behaviour of this model will be checked. Theory on dynamics and research on dynamic behaviour of the stadium is presented in the next section.
13.3 DYNAMIC BEHAVIOUR

The dynamic behaviour of the stadium is very important since it is subjected to both crowd and dynamic wind loads. To investigate the dynamic behaviour of the stadium, a dynamic analysis will be performed on the stadium structure. Together with theory on dynamic behaviour, the outcome will be explained.

The following quote of Reynolds (2002: 1037) illustrates the influence of design on dynamic behaviour:

“Sports stadia, like many other civil engineering structures, are being pushed to their limits in terms of slenderness and structural efficiency. This normally has benefits such as increased capacities and improved lines of sight for spectators. However, the increased use of more slender stadium structures is causing concern as they may be susceptible to excitation by the increasingly lively spectators that they accommodate.”

Theory

Before elaboration of the behaviour of the model in Oasys GSA, a brief introduction to the theory of dynamic behaviour of structures is given with the help of some formulas.

Besides static behaviour of a structure, dynamic behaviour is a very important issue because it explains the behaviour of a structure under dynamic loads. Dynamic loads acting on the stadium are wind loads and public loads.

A system, subject to a certain dynamic load, is brought into motion; this motion is described by a second order differential equation:

\[ mx'' + cx' + kx = F(t) \]  \hspace{1cm} (1)

- \( m \) mass
- \( c \) viscous damping coefficient
- \( k \) stiffness
- \( x \) absolute displacement of the mass

Solutions of this formula represent modes of frequency of a system, starting with the fundamental frequency being (derived from the fundamental period of the oscillation):

\[ f = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \]  \hspace{1cm} (2)

- \( k \) stiffness
- \( m \) mass

An increased stiffness leads to a larger natural frequency, while an increase of mass decreases the fundamental frequency. The effect of mass is twofold; a decrease causes a higher fundamental frequency but mass also influences on the motion of a system (formula 1); a more lightweight structure is more easily brought into motion than a heavy structure.

The structural response of system depends on the ratio of the frequency of the load to the structural frequency. This ratio having a value 1 causes resonance.

Resonance is the phenomenon of amplification of a free wave or oscillation of a system by a forced wave or oscillation of exactly equal period. The forced wave may arise from an impressed force upon the system or from a boundary condition. A deviation between these periods causes less magnification. This magnification is taken into account with a factor \( \csc \theta \).

Due to an exchange of energy with the surroundings, movements in a system occur. Reaction of the system due to externally applied loads is called the response of a system.

The response of a structure depends on the transfer function, also called the frequency-response function. The spectrum of the dynamic load combined with the frequency-response function of the system, determines the reaction of the system to the load. This phenomena is illustrated with figure 147. The energy of the load combined with the frequency-response determines the response of the system. Response-frequencies equal to frequencies of the load spectrum cause dynamic amplifications.
Whenever a peak in the load spectrum corresponds with a peak in the frequency-response function, amplification of oscillation of the system occurs due to oscillation of exactly equal periods. This phenomenon is called resonance and is depicted in figure 148. This figure shows the ratio between dynamic displacements compared to static displacements on the vertical axis and the ratio between dynamic load frequency to the response frequency of the structure. Due to dynamic excitation of the structure in its response frequency enlarged displacements occur.

Wind load
Wind causes both static and dynamic load, causing a system to vibrate. Dynamic wind load is caused by vortices. Due to sharp edges in a structure, release of wind from the structure occurs. The frequency of these releasing vortices is important to calculate the impact of this dynamic wind load to the structure.

Wind pressure is calculated with the following formula:

$$qw = \frac{1}{2} \rho v^2 (1 + 7I) \cdot ct \cdot c_{sd}$$

Pressure of the wind depends on mean wind ‘v’ and wind turbulence ‘I’. The mean wind is based on the basic wind velocity and the terrain (orography and roughness). Turbulence occurs due to obstacles in the wind flow, such as trees and buildings. All these factors together lead to the peak velocity pressure at a certain location. The factor $c_{sd}$ takes into account the dynamic amplification. The effect of driving vortices compared to the global frequency of the building depends on the transfer function.

Calculation of the natural frequency with this formula (1) shows that the mass stays within the formula and influences the natural frequency, while the load applied to the structure is not within the equation. The way spectators should be modelled in GSA is explained in the following section.
DYNAMIC BEHAVIOUR OF THE MODEL
To investigate the dynamic behaviour of the stadium a modal P-delta analysis is performed in Oasys GSA (1). Mode shapes of the structure together with dynamic loads acting on the structure are used to elaborate the structural response of the system to dynamic loads.

The analysis is performed with an empty stadium. Influence of the crowd load on the response of the structure will be discussed later on. Dead weight of the secondary structure is added as a mass that will resonate with the structure.

Mode shapes
Graphic presentations of the modes of frequency of the stadium are presented in figures 149-154. Each mode has a different frequency, starting with the first mode occurring at the lowest frequency. Note that displacements are normalized to a displacement of 1 metre showing the relationship between movements but not being the real displacements. 

The first mode of the modal analysis is the fundamental frequency of the system. From figure 149 it can be concluded that the first mode in this case has a frequency of 0.46 Hz. This mode shows an upward movement of the roof and the grandstand moving down a bit. Mode shapes 2, 3 and 4 are in the same mode family, all presenting a torsional mode shape (figure 150-152); one half of the roof structure moves up while the other half down.

Mode 1; 0.46 Hz
Mode 2; 0.55 Hz
Mode 3; 0.57 Hz
Mode 4; 0.78 Hz
Mode 5; 0.82 Hz
Mode 6; 0.82 Hz

1) A modal analysis is used to determine the dynamic characteristic of a structure. The results of a modal analysis are a set of natural frequencies and the accompanying mode shapes, which represent free vibration of the structure without reference to any loads (Oasys 2010).

A modal P-delta analysis is similar to a modal analysis, only the deflected shape is the mode shape. The same model (with a few changes) can be used for both. The difference in the case of P-delta analyses is that the stiffness is modified to include geometric stiffness effects.
opposite part moves down. Mode shape 5 shows a large vertical and horizontal displacement of the grandstand; one half falls down while the opposing half moves up. The vertical displacement is about twice as big as the horizontal displacement.

Frequencies of different mode shapes are very close to each other; this has to do with the symmetry of the stadium structure. Within the roof structure, a lot of possible mode shapes are conceivable, all having a slightly different frequency.

**Influence of crowd loads to the dynamic behaviour of the structure**

Unlike added weight due to the secondary structure, the crowd cannot be represented solely as a mass. Research shows significant increase in the damping capacity of a system due to a stationary crowd (Ellis 2000). This phenomenon is depicted in figure 155. The full stadium shows a significant increase in the damping capacity compared to the empty stadium.

However, the critical load situation applies when the total crowd is jumping and there is no interaction with the structure. In this situation, the crowd is acting as a load. For this situation the characteristics of the empty stadium are required to determine the structural response.

The above explains the behaviour of the stadium in two different situations. First of all the situation in which just a small group of spectators is jumping. Assuming a full stadium, the dynamic excitation of this small group will be diminished by the damping effect of the rest of the (stationary) crowd.

The effects of this situation should be calculated for an accurate assessment of the structure due to this effect. The modelling of a partial crowd jumping and the damping effects of the stationary crowd are very complex and do not lie within the scope of this project.

The second (governing) situation when all of a crowd is jumping is more critical to the stadium. This situation is most likely to occur when the stadium will be used during concerts. No additional damping from the crowd is to be applied, this means structural response of the stadium is determined by the characteristics of an empty stadium, as is represented in figures 149 to 154. A good estimation of the dynamic response of the structure due to spectators' movements is achieved with the help of load spectra of a moving crowd.

Figures 156 to 159 show dynamic loads and accompanying load spectra of upper-body movements, while figure 160 to 163 show dynamic loads and load spectra of vertical excitation such as foot stamping and in place jumping.

Continuous and periodic dynamic loads can result in a very bad influence on the safety and serviceability of a structure, such as the occurrence of resonance.

**Impact of jumping crowd to a structure is simplified to:**

\[
F = ma 
\]

\[
m = \text{mass} \\
 a = \text{acceleration} 
\]
Dynamic load due to swaying back and forth (Kim 2009)

Load spectrum of swaying back and forth

Load spectrum of swaying sideways

Load spectrum of jumping in place

Depending on the mass of jumping crowd and the energy it is accompanied by, the impact on the structure is determined. Figure 162 shows jumping in place has the highest impact energy compared to other movements. 80 kgf equals 0.78 kN in standard units.

From the above figures (Kim 2009) (figures 156 to 163) the following can be concluded. Peaks in the load spectrum associated with footstamping are at 1.7Hz, 3.4Hz and 5.1Hz. The load spectrum of jumping in place shows a peak at 1.7Hz, having the largest dynamic load among dynamic loads induced by spectators.

Regarding upper-body movements the peak load amplitude of swaying back and forth lies around 1.4Hz, while a dominant frequency of the dynamic load due to swaying sideways is 1.0Hz.
Effect of a jumping crowd
A critical situation arises when the grandstand is excited by a dynamic load in its natural frequency. Because this is a situation that has probability of occurrence it needs further investigation.

The grandstand is schematised as an non-damped one mass-spring system. Because damping of the current structure is low, the difference with a damped situation will be small. The system is illustrated in figure 164.

\[ F(t) = m \cdot \text{jumping crowd load as a function in time} \]

\[ k = \text{stiffness of the system, chosen such that } \omega_0 = \sqrt{\frac{k}{m}} \]

Table 14 Data used for the calculation of the effect of a small group jumping

<table>
<thead>
<tr>
<th>Data</th>
<th>Calculation</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>jumping frequency of a spectator (f)</td>
<td>1 / f</td>
<td>1.0</td>
<td>Hz</td>
</tr>
<tr>
<td>period (T)</td>
<td>1 / f</td>
<td>1.0</td>
<td>s</td>
</tr>
<tr>
<td>fundamental frequency ((\omega_0))</td>
<td>(2\pi / T)</td>
<td>6.28</td>
<td>rad/s</td>
</tr>
<tr>
<td>cooperating mass (m)</td>
<td>1/2 * total mass (Steenbergen 2011) (\dagger)</td>
<td>2.35*10^6</td>
<td>kg</td>
</tr>
<tr>
<td>stiffness (k) derived from (\omega_0 = \sqrt{\frac{k}{m}})</td>
<td>(m \cdot \omega_0^2)</td>
<td>9.3*10^7</td>
<td>N/m</td>
</tr>
</tbody>
</table>

Data on this schema are presented in table 14. The jumping of the spectators is modelled as a pulse series (Steenbergen 2011) (figure 165). Every pulse adds an energy \(S_0\) to the system. This energy is calculated with the following formula:

\[ S_0 = m_s \cdot v_0^2 \quad [Ns] \quad (4) \]

With the data of table 14 and figure 166 this becomes: \(S_0 = 90 \times 1.4 = 126 \ Ns\)

Every pulse has an excitation on the stadium causing a displacement \(u\) of the system. A summation of the response of all separate pulses is the response of the system (figure 167). Because the schematization is based on an undamped system, the amplitude increases in time.

\[ \text{Energy balance} \]

\[ m_s \cdot g \cdot h = \frac{1}{2} \cdot m_s \cdot v_0^2 (1) \]

\[ m_s = \text{mass spectator; } 90 \ \text{kg} \]

\[ g = \text{gravity; } 9.81 \ \text{m/s}^2 \]

\[ h = \text{height of jump; } 0.1 \ \text{m} \]

From equation (1) the velocity in which spectators excite the system is calculated.

\[ v_0 = \sqrt{(m_s \cdot g \cdot h)/(1/2 \cdot m_s)} = \sqrt{(2gh)} = 1.4 \ \text{m/s} \]

A check on the cooperating mass in reality should be made by deriving the stiffness \(k\) from the model in GSA. Knowing \(k\) and \(\omega_0\), the cooperating mass can be calculated. This might be more than assumed here.
Peoples’ discomfort is measured by the acceleration of movements. Accelerations above 2.5 m/s² cause unacceptable discomfort (Heinemeyer 2009). By differentiating the formula of displacement twice, the acceleration of the system is described.

\[ a(t) = u''(t) = - \frac{S_0}{k} \omega_0^3 \cdot \sin(\omega_0 t) \]  (6)

Based on the group of 100 people jumping the acceleration of the movements of the stadium over time is depicted in figure 169.

Figure 169 shows an acceleration of 2.5 m/s² after 80 seconds of jumping.

The equation of movement of the system due to a pulse load is described by formula (5) (Blaauwendraad 2010).

\[ u(t) = \frac{S}{k} \cdot \omega_0 \cdot \sin(\omega_0 t) \]  (5)

The response of the system depends on the duration of jumping together with the energy of the jumping crowd. The displacement \( u \) is represented in a graph showing the response of the system over a time of two minutes (figure 168).

Figure 168 shows a harmonic response with an increased amplitude over time. After two minutes of jumping with a group of 100 people the stadium shows an amplitude of 0.1 m. Note that this response does not take into account damping of the system or damping of the stationary crowd, so this graph shows an unfavourable view of reality.

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\[ u(t) = \frac{S}{k} \cdot \omega_0 \cdot \sin(\omega_0 t) \]  (5)

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Figure 168 shows a harmonic response with an increased amplitude over time. After two minutes of jumping with a group of 100 people the stadium shows an amplitude of 0.1 m. Note that this response does not take into account damping of the system or damping of the stationary crowd, so this graph shows an unfavourable view of reality.
Wind uplift is caused by the release of vortices from the structure, perpendicular to the roof surface, known as vortices of Von Karman. The release of each vortex is accompanied by and underpressure. The frequency of these vortices is calculated with the following formula (Vandepitte 2003):

\[ f = \frac{St \cdot v}{b} \]

where:
- \( St \) = number of Strouhal
- \( v \) = wind velocity
- \( b \) = transverse dimension perpendicular to the wind

It can be concluded that a small group of jumping spectators can have a large effect on the response of the stadium. However, these results will be less in reality due to the damping capacity of the stadium itself together with the damping of the stationary crowd (which is large when only a small group is jumping).

**Influence of wind loads to the dynamic behaviour of the structure**

Regarding wind, the effect on the structure is three-fold. First of all, the structure should have sufficient strength to resist wind-induced forces, secondly, the structure must have enough stiffness to satisfy spectators’ comfort and serviceability criteria and third, wind may produce dynamic response of the stadium. The third effect may amplify first two effects (Boggs 2006). Most important influence is the effect of wind uplift on the roof structure, because the roof structure behaves very slack in this direction.

The number of Strouhal is determined by figure 170. Using a width \( (d) \) of 180m and a height \( (b) \) of 30m, the ratio \( d/b \) becomes 6, resulting in \( St = 0.106 \) (interpolated between \( d/b \) being 5 and 10).

The maximum wind velocity being \( v = 29.0 \text{ m/s} \), and \( b \) being 30m, this results in a release frequency of:

\[ f = \frac{0.106 \cdot 29}{30.0} = 0.1 \text{ Hz} \]

From figure 171 it shows that the wind spectrum in horizontal direction has a peak at 0.05 Hz.

The structural response of the stadium due to the dynamic loads due to wind and spectators is discussed next.
Structural response

To investigate critical situations for the stadium structure, a comparison will be made on natural frequencies of different parts of the structure and the load spectrum of applied loads acting at these parts. Whenever the frequency spectrum of the applied load has the same values as the natural frequency of the structure in the same direction as the load, a problem arises because resonance may occur.

Response of roof structure (horizontal)

Wind loads act horizontally on the roof structure. The load spectrum of wind waves shows a peak at 0.05Hz. Although the horizontal frequency of the roof structure is hard to determine this is far below the fundamental frequency of the stadium and will not cause problems.

Response of the roof structure (vertical)

Vortices of Von Karman cause vertical dynamic excitation of the roof structure at a frequency of 0.1Hz. The lowest frequency of the roof structure amounts 0.46Hz so no problems occur.

Response of the grandstand (horizontal)

Dynamic loads acting on the grandstand are wind and public loads. Wind waves have frequencies of about 0.05Hz. Dynamic loads due to upper body swinging of spectators acts in horizontal direction. Peaks in the load spectrum are at 1.0Hz and 1.4Hz (figure 157 and 159).

Table 15  Overview of maximum forces occurring in the structure and corresponding profile types (all values are design values resulting from ULS)

<table>
<thead>
<tr>
<th></th>
<th>frequency</th>
<th>structure [Hz]</th>
<th>spectrum load [Hz]</th>
<th>problem</th>
</tr>
</thead>
<tbody>
<tr>
<td>roof</td>
<td>(1)*</td>
<td>h ≥ 0.82</td>
<td>0.05</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>(2)</td>
<td>v ≥ 0.46</td>
<td>0.1</td>
<td>no</td>
</tr>
<tr>
<td>grandstand</td>
<td>(3)</td>
<td>h ≥ 0.82</td>
<td>1.0, 1.4</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>(4)</td>
<td>v ≥ 0.46</td>
<td>1.7, 3.4, 5.1</td>
<td>yes</td>
</tr>
</tbody>
</table>

* The number refers to the number in figure 172.

At mode 5, having a frequency of 0.82Hz, significant horizontal displacement of the grandstand occurs. This is a critical situation because resonance may occur when amplification of oscillations arises due to insufficient damping capacity of the stadium. Enough dynamic load should be present to create the total stadium bringing in vibration.

Response of the grandstand (vertical)

In vertical direction spectators cause dynamic loading due to in place jumping and footstamping. Load spectra associated with vertical jumping in place and foot stamping have peaks at 1.7Hz, 3.4Hz and 5.1Hz (figure 161 and 163). Together with a large dynamic load this may cause problems when to total crowd start jumping because frequencies of the grandstand are in that range as well.
13.4 CONCLUSIONS ON FINAL MODEL
With the help of the output of the model and the knowledge on dynamics, the behaviour of the structure will be explained and conclusions are drawn regarding this model.

To understand why the natural frequency is this low, an explanation is given on the model. Referring to the strength of a shell structure, double curvature is very important to achieve stiffness in a shell structure. Radial curvature is present due to curvature around the pitch, however the curvature along the edges is very gentle. Curvature in tangential direction is achieved by the parabolic shape of the grandstand due to ideal lines of sight. This is also a very gentle curvature. Because of double curvature being almost absent, choosing different profile types will not contribute very much to the stiffness in the shell. In line with the idea of shell action, the best way of increasing stiffness is by increasing curvature. Besides increasing stiffness by means of improved shell action other measures are possible.

The large deflections found before are already an indication of the weakness of the structure. Although the deflections of the grandstand are within limits regarding demands on maximal deflections (0,006*l), this deflection is not realistic for a large cantilever as present at the grandstand (=50m). Spectators will experience unsafe feelings which is not wanted. Especially deflections of the roof structure are too large.

Regarding the roof structure it is concluded that the structure behaves very slack which is mainly a problem regarding the wind uplift that is quite large due to the sharp edges of the roof.

To take a next design step in achieving a structural design that meets all demands, possible solutions and its measures are listed in the next paragraph.

*Dynamic behaviour*
Frequencies of dynamic loads applied to the structure are close or equal to frequencies in load spectrum of stadium structure.

Problems arise in case of:
- resonance without (sufficient) damping
- dynamic excitation of entire crowd
- stresses due to dynamic excitation exceeds maximum allowable stress

No problems when:
- small part of stadium performs dynamic excitation, because stationary crowd increases damping capacity of the structure (in this case more research should be done on the negative influences of the mass of spectators to the structural response of the system).
- entire stationary crowd

Problems can be avoided by:
- design for higher dynamic stresses (warn spectator at entrance; safety aspect)
- realise higher damping; resonance will not lead to dangerous situations when enough damping capacity is realised (apply dampers and use energy dissipating elements).
- monitoring dynamic response of the stadium; intervene when structure is excited in natural frequency with large impact.
13.5 MEASURES FOR OPTIMISATION ON FINAL MODEL

*Because the main problem arising with the final model include the dynamic behaviour of the structure, optimisations are regarding this topic.*

Parameters that are of influence on the dynamic behaviour are mass, damping and stiffness. From the formula \( f = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \), it can be concluded that the stiffness needs to be increased or the mass needs to be decreased in order to achieve higher values of natural frequency. The damping coefficient is a material dependent factor but can also be increased by applying dampers. Each of these three factors will be judged by their usefulness to the Lotus stadium.

Requirements on the dynamic behaviour are valid for the grandstand structure (not for the roof structure); solutions need to be based on improvements regarding the grandstand structure instead of the roof structure.

Reduce mass

The mass is inversely related to the natural frequency of the structure. Creating a more lightweight structure leads to an increase of the natural frequency. As was mentioned before, elements are grouped together, having mainly the same function. This means all elements on one group (radial, tangential, braced) have the same profile, which leads to overdimensioning at some places. On this topic, some weight reduction can be achieved, but this will not lead to enough increase of frequency. On the other hand a more lightweight structure is more easily brought in motion by dynamic loads.

It should be noted that adding *structural* mass can have positive influence on the structural behaviour of the model.

Previous calculations were all based on the characteristics of an empty stadium. In fact the mass of the crowd (although the crowd does not act solely as a mass) is cooperating mass regarding the behaviour of the structure. This phenomenon is not taken into account in calculations, which might lead to a more positive outcome compared to reality. A more accurate model should be used to model the contribution to the structural behaviour, together with an estimation of the damping capacity of the structure. This lies beyond the scope of this project but is definitely worth further examination.

Enlarge stiffness

Enlarging the stiffness will lead to higher natural frequencies. From the graphic statics we learned that forces are high due to the lack of curvature in the design. Most efficient forces are reached when an optimal shell structure is created. Because shell action is dependent on double curvature in this case, it is obvious that a lack of curvature leads to a structure that behaves slack and has low natural frequencies. A lot of measures can be taken to increase this stiffness of the structure, these measures are listed below.

> Enlarge curvature

Because shell stiffness is mainly depending on double curvature an increase in curvature should help to provide part of the extra stiffness needed to increase the natural frequency. From the method of graphic statics it is concluded that a stronger curvature leads to lower forces and creates more stiffness. Curvature in radial direction as well as in tangential direction is not very large in the present design, as was concluded earlier. An increase in radial curvature will influence the appearance of the stadium; the amount of seats will get smaller due to the demand of the 90m radius, which will also influence the undulating upper edge by getting less. A totally different solution would be to create additional curves in radial direction in the grandstand.

> Enlarge moment of inertia

The stiffness of an element is dependent of its moment of inertia. When the moment of inertia for the total model is increased this will create a lot of stiffness to the structure. Several ways to realise this are mentioned.

- Apply a double layered grandstand; by creating a
double layered grandstand an inner and outer shell are realised and when connected to each other together the moment of inertia will be very large (=truss principle).

- Apply gigantic concrete tangential elements to take up the compression forces. The bigger these elements are, the larger the I. Besides in increase of moment of inertia, the damping of concrete has higher values compared to steel. However, this solutions adds a lot of mass which has negative influences on the natural frequency.

> Additional elements
Adding additional elements is mainly accompanied by a change in appearance of the stadium. Because the appearance of the stadium is one of the most important properties of the stadium, following from an ideal stadium, this is in most cases not preferred for architectural reasons. The outer shape is set by the shape of the grandstand resulting from ideal lines of sight and optimal ‘C’ values. While the inner space needs to be without structural elements to avoid an obstructed view to the pitch.

- Add columns; columns are a direct support to the grandstand in vertical direction and will increase the natural frequency enormously.

> Use stiffness of roof
From the previous chapters we saw that the roof has a structural effect on the grandstand structure in a positive way. The roof structure can limit movements of the grandstand in a horizontal way. However, the direction of the movements of the spectators (and therefore the direction of vibrations) is in a vertical direction so this would not be effective because the roof structure will not limit translations of the grandstand in vertical direction.

- Close the oculus of the roof (less movement possible between opposite sides)
- There are no regulations on global natural frequencies of the roof structure. Resonance causing damage needs to be avoided but as long as its safe no measurements on increasing frequency hold. Closing the oculus will mainly have effect to the roof structure and not to the grandstand structure, while this is the structure that needs an enlarged frequency (above 5 Hz).

**Enlarge damping coefficient**
The damping coefficient is a material dependent factor and influences the natural frequency of a structure. Concrete has better damping values compared to steel, but adds a lot of weight which is negative. Increasing damping can also be done in an artificial way.

- Apply dampers; this will increase the natural frequency and has a positive effect on the amplification of oscillations due to resonance in the structure. Dampers could be applied at connections in the structure or can be applied in pre-manufactured elements to safe time during assembly.

**Choice**
From the measurements that are possible to increase the natural frequency, increasing the stiffness of the structure is a very effective way. What is the best way to realise this?

Besides the global shape of the stadium (curvature) also local changes in shape have effect on stiffness. As was mentioned stiffness is increased by increasing the moment of inertia of the element sections. A good example of increasing the moment of inertia in a very effective way is the use of a truss. Using this method within the stadium a double facade will be able to increase the stiffness significantly depending of the offset of the inner and outer layer of the shell. By coupling the inner shell to the outer shell a spaceframe is obtained.

The appearance is hardly effected by the use of a space frame. The shape of the stadium is still the same, although the total structure becomes a bit bigger.

Creating a spaceframe will lead to a lot more elements and an increase of material used. On the other hand elements can have smaller dimensions while still creating a larger moment of inertia, all by the offset of the facade.
A space frame or space structure is a truss-like, lightweight rigid structure constructed from interlocking struts in a geometric pattern. Space frames can be used to span large areas with few interior supports. Like the truss, a space frame is strong because of the inherent rigidity of the triangle; flexing loads (bending moments) are transmitted as tension and compression loads along the length of each strut.

13.6 IMPROVED MODEL

Following the measurements stated before, an improved model will be checked on its dynamic behaviour.

To realise the increased stiffness the inner- and outer shell should be structurally related to each other, which means good connections between these two shell needs to be applied. A common way to do so is using the grid of a spaceframe. There are a lot of possible ways to create a grid for a spaceframe, this is illustrated with figures 173 to 175.

The behaviour of the spaceframe is presented at the next pages.

Improvement A
• increase moment of inertia, wall thickness over all 3 metres (due to a horizontal offset of about 6 metres), connection via diagonals, creating a spaceframe.

Improvement B
• increase moment of inertia and curvature; outer layer has more curvature compared to inner layer. because offset is a function of the height, the offset is larger along the large grandstand and smaller in the corners. This creates more curvature tangentially but at the same time this measure increases the radial curvature slightly.
The two models that will be used for further research are depicted in figure 176 and 177. These figures show a section of the grandstand without the roof. The spaceframe model (figure 176) is developed as a real spaceframe in the computer. A horizontal offset of 6 metres is applied to realise this frame (this amounts to a perpendicular offset of 3 metres).

The double layered shell with a stronger curved outer layer (figure 177) is modelled a bit different. The outer layer is connected to the inner layer by means of tangential trusses, as is shown in the section. Due to the curvature of the outer shell being related to the height of the grandstand, a slightly stronger curvature in radial direction is achieved as well. This phenomenon is illustrated in figure 178, which shows a horizontal section halfway the grandstand.

Both models have double supports at the foundations to enlarge structural stiffness.

For now, the focus lies on improvement regarding the dynamic behaviour of the models. The output will mainly be on this topic to compare both models. The model of choice will be further elaborated and design regarding dimensions, assembly and a cost estimation.
Input
The input for both the spaceframe and the model with strongly curved outer shell are chosen to be almost consistent with each other to make a good comparison possible.

> spaceframe
The input as was used to calculated the dynamic behaviour of the grandstand constructed as a spaceframe are mentioned here.

<table>
<thead>
<tr>
<th>Material</th>
<th>Type</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>gr bracing</td>
<td>Steel</td>
<td>STD CHS 600, 30</td>
</tr>
<tr>
<td>gr vertical</td>
<td>Steel</td>
<td>STD CHS 1000, 40</td>
</tr>
<tr>
<td>gr horizontal</td>
<td>Steel</td>
<td>STD CHS 300, 25</td>
</tr>
<tr>
<td>roof braces</td>
<td>Steel</td>
<td>STD CHS 600, 30</td>
</tr>
<tr>
<td>roof tangential</td>
<td>Steel</td>
<td>STD CHS 400, 30</td>
</tr>
<tr>
<td>roof ring</td>
<td>Steel</td>
<td>STD CHS 2000, 700, 50, 50</td>
</tr>
<tr>
<td>gr edge</td>
<td>Steel</td>
<td>STD CHS 600, 30</td>
</tr>
<tr>
<td>constr edge</td>
<td>Steel</td>
<td>STD CHS 400, 25</td>
</tr>
<tr>
<td>hOuter</td>
<td>Steel</td>
<td>STD CHS 300, 25</td>
</tr>
<tr>
<td>vOuter</td>
<td>Steel</td>
<td>STD CHS 1000, 40</td>
</tr>
<tr>
<td>xOuter</td>
<td>Steel</td>
<td>STD CHS 300, 25</td>
</tr>
<tr>
<td>spiders</td>
<td>Steel</td>
<td>STD CHS 400, 30</td>
</tr>
</tbody>
</table>

> strongly curved outer shell
The input of this double layered shell is almost the same as the spaceframe model.

Dynamic behaviour - spaceframe
Mode shapes 1 to 8 are depicted in figure 179-186. The value of the first natural frequency has hardly changed due to using the same roof type and this mode affecting the vibrations of the roof structure.

The first mode really affecting the grandstand is mode 8 with a frequency of 1.02Hz. This means an increase of 0.6 (1.02 minus 0.46) compared to the single layered model.

From the modes as depicted it can be concluded that the natural frequency of the grandstand is still very much below the demand of at least 5Hz. Regarding damage to the structure due to resonance as a result of dynamic excitations from spectators, this is not an acceptable design in case no additional measures are applied.
Figure 187 shows the possible dangers in the structure by indicating response frequencies and load spectra at both the roof structure and the grandstand, horizontally and vertically.

Overview structural frequency vs load spectrum of applied loads

Mode 1; 0.50 Hz
Mode 2; 0.51 Hz
Mode 3; 0.57 Hz
Mode 4; 0.67 Hz
Mode 5; 0.70 Hz
Mode 6; 0.88 Hz
Mode 7; 0.88 Hz
Mode 8; 1.02 Hz
Dynamic behaviour - strongly curved outer shell

Modes of frequency of the model with a strongly curved outer shell compared to the inner shell are depicted in figures 188 to 195 starting at mode eight. Note that modes 1-7 are not shown; this is done because not much difference in shapes occurs compared to the spaceframe model, although frequencies affecting the grandstand start at higher values.

Mode 12 shows a vertical displacement of the grandstand at a frequency of 1.37Hz. This is close to the load spectrum of vertical dynamic crowd loads and should be investigated on its danger.

Mode shape 14 shows both horizontal and vertical displacements, also in the range of the spectrum of dynamic crowd loads in these directions.

This structure has gained a little stiffness compared to the spaceframe model although the demand of a frequency of 5Hz is not reached. The natural frequency of the structure should be increased or the response of the structure should be investigated in more detail regarding damping capacity and the sensitiveness to small groups of people jumping.
13.7 CONCLUSIONS

Structural

Strength
Regarding strength, no problems arise. When using S355, stresses are within limits without using extremely large dimensions. Because the model is based on groups of elements with the same kind of behaviour instead of all elements having the most optimal section properties, this means a margin for better performance. Because a spaceframe is used bending moments will be taken up by compression and tension in the elements. Except for the roof, where no stiffness out of plane is present, moments are not a problem. Stiffness out of plane for the roof needs to be designed for; by a slender structure with additional measures or by applying a large profile around the oculus. Because the slack roof, all opposing movements of the stadium structure show itself by large bending moments around the opening in the roof.

Stiffness
Within the spaceframe model, limitations on the sag of the grandstand are met. For the roof there are no special regulations on the sag, however the structure should not move too much because this will give an unsafe feeling to the spectators. Sag of the roof of 1 metre should be limited.

Stability
By bracing the total structure, in plane stiffness is created and side to side stability is provided for. The spaceframe model has lateral stiffness due to the application of diagonal connection between inner and outer layer. This is not the case with the more curved model, where trusses realise the offset to inner and outer layer and no diagonal connections are realised.

Dynamic behaviour
Although the stiffness of the stadium is increased by applying a large moment of inertia, natural frequencies of the stadium are still small due to the absence of enough structural stiffness.

Regarding dynamic behaviour the demand of 5 Hz is not met. Dynamic wind loads are not of danger to the structure, because the load spectrum is beyond the response-frequency of the structure.

Dynamic excitation of spectators has frequencies within the response spectrum of the stadium and will cause resonance if low damping capacities are present and all of the crowd starts jumping. Because of the fact a stationary crowd increased damping capacity of the system, jumping of small groups will most likely cause no problems.

Shape
From the beginning the shape of the structure has been the most important boundary condition for modelling. Based on ideal lines of sight and a maximum viewpoint from the centre of the pitch, the lotus shape arises as a natural shape following from these measures. Because from the lines of sight this shape is natural, the main focus was to find a structure within this shape. Regarding the dynamic behaviour of the stadium this shape does not provide a solution for increasing the stiffness till demands on this topic are met.

Another important aspect of the stadium is the transportability. All elements need to be transported preferably over the road. This limits the dimensions of all elements or modules. Although far-reaching measures need to be taken to get the structure within dynamic demands, the current adjusted model will be used to elaborate the assembly after materialisation.

Because dynamic behaviour is not extremely different in both models the assembly of the structure plays a major role in chosing the model for further research. Because the dimensions of the spaceframe and its uniformity in shape along the height, this model will be elaborated regarding dimensioning, assembly, transport and finance (figure 196).
Materialisation

Materialisation deals with the translation of the output of the model to a material to be applied together with its dimensions. The idea of the architecture is to create a modular volumetric element that contains seating elements and also provides, when connected to each other, the load bearing structure. These elements will be structurally connected by tensioned cables running around the stadium at a particular height. It is beyond the scope of the research to completely design a system based on this idea, this is why the focus will be on a wire frame model based on the results.

Further research should investigate the materialisation of the architectural model which can be based on results that are obtained here. Structural aspects regarding a model consisting of volumes together with post-tensioning are shortly stated in section 16.4. Detailing is limited to the design of the main connection principles. The connection between the roof and the grandstand is a very important one, and will be elaborated upon, in addition to the connection to the foundation. The connection between load bearing elements will also be designed. From the forces that need to be transferred, a connection principle with its appearance will be presented in section 16.2.

This chapter deals with forces that should be transferred through the structure. At the end a preliminary design of a foundation is calculated.

14.1 MATERIALISATION

The wire frame as modelled in Oasys GSA was made out of steel beams. This was mainly done to investigate the forces in the model rather than to prescribe a total steel design.

The outcome shows a shortcoming on the field of natural frequency. Higher damping has a positive influence on the stiffness and therefore the dynamic behaviour of the structure.

The shell is based on radial tension and tangential compression. Steel is a perfect material when it comes to tension or compression, while concrete is ideally suitable for elements in compression. Concrete has better damping qualities compared to steel. However, adding a lot of mass without creating significantly more stiffness has a negative influence on the dynamic behaviour. This leads to the decision to use steel for the total load bearing structure of the stadium. Excellent qualities regarding the resistance to both compression and tension, and steel being a relative cheap material, are decisive factors in choosing steel as a structural material in this case. Steel is also rather good when it comes to construction time.

14.2 FORCES IN THE STRUCTURE

Using the forces occurring in the structure, calculated with Oasys GSA, materialisation of the grandstand will be elaborated upon. The most important issue for materialisation of different elements is the way these elements are loaded: compression elements are materialised differently than elements in tension. Below, an overview of forces in different zones of the stadium is shown.

Elements are designed regarding strength, stiffness and stability. Strength defines the necessary area of the section, while stiffness is influenced by the moment of inertia $I_{yy}/I_{zz}$. Compression elements need to be designed to avoid buckling.

Different load cases show different forces in the structure. Every element needs to be dimensioned for the governing load combination.

Although the dynamic behaviour of the grandstand is not within limits yet; from the two previous models of investigation, the spaceframe model is chosen for design regarding dimensioning and assembly.
The output generated in this section is based on the following profile types.

- gr bracing Steel STD CHS 200, 25
- gr vertical Steel STD CHS 600, 40
- gr horizontal Steel STD CHS 200, 25
- gr edge Steel STD CHS 600, 30
- roof tangential Steel STD RHS 1500, 300, 30, 30
- roof braces Steel STD CHS 400, 30
- roof ring Steel STD CHS 1500, 40
- constr edge Steel STD CHS 600, 30
- hOuter Steel STD CHS 200, 25
- vOuter Steel STD CHS 600, 40
- xOuter Steel STD CHS 200, 25
- spiders Steel STD CHS 200, 25

> Displacements
Forces in the system are related to the displacements of the structure. Both the deflected shape and the displacements of the model are depicted in figures 197 to 199.

Due to dead weight the roof moves down, while the roof structure moves up due to wind uplift. Dead weight and wind load do not intensify each other, but cancel each other out. A situation in which both dead weight and wind uplift are present is depicted in figure 199.
Maximum forces that occur in tangential elements of the stadium are listed below.

- Max compression: 12500 kN (15000 kN at bottom)
- Max tension: 10000 kN

Both the inner and the outer shell are loaded in tension as well as compression. To simplify the elements, all tangential elements will be modelled to take up 12500 kN.

Due to the undulating boundary of the grandstand, shell action is disturbed; ring forces are curved along the upper boundary, compression elements are perpendicular to it, which means in a fanning pattern and not necessary in the way they are visualised (and realised) in the figures. Compression perpendicular to the tension along curved paths, is partly taken up by the braces in the grandstand. This means, the current placement of tangential elements might not be the most suitable for the situation.

Because similarity of elements is very important for this structure regarding assembly and manufacturing, tangential elements will all be dimensioned on maximum occurring forces in the structure. This will lead to inefficient dimensioning at some locations, but will still give a good estimation of the structural feasibility despite efficiency improvements that are possible.
Radial and diagonal elements
From the pictures 202 to 205 it can be seen that forces in radial direction (horizontal and diagonal) are smaller than vertical forces. Due to the reaction force of the roof structure, tension (or compression) forces are highest at the upper edge. Tension is large in the corner, because the grandstand edges tend to fall backwards, causing tension in these corners. To increase similarity within elements, the forces that will be designed for, are forces occurring in the grandstand. Extremely large forces at the upper edge are taken up by an additional structure along the top, which will also be the connection to the roof structure.

Max compression: 2000 kN
Max tension: braces 3000 kN/horizontal 2000 kN
**Connection inner and outer layer**

The spaceframe

As modelled (a spaceframe) the diagonals that connect the inner and outer layers together, also provide lateral stiffness, because inner and outer layer are moved half a gridsize relative to one another.

The governing load combination of these forces is depicted in figure 206.

max compression: 5000 kN
max tension: 6000 kN
Function of the roof is providing shelter and at the same time providing structural stiffness to the grandstand structure. Wind forces play a major role regarding the roof structure, because it is a very slack structure out of plane.

For the roof, compression and tension are not located in special element groups. Tangential elements are loaded in both tension and compression. Diagonal elements are also loaded in tension and compression. The largest axial forces arise around the oculus, this part needs special attention (figures 207 to 209).

**Tangential elements**
max tension: 6000 kN
max compression: 5000 kN

**Braces**
max tension: 10000 kN
max compression: 5000 kN

**Ring**
max tension: 20000 kN
max compression: 15000 kN
Bending moments roof structure

Within the roof structure, bending moments occur (figures 210 to 212). The roof structure undergoes a great deal of deformation due to the movements of the grandstand, and its irregular shape. Irregularities in shape cause opposing movement which in turn causes bending moments out of plane. Because the roof structure is not realised as a spaceframe, these bending moments are taken up by the elements in the roof. During dimensioning this must be taken into account.

Tangential elements
max positive moment: 10000 kNm
max negative moment: 15000 kNm

Ring
max positive moment: 10000 kNm
max negative moment: 10000 kNm

Table 16
Overview of maximum forces occurring in the structure in ULS

<table>
<thead>
<tr>
<th>Element</th>
<th>tension (kN)</th>
<th>compression (kN)</th>
<th>Myy (kNm)</th>
<th>Mxx (kNm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grandstand</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Tangential</td>
<td>10000</td>
<td>12500</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>- Horizontal</td>
<td>2000</td>
<td>2000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>- Diagonal</td>
<td>3000</td>
<td>2000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>- Edge</td>
<td>4000</td>
<td>4000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>- Spiders</td>
<td>6000</td>
<td>5000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Roof</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Tangential</td>
<td>6000</td>
<td>5000</td>
<td>15000</td>
<td>-</td>
</tr>
<tr>
<td>- Diagonal</td>
<td>10000</td>
<td>5000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>- Ring</td>
<td>20000</td>
<td>15000</td>
<td>10000</td>
<td>6000</td>
</tr>
</tbody>
</table>
14.3 FOUNDATION
From the structure, vertical and horizontal forces are transferred to the foundations. The foundations need to withstand these forces under different circumstances, regarding different kinds of subsoil in Europe.

The design of the vertical bearing resistance may be calculated with the approximate equations. Allowance should be made for the effects of the following (NEN-EN 1997):
- strength of the ground
- eccentricity and inclination of design loads
- shape, depth and inclination of the foundation
- inclination of the ground surface
- ground-water pressures and hydraulic gradients
- variability of the ground

Formula to calculate the design bearing resistance:
\[ R/A' = c'Nc \cdot bc \cdot sc \cdot ic + q'Nq \cdot bq \cdot sq \cdot iq + 0.5 \cdot y' \cdot B' \cdot Ny \cdot by \cdot sy \cdot iy \]

Because circumstances differ a lot in Europe, the above will not be elaborated upon in detail. From the model the reaction forces are shown in the pictures 213 to 215. These visualisations show the reaction forces resulting from the total structure on the foundations.

Reactions forces in vertical direction show besides compression forces also tension forces on the foundation. This bending moment is an indication of the structure not acting totally as a shell, because shell action relies on the principle that all forces are guided to the foundation via compression in tangential direction; the line of thrust being in line with the section with the presence of ring forces.

Forces are highest along the long edge, because of the largest grandstand. Due to symmetry around the x and y axis, horizontal forces occur at every side, but have opposite signs. Figure 214 (Fz) teaches us that tension forces are small compared to the pressure on the foundation, however this is a very unfavourable
situation, especially regarding the temporarity of the foundation.
Vertical forces $F_z$: -5000 to 12500 kN
Horizontal forces $F_x$: -6000 to 8000 kN
Horizontal forces $F_y$: -15000 to 15000 kN

Forces in x direction differ due to the impact of the wind loading on the reaction forces.

The large cantilever of the total structure causes the total weight to be concentrated along the pitch. To evenly spread the concentrated point loads along the ground, footings should be applied.

Regarding the temporarity of the structure the foundation should be of temporary nature as well. However, weak subsoils will require a pile foundation regarding the large forces occuring. Furthermore a bending moment is present which causes tension on the foundation, prescribing tension piles because this can not be taken up by a shallow foundation. Due to the need of a pile foundation the foundation will not be a temporary nor a demountable construction, and needs to be rebuilt every time the stadium is relocated.

Apart from tension forces large horizontal forces act on the foundation. Horizontal forces can be taken up by the application of raker piles. The ratio between horizontal and vertical reaction forces is almost 1, which means more raker piles compared to regular piles are necessary. The extent to which raker piles can be applied in a diagonal way has a ratio of 1 to 15. This means additional measures should be applied to take up these large horizontal forces.

To illustrate an example of a foundation as it could be applied, a maximum pile resistance is calculated with the help of the following formula.

$$ F_{r_{\text{max;punt}}} = A_{\text{punt}} \times p_{r_{\text{max;punt}}} $$

$A_{\text{punt}}$ = area of the pile tip
$p_{r_{\text{max;punt}}}$ = maximum resistance according to Koppejan with a maximum of 15 MPa [=15N/mm²].

Assuming a pile resistance of 15 MPa and a pile of 500x500, this pile can take up 3750 kN (500x500x15).
The maximum occuring vertical force amounts 12500 kN, which means a 3 to 4 pile footing should be applied ($12500/3750 = 3.3$). The average reaction force (6000 kN) can be taken up by 1 or 2 piles at every support.

Placement of piles next to one another occurs at a closest distance of 2.5 times the diameter of the pile itself. For a 500x500 pile this means a distance of 1250 mm. Footings will be applied around the pitch; the amount of piles depending on the reaction force at every support. The type of pile that should be used is dependent on soil conditions, price, availability at the location, among other factors.
**Design of foundation**

For the design of the foundations the governing situation along the long edge and the short edge will be used. Maximum forces occurring along these edges are visualised in figures 216 and 217.

Because of the high forces concentrated at each support, multiple-pile footings will be applied. The distance between the supports of the inner and outer shell is small; along the long edge these footings will be connected to each other so a concrete slab arises. Due to this connection part of the opposite horizontal forces can be taken up by the concrete slab via compression. Note that due to tension and compression a bending moments occurs in the concrete footing, which should be designed for.

From the results presented in figures x, x and x it shows that besides vertical forces also large horizontal forces should be taken up. These forces should be taken up by the application of raker piles.

An example of a possible pile foundation along the long edge and the short edge is presented in figures 218 and 219, based on forces as shown in figures 216 and 217.

Along the long edge each support consists of five piles; two vertical piles and three diagonal piles. The short edge with smaller reaction forces consists of three piles, containing two diagonal piles.

The amount of supports along the long edge: 32
The amount of supports along the short edge: 16

Total amount of piles
- long edge: $32 \times 5 = 160$ piles (96 diagonal piles)
- short edge: $16 \times 3 = 48$ piles (32 diagonal piles)

Total: 208 piles (including 128 diagonal piles)

Note that the design of the foundation is based on the grid of the model. In reality this grid will be smaller, resulting in smaller reaction forces divided along more supports.
As mentioned concrete slabs will be used for the foundation of the stadium together with a pile foundations. Because of the large amount of supports of the stadium (160 times) in the real design, this is more suitable than separate footings.

Segmentation of the slabs is depicted in figure 220. Due to the presence of horizontal forces that need to be transferred an additional edge is applied to transfer a part of the horizontal forces via de mass of the ground. Section A-A as depicted in figure 220 is presented in figures 218 and 219. The slab is divided in four parts, to avoid unwanted forces in the concrete ring due to a total connection.

The slab has a width of 8 metres and a thickness of 800mm.

The total amount of cubic metres of concrete needed for the slabs is about:
- long edge: \(2 \times 120 \times 8 \times 0.8 = 1536 \text{ m}^3\)
- short edge: \(2 \times 80 \times 8 \times 0.8 = 1024 \text{ m}^3\)

Total: \(1536 + 1024 = 2560 \text{ m}^3\)
Demountability

Within this design the demountability is one of the key elements as the existence depends on the possibility to facilitate a stadium at every location in Europe within a limited time span. This part of the report deals with the aspects of assembly and transportability.

15.1 FOLDING PRINCIPLE
The folding principle deals with the principle that covers a quick erection of the elements and describes the system of easy connection of all different elements together. This system is closely related to the assembly process and will be elaborated upon in more detail in part 15.3 'Assembly'.

Grandstand
The outer and inner shell of the spaceframe have an offset of three metres. The longest section of the grandstand has a length of 56 metres. The section at the corners amounts to 29 metres. The structure consists mainly of tangential compression elements and radial tension elements.

Further limitations regarding (vertical) transportation are the weight of the elements. For trucks a limit of 40 tonnes is in place for standard transportation. The use of standard transportation is more desirable than special transportation, because of the additional costs it entails. Another important issue during assembly is stability. Preferably direct stability is created to eliminate the need of temporary structures. This desire demands an element that is stable in itself due to its shape.

First of all we have a look at the dimensions of the stadium and an appropriate segmentation. As mentioned before, transportation limits elements to dimensions of 3.5 * 3.5-4.0m to remain below the limits for guided transportation. Regarding length we try to stay within 18m.

The outline of the stadium amounts to 565m (180*π). For modelling we used a deviation in 48 segments, which means segments of 11.7m (565/48). In reality we divide the perimeter by 3.5 to calculate the largest size of the elements. Because the thickness of the shell is three metres, which will fit in a container, this size does not have to be split into multiple elements.

Because of the shell shape, vertical elements become wider at the top of the stadium compared to the bottom. The amount of elements needed is 160 (565/3.5). The width at the bottom of the grandstand will be about 2.2m ((2*105+2*68)/160). To create proportions that are convenient to handle, the stadium will also be divided into sections in horizontal direction. The shortest section is in the corners, and has a length of about 29 metres. At this height the total stadium will be separated into two. Both the bottom half and the upper half will be divided into two. The segmentation of the stadium is depicted in figures 221-223.
As wind does not have a large influence on the compression forces in the grandstand, the compression forces as depicted in this figure are still a good estimation of maximum compression arising in the tangential elements due to pure shell action. In reality, bending moments will also occur, which result in compression and tension forces within the space frame. Compression as calculated was based on a segmentation in 24. These values should be converted to smaller sections that will be used in reality. In addition the reaction force of the roof that rests on the grandstand needs to be included in the calculation.

A quick calculation is made:

Total vertical force on grandstand
\[ Q_{\text{gr}} = 1.2 \times (1.75 + 2.5) + 1.5 \times (4.0) = 11.1 \, \text{kN/m}^2 \]
\[ F_{v,\text{gr}} = 11.1 \times 56 \times 3.5 = 2175 \, \text{kN} \]
\[ Q_{\text{roof}} = 1.2 \times (1.2 + 0.5) = 2.0 \, \text{kN/m}^2 \]
\[ F_{v,\text{roof}} = 2.0 \times 40 \times 3.5 = 280 \, \text{kN} \]
Compression in tangential elements at the bottom (using a slope of 24 degrees) becomes:
\[ \text{Total } F_v = F_{v,\text{gr}} + F_{v,\text{roof}} = 2175 + 280 = 2455 \, \text{kN} \]
Compression force over an angle of 24 degrees:
\[ 2455 / \sin(24^\circ) = 6035 \, \text{kN} \]

This calculation is an estimation only to check the results of the computer model. This calculation does not take into account that compression forces are smaller at the top, and also smaller at the bottom by means of the tapered shape of the tangential elements from 3.5m at the top to 2.2m at the bottom.

From the model we observe forces of 15000 kN in tangential elements, in a grid two times the size. This means we should design for values of 7500 kN (15000/2) at every 3.5m of the grandstand. This force can be taken up by compression elements in both the inner and outer ring. Previous to dimensioning, the ideal shape for the elements needs to be investigated.

All elements are designed regarding:
- forces (following from the model in GSA)
- shape
- connections (radially and tangentially)
- dimensions
- assembly

Referring to the principles of graphic statics, vertical elements will be loaded in compression. In the most ideal situation this will be pure compression due to the line of thrust being within the section. From the model, having a radial segmentation of 48 elements, a maximum compression force of 15000 kN occurs in some locations. Tension is also visible in the vertical elements of the spaceframe. This is because the structure does not act as an ideal shell and also bending moments are taken up by the shell by means of tension and compression in the spaceframe. Because steel has equal qualities for taking up compression and tension, design for governing compression forces will be good in tension as well.

Considering the theory of graphic statics (chapter 9), compression is largest at the bottom of the grandstand, and depends on the slope of the grandstand. Compression along the section of the grandstand is depicted in figure 224.
> Shape
Within the limitations of transportation a few configurations of the tangential elements are possible. Because of the basis being a space frame, elements will be configurations of trusses. Trusses are very stiff in nature and transfer forces by means of compression and tension only, which is advantageous for connection types not needing to be moment stiff. Easy connections are desirable regarding the demountability of the stadium. From the configurations mentioned in the boxed text below, the L-shaped configuration is chosen. This configuration creates direct stability and provides efficient transportation. Within this L-shaped truss still many shapes or placement principles are possible. Figure 225 shows some of these arrangements. Note that diagonal elements need to be added to provide for stability.

### Rectangular/squared

**Advantages:**
- The largest configuration possible within a square of 3.5*4.0m
- Direct stability after placement
- Fewer connections to be made at building site

**Disadvantages:**
- Inefficient method of transportation, because stapling not possible. Smaller elements can be put inside, but will probably not require as much space as all the remaining space in the rectangular trusses.
- Heavy elements

### L-shaped truss
(2 ways: recht en schuin)

**Advantages:**
- Stability due to L-shape
- Space-efficient transportation because stapling is possible
- Fluent curvature due to parabolic shape makes folding difficult.

**Disadvantages:**
- Asymmetric element might cause irregularities in the transfer of forces
- More connections to be made at building site

### 2D truss

**Advantages:**
- Very efficient transport due to excellent stapling qualities. Weight limitations might be a limiting factor when it comes to the amount of plates in one truck.
- Relatively lightweight; easy handling on the building site

**Disadvantages:**
- Many connections to make at the building site
- No direct stability; temporary supporting structure will be needed during assembly

These pictures show a topview of the possibilities of configurations of L shapes and I shapes to create a double layered shell. In addition to these elements diagonal braces will be added to avoid tilting.
Besides the desire for efficient transport, modularity within elements is also very important. The more elements that have the same shape and size, the cheaper the manufacturing costs are and the fewer mistakes will be made at the building site. From this point of view, the chosen configuration will be ‘c’ (figure 225). All L-trusses in one layer (remember the deviation into four along the height) are equal to each other. Within the concept ‘c’ two different ways of placement are possible (figure 226). 2D trusses need to be added to create the inner or outer shell (depending on placement of the ‘L’s’).

The curvature in tangential direction is the same for every element within a certain level. However, due to the rectangular shape of the pitch, radial curvature is not the same around the stadium. Due to the strong curvature in the corners, elements will have a different shape at these locations. This is visualised in figures 227 and 228.
At every location where the curvature around the pitch varies, elements need to be adjusted to this curvature. In the corners, special elements are placed to provide a smooth surface around the grandstand. Whenever the curvature along the long edge differs from the curvature along the short edge, these elements need to differ as well. In addition to the L shapes, the 2D trusses that are placed in between, should also have a variance dependent on the location around the pitch. Marking should be added to be able to see the distinction between elements during assembly.

A detailed 3D representation of both trusses used for the grandstand is depicted in figures 229 and 230. Tangential elements are connected together with horizontal and diagonal beams. A topview to show the assembly for L and I trusses is depicted in figure 231.

The 2D trusses will be used as the seating part or will create the outer look of the stadium (when used as outer shell). When the trusses are used for seating, seats and floors can be directly added to the trusses and assembled in advance (figure 232). This saves a great deal of work at the building site, although this might not be desirable due to the accessibility during assembly.
When all four layers are erected, the section of the grandstand looks like figure 233. To clarify the assembly principle of the grandstand structure, simplified graphics are shown. Figure 234 shows the placement of the first layer of L-shaped trusses next to one another; stability is provided for due to the L-shape. After placement of the L-trusses the seating elements are connected to them (figure 235). In 3D the result is depicted in figure 236.

The outside of the shell structure and its thickness is created by the L-shaped trusses. The inner shell is created by trusses in plane that are connected to this. To avoid tilting of the grandstand shells, diagonals will be applied (figure 237).
Connections

Connections that are to be achieved at the building site, are not the strongest point in a structure. Connections are preferably present in directions where no huge forces need to be transferred and provide a good transfer of forces from one element to the other.

Main connections in the grandstand are connections between tangential elements and connections to couple separate L-shapes together. After dimensioning of the main elements, connections are calculated in section 15.2. Three types of connections need to be designed.

Connection between layers (tangential direction)
The undulating edge of the stadium causes irregular lengths of the tangential elements. The two lower layers have the same height around the stadium. At the short edge and the long edge, three layers are present. The length of the elements at the upper layers differs in length to create the undulating shape. Making use of the symmetry of the stadium when viewed from above, this will limit the amount of different elements used to create the highest layer (layer 3 at the short edge, layer 4 at the long edge).

Structural stiffness is a very important issue within this design. Connections are a key element in achieving the correct structural stiffness. Due to application of the principle of a spaceframe, all forces are transferred via tension and compression in sub elements. This causes the connections to be designed for tension and compression only, which is a very favourable situation. Excentricities need to be avoided to ensure pure axial forces.

Lateral connection in radial direction
Shell action is partially based on ring forces in radial direction transferring tension forces in the grandstand. Connections between L-shaped trusses will be designed for these tension forces.

Connection of diagonal truss
To create a spaceframe and provide for lateral stability, diagonal elements are added between the inner and outer shell. To avoid excessive bolting on site, these elements will be connected to the I-shaped truss with a hinge and connected to the L-shaped truss on site.

All connections depend very much on the profile sections that will be used, as well as the forces that need to be transferred.

A few examples of possible connections are depicted in figure 238. Applicability depends on the forces that need to be transferred. This will be examined at section 15.2.
> Dimensions
Because the grid of elements in the computer model differs from the grid as used in reality, the forces occurring in the model need to be converted to forces to design for in reality. Tangential elements have a closer grid which decreases forces to be transferred. The horizontal grid almost stays the same, however, in the computer model the distribution of horizontal elements is evenly distributed along the height, which causes a closer grid in the corners. This grid will not be adopted in reality, because primarily uniformity between elements is pursued. Table 17 shows an overview of forces occurring in separate elements in the modelled structure. Forces in brackets are converted forces to be used in the real structure that account for the adjusted grid explained as follows. All forces mentioned are design forces, following from the governing ultimate limit state combination.

Grandstand
- Tangential
  Amount of elements used in model: 48 per layer
  Amount of elements used in structure: 160 per layer
- Horizontal
  Amount of elements used in model: 12 along height
  Amount of elements used in structure: 12 along height
- Diagonal
  Bracing is applied within the grid of tangential and radial elements. Because the radial grid in the structure is a closer grid, diagonal elements will have a steeper slope and more diagonals are applied regarding the total structure. Forces are limited in tangential direction and slightly increased in radial direction.
- Connection inner and outer layer
  Amount of ‘spiders’ used in model: 96
  Amount of trusses used in structure: 160

Profile type
Regarding the profile section, many choices can be made. From hollow sections to I or H profiles; this is all possible, every profile has its own advantages. The Lotus stadium is a stadium that will be used once a year at a different location. This means a lot of transportation and handling of the elements at the building site. This kind of use of the structure asks for easy maintenance, because damage might occur sooner compared to regular situations. When it comes to painting of the structure, hollow sections are advantageous above I or H profiles, because of the reduced area to paint. On the other hand I or H profiles are cheaper because they are easier to manufacture. These costs are non-recurrent and are part of the investment. This stadium might be more expensive than permanent stadiums, but benefit will result from repetitive use. Many connections are present in a spaceframe structure. Whether this is done by bolting or welding, flat edges are easier to connect

Table 17 Overview of maximum forces occurring in the structure and corresponding profile types (all values are design values resulting from ULS)

<table>
<thead>
<tr>
<th>Element</th>
<th>tension [kN]</th>
<th>compression [kN]</th>
<th>Myy [kNm]</th>
<th>Mxx [kNm]</th>
<th>A needed [mm²] (S355)</th>
<th>Section [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grandstand</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Tangential</td>
<td>10000</td>
<td>12500 (3800)</td>
<td></td>
<td></td>
<td>10700 (per 2)</td>
<td>250<em>150</em>8 (6080 mm²; S355)</td>
</tr>
<tr>
<td>- Horizontal</td>
<td>2000</td>
<td>2000 (2200)</td>
<td></td>
<td></td>
<td>6200</td>
<td>250<em>150</em>8 (6080 mm²; S355)</td>
</tr>
<tr>
<td>- Diagonal</td>
<td>3000 (1000)</td>
<td>2000 (800)</td>
<td></td>
<td></td>
<td>2800</td>
<td>150<em>150</em>5 (2840 mm²; S355)</td>
</tr>
<tr>
<td>- Edge</td>
<td>4000</td>
<td>4000 (800)</td>
<td></td>
<td></td>
<td>10700</td>
<td>300<em>150</em>12,5 (10500mm²; S355)</td>
</tr>
<tr>
<td>- Spiders</td>
<td>6000 (3800)</td>
<td>5000</td>
<td></td>
<td></td>
<td>11300 (2 layers)</td>
<td>250<em>150</em>8 (6060 mm²; S355)*</td>
</tr>
</tbody>
</table>

* Due to the application of diagonal beams to avoid tilting, these elements can have smaller dimensions.
than round surfaces. Regarding maintenance hollow sections are advantageous regarding the surface to be painted. Because maintenance and appearance are of great importance rather than costs, rectangular hollow section profiles will be used.

Dimensions as listed in table 17 are shown in figures 239 to 241.
Roof
Compatibility with the grandstand structure is also very important for the roof. Regarding segmentation, the same principle is used as was done for the grandstand. Radially the roof structure is divided into 160 elements, tangentially the roof structure is split up into 4 rings. Dimensions of elements should all be within 3.5*4.0*18.0 metres to ensure transportation is possible by standard trucks. The model in GSA was based on a single layered roof structure. In reality a truss frame is used in tangential direction of the roof.

> Forces
Previous calculations show a very asymmetric load pattern in the roof structure, due to the large influence of wind uplift. This means both tension and compression are present in almost all elements, and a division between compression and tension elements is barely distinguished. Main focus lies on the transfer of bending moments around the edge and around the oculus, together with large tension forces around the oculus.

> Shape
The roof structure consists of three types of elements; tangential elements from the outside to the inside, diagonal elements, and the ring around the oculus (figures 242, 243 and 245). From the forces following from the model, it appears that both diagonal and tangential elements are loaded in tension and compression. Because bending moments are present along the edge of the roof due to wind uplift or the sag due to dead weight, stiffening in this direction is preferred.

Between triangular trusses, trusses are applied in a horizontal plane (figure 244). These trusses provide in plane stiffness to the roof structure. Together with these trusses, a membrane will be rolled out over the roof structure and fastened together with a waterproof zipper.

For the roof structure the same limitations regarding the transportation dimensions holds; trusses should not be wider than 3.5m and are cut in multiple sections along the length.

The ring around the oculus is subject to extremely large tension forces. To take up these forces in an efficient way, the segmentation of the roof is adjusted at the inner ring. In plane trusses at the inner ring, are placed radially instead of tangentially, to limit the amount of connections in the main transfer direction. This segmentation of the roof area is depicted in figure 245.
Connections
First of all the roof structure needs to be connected to the grandstand. Because bending moments occur around the edge of the roof structure, a triangular truss is used to transfer this moment by tension and compression forces.
Separate roof rings are connected together in tangential direction with the help of a tent pole connection. The inner two rings are connected with a hinge to ensure quick assembly on site.

Dimensions
The forces that are observed from the computer model are converted to forces acting in the structure.

**Roof**
- **Tangential**
  Amount of elements used in model: 48
  Amount of elements used in structure: 160

- **Diagonal**
The grid will be smaller in both tangential and radial direction with a factor of 3. (+/- 160/48) Forces in diagonal elements in the roof may be divided by three.

An overview of these forces is listed in table 18 together with the profile types that will be used. In 3D the roof structure is visualised in figure 245.
> Assembly

During assembly of the roof, of main concern is the stability and how the roof structure will be hold in the air as long as not all elements are connected together and no ring forces are present yet.

First of all the first parts of the triangular trusses are connected to the grandstand edge and are connected in a lateral direction by means of the in plane trusses. When the trusses are cut in three, this results in a cantilever of 13 metres (40/3) for the first ring. The trusses with a basis of almost four metres high (and a length of about 13 metres) are able to carry their own weight, and as soon as the lateral connection is made, the first stiff ring with ring action is present. The other two rings will be built up from this point.

After assembly of the roof structure, the membrane is attached to it to cover the stadium and provide shelter to the spectators. The way the membrane will be applied is depicted in figure 246.

<table>
<thead>
<tr>
<th>Table 18</th>
<th>Overview of maximum forces occurring in the structure (all values are design values resulting from ULS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Element</td>
<td>tension [kN]</td>
</tr>
<tr>
<td>Roof</td>
<td>- Tangential</td>
</tr>
<tr>
<td></td>
<td>- Diagonal</td>
</tr>
<tr>
<td></td>
<td>- Ring</td>
</tr>
</tbody>
</table>

*1 The axial force in the tangential elements is based on one layer, as is present in the model. Because the tangential element will be a truss, this force can be divided by two. However, a bending moment of 4600 kNm needs to be taken up by this truss. A truss with a height of 3 metres causes compression and tension in the upper and lower beam.

\[ M_t = 4600 \, \text{kNm} \]
\[ z = 3 \, \text{m} \]
\[ N_t = 4600/3 = 1530 \, \text{kN} \]
\[ A_{\text{needed}} = 4300 \, \text{mm}^2 \]

Section: 150 x 150 x 8

*2 Both radial tension forces and existing bending moments around the oculus are taken up by a truss. Dimensions of this truss are shown in figure 245.

Membrane rolls are placed along the edge of the grandstand. After unrolling the membrane, separate strips are connected together with a waterproof zipper.

246 Application of membrane to the roof structure
As was concluded, the upper and lower beam of the triangular truss are loaded in compression or tension alternately, depending on self weight or the results of wind uplift. To avoid buckling, lateral beams should be connected between the lower beams of the triangular trusses. This measure is not taken into account yet.

Due to the undulating edge of the grandstand, the steepness of the roof varies along the circumference. This variation in the slope will be achieved through a different angle of connection to the grandstand. Difference in slope of neighboring trusses, will cause a skewed surface for the lateral truss that will be placed in between. Skewness of this surface needs to be investigated.

The tangential truss in the roof structure is subdivided into four parts to make transportation possible. The first part is the connection to the grandstand edge. The second part creates the first ring of the roof structure and will be put in place afterwards. The second and third part of the truss that form the second and third ring, are connected with a hinge connection (figure 248). This limits assembly time at the building place and is possible because of the limited dimensions of both the trusses.

As was concluded, the upper and lower beam of the triangular truss are loaded in compression or tension alternately, depending on self weight or the results of wind uplift. To avoid buckling, lateral beams should be connected between the lower beams of the triangular trusses. This measure is not taken into account yet.

Figure 247 shows a topview of the roof structure together with dimensioning of in plane trusses.

247 Roof trusses with zoom view of lateral truss

248 Folding principle of the truss in the roof structure
15.2 CONNECTIONS
Different connection types are applied to the stadium structure. Connection between grandstand and roof structure as well as mutual connections between both roof and grandstand elements are calculated.

Grandstand
Connection between horizontal elements of the grandstand is achieved by bolting two plates connected to the trusses together. Attention should be paid to local wrinkling of the hollow section profile. This issue is dealt with by application of a plate that is present through the section of the profile; in this case forces are transferred in a straight line. A calculation of the necessary bolts and plates to be used in this connection is performed below.

\[N_d, \text{horizontal} = 2200 \text{ kN}\]
\[A_{\text{needed}} = \frac{2200 \times 10^3}{355} = 6200 \text{ mm}^2\]
\[V_{\text{per bolt}} = \frac{2200}{10} = 220 \text{ kN}\]
\[D_{\text{needed}} = \frac{1}{4} \pi d^2 = \frac{160 \times 10^3}{(355\sqrt{3})}\]
\[d = \sqrt{\frac{(4 \times 160 \times 10^3)}{(355\sqrt{3})}} = 36 \text{ mm}\]
Apply: 10 bolts M36

Tent-pole connection, area of profile used (6080 mm²)
Bolt together:
\[V_{\text{per bolt}} = \frac{1900}{12} = 160 \text{ kN}\]
\[D_{\text{needed}} = \frac{V_{\text{per bolt}}}{f_y / \sqrt{3}}\]
\[1/4 \pi d^2 = \frac{160 \times 10^3}{(355/\sqrt{3})}\]
\[d = \sqrt{\frac{(4 \times 160 \times 10^3)}{(355\sqrt{3})}} = 31.5 \text{ mm}\]
Apply: 12 bolts M33

Horizontal (figure 249)
\[N_d, \text{horizontal} = 2200 \text{ kN}\]
\[A_{\text{needed}} = \frac{2200 \times 10^3}{355} = 6200 \text{ mm}^2\]
\[V_{\text{per bolt}} = \frac{2200}{10} = 220 \text{ kN}\]
\[D_{\text{needed}} = \frac{1}{4} \pi d^2 = \frac{160 \times 10^3}{(355/\sqrt{3})}\]
\[d = \sqrt{\frac{(4 \times 160 \times 10^3)}{(355\sqrt{3})}} = 36 \text{ mm}\]
Apply: 10 bolts M36

Tangential (figure 250)
\[N_d, \text{tangential} = \frac{1}{2} \times 3800 = 1900 \text{ kN}\]
\[A_{\text{needed}} = \frac{1900 \times 10^3}{355} = 5350 \text{ mm}^2\]
Diagonal
Diagonal profiles that are added to avoid tilting of the L- and I-trusses are connected to the in plane truss with a hinge connection so easy application on site is possible.

Grandstand to foundations
The grandstand will be connected to the foundations by means of a moment stiff connection with a base plate connected to the end of the tangential profile. This plate will be connected to the foundations with bolts that are cast in the foundations. A representation of such a connection is presented in figure 252. In reality this will be a rectangular hollow section profile.

Roof
Trusses
The same connection as is used for the tangential connection in the grandstands between tangential elements. The third element of the roof has a hinge connection, that can be folded out during assembly.

In plane trusses to triangular truss (figure 251)
\[ N_\text{diagonal elements} = 3400 \text{ kN} \]
\[ A_{\text{needed}} = \frac{3400 \times 10^3}{355} = 9600 \text{ mm}^2 \]
Directly bolted together:
\[ A_{\text{per bolt}} = \frac{9600}{10} = 960 \text{ mm}^2 \]
\[ A_{\text{per bolt}} = \frac{1}{4} \pi d^2 \]
\[ d_{\text{needed}} = \sqrt{(4 \times 960)/\pi} = 35.0 \text{ mm} \]
Apply 10 bolts M36

Connection roof to grandstand
The connection of the triangular roof truss to the grandstand is depicted in figure 253. Both the upper and the lower beam of the truss are connected to the grandstand with a ‘shoe’ connection (figures 254).

\[ N_r = 1800 \text{ kN} \]
\[ V_{\text{per bolt}} = \frac{1800}{8} = 225 \text{ kN} \]
\[ \frac{d_{\text{needed}}}{d} = \frac{1}{4} \pi d^2 = 225 \times 10^3/(355/\sqrt{3}) \]
\[ d = \frac{\sqrt{(4 \times 225 \times 10^3)}/(355/\sqrt{3})}{\pi} = 36 \text{ mm} \]
Apply: 8 bolts M36
15.3 ASSEMBLY
Once all elements are present at the building site, the stadium needs to be erected in a very short period of time. This is why the assembly needs to be quick and easy. Consideration should be given to whether few large, heavy elements is preferable to many small, light elements. The fewer elements that need handling at the building site, the quicker the assembly will be.

One of the main aspects of importance during assembly, is the stability of the structure. Whenever temporary support structures can be excluded, the process is economised, this is why direct stability should be pursued.

The previous section contained an overview of the folding principle and presented different elements used for the grandstand and the roof structure. Issues mentioned above were all taken into account. This section contains a summary of what is mentioned previously for clarity.

Assembly
For assembly the order of the handling is very important. The stadium will be built layer by layer (figure 255). First of all the tangential elements of the lowest layer are placed. Because of the L shape these elements are stable in themselves and no additional support is needed as one single element can bear its own weight without shell action. L shapes are connected together and the trusses for seating are added and connected. The double shell of the first layer is completed and it is continued with the next level. Till the second level all elements have the same height. From the 3rd level on elements have different lengths due to the undulating upper boundary.

After the grandstand is assembled and the upper beam is connected to the grandstand, the roof structure will be applied to the stadium. Starting from the outside to the inside the triangular trusses will be connected to the edge (figure 256). After a ring of triangular trusses is applied, lateral trusses are connected in between to create in plane stiffness by means of ring action.
Order of assembly - step by step

1 - land leveling
2 - pile foundation
3 - hoist first layer of tangential elements - connect to foundation
4 - connect I-shaped trusses to first layer
5 - hoist second layer of tangential elements - connect to first layer
6 - connect I-shaped trusses
7 - assembly layer 3 and 4
8 - hoist first part of roof - connect to edge beam and grandstand
9 - connect lateral trusses and provide stability first ring
10 - connect second roof ring to first ring
11 - placement lateral trusses of second ring
12 - assembly roof ring 3 and 4
13 - placement roof ring
14 - placement of membrane rolls at edge beam
15 - roll out membrane and connect to neighboring roll
16 - fix installations to roof
17 - apply seats to grandstand (whenever not integrated with the trusses as one element)

Regarding assembly the main issues are stability and efficiency. Direct stability is realised by building the stadium layer by layer; once a layer is stable and relies on shell action, the next layer is built up. This limits the possibilities of assembling large parts on the ground and lifting them at once.

When temporary support structures are used, more possibilities arise regarding the order of assembly. Because accessibility of the roof is a point of attention, some ways of assembly for the roof structure are presented (figure 257 and 258). Not using shell or ring action during assembly prescribes temporary supports. Preassembly on site should be done with a crane because of heavy elements. An explanation of alternative I and II is given in the gray frame.

Alternative I (figure 257)
- construction of grandstand
- assembly of roof ring at ground level
- lift roof ring and keep up with temporary supports
- connect triangular roof trusses (preassembled) to roof ring
- finish construction of roof
- release temporary supports

Alternative II (figure 258)
- construction of grandstand
- assembly of triangular trusses at ground level
- lift triangular trusses in place and support with temporary support at each truss
- finish construction of roof
- release temporary supports
15.4 QUICK ERECTION PRINCIPLES

Refering to section 7.1 in which portable structures were elaborated, the methods of sliding and folding will be investigated here and judged on their usefulness to the structure of the Lotus stadium.

**Folding**

Folding in its most natural form happens by folding two or more elements together while connected to each other at one side. When this is done to a double curved structure, folding along an edge becomes impossible due to the curvature (figure 259). Folding is only possible when connected at the middle of the edge or the two ends of the edge, depending on the direction of preferred folding.

![Figure 259: The effect of application of folding along a curved edge](image)

> Grandstand

When the double curved structure is simplified to a structure consisting of small flat elements, folding becomes possible. An example of application of folding to the inner and outer shell of the structure is illustrated in figure 260. First of all tangential elements will be erected. At the top the folded inner and outer shell will be connected and folded out along the section. Guidance via profiles is not possible due to the tapered shape of the shell elements. The inner shell will be folded out till the right stair shape is achieved; after which seats can be connected. The outer shell will be folded out totally. Shell elements have limited width due to the length of transportation (<18m) and limited height and length (<3.5-4.0m).

> Roof

A folding principle could also be applied to the roof structure. Triangular trusses can be folded in 4, lifted at once and ring by ring folded out to secure stability during assembly. Every second ring will be applied when the previous ring is connected laterally by in plane trusses. The folded triangular roof does not fit in a truck at once, which means pre-assembly at the ground should be done. None of the elements can be lifted by hand and a crane should lift elements in plane at the ground as well. From the above it can be concluded that pre-assembly in this way does not really create efficiency advantages.

![Figure 260: Application of folding to the grandstand structure](image)

**Sliding**

Sliding is used to create a telescopic principle. Two or more elements are slid into or onto each other and by means of pulling the structure slides in its final position. To apply a telescopic principle, uniformity within elements needs to be realised, together with a tapered shape. Because of the parabolic curvature in tangential direction, curvature of tangential elements is not the same along the height, which makes a telescopic principle hard to realise.
The advantages and disadvantages of both the principle of folding and sliding are listed below.

**Folding**

Advantages of folding a structure are:
- Less connections to be realised on site
- When applied in an efficient way, stapling of elements is directly achieved.
- Less but heavier elements are realised; this limits the amount of lifts to perform at the building site.

Disadvantages of folding a structure are:
- A lot of hinged connections are present. Hinged connections are more vulnerable to damage and more expensive to realise.
- No smooth curvature is possible when folding along an edge is to be realised. Whenever folding along certain points is applied due to the presence of curvature, stapling becomes less efficient.

Regarding assembly it should be stated that quick erection is realised by a limited amount of lifts accompanied by a limited amount of handlings. Pre-assembly on the ground can help to erect a building in a very short time.

Advantages of sliding:
- Allows quick erection
- Less but heavier and larger elements are realised; this limits the amount of lifts at the building site
- Simplifies stapling in trucks

Disadvantages:
- Sliding requires a lot of smoothness of the structure, to ensure flexibility while sliding
- Connections need to be designed for sliding as well as the final positions at which the structure need to be locked
- Requires a lot of uniformity within elements especially regarding curvature; this is not present in tangential direction
- Vulnerable to damage

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> Grandstand
When the principle of sliding is applied in tangential direction the parabolic shape should be carefully considered because this limits efficient sliding of elements and an economic shape when not slided out. When sliding is created due to moving elements next to each other, inefficient transfer of forces occurs at the connections. Figure 261 illustrates a possibility of sliding segments of the grandstand to create the final shape. At connections forces are not transferred in a direct way.

![Image of grandstand structure](image)

261 Sliding of segments along the grandstand section

> Roof
Sliding can be applied to the roof structure because in tangential direction because each triangular truss has a constant slope.

The advantages and disadvantages of both the principle of folding and sliding are listed below.

**Folding**

Advantages of folding a structure are:
- Less connections to be realised on site
- When applied in an efficient way, stapling of elements is directly achieved.
- Less but heavier elements are realised; this limits the amount of lifts to perform at the building site.

Disadvantages of folding a structure are:
- A lot of hinged connections are present. Hinged connections are more vulnerable to damage and more expensive to realise.
- No smooth curvature is possible when folding along an edge is to be realised. Whenever folding along certain points is applied due to the presence of curvature, stapling becomes less efficient.

**Sliding**

Advantages of sliding:
- Allows quick erection
- Less but heavier and larger elements are realised; this limits the amount of lifts at the building site
- Simplifies stapling in trucks

Disadvantages:
- Sliding requires a lot of smoothness of the structure, to ensure flexibility while sliding
- Connections need to be designed for sliding as well as the final positions at which the structure need to be locked
- Requires a lot of uniformity within elements especially regarding curvature; this is not present in tangential direction
- Vulnerable to damage
15.5 ANALYSIS OF THE POSSIBILITIES OF A STADIUM BUILD OUT OF VOLUMES AND THE USE OF PRE- OR POST TENSIONING

The original idea of the Lotus Stadium was based on shell action. Originally, with the help of the theory of graphic statics, shell action in the stadium structure was examined and further developed with the help of a wire frame model in GSA. The original architectural idea will now be analysed on its feasibility and elaborated with the help of the knowledge gained during modelling.

First pictures of the Lotus stadium showed a model based on tangential volumetric elements connected together by post-tensioned cables running around the edge of the stadium and along the total section, pushing the elements together by bringing tension in the cables (figure 262).

The idea of cables loaded in tension combined with tangential elements loaded in compression is very much in line with the principles of shell action; radial tension and tangential compression being in equilibrium, avoiding bending moments.

The consequences of applying this principle will be elaborated. First of all the same problems as encountered during the research done with graphic statics are present here. The undulating boundary of the grandstand makes horizontal transfer of ring forces impossible. The transfer of large tension forces in a diagonal downward direction causes large compression forces in the section of the grandstand to realise equilibrium. This phenomenon is graphically shown in figure 263. Most natural shape of a cable in tension is a straight line, which it will try to reach by causing downward pressure at highpoints and upward force at lowpoints. The upward force along the corner sections will cause tension in the tangential elements if big enough (figure 264). This is the case for the upper cable, while lower cables are able to run around the stadium in a horizontal position, which is more favourable.

The idea of radial cables purely loaded in tension and tangential elements purely loaded in compression is a very favourable situation regarding fatigue. Elements alternately loaded in tension and compression are very sensitive to fatigue which is unfavourable. Post-tensioning of the cable causes compression in the tangential volumetric elements. Varying with the tension force in the cable, a situation can be created in which tangential elements will always be in compression. This
Concerning the feasibility of the structure, the architectural model in which post-tensioning and stiffness by volumes (and planes) is used, will not be sufficient to achieve a feasible structure. From the previous calculations it showed that large measures are needed to enlarge the stiffness till a sufficient amount to increase the natural frequency substantially. This will not be achieved by post-tensioning of a hardly curved shape.

Although the idea of post-tensioning and using in plane stiffness are useful, additional measures should be taken to enlarge the effectivity of it.

From the research done on the wire frame model, eventually a spaceframe with a thickness of 3 metres was not yet stiff enough (within this shape) to provide sufficient stiffness in order to achieve acceptable values of natural frequencies. This means when such a model is converted to a model using volumes and cables still a certain thickness should be taken into account; creating a lot more slender structure will not be possible just by applying post-tensioning. Post-tensioning will not increase the stiffness drastically, but will rather provide stability regarding loose connections and tolerances. Furthermore double curvature is not ideal in the current shape for relying on pure shell action; in radial direction most optimal shape is a pure circle, which in reality is a rounded rectangular shape around the pitch.

The stiffness of this structural principle is based on the tension force achieved by post-tensioning cables around the stadium at multiple levels. This is only realised when cables are tensioned at every location and the structure works as a whole. As long as not all cables are tensioned, a temporary support structure should be applied until the shell is brought in tension and gets stiffness from its shell action. Apart from any temporary support, the way cables are tensioned should be elaborated.

A few consequences are mentioned and points of attentions that need further research. To fully elaborate the feasibility of this principle, further research should be done on the effect of post-tensioning along an undulating shape and the most appropriate material that should be used for tangential elements. Besides a smart system during assembly should be designed to limit temporary support structure during assembly and create instant structural stability at all phases of assembly.

The amount of cables and length should be examined. The most optimal locations of tensioning should be searched for.

Regarding forces in the model, the use of a triangulated pattern resembles the situation when plates are used very much and gives a realistic view of in plane forces in this way.

Regarding the feasibility of the structure, the architectural model in which post-tensioning and stiffness by volumes (and planes) is used, will not be sufficient to achieve a feasible structure. From the previous calculations it showed that large measures are needed to enlarge the stiffness till a sufficient amount to increase the natural frequency substantially. This will not be achieved by post-tensioning of a hardly curved shape.

Although the idea of post-tensioning and using in plane stiffness are useful, additional measures should be taken to enlarge the effectivity of it.
15.6 TRANSPORTABILITY
Transport is a key-issue in the concept of a demountable stadium. Because the Lotus stadium will be used at every location in Europe, transport should be possible between all future locations in Europe. To be able to place the stadium without limitations, transport should preferably happen over the road. Standard sizes to transport over the road by truck are container sizes. Capacities for common container sizes (TEU’s) are listed in table 19. These standard-sized metal boxes can be easily transferred between different modes of transportation, namely ships, trains and trucks.

When it is not possible to fit elements or modules in a container, abnormal road transport should be used. This kind of transport has bigger capacity, but sometimes permits are needed and it is a very costly way of transport (table 20). Preferably not too many elements should be transported with special transport, because it will raise the costs enormously. Besides, this way of transport is less quick than transport by regular transport.

The most efficient way to transport all elements by truck, taking into account efficiency of weight distribution and an efficient way of stacking is investigated.

From the list of demands and preferences the following was stated:

<table>
<thead>
<tr>
<th>Demand</th>
<th>Option 1</th>
<th>Option 2</th>
<th>Option 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>No permit needed</td>
<td>0 begeleiders</td>
<td>1 begeleider</td>
<td>2 begeleiders</td>
</tr>
<tr>
<td>Long term permit (2)</td>
<td>4.01 m t/m 4.50 m</td>
<td>3.51 m t/m 4.00 m</td>
<td>breder dan 4.50 m</td>
</tr>
<tr>
<td>Weight (3)</td>
<td>40.01 m t/m 50.00 m</td>
<td>40.01 m t/m 50.00 m</td>
<td>breder dan 4.00 m</td>
</tr>
<tr>
<td>Transportbegeleiding</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soort wegen</td>
<td>automobilweg</td>
<td>t/m 100,000 kg</td>
<td></td>
</tr>
<tr>
<td>Breedte</td>
<td>0 begeleiders</td>
<td>1 begeleider</td>
<td>2 begeleiders</td>
</tr>
<tr>
<td>overige wegen</td>
<td>t/m 3.50 m</td>
<td>3.51 m t/m 4.00 m</td>
<td>breder dan 4.50 m</td>
</tr>
<tr>
<td>Lengte</td>
<td>automobilweg</td>
<td>t/m 40.00 m</td>
<td>breder dan 4.00 m</td>
</tr>
<tr>
<td>overige wegen</td>
<td>t/m 27.50 m</td>
<td>27.51 m t/m 32.00 m</td>
<td>breder dan 4.00 m</td>
</tr>
<tr>
<td>Massa</td>
<td>alle wegen</td>
<td>t/m 100,000 kg</td>
<td></td>
</tr>
</tbody>
</table>

Table 19 Most commonly used container types (TEU’s)

<table>
<thead>
<tr>
<th>Inside measures</th>
<th>20’container</th>
<th>40’container</th>
<th>45”high-cube’container</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length [m]</td>
<td>5.87</td>
<td>12.03</td>
<td>13.56</td>
</tr>
<tr>
<td>Width [m]</td>
<td>2.35</td>
<td>2.35</td>
<td>2.35</td>
</tr>
<tr>
<td>Height [m]</td>
<td>2.39</td>
<td>2.39</td>
<td>2.70</td>
</tr>
<tr>
<td>Volume [m³]</td>
<td>33.1</td>
<td>67.5</td>
<td>86.1</td>
</tr>
<tr>
<td>Max weight [kg]</td>
<td>24,000</td>
<td>30,480</td>
<td>30,480</td>
</tr>
</tbody>
</table>

Table 20 Framework for abnormal road transport permits (European Commission 2006)

<table>
<thead>
<tr>
<th>Width</th>
<th>Overall length</th>
<th>Overall height</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0 m</td>
<td>24.0 m</td>
<td>Directive 96/53/EC</td>
<td>80 tonnes</td>
</tr>
<tr>
<td>3.5 m</td>
<td>30.0 m</td>
<td>Directive 96/53/EC</td>
<td>100 tonnes</td>
</tr>
<tr>
<td>4.2 m</td>
<td>4.0 m</td>
<td>Directive 96/53/EC</td>
<td>12 tonnes</td>
</tr>
<tr>
<td>4.4 m</td>
<td>4.0 m</td>
<td>Directive 96/53/EC</td>
<td>12 tonnes</td>
</tr>
<tr>
<td>4.5 m</td>
<td>4.0 m</td>
<td>Directive 96/53/EC</td>
<td>15 tonnes</td>
</tr>
</tbody>
</table>

Table 21 Regulations on transport guidance (RDW 2011)
At certain transportation dimensions, transportation guidance is prescribed. Regulations on this topic are included in the rules of Exceptional Transport, Article 11. Some important rules are stated in table 21.

An overview of all elements that are part of the stadium structure is given in table 22. To make an estimation of the amount of truckes needed the distribution of elements over different trucks is visualised (table 23).

Table 22 List of elements for total Lotus stadium

<table>
<thead>
<tr>
<th>Description</th>
<th>Amount of elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grandstand:</td>
<td></td>
</tr>
<tr>
<td>- L shaped trusses</td>
<td>160 per layer; 2 full layers, layers 3 and 4 half (+/- 447)</td>
</tr>
<tr>
<td>- I shaped trusses</td>
<td>160 per layer; 2 full layers, layers 3 and 4 half (+/- 447)</td>
</tr>
<tr>
<td>- edge beam grandstand</td>
<td>Integrated with grandstand trusses layer 4 capacity +/- 30,000 (30,000)</td>
</tr>
<tr>
<td>- seating elements + floors</td>
<td>lighting, screens, speakers</td>
</tr>
<tr>
<td>- installations</td>
<td></td>
</tr>
<tr>
<td>Roof:</td>
<td></td>
</tr>
<tr>
<td>- triangular trusses</td>
<td>divided in 3 parts, each 160 times (480)</td>
</tr>
<tr>
<td>- in plane trusses</td>
<td>4 parts in tangential direction, each 160 times (640)</td>
</tr>
<tr>
<td>- membrane</td>
<td>rolls with a length of 40 metres, 3,5 m wide (160)</td>
</tr>
</tbody>
</table>

Table 23 Distribution of elements over trucks

<table>
<thead>
<tr>
<th>Truck</th>
<th>aantal</th>
<th>L</th>
<th>I</th>
<th>Roof 1</th>
<th>Roof2</th>
<th>Roof3</th>
<th>Roof truss</th>
<th>seats</th>
<th>installations</th>
<th>membrane</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>4</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>19</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>19</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>24</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>29</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>22</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>49</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>270</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>31</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>540</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>2</td>
<td>30</td>
<td>0</td>
<td>13</td>
</tr>
<tr>
<td>Total</td>
<td>181</td>
<td>447</td>
<td>450</td>
<td>162</td>
<td>160</td>
<td>160</td>
<td>640</td>
<td>30000</td>
<td>0</td>
<td>160</td>
</tr>
</tbody>
</table>
The distribution of all elements in the trucks is listed in table 23 and visualised in figure 265 for the first four trucks. To be able to reach the efficient stapling as shown in this figure, a smart system should be designed. An additional frame to place the elements on will increase efficiency and simplify loading of the trucks.

Within the list installations are not taken into account yet. This might prescribe two more trucks.
Finance

Prior to start calculations, a few comments on the project should be stated in general. The feasibility of a demountable stadium is highly dependent on the concept of assembly and the way separate elements are connected together. Detailing therefore becomes determinative regarding feasibility of this project in its entirety.

Logistics on site is of major essence because a large amount of elements is present and need to be assembled in a specific place and order. Because the desired quick assembly time, the occurrence of mistakes during assembly need to be minimised. Costs on logistics will be dominant for this project.

Cost-effective measures should be taken regarding a smart assembly and transportation system. The more easy and clear this process is, money is saved every time the stadium will be used.

With the help of N. Hoogendijk, manager business unit infra and K. van Rooijen, manager tendering, both employed at Hollandia b.v. estimations are checked on their correctness and price indicators are set for several items regarding the calculation of financial feasibility of the stadium.

To make an estimation of the viability of the design and the benefits of it compared to a permanent stadium, a rough calculation is made on the basis of recurrent costs and non-recurrent costs. Note that the structural feasibility of the stadium is not yet demonstrated regarding the dynamic behaviour and needs further research. However, some things can be assumed regarding financial aspects.

The idea of the Lotus stadium that is demountable in nature, relies on several temporary ‘owners’ that rent the stadium for an event. To investigate the cashflow regarding the stadium this needs to be investigated into detail, taking into account all parties involved. This is beyond the scope of this project, but for completeness it is tried to mention all issues relating finance.

Within the material costs, changing rooms and other facilities that are housed in tents around the stadium, are not taken into account.
The total weight of the structure (grandstand + roof) is 4695 tons. Regarding material costs the price per kilogram of the structure amounts:
\[
\frac{14.50 \times 10^6}{4695 \times 10^3} = 3.09 \text{ €/kg}
\]

Manufacturing
Manufacturing consists of a lot of handlings to be performed on the elements. From cutting, welding and drilling the an appropriate preservation method. Because of the use of hollow section profiles, welding becomes more labour intensive compared to regular profiles. Benefit is realised by creating a lot of uniformity within the elements.

Regarding preservation hot dip galvanizing is very suitable to this project, given the amount of times the structure needs to be assembled and deconstructed. Hot dip galvanizing limits sensitivity to damage compared to painting.

Maximum dimensions of a hot dip galvanizing bath are:
\[
7500 \text{ mm} \times 1450 \text{ mm} \times 2700 \text{ mm}
\]

(De Cromvoirtse 2011)

Prices that are used for calculation of manufacturing of trusses are (Hoogendijk 2011):

- cutting, welding, drilling
  \[
  \frac{25 \text{ h/ton} \times \text{ €55/h}}{4695 \text{ tons} \times \text{ €400/ton}} = 1.88 \text{ mln}
  \]

- painting/hot dip galvanizing
  \[
  \frac{117378 \times \text{ €55,-}}{4695 \text{ tons} \times \text{ €400,-}} = 6.46 \text{ mln}
  \]

The total price per kilogram of the structure becomes:
\[
(3.09 + 1.77) \text{ €/kg} = 4.86 \text{ €/kg}
\]

Material costs are relatively high compared to manufacturing costs. This has to do with the high price to be paid for rectangular hollow section profiles.

Other elements apart from steel
Apart from the steel structure, the membrane for covering the roof structure and seating elements are calculated.

> Membrane
PVC coated membrane is used to cover the load bearing structure of the roof and guarantee a waterproof shelter for spectators.

- Price per m² membrane: € 20,-/m²

This price includes cutting to size and application of connection elements to the membrane to ensure the structure becomes waterproof. The price for the

1 This is the price paid for the steel structure, membrane for covering of the roof is not included.
membrane is calculated on the basis of the roof surface to cover.

Calculation roof surface:
outer radius: 96m, inner radius: 49
Total m²: \( \pi \times 96^2 - \pi \times 49^2 = 21410 \ m^2 \)
\[ 21410 \ m^2 \times \varepsilon \ 20/m^2 = \varepsilon \ 0.43 \ mln \]

> Seats
The capacity of the stadium is 30,000. Based on a price of €20,- per seat this adds up to:
\[ €20,- \times 30,000 = \varepsilon \ 0.60 \ mln \]

**Detailing/connections**
Apart from the above mentioned items a lot of other issues needs to be included in the price but are not further specified in this chapter.
Regarding the roof structure accessibility needs to be provided for by means of walking bridges. This will cost a lot of extra material.
The connection of the membrane to the roof structure needs to withstand high wind forces and needs to be watertight. This can be done by connection a special profile to the edges of the membrane and sliding them in a profile connected to the roof structure.
16.2 RECURRING COSTS
Because of the demountable aspect of the stadium, a lot of costs are recurring and play a role every time the stadium will be built. Besides, operating costs are of importance during the total life span. An overview of all recurring costs is given below.

Operation
Maintenance € 1.19 mln
Regarding maintenance this is taken into account to a percentage of total material costs. Per year 5% of the material costs are counted for painting, replacement of elements etcetera.

Cleaning
Cleaning is not taken into account.

Actual operation of stadium (staffing, lighting, heating, security)

Staffing costs

Assembly
Assembly is an important topic for this project, because it is a repetitive handling that needs to be done every time the stadium will be relocated. Logistics herein is a key element to reduce costs and minimise mistakes on the building site. Because a lot of elements are involved a good and smart layout of the building site should be achieved.

Equipment (crane, scaffolding, etc)
Because instant structural stability is achieved by making use of shell action ring by ring, this determines the order of assembly of the elements. Once the first ring is completed, no cranes of other large equipment should be inside the stadium on the pitch. After constructing the grandstand, the roof structure will be built up. The scope of a crane becomes of importance when the inner rings of the roof are assembled. During construction of the roof, accessibility to the site for construction workers should be provided for.

The equipment needed on site:
- 2 large cranes, 1 small crane
- manlift
- energy generator

Total estimated assembly time will be 8 weeks full time with a team of 40 assemblers. In total there are about 2180 elements that are lifted by crane. Using 2 cranes during these 8 weeks on a full time basis, the amount of minutes for every lift is calculated.

Assuming crane capacity of 80%:
- 2 cranes: $2 \times 40 \times 8 \times 0.8 = 512$ hours
- 512 hours = 30720 minutes
- 30720 / 2180 = 14 minutes per lift

This is the time used for coupling of the element to the crane, lifting it, bringing it into position and hold it at its position till it is fastened to its final position. The crane will not have a capacity of 100% due to relocation of the cranes, breaks for the driver and bad weather conditions. Because a significant scope is needed, two 80 tons crawler cranes will be used. These cranes can be rented at Sarens (Sarens 2011).

Rental price a week € 4000,-
rent of 2 cranes, 8 weeks: € 0.064 mln

On site energy for equipment should be present. Cranes provide for their own energy, diesel. Lighting on site and electric tools for construction workers will need some energy. For this one generator will be rented during construction time.

Generator 700kV € 1500,- a week
rent of one generator 8 weeks: € 0.012 mln

Man hour
During construction time, 40 assemblers are on site on a full time basis with an average rate of 40 euro's per hour.

Total amount calculated for man hour:
- 40p a €40,-/h full time
- 40p, 8 weeks: 40*40*8 € 0.51 mln

Deconstruction
Deconstruction with the idea of re-assembly at another location will take about as much time as construction time. The same handlings need to be performed. The same amount of lifts by crane will be necessary and again logistics is very important. Elements needs to be ordered and stapled at the right position that guarantees
efficient transportation. This leads to deconstruction costs being 100% of construction costs (Hoogendijk 2011).

Deconstruction costs

\[ \text{cranes + energy + man hour: } € 0.60 \text{ mln} \]

**Transportation**

*Transportation*

For a regular truck with a maximum weight of 25 tonnes a price of €1,- per kilometre is calculated (Hoogendijk 2011). Accounting additional time for secure and efficient stapling of elements and additional fuel for heavy loads a price of €2,- per kilometre is used. The amount of trucks is about 190, assuming a distance of about 1600 km (The Netherlands to Barcelona), this adds up to the following:

\[ \text{Transport 190 trucks, 1600km} \]
\[ \text{Transport costs: 190*2*1600: } € 0.61 \text{ mln} \]

Vertical transportation by crane is included at the assembly.

**Storage**

Depending on the frequency of use and the distance between two successive locations, the elements of the stadium needs to be stored. Based on a capacity of 190 trucks this adds up to a volume of 210 m³ (3.5*4.0*15.0). Costs for storage are not taken into account. Based on estimated times of (de)construction (2 times 8 weeks) and the time the stadium is in use (4 months), this means a storage time with a maximum of 4 months, including the transportation time.

**Terrain**

Depending on the type of terrain of the new location, additional measures should be taken. First of all the total building area needs to be flattened. Costs for land loan are also of importance but not taken into account here. This is a very complicated topic because it very much depends on the type of business case used for exploitation of the Lotus stadium.

- Land loan
- Land leveling

**Foundation**

Because of high reaction forces, a demountable foundation is not realistic for most soil conditions in Europe. Most likely a permanent pile foundation should be applied to provide sufficient support to the stadium. A foundation will be applied as calculated in section 14.3.

- Amount of piles used 208 (128 raker piles)
- Price piles (delivery+application)
  - (D. van Biezen 2011)
  - € 1000,- / pile
  - piles: 208 * 1000
  - € 0.21 mln

- Amount of m³ concrete: 2560 m³
- Price concrete (including reinforcement)

\[ \text{€ 200,- / m³} \]
\[ \text{concrete: 2560 * 200 } € 0.51 \text{ mln} \]

**Infrastructure**

The final location of the stadium probably asks for additional accessibility. This should be realised by road construction. Besides parking places need to be realised. This topic will not be taken into account.
16.3 EXPECTED INCOME GENERATION FUNDS

Within this report, a total business model of the stadium and all facets playing a role regarding finance, is not provided. However, for completeness some important aspects that need to be taken into account regarding income generation are mentioned to give a clear idea of what still needs to be done.

The business model of the Lotus stadium will be very complex due to the presence of multiple stakeholders and funds for generating income. A list of the expected income generation from several sources is given below.

- Sponsorship
- Advertising
- Seating
- Named stadia
- Concessions
- Parking
- Club funding
- Grants

<table>
<thead>
<tr>
<th>Times of use</th>
<th>costs [mln €]</th>
<th>per seat [€]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>€ 30.81</td>
<td>€ 1.027</td>
</tr>
<tr>
<td>2</td>
<td>€ 17.08</td>
<td>€ 569</td>
</tr>
<tr>
<td>3</td>
<td>€ 12.51</td>
<td>€ 417</td>
</tr>
<tr>
<td>4</td>
<td>€ 10.22</td>
<td>€ 341</td>
</tr>
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<td>5</td>
<td>€ 8.85</td>
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<td>€ 7.93</td>
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</tr>
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<td>€ 7.28</td>
<td>€ 243</td>
</tr>
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<td>8</td>
<td>€ 6.79</td>
<td>€ 226</td>
</tr>
<tr>
<td>9</td>
<td>€ 6.40</td>
<td>€ 213</td>
</tr>
<tr>
<td>10</td>
<td>€ 6.10</td>
<td>€ 203</td>
</tr>
<tr>
<td>11</td>
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<td>€ 195</td>
</tr>
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<td>12</td>
<td>€ 5.64</td>
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</tr>
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<td>€ 4.88</td>
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<td>19</td>
<td>€ 4.80</td>
<td>€ 160</td>
</tr>
<tr>
<td>20</td>
<td>€ 4.73</td>
<td>€ 158</td>
</tr>
</tbody>
</table>

Recurring costs (except operation and storage)
€ 4.05 mln
Permanent costs
€ 27.46 mln

Total costs as elaborated in this section are presented in table 25. The origin of some of the costs is described in the column ‘description’. Because some costs are hard to predict exactly, they are adopted as a percentage of material costs or total costs.

Costs of the stadium are an important measure to calculate the benefits of the use of a demountable stadium above a permanent stadium. The price per seat over time is calculated in table 24.

At this stage it is difficult to formulate concrete conclusions on these tables, because a lot of costs are not yet taken into account and some issues need further research before something can be said about the price.

A comparison with permanent stadiums is hard to perform, because facilities are not taken into account yet.
<table>
<thead>
<tr>
<th>Item</th>
<th>Costs [mln €]</th>
<th>Temporary</th>
<th>Permanent</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Development &amp; Design</td>
<td>3.62</td>
<td>1</td>
<td>1</td>
<td>13% of total costs</td>
</tr>
<tr>
<td>Material costs</td>
<td>23.87</td>
<td>1</td>
<td>1</td>
<td>This price includes connections (10% of material costs) and manufacturing</td>
</tr>
<tr>
<td>Steel</td>
<td>14.50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Membrane</td>
<td>0.43</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seats</td>
<td>0.60</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manufacturing</td>
<td>8.34</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>General construction site costs</td>
<td>0.33</td>
<td>n</td>
<td>1</td>
<td>13% of building costs</td>
</tr>
<tr>
<td>Foundation(^{1})</td>
<td>0.72</td>
<td>n</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td>0.12</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Piles</td>
<td>0.21</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assembly</td>
<td>1.20</td>
<td>n</td>
<td>1</td>
<td>This price also includes deconstruction</td>
</tr>
<tr>
<td>Assembly (man hour)</td>
<td>0.51</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equipment</td>
<td>0.09</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deconstruction</td>
<td>0.60</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transportation</td>
<td>0.61</td>
<td>n</td>
<td>1</td>
<td>This price does not take into account storage costs of the stadium</td>
</tr>
<tr>
<td>Transport</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Storage</td>
<td>---</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating</td>
<td>1.19</td>
<td>n</td>
<td>n</td>
<td>This price includes maintenance; actual operation is not taken into account</td>
</tr>
<tr>
<td>Actual operation</td>
<td>---</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maintenance</td>
<td>1.19</td>
<td></td>
<td></td>
<td>Maintenance is calculated being 5% of the materials costs a year</td>
</tr>
</tbody>
</table>

\(^{1}\) Foundation costs are calculated as part of recurring costs, assuming a non-reusable pile foundation in most unfavourable situation. Depending on the soil conditions of the location of the stadium, foundation costs may differ from what is calculated above.
Evaluation
Evaluation

As a starting point for this project a list of demands and preferences is set up to list all qualitative and quantitative issues regarding the stadium that needs to be satisfied within the design. For a quick evaluation this list is evaluated to see which demands or preferences are met.

17.1 LIST OF DEMANDS AND PREFERENCES

Safety and comfort
To prevent undesired vibrations, the natural frequency of the stadium should be at least 5 Hz by rule. This increases to 7 Hz by desire. The first mode of vibration affects the roof structure and has a value of 0.5 Hz. Natural frequency of the grandstand amounts 1.0 and is therefore not met.

In serviceability limit state the maximum sag due to the variable load is limited to 0.003*l. For the cantilevered structure an increased sag of 0.006*l is permitted. Deflection of the grandstand is within limits. Deflections of the roof due to wind uplift are quite large but no requirements hold other than not to get damaged.

Fire protection between 90 and 120 minutes is obliged.

During evacuating everybody should be able to leave an open air stadium within 12 minutes. For a covered stadium this time is reduced to 6 minutes.

Walking distance to the entrance has a maximum of 50 metres, this is covered within 12 minutes.

The steepness of the grandstand should not exceed 34 degrees.
Steepness has a maximum of 32 degrees.

To provide for optimal sightlines throughout the whole stadium, a ‘C’ value of 120mm should be achieved.
Shape is designed with C values of 120mm and higher.

Spectators should always have a clear, unrestricted view of the whole of the football playing area, this prohibits obstructions in view.
No elements are obstructing the view of spectators.

Gangways in seated accommodation should be at least 1.2m wide.

Based on an optimal viewing distance of 150m from the far corners, an assumed optimum viewing distance of 90 metres from the centre of the field should be adopted.
No seats are out of the 90m radius.

The roof should provide enough shelter to the spectators. Due to the roof hanging down it provides enough shelter to the spectators.

From all seats a point at 18 metre above the pitch should be visible.
To avoid the roof obstructing the view of spectators by hanging down, the total roof is lifted a few metres within the design. Sag of the roof should be limited.

Functionality - Demands

The dimensions of the field are determined by the Union of European Football Associations (UEFA) and are described in the next two requirements.

(1) The dimensions of the inner edge are dictated by the dimensions of the field (68*105m²), a border around the field of 7.5m and a safety barrier. Within this limitations, the seats should start as close to the field as possible.

(2) The dimensions of the outer edge are in this particular stadium not determined by the required capacity, but by the maximum acceptable distance from the field to the outer seats and the preferred viewing locations (maximum radius 90m).

No element should be heavier than 40 tons; this is the maximum weight to transport by a regular truck in Europe.

The heaviest element is the L-shaped truss for the grandstand; this element weighs 4.5 tonnes.

All elements could be lifted by crane. Based on a flight
The stadium should be designed conform requirements in the Eurocode Principles of the structural design, Eurocode 1 and 4; loads on structures.

Financial aspects
Preferably the demountable stadium should be beneficial above permanent stadiums after 5 times of use.

Conclusions on this topic are not leading if structural feasibility is not demonstrated.

The portable stadium will be designed for a life span of at least 15 years.

Sustainability
Preferably the stadium is made of sustainable material concerning production/origin, manufacturing, transport, reuse and life span.

Appearance
The stadium should have the look of a permanent stadium.

Functionality - wishes
Between the separate elements there is preferably as much uniformity as possible. Elements are uniform within each construction layer. However, difference in curvature causes difference in elements.

Preferably the stadium is useful to other functions besides football as well. Flexibility of the stadium contributes to multiple function use. (co-habitation).

The roof should limit shading on the pitch.

Structural aspects
Elements should be designed for forces during transport that are different from loads during use/assembly. It is desired that there is a lug to handle the elements. The trusses are easy to handle and provide enough grip for handling.

Connections should be designed for repeated use. An important issue herein is fatigue.

The structure should be able to bear the loads; Dead load (Weight of stadium (↓)), Variable load (Imposed load (↓ + →) (↓ = 4.0 kN/m²; → = 6%*4.0 = 0.24 kN/m²), Wind (→ + ↓ + ↑))

Preferably a temporary and transportable foundation is used to found the stadium. For weak soils a pile foundations is inevitable.

Preference all elements should fit in a truck without guidance (4.0*3.5*18.0 m³) and be lighter than 40.000 kg.

The stadium should be designed conform requirements in the Eurocode Principles of the structural design, Eurocode 1 and 4; loads on structures.

Change of location should be possible within eight months. Within this time maintenance is included. Assembly time with a team of 40 assemblers is set to eight weeks. This provides enough time for deconstruction and maintenance within eight months.

Maintenance should not be necessary during use and will be performed during the moving time of eight months.

In and around the stadium there should be enough space to accommodate the functions that should be present.

Stadium placement should be possible within at least 60% of locations in Europe. Regarding transportation and taken into account a permanent foundation, this demand is met.

Functionality - wishes
Between the separate elements there is preferably as much uniformity as possible. Elements are uniform within each construction layer. However, difference in curvature causes difference in elements.

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V

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V
The appearance should be attractive to visitors.

The appearance should be adaptable to different (club-) styles to a certain level.
Conclusions

At the start of this master thesis a research question is posed. Several issues are thoroughly investigated to arrive at an answer to this question. An answer is given based on several conclusions drawn from the research carried out.

Research question
How can the design proposed by Zwarts & Jansma Architects be translated into a structural design in a way that it is technically (and financially) feasible within the idea of a demountable stadium?

Together with this research question sub questions are formulated that are of relevance to answering the research question.

Sub-questions
- What are the possibilities of a demountable shell structure within the design of the architect?
- How is the connection between the different (shell) modules achieved in a way that they act together like a shell?
- What are the most efficient and quick ways to (dis)assemble a shell structure and transport it?
- In which way will stability be provided during assembly, preferably without the need for a temporary structure?

Regarding technical feasibility, the Lotus stadium is primarily investigated with the help of graphic statics, to study and understand the working of shell action and the influence of shape differences on this behaviour. The lack of double curvature in both radial and tangential direction together with a large cantilever, leads to a low structural stiffness of the system. Structural stiffness influences the natural frequency of a system, a lack of stiffness causes a low natural frequency. The grandstand, being agitated by dynamic loads in its natural frequency will be subject to resonance, causing dynamic amplification of oscillations. Irreparable damage may result.

Regarding financial feasibility, not much can be concluded as this research is based on a structural design which as of yet is not demonstrated to be feasible.

The above aspects are explained in more detail in the following pages.
due to the asymmetric shape of the grandstand and its undulating edge. This causes disturbance in the roof structure and causes therefore both compression and tension in the roof structure. The grandstand structure along the long edge tends to fall backwards, which squeezes the grandstand along the short edge together and creates compression forces in the roof.

**Dynamic behaviour**

Regarding the desired frequency of the grandstand stadium it can be concluded that a frequency of 7 Hz (5 Hz by demand) is not met. The natural frequency of the grandstand is far below this value. Values below the demand of 5 Hz are permitted as long as the response of the stadium is precisely monitored. Frequencies of dynamic crowd loads are in the range of 1 to 5 Hz and cause problems when amplification magnification occurs resulting in resonance. Damping has a large effect on the response of a system to dynamic loads; when damping is very large, vibrations caused by dynamic excitation do not result in dangerous situations as long as stresses in that particular mode are within limits.

Another factor playing a role regarding dynamic behaviour, is the behaviour of the crowd itself. Whenever a small group of people jumps up and causes dynamic excitation, the mass together with the energy of this group may be large enough to cause a certain mode shape of the stadium. Knowing a stationary crowd
largely increases the damping capacity of a system, the effect of a small group jumping will be minimised by the stationary crowd. Attention should be paid to the cooperating mass of the stationary crowd being of influence on the structural behaviour. However, the structure should be designed for the governing ultimate limit state situation, which is the whole crowd jumping simultaneously, and causing a dynamic excitation. In the case of this stadium, dynamic excitation lies within the response frequency of the stadium, this can cause resonance within the structure, resulting in large amplifications leading to irreparable damage when damping is insufficient.

**Roof structure**

The roof structure behaves in a very slack manner. Due to wind loading, displacements of almost 1.5 metres are reached, which are unacceptable. Because of the downward hanging roof, a sharp edge is created which causes large wind uplift, resulting in the roof moving upwards. The stiffness of the roof needs to be increased in order to limit displacements due to wind uplift. The membrane covering the stadium needs to be rolled up whenever frequencies larger than the adopted 20 m/s occur. A mechanical system that can be controlled from the highest point behind the seats should be provided for.

**Demountability**

Regarding assembly it is desirable to have as much uniformity within elements as possible. This is achieved due to the shape of the structure and difference in curvature along the pitch, elements within the same layer are not all identical. Logistics on site are a very important measure, that can avoid mistakes and at the same time lead to cost reduction.

Due to weight restrictions with non-guided transport, many, more lightweight elements are required. This has additional benefits, as narrow roads can be navigated more easily, therefore increasing the range of possible locations around Europe.

**FINANCIAL ASPECTS**

Although there are many topics to be elaborated upon more detail before a conclusion can be drawn, some comments can be made about the expenses. Non-recurring costs are within limits and will be spread over time due to repeated use of the stadium. Recurring costs are the main focus to achieve a more economic structure.

To formulate a substantiated conclusion, more detailed research should be carried out on all cost aspects that are of relevance to the stadium. Furthermore structural feasibility should be proven before judging the design on its financial feasibility.

**APPEARANCE**

Some adjustments have been made to the stadium shape, however the characteristic appearance of the Lotus stadium is still retained; a cantilevered shell with a parabolic shape and an undulating boundary due to the optimal ‘C’ values.

Application of a minimal surface roof creates the strong look of the undulating edge as this edge is still clearly visible within the design.

Application of a structure based on volumes and post-tensioned cables going around has potential, but needs further research into its stability during assembly and the way should be dealt with additional forces due to the tensioned cables having an undulating shape.

**IN GENERAL**

With respect to functionality, the idea of the Lotus stadium is the most natural shape that arises due to the optimal sight lines. However, the natural shape regarding function does not make this design the most natural shape in a structural way.
Recommendations

Based on the research done and conclusions drawn from this research, recommendations are formulated. Recommendations are made in terms of safety and comfort, functionality, structural and financial aspects, sustainability and appearance. At the end of this report subjects for further research are listed.

SAFETY AND COMFORT
Regarding safety and comfort, vibrations due to dynamic response should be limited. This issue is explained in the section ‘structural aspects’.

Fire safety
Special attention should be paid to the (fire) safety of the stadium. An entire evacuation of the stadium should be achieved within certain time limits. Sufficient emergency exits should be present, keeping in mind the fact the stadium becomes smaller towards the lower levels. Construction and installation of this facility adds up to the total costs and require additional research.

Installations
The current era has high standards when it comes to the level of information, safety and comfort of spectators. Adequate lighting should be present to illuminate the whole stadium during match time. Screens with live views of the pitch and important information are also integral to a stadium structure. Speakers are needed to provide spectators with comments and announcements.

These installations should be accessible during the operation time of the stadium, in case of the need for maintenance.

FUNCTIONALITY
Due to the design being based on the ideas of a functional design, this topic is in control.

STRUCTURAL ASPECTS
Dynamic behaviour
Regarding the dynamic behaviour of the stadium, adjustments need to be made. Several measures are possible to achieve this and will be explained here. As was mentioned previously, a jumping crowd can cause large displacements whenever the dynamic excitation is in the same frequency as the structural response frequency of the grandstand.

A more accurate model should be used to model the contribution of spectators’ mass to the structural behaviour, together with an estimation of the damping capacity of the structure. This issue lies beyond the scope of this project but is definitely worth further examination.

Problems are avoided whenever the frequency reaches values of above 5 Hz or whenever the response of the stadium is limited by certain measures.

The first assumption needs an increase of the natural frequency of about 5 times. An effective way to increase the natural frequencies of the stadium is to create an increase in structural stiffness. This can be done in several ways which will be explained below.

(1) Creating more (double) curvature in the shell which enhances the shell action and creates more stiffness. Although the increased stiffness in vertical direction is limited, horizontal stiffness is increased, which limits possible displacements in this direction causing in turn less vibration possibilities in a vertical direction.

(2) Applying wire ropes spanning from the edge of the stadium to the ground. By bringing these cables under tension (post-tensioning), upward movements are prevented resulting in damping of the vibrations caused by resonance because an amplification of oscillations is counteracted. To allow this principle to work, tension forces in the cables need to be very large to assure cables are still in tension with deflections of about 200mm. Apart from a large tension force, this influences the shell action in the structure enormously. Large disturbance of natural forces in the structure occurs due to this measure.

(3) Apply opposite curved columns to partly support the stadium structure. An opposing curvature to the parabolic curvature following from the ideal shape, has
favourable forces (section 9.3 figure 061) compared to the current shape. Together with this vertical support (in the direction of the vibrations) this is an effective way to increase stiffness.

Structural stiffness of the stadium needs to be increased to a greater amount to reach values approaching 5 Hz. Adopting several measures at the same time will intensify the effects and may lead to the desired result. However, a five fold increase in natural frequency implies an increase of stiffness by 25 ($5^2$) times.

Besides measures to increase structural stiffness to create an increase in natural frequencies, measures can also be taken to limit structural response.

(a) Increase the damping capacity of the system. Resonance can cause large oscillations when no damping is present; the amplification of oscillations is strongly influenced by damping and can be minimised in a way so that dangerous situations can be avoided. Dampers should be applied at connections or integrated with pre-assembled elements. Together with this, structural mass can be added to increase damping.

(b) Monitoring of the response of the structure should be performed when measures made to increased stiffness and damping are insufficient to ensure a safe situation. Whenever the structure is excited at its natural frequency, measures should be taken and the crowd should be warned about the occurrence of vibrations.

(c) Vibration in a system causes stresses to be increased due to dynamic amplification. This enlarged stress can be designed for to create a safe structure for spectators. However, a warning in advance should be given, because large displacements may arise and spectators will experience unsafe feelings. These measures should be taken together with the application of an increase in damping capacity.

Modelling
The models used during calculation were all wire frames. Steel elements were placed in a triangular grid to approach a shell surface. Calculations of plate models will have a positive influence on the forces, as forces can follow their natural trajectories without disturbance due to a less dense grid. A more accurate outcome will be generated and this might lead to more efficient dimensions of the structure. However, this will be useful when a structural shape is found that has natural frequencies within limits; in this phase it is not necessary to calculate in such detail. Other measures should be taken into account first, to increase natural frequency, or limit consequences resulting due to dynamic loading. On the other hand the triangulated grid as used for calculation very much resembles a plane.

FINANCIAL ASPECTS
Regarding financial aspects no clear recommendations can be formulated yet, as structural feasibility of the stadium should be achieved first. Following, a closer look should be taken into logistics and efficiency on the building site. Efficient assembly has a direct effect on the benefits of the stadium. Non-recurring costs may be higher compared to a permanent stadium, as long as an easily erectable structure arises that has a relatively long life span, without the need for excessive maintenance.

Accessibility
Accessibility is of major importance during the entire time of assembly and deconstruction. First of all the accessibility of all elements and subsequent accessibility during positioning and connection of elements. The stadium in its completed state needs to provide accessibility to the roof structure to ensure access to installation of the roof.

APPEARANCE
Shape
Enlarging double curvature is mentioned several times as a measure to increase structural stiffness. An enlargement of this curvature has several effects on the appearance of the structure. Enlarging radial curvature of the grandstand along the pitch will reduce the number of seats in the stadium, due to the limitation of the 90 metre radius which ensures
good view of the pitch. This means all grandstands are reduced in height. The more circular the curvature becomes, the more the undulating upper boundary becomes less undulating.

The shape is a very important aspect when it comes to stiffness. Achieving stiffness with shape is recommended rather than application of high strength material or large dimensions. Post-tensioning can be applied to a more curved design because in this situation it will be an effective way to increase stiffness in addition to being resistant to fatigue.

Whenever post-tensioning is applied, a smart system should be designed with regard to direct stability during erection.

FURTHER RESEARCH
Summarised, the following topics need further research.

> Structural issues
  Stiffness roof structure
  Increase of natural frequency
  Economic foundation

> Assembly
  Accessibility
  Logistics

> Finance
  Smart systems on site (logistics, assembly order, transport)
  Facilities

> Volumes/post-tensioning
  Applicability USPC
  Assembly without temporary support structure
References
References


Nussli (2011) Sources available at <http://www.nussli.us/projects.html?tx_ttnews%5Bpointer%5D=1&cHash=9a90cd41829d2898ab9e944d589367ec> [June 2011]


Appendices

A1: ROOF
A2: GRANDSTAND
A3: LOAD CASES
A4: MODELLING
A5: FOUNDATION
A6: FINANCE
A1.1 FORCES GRANDSTAND DUE TO ROOF

Grandstand combined with roof configuration 1
Adding the roof to the structure and visualise this in the force polygon, makes clear that hoop forces in the grandstand will change. The arrows in cyan represent the reaction forces from the roof. The vertical part is a sum of all the vertical forces of the roof elements (dead weight). The horizontal component represents the hoop forces present in the connecting part of the roof with the grandstand.

Grandstand combined with roof configuration 2
To close the force polygon of the upper part of the grandstand, more tension in the grandstand is needed due to the compression in the roof element at the connection. Roof configuration 3 does not have horizontal forces at the connection, so only the vertical forces act on the grandstand structure. This supports the choice made for roof configuration 3.
A1.2 ROOF RING FORCES

267 Ring forces of roof configuration 1

268 Ring forces of roof configuration 2

269 Ring forces of roof configuration 3
Grandstand

A2.1 FORCE POLYGON GRANDSTAND

270 Force polygon grandstand configuration 4

271 Force polygon configuration 5

272 Compression in tangential elements of configuration 4 and 5
A2.2 CORNER SECTION
Besides the section along the long edge of the stadium, also the corner section is analysed. This section behaves different because of the smaller height and therefore smaller weight.
A3 Load cases

A3.1 Users Class

Table 26 Users classes *A4.1

<table>
<thead>
<tr>
<th>Klasse</th>
<th>Specifiek gebruik</th>
<th>Voorbeeld</th>
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<tbody>
<tr>
<td>A</td>
<td>Ruimten voor wonen en huishoudelijk gebruik.</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Kantoornuimten</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Ruimten waar mensen kunnen samenkomen (met uitzondering van de onder klasse A, B en D genoemde ruimten)</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Winkelruimten</td>
<td></td>
</tr>
</tbody>
</table>

*C4.1 En NL 1991-1-1, zie 6.3.2 voor opslag of industrieel gebruik.

*OPMERKING 1: Afhankelijk van het te verwachten gebruik, mogen ruimten die doorgaans worden ingedeeld bij C2, C3, C4 zijn ingedeeld bij C5 door een bepaling van de opslag/stakers en de nationale bijlage.

Pakar Grandstand Technical Specifications

Grid: 1.80m x 3.00m or 2.00m x 3.00m

Platform depth: 125mm, 250mm, 375mm

Platform depth: 750mm

Seat spacing: 450mm for Bucket Seat 500mm for Tip-Up Seat

Seat rest: 370mm for Bucket Seat 400mm for Tip-Up Seat

Spacing between 2 rows: 350mm for Bucket Seat 400mm for Tip-Up Seat

Load capacity: 5KN/m2

Dead Load: 0.25KN/m2
**A3.3 PEAK VELOCITY PRESSURE**

**Climate**
- Basic wind velocity
  - wind direction
  - season

**Terrain**
- Mean wind
  - roughness
  - orography

**Building**
- CsCd
  - shape
  - dynamic behavior

---

### Climate

- Basic wind velocity; determined as a function of wind direction and season measured at 10 metre above ground with terrain category II

\[ v_b = c_{dir} \cdot c_{season} \cdot v_{b,0} \]

\[ v_{b,0} \text{ fundamental value of wind velocity (29.5 m/s)} \]

\[ c_{dir} \text{ wind direction factor (1,0)} \]

\[ c_{season} \text{ season factor (1,0)} \]

\[ v_b = 1,0 \times 1,0 \times 29,5 = 29,5 \text{ m/s} \]

### Terrain

- Mean wind

\[ v_m(z) = c(z) \cdot c_o(z) \cdot v_b \]

\[ c(z) \text{ orography factor (flat terrain; } c(z) = 1,0) \]

\[ c_o(z) \text{ orography factor (flat terrain; } c_o(z) = 1,0) \]

\[ v_m(z) = 0,156 \cdot \ln(z/0,003) \times 1,0 \times 29,5 = 4,6 \cdot \ln(z/0,003) \]

\[ v_m(30) = 42,4 \text{ m/s} \]

### Building

- Building type factor \( c_{sCd} \)

\[ c_{sCd} = (1+2*k_{t} \cdot l(z) \cdot \sqrt{(B^2 + R^2)})/(1+7*l(z))^* \]

\[ B^2 = 1/(1+(3/2) \cdot \sqrt{(b/L(z))^2 + (h/L(z))^2 + (b/L(z))^2 + (h/L(z))^2}) \]

A safe estimation of \( B^2 \) is 1.

1. **Roughness factor \( c(z) \)**

\[ c(z) = \text{influence of mean wind velocity on location} \]

\[ c(z) = k_r \cdot \ln(z/z_0), z_{min} \leq z \leq z_{max} \]

\[ z \text{ height of structure (30 m)} \]

\[ z_{min} \text{ minimal height} \]

\[ z_{max} \text{ 200 m} \]

\[ z_{z_{min}} \text{, depending on terrain category (table 12); most negative: } z_0 = 0,003 \text{m, } z_{min} = 1 \text{m} \]

\[ c(z) = 0,156 \cdot \ln(z/0,003) \]

\[ c(z)(30) = 0,156 \cdot \ln(30/0,003) = 1,437 \]

2. **Terrain factor \( k_{t} \)**

\[ k_{t} \text{ terrain factor, depending on roughness length} \]

\[ z_{s} \text{ calculated according:} \]

\[ k_{t} = 0,19 \cdot (z_{s0}/z_{sII})^{0,07} \]

\[ z_{s_{II}} = 0,05 \text{m (terrain category II)} \]

\[ k_{t} = 0,19 \cdot (0,003/0,05)^{0,07} = 0,156 \]

3. **Standard deviation of turbulence \( \sigma_{v} \)**

\[ \sigma_{v} \text{ standard deviation of turbulence} \]

\[ \sigma_{v} = k_{t} \cdot v_{b} \cdot k_{t} \]

\[ k_{t} \text{ terrain factor (0,156)} \]

\[ v_{b} \text{ basic wind velocity (1.1)} \]

\[ k_{t} \text{ turbulence factor (1,0)} \]

\[ \sigma_{v} = 0,156 \times 29,5 \times 1,0 = 4,6 \]

\[ \sigma_{v} \]

*A lot of the factors of which \( c_{sCd} \) exists are difficult to estimate because the unconventional shape of the stadium. The factor cscd will be estimated with the help of a data sheet (Codeform).*
Note that the rounded shape leads to more favourable values for pressure coefficients because the edges are less sharp which causes smaller whirls.

**Table 27** Terrain category

<table>
<thead>
<tr>
<th>Terreincategorie</th>
<th>( z_0 ) m</th>
<th>( z_{\text{min}} ) m</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 Zee of kustgebied met wind aarstromend over open zee</td>
<td>0,003</td>
<td>-</td>
</tr>
<tr>
<td>I Meren of vlaak en horizontaal gebied met verwaarloosbare vegetatie en zonder obstakels</td>
<td>0,01</td>
<td>-</td>
</tr>
<tr>
<td>II Gebied met lage begroeiing als gras en vrijstaande obstakels (bomen, gebouwen) met een tussenruimte van ten minste 20 obstakelhoogtes</td>
<td>0,05</td>
<td>2</td>
</tr>
<tr>
<td>III Gebied met regelmatige begroeiing of gebouwen of vrijstaande obstakels met een tussenruimte van ten hoogste 20 obstakelhoogtes (zoals dorp, voorstedelijk terrein, blijvend bos)</td>
<td>0,3</td>
<td>5</td>
</tr>
<tr>
<td>IV Gebied waar ten minste 15 % van de oppervlakte is bedekt met gebouwen met een gemiddelde hoogte boven 15 m</td>
<td>1,0</td>
<td>10</td>
</tr>
</tbody>
</table>

De terreincategorieën zijn geïllustreerd in A.1.

**Table 28** Values of external pressure coefficients on vertical facades based on a rectangular floor plan **

<table>
<thead>
<tr>
<th>Zone</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>( h/d )</td>
<td>( C_{pe,10} )</td>
<td>( C_{pe,1} )</td>
<td>( C_{pe,10} )</td>
<td>( C_{pe,1} )</td>
<td>( C_{pe,10} )</td>
</tr>
<tr>
<td>5</td>
<td>-1,2</td>
<td>-1,4</td>
<td>-0,8</td>
<td>-1,1</td>
<td>-0,5</td>
</tr>
<tr>
<td>1</td>
<td>-1,2</td>
<td>-1,4</td>
<td>-0,8</td>
<td>-1,1</td>
<td>-0,5</td>
</tr>
<tr>
<td>( \leq 0,25 )</td>
<td>-1,2</td>
<td>-1,4</td>
<td>-0,8</td>
<td>-1,1</td>
<td>-0,5</td>
</tr>
</tbody>
</table>

**Table 27** Terrain category

**275 Zones at vertical facades**

The circular shape eliminates values A and C because of the absence of corners. To determine what zone we should use, the used height and width are of importance.

The height of the stadium \( h \); 30m
The width of the stadium \( d \); 180m
\( h/d = 30/180 = 0,17 \rightarrow 0,17 \leq 0,25 \); this zone is marked with in blue in table 27.

This results in the following factors for zone B, D and E.

\* Note that the rounded shape leads to more favourable values for pressure coefficients because the edges are less sharp which causes smaller whirls.
B = -0.8
D = +0.7
E = -0.3

b1 = width of stadium; 180m
d1 = length/cantilever; 40m
h = building height; 30m
h1 = distance from ground level to canopy; 30m

Within the stadium, zones A and B as depicted in figure x are not applicable. Because the roof (treated as a canopy) is present along the whole stadium, there is no corner area (zone B) and the width can be seen as the width of the stadium. The cantilever of the canopy reaches up to values of 40 metres.

h1/h = 30/30 = 1.0
h1/d1 = 30/40 = 0.75

A3.5 CANOPY AND LOAD COMBINATIONS

Table 29 Net pressure coefficients for canopies

<table>
<thead>
<tr>
<th>Zone</th>
<th>Netto drukcoëfficiënt</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Zone A</td>
</tr>
<tr>
<td></td>
<td>neerwaarts gericht</td>
</tr>
<tr>
<td>h1/d1 ≤ 0.1</td>
<td>1.1</td>
</tr>
<tr>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>0.3</td>
<td>0.7</td>
</tr>
<tr>
<td>0.4</td>
<td>0.7</td>
</tr>
<tr>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>0.6</td>
<td>0.7</td>
</tr>
<tr>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>0.8</td>
<td>0.7</td>
</tr>
<tr>
<td>0.9</td>
<td>0.7</td>
</tr>
<tr>
<td>1.0</td>
<td>0.7</td>
</tr>
</tbody>
</table>

* Voor tussengelegen waarden van h1/d1 en h1/h, meet lineair zijn gecorrigeerd.

* A4.2 NEN-EN 1991-1-4; table NB.8
* A4.3 NEN-EN 1991-1-4; figure NB.6
Table 30  Design values of actions (EQU)\textsuperscript{ref A4.4}

<table>
<thead>
<tr>
<th>Persistent and transient design situations</th>
<th>Permanent actions</th>
<th>Leading variable action</th>
<th>Accompanying variable actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Eq. 6.10)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Unfavourable</td>
<td>Favourable</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1,1 $G_{Kj,\text{sup}}$</td>
<td>0,9 $G_{Kj,\text{inf}}$</td>
<td>1,5 $Q_{k,1}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1,5 $\psi_{ij} Q_{k,j}$</td>
</tr>
</tbody>
</table>

Table 31  Design values of actions (STR/GEO)\textsuperscript{ref A4.5}

<table>
<thead>
<tr>
<th>Persistent and transient design situations</th>
<th>Permanent actions</th>
<th>Leading variable action</th>
<th>Accompanying variable actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Eq. 6.10a)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Unfavourable</td>
<td>Favourable</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1,35 $G_{Kj,\text{sup}}^a$</td>
<td>0,9 $G_{Kj,\text{inf}}$</td>
<td></td>
</tr>
<tr>
<td>(Eq. 6.10b)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1,2 $G_{Kj,\text{sup}}^b$</td>
<td>0,9 $G_{Kj,\text{inf}}$</td>
<td>1,5 $\psi_{ij} Q_{k,j}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1,5 $\psi_{ij} Q_{k,j}$</td>
</tr>
</tbody>
</table>

\textsuperscript{a} For fluid pressures of a physically limited value 1,2 $G_{Kj,\text{sup}}$ will be sufficient.

\textsuperscript{b} This value is calculated with $\xi = 0.89$.
A4

Modelling

A4.1 MINIMAL SURFACE ROOF (VARIANT A)

> Deformation

The deformation is shown in figure 277 and 278. The deflected shape shows the movement under loading. The grandstand along the short edge does not move a lot. The dead weight pushing backwards and the roof pulling inwards are in equilibrium. The circular shape of the oculus deforms into a square under loading. The displacements of the inner roof circle are in plane, unlike the displacement of the shell roof, which is out of plane, upwards and downwards.

Max displacement due to dead weight; 9m
Max displacement due to public load; 4m
Total displacement (sls); 13m
> Axial force
Shell action shows clearly along the edges of the stadium. Forces in the roof structure are relatively small; radial elements in the corner of the roof are in compression. The radial elements in the roof at the grandstand parts are in tension.

Output-in general
Because the braces are needed to create stiffness in plane and minimise sag, the roof is not suitable for a cable roof, because it is concluded that forces are transferred through the roof via tension and compression forces.

> Bending moments
Large bending moments around the oculus. A lack of stiffness causes large opposite deformations and therefore bending moments.

To provide a more direct transfer of the tension forces from grandstand to grandstand through the roof, diagonal elements are added. These elements are placed in both directions, which creates the look of a bicycle wheel (variant c; figure 279).
A4.2 MINIMAL SURFACE ROOF (VARIANT C)

> Deformation

This model shows relative small displacements (figures 286 and 287). The roof along the short edge of the grandstand tends to sag.

Maximum total displacement 1.4 metres.
Axial force

The tension to take up the backward movement of the grandstand shows in the roof elements. Compression in the roof is present in the corners because these parts are pressed inside as can be seen in the deformed shape (figures 288 and 289).

Bending moments

Bending is present in the tangential elements in the grandstand. Around the opening in the roof bending is present due to displacements that are present here (figures 290 and 291).
Foundation

Preferably a demountable foundation is applied to avoid large recurring costs and to be in line with the temporarity of the Lotus stadium. This means a shallow foundation should be applied.

Shallow foundation principles

Shallow foundations are those founded near to the finished ground surface; generally where the founding depth (Df) is less than the width of the footing and less than 3m. These are not strict rules, but merely guidelines: basically, if surface loading or other surface conditions will affect the bearing capacity of a foundation it is ‘shallow’. Shallow foundations (sometimes called ‘spread footings’) include pads (‘isolated footings’), strip footings and rafts.

Shallow foundations are used when surface soils are sufficiently strong and stiff to support the imposed loads; they are generally unsuitable in weak or highly compressible soils, such as poorly-compact ed fill, peat, recent lacustrine and alluvial deposits, etc.

Spread footings

Spread footings consist of concrete slabs that are cast under each pillar or wall which spread the load over a larger area of soil. This is de most simple and cheap technique.

- Pad foundations are used to support an individual point load such as that due to a structural column. They may be circular, square or rectangular. They usually consist of a block or slab of uniform thickness, but they may be stepped or haunched if they are required to spread the load from a heavy column.

- Strip foundations are used to support a line of loads, either due to a load-bearing wall, or if a line of columns need supporting where column positions are so close that individual pad foundations would be inappropriate.

Raft foundations

Raft foundations are used to spread the load from a structure over a large area, normally the entire area of the structure. They are used when column loads or other structural loads are close together and individual pad foundations would interact. A raft foundation normally consists of a concrete slab which extends over the entire loaded area. It may be stiffened by ribs or beams incorporated into the foundation. Raft foundations have the advantage of reducing differential settlements as the concrete slab resists differential movements between loading positions. They are often needed on soft or loose soils with low bearing capacity as they can spread the loads over a larger area.

Soil improvement

These techniques make it possible to support structures without using deep foundations of the conventional type. This is particularly useful for the foundations of roads and railway lines, industrial platforms and buildings, commercial buildings and storage areas, port platforms and airports. If the soil is of poor quality or very recent, or if surface areas are large and loads per unit surface area are moderate these techniques are appropriate and economical. The following techniques are available: dynamic compaction, rubble fill columns, vibroflotation and vertical drains.
Table 32 Cost calculation load bearing structure\textsuperscript{refA5}

<table>
<thead>
<tr>
<th>Load bearing structure</th>
<th>profiel</th>
<th>amount per unit</th>
<th>layer 1</th>
<th>layer 2</th>
<th>layer 3</th>
<th>layer 4</th>
<th>kg/m</th>
<th>kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRANDSTAND</td>
<td></td>
<td></td>
<td>l. [m]</td>
<td>l. [m]</td>
<td>l. [m]</td>
<td>l. [m]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tangential</td>
<td>250x150x8</td>
<td>3</td>
<td>14,5</td>
<td>14,5</td>
<td>13,5</td>
<td>13,5</td>
<td>46,5</td>
<td>886731,75</td>
</tr>
<tr>
<td>Horizontal</td>
<td>250x150x8</td>
<td>3</td>
<td>2,5</td>
<td>2,7</td>
<td>3</td>
<td>3,3</td>
<td>46,5</td>
<td>170357,4</td>
</tr>
<tr>
<td>Diagonal</td>
<td>150x150x5</td>
<td>3</td>
<td>5,2</td>
<td>5,2</td>
<td>5,2</td>
<td>5,2</td>
<td>22,6</td>
<td>157944,32</td>
</tr>
<tr>
<td>Spiders</td>
<td>300x150x12,5</td>
<td>3</td>
<td>7,4</td>
<td>7,4</td>
<td>7,4</td>
<td>7,4</td>
<td>82,1</td>
<td>814711,14</td>
</tr>
<tr>
<td>Edge</td>
<td>250x150x8</td>
<td>565</td>
<td>46,5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Edge beam</td>
<td>250x150x8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROOF</td>
<td></td>
<td>161</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tangential</td>
<td>150x150x8</td>
<td>2</td>
<td>14,5</td>
<td>14,5</td>
<td>13,5</td>
<td>13,5</td>
<td>35,1</td>
<td>446226,3</td>
</tr>
<tr>
<td>Horizontal</td>
<td>250x150x8</td>
<td>3</td>
<td>2,5</td>
<td>2,7</td>
<td>3</td>
<td>3,3</td>
<td>46,5</td>
<td>170357,4</td>
</tr>
<tr>
<td>Diagonal</td>
<td>150x150x5</td>
<td>3</td>
<td>5,2</td>
<td>5,2</td>
<td>5,2</td>
<td>5,2</td>
<td>22,6</td>
<td>157944,32</td>
</tr>
<tr>
<td>Edge</td>
<td>250x150x8</td>
<td>565</td>
<td>46,5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Edge beam</td>
<td>250x150x8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Totaal grandstand + roof</td>
<td></td>
<td>1465</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Totaal gewicht</td>
<td></td>
<td>4268 ton</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>€/kg</td>
<td></td>
<td>3,09</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>verbindingen 10%</td>
<td></td>
<td>427 ton</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>€/m</td>
<td></td>
<td>1,32 mln</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\textsuperscript{refA5} Prices (Breedveld Staal 2010)