MASTER

Reedriden Arena
an architectural and structural design of a new ice skating stadium in Heerenveen

van den Heuvel, P.T.M.

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Reedrinden Arena
An architectural and structural design of a new ice skating stadium in Heereneven
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An architectural and structural design of a new ice skating stadium in Heerenveen

PTM van den Heuvel
0568130

Graduation committee:
dr. ir. S.P.G. Moonen
ir. A.P.H.W Habraken
ir. J.J.P.M. van Hoof

Date: 07-07-2011
Summary

The subject of this graduation project is the design of an ice skating stadium in the city of Heerenveen in which both the architectural and structural aspects are integrated in the design. The relation between architecture and structure is of special interest since this graduation project is a combination of the master programs of architecture and structural design.

The current accommodation of the ice skating facility in Heerenveen (Thialf) becomes outdated by new, more modern, stadium built around the world. In order to facilitate large international competitions in the future, a modern stadium is necessary. Based on the initiative of Thialf and the community of Heerenveen, the new stadium will be located on a plot next to the Abe Lenstra stadium, relatively close to the centre of Heerenveen. This location is characterized by a contrast between the large buildings in the south including the Abe Lenstra stadium and office buildings and the small scaled houses on the north side of the plot. The building addresses to this contrast and the proximity of the Abe Lenstra stadium is considered in the design.

The design combines two 400 meter ice tracks and an ice hockey rink in one building, more precisely in one central space. This central space facilitates the interaction between the different users of the stadium, especially between the professional skaters and the recreational skaters on both tracks. The interaction between the tracks is improved by a shift between the ice tracks. Varying angled columns in the façade of the building create a curved façade creating the sense of movement caused by the shift of the tracks.

Another feature of this central space is the lighting with daylight passing through the translucent roof structure, creating a pleasant atmosphere in the hall. The roof structure is composed of a combination between a tensegrity structure and a pneumatic roof structure, in which the two structural type complement their structural working. The structural design of the roof structure focuses on the tensegrity structure, because this is the most complex part of the structure. The design of the tensegrity structure is based on a study to the planar behavior of the tensegrity structure and a study to the morphology of the tensegrity in relation to the irregular building form of the ice skating stadium. The resulting tensegrity is analyzed and the results are discussed.
Preface

The design discussed in this report is the product of more than a year of hard work. The subject of the design comes from my passion for lightweight structure and the interaction of the architecture and structure of a building. This reason was the basis for my decision to graduate in both architectural design as in structural design, which is reflected in this graduation project.

The design process was a year with many ups and downs. When I started in December 2009, I did not realize the implications of designing such a large building as a stadium. Since the building is so large, many aspects in the design have to be considered and it is impossible to think about every detail of the building. I hope that I covered most of the important aspects of the design in this report.

During the graduation project, I have visited the current facility of Thialf which gave a good impression of an ice skating stadium. I also visited the finals of the world cup skating in 2010, which was an exciting experience and gave a good idea of the festive atmosphere of Thialf.

I would like to thank a few people for their help and support in my graduation project. Firstly, I want to thank my graduation committee for their guidance in the design process: Faas Moonen, Arjan Habraken and Sjef van Hoof. I also would like to thank Gerda Schilder of the municipality of Heerenveen for sharing information about their plans for the new Thialf building. Additionally, I would like to thank my family, friends and especially my girlfriend for their support and their feedback on my ideas.
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1. Introduction

This introduction will explain the choice of the subject of my graduation project. Subsequently, the purpose of this graduation project will be discussed. Finally, the structure of this report will be given to serve as a guideline for reading this report.

1.1 Subject

My fascination for buildings with a large span has determined the subject of my graduation project. This fascination for lightweight structures spanning these large distances only using a small amount of material is based on the large interdependence of the architectural form and appearance and the form and appearance of the structure in these kind of buildings. The interaction between the architecture and the structure of a building is of special interest in relation to my combined graduation project. The way to deal with the interaction between these two aspects is an interesting discussion. The literature survey performed before this design project examines this discussion and different approaches are discussed. Paragraph 1.2 will provide more background about this discussion.

The subject of the design should therefore be a building facilitating the opportunity to design a lightweight structure with a large span. Another aspect in the search for a design assignment was the actuality of the project. Basically, the design subject should be a real assignment with a connection to reality. This resulted in the design of a new ice stadium (Thialf) in Heerenveen. The plans for a new ice skating accommodation are in a relatively far stage and the ideas for the new stadium are translated into concrete requirements. As a result, the problem is concrete and realistic. Additionally, my interest in the speed skating sport was another motivation to select this project. In short, the background of this design project is the age of the current accommodation. Thialf is built in the eighties and is outdated by more modern stadiums around the world. Since speed skating is a popular sport in the Netherlands and the Dutch skaters are one of the best in the world, the accommodation should express this popularity. Therefore, a new stadium is desired to improve the ice skating facilities in Heerenveen. The next chapter will discuss the background of the design assignment in more detail.

1.2 Interaction between architecture and structure

The architectural form of buildings with a large span is more determined by the structure of the building than in most other building types. Since large spans are mostly constructed using lightweight structural principles, the form of the structure and the structural action are closely related. Obviously, the structural form affects the architecture of the building. However, the degree in which the structural form should affect the architectural form is indistinct. In other words, in some buildings the structure is to follow the already designed shape, while in other buildings the structure determines the building form.

In the literature study about the interaction between architecture and structure, a few different approaches to this relation are discussed. On the one hand, the structure could determine the form and appearance of the building, such as the Eiffel Tower. On the other hand, the architectural form and appearance could be followed by the structure. Between these two extremes, other approaches to the interaction between architecture and structure are possible. Figure 1.2 shows a distinction between different approaches made in the literature study. A more detailed description can be found in the literature survey.

Fig. 1.1. Four examples of designers or buildings examined in the literature survey (top left: Hanging model Gaudi; top right: Olympic stadium Munich, Frei Otto; bottom left: Palazzo della sport, Nervi; bottom right: TGV station Liege, Calatrava)
Fig. 1.2. Categorization of the relation between architecture and structure
in the design should be an aspect of the design process. The insights gained in the literature study on the different design approaches and the examination of different designers, who use the interaction between architecture and structure, are used in the design process. In the design process, both aspects should be designed simultaneously in such a way that they become interdependent. In this way, an integration of architecture and structure could be obtained. An example of this approach is the design of the building form using the structure to define the form. An important tool in such a design process are conceptual models. Models are an ideal tool to see the visual consequences of a certain structural configuration. The other way around is useful as well; it is more easy to see in which way the structure could define a certain form.

Summarily, the goal of my graduation project is to design an ice skating stadium in which the integration of architecture and structure plays an important role that will be based on the real design assignment.

1.3 Structure of this report
The integration of architecture and structure is an important aspect in the design of the new ice skating stadium. In this report, these two aspects of the design will be discussed together; especially, in the conceptual design. In this way, the interaction of the architectural design and the structural design will be emphasized. Design decisions made in the process are often based on both architectural aspects and structural considerations.

Before the actual design of the ice skating stadium is discussed, the background of the project and the requirements of the new stadium will be discussed in more detail in chapter 2. Subsequently, the location of the new building in Heerenveen will be discussed in chapter 3, followed by the conceptual design of the building explained in chapter 4. Chapter 5 will discuss a specific aspect of the design largely influencing the eventual appearance and shape of the building. The next chapter will take a more detailed look on the architectural design of the building. In this chapter, the section of the building will be examined in more detail. After the architectural design, the roof, which is an important aspect of the design of a building with a large span, will be elaborated in chapter 7. In this chapter, the lay-out of the roof design will be discussed. Chapter 8 and 9 will take a deeper look at the tensegrity part of the roof structure, of which the structural behavior is analyzed and optimized. Chapter 10 will discuss some other structural aspects regarding the roof structure and supporting structure. Finally, chapter 11 will discuss some of the structural details in the building in order to illustrate the appearance of the structure. The report will finish with an overall conclusion and evaluation of the design process.
2 New Thialf

As is discussed in the introduction, this graduation project will consist of a design for a new ice skating stadium in Heerenveen. This chapter will provide the background of this project and the requirements for the new stadium.

2.1 History of Thialf

The speed skating facility in Heerenveen is named Thialf, which is derived from the name of the loyal servant of Thor (Nordic God of thunder), Thialfi. Thialfi was sportive, smart and a real daredevil.

The first artificial ice rink of Thialf was one of the first artificial ice tracks in the Netherlands. The construction was started in 1966 and the track was officially opened on 14 October 1967. At that time, only the ice hockey hall was covered; the 400 meter track was entirely covered by a large renovation in 1986 after the example of the skating rink in Berlin. As a result, many world records were broken in Thialf in the eighties.

In the summer of 2001, the ice track was fully renovated for the second time in order to update the facilities to the modern standards of speed skating. The ice track was replaced by a more environmental friendly installation, which is ammonia free and has more capacity. Additionally, a tunnel under the 400 meter track was built to digest the middle ground of the track. The ice hockey hall was revised in the summer of 2004 with a new concrete floor and cooling installation.

2.2 New Thialf

2.2.1 Current facility

Thialf is currently the only artificial ice rink in the Netherlands with an A-status, which means that all major international competitions held in the Netherlands are accommodated in Heerenveen. The present facility is composed of two building volumes connected by a central serving area. The two volumes correspond to the spaces containing the 400 and 333 meter track and the ice hockey hall, which can also be used for figure skating and curling. The largest volume accommodates the national and international major competitions and the ice hockey rink is home to the Heerenveen Flyers, who play in the highest ice hockey league of Holland.

The entrance of the complex is placed between the two volumes and is used for the athletes, both amateur and professional. During competition days, this entrance is used to access the VIP-tribune and hospitality spaces as well. The serving area between the two skating halls contains the facilities, like changing rooms, jury rooms, technical spaces for both the skating halls. This area also contains the entrance to the tunnel digesting the middle terrain of the 400 meter track.

The stand of the 400 meter track consists of seatings on the long sides of the track and standing places in the curves. These stands are accessed by local entrances around the building. Spectators access the stands by moving outside the building to the local entrance corresponding to their seating or standing places. An important feature of the present situation is the ambience during the international races. These festive atmosphere is largely created by the spectators in the standing areas of the stand, while the long sides accommodate the more expensive tickets including VIP places.

2.2.1 Shortcomings current facility

Since the current facility is originated in the eighties, with some renovation in 2001, some aspects of the current Thialf building do not meet the modern standards anymore. As a result, the current facility has some shortcomings:

- The entrance to the stands are directly at the building envelope, resulting in a direct connection from outside to the ice hall. The outdoor air flows directly into the hall negatively influencing the indoor climate.
- A large amount of energy is necessary to cool the ice and
2.2 The need for a new ice skating stadium
Because of the mentioned shortcomings of the building and more high tech and faster speed skating accommodations were built recent years, especially in Germany, the current Thialf building becomes more and more outdated. At the moment, the current stadium Thialf is one of the most popular skating facilities in the world in the opinion of both skaters (amateur and professionals) and spectators. Until 2013, Thialf will be able to host a large international tournament every year. However, after 2013 Thialf will no longer be secured of obtaining the large international competitions as a result of large competition between the accommodations.

This perspective fostered the need of a new ice skating stadium in Heerenveen to secure the organization of international competitions. The municipality of Heerenveen, the province Friesland, Thialf BV and Sportstad Heerenveen BV initiated the development of a new ice skating stadium in Heerenveen. The following ambitions for the new building were formulated:

1. Maintaining and developing the international top-class sport accommodation.
2. The new Thialf must become an ultra-modern stadium with a special appearance and it has to be leading in sustainability and innovation.
3. New Thialf has to distinct itself from other ice skating facilities in the world by a second 400 meter training track.
4. New Thialf has to be integrated in the program “Heerenveen Stad van Sport” in which both synergy and integral area development are the central elements.

2.3 Schedule of requirements
The ambitions for a new Thialf building are translated into a schedule of requirements. In this paragraph the most important aspects of the programmatic requirements are discussed. A more detailed overview and a total overview of all spaces required can be found in appendix 2.

2.3.1 Mix of Users
An important aspect of the design of a new ice skating stadium is the combination of different users. The different groups of users have to move separately through the building. For example, the athletes should be able to move separately from the press through the stadium, while they will be able to meet the press at some point for interviewing. Basically, six different types of users could be distinguished: professional athletes, amateur skaters, spectators, VIPs, press and personnel. Amateur skaters include individual recreational skaters, but also skating clubs. Additionally, there are two or three very different types of use of the stadium, which have a very different impact on the appearance and use of the building. Normally, the building is mostly used by amateur skaters who will skate independently or in classes. On the other hand, during event days, the stadium is used by a large number of spectators, VIPs and media in addition to the athletes, resulting in a very different need of the building compared to the daily use. However, these are two extremes and combinations of these two could also occur. For instance, a competition for amateur skaters or youth on the competition track while recreational skaters are skating on the training track.
<table>
<thead>
<tr>
<th></th>
<th>Professional athletes</th>
<th>Amateur skaters</th>
<th>Spectators</th>
<th>VIPs</th>
<th>Press</th>
<th>Personnel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily use</td>
<td>X</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td>Congress</td>
</tr>
<tr>
<td>Skating competitions</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Entertainment events</td>
<td>x</td>
<td>x</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Artists</td>
</tr>
</tbody>
</table>

*Fig. 2.3. Overview of the different users during different types of usage of the stadium.*

<table>
<thead>
<tr>
<th></th>
<th>Dimensions</th>
<th>Surface</th>
<th>Sport</th>
</tr>
</thead>
<tbody>
<tr>
<td>Competition track</td>
<td>400 – 12m</td>
<td>13523 m² (including inner area)</td>
<td>Speed skating, recreational skating</td>
</tr>
<tr>
<td>Training track</td>
<td>400 – 12m</td>
<td>12510 m² (including inner area)</td>
<td>Speed skating, recreational skating</td>
</tr>
<tr>
<td>Ice hockey rink</td>
<td>40 x 60m</td>
<td>2545 m²</td>
<td>Ice hockey, figure skating, curling, recreational skating</td>
</tr>
</tbody>
</table>

*Fig. 2.4. Overview of the ice tracks necessary*
A third, less regular, type of use are entertainment events, such as concerts, trade fairs and flea markets. As a consequence, the building should be flexible to also accommodate these type of events as well. Illustratively, sport zones, changing rooms etc, could be used as the artist zone and the spectator zone will be used in the same way as during skating races.

Important in the design regarding the users is the strict separation of the zone for spectators from the athlete zone; therefore, an different circulation space is required for the spectators and the athletes. Another distinction could be made between two categories of athletes: the amateurs/recreational and the professional athletes. These two categories should have their own facilities and circulation spaces in order to obtain optimal training conditions for the professional skaters. However, some overlap is acceptable and could result in interaction between these two categories of users.

2.3.2 Ice tracks in the building
One of the shortcomings of the current building is the busy time schedule of the 400 meter competition track. Therefore, one of the requirements of the KNSB and Thialf is the combination of two 400 meter tracks in one building. In this way, the professional skaters can use one of the ice tracks to train, while the other one is used by recreational skaters. As a consequence, not only the availability of the track will improve, but also the other circumstances of the training track such as quality of the ice, humidity and temperature will improve as well. Both the competition and training track will have to be of 400 meters length and be composed of two competition lanes (inner and outer) and a warming-up lane. The competition track should have a stand accommodating about 15000 spectators. An athletic running track should be accommodated around the 400 meter track for indoor endurance training and warming-up. In addition to the two 400 meter ice tracks, the building should accommodate an ice hockey rink with 5000 seatings of which 1000 seats may be extendible tribunes. An ice hockey rink could not only accommodate ice hockey, but also figure skating and curling. The ice floor of the hockey rink should have a surface of 30 x 60 meters. Figure 2.4 shows an overview of the different ice floors necessary.

2.3.3 Additional facilities
Besides the ice tracks, the new building should accommodate some other top-class sport facilities. These facilities include a fitness room for strength and endurance training with cardio and fitness equipment and a separated room with three running and sprint tracks of 60 metres (total length 80 metres). The training track will also be surrounded by a running track for long duration training and warming up. This could be complemented with several wellness and leisure facilities, which may also be commercially usable.

In addition to the sport-related facilities, extensive facilities to accommodate spectators, VIPs and press are necessary. Hospitality spaces are necessary to accommodate VIPs. Some of these hospitality spaces may have a direct sight relation with the competition track, while others do not. These last ones are more flexible hospitality spaces which could also be used for other activities such as congresses and meetings. The hospitality room must have an entrance to the VIP seats and must have a collective reception space with cloakroom. Additionally, the stadium should accommodate a press zone with its own entrance, a cloakroom, commentary cells, a control room and a mixed zone in which athletes and press can meet. This mixed zone should be easily accessible from the athlete zone.

2.3.4 Accessibility
Thialf should be easily accessible by car, public transport and slow traffic. 400 parking places must be accommodated directly adjacent to the building and an additional amount of parking spaces in the direct surroundings of the building on short walking distance. The next chapter will dwell on this in more detail.
3 Urban situation

The previous chapter discussed the background of the new ice skating stadium and the requirements to the new building. Obviously, this ice skating stadium should be built in Heerenveen, where the current facility is accommodated. This chapter will take a deeper look on the precise location of the new building in Heerenveen.

3.1 Heerenveen

Heerenveen is a small city in the north of the Netherlands and is the fourth city of Friesland with 28500 residents. The city originates from the peat extraction business in the 16th century. Heerenveen is located on a crossing of two canals used for the peat extraction, namely the Heerensloot and the Schoterlandse Compagnonsvaart. The city is developed along a few roads resulting in a long stretched city, which is relatively long in the north-south direction and small in the east-west direction. This can still be seen on the map of Heerenveen.

Heerenveen is a relatively well-known city in the Netherlands as a result of two important sport facilities in the city. Firstly, the soccer club of Heerenveen, SC Heerenveen, is a constant-performing club in the top league of Dutch soccer. And secondly, the ice skating stadium Thialf, which is the largest ice skating stadium in the Netherlands and hosts large international skating competitions such as world cups, European and World Championships.

3.2 The location

Three different locations were examined to locate the new stadium in Heerenveen, which can be seen in appendix 3. The fallow area directly north of the Abe Lenstra stadium appeared to be the most suitable. This location is adjacent to the highway and therefore has a relatively good accessibility. Additionally, the location is situated in Sportstad Heerenveen, which is an area with a large concentration of sport facilities including the Abe Lenstra stadium. This results in the opportunity to create a relation with the Abe Lenstra Stadium and the other sport facilities in its direct surrounding and share facilities. For instance, the parking space could be shared with the Abe Lenstra Stadium and the offices for an optimal use of space. Additionally, the scale of the skating accommodation fits in the situation because of the large scale of the stadium.

The location is relatively close to the city centre of Heerenveen. The current stadium lies in another part of the city, which is relatively far from the city centre. A shorter distance between the centre and the stadium could strengthen the relation between the city and Thialf. Moreover, Thialf may improve the image of Heerenveen and could become an icon for Heerenveen.

3.2.1 Accessibility

A stadium is visited by large number of spectators at the same time. Therefore, the accessibility of the building is an important aspect of the design. The main three types of accessibility are by car, public transport (busses) and foot (mainly from the train station). As a result of the proximity to the Abe Lenstra stadium, many of these facilities are already present.

The accessibility by car is guaranteed by a northern link to the highway by the Stadionweg/parallel road and a southern link by the Abe Lenstra boulevard. These links are currently designed to digest the soccer stadium on match days and are thus appropriate for the ice skating stadium. However, it is important that events in the two stadiums don't coincide. The same is true for the number of parking spaces, which is already based on the need of the soccer stadium. However, the location of the design contains a number of parking places which must be replaced.

During the daily usage of the building, the area around the stadium will also be accessed by the local roads, such as the road to the city centre. Secondly, the Abe Lenstra stadium is already connected to the train station by a regular bus connection which goes almost directly from the train station to the stadium. This should be
Fig. 3.2. Accessibility of the location for the new Thialf building

Fig. 3.3. Linearity of the morphology of Heerenveen

Fig. 3.4. The two important sightlines to the building's location

Fig. 3.5. The contrast between the small scale buildings in the north and large scale building in the south
enough in the daily use of the building. During events, extra shuttle busses should connect the stadium with the train station to accommodate the large crowds. Additionally, the train station is also on walking distance. Therefore, a part of the spectators/visitors will access the area in the north from the canal.

3.2.2 Linearity of Heerenveen
An interesting aspect of Heerenveen is its linear morphology. This linearity is caused by the parcelization of the polder, which is illustrated by the repetition of the linearity in the patron of ditches in the polders next to Heerenveen. As a consequence, Heerenveen is mainly composed of strips of buildings and streets running southeast to northwest. The location is marked by one of these axes, namely the Abe Lenstra Boulevard. This boulevard is of major importance to the appearance of the surroundings. The boulevard starts in the south with an access point to the highway and ends with a small bush surrounding a villa in the north. Thus, the boulevard lacks some good physical ends. The new skating stadium and its direct context could create one end of the boulevard. This will be discussed in the conceptual design of the building and its context. The location for the new Thialf building together with the Abe Lenstra Stadium forms one of these linear strips of Heerenveen. Aligning the skating stadium with the Abe Lenstra stadium will strengthen the relation with the Abe Lenstra stadium. The ensemble of these two stadiums can be of iconic value for the city of Heerenveen, because Heerenveen is well-known for its soccer club and skating stadium. Consequently, the new ice skating stadium should reinforce this ensemble and therefore orientate to the Abe Lenstra Stadium.

3.2.3 Sightlines
The close proximity of the city centre of Heerenveen provides the possibility to create a sightline from the centre to the location. These sightlines could strengthen the relation between the city and the stadiums in the same manner as the Philips stadium is visible from the centre of Eindhoven. The ensemble with the Abe Lenstra stadium should be the iconic image of the Sports-tad area. Another major sightline is the Abe Lenstra Boulevard, because this axis largely determines the image of the surroundings. Most people approach the building from this side, so it will be the first glance of the building for most spectators. This is the same side of the building as in the sightline from the city centre.

3.2.4 Contrast north and south
Another important aspect of the site is the contrast between north and south. The north side of the location is marked by small-scale houses along a traditional road. These house are mostly two or three storied with a sloping roof. On the contrary, the office buildings along the boulevard and soccer stadium marking the south side of the location have five or six stories. Moreover, the width of the boulevard strengthens this large-scale appearance. Additionally, the east side is marked by the highway and an ensemble of three office buildings. The design for the stadium should anticipate to this contrast between large-scale and small-scale building.

3.3 The design
The aspect discussed in the previous paragraph are used in the conceptual design for the urban situation. As is mentioned, the new skating stadium should be aligned with the adjacent soccer stadium resulting in a relation between these two stadiums in which none of them is prevailing. Between the two stadia, an urban square arises with the potential to become an iconic image of the city Heerenveen, especially for its sport facilities. Although the stadium conforms to the linear character of Heerenveen, the building has a small rotation in order to create a more playful urban situation and to create a larger urban space in front of the main entrance. This public square is necessary to accommodate the large crowds visiting the stadium at the same time. For the same reason, an additional urban square on the other side of the building is designed to disperse the spectators over different squares.
The public square in front of the building marks the end of the boulevard. The square is defined by new building volumes which complete the axis of the boulevard and the small-scaled street in the north. The public space on the other side of the building is defined by the three existing office buildings and additional new building volumes. In this way, a more fragmented urban context is created with the capacity to accommodate large numbers of spectators, while offering a more small-scaled spatiality in daily use as well.

In this concept the Abe Lenstra Boulevard will be the main access to the stadium area with its link to the highway in the south. A parking garage will be located under the square in front of the stadium. This garage will serve as the necessary parking places in the daily situation. During competition days, this parking garage will mainly be used by athletes, officials and VIPs. Other parking places in the direct surroundings will be used for the spectators. The highway link in the north will be an additional access to the area and to the parking places in front of the stadium. People coming from Heerenveen itself or from the train station by foot can access the area in the north or in the south-west.

The contrast in the urban context between the small-scale building in the north and the large-scale building in the south is used in the design. The building will adjust to the small-scale houses in the north to reduce the impact on these houses and street. Therefore, the north side of the stadium will have less height. On the other side, the height of the south side of the building will be larger to obtain a relation with the Abe Lenstra stadium and to conform to the height of the office buildings. As a result, the building emphasizes the square and ensemble between the skating stadium and the soccer stadium. This side of the building with the largest height is also the rounding of the building which is visible in the sightlines from the city centre and on the boulevard. From the boulevard, the rounding is only visible due to the rotation of the building, which marks the beginning of the urban square and therefore divides the boulevard from the square, making this rounding a very characteristic image of the building. It will be the first acquaintance with the building for people coming from the boulevard or the city centre and for people coming with the bus or from the northern highway link.

Summarily, the stadium will have a sloping form resulting from adjusting to the urban context. The south side with the largest height will be an important aspect of the design since this image of the building is most visible from important sightlines. The north side of the building, however, will have to be reserved and should have less impact on its direct surroundings. These aspects will be used in the conceptual design which will be discussed in the next chapter.

Left: Fig. 3.6. The urban concept of the ice skating stadium
Bottom: Fig. 3.8. The sloping building form based on the contrast in scale between the north side and south side of the plot
4 Spatial concept

The previous chapter discussed the urban situation of the new ice skating stadium and how the building will respond to this context. These aspects will be used in the conceptual design of the stadium, which will be explained in this chapter. Firstly, the method used in the design process will be described to illustrate the design process, especially in relation to the integration of architecture and structure. Secondly, the configuration of the ice tracks will be discussed, because these ice floors will largely determine the building form due to their size. Another very important aspect of such a large building is the structural principle of especially the roof structure, since this will determine the shape, appearance and character of the building. Therefore, this will be discussed in paragraph 4.3. The configuration of the tracks and the structural concept in addition to the aspects from the urban context will result in a conceptual design of the building, which will be explained in paragraph 4.4.

4.1 The role of conceptual models in the design process

An important issue in the design process is the integration of architecture and structure in the building design. However, it is difficult to design the building both architecturally and structurally at the same time. Therefore, conceptual models were used to visualize the spatial consequences of different design considerations and especially for the different structural types examined. In this way, it was easier to work on the spatial design and the structural design at the same time in the conceptual design phase.

A few of these models are shown on the other page. These models show only the important elements of the building, such as the ice tracks and important structural elements. They clearly show the main structural principle and the building volume resulting from it.

Fig. 4.1. Selection of models made in the design process

4.2 Configuration of the tracks

4.2.1 Stacking the ice floors

As is mentioned in the program of requirements, there are two 400 meter ice tracks required in the ice skating stadium. Two 400 meter ice tracks in one building is a completely new challenge since this will be the first building in the world with two ice tracks in one building. Normally, the 400 meter ice track is placed on ground floor level with additional ice tracks in the inner area surrounded by a hall built over the track. However, the combination of two tracks results in new possible spatial qualities and forms of interaction between the tracks.

The two ice tracks should be on top of each other instead of next to each other to facilitate the interaction. It also minimizes the footprint of the building and roof structure. The top track must be the competition track, because this track should have clear views from the stands to the whole track. Therefore, this part of the hall should have a clear span. This is less important for the training track, where structural elements supporting the top track are allowed. If the training track is on top of the competition track, a clear span is needed for the bottom track resulting in a much more problematic structure of the top track.

Interaction between ice tracks

The main reason for the combination of two ice tracks in the building was that athletes and recreational skaters could use the tracks at the same time without hindering each other. This means that the building is used by both professional skaters and recreational skaters at the same time. Interaction between these two types of users could improve the experience of skating, both for the athletes and recreational skaters. While skating, the amateurs can see or hear the pros training and compare their speed to the pros or learn something of the training patterns of the pros. On the other hand, the professional athletes could pick up some of the pleasure of the amateurs which can bring them back to the pleasure in skating.

These relations could be obtained by an open space in the inner area...
Fig. 4.2. Sketches of the combination of two ice tracks. Left: during normal days Right: during competition days.

Fig. 4.3. Image of the central space from the ice hockey track.
area of the stacked tracks. As a consequence, the athletes on the competition track could look at the amateurs on the training track underneath, while maintaining privacy because of the difficulty to look upwards. It is not important that the sights to the other track are not clear, more important is the feeling that there are other tracks in the same space. This feeling is a large factor of the interaction between the tracks. The competition track offers the best training conditions to the athletes corresponding the competition circumstances. Additionally, the amateur skaters could hear the sound produced by the athletes and the other way around. They may even catch a glance of their heroes on the competition track.  

In situations when the profs are not using the competition track, this track can be used by the recreational skaters as well, for example for club trainings or individual training. The interaction between the tracks changes in these situations to an interaction between the more skilled skaters on the competition track and the rookies underneath. This results in a comparable interaction quality.

**Ice hockey track**

The building not only contains two 400 meter tracks, but also an ice hockey track surrounded by stands. Ideally, this ice hockey rink should also be integrated in the design. This integration could be obtained by placing the hockey rink in the inner area of the training track. Consequently, the rink is in the central void extending the sight and sound relation between the 400 meter tracks to the hockey rink. In this way, all the ice floors in the building are integrated in one large space, while the different tracks have their own spatiality and ambiance. Thus, the hockey rink will be positioned in the inner area of the training track; there is enough space around the ice rink for a stand with enough seating. The hockey rink with stands lies as a tub in the inner area, keeping the relation of the training track with the void intact. The stand of the ice hockey rink ends on the same level as the training track, which makes it possible to enlarge the stand over the training track during events. The extra seating created has only a hindered sight due to the columns supporting the competition track. However, this will not occur very often and is only used during special events.

### 4.2.2 Shifting the ice floors

The two 400 meter tracks are now stacked straight on top of each other. However, this will result in a relatively dull spatiality. A different kind of configuration could introduce a more interesting spatiality. For instance placing the competition perpendicular on top of the training track or shifting the tracks in longitudinal or perpendicular direction. The first will result in a difficult interaction between the two ice tracks, since the skaters will see flashes of other skaters in another direction, which is confusing. Shifting the tracks in perpendicular direction results in a difficult position of the structure and building. On the other hand, shifting the track in longitudinal direction will result in a more logical building layout. These different variants will not be discussed in more detail here; only the configuration with a shift of the tracks in longitudinal direction is interesting. By shifting the two tracks in longitudinal direction, the relation between the two long tracks could be improved. As a result of this movement, in some places the training track gets out of the competition track causing a more clear sight to one of the curves of the training track. In other words, the training track will pass through the central open space. The skaters will be fully visible for a short moment. On the other hand, another part of the track will be less visible from above, because it disappears under the stand of the competition track. Therefore, the shifting the tracks will create a differentiation of the sight relation between the two tracks. The difference in spatiality resulting in the training track is no problem, since this track is only used by recreational skaters. More precisely, the changing spatiality creates a more exceptional skating experience compared to other ice tracks. Additionally, the resulting longitudinal section corresponds with the sloping contour which emerged from the urban context, as could be seen in figure 3.8. The side of the building with only the training track needs less height than the side with competi-
Fig. 4.4. Firstly, the two tracks are stacked on top of each other. Subsequently, a swift between the two tracks is applied. And finally, the ice hockey track is situated in the center of the two tracks.
tion track with its stands. Therefore, the shifted tracks would also lead to a building with a sloping character. To strengthen this sloping character, the stands will be asymmetrically. More precisely, the stands in the northern curve of the track have less rows and, thus, less height. The southern curve have more height and can accommodate much more spectators and therefore suitable for the festive ambiance.

Another advantageous consequence of the shift between the two tracks is a non-overlapping zone arising underneath the competition track. As a result, the inner area which give to access the ice track is created in a natural way. Additionally, this zone is extremely suitable for the changing rooms and other facilities for the sportsmen. The inner area of the competition track is easily accessible from this point with short walking distances. This zone could serve as the linking area between the two 400 meter tracks.

4.2.3 Other spaces
The ice tracks are the most important spaces in the building; the other spaces are serving these ice tracks. The stands follow the shape of the competition track in order to obtain the best sight on the track. These stands create enough space underneath to accommodate the other facilities and spaces necessary. Moreover, by placing all the spaces underneath the stands a clear building volume could be obtained without all sorts of volumes stuck to the main building volume. Another reason is the close distance between the facilities and the ice tracks, which makes all sorts of relations between these spaces and the tracks possible. For instance, the restaurant could offer views on the bottom ice track or the sprint track could be next to the ice track.

4.3 Structural concept
As is discussed before, the upper competition track will have a large clear span. As a consequence, the structure of the clear span will have a large influence on the architecture of the building and its shape. Moreover, the integration of architecture and structure is a leading aspect of the design process. Thus, the structural concept should be part of the design concept.

In the design is sought to a lightweight structure to span the large distance, since these kind of structures span the distance more efficiently and economically. Appendix 4 shows an overview of different types of lightweight structural types. However, before the different structural variants examined are discussed, the separation of the structure of the competition track and the roof structure with its support structure is explained.

4.3.1 Separating the structure of track and roof structure
Initially, a starting point in the design process was to use one of the tracks as a structural element in the building structure. As a result, an exciting interaction between structure and architecture of the building could be obtained. Some of the models resulted from this study are shown in figure 4.1. Illustratively, in one of these models, one track is used as a counterweight to the tensile roof structure. The weight of the track resulted in a tension force in the roof structure. In another model, the track was used as a compression ring.

However, these models did not result in practically feasible structures. An important conclusion was that the combination of the competition track with the load-bearing structure is undesirable, because of deformations in the load-bearing structure resulting in deformations of the track. As a matter of fact, minimal deformations of the track are allowed since this will negatively affect the quality of the ice, which is one of the most important aspects of an skating stadium. As a consequence, it is desirable to separate the structure of the ice track from the rest of the building. In this way, the track could have its own structure and deformations. More generally, the ice track could therefore not be used as a structural element in the load-bearing structure of the whole building.

4.3.2 Compressive roof structure
The roof structure could be made of a structural type, which load-bearing capacity is based on compression, such as arches,
Fig. 4.5. Model of the building with a compression roof structure

Fig. 4.6. Sketch of the building with a compression roof structure

Fig. 4.7. Model of the building with a saddle shaped cable net structure

Fig. 4.8. Sketch of the building with a saddle shaped cable net structure
shells and vaults. Since their load-bearing capacity is based on arch-working, these kind of structures have a convex form. This convex form could reinforce the concept of a sloping form with less height in the north and more height in the south, as discussed in previous chapter. The curvature of the roof creates a sense of movement to the front of the building, coinciding with the shift of the tracks. The convex form of the roof structure will also affect the spatiality of the large hall with the competition track. As a result of the convex form, the height to the centre of the space increases, creating a spacious atmosphere. The pattern of the structural elements in the roof could create a very characteristic and even impressive space, which could be seen in the buildings of for instance Luigi Nervi. However, the largest height of the internal spaces is more needed above the stands than in the centre of the building with its large void to the ice hockey rink. Additionally, the space in the hall is very large, which makes it more difficult to maintain the air quality necessary for the ice. Moreover, the warm air in a interior space with a convex ceiling will accumulate in the middle high point of the roof. On the other hand, a compression roof will have more mass and could therefore be isolated more easily.

For an optimal arch working of the structure, the curvature of the roof should be relatively large resulting in a very large height of the internal space. This also affects the building height in its urban context. Too much height will result in a disturbance of the rural character of the north side of the plot and in a more overwhelming interaction with the soccer stadium. Reducing the height of the roof compared to the optimal height will result in a less efficient roof structure, with large lateral forces in the supports. These lateral forces could be balanced, for instance, by a tension ring at the base of the roof structure or by cables running through the interior space.

Another aspect of a roof structure with compression elements is that compression is generally less efficient than tensile forces in the structure. This is caused by the fact that compression elements are subjected to buckling instability. As a consequence, more material is necessary than strictly necessary to carry the forces itself. Therefore, compression structures are basically less efficient than tension structures. Conclusively, these kind of structures based on arch working are possible for the design of the roof structure. However, these structures will result in a large height of the internal space. Additionally, structures based on tension will result in a more lightweight structure. Therefore, structures based on tension will be examined before deciding which structural type is used.

4.3.3 Cable net roof structure

A cable net structure is a structural type with a load-bearing capacity only depending on tension. It is a tensile roof structure consisting of a mesh of cables running in two separate directions. The cables in these two directions must have opposite curvature in order to obtain a stable roof structure, because opposite curvature will allow the structure to resist both downward as upward forces. These opposite curvatures result in a double curved surface with two high points and two low points; this type of surface is called a saddle shape. However, applying this a saddle form to the sloping asymmetric building form of the conceptual design is problematic. In a saddle form, the high points are opposite to each other, while in the asymmetric building form the highest point is opposite to the lowest point. By adapting the building form to a saddle shape, the middle point will be the high points. As a consequence, the sloping concept is not clearly visible anymore. Additionally, the characteristic rounding of the building will get less importance and the relation with the soccer stadium will decrease in strength. This effect is increased by the fact that the difference in height between the high and low points should be large enough to create enough curvature in the cable net. More curvature of the cables results in smaller forces in the cables and thus in a more efficient structure. The degeneration of the original form is illustrated by the model in figure 4.8. In this model the curvature of the cable net is too small for a stable roof structure; the saddle shape should be even more pronounced, while the
Fig. 4.9. Model of the building with a cable net structure supported by an arch in longitudinal direction

Fig. 4.10. Sketch of the building with a cable net structure supported by an arch

Fig. 4.11. Spatiality of the indoor space comparable to the cable net with an arch (Olympic Gymnasium Tokyo - Kenzo Tange)
Another aspect of this structural type is the spatiality of the interior space of the competition hall. The height of ceiling will be minimised by a cable net, which is, on the one hand, advantageous for the energy consumption of the building, but on the other hand it will obstruct the sight from the stand to other places in the stadium. In other words, the spatiality and atmosphere of the stadium hall is affected by the small height of the ceiling.

Conclusion, the spatiality of the interior competition space underneath the roof structure and the exterior form of the building will be affected too much by a saddle shaped cable net structure. Therefore, this structural type is not suitable for the design.

4.3.4 Cable net structure supported by an arch
A variant on the saddle shaped cable net structure is a cable net structure supported by an arch. The central arch divides the roof structure in two cable nets, resulting in two saddle shapes on either side of the arch. The effect of the arch is that the cable net is pushed up, creating more structural height. As a consequence the curvature in the cable nets is increased, creating a more efficient structure. Additionally, the height of the interior space underneath is also increased, which improves the sightlines in the stadium compared to the saddle shaped cable net. The arch will be a large element dominating the appearance of the building, which can give the building character and an iconic value. The form of the arch is corresponding with the concept of the sloping form, but since it will have a symmetric form, it will not create more height in the south and less in the north.

Figure 4.10 shows a model with an arch in the longitudinal direction and with a sloping form. In this model, the arch is growing out of the building form in the north. However, the south side of the building is more problematic. The arch should continue till it reaches the ground because of the lateral support forces. However, in that case the arch will come out of the building or the building would have the same kind of facade on both sides. The first will create a strange appearance of the arch in relation to the rest of the building. The second is not in line with the concept of more height of this side of the building and will not result in the characteristic appearance of the building desired for this part of the building, because of its relation to the soccer stadium and the sight lines.

However, the largest disadvantage of the structure with an arch is the spatiality of the interior space beneath it. Due to the arch and the saddle shape of the cable net, the ceiling firstly lowers above the stand and then rises to the arch, as can be seen in the sketch in figure 4.9. This results in two spatial problems. Firstly, the lowering of the ceiling above the stands will create a narrow feeling and a claustrophobic spatiality. Secondly, the sudden increase in height in the centre creates a strange spatiality of the stadium space. In other words, the consequence of this structural principle is far from ideal regarding the interior spatiality. Conclusively, the cable net structure supported by an arch results in an awkward looking element in the building in addition to a bad quality of the interior space underneath. Therefore, this type of structure will not be used in the design.

4.3.5 Globally pressured pneumatic roof structure
Another structural type based on tension forces in the structure resisting is a pneumatic structure. A pneumatic structure is a membrane structure in which the membranes are stabilized by the pressure of internal compressed air. The inner overpressure pre-tensions the membranes resulting in the load carrying capacity of the structure. There are two main types of pneumatic structures, namely global pre-tensioned pneumatic structures and local pre-tensioned pneumatic structures. In global pneumatic structures, the interior of the building is subjected to overpressure pressing the membrane outwards resulting in pre-stressing of the membrane. As a result, a very efficient structure is obtained with only the pneumatic membrane, eventually strengthened by cables, as structural element. A large advantage of membranes as structural elements is their translucency. They allow daylight to pass through the membranes creating an interior space lightened by natural daylight,
Fig. 4.12. Sketch of the building with a globally pre-stressed roof structure

Fig. 4.13. Model of the building with a lens-shaped pneumatic roof structure

Fig. 4.14. Sketch of the building with a lens-shaped pneumatic roof structure
which gives a more pleasant atmosphere than artificial lighting. Moreover, the natural daylight will give a more outdoor feeling to the ice track space. In this way, the skaters will be more connected to outside. During competition days, however, the natural daylight could cause problems with the lights and television cameras. This has to be solved in the design. However, this structural type is not suitable for a building with ice skating tracks. The best skating conditions can only be obtained with low air atmospheric pressures, because it decreases the air resistance and thus reduces the air friction. Since a globally tensioned pneumatic roof structure acquires an high interior atmospheric pressure, this structural type is not suitable in the design of an ice skating facility. However, the idea to lighten the stadium space with natural daylight can be used, because it provides extra qualities to the stadium.

4.3.6 Pneumatic lens-shaped roof structure
Instead of a globally pre-tensioned pneumatic structure, it should be possible to use a closed pneumatic structure, in other words, a local pre-tensioned structure. This type of structure could be compared to an air cushion or an air mattress. The roof structure consists of two layers of membranes, which are tensioned by the pressure of the air compressed between them. As a result, a lens-shaped roof structure is achieved, with an lower and an upper membrane layer. The upper membrane layer will create a convex exterior roof form, which could reinforce the concept of a sloping building form in the same way as the compression roof structures. The curvature of the upper membrane largely influences the exterior appearance of the building. A low curvature will reduce the visibility of the membrane and a larger curvature will give the building a bloated appearance. With the right curvature, the roof appears to come from the facade at the back of the building and creates an head at the front of the building, which emphasizes the relation with the Abe Lenstra stadium. Additionally, the building shape obtains a sense of movement, which is also apparent in the shift of the tracks and in the speed of skaters on the ice track.

The spatiality of the interior space underneath the lower membrane is less preferable. On the one hand, the membranes will allow natural daylight to pass through and lighten the hall with natural daylight. On the other hand, the lower membrane will result in a low ceiling height if the stadium hall and in some places blocking the sightlines to the other side of the stadium. The low ceiling results in a oppressive atmosphere in the hall. Additionally, the curvature in this membrane is relatively small. Since the membrane stress increase with a decrease of curvature in the membrane, this will result in large membrane forces. However, the curvature cannot be increased, because this will result in decrease of ceiling height of the skating hall. This will increase the oppressive spatiality of the interior space. On the other hand, a low internal space will decrease the difficulty of controlling the air quality and temperature. Conclusively, the form of the upper membrane fits well in the concept of the sloping building form and the shift of the ice tracks. However, the lower membrane layer will result in a less preferable spatiality of the interior space and has a structurally inefficient form with low curvature.

4.3.7 Tensegrity dome structure
A tensegrity structure is another type of structure of which the load-bearing capacity is characterized by tension forces. A tensegrity structure is a structure with discontinue compressive elements connected by continuous tension elements. In other words, the compressive elements are only connected to tension elements and these tension elements provide the continuity of the system. As a consequence, the elements could be dimensioned according to the characteristic of the force in the element. In other words, tensile elements could consist of cables and compressive elements of struts. This results in a lightweight structure. A tensegrity dome has a convex roof form with relatively low curvature. Therefore, the influence of the roof form on the exterior appearance of the building is relatively small. Illustratively, most
Fig. 4.15. Sketch of the building with a tensegrity dome

Fig. 4.16. Model of the building with a combined structure of a pneumatic element and a tensegrity structure

Fig. 4.17. The roof structure is composed of a combination of a pneumatic element and a tensegrity structures
parts of the roof will be invisible from street level. Regarding the concept of a sloping building form, this structure will fit into the concept. However, it will not really strengthen the concept.

Interiorly, the appearance of the ceiling is dominated by the compressive roof elements and the ceiling material, while the tensile elements, mostly cables, will be relatively unobtrusive due to their small size. The discontinuity of the compressive elements and invisibility of the cables will create a mystic appearance of the structure, because it looks unnatural to not connect the compressive elements. Since the roof material is on top of the tensegrity structure, the compression bars and cables will run through the space beneath the structure. However, this will have a minimal influence on the spatiality, because the ceiling height is more important for the spatiality. This aspect is most applicable to the top of the stands, where the cables are relatively low, but the ceiling height will create a more spatial feeling. Additionally, tensegrity domes are often covered with membranes or pneumatic cushions as roof material, because of their low weight. Therefore, natural daylight could enter the large stadium hall creating a natural lit ambiance.

Structurally, an important aspect of this structural system is its flexibility under loads, especially asymmetrical loads. This flexibility is caused by the principle of structural action of a tensegrity structure. As a consequence of this flexibility, large deformations visible to the visitors could appear. The movements of the roof could also create cracking sounds. Another aspect is the insulation of the roof structure. The pneumatic cushions will have a good insulation ratio, but the places where the cushion meets the cables and compression bars, the insulation will be relatively small.

Conclusively, a tensegrity structure is suitable for the design, but it has some disadvantages. The exterior roof form will not strengthen the concept of the sloping building shape in its context compared to the pneumatic roof structure. Another disadvantage of the structure is the flexibility of the tensegrity. However, the tensegrity structure resulted in a more spacious atmosphere lightened with natural daylight. The next step is to examine a combination between a tensegrity structure and a pneumatic structure.

4.3.8 Pneumatic roof structure combined with a tensegrity dome

There has been shown a pneumatic lens shaped structure is not appropriate due to the low curvature of the lower membrane and that a tensegrity structure less preferable due to its flexibility. However, if the convex exterior appearance and lightness of the pneumatic roof could be combined with the interior qualities of the tensegrity, an efficient elegant structure could be created. In other words, the top (outer membrane) of the pneumatic structure will be combined with the tensegrity structure. As a result, a variant of the lens shaped pneumatic roof structure is created in which the lower membrane is pushed upwards by the tensegrity structure. Consequently, the curvature of the lower membrane will be increased.

As a consequence of using the exterior appearance of the lens shaped pneumatic structure, the roof form will strengthen the sloping building concept and the building form will create a sense of movement corresponding to the shift between the tracks and the nature of the activity in the building. As is mentioned earlier, the convex roof form will emphasize the relation with the Abe Lenstra stadium and strengthen the ensemble.

In the same way, using the interior qualities of the tensegrity structure, the interior space has a spacious atmosphere. The structural system of cables and bars will dominate the ambiance of the hall.

Moreover, this roof structure will allow natural daylight to pass through the structure to enlighten the large stadium hall. This will result in a more pleasant atmosphere on normal days; thus, in daily use. Additionally, the use of different membrane layers enables extra possibilities. With a combination of three membrane layer separated by different overpressures, of which one layer has a positive and another a negative pattern, the opacity of the structure could be adjusted. The roof could block all sunlight causing the hall to darken. A more detailed description of
Fig. 4.18. Sketch of the building form with the varying steepness of the façade
this principle can be found in paragraph 8.2.3. Another possibility is to block direct sunlight and passing through natural daylight similar to roof structures passing through the northern light. Structurally, these two structural types can complement each other. The constant air pressure in the pneumatic lens shaped element will result in a constant loading of the tensegrity structure. This will reduce the effect of the flexibility of tensegrity structures, because the loads on the tensegrity will be constant. Asymmetrical loads on the upper membrane, such as wind loads, will cause the membrane to deform. However, the air pressure inside the element will remain relatively constant resulting in a constant load on the tensegrity, which will therefore deform minimally. This principle will be discussed in more detail in paragraph 7.1. On the other hand, the structural efficiency of the pneumatic element is improved since the curvature in the lower membrane is enlarged by the tensegrity structure. Conclusively, this combination of a tensegrity and a pneumatic lens will result in large opportunities for the architectural and structural quality of the building’s design. The outer membrane will reinforce the sloping form of the building in its surroundings. The combination with a tensegrity will result in an interesting spatiality of the competition hall. Additionally, the combination could result in an interesting structural behavior in which both systems complement each other. And finally, the pneumatic elements introduces a number of opportunities regarding light, isolation and appearance.

4.3.9 Conclusion

Important aspects in the design of the roof structure are the exterior form in relation to the concept of a sloping form with less height in the north and more height in the south and the sense of movement created by the building shape. Subsequently, the spatiality of the interior stadium space, which is largely determined by the shape of the roof structure, and the admission of natural daylight into the interior were important aspects. Based on the variants shown, a structure which is composed of a combination of a pneumatic structure with a tensegrity structure has come forward regarding these aspects. In comparison to, for instance, the compression structure variant, this structure will offer more opportunities regarding light and interior spatiality. Additionally, a very efficient structure can be obtained with this combination. Figure 4.17 shows the conceptual idea of the combination of a pneumatic lens shaped element with a tensegrity structure.

4.4 Building shape

The concept of the sloping building form in combination with the shift of the two tracks and the concept of the roof structure, resulted in the building shape. The building shape is a result of interaction between the design of the structural concept and the spatial building shape. The building expresses the movement caused by the longitudinal shift of the two tracks. This effect is obtained by a comparable shift between the roof structure and the footprint of the building. As a consequence the façade has a varying angle along the building. This effect reinforces the idea behind the sloping form of the stadium. The façade in the north side of the building is leaning backward, forming a sort of roof, decreasing the sense of height of the building and creating a reticent appearance of the building. On the other hand, the façade of the south side leans over, which increases the sense of height. Moreover, the steepness of the façade is largest where the height is largest, which is the curved side adjacent to the other stadium where the buildings have an iconic relation. The façade of the long side forms a transition between the steep leaning over façade in the south and the backward leaning façade in the north. Conclusively, the exterior of the building with the varying steepness of the façade expresses the move of the ice tracks and reinforces the sloping contour of the building. Additionally, the building shape, as is shown in figure 4.18, is a clear building volume, which is an important characteristic of a stadium. The iconic image of a stadium building will be strengthened by a clear building form.
Fig. 5.1. Increasing the amount of material in the middle straight section of the ring structure

Fig. 5.2. Extra compression struts are added in the straight section
5. Undulation of the building

In the previous chapter, the conceptual design of the ice stadium is discussed. This conceptual design is composed of a tensegrity combined with a pneumatic element roof structure. This chapter will discuss the consequence of this idea on the structure supporting the roof. Firstly, the necessity of a compression ring will be discussed followed by the architectural consequence of the compression ring. Finally, the structural concept for the rest of the support structure will be discussed.

5.1 Compression ring
The roof structure will be composed of a combination between a tensegrity structure and a pneumatic roof structure. Therefore, the support structure carrying the roof structure will be loaded by a lateral force. These lateral forces can be balanced by a compression ring; the working of a compression ring will be examined in this paragraph. The following paragraphs will discuss the influence of the compression ring on the design and support structure.

5.1.1 Problem of the building form on the ring action
In a perfect circular form, the lateral loads on the compression ring will result in a constant compression force in the compression ring. However, the building form is not circular, but more longitudinal with a relative straight section between two circular ends. As a consequence, the building form is not optimal for an efficient structural action of the compression ring. The lateral forces acting on the straight section of the ring structure cause bending moments in these section. Therefore, the ring structure is not actually a compression ring, but more or less a combination of two half compression rings connected by two beam sections.

In order to make more use of the ring structure, the ring structure could be improved. Generally, more curvature will create a more efficient ring structure, because a larger curvature will result in a smaller compression force in the ring by a constant lateral load acting on the ring. Projecting this on the building form, the curvature of the middle section should be increased to obtain a more efficient structure. However, creating a large elliptical or circular ring will change the building form too much. The complete architectural appearance of the building would change comparable to the effect of the cable net structure on the building form. Therefore, the different variants of the ring structure, which will be discussed in the following paragraphs, will be constrained to approximately the building form.

5.1.2 Increasing the amount of material in the ring structure in the middle section
Principally, the form of the ring structure could follow the form of the roof structure of the concept design discussed in the previous chapter. In this case, the ring structure, as is mentioned, is composed two half compression rings connected by a beam section loaded with bending moments. The beam section is not only loaded with the bending moments caused by the support forces of the roof, but also by the compression force transferred between the compression rings. The amount of material, most likely steel, of the beam section will have to be largely increased in order to carry the bending moments. This results in a less efficient structure with an enormous ring structure in the longitudinal part. Therefore, the amount of material used differs between the beam section and the compression ring parts. This is illustrated in figure 5.1. However, this does not result in an attractive solution; a more efficient solution for the ring structure is desired.

5.1.3 Adding extra compression struts
The bending forces in the middle section of the ring structure could be decreased by adding extra compression struts to the structure that balances the lateral forces between both sides of the ring structure, which is illustrated in figure 5.2. This principle could be compared to a tension cable between the supports of a compression arch which balances the lateral reaction forces. However, in this case a compression force has to be balance instead of a tension force. Additionally, the length of the struts is
Fig. 5.3. Extra compression struts in two direction, resulting in a smaller buckling length of the struts

Fig. 5.4. Combination of two compression rings
very large, causing buckling instability problems. Therefore, the dimension of the compression bars should be relatively large. The buckling problem could be decreased with extra struts in two direction, as is illustrated in figure 5.3. Then, the struts support each other reducing the buckling length of the elements. As a result, the dimensions of the struts will be decreased. However, the number of elements is increased resulting in an even larger density of the structure. These large elements will have a large negative effect on the spatiality of the interior space of the stadium hall. The large amount of elements in the structure will result in a dense appearance. Moreover, the lightness and transparency of the tensegrity structure with pneumatic elements will be destroyed. The appearance of the structure will change to closed and heavy. This effect is undesirable and the use of the bars is not very efficient therefore, this principle will not be used in the design.

5.1.4 Combining two compression rings
The efficiency of the compression ring could be improved by creating a ring structure combining two ring structures. In this way, the two compression rings are perfect circular. However, the rings do not cover the whole roof area. Additionally, the compression rings should be loaded uniformly in order to achieve a constant compression force in the ring and to prevent asymmetric deformations of the ring. Therefore, a mesh of suspension rods in the middle area is necessary to transfer the lateral force to the compression rings. This principle can be seen in figure 5.4. It is unlikely that the loads on the compression ring transferred by struts in the mesh are equal to the loads caused by the tensile structure on the other side of the compression ring. Additionally, the two compression rings will not have equal size, and will therefore not be in equilibrium. Therefore, the compression forces in the ring structures will not be constant, which will result in a difficult behaviour of the ring structure.

Another aspect is that the compression rings will have to be supported in the middle of the span, because of sagging as a consequence of their own weight. The compression rings could be suspended from the structure above, but this will result in large loads on the relatively lightweight structure. Moreover, the compression ring will have a large influence on the spatiality of the stadium hall. The compression rings running through the space in the middle of the building will visually divide the space of the large hall into two segments. The division of the space in two segments is undesired, because an important quality of the stadium is its large interior space, while the division will weaken this quality. Therefore, this principle of the compression ring structure will not be preferred in the design.

5.1.5 Applying a tension arch to the straight section of the compression ring
In paragraph 5.1.1 is discussed that more curvature will result in a more efficient ring structure, but that curving the straight section outwards will result in loss of the building form. However, this curvature could be applied inward as well, resulting in a tension arch, as can be seen in figure 5.5. As a result, a ring structure will be obtained composed by two half compression rings connected by a compression bar with a tension arch. The lateral force caused by the tensile roof will result in compression force in the two compression ring sections at the end of the ring structure. The compression bar connects these two half ring structures and will transfer the compression force between these ring sections. The arch added to the longitudinal section of the ring will be loaded with tension. As a result, an extra compression force is added to the compression bar connecting the two halves, in the same way as tension will occur in a cable connecting the supports of a compression arch. Summarily, the compression force in the compression bar is composed of a force due to arch action of the tension arch and the force which is transferred between the two halves of the compression ring. The combination of a tension arch and compression bar can be seen as a form of optimization of a beam. In figure 5.5, the tension arch and compression bar are not connected in order to clarify the principle, but some connection will be made to reduce the buckling length of the compression bar. The tension force
Fig. 5.5. Extra tension arch in the longitudinal part of the building

Fig. 5.6. Undulation of the stand and the inward curve in the facade as a result of the inward curve of the tension arch
and the compression force together form a couple of forces, which is able to resist bending moments. The impact on the spatiality of the large stadium hall is relatively minimal, because no extra structural elements are added to the space. The roof structure is namely connected to the tension arch, resulting in an inward curve of the roof structure in the interior. The partition of the tension arch and compression bar will add a characteristic element to the architecture of the building. These extra qualities and the efficient action of the tension arch cause this variant to be preferable in relation to the previous variants.

5.1.6 Conclusion
The variant with an added tension arch will have interesting qualities regarding the spatiality of the interior stadium hall and the extra characteristic quality of the partition between the tension arch and compression ring. The other variants examined resulted in a more negative influence on the spatiality of the stadium hall, because of the addition of extra structural elements in the interior space, that counteracts the lightness of the roof structure. Moreover, the extra structural qualities of most of these improvements are questionable. The addition of a tension arch could result in a more efficient ring structure, but the middle section will not be as efficient as the circular parts of the ring structure. Since both the structural as the architectural qualities of the structure with tension arch will be the best of the here discussed variants, this structure will be used in the design of the stadium.

5.2 Architectural aspects of undulating the ring structure
As mentioned in the previous paragraph, the inward curve of the tension arch in the ring structure affects the architectural design of the stadium. The roof structure and the stand are connected to the inward curved tension arch. As a consequence, the stands and structure have an inward curve in the interior space. Additionally, the facade is also connected to the tension arch, resulting a varying angle of the facade columns creating the inward curve in the facade. Another consequence is that the compression bar is on the outside of the building. These different aspects can be seen in the model shown in figure 5.6. The inward curve in the facade accentuates the entrances of the building, which are positioned on the longitudinal sides of the building. Decreasing the steepness of the facade columns creates a subtle hint of the entrances. This is strengthened by the compression bar of the ring structure, which passes outside the building giving a characteristic appearance to the facade of the building.

5.2.1 Undulation of the stands
The undulation of the stand caused by the inward curve of the tension arch will be examined in more detail. As a result of the undulation the height of the stands increases in the middle of the longitudinal section, which creates a differentiation of the spatial qualities of the stand. The middle section has better sightlines due to its higher position, this section of the stand will be reserved for press and VIPs. However in some parts of the stadium, the quality of the sightlines is decreased. Based on investigation of different sightlines from different positions on the long side of the stand, there could be concluded that in most places the competition track will be visible very well. The largest differences can be found in the area between the competition track and the stand will be less visible and in some places other parts of the stand will be less visible. However, these effects are relatively small and the competition track will be good visible.

5.3 Support structure
The ring structure is improved by the application of a tension arch resulting in a more efficient structural action of the middle longitudinal section of the ring structure. However, the ring structure is not perfect circular. So the ring structure will not be
Fig. 5.7. Geometry of the support structure
a perfect ring structure. It will have implications on the distribution of forces in the support structure. The consequences of the structural behavior on the support structure will be discussed. However, before this could be discussed, the basic concept for the support structure should be described.

5.3.1 Basic principal of the support structure
Basically, the structure supporting the roof structure and the compression ring is composed of a hinged column in the facade of the building and a beam also supporting the stands. Since the structure of the ice tracks is separated from the structure of the rest of the building, the beam cannot be extended to the ground. Therefore, the beam will be supported by a hinged column. However, this will result in a lateral force at the connection. Diagonals resisting these lateral forces are not accepted because of their negative influence on the spatiality of the functions around the tracks. Therefore, the lateral forces will be transferred by the floor to stability walls on a regular interval. Thus, the floor serves as a kind of beam.
An extra column is added between the inner column and the hinged column in the facade as an extra support for the stand beam. Most of the loads from the stands acting on the beam are within the inner two columns. Therefore most of these forces are carried by these two columns, resulting in a minimal load from the stands on the hinged column.

5.3.2 Ring action
The structural behaviour of the compression ring will affect the structural action in this support structure. Three different degrees of ring action will be discussed. Firstly, the situation without ring action of the ring structure; thus, when the structure would be loaded by the full lateral support force of the roof structure. Secondly, the situation in which the ring structure has full ring structure as is the case with a perfectly circular compression ring. And finally, the situation in between, in which the ring structure will show ring action, but also shows larger deformations as is the more realistic behaviour of the ring structure of this building.

No ring action
If the ring structure does not contain a compression ring, the support structure will be loaded by the lateral inward support force resulting from the roof structure in addition to the vertical reaction forces of the roof structure. As a consequence, the hinged column in the facade is loaded by tension forces due to the constant inward pull, resulting in slender columns. The beam will be loaded by a compression force caused by the inward pull in addition to the bending moments caused by the stand. The lateral forces caused by the compression in the beam are carried by stability walls on a regular distance as is mentioned in the previous paragraph. This is illustrated in figure 5.9.
Contrastingly, the own weight of the structure will give a vertical downward component in the tension force, reducing the tension force in the facade column. On the other hand, a pulling force due to, for instance, wind suction will result in extra tension and compression in the column and beam. The support structure without a compression ring is subjected to changing loadings from the roof.

Full ring action of the ring structure
A structure without ring action is one extreme; the other extreme is full ring action of the compression ring. In a structure with a perfect circular compression ring structure, the loads on the ring structure will only result in a compression force in the ring structure. The deformation caused by this compression force is relatively small, because the compression ring keeps its circular form. The compression force only causes the ring to become slightly smaller. However, it will not have a large influence on the support structure.
Since the lateral forces are balanced in the ring structure, only the weight of the roof structure and vertical loads will act on the support structure. Figure 5.10 shows the distribution of forces when the structure is only loaded by a vertical downward load.
The hinged column in the facade is loaded by a compression
Fig. 5.8. Scheme of the support structure

Fig. 5.9. Support structure with the force distribution by no ring action

Fig. 5.10. Support structure with the force distribution by full ring action

Fig. 5.11. Support structure with the force distribution by a spring supported ring structure
force. The beam supporting the stands is loaded by a tension force in order to prevent the hinged column to fall over, while the stand causes bending in the beam. This combination has a positive effect on the stiffness of the steel beam, because the tension will counteract the deformation due to bending. The lateral force in the structure are carried by walls on a regular interval.

Wind suction will give an upward vertical component force on the compression ring, which will be counteracted by the weight of the compression ring, resulting in a small vertical force on the support force. The direction of this vertical load depends on the amount of wind suction and the weight of the compression ring and roof structure. Other vertical loads, such as snow loads, will increase the downward force on the support structure, increasing the compression in the hinged column and tension in the beam.

Incomplete ring action or spring supported ring structure
Full ring action of the compression ring can be obtained with a perfect circular form, because it will result in small deformations of the ring structure. However, the form of the compression ring has a relatively straight section that will deform significantly. Therefore, the structural behaviour of the compression ring cannot be typified as full ring action.

The deformations of the compression ring are hindered by the support structure, because it will prevent the compression ring from deforming. Therefore, the compression ring can be seen as a spring supported ring in which the spring stiffness depends on the stiffness of the support structure. The consequence on the distribution of forces can be seen in figure 5.11.

The compression ring will give a downward vertical force on the support structure similar to the full ring action of the ring structure, resulting in compression in the facade column and tension in the beam. However, the ring structure will also deform inwardly, especially in the relatively straight section. As a consequence, a tension force component arises in the hinged facade column combined with a compression force in the beam. The effect of the downward force and the inward force are opposed and counteract each other. The size of these effects is hard to estimate, because it depends on a large number of factors, such as the stiffness of the support structure, the weight of the roof, the deformation of the ring structure etc.
6. Architectonic elaboration of the concept

The previous chapters have discussed both the architectural and structural concept. This chapter will discuss the further elaboration of the architectural design of the building using the various sections of the building. The section shows the interaction between the different levels of ice tracks and the other functions around these tracks and how all the pieces are coming together.

6.1 Facade

The façade is an important architectural aspect determining the appearance of the building. The design concept contains a double curved façade. The appearance of the double curved façade will be discussed in this paragraph.

6.1.1 Principle of the façade

In the design concept, the steepness of the façade is varying as a result of the shift in the building, emphasizing the difference in height between the small-scale building on the north side and the stadium in the south. As a consequence, the façade is a double curved surface twisting around the building from leaning over in the south to leaning backward in the north. A more lively appearance of the building can be obtained by a more layered and differentiated façade, which will add human scale to the building as well.

This effect is obtained by a layer of façade columns with varying steepness that define the original building form, in front of the actual façade, situated a few meters behind the columns. The layer of structural elements serves as a filter in front of the actual façade, which can therefore be more differentiated. For instance, protruding elements for circulation or other functions could be added to the façade without disturbing the clear building volume.

Additionally, the spatiality of the spaces behind the façade can be more optimal for their function because the spaces do not have a sloping façade. The spaces arising between the columns and the actual façade will be a buffer between the outside and inside. When entering the building, this space serves as a vestibule. It results in more consciousness of entering, because you have to step through the layer of columns.

An important aspect of the structural layer is the rhythm of the columns, which largely determines the image of the façade. On the one hand, this rhythm is determined by the structural demands for supporting the stands and the roof structure and on the other hand, it is determined by the desired image in the façade. The columns should not have a constant intermediate distance, because that would result in a boring constant repetition of the elements. Instead, a more changing repetition of the elements is sought based on the structural demands.

Firstly, the entrances of the stand will interrupt the stand element. Consequently, beams on both sides of the entrance are necessary, resulting in two close façade columns. Secondly, the distance between two successive pairs of close façade columns is divide in three equal parts by two columns. In the curves, the same principle of the rhythm is used with one difference. Three columns are used between two pairs of columns, because the distance was larger.

The layer of façade columns largely determine the high tech character of the façade. This character is strengthened by the ring structure, which has a large influence on the appearance of the stadium, partially as a result of its size. This character fits with the appearance of the membrane and tensegrity structure and with the modern high tech image desired by Thialf.

6.1.2 Facade of the north side

The principle of the façade is true for the part of the façade leaning over. However, the façade of the backside of the building is leaning backward, which makes the façade partly roof. Therefore, a different kind of façade is necessary. The change in façade principle coincides with the change of leaning over in leaning backward of the façade. In other words, the location where the façade is perfectly vertical.

Fig. 6.1. Render of the façade with the columns
Fig. 6.2. Section of the principle of the façade

Fig. 6.3. Section of the circulation space

Fig. 6.4. Section of the north façade with the interaction between inside and outside
At this place, the facade will follow the curved form of design concept to continue the form generated by the columns. The facade will define the spatiality of one of the curves of the training track and the circulation space of the competition track. It will cover the curve of the training track coming out of the competition track. A light and open atmosphere is desired to resemble the outdoor qualities, causing the image of skating outdoors. As a consequence, skaters will get the feeling of skating from inside (the open space centrally in the stadium) to outside by skating into the light. Therefore, a light and open facade is desired. This part of the facade will therefore be made of glass, with a coating to block direct sunlight which could affect the ice quality.

Another aspect of a transparent facade is the interaction between inside and outside. It will be the only place where you could see the outside world from the ice track and the other way around. People passing by could take a look at the skating track and watching people skating. In order to facilitate this interaction, an extra element is added to the building creating a straight façade in order to make watching inside more easy. The straight façade is covered by and overhang to complement the addition.

The stadium hall is by definition introvert, since the stands will be directed to the activity on the ice track. Contrastingly, the circulation spaces will be directed to the outside world and are therefore more extrovert. As a result, going to the toilet or get something to drink will also give you a view of outside. Another aspect is the appearance from outside. The extrovert character of the circulation space will expose the spectators to the outside world resulting in a more lively facade. Especially, in relation to the normal introvert character of stadium buildings. This effect is strengthened by placing the circulation space before the 'actual façade'.

However, this principle will change on the backside as a consequence of the different facade type and the shift of the ice tracks. The circulation space will be totally inside the building, creating views to the training track, which is illustrated in the section in figure 6.4. Additionally, the glass facade will create views to the outside world and let through enough light to create the same outdoor atmosphere as in the circulation space on the other side of the building.

6.2 Circulation space stands
Another important aspect of a stadium is the routing of the supporters from outside to the stands. The circulations spaces of the competition track, which also contain catering and toilet facilities, are placed directly around the competition track. It creates short walking distances between the serving facilities and the stands. The circulation space is located on the same level as the first row of seating, because then the stands will be entered on nearly the same height as the competition track. Therefore, all the spectators get the change to come close to the competition track and get a good view of the skaters.

The circulation space is entered by stairs which are located on the straight sides of the building on the public squares in front of the building.

6.3 Deepening of the training track
The competition track and ice hockey rink are lying underground, which will reduce the total height of the building. This is most important for the backside of the building, because of the small scaled houses. Even more important for the building itself, is the fact that the entrance is located between the competition track and the training track. This will decrease the distance from the entrance to both ice tracks. Another aspect is the nice view from above on the training track and ice hockey rink when entering the building or can be seen from the other functions around the training track.

The space between the actual façade and the layer of columns is extended to the training track level allowing daylight to enter the underground spaces. Most of these spaces contain installations and storages as well as functions like workshops and a sprint
Fig. 6.5. Section of the underside of the building

Fig. 6.6. Section of the building with the balcony in the space

Fig. 6.7. Section with the stairs connecting the different ice tracks and the changing rooms and other facilities.
track. The daylight will improve the quality of the working places of the people working here. In this same way, the entrance of the stands of the ice hockey track is created.

6.4 Interaction between the training track and surrounding functions
The ice tracks form the heart of the building; it is the central place where most of the people are coming for. The fact that the stands surrounding the track are focused on the competition track is a logical and direct result of the function of these stands. However, the relation between the training track and the spaces surrounding the training track can be more interesting. This relation will be discussed in more detail.

6.4.1 Interaction between the training track and surrounding functions
From the spaces surrounding the track, the skaters on the track could be observed and followed. This is especially valuable for parents watching their kids skating on the track or other spectators watching acquaintances. Another important group of users of the functions around the ice track are the professional athletes. They will also have a view of the ice track with the recreational skaters having fun on the ice and amateurs skating their rounds. Other people visiting the building could pick up something of the atmosphere on the track as well. However, the sight on the track is not the only important way to receive the atmosphere. The sounds, such as the sounds of the skates, feeling the temperature of the space and the wind produced by the skaters etc are even important. Therefore, people must enter the space with the tracks.

This is obtained by a large balcony around the ice track which is also used as circulation space for the skaters throughout the building. In this way, parents can stand on the balcony watching their kids, professional athletes walking from the changing rooms to, for instance, the fitness room will pass through the space with ice track etc. On the other hand, there is also interaction the other way around. Recreational skaters skating on the training track could see their heroes passing by over the balcony or see them sprinting on the sprint track.

The functions that can have an interesting relation with the competition track are placed around the training track. These spaces can be divided in two categories, spaces wherefore it is valuable to receive the atmosphere of the track and spaces which are interesting to be observed by the people on the track. The first category includes the entrance and the restaurant and the second category, the fitness space, the sprint track and the athlete's lounge.

These functions are placed along the balcony with some exceptions. The sprint track is on the same level as the training track separated from the training track by a glass wall. Therefore, a relatively direct relation between these spaces is obtained. For instance, the fitness room is placed above the training track on the second floor and has a glass wall directly at the training track, without a balcony in front.

6.4.2 Stairs connecting the sport facilities
As is mentioned in the discussion of the design concept, the changing rooms are located under the inner area of the competition track. The changing rooms are spread over three different levels; the changing rooms for the competition track on the level directly underneath the inner area and the changing rooms for the training track on the level of the training track. The levels with changing rooms and other facilities are connected by two central stairs in the open central space and are connected to the balconies as well.

These stairs are also used to enter the inner area of the competition track. Professional athletes will first enter the open inner area beneath the competition track receiving the atmosphere in the stadium but not optimally visible to the spectators on the stands. In this way, they will have a few minutes to get used to the atmosphere before entering the inner area. After their race, when their legs are hurting, they can use the lift to get to the
Fig. 6.8. Render of the straight section of the training track

Fig. 6.9. Render of the training track in the curve in the central open space

Fig. 6.10. Render of the training track in the curve on the backside of the building
rooms. The lifts also connect the two ice tracks and the changing rooms.
In situations that both tracks are open to public use, the stairs could be used by skaters to go from one track to the other. In other situations, some parts of the stairs have to be blocked to guide the skaters to the correct track. In this way, the stairs are flexible to serve for different situations.

6.5 Spatiality of the training track
An important aspect defining the spatiality of the ice track not discussed yet, is the structure of the competition track that significantly defines the spatiality of the recreation track. The spatiality of the competition track has a varying character with three different kinds of spatiality that will be discussed separately.

6.5.1 Straight section
In this section of the training track, both track are exactly on top of each other. Therefore, the spatiality of this section is largely determined by the structure of the competition track. The structure of the competition track is composed of concrete portals supporting a concrete slab. Its relation with the central open spaces, is important for the spatiality of the training track. Therefore, these portals are designed in a way that the inner side of the competition track is made of columns, which can be relatively slender. The columns on the outer side of the track must therefore be thicker, since the connection with the beams has to be fixed in order to obtain stability. Another consequence is that the space of the training track is more focused to the central open space and therefore to the ice hockey rink. This effect is increased by a triangular pattern of the portals. The maximal span in a triangle is smaller than in a regular repetition of the portals, resulting in less deformations of the competition track and therefore a better ice quality. The triangular pattern of the beams give more direction to the space underneath, strengthening the focus to the central open space. The influence of the structure on the spatiality of the training track can be seen in figure 6.8.
It also illustrates the balcony serving as a circulation space throughout the building connecting the different facilities and facilitating the interaction between the training track and the surrounding functions.

6.5.2 Curve in open space
At the end of the straight section, the track curves into the central open space, passing through to the other side. The skater comes from under the competition track into the large open space. As a result, the skater will perceive a spacious feeling due to the absence of the sheltering effect of the competition track. Another effect of the absence of the competition track is the clear view of the stadium hall with competition track and stands above and the ice hockey rink in the middle. The skater obtains an image of the whole building including the stairs connecting the different levels with tracks and changing rooms.

6.5.3 Backside
This curved section of the track is followed by another straight section of the track which is almost similar to the other straight section. At the end of this straight section, the competition track on top curves to the inside, while the training track continues. Firstly, the track will be darker, but this is compensated by the light space behind the darker zone. This creates a dramatical effect, resembling the feeling of skating from inside to outside, which was also mentioned in paragraph 6.1.2. This effect is strengthened by the view outside through the glass façade. Actually, this is the only location with a direct view from the ice track to outside.
Another aspect of this curve of the track is the relation to the circulation space of the competition track. The spectators wandering in the circulation space can see skaters passing by over the training track and vice versa. However, it will be more difficult. The recreation track is related to sprint track next to the track and the restaurant where the skaters are skating to in the curve.
Fig. 7.1. Stage 1: pre-stressing of the tensegrity structure

Fig. 7.2. Stage 2: applying the internal overpressure to the pneumatic element.
7. Elaboration of the roof structure

The overall design of the building is now mainly discussed. The roof is an important element in the design that largely determines the appearance of the building, both exteriorly and interiorly. In this chapter, the design for the roof structure will be discussed in more detail. Firstly, the structural principle of the roof structure will be discussed in more detail. Subsequently, the lay-out of the roof structure will be discussed; this contains the number of membrane layers, the location of these layers, the light aspects of the roof etc. Finally, some building physical aspects of the design will be discussed, which also contain the installations of the structure.

7.1 Structural principle of the roof structure

The structure is composed of a combination of two structural principles, as is discussed in the conceptual design. As a consequence, the structural action of the total structure is a little bit different from a normal structure. In this paragraph, the structural action of the combination of a tensegrity structure with a pneumatic structure as applied in the design will be discussed. In order to obtain a clear understanding of the structure, the different type of loads (pre-stress forces could also be seen as loading) are discussed in the sequence of loading.

7.1.1 Stage 1: Pre-stress forces in the tensegrity structure

The pre-stress forces in the tensegrity structure are important to the structural action of the structural system. These pre-stress forces provide the stiffness of the structural system and the ability to carry the loads that are applied to the tensegrity structure. In order to obtain tension forces in the cables, a horizontal support force is needed. Since the vertical component of the total pressure on the upper membrane should be equal to the total downward pressure on the lower membranes (or tensegrity), this is the same as in a pneumatic cushion in which the membrane force in the upper membrane is the same as in the lower membrane, resulting in only horizontal support forces. Consequently, the vertical components in the supporting forces of the upper membrane and tensegrity structure should be scored out together, so only a horizontal force will remain.

7.1.2 Stage 2: Applying an internal overpressure in the pneumatic element

The next step in the structure is pre-tensioning the pneumatic element. A pneumatic element is pre-tensioned by applying an internal overpressure pushing the membrane layers outside. When an internal overpressure is applied, the upper membrane is pushed outwards resulting in a pulling reaction force in the supports.

Since the lower layers of membranes are carried by the tensegrity structure, the tensegrity structure is loaded by the internal pressure of the pneumatic element. As a result of the vertical loading of the tensegrity structure, the tensegrity will deform resulting in an additional vertical support force as can be seen in figure 7.2.

Since air in the pneumatic element results in the same pressure in every direction of the element, the upward component of the total pressure on the upper membrane should be equal to the total downward pressure on the lower membranes (or tensegrity). This is the same as in a pneumatic cushion in which the membrane force in the upper membrane is the same as in the lower membrane, resulting in only horizontal support forces. Consequently, the vertical components in the supporting forces of the upper membrane and tensegrity structure should be scored out together, so only a horizontal force will remain.

7.1.3 Stage 3: Loading of the structural system

The first two stages were both a form of pre-stressing of the system in order to allow it to fulfill its load-bearing capacity. The third step is the application of the actual loading, such as snow loads and wind loads. Firstly, snow loads will be discussed because it is a symmetrical load case followed by a discussion of an asymmetric load case such as wind loads.

Symmetrical downward loading, such as snow loads, will cause a decrease of the pre-tension in the upper membrane resulting in a smaller support force. The snow loads will also cause the upper membrane to deflect and the pneumatic element will be compressed. As a consequence of the decrease in size of the
Fig. 7.3. Stage 3: Loading of the structural system with snow loads

Fig. 7.4. Stage 3: Loading of the structural system with wind loads
pneumatic element, the air will be compressed and the over-pressure will increase. However, the difference in size before and after loading is small and hard to predict, so the effect is minimal. A larger over-pressure will also increase the pre-tensioning of the upper membrane, decreasing the deformation of the upper membrane. Conclusively, the complexity of this process and the small effect on the internal over-pressure justifies the simplification of the over-pressure as a constant or almost constant pressure.

If the pressure of the pneumatic element on the tensegrity is almost constant, the forces in the tensegrity will be almost constant also, because the air pressure is the most important load on the tensegrity. Constant loading of the tensegrity has a positive effect on the tensegrity, since a tensegrity structure is a relative flexible structural type. This flexibility could lead to large movements of the structure in some cases. However, as a result of constant loading, the deformation would remain the same. Concentrating on the effect of the snow loads on the forces in the supports, we have seen that the forces in the tensegrity structure remains constant and these forces are not largely influenced by the snow loads. On the other hand, the reaction force of the upper membrane decreases due to a decrease in tension. Consequently, the vertical component of the support force of the membrane is also smaller resulting in a resultant force with an upward vertical component besides the large vertical component. More precisely, this upward component is the vertical loading of the snow which could be compared to the upward reaction force of a beam loaded by snow.

Another important effect of the pneumatic element on the structural action of the structure could be explained by an asymmetrical loading, in this case wind loads. Wind loading is a difficult type of load because it can cause wind pressure on one side of the building and wind suction on the other side. This will result in asymmetrical deformations of the membrane, as can be seen in figure 7.4. The reaction forces are generated in the same way as for snow load; wind pressure will result in a decrease of pre-tension in the membrane, while on the other hand wind suction will increase the tension. As a consequence, wind pressure gives a more upward direction of the resultant force in the supports and suction in a more downward one.

More important is that the internal over-pressure of the pneumatic element, as is noticed earlier, will be relatively constant. This is also true for an asymmetrical deformation of the pneumatic element. The difference with snow loads is that the air inside is redistributed in the element due to change of element shape. Consequently, the loads on the tensegrity remain the same, namely the internal over-pressure of the element. In other words, the pneumatic element levels the asymmetrical loads so that the tensegrity is loaded symmetrically. This means that the tensegrity can be fully designed for the symmetrical load of the pneumatic element instead of different load cases with asymmetrical loads which could cause large asymmetrical deformations.

7.1.4 Deformations
Deformations of such a large span roof structure are a difficult subject. Normally, deformations of structures are restricted by the usability of the structure. Large movements could be felt by the users; deformations could cause problems in other building elements, for instance walls carried by a floor could crack by large deflection of the floor. However, these considerations are less important for large spans. Therefore, the influence and consequences of the deformations should be considered in order to conclude to what extend the deformations can be allowed.

The loads have almost no influence on the forces in the tensegrity structure. These forces are determined by the pre-stressing forces and the air pressure of the pneumatic elements. Both of these two types of loads can be seen as a form of pre-stressing, so both are applied in order to provide the load-bearing capacity of the structural system. The deformations caused by these loads occur before the building is taken into account, so the size of these deformations are thus not important for the building's
Fig. 7.5. The pneumatic element located on top of the tensegrity structure

Fig. 7.6. The tensegrity structure is located in the pneumatic element

Fig. 7.7. Varying the location of the layer of membranes in relation to the tensegrity structure
use. For instance, there are no large movements of the structure visible or users do not feel vibrations. This means that there are no special restriction to the deformations caused by the forces in the structure. However, the deformations cannot be too large, because it will result in bars being out of line. This is a more aesthetical limitation to the deformation of the system. Additionally, too large deformations could cause problems in the connections of the elements and should be taken into account in the design of these connections.

7.2 Lay-out of the roof structure
The roof structure is based on a combination of a tensegrity structure and a pneumatic element. Besides structural advantages, it also creates opportunities in the use of membrane layers. Using different layers of membranes, for instance, could create an adaptable system of light controlling. This lay-out of the roof structure will be discussed in this paragraph.

7.2.1 Location of the tensegrity in relation to the pneumatic element
The principle of the combination of the tensegrity dome structure with the pneumatic lens-shaped element is that the tensegrity is supporting the pneumatic element. Illustratively, the tensegrity pushes the membrane up, creating more curvature in the membrane. From this point of view, the tensegrity is placed under the pneumatic element.

However, the tensegrity could also be positioned inside the pneumatic element. The structural working of the pneumatic element will not be affected, since the tensegrity is still supporting the bottom membrane of the pneumatic element. An interesting appearance of the roof structure will appear, because the bottom layer of membranes will act as a filter before the tensegrity structure. As a result, the structural elements will be visible more vaguely from the stadium hall, creating a calmer appearance. It will mystify the complexity of the structure, with its complex configuration of cables and bars.

The location of the layer of membranes will influence the spatiality of the stadium hall underneath the roof structure. If the membranes are on top of the tensegrity structure, the ceiling will have a convex form, which goes directly upwards from the supports. The structural elements of the tensegrity structure, on the other hand, will go downward. Contrastingly, the ceiling will first go downward and then upwards when the tensegrity is in the pneumatic element, as can be seen on figure 7.6. This creates a space with less height.

Another aspect is the possibility to place installations in the roof structure. When the tensegrity is placed under the pneumatic elements, a walkway could be placed near one of the rings with compression bars enabling people to work on the installations in the roof of the building.

However, the first bar has to have enough height in order to create a large enough angle of the first diagonal from a structural point of view. This will result in a large downward distance of the ceiling in the case the tensegrity is fully in the pneumatic element. As a result, a claustrophobic spatiality is created on the stands. Therefore, the tensegrity will be under the pneumatic element above the stands, so a walkway could be applied to the structure. In the middle, the layer of membranes will go under the tensegrity structure, as is illustrated in figure 7.7. A more quiet centre of the structure and a more straight ceiling will be created, which positively affects the air quality. This will be discussed in more detail in paragraph 7.3.

7.2.2 Transparency of the roof structure
The combination of a tensegrity structure with pneumatic elements creates the opportunity to let daylight enter the building. It will create a natural lightened stadium hall, which creates a good natural atmosphere during normal days.

Direct sunlight
However, an important aspect of natural daylight entering an ice skating stadium is the direct sunlight. Direct sunlight could create large problems with the ice quality when the sun shines directly
Fig. 7.8. Dolce Vita Tejo shopping centre in Portugal

Fig. 7.9. Example of cushions with a positive and negative pattern (Duales Pavillion Hanover Expo)

Fig. 7.10. Sketch of the principle of the light controlling by a cushion

Fig. 7.11. Schematic principle of artificial lighting of the hall
on the ice track. The sunlight will create locally large temperatures, causing the ice to melt and become soft. The sunlight causes large temperatures in the hall, which could be illustrated with a comparison to a glass house. Therefore, direct sunlight have to be blocked. Another aspect of direct sunlight in the hall is the blinding effect of the sun. Direct sunlight could blind the skaters, distracting them from the focus on skating. Consequently, the roof structure should block direct sunlight, while allowing natural daylight (or indirect daylight) to pass through. Some methods to block direct sunlight could be applied without affecting the lightweight appearance of the building. The sunlight could be blocked by a layer of membranes in different ways. The first way is to use a translucent fabric, such as PTFE coated polyester, which is often used for tensile structures. Another way is to apply a mirroring film to the membrane used in the structure that will reflect the sun. However, applying this solution will result in a reflecting appearance of the building, which is not desired. A third method is to use cushions printed in such a way that only light from the north can pass through the cushion, which is shown in figure 7.8. Paragraph 7.2.3 will discuss the configuration of membrane layers in which the definite choice for a type of sun blocking will be made.

Controlling the amount of daylight
Another aspect is the lighting of the hall during competition days or other events in the hall. During these events, it will be desired to darken the hall in order to have larger influence on the lightening of the hall with artificial lighting. It could be useful for, for instance, television cameras or shows held in the stadium. It differs from blocking the sunlight, since all daylight should be blocked.

The daylight controlling could be integrated in the design of pneumatic cushions by using a cushion composed of three layers of membranes. Two of the layers must be printed by opposite patterns, a positive and a negative pattern. When the patterns are on either side of the cushion, light is passing through the cushion. When both layers of the membrane are close to each other, the pattern is closed and light is blocked, as is illustrated in figure 7.9. The location of the middle membrane in the cushion is determined by the air pressure on both sides of the membrane. If the pressure in the upper chamber is increased in relation to the pressure in the bottom chamber, the middle membrane is pushed downward. Similarly, increasing the air pressure in the bottom chamber will push the middle membrane upward.

Figure 7.10 shows the two extreme positions, but a position in between should also be possible. In this way, the amount of daylight in the hall can be adjusted to the use of the building at that moment.

Figure 7.9 shows an example of a building in which this principle. If this pattern is more fine-meshed, the pattern will less influence the appearance in the hall.

Artificial lighting
The artificial lighting of the hall could be integrated in the roof design by applying the artificial light to the structure in such a way that the hall is lightened in the same way as in the daytime situation. This could be obtained by applying the artificial lighting inside the pneumatic element. The light will be leveled by the pneumatic cushions, resulting in a evenly divided lighting of the hall. That will be filtered in the same way as the natural daylight passing through the structure.

Another aspect of this way of lightening the hall is the exterior appearance of the roof. The artificial light will also pass through the outer membrane, because of its translucency. The presence of activity will be clear from outside. The intensity of the light passing through the outer membrane is filtered and decreased by the membrane. Therefore, the building will not be too bright and less disturbing the direct surrounding of the building. Finally, extra lightening specifically for certain events could be placed under the roof structure. Via the walkway under the roof structure, these lights could be adjusted according to the demands of the specific event. It increases the flexibility of these lights, because the lights in the pneumatic element are accessed less easily, and are therefore less flexible.
Fig. 7.12 Basic configuration with two layers of membranes

Fig. 7.13. Configuration of the membrane layers with cushions as the top layer and a single membrane as the bottom layer
7.2.3 Amount and location of the membrane layers

The application of lightening of the hall is influenced by the configuration of the membrane layers in the roof structure. An important aspect of this configuration is not only the location of the membranes, but also the amount of layers used in the roof structure and the division of these layers over the roof structure. Basically, two layers of membranes are strictly necessary for the working of the pneumatic element. These two layers create the airtight element in which an overpressure can be generated. This strictly necessary basic configuration can be seen in figure 7.12.

The layers of membranes of the pneumatic element should not necessarily be composed of one single layer, but could also be composed of multiple layers resulting in layers of cushion elements. These cushion elements have a larger insulation quality than a single membrane layer, because the still air inside the cushion provides the insulating effect. The insulating quality of the large pneumatic elements, however, is very small, since the space inside the element is too large. The insulating quality will disappear as a result of the air flows arising in the element. Therefore, a layer of cushions is necessary to provide the insulation of the roof structure.

The configuration of the layers of membranes determines the light working of the roof structure as well. The location in the roof where the direct sunlight is blocked is also of importance for the insulation working of the roof. The different configurations of membrane layers will be discussed.

Replacing a single membrane layer with a layer of multiple membranes will increase the insulating capacity of the structure, as is seen above. Two different configuration are possible when a single membrane is replaced with a layer of cushions. That can replace the bottom membrane or the upper membrane.

In this case, the bottom layer forms the physical barrier, while the pneumatic element acts as a buffer between the outdoor air and the cushions, adding an extra insulation buffer. The sun can be blocked by the outer membrane layer, reducing the heat gained by the sun in the pneumatic element. Therefore, the cushions will be even less heated by the sun, while the temperature inside the cushions can be controlled in order to obtain the ideal temperature of the cushions in relation to the hall. This results in an optimal insulating capacity and a system in which the cushions could darken the interior in the way described in paragraph 7.2.2. The size of the cushion will correspond to the pattern of the tensegrity structure, resulting in coherent appearance of the roof.

The other option is a roof structure composed of a top layer of cushions and a bottom layer consisting of a single membrane. As a consequence, the top membrane is the most important insulating barrier in the roof structure. In this way, the sunlight should also be blocked by the cushions to prevent the air in the large pneumatic element to be heated by the sun. In this case, the cushions should not only provide the light controlling ability of the roof, but also the sun-blocking action. Another consequence is that the temperature of the air inside the large pneumatic element will be lower than in the previous configuration. However, the temperature cannot be controlled as easily as the temperature in the cushions of the bottom layer of the previous configuration, because of the volume of the pneumatic element.

The appearance of the roof in the stadium hall is mainly similar to the appearance with a bottom layer of cushions, since the membrane bubbles between the tensegrity in the same way. The exterior appearance, on the other hand, of the outer layer of membranes is different as a result of the cushions. The cushions will create a more bubbling effect than a single layer of membranes strengthened by cables, since the cushions will have more curvature. The printings on the cushions will determine the outdoor appearance of the roof, while a single membrane layer will have a more constant appearance.

Finally, another possibility is to replace both membrane layers with a layer of cushions. In other words, both the top layer and the bottom layer of the roof structure will be composed of pneumatic cushions. In this way, the structure has two layers of
Fig. 7.14. Both the top layer as the bottom layer of the pneumatic element is composed of cushions.

Fig. 7.15. Tensegrity structure with one layer of cushions.
the insulation barriers, whereby the light controlling aspect of the roof structure can be divided over the two layers of cushions. The upper layer blocks direct sunlight and the bottom layer controls the amount of daylight entering the building. These two could also be integrated in the same layer of cushions as well. Two layers of cushions will improve the insulating quality of the roof structure. The temperature in the bottom layer of cushions can be controlled to keep the optimal difference in temperature with the hall. However, as could be seen in the variants previously discussed, one layer of cushions in combination with a single layer of membranes should be enough and the extra layer of cushions is, thus, not strictly necessary. The exterior appearance is similar to the previous configuration, which is the bubbling effect of the cushions.

Conclusively, the variant with two single layers is not suited for the design, since its insulating qualities are relatively small due to the large volume of the air inside the element. The configuration with two layers of cushions is not efficient, since only one layer of cushions is enough. Therefore, a configuration composed of a single membrane layer and a layer of cushions should be used in the design.

The exterior appearance of an upper layer of cushions is generally more bubbling than a single large membrane. Additionally, the positive and negative printing on the cushions in order to control the amount of daylight in the stadium has a characteristic appearance, largely influencing the image of the stadium. The temperature in the cushions of the variant with a bottom layer of cushions could be controlled more easily, resulting in a large influence on the insulating capacity of the roof structure. The air inside the large pneumatic element could be used as a buffer between outside and inside in this variant. Therefore, this variant will be applied in the design.

7.2.4 Comparison to one layer of cushions
A comparison between the roof structure with a layer of cushions and a single membrane layer with a tensegrity structure with a single layer of membranes will be made to show the function of the extra upper membrane. In the tensegrity structure with only cushion elements, these cushions will have both the sun-blocking as light controlling function similar to the variants with an upper layer of cushions. Additionally, the layer serves as the barrier between inside and outside. The temperature of the air in this layer of cushion can be adjusted according to the circumstances and the temperature desired in relation to the indoor air quality.

In relation to the configuration with an extra upper layer, the buffer action of the air inside the large pneumatic element is missing. The upper membrane results in less effect of thermal bridges, since the air inside the roof is secluded from the outdoor air.

Not only the buffer action in relation to the insulating function of the roof, but also in relation to the structural action of the roof structure. As is discussed in paragraph 7.1, the air inside the pneumatic element causes in a even loading of the tensegrity structure, which is relative constant under different load cases. Additionally, the form of the upper membrane is lost, resulting in a different appearance of the building. Thus, the extra upper membrane of the roof structure has an additional value for the quality of the roof structure and the whole building.

7.2.5 Materialisation roof structure
In this paragraph the materialisation of the different layers of membranes in the roof structure will be discussed. As said before, the outer membrane will serve as the sun-blocking layer of the roof structure, which can be done with a translucent fabric or a printing or film on a transparent membrane. The used material will have a large influence on the exterior appearance of the building. The outer membrane should not be transparent, because the roof will then be relatively unobtrusive. Using a translucent fabric instead of a transparent membrane will give more body to the roof structure, while keeping some of the unobtrusive qualities. The white colour of the fabric has little
Translucent: The upper membrane blocks direct sunlight, preventing the air in the roof structure from heating up.

Ceiling: The ceiling should reflect the radiation to minimize the radiation lost caused by the difference in temperature between the roof and the ice track.

Radiation: The larger the difference in temperature between roof and track, the larger the radiation loss will be.

Ceiling: The air will be blown to the sides of the hall, where the air is removed for an optimal air flow, the roof should be retanet flat.

Stands: The air above the stands will be removed directly on top of the stands.

Ring structure: Air removal.

Transparent: Pattern on the cushions could be closed to darken the hall.

Ceiling: The ceiling should reflect the radiation to minimize the radiation lost caused by the difference in temperature between the roof and the ice track.
contrast with the Dutch skies, because it matches the often white or grey clouds. Fabrics have better structural properties than membranes than membrane foils, such as ETFE, resulting in less cables necessary to strengthen the membrane layer and, thus, less blobs in the roof. Conclusively, a fabric will be used for the outer membrane layer to block the direct sunlight and to create the exterior appearance of the roof structure.

The cushions, on the other hand, should be more transparent, since the light passing through the upper membrane, should also pass the cushions. Therefore, ETFE foils are used for the cushion elements. The cushions will be composed of three membranes for the light controlling function. The upper two layers will be printed with the pattern, because the light will then be reflected by the upper side of the cushion. In this way, the temperature inside the element is least affected by the light.

7.3 Building physical aspects important in the design

Controlling the air quality of an ice skating stadium is very important for the ice quality and, therefore, for the speed of the skaters. Therefore, some basic building physical aspects will be discussed here globally. More detailed examination of the building physical aspects and installations in the stadium are out of the scope of this graduation project. Appendix 5 shows two references of the installations in existing speed skating stadiums. Firstly, the current facility of Thialf and the second a newly build complex in Russia, which has an optimal design regarding the physical conditions (according to themselves).

An important aspect of the air quality in an ice skating stadium is the pollution caused by the spectators. These spectators bring humidity into the skating hall, which affect the air quality. Therefore, the air above the stands should be discharged as soon as possible without passing the ice track. It will be removed on the top of the stands, by the compression ring. The air is supplied from the bottom of the stands and from the roof. As a result, the air above the stands will be pushed to the air removal above the stands and the pollution will be removed without affecting the ice. This air could be heated to improve the comfort on the stands. The air flows are illustrated in figure 7.16.

Installations integrated in the cushions surrounding the ice track will bring an extra layer of clean cold air above the ice track, maintaining a constant air quality above the ice. This system is also applied in the ice skating stadium in Russia in (see appendix 5).

Another important aspect of ice tracks is the radiation loss due to differences in temperature of the ice track and the roof of the hall. This radiation loss could be minimised by a reflecting ceiling. This could be obtained by treating the foils of the cushions in the roof in such a way that the radiation is reflected, while the passing of natural daylight is not affected. There are methods to condition a foil in a way that certain radiations are reflected and other are transmitted through the foil. Another way to minimise the radiation loss is to minimise the difference in temperature between the ice and the roof. This could be obtained by controlling the air temperature in the cushions. However, the cushions cannot be too cold, since this will result in condensation and freezing on the cushions. Condensation will affect the ice quality when it is falling on the ice.

The form of the ceiling is another aspect of importance to the air quality of the hall. A convex shaped ceiling causes an accumulation of hot air in the top of the space, which is difficult to remove with installations hanging under the ceiling. If the ceiling form is relatively straight or concave, the hot air will not accumulate under the roof, because it can be pushed away more easily by supplied air.

These were the most important aspects considered in the design process. Conclusively, air supplies are needed in the centre of the stadium hall, in the cushions surrounding the ice track and at the bottom of the stands. The air will be removed above the stands, via the compression ring structure and a radiation reflecting layer will have to be applied to the underside of the cushions in the roof.
Fig. 8.1. Scheme of a 2D tensegrity structure with three tension hoops (G=top cable, D=diagonal cable, P=strut and R=tension hoop)

Fig. 8.2. Cremona diagram of the tensegrity structure with only pre-stress forces (LC 1)

Fig. 8.3. Cremona diagram of a tensegrity with an increased angle of the diagonal and a decreased angle of the top cable loaded by pre-stress only
8. Analysis of the planar load-bearing behavior of the tensegrity

In the previous chapter, the lay-out and structural principle of the roof structure were discussed. The tensegrity element of the structure is the most complex part and it mainly determines the structural behavior of the roof structure of the combined structure. The next two chapter will focus on the tensegrity part of the roof structure. This chapter will examine the planar behavior of the tensegrity structure to get an understanding of tensegrity structures that can be used in the spatial design of the tensegrity structure, which will be discussed in the following chapter.

8.1 Structural behaviour of planar tensegrity structure

The distribution of forces is explained using a tensegrity structure with three struts on both sides, thus, with three tension hoops, as is illustrated in fig. 8.1. Firstly, the loads used in the analysis of the structure will be discussed.

8.1.1 Loads

The loads on the tensegrity structure consists of the pre-stress forces applied to the structure and the downward air pressure of the pneumatic element. The assumption for the internal overpressure is 0.5 kN/m².

The loads on the tensegrity are applied on the compressive bars of the structure, as shown in figure 8.1. The structure is assumed to be on a regular interval with a constant distance in between. This design is chosen above a section of a dome, because the three dimensional structure will also contain a straight part with constant distance between the elements and because this will result in larger loads on the structure.

Three load cases are used in the calculations for the two-dimensional structure:

1. Load Case 1 (LC1): pre-stress forces in the structure
2. Load Case 2 (LC2): only vertical air pressure loads
3. Load Case 3 (LC3): horizontal pre-stress forces and vertical air pressure loads

8.1.2 Dimensional stability of the planar tensegrity structure

The dimensional stability of structures is discussed in the course Mechanica 3. There is stated that a structure will only be dimensional stable if the number of bars (s) is equal to 2k-3, in which k is the number of hinged connections. If the planar tensegrity in figure 8.1 is observed, it can be seen that the number of connections is twelve. The theory of dimensional stability suggest that the structure should have:

\[ s = 16 < 2k - 3 = 2 \cdot 12 - 3 = 21 \]

The number of bars in the planar tensegrity is thus smaller than the number of bars necessary according to the theory of dimensional stability. However, we know that the three dimensional structure will be stable, which can be explained by the geometrical non-linear behavior of the structure. The pre-stress applied to the structure provides the stiffness that is necessary to certain loads on the structure. However, certain load configurations can cause instability of the structure.

A non-linear analysis will also take into account the influence of the deformations on the equilibrium of forces. Since the structure is relatively flexible and relatively large deformations will occur, the distribution of forces is largely influenced by the these deformations. The non-linear analysis process is an iterative calculation process in which the equilibrium is determined in the deformed state of the structure. This will be seen in the paragraph on the non-linear analysis of the structure.

8.1.3 Hand calculation

A hand calculation is made to observe the distribution of forces in a tensegrity structure and to compare to the computer analysis. The non-linear behavior of the structure is simplified to linear behavior to make a hand calculation. Cremona diagrams are used in the hand calculation to determine the forces in the structure graphically. A Cremona diagram is a useful method to determine the forces in different elements with different angles relative easily.
\[ H_3 = R_4 + R_3 \]
\[ H_2 = R_4 + R_3 + R_2 \]
\[ F_h = R_4 + R_3 + R_2 + R_1 \]

Fig. 8.4. Scheme of the structure with the distribution of the forces

Fig. 8.5. Cremona diagram of the tensegrity structure with vertical loads

Fig. 8.6. Cremona diagram of the vertical loads in a tensegrity with increased angle of the diagonals and a decreased angle of the top cables
Load case 1: pre-stress
The tensegrity structure is pre-stressed by a horizontal force (Fh) applied to the supports, as can be seen in figure 8.1. The pre-stress force results in the following Cremona-diagram (figure 8.2).
Based on the Cremona diagram can be concluded that the forces in the elements are decreasing to the top of the structure. The forces in the outer diagonal, tension hoop, top cable and strut are largest and the forces in the top are smallest. This can be explained by the small angle of the first diagonal, resulting in a large force.
A larger angle of the diagonals and a smaller angle of the top cable will result in smaller forces in the diagonals and larger forces in the top cables. This means that the forces in the top of the structure will increase and the pre-stress force is distributed more efficiently.

Load case 2: air pressure
The loads caused by the pneumatic element result in vertical forces which must be carried by the tensegrity to the supports. Without pre-stress forces, it will result in compression forces in some cables and tension in some struts. This can be seen in the Cremona diagram for the structure with only vertical loading (figure 8.5).
Compression will occur in the third and fourth tension hoop, the third diagonal and in all the top cables; additionally, tension will occur in the third strut. This behavior can be explained by looking at a normal beam under a vertical load. The bending caused by these vertical loads exists of a compression force on top and a tension forces at the bottom. Similarly, the upper two tension hoops carry compression forces and the bottom two tension hoops tensile forces.
As can be seen in the Cremona diagram in figure 8.6, decreasing the angle of the top cables (G1, G2, G3) will result in large compression forces in the bars and tension forces in the diagonals and tension rings. Increasing the angle of the diagonal will also result in larger compression forces in the bars. Moreover, the compression force in the top cables will be decreasing, as well as the tension in the tension hoops.

Load case 3: pre-stress and air pressure
The vertical loads will result in compression in a number of cables resulting in an unstable structure (the cables are unable to carry compression loads and will sag), as is shown in load case 2. However, the pre-stress forces in the tensegrity will compensate these compressive forces. Thus, the compression caused by the loads will decrease the pre-tension forces in these elements. Therefore, the pre-tension force should be larger than the compression caused by the loads to keep the cables under tension at all times. The same is true for the compressive bars, which should be under compression at all times in order to obtain a stable structure. Therefore, this load case will be normative for the amount of pre-stress necessary in the structure. The minimal pre-stress necessary is the force causing tension in all the cables and compression in the struts.
The Cremona diagram obtained by this load case can be seen in fig. 8.8. The top tension hoop (R4) is the element in a two-dimensional structure, which will be the first element to be under compression when the pre-stress force is decreased. Thus, this element determines the minimal pre-stress necessary.
Figure 8.9 shows the distribution of forces in the tensegrity structure. The reaction force in the support is composed of a horizontal force, which is the pre-stress force applied to the structure and is constant, and a vertical component, which is equal to the amount of vertical loads. This component is thus dependable on the amount of loads on the structure.

8.1.4 Computer analysis
The hand calculation is based on linear behavior of the structure. However, a tensegrity structure is a relative flexible structure in which the stiffness of the structure depends on the forces in the structure. More pre-tension of the structure will result in less deformations. Since the deformations of the structure are
Fig. B.7. Scheme of the structure with the distribution of the forces

\[
H_3 = R_4 + R_3 \\
H_2 = R_4 + R_3 + R_2
\]

\[
F_v = V_1 + V_2 + V_3
\]

Fig. B.8. Cremona diagram of the tensegrity with both pre-stress and air pressure loads
Fig. 8.9. Scheme of the structure with the distribution of the forces

\[ H_3 = R_4 + R_3 \]
\[ H_2 = R_4 + R_3 + R_2 \]
\[ F_h = R_4 + R_3 + R_2 + R_1 \]
\[ F_V = V_1 + V_2 + V_3 \]

Fig. 8.10. Left: structural action in a beam. Right: distribution of forces over the tension hoops in a tensegrity structure.
Fig. 8.11. Distribution of the force calculated by the GSA model in load case 1

Fig. 8.12. Distribution of forces calculated by the GSA model in load case 2

Fig. 8.13. Distribution of the forces calculated by the GSA model in load case 3
relative large, the deformations have a large influence on the equilibrium in the structure. The structure is therefore geometrical non-linear. In other words, the loads will cause the structure to deform. These deformations result in a different distribution of forces. However, these forces will subsequently lead to new deformations resulting in a different equilibrium of forces. This iterative process has to be taken into account in the analysis, so a non-linear analysis has to be made.

Since the structure will behave non-linearly, the equilibrium of forces in the structure will be calculated using the structural software Oasys GSA 8.4. The results found with the computer analysis will be compared to the results found with the hand calculation. In order to make a clear comparison, the structure is first analyzed linearly. Therefore, the structure is modeled using beam-elements for both cables and bars and rigid connections between the elements. Beam-elements are elements able to carry both tension and compression as well as bending moments. This simplification together with the rigid connections solves the problem of dimensional instability enabling a the possibility of a linear analysis. The bending moments caused by the rigid connections are insignificant and will cause a minimal error in the analysis results. However, the deformations found in the analysis will largely differ from the actual deformations. First the linear analysis will be discussed followed by a discussion of the differences between the linear and non-linear analysis.

**Load Case 1: pre-stress**
The force equilibrium calculated by GSA shows a distribution of forces similar to the forces found with the hand calculation, as can be seen in figure 8.11. This figure shows clearly that most of the pre-stress forces will go directly to the lowest tension hoop, which is not efficient. In appendix 6, a diagram can be found showing a comparison between the forces found with the hand calculation and with the linear analysis. From this comparison can be concluded that the pre-stress forces found with both methods are almost similar.

**Load Case 2: air pressure**
The force distribution calculated by GSA for load case 2 are shown in figure 8.12. Clearly visible in this figure are the large compression forces in the top cables and the large tension force in the lowest tension hoop. Tension hoop three (R3) carries a small compression force, while tension hoop R2 carries a small tension force comparable to the hand calculation. Diagram 2 of appendix 6 shows that the differences between the hand calculation and the GSA analysis are very small.

**Load case 3: pre-stress and air pressure**
The force equilibrium shown in figure 8.13 is the combination of the pre-stress force and the vertical loads. The distribution of forces is similar to the distribution found in the hand calculation. Since the pre-stress forces are larger than the forces caused by loads, the equilibrium of forces of load case 3 corresponds more to the force distribution due to pre-stress than to the loads. From appendix 6 can be concluded that the forces found with the hand calculation and GSA correspond.

From the comparison of the hand calculation to the computer analysis using GSA, can be concluded that both methods provide similar results. It can be stated that the model gives usable results and that the model can be used further studying the structural behavior of the structure and analyzing the structure non-linearly.

**8.1.5 Non-linear analysis of the structure**
In the linear analysis of the structure, beam-elements were used in the model. These beam-elements can carry bending moments, which was necessary in the linear analysis due to the rigid connections. In the non-linear analysis, the dimensional stability is taken into account through the iterative analysis process in which the equilibrium is determined in the deformed state. Additionally, the stiffness is determined by the forces in the structure. Since the elements in a tensegrity structure should carry axial forces only, other elements than beam-elements should be used. Bar-elements are chosen for all the structural elements, which
Fig. 8.14. Non-linear equilibrium of forces of load case 1 (pre-stress) in load case 1

Fig. 8.15. Non-linear equilibrium of forces of load case 3 (pre-stress and air pressure loads) in load case 3
are elements being able to carry both tension and compression. In this way, it is possible to see the magnitude of the compression force which could occur in a tension element. A zero-force will occur in the element if elements are used which can only carry tension and a element will carry a compression force. In this case, it is hard to estimate the amount of extra pre-stress necessary, so bar-elements are used in the model. As a result of using elements only being able to resist axial forces, the connections in the model are hinged.

The supports in the linear model were pin and a roller support, but in the non-linear model fixed supports are used. Consequently, the structure cannot be pre-stressed by applying a horizontal force to the supports. This is solved by moving the supports causing tension in the tensegrity structure. The displacement applied to the supports is similar to the displacement of the roller support caused by the pre-stress forces in the linear analysis of the structure.

The results of the non-linear analysis are discussed below. A comparison of the results of the linear and non-linear analyses can be found in appendix 7.

Load case 1: pre-stress
The pre-stress forces resulting from the non-linear analysis differs from the linear equilibrium of forces in some respects. As can be seen in figure 8.14, the maximal tension force in the lowest ring is smaller than in the linear calculation. Contrastingly, the forces in the rest of the tension hoops are larger in the linear calculation. This is shown more clearly in the diagram in appendix 7. It clearly shows that the forces in the upper part of the structure are larger in the non-linear analysis.

Generally, it could be said that the pre-stress forces is distributed more advantageous throughout the structure, which can be explained by looking at the deformation. The lower tension hoop will move downwards resulting in a larger angle of the diagonal and in a smaller angle of the top cable. The advantageous effect of this is mentioned in the discussion of the Cremona diagram.

Load case 2 will not be discussed since this load case will not lead to results in a non-linear calculation. The pre-stress forces are necessary to obtain a stable structure, thus a structure with only vertical loads will be unstable.

Load case 3: pre-stress and air pressure
In load case 1 the tension in the lower tension hoop was decreased and the forces in the rest of the hoops was increased compared to the linear analysis. The results for the combination of pre-stress and air pressure are the same. As a result, the tension force in the upper tension hoop is much larger than in the linear calculation, so the structure is more efficient. Moreover, the minimal pre-stress force of the structure will be less than the minimal pre-stress force in the linear analysis.

8.1.6 Deformations
The structure will not only deform due to the loads on the structure, but also due to pre-stress forces in the structure. In this paragraph the deformations caused by both cases are discussed. The deformations which will be shown are calculated using the minimal pre-stress necessary. Increasing the pre-stress will result in a stiffer structure and, thus, in less deformations. The deformations in the figures are magnified by a factor 10 in order to get a more clear image.

The pre-stress force will cause the whole structure to move down, which can be explained by the fact that a cable under a tension force tends to a straight line. However, it is prevented by the compression bars. The structure will therefore deform in a way that the top cables and diagonals + tension hoops will be as straight as possible.

When vertical loads are applied to the structure, the structure will move further downward, as can be seen in figure 8.17. The deformations caused by the vertical loads can be decreased by increasing the pre-stress forces in the structure, because it will decrease the influence of the vertical loads on the force equilibrium of the structure. Consequently, the difference between the deformations caused by the pre-stress forces and the deforma-
Fig. 8.16. Deformation of the tensegrity structure caused by pre-stress forces (LC1)

Fig. 8.17. Deformation of the pre-stressed tensegrity structure caused by the vertical loads (LC3)

Fig. 8.18. The different parameters used in this study.
tions caused by the vertical loads will be smaller. However, a larger pre-stress force can increase the deformation due to pre-stress forces, but these deformations are not important to the usability of the structure.

8.2 Study of the structural behavior of a planar tensegrity structure
The purpose of the study to the structural behavior of a planar tensegrity structure is to get insight in the behavior of tensegrity structures that can be used in the three dimensional design of the structure. Different parameters will be studied in order to get insight in its influence and usability in the actual design. It does not mean that this is a search for the most efficient structure, because other aspects such as the architectural appearance will determine the actual design as well as the structural efficiency. However, the study can help to structural design the roof structure in relation to the other aspects influencing the design. The following the parameters will be studied (the indicator is refers to the coding of the different variants):

1. Number of compression bars or tension hoops (3 = 3 hoops, 4 = 4 hoops)
2. Total height of the structure (Less height = lower behind the coding)
3. Shape top cable (R = straight, H = hollow)
4. Height above support (H = basis/larger, L = smaller)
5. Variable bar length (g = constant, gk = varying from large to small, kg = varying from amill to large, kgk = varying from large to small to large, KGk = varying from small to large to small)
6. Distance between the tension hoops (K behind teh coding = smaller distance between bars, K2 = smallest distance between bars)
7. Varying distance between the tension hoops (G = constant, GK = varying from large to small, KG = varying from small to large, GKG = varying from large to small to large, KGK = varying from small to large to small)

8.2.1 Method used to study the structural behavior
The minimal pre-stress force necessary of the tensegrity structure, through which all the cables are loaded with tension and all the bars with compression, is an important property of the tensegrity that says a lot about the efficiency of the structure. Principally, it can be said that the lower the minimal pre-stress force necessary, the more efficient the structure is. The weight of the steel is another important aspect, because a small pre-tension force could be necessary, which does not automatically result in less steel necessary. For instance, when one element has a very large force, the steel weight necessary could be large, while the pre-tension is small.

Thirdly, the deformations will be examined as an indication of the stiffness of the structure. Larger deformations are caused by less stiffness of the structure. The deformations given in the study are calculated with the minimal pre-stress necessary in load case 3. These deformations can be decreased by increasing the pre-stress as is discussed earlier.

In the analysis process the sections of the elements will influence the equilibrium of forces, because the sections of the elements influence their deformation. These deformation will influence the equilibrium of forces. Therefore, the sections are optimized in the analysis process to minimize the error, whereby buckling of the compression bars is taken into account. However, decreasing the sections of the elements will cause the top tension hoop to be under compression. Consequently, the pre-tension has to be increased by increasing the displacement of the supports. Larger sections are necessary resulting a decrease of the forces etc. This process is repeated two times in order to reduce the largest error.

This results in the following steps in the analysis process:
- Determine the loads
- Determine the minimal pre-stress force necessary (Fh) by increasing the pre-stresses until all the cables are loaded with tension (the fourth tension hoop R4)
• Optimize the section of the structural elements (elements of the same type have the same sections)
• Determine $F_h$
• Optimize the section of the structural elements
• Determine $F_h$
• Determine the equilibrium of force and the deformations
• Determine the amount of steel in the structures using the sections in the model

The differences between the variants examined are minimized for an optimal comparison. The aim was to only vary one parameter. However, adjusting one parameter could cause other parameters to change. For instance, increasing the length of the bars will result in a larger angle of the diagonals. Each discussion of a variable is started with a discussion of the changed variables. Figure 15 shows the different variables used.

The results of the different variants are presented in figure 8.22. Additionally, diagrams comparing the results can be found in appendix 8.

8.2.2 Number of tension hoops
An important choice in the design of the tensegrity structure is the number of tension rings. Using more tension hoops can maximize the angles of the diagonals and can create a larger total height more easily. However, more tension hoops will also result in more elements and thus the use of more material and will increase the number of connections. The number of connections should be minimized, because they are difficult to construct and are an expensive part of the structure.

The variants discussed in this paragraph will be used as the base variants in the rest of the study.

Variables
From practical considerations, the study is limited to the comparison between three and four tension hoops. Less than three tension hoops will result in very large elements and in large spans of the pneumatic cushions between the elements. Using more than four tension hoops will result in a very large number of elements and connections. Therefore, three and four tension hoops are chosen.

In order to accommodate an optimal comparison between the three and four hooped structure, the following variables are kept constant:
• Angle of top cable ($\alpha$)
• Distance between the middle bars
• Total height
• Height above supports

As a result of varying the number of compression bars, the distance between the tension hoops is also varied. The length of the bars cannot be similar between the structure with three hoops and four hoops, because it would have changed the total height of the structure. However, the length of the bars is constant inside a variant, as well as the angle of the diagonals, because these two variables are coherent. Summarily, the following variables were varied:
• Number of tension hoops
• Angle of diagonals between the two variants
• Length of the bars between the two variants

Conclusions
The differences in the number of elements of the base variant with three tension hoops and with four tension hoops can be found in figure 8.19. The amount of elements is given in total lengths of elements in order to take the large lengths of the elements in a structure with three hoops into account. The largest difference between the two variants are the length of tension hoops. The extra tension hoop in a tensegrity with four hoops results in more cable length in the structure. Additionally, the difference in number of connections is relatively small, but when this is translated to the three dimensional structure the difference is much bigger.

The minimal pre-stress force necessary in a tensegrity with four hoops is larger than in the structure with three hoops. An expla-
nation can be that the pre-stress force will have to be distributed over more tension cables. On the other hand, the angle of the diagonals are more advantageous, but this effect is negated by the larger pre-stress force applied in the supports. The large amount of pre-stress necessary can also be seen in the amount of steel weight necessary in a structure with four hoops due to the larger forces in the structure. Additionally, the deformations of both structures are almost similar; the deformations differ two percent in the advantage of the structure with three hoops. Consequently, the structure with the three hoops is a little bit stiffer than the structure with four rings.

On the other hand, the distances between the tension hoops are smaller in a structure with four rings, which is advantageous for the pneumatic cushion on the roof structure. A smaller span of the pneumatic cushion will result in a large curvature in the membranes of the cushion reducing the stresses.

8.2.3 Total height of the structure
In almost all variants studied, the total height of the structure is similar. However, in this paragraph the influence of the total height of the structure on the structure will be discussed.

Variables
The following variables are constant in relation to the base variant in order to accommodate an optimal comparison:
• Angle of the top cable (α)
• Distance between the middle bars
• Height above supports
The total height of the tensegrity is decreased by moving the lowest hoop upward decreasing the length of the bars and the angle of the diagonals. Inside a variant, the length of the bars and the angle of the diagonals is constant. The height of the bar in the lower tensegrity with three rings is similar to the bar length in the base variant with four rings facilitating a possible comparison between these two variants. Summarily, these variables are changed.

• Total height
• Angle of the diagonals between variants (β)
• Length of the bars between the variants

Conclusions
The minimal pre-stress forces necessary in both variants are much larger than in the variants with a larger total height of the tensegrity structure. It can be explained by the smaller angle of the first diagonal by a constant angle of the upper cable, which causes a larger tension force in the lower cable and thus a less efficient distribution of the force in the structure. Consequently, the amount of steel necessary in the structure increases even more in relation to the base variant. This is caused by the fact that the sections of the tension hoops have the largest influence on the amount of steel necessary, which are the elements with the largest increase in sections.

Another effect of decreasing the total height of the structure is a decrease of the stiffness of the structure. As a result, the deformations will increase. Generally, an increase in height increases the largest distance between the tension hoops resulting in a larger moment arm and, thus, increasing the stiffness of the structure.

However, if the total height is decreased by decreasing the angle of the top cable, it will result in totally different results. This variant has the same total height as the other lower variant discussed in this paragraph. As can be seen the minimal pre-stress necessary is decreased, because of the advantageous effect of a larger angle of the diagonal and a smaller angle of the top cable compared to the other lower variant.

In this variant, the decrease of total height also results in large deformations and this in less stiffness, but this is a logical consequence of a decrease in structural height.

8.2.4 Shape of the top cable
In the variants discussed in the last two paragraphs, most of the pre-tension force ends up in the lowest tension hoop, which is not an efficient distribution of forces. Therefore, the angle of the
first top cable can be decreased resulting in more stresses in the upper part of the structure. This could be obtained by a hollow top cable, which is discussed in this paragraph.

Variables
In order to obtain an optimal comparison between the variants, the following variables are constant compared to the base variant:
- Total height
- Distance between the tension hoops
- Distance between the middle bars
- Height above supports
- Angle of the diagonals (α)

The angle of the diagonals is constant inside a variant in order to minimize the influence of the angle of the diagonals. As a consequence, the bars in the structure have varying length. Tensegrity structures with a convex are outside the scope of this study, because these structures are more efficient for upward vertical loads while the air pressure causes a constant downward loading.
- Shape of the cable
- Length of the bars

Conclusions
A hollow shape of the top cable will result in a smaller minimal pre-stress force necessary compared to the base variant. As a matter of fact, this effect increases when the degree of concavity increases. This advantageous effect of concavity of the top cable can be explained by the fact that the angle of the first top cable G1 is smaller causing larger stresses in this cable. Therefore, relatively more pre-tension will be distributed along the upper three tension hoops compared to the base variant. In these tension cables the pre-tension forces are necessary to compensate the compression caused by the vertical loads. As a consequence, the structure will be more efficient and the minimal pre-stress necessary will decrease as well as the amount of steel necessary

Fig. 8.19. Table with a comparison between the number of elements and their length of a tensegrity with three and four elements.

<table>
<thead>
<tr>
<th></th>
<th>3-R-g-G-H</th>
<th>4-R-g-G-H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total cable length (m)</td>
<td>398</td>
<td>475</td>
</tr>
<tr>
<td>length top cables (m)</td>
<td>93</td>
<td>93</td>
</tr>
<tr>
<td>length diagonals (m)</td>
<td>91</td>
<td>91</td>
</tr>
<tr>
<td>length tension hoops (m)</td>
<td>214</td>
<td>290</td>
</tr>
<tr>
<td>Total length bars (m)</td>
<td>36</td>
<td>40</td>
</tr>
<tr>
<td>Number of connections</td>
<td>14</td>
<td>16</td>
</tr>
</tbody>
</table>

Fig. 8.20. Results of the analysis of a tensegrity structure with less height by a decrease of the angle of the top cable.
due to the smaller forces in the structure. Another important aspect is the increase in deformations. These deformations increase with an increase of the degree of concavity of the top cable. An explanation can be that the forces in the lower part of the structure are decreased in comparison to the base variant. Therefore, this part of the structure has less stiffness causing larger deformations. Finally, changing the shape of the top cable will influence the overall shape of the structure and more precisely the shape of the ceiling. The difference in height between the outer tension hoops and the middle tension hoops increased with a larger degree of concavity, which has to be taken into account in the design of the structure.

8.2.5 Height above supports
As is mentioned in the previous paragraph, decreasing the angle of the top cable can have an advantageous influence on the efficiency of the structure. A smaller angle of the top cable will result in a smaller height above the supports. Therefore, the influence of this height supports is examined in this paragraph.

Variables
The following variables are constant for the comparison to the base variant:
- Distance between the tension hoops
- Distance between the middle bars
- Total height

The other variables are changing as a result of the smaller height above the supports. Reducing the height above the supports can be seen as moving the total height of the structure downwards, resulting in larger lengths of the bars in order to keep the total height constant. As a consequence, the angle of the diagonals increases as well.
- Height above supports
- Angle of the top cable
- Length of the bars
- Angle of the diagonals

A variant with a straight top cable is examined, which can be compared to the base variant. Additionally, a variant with a hollow top cable is analyzed.

Conclusions
Reducing the height of the tensegrity above the supports will result in a large reduction of 82% of the minimal pre-stress force necessary in comparison to the base variant. This is caused by the decrease of the angle of the top cable and an increase of the angle of the diagonals. As a consequence, the pre-stress forces will take the route through the top cable to the top of the structure resulting in relatively more pre-tension in the upper tension hoops, which is illustrated in figure 18. The force in the first tension hoop is much smaller, while the forces in the rest of the structure are larger. Due to the study method, the force in R4 is as minimal as possible to determine the minimal state of pre-stress.

On the other hand, the reduction of the height above the supports causes larger compression forces in the top tension hoop and the top cables. This can be explained by the analogy with a compression arch. If the height of an arch decreases, the compression in the arch will increase. This is similar to the effect of increasing compression in the top cables due to a decrease in height above the supports. However, this effect is smaller than the effect of increasing pre-stress forces in the top tension hoop due to a more advantageous distribution of forces.

The variant with a hollow top cable will have an even more favorable distribution of pre-stress over the tension rings. This is also reflected in the minimal pre-stress force necessary, which is smaller than the force of the variant with a straight top cable. However, the difference in amount of pre-stress necessary between the variant with straight top cable and the variant with a hollow top cable is only 2% with respect to the base variant. All the variants with a smaller height above the supports result in large decreases of the amount of steel weight necessary, which is
caused by the large decrease of forces in the structure. However, this effect is a bit tempered by the large compression bars in the structure. Since the total height of the structure is similar to the base variant and the height above the supports is largely decreased, the length of the compression bars has increased significantly. Consequently, buckling of these bars will have a larger influence on the dimensions of the steel sections resulting in relatively more steel weight in the compression bars. However, the effect disappears in the context of the enormous reduction of steel weight due to smaller forces in the structure.

The stiffness of the structure is slightly larger than the stiffness of the base variant, the deformation of the variant 3-R-gk-G-L will be 40% less compared to the base variant. The increase of stiffness is larger in the variant with a hollow top cable, which will deform 8% less than the 3-H1-kg-G-H. Generally, reducing the height above the supports will result in more stiffness of the structure.

Spatially, this variable could be very problematic in the design. The reduction of height above the supports causes larger heights under the supports resulting in reduction in height of the ceiling. As a consequence, the structure could block sightlines from the stand to the other side of the stadium. Additionally, a low ceiling could create claustrophobic spaces in the top of the stands, which has to be prevented. Therefore, the height under the supports should be minimized in order to create a nice spatiality of the stands, while at the same time the structure will have to be efficient. A balance must be found between these two extremes, which could be done by decreasing the angle of the top cable instead of increasing the height under the supports resulting in less total height. However, it will reduce the stiffness of the structure.

8.2.6 Varying length of the bars
A varying length of the bars in a structure already appeared in the variants discussed. However, in this case was the consequence of a constant angle of the diagonals. In this paragraph, the influence of a varying length of the bars and the resulting varying angle of the diagonals will be discussed.

Variables
The following variables are constant in relation to the base variant:
- Total height
- Distance between the tension hoops
- Distance between the middle bars
- Height above supports
- Angle of the top cable (α)

As a consequence of varying the length of the bars, the angle of the diagonals (β) will vary as well. However, the length of the first bar will be constant because the total height is similar to the base variant in addition to the height above the supports and the angle of the top cable. As a result, the angle of the first diagonal will be constant as well, so the difference in relation to the base variant is in the second and third bar.
- Length of the bars
- Angle of the diagonals

The following variants with a varying length of the bar will be examined in the report.
- A variant in which the first bar will be largest, followed by a smaller bar and the last bar will be largest again varying from large to small to large = gkg
- A variant in which the first bar will be largest followed by smaller bars. This variant is not made for a tensegrity with 4 tension hoops, because the last bar will be too small. (varying from large to small = gkg)
- A variant in which the first bar is the smallest followed by a larger bar and ending with a smaller bar (varying from small to large to small = kgk)
- A variant in which the first bar is the smallest followed by bars of increasing length (varying from small to large = kg)
Conclusions

The tension force due to pre-stressing in the lowest tension hoop will be relatively similar to the base variant since the first compression bar is similar to the base variant in addition to a similar angles of the top cables and diagonals. The differences in the equilibrium of forces between the variants in this paragraph and the base variants are resulting from the variances in the length of the other bars and the resulting variances in the distribution of forces.

Another aspect resulting from the similarity between the first bar of the variants in this paragraph and the base variant is that the angles of the diagonals will be smaller compared to the base variants in the gk and gkg variants, while the angles in the other variants (kg and kgk) are larger. The last variants should be more efficient, since increasing the angle of the diagonals will have a beneficial effect on the distribution of forces.

The first three variants will result in large minimal pre-stress forces necessary caused by the smaller angles of the diagonals. Therefore, the variant with a smaller cumulative angle of the diagonals is the least efficient structure. The structures with an increasing length of the bars will thus result in a reduction of the pre-tension forces necessary.

These differences in the amount of pre-stress necessary can also be seen in the amount of steel weight necessary. The larger forces in the first three variants result in larger steel weights necessary, while the less pre-stress forces in the other four variants results in less steel weight necessary. A remark in this context is the increasing length of the bars, which will result in a larger influence of buckling resulting in relatively larger sections of the bars.

The deformations also decreases in the variants with larger compression bars in relation to the base variant. On the other hand, the deformations of the variants with decreased bar length are larger than the deformations of the base variant. It can be stated that increasing the length of the bars will increase the stiffness of the structure.

If we look at the graphical implication of the conclusions made, it can be said that the tension hoops, except the top one, should be as low as possible. This is a result of increasing the length of the bars, because increasing the length of the bars will enlarge the distance between the top cable and the other cables, which is beneficial for the efficiency of the structure.

The compression force due to vertical loading in the top cable will increase, because the other cables will be loaded increasingly with tension. This can be illustrated with a the comparison of a bending moment in a beam with the distribution of forces in the tensegrity. The forces in the tension hoops will have to carry this bending moment by reducing and increasing the tension in the cables, compared to a beam under pre-tension.

8.2.7 Distance between the tension hoops

The distance between the tension hoops can vary in the spatial design of the tensegrity structure, which will be discussed in the next chapter. This variable will be examined in this and the next paragraph. This paragraph will discuss variants in which the distance between the hoops is increased and the distance between the middle bars is decreased.

Variables

Only the one variable is similar to the base variant:
- Angle of the top cable

The angle of the top cable is similar to the base variant in order to eliminate the influence of it on the distribution of forces. In the connection with the diagonals, the direction of the top cable is similar, and will have a similar influence on the route of the pre-stress force. However, increasing the distance between the tension hoops with a constant angle of the top cable will result in a larger total height of the structure. The height of the structure under the supports is similar to the base variant; thus, the height above the supports increases.
Increasing the distance between the tension hoops will logically decrease the distance between the middle bars. Additional, in order to obtain the same height under the supports, the length of the bars is increased. The angle of the diagonals will be smaller, since the distance between the bars is increased. The length of the bars and the angle of the diagonals is constant inside a variant.

- Distance between the middle bars
- Distance between tension hoops
- Height above the supports
- Total height
- Angle of the diagonals between variants
- Length of the bars between the variants

**Conclusions**

From the results of the analysis of these variants can be concluded that increasing the distance between the tension hoops will result in a larger minimal pre-stress force necessary. The pre-stress forces are 10-15% larger compared to the base variant, which can be explained by the decrease of the angle of the diagonals since the angle of the top cable is constant. The increase in steel weight necessary in the structure is increasing less than the pre-stress forces necessary.

Initially, the deformations are increasing as a result of the increasing distance between the tension hoops. However, further increasing the distance will result in smaller deformations, which indicates that two effects on the deformations play a role. Firstly, the reduction of the angles of the diagonals is resulting in less stiffness of the structure. Second and more significant is the increase in stiffness due to an increasing total height of the structure, which will result in larger stiffness as is illustrated in paragraph 2.3. Initially, the first effect will be dominant, while the second effect will have the upper hand when the total height is further increased by enlarging the distance between the hoops.
8.2.8 Varying distance between tension hoops

Finally, the distance between the tension hoops can be varied while the distance between the middle bars is constant. The difference with the previous paragraph is that the total height of the structure will be constant in this variant and that the distance between the hoops will vary.

Variables

The following variables are similar to the base structure in order to accommodate an optimal comparison:

- Distance between the middle bars
- Height above the supports
- Angle of the top cable (α)
- Total height

As a consequence of varying the distance between the tension hoops, the angle of the diagonals or the length of the bars will vary as well. In this paragraph, both types of variants will be examined; one with a constant angle of the diagonals based on the first diagonal, and one with a constant length of the bars based on the length of the first bar. The first will result in a varying the length of the bars and the second in a varying the angle of the diagonal.

- Distance between the tension hoops
- Length of the bars
- Angle of the diagonals

In this paragraph, the following variants will be examined, both with constant angle of the diagonals and constant length of the bars.

- A variant in which the first distance is smallest, followed by an increasing distance (varying from small to large KG)
- A variant in which the first distance is the smallest, followed by a larger distance and ended with a smaller distance (varying from small to large to small KGK). The distance between the support and the first hoop is in this variant larger than in the KG variant.

Conclusions

The minimal pre-stress force necessary in the tensegrity structure in both variants with a constant angle of the first cable is less than the minimal pre-stress of the base variant. The angle of the diagonal is larger than in the base variant, because the angle of the diagonal is based on the first diagonal in combination with the fact that the distance between the support and first tension hoop is smaller in comparison to the base variant. This will have a beneficial effect on the distribution of forces. As a consequence, the variant with the smallest distance between the support and first hoop (3-R-kg-KG-H) has a smaller minimal pre-stress necessary.

On the other hand, the variants with the constant length of the bar results in a larger minimal pre-stress force. This is caused by the small angle of the diagonal in the parts of the tensegrity with the largest distances between the hoops. The angle of the diagonal will be so small in these parts that the almost all the force will be in this diagonal resulting in an inefficient distribution of forces.

These differences can also be seen in the amount of steel weight necessary in the structures. The deformation of almost all the variants are larger than the deformation of the base variant, except the 4-R-kg-KG-H and 3-R-g-KGK-H variant of which the deformations are almost similar to the base variant. This means that the variants discussed in this paragraph have less stiffness than the base structure.

Varying the distance between the tension hoops could be very useful in the spatial design of the structure. By decreasing the distance between the supports and the first tension hoop, given a certain angle of the diagonal, the length of the bar will decrease. Beneficially, it will reduce the height under the supports resulting in more spatiality of the stands under the ceiling.
8.2.9 Conclusion
A total overview is given of the different variants examined in this study in figure 8.22. The most important values are presented as well as the most important conclusions. In the scheme, colors are used to value the different variants, based on the minimal pre-stress necessary and the deformations of the structure. This evaluation is a more global scaling of the different variants and not a strict evaluation based on precise numbers. The conclusions will be used as the basis of the spatial design of the structure in addition to other significant aspects in the design.

The largest decrease of the pre-stress necessary in the structure can be obtained by reducing the height above the supports. Additionally, the amount of steel used in the structure and the deformation will be reduced. Thus, all three effects are beneficial for the structural action. However, as is discussed in paragraph 8.2.5, the reduction of height above the supports results in a large height under the supports which has a negative effect on the spatiality of the stands. Thus, these variants are practical not ideal, but the variable applied to a lesser extent (less increase of height under the supports) can be useful in the design to achieve large improvements.

Another variable with beneficial effects on the minimal pre-stress force, steel weight and deformations is increasing the length of the bars. Increasing the length of the bars will result in smaller forces in the structure and in more stiffness of the structure. Consequently, adapting this variable can be useful in the spatial design.

A variable which is useful in the design to a lesser degree is the shape of the top cable. A hollow shape of the top cable can result in relatively large reductions of the minimal pre-stress necessary due to a more efficient distribution of forces in the structure. The reduction of the total steel weight necessary in this case can improve more than by increasing the length of the bars. However, the hollow top cable will have a negative effect on the stiffness of the structure. Thus, adjusting the shape of the top cable in the design could reduce the forces in the structure, but will increase the deformations of the structure. Varying the distance between the tension hoops could reduce the forces in the structure as well, but the reduction is of the pre-stress forces is smaller than in the previous variable. However, the increase of the deformation due to the varying distance between the tension hoops is smaller than due to change of the shape of the top cable. It depends on the situation which of the two variables will be more useful in the design.

The four variables discussed above are the most useful ones in the design of the structure of the variants examined in this study. These four variables should be applied first in the spatial design of the structure in respect to the situation.

More generally, the angle of the top cable and the angle of the diagonals are important aspects determining the distribution of forces in the structure. The variables discussed above are methods which can be used to change these angles. In relation to the deformation, the total height is also important. Complementary, a larger total structural height of the tensegrity will result in more stiffness and in less deformations.

Fig. 8.22 Overview of the study to the planar behavior of the tensegrity structure.
Fig. 9.1. Left: the initial form of the tensegrity. Right: Enlarging the compression bar will result in lengthening of the cables causing tension in these cables.

Fig. 9.2 Distribution of forces in a three dimensional tensegrity structure.
9. Spatial design of the tensegrity structure

The planar behavior of the structure is discussed in the previous chapter. This knowledge will be used in the spatial design of the tensegrity structure, which will be discussed in this chapter. Therefore, the spatial behavior of tensegrity structures will be discussed first. Subsequently, the pattern of the tensegrity roof structure will be discussed resulting in a three dimensional design of the roof structure.

9.1 Structural action of a three dimensional tensegrity structure

In the previous chapters, the planar behavior of a tensegrity structure is discussed. This chapter will use this knowledge to comprehend the spatial structural behavior of a tensegrity structure.

9.1.1 Loads

*Method of pre-stressing*

In the planar tensegrity structure, the pre-stress forces were applied by applying a displacement to the supports of the structure. However, applying this method will result in a too complex process of introducing the pre-stress forces, since each planar section of the three dimensional tensegrity will have a different direction. The displacement applied to the support should have the same direction as the cables. Therefore, it is difficult to apply the correct displacements to obtain the correct state of pre-stress. So, another method of pre-stressing will be used.

Another way of applying pre-stress to the tensegrity is to increase the length of the compression bars. This can be obtained by increasing the temperature of the compression bar causing the bar to expand linearly with the increase of temperature. As a result of the extra length of the bars, the tension cables will be stretched causing tension forces in these cables. Consequently, the other elements of the structure will be stressed and the pre-tension forces are applied.

However, the deformations found in the analysis will contain the enlargement of the bars, which will be discussed in the analysis of the spatial tensegrity structure.

A second alternative method is by shortening the tension hoops. It will cause the structure to be pre-tensioned in the same way as enlargement of the compression bars. The length of the tension hoops can be decreased by decreasing the temperature of the tension hoop, which will cause the hoop to shrink. However, this method will result in a strange tension force in one of the compression bars in the structure. This tension force will increase by an increase of pre-stress force in the structure, resulting in an unusable model. Therefore, the pre-stress will be applied by increasing the length of the compression bars.

*Vertical loads*

The vertical loads in the structure are similar to the planar tensegrity structure. The only vertical load acting on the tensegrity is air pressure load of the pneumatic element, because the pneumatic element will carry other vertical loads, such as snow load, to the supports. The air pressure load of the pneumatic element is 0,5 kN/m².

*Load cases*

The following load cases are used:

- Load Case 1 (LC1): Pre-stress forces in the structure
- Load Case 2 (LC2): Horizontal pre-stress forces and vertical air pressure loads

The load case with only vertical loads used in the study of the planar behavior of tensegrity structure will not be used here, since this load case will not result in usable result form the non-linear analysis. Additionally, this load case is not important in the analysis, since pre-stress is necessary to obtain load-bearing capacity for vertical loads.

9.1.2 Tensegrity dome structure

The structural behavior in a tensegrity with a circular plan will be discussed first, because in a circular tensegrity structure the force in similar elements throughout the structure will be constant. For instance, the forces in all the top cables in the same
Fig. 9.3. Distribution of forces in the tensegrity dome due to load case 2 (pre-stress force and air pressure loads).

Fig. 9.4. Deformations of the tensegrity dome due to load case 2 (pre-stress forces and air pressure loads)
ring will be similar. The structural behavior of a circular dome will be relatively similar to the behavior of the planar section except for some large differences. Firstly, in the two dimensional analysis, the component force of the tension ring is used; as a consequence, the tension force in a spatial tensegrity structure will be larger in order to create this component calculated in the two dimensional structure. This can be seen in figure 9.2. Secondly, the loads on the planar structure were based on a constant distance between the planar section, while this distance is not constant in a dome structure. Moreover, this distance will decrease to the top of the structure, resulting in a decrease of the loads applied to the structure causing smaller forces in the structural elements. Thirdly, the way in which the pre-stress forces are applied to the structure is different. In the analysis of the planar behavior of the structure, the pre-stress forces were applied by applying a displacement to the supports. In the dome structure, however, these forces are applied by increasing the length of the compression bars. This will have an influence on the distribution of the forces over the tensegrity, since the increase of length of the bars causes different angles of the top cables and diagonals.

Figure 9.3 shows the distribution of forces in load case 2, while the distribution of force in load case 1 can be found in appendix 9. The amount of pre-stress in the structure is determined by the minimal pre-stress force necessary in load case 2 to load all cables with tension and all compression bars with compression forces. As can be seen in the equilibrium of force of both load cases, the differences in forces between these two load case are relatively small, which could be caused by an inefficient distribution of forces throughout the structure. As can be seen in figure 9.3, the forces in the tension ring are indeed larger in relation to the forces in the other cables and bars compared with the planar tensegrity structure. The component acting on the planar section of the outer tension ring is:

\[ R_1 = 2 \cdot F_{\alpha_1} \cdot \tan(4.5) = 2 \cdot 15080 \cdot \tan(4.5) = 2374 \text{ kN} \]

In the two dimensional structure, the force in the first tension hoop is 5296 kN. However, this difference is in line with the general decrease of forces due to the circular plan instead of constant distance between the planar sections. The forces in most of the elements are more than half the forces in the two dimensional structure, but the loads on the structure are also more than half of the loads in the planar section. However, the actual building will not have a circular plan, but a more rectangular one in which the loads will be more like the loads in the planar behavior of the structure. Therefore, it is more important that the global distribution of forces resembles the equilibrium of forces of the planar section of the tensegrity structure. Similar to the two dimensional analysis of the structure, the force in the cables and bars will decrease to the top of the structure. In other words, the forces in the outer cables are larger than the forces in the inner cables. Generally, it can be said that the equilibrium of forces appear to resemble the planar analysis of the tensegrity.

9.1.3 Deformations

The deformations in the structure will appear before the building is in use, as is discussed in the structural principle of the combined structure of a tensegrity with a pneumatic roof structure. Therefore, the deformations will not largely influence the building’s use. Therefore, it is not restricted to the guidelines for the maximum deformation. However, the deformations are more or less restricted to the detailing of the structure and the appearance of the structure. Large deformations could result in large out of alignments of the compressions bars visible to the users.

The deformation of the structure can be seen in figure 9.4 and in appendix 9. Partly, the deformations shown are caused by the increase in length of the compression bars. The difference in length before and after applying the pre-stress force is \( \Delta l = \alpha \cdot l \cdot 1.2 \cdot 10^{(-6)} \cdot 5 \cdot 15000 = 0.9 \text{ m} \). A large part of the deformations are thus caused by the increase in length of the bars.
Fig. 9.5. Difference in effect of the component force of the tension hoop on the tensegrity structure.

Fig. 9.6. Problem of the structural behavior of an inward curve in the compression ring.
Additionally, the pre-stress forces cause deformations of the structure. These deformations will increase as the pre-stress forces increase. In this tensegrity dome, the deformations due to pre-stress are 1.089-0.9=0.189 m. Thirdly, the vertical loads will result in an increase of the deformations. The difference between the deformations caused by pre-stress and vertical loading will decrease when the pre-stress force increases. In this structure, the differences are already small, which is caused by the small difference between the forces due to pre-stress and due to vertical loads in the structure. The larger the pre-stress forces are, the less influence the vertical loads have on the structure and therefore, the difference in deformation will decrease. As a result of this effect, pre-stressing the structure can be used to decrease the deformations due to vertical loads.

9.1.4 Curved plan
The previous paragraph discussed the spatial equilibrium of forces in a tensegrity dome. However, the structure of the building does not have a circular plan and will therefore have a different structural behavior. Especially the structural behavior of the middle part of the structure will be different because of its longitudinal direction instead of a circular form. Moreover, the middle section of the compression ring will be composed of a tension arch and a compression bar resulting in an inward curve of the compression ring. The inward curve of the compression ring will result in a problem in the structural behavior of the tensegrity. The problem caused by the inward curve is the undermining of an essential aspect of the structural action of a tensegrity structure. If a planar section of a tensegrity is examined, the inward component force of the tension ring is an important aspect of the equilibrium of forces. More specifically, this component is necessary to balance with the horizontal component of the force in the diagonal. In a domelike tensegrity, the planar component of the tension force will always be directed to the center due to a constant curvature of the tension hoop. Contrastingly, the inward curve of the compression ring will result in opposed curvature of the tension hoop in the middle section, as can be seen in figure 9.6. Consequently, the component of the tension hoop will have an outward direction in the same direction as the horizontal component in the diagonal. Thus, the diagonal and the tension hoop will not be in equilibrium causing instability of the tensegrity structure.

This problem can be solved in the pattern of the tensegrity structure. The next chapter will discuss the design of the pattern of the tensegrity structure. The proposals will be based on possible solutions to this problem.

9.2 Morphology of the tensegrity structure
The design of the morphology of the tensegrity structure will be discussed in this paragraph. An important aspect of this design is the problem discussed in the previous paragraph. Therefore, the morphologies proposed in this chapter will be based on a solution to this problem. Another aspect largely influencing the design is the degree of curvature in the tension hoops in the middle section of the structure. More curvature will result in a large component force on the planar sections of the roof. The plans of the different morphologies discussed shown in the figures are all composed of three tension hoops.

9.2.1 Extra cables compensating the inward curved tension hoop
In this variant, the tension cables follow the curvature of the compression ring, resulting in a constant distance between the tension hoops and the compression ring. Additionally, the similar form of the tension hoops and compression ring will visually emphasize the inward curve of the compression ring and the stands. However, the inward curve of the tension hoops will result in an instable structure. Therefore, extra cables spanning between both sides of the middle section is applied. These cables will balance both sides of the structure and causes an equilibrium with the horizontal component of the diagonals and the component of
Fig 9.7. Plan of a tensegrity with three tension hoops and extra cables to compensate the inward curve of the tension hoop.

Fig. 9.8. Schematic section of the longitudinal section of the tensegrity with in red the extra cables running in transverse direction.
the tension hoop, which can be seen in figure 9.7.
Disadvantageously, it will result in a large amount of extra cables in the structure, which is inefficient and will increase the costs. Besides, sagging of these cables should be prevented since these cables will have to span large distance. The cables could be hung to the bars above, which will result in additional elements in the roof structure.
These cables will negatively influence the spatiality of the space underneath the structure seen from an architectural point of view. Especially, the division of the structure in a spatial structure of two half domes and a linear two dimensional structure in the middle section. This will result in an incoherent appearance of the structure. A more spatial uniform structure could create a good uniform atmosphere, but not with this morphology of the tensegrity.
Conclusively, this morphology will not result in a coherent efficient structural design and will therefore not be used in the design of the tensegrity structure.

9.2.2 A tensegrity structure composed of two elliptical domes
Another possibility is to create a tensegrity structure by a combination of two tensegrity domes. A tensegrity dome will have a constant curvature in the tension hoops with a component in the good direction. However, if two circular domes are used, the domes will not intersect resulting in a zone between these two domes. Therefore, two elliptical domes are used, which will intersect each other due to the extra length in comparison to the circular domes. In order to link the two domes, a central tension truss will be necessary because of the interruption in the outer tension hoop, as could be seen in figure 9.9.
A large advantage of this morphology is the relatively large curvature of the tension hoops throughout the structure. Other morphologies discussed in this chapter will have less curvature of the hoops in the middle longitudinal section of the tensegrity. The two elliptical domes will not be similar sized, causing the smaller dome to be loaded by the larger dome. Additionally, asymmetric deformations will appear in the linking zone between both domes, especially the linking truss will deform out of its plane. Another disadvantage of this morphology is the relatively large distance between the outer tension hoop and the compression ring in the middle section. As a consequence, the stiffness of this part of the structure will be relative small resulting in larger deformations. This effect could be reduced using four tension hoops, because it will reduce the distance between the outer tension hoop and compression ring.
Another problem of linking two domelike tensegrity is pattern of the transition area, this pattern will deviate from the rest of the mesh. As a result, the pattern of this transition area will have an awkward appearance that will visually divide the structure of the central space of the stadium in two parts due to the combination of two domes. Especially, the reduction in height of the hall in the middle of the space will cause this visual division, as can be seen in figure 9.10. The visual division could be softened by placing the pneumatic cushion on top of the tensegrity, which decreases the impact of the reduction in height. However, it will remain visible. Conclusively, the visual division of the stadium will not be preferred and therefore another morphology will be used despite the interesting structural possibilities of the combination of two dome structures.

9.2.3 A tensegrity composed of an elliptical-like tensegrity dome
A third solution is to use one elliptical dome, resulting in positive curvature of the tension hoops and thus in a stable structure. In this variant, a combination of different circular segments is used, which is not an exact ellipse. In this way, the tension hoops can follow the compression ring in the circular ends of the structure, which will result in a constant distance between the hoops and compression ring in these parts. On the contrary, this distance will vary in the middle section of the structure. This distance will decrease to the center of the structure due to the inward curve of the compression ring and the outward curving tension hoops. As can be seen in figure 9.11, the curvature in the middle section of the tension hoops will be relatively small. The curvature could
Fig. 9.9. Plan of a tensegrity structure with three tension hoops composed of two elliptical domes

Fig. 9.10. Schematic section of the building with the roof form with a decrease of height in the centre of the stadium
be increased by decreasing the distance between the compression ring and tension hoop in the middle. However, the distance could not be too small, since it will cause other structural problems, such as large differences in stiffness in the structure. If this distance is minimal, the curvature in the tension hoop will be larger in a tensegrity with three tension hoops than one with four hoops, because the distance between the outer hoop and compression ring will be smaller in the circular sections, while the minimal distance in the longitudinal section remain constant. This will result in less curvature in the tension hoops.

As is mentioned, the tension hoop is composed of sections with different curvature, resulting in a difference in angle in the connection. As a result, the forces in the planar section connected to these links are loaded by larger forces. This morphology will result in a large central cushion, which is largest in the variant with three tension hoops. Additionally, a large amount of compression bars will be relatively close to each other in the circular section of the inner tension hoop. As a consequence, the appearance of this part of the structure will be more closed and massive due to the proximity of bars in contrast...
to the lightweight open appearance of the rest of the structure. However, a large advantage of this morphology over the previous morphologies is the uniform structure. The structure exists of one spatial solution for the whole roof instead of combining different patterns resulting in an uniform spatiality of the stadium hall. Therefore, the next morphologies discussed will be based on this principal trying to improve the above discussed negative points of this structure.

9.2.4 A tensegrity composed of an elliptical tensegrity dome

This morphology is based on the previous one with the difference that the tension hoop will be a perfect ellipse instead of a combination of different circular sections. It will eliminate the problem of increasing forces in the planar sections due to the change of curvature. Additionally, the structure exists of an uniform spatial solution for the whole structure. As a result of using a perfect ellipse, the curvature in the centre of the tension hoops will be increased in relation to the elliptical-like morphology. However, the part with large curvature in the circular ends of the structure is smaller in relation to the previous variant. Thus, less planar sections will benefit from the larger curvature of the tension hoop. The variant with three hoops will
have more curvature in the hoops than the variant with four hoops. Similar to the previous morphology, there is a large concentration of compression bars in the inner hoop of the circular section of the tensegrity, which is a disadvantage. Another disadvantage is the increased variation of the distance between the tension hoop and the compression ring, which will result in larger differences in stiffness and less efficient force distribution. A larger distance between the hoops will result in smaller angles of the diagonals and top cables causing less stiffness and a less efficient force distribution comparable to the planar behavior. However, this is compensated by the increase of curvature of the tension hoops. Conclusively, the morphology has improved due to the elliptical ellipse, but the disadvantage of the large concentration of bars is still present.

9.2.5 A tensegrity structure composed of an eye-like patterned dome

This variant of a pattern for the tensegrity structures merges the compression bars in the inner hoop of the circular sections, resulting in a larger central compression bar that will improve
the lightweight and open appearance of the structure. In this variant the planar sections in the circular section are perpendicular to both the tension hoop and compression ring, while the planar section of the middle section are only perpendicular to the tension hoops resulting in the lack of a component force in the direction of the tension hoop. The planar section on the transition between the circular and longitudinal section is perpendicular to both the curvature of the tension hoop in the circular section as to the hoop of the longitudinal section. The change of curvature will not cause large forces. Additionally, the curvature in the tension hoops will be increased since the inner hoop starts in the central compression bar, which will increase the space for the tension hoop to increase the curvature. This curvature is here also largest in the variant with three tension hoops, while the size of the central cushion is decreased. On the other hand, the varying distance between the outer tension hoop and the compression hoop still exists, which can have a negative influence on the structural behavior of the tensegrity. However, the varying of the distance between hoop and compression ring accommodates the increase of curvature of the tension hoop. Decreasing the variation in this distance causes

Fig. 9.14. Plan of a tensegrity structure with three tension hoops composed of two domes with an eye-like pattern
the curvature to decrease, which will also have a negative effect on the structural behavior of the structure. Most of the disadvantages occurring in the other morphologies are absent in this variant except the varying distance between the outer hoop and the compression ring. However, it depends on the curvature of the tension hoop, which should also be maximized.

9.2.6 A tensegrity composed of two eye-like patterned domes

Based on the eye-like patterned dome tensegrity discussed in the previous paragraph, a combination of two domes could be created resulting in the morphology shown in figure 9.14. Similar to the morphology in the previous paragraph, all the diagonals are connected perpendicular to the curvature of the tension hoop. Due to the composition of two domes, the curvature in the tension hoops is increased resulting in a larger component of the tension hoop on the planar sections. As a consequence, the distribution of forces will be more efficient and the tension force in the hoops will decrease. This curvature is largest in the variant with three tension hoops.

Similar to the combination of two domes earlier, there is a central tension truss necessary to connect the two parts. However, the decrease in height in the centre of the building will be less. Additionally, the distance between the outer tension hoop and the compression ring will not be as large as the distance in the middle between the outer hoop and compression ring in the combination of two elliptical domes. Therefore, the angles of the diagonals and top cables will be more favorable, resulting in a more efficient force distribution and more stiffness. Moreover, the distance between the outer tension hoop and the compression ring is less varying than in the previous morphologies. However, this distance is not constant throughout the structure.

The largest disadvantage of a tensegrity structure with a composition of two domes is the visual division of the space under the structure. This visual separation of both sides is less in this variant than in the morphology in paragraph 2.2, but it is still present. Additionally, the transition area shows an abnormal pattern in order to connect both domelike tensegrities.

9.2.7 Conclusion

Different morphologies are discussed in this chapter, in which basically three different types of solutions can be distinguished. That is, a tensegrity structure with extra cables running in transverse direction to balance both sides, a tensegrity composed of two tensegrity domes and a tensegrity composed of one elliptical formed tensegrity structure.

The first type is rejected because of the large number of extra cables necessary to achieve a stable structure and the negative influence of these cables on the spatiality of the stadium hall under the structure. Additionally, this principle is based on a combination of a linear structure in the middle section ended by two spatial structures, which are the half domes. A more spatial structural solution for the roof structure is desired.

The second type, the combination of two domelike structures, can result in an interesting tensegrity structure with a relatively large curvature of the tension hoops. However, the connection of the domes will result in a little bit awkward appearing transition pattern. Additionally, the structure will cause a visual division of the stadium hall with the ice track and stands. This last disadvantage is especially undesirable in the design of ice stadium. Therefore, the last type of morphology could be the solution.

A single elliptical domelike tensegrity spanning the whole roof structure will result in a uniform spatial solution for the whole roof. However, this will result in a varying distance between the outer tension hoop and the compression ring causing large differences in stiffness. However, the varying could be decreased by decreasing the curvature of the tension hoop, but this has a negative influence on the structural behavior of the structure. A balance must be found between these two aspects.

Considering the different morphologies discussed that are composed of a single elliptical-like domed tensegrity, the third variant with the eye-like patterned dome will be the most preferred. As is concluded in paragraph 2.5, the tension hoop of this variant has the most curvature of the variants with a single dome. Ad-
Fig. 9.15. The different zones with same vertical air pressure loads.

Fig. 9.16. Sections of the spatial base variant of the tensegrity structure
ditionally, most of the disadvantages of the other morphologies are solved in this morphology. Since this type of tensegrity will have the best spatial qualities in the design and should have a relatively favorable structural behavior, this morphology will be used in the spatial design of the tensegrity. The tensegrity will be composed of three tension hoops, because of larger curvature of the tension hoop possible. The next chapter will discuss the spatial design of the tensegrity.

9.3 Design of the tensegrity
The three dimensional design of the tensegrity structure will be discussed in this chapter. Besides, the forces and deformations calculated are discussed and the effects of some improvements will be shown.

9.3.1. Loads
The way of applying the pre-stress forces to the structure is already discussed in paragraph 1.1. However, the vertical loads will have to be determined for this specific pattern in order to analyze the spatial structural behavior of the structure. The tensegrity structure is divided into eight zones in order to simplify the calculation of the loads. Since the distance between the elements are not constant in the structure, an exact calculation of the loads in each specific point would take too much time. The error resulting from this simplification would not be a problem since the analysis is also a calculation for the preliminary design of the structure. The eight zones distinguished and the values of the loads in these zones can be seen in figure 9.15.

9.3.2. Base structure
A basic structure with a constant height of the struts will be discussed, as the starting point of the design of a three dimensional structure based on the chosen pattern. The height of the structure is based on a straight top cable with constant distance between the tension hoops as in the small dome. The inner two rings with diagonals and top cables are thus the same throughout the structure. However, the distance between the outer tension hoop and the compression ring is variable resulting in varying angles of the diagonals and top cables. This also means that the top cable, which is straight in the small dome, is not straight throughout the structure. Since the angle of the outer top cable is smaller in the large dome, the top cable has a hollow form. The middle section, on the other hand, shows a more convex shape, which can be seen in figure 9.16.

Distribution of forces
The amount of pre-stress of the structure necessary is determined by the load case with vertical air pressure loads. More specifically, the top cables in the inner ring of cables of the dome sections are the last cables in tension when increasing the pre-stress forces. This can be explained by the large density of diagonals and top cables in the top parts of the dome sections and the stresses introduced by enlarging the shared central bar that have to be distributed over these cables. The compression force in this shared central bar is also the largest compression force in the structure due to the large amount of cables connected to this bar. If the compression force in this bar is divided by the number of cables (15 cables), then the compression force will be in proportion to the compression forces in the other bars. We could reduce the amount of elements in the dome sections of the tensegrity, but then it will increase the stresses in the remaining elements and will result in less stiffness. The dome sections are the stiffer parts of the tensegrity and if the deformation of these parts increases, the deformation in the middle section would also increase. Therefore, the amount of elements in the dome sections will not be reduced.

Another important aspect of the pattern of the tensegrity is the difference in curvature of the tension hoops in the middle section and in the dome sections. Since the curvature in the dome section is larger, the component of the hoop force will be larger. Consequently, the element forces in the dome sections will be larger than the forces in the middle section, which can be seen in
Fig. 9.17. Geometry of the basic variant of the tensegrity structure with constant bar height throughout the structure
Fig. 9.18. The distribution of forces in the tensegrity structure calculated by GSA (above: LC1, below: LC3)
Fig. 9.19. Larger element forces in the diagonals, compression bars and tap cables near the smallest distance between tension hoop and compression bar (tension hoop is omitted to get a clearer image of the element forces)

Fig. 9.20. Diagram showing the level of the reaction forces (the direction of the force is in line with the diagonals and top cable)
the distribution of the forces in figure 9.18. Additionally, the element forces are larger in the middle of the middle section. The distance between the outer tension hoop and the compression ring is smallest in this part of the structure, resulting in larger angles of the diagonals and top cables. A larger angle of the diagonal and constant component of tension hoop will result in a larger diagonal force. Moreover, the compression force in the bar will also increase since the vertical component of the diagonal force increases.

As a result of the pre-stress forces, the outer tension hoop carries the most tension, while the inner tension hoops carry the smallest tensile forces. The tensile forces in the outer tension hoop will increase as a result of the vertical loads (±10%) while the pretension of the inner hoops will decrease (±150%). As a consequence, the forces in the diagonals, top cables and struts near these ring will also decrease or increase dependent on the location. These effects of the vertical loading corresponds with the force distribution found in the two dimensional analysis.

Support forces
The reaction forces in the supports in the dome sections are larger than in the longitudinal section of the roof, as can be seen in figure 7. This could be explained by the larger forces in the top cables and diagonals in the base dome section compared to the forces in the longitudinal section. As a consequence, the compression ring will be loaded by larger forces in the dome sections than in the longitudinal sections. It will have a positive effect on the compression ring, because circular curvature of the dome sections will have a larger resistance to these forces than the relatively weaker longitudinal section due to the lesser curvature. The structural behavior of the compression ring will be discussed in the next chapter.

Deformations
The angles of the diagonals and top cable are larger resulting in larger forces in the middle of the middle section. This effect can also be seen in the deformations; the larger forces and larger angle of the diagonals cause a large stiffness. Consequently, the deformations of the outer tension hoop is less in the middle, and the tension hoop is pulled outside more than on other parts of the structure resulting in a bulge in the hoop.

This bulging of the outer tension hoop can be minimized by decreasing the difference between the angles of the diagonals and top cables in the middle with the angles of the cables right next to the bulge.

Another aspect of the structure are the larger forces in the dome sections. As a result of these forces, the dome sections have more stiffness compared to the middle section. The largest deformations can therefore be found in this middle section. Additionally, the larger dome shows larger deformations than the smaller dome section, which can be explained by the larger distance between the outer tension hoop on the compression ring in the large dome. The resulting smaller angle of the diagonals and top cable leads to less stiffness and thus more deformations.

A problem of the way in which pre-stress is applied to the tensegrity structure is the large deformation of the compressive bars necessary to introduce large enough forces in the structure. More precisely, the bars have to be enlarged with \( \Delta l = \alpha l \cdot \Delta T = 12 \cdot 10^6 (-6) \cdot 6.8 \cdot 30000 = 2.54 \text{ m} \), which is an enlargement of more than 35%. These enlargements suppose that the structural system has less stiffness, which could be a problem. A cause of this problem can be found in the small angle of the diagonals, especially the angles of the outer diagonals. In the study to two dimensional tensegrity structures, it emerged that larger angles of the diagonals should result in a stiffer structure with less pre-stress forces necessary. Additionally, if the angle of the diagonal is too small, large deformation of the bar is necessary to influence the force distribution.

In other words, increasing the angles of the diagonals should result in less enlargement of the bars necessary in order to obtain pre-stress forces large enough. However, increasing the angles of the diagonals will result in larger bars and, thus, in a larger height...
**Fig. 9.21.** Bulging of the outer tension hoop, the dotted line is the undeformed geometry

<table>
<thead>
<tr>
<th>Bar length in basic variant</th>
<th>Enlargement in geometry</th>
<th>Enlargement pre-stressing</th>
<th>Total enlargement</th>
</tr>
</thead>
<tbody>
<tr>
<td>6,8 m</td>
<td>0 m</td>
<td>2,54 m</td>
<td>2,54 m</td>
</tr>
<tr>
<td>8,8 m</td>
<td>2 m</td>
<td>1,43 m</td>
<td>3,43 m</td>
</tr>
<tr>
<td>9,8 m</td>
<td>3 m</td>
<td>1,24 m</td>
<td>4,24 m</td>
</tr>
</tbody>
</table>

**Fig. 9.22.** Table showing the enlargements in the enlargements necessary to obtain the minimal pre-stress necessary using different bar heights
of the structure under the supports. This could be a spatial problem, because the structure could obstruct the sightlines from the stands. Therefore, the enlargement of the bars should be minimized to a size in which the stiffness is acceptable and the height under the supports is minimal.

However, the problem of enlarging the bars is that even when the bars are longer, they have to be enlarged to obtain the pre-stress necessary. To obtain a certain amount of stress in a cable, this cable has to be pulled to a certain extend. Since the pre-stress forces are relatively large, the enlargement by pulling of the cables should be large enough.

Figure 6 shows the enlargements necessary to obtain the minimal pre-stress necessary using different heights of the bars. As can be seen, the increasing the height of a bar results in less enlargement necessary to obtain the minimal pre-stress. However, the total enlargement of the bars compared to the basic variant with bar length 6.8 meters is increasing.

This could be solved by using the deformed geometry of the structure caused by the pre-stress forces, found with GSA, as the initial geometry of the structure. This idea is based on the knowledge that the deformed state of a lightweight structure approaches the ideal form under the specific loading. The pre-stress forces should be applied in a different way. The output forces of the first calculation are used as pre-stress forces in the analysis of the deformed geometry instead of pre-stressing by enlarging the bars. No deformations are allowed since the geometry of the deformed geometry coincides with the distribution of forces. The deformations found in the analysis of the load case with the vertical loads could be read more easily since the deformations of enlarged bars is absent.

However, before we will use the deformed geometry as the geometry of the structure, some possible improvements are discussed in order to obtain a more efficient structure.

10.3.3 Influence of the sloping form of the roof
The variant discussed in the previous paragraph was based on a horizontal position of the compression ring. However, the actual position of the compression ring in the design of the stadium will not be horizontal, but will have a small angle resulting in the sloping form of the building. This sloping position of the compression ring will have an influence on the structural behavior of the tensegrity.

The tensegrity structure should follow the sloping form of the compression ring. A basic aspect of the design of the sloping tensegrity is that the compression bars should have a vertical position. Otherwise, the vertical loads will result in rotation of the bars leading to large deformations of the bars. Therefore, the bars are vertically translated over the distance from the horizontal plane to the sloping plane of the structure. The bars will have the same vertical position in relation to the sloping plane than to the horizontal plane of the compression ring in the base variant.

The angles of the cables are adjusted to the translation of the bars. This will result in larger angles of the diagonals and smaller angles of the top cables in the largest dome section, resulting in a positive effect on the stiffness. The angle of the diagonals will decrease and the angle of the top cable will increase in the smaller dome section. As a result, the difference in stiffness between both dome sections could decrease, resulting in a more equal deformation of both dome sections. The angles of the cables in the middle section will be more similar to the angles in the original base variant. Figure 9.23 shows the sections of this tensegrity with a sloping form.

The forces in the tensegrity with a sloping form are relatively corresponding with the equilibrum of forces of the base variant. The differences in forces between the base variant and the sloping form are small; the maximum forces due to pre-stress are 3% smaller in the sloping form and the forces in load case 2 are 4% smaller. These differences are approximately similar throughout the structure. Additionally, the differences in the deformations are small (1-4%). The maximal deformations are a little bit larger.
Fig. 9.23. Sections of the tensegrity with a sloping form

Fig. 9.24. The distribution of forces in the tensegrity with a sloping form due to load case 2
in the sloping tensegrity. Figure 9.24 shows the distribution of forces in load case 2, a more complete overview can be found in appendix 10.

Since the difference between the base variant and the sloping tensegrity are relatively small, and it is more likely for errors to occur in the drawing and analyzing process of the sloping form, the base variant is used to simplify the sloping form.

9.3.4 Improving the initial shape of the tensegrity structure

The analysis of the base variant showed some critical points in its structural behavior. This paragraph will discuss some improvements that can be made to improve the structural behavior of the structure. Four variables are useful in the design of a tensegrity structure, illustrated in the figure 8.22. Three of these variables will be discussed in this paragraph. The fourth, varying the distance between the tension hoops will not be used because it will adjust the pattern of the tensegrity that is already determined.

**Decreasing the height above the supports**

As is concluded in the study to the planar behavior of the tensegrity structure, decreasing the height above the supports can result in a large reduction of the pre-stress force and in a reduction of the displacements. The angle of the top cable will be decreased, while the angle of the diagonal will be increased. Both are positive effects.

However, decreasing the height above the supports would result in a larger height under the supports, which will result in problems with the stand, such as blocking views. Therefore, the compression ring should be raised, resulting in large facades and longer structural members in the supporting structure. Therefore, the height above the supports cannot be reduced too much.

This variable will be applied to the structure, since the forces and displacements of the spatial base structure are large. The total height of the structure will be moved down by one meter. The height of the structure under the structure will also be increased by enlarging the bars in order to apply the pre-stress to the structure. As a consequence of using the deformed state as the initial form of the structure, this enlargement will exist in the deformed state of the structure and will be part of the total increase of the height under the supports. Therefore, increasing the height under the structure with more than one meter will result in a too large total increase of the height under the supports.

**Increasing length of the bars**

Another variable with a positive decreasing effect on the pre-stress forces in the structure and the deformations is the length of the bars. Increasing the length of a compression bar in the tensegrity will result in a larger angle of the diagonal connected to this bar. Increasing the angle of a diagonal will result in a beneficial effect on the distribution of forces and stiffness.

Because the height under the supports should not be increased further than the increment due to decreasing the height above the supports and the lengthening of the bars for pre-stressing the structure, the length of the first bars in the first ring will not be increased. The bars in the other two rings could be enlarged with as maximum the height of the first tension hoop. However, it would result in a large length of the compression bars resulting in large buckling lengths, which is inefficient.

The inner two rings with compression bars are enlarged to a maximum length of the bars of ten meters in order to obtain the improvement in the angle of the diagonals desired. As a consequence, the buckling height is relatively large, resulting in larger dimensions of the steel sections. The enlargement of the bars will result in an improvement of the distribution of forces and the deformations.

**Hollow top cable**

Thirdly, the shape of the top cable will be changed from the straight or concave form in the base variant to a hollow shape. As a result, the distribution of forces should be more efficient. Consequently, the minimal pre-stress forces in the structure
Fig. 9.25. Sections of the tensegrity with the improvements

Fig. 9.26. Distribution of forces in the improved tensegrity due to pre-stress forces
necessary should decrease resulting in smaller forces in the structure. The stiffness of the structure, on the other hand, will decrease as a result of the hollow shape of the top cable, but the previous two improvements, on the other hand, will increase the stiffness. Therefore, this negative effect on the stiffness compensate each other.

Since the distance between the outer tension hoop and the compression ring is varying, the degree of concavity can not be similar throughout the structure. Therefore, the angle of the first top cable is similar throughout the structure, resulting in a larger degree of concavity in the middle section of the building and a smaller degree of concavity in the larger dome section.

As a consequence, the difference in angle of the top cable in the middle section of the building has disappeared, through which the large force in the middle are decreased. The large degree of concavity in the longitudinal section, results in smaller lengths of the compression bars and thus in smaller angles of the diagonals. This will have a negative effect on the structural behavior of the middle section of the tensegrity, while the structural behavior of the dome-sections is improved.

Summarily, these three improvements of the tensegrity can be seen in figure 9.25.

9.3.5 Equilibrium of forces in the improved tensegrity structure

The geometry of the tensegrity structure with the suggested improvements is analyzed in the same way as the base structure. Thus, the pre-stress forces are applied by increasing the length of the bars.

Load case 1: Pre-stress forces

The distribution of forces due to pre-stress forces is shown in figure 10. A number of difference could be distinguished between this equilibrium and the base structure. Generally, the forces in the improved tensegrity are smaller than the forces in the base structure, because the minimal pre-stress force necessary is decreased. For instance, the maximum force in the outer tension hoop is decreased by 62%. The less pre-stress forces necessary is a result of the more efficient distribution of forces in the structure, which can be seen in the relatively larger tension force in the inner tension hoops. Additionally, the pre-tension of the top tension hoop of the improved tensegrity is larger than the pre-tension in the top tension hoop of the base structure. This means that the difference in tension in the hoops is smaller in the improved tensegrity, which is a more efficient use of pre-tension.

Secondly, the tension forces in the top cables are relatively larger in relation to the forces in the tension hoops, which can be seen in figure 9.26 on the green color of the forces in the dome section. This could be explained by the decreased angle of the first top cable as a result of the concavity of the top cable and the increase of the angle of the diagonal as a consequence of the reduction in height above the supports. These two effects causes the tension in the top cable to increase and the tension in the diagonal to decrease. However, the last effect is opposed to the effect that the component of the tension hoop will result in a larger force in a diagonal if the angle is increased. Additionally, the forces in the compression bars increase if the forces in the tension cables increase; thus, these forces are relatively larger.

Thirdly, the large elements forces in the middle of the longitudinal section due to the short distance between the outer tension hoop and the compression ring are minimized. In the top cables and compression bars, these forces disappeared and the remaining forces are similar to the forces in the rest of the elements in the longitudinal section. The forces in the diagonals show a small increase in the middle, which is caused by the larger angle of these diagonals due to the short distance.

Finally, the compression forces in the two central compression bars is much larger than the compression in the rest of the bars, which is the result of the large number of cables connected to this bar. If this compression force is divided by the number of cables connected (14187 + 15 = 280kN), then it can be concluded that this force has a normal value compared to the other compression forces. Thus, the larger force is caused by the large number of cables connected.
Fig. 9.27. Distribution of forces in the improved tensegrity due to pre-stress forces and vertical air pressure loads.

Fig. 9.28. Reaction forces in the supports of the tensegrity.
Load case 2: Pre-stress forces and air pressure loads

In the base structure, the top cables of the inner ring of the dome sections were determinate for the minimal pre-stress necessary. However, in this improved tensegrity other elements determine the minimal pre-stress forces, which are the specific compression bars in the second tension hoop in the first planar section of the dome section. This is caused by the larger deformation of the tension hoop in the longitudinal section in relation to the relatively stiff dome section. As a result, the tension hoop will give a downward tension force on the compression bar, resulting in a tension force in the compression bar. Thus, it is a consequence of the large difference in stiffness between the middle longitudinal section and the dome section.

As a result of the vertical loads, the tension force in the top hoop will decrease, as discussed earlier. Additionally, the force in the top cable will decrease and the forces in the diagonals will increase. The tension force in the outer hoops will increase and the tension in the inner hoops will decrease under the influence of the vertical loads. These effects of the vertical loads are already discussed in the planar behavior of the structure.

The difference with the base structure in the equilibrium of forces due to pre-stress forces are also true for the forces in load case 2. This distribution of forces is more efficient, the forces in the cables of the dome section are relatively larger and the forces due to the short distance between outer hoop and compression ring are minimized.

Reaction forces in the supports

Similar to the base structure, the reaction forces of the improved structure are larger in the dome sections of the tensegrity due to the larger forces in the diagonals and top cables. This will have a positive effect on the compression ring, since these dome sections coincide with the strongest parts of the compression ring due to the large curvature of the compression ring in these dome parts.

9.3.6 The deformed geometry

As is discussed in paragraph 3.2, the deformed geometry will be used as the initial geometry of the structure, since very large increases of bar length were necessary to apply the necessary pre-stress forces. Therefore, this extra length could not be neglected in the determination of the exact geometry of the tensegrity structure.

The deformed geometry is based on the deformations caused by the pre-stress forces, because this is the geometry which coincides with the equilibrium of pre-stress forces, and is illustrated in figure 9.29. The pre-stress forces found in the analysis of the improved structure by enlarging the compression bars are applied as pre-stress forces to the deformed geometry. This results in an exact similar distribution of forces as shown in the previous paragraph for both load case one and two. Therefore, for the equilibrium of forces can be found in the previous paragraph.

The deformations due to the pre-stress forces are minimal, which is logical since the geometry coincides with the geometry of the equilibrium of pre-stress forces.

Optimizing the steel sections

Since the equilibrium of forces is now determined for the deformed geometry, the steel section of the elements can be discussed. In the model four different steel sections are used, namely for the tension hoop, top cables, diagonals and compression bar. In other words, each type of element has a constant steel section throughout the structure, which can be seen in figure 9.30.

The dimensions of the steel sections used in the design are a little bit larger than the minimal dimensions necessary due to the analysis process. The forces in the structure will decrease if the dimensions of the structural members are decreased. These forces will decrease again when the steel section are altered according to the forces in these elements, resulting in another alteration of the steel sections and thus another decrease of forces etc. However, another consequence of decreasing the dimensions of the steel sections is a decrease in stiffness of the structure resulting in larger deformations. Therefore, this process is stopped after the largest error is eliminated.
### Table with the dimensions used in the model and the force in the structures calculated with GSA

<table>
<thead>
<tr>
<th></th>
<th>( F_{\text{max, LC1}} ) (kN)</th>
<th>( F_{\text{max, LC2}} ) (kN)</th>
<th>( A ) (mm(^2))</th>
<th>( d ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top cables</td>
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<td>2751</td>
<td>3525.7</td>
<td>67</td>
</tr>
<tr>
<td>Diagonals</td>
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<td>2482</td>
<td>3019.1</td>
<td>62</td>
</tr>
<tr>
<td>Compression bars</td>
<td>-4187</td>
<td>-2754</td>
<td>2473.1</td>
<td>508 x 16</td>
</tr>
<tr>
<td>Tension hoops</td>
<td>10170</td>
<td>14090</td>
<td>16972</td>
<td>181</td>
</tr>
</tbody>
</table>

**Fig. 9.30.** Table with the dimensions used in the model and the force in the structures calculated with GSA

**Fig. 9.29.** The deformed geometry of the improved tensegrity

<table>
<thead>
<tr>
<th></th>
<th>( F_{\max, LC1} ) (kN)</th>
<th>( F_{\max, LC2} ) (kN)</th>
<th>( A ) (mm(^2))</th>
<th>( d ) (mm)</th>
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<td>Tension hoops</td>
<td>10170</td>
<td>14090</td>
<td>16972</td>
<td>181</td>
</tr>
</tbody>
</table>

**Fig. 9.31.** More differentiation of the steel sections used
There are certain elements which carry relatively larger forces compared to the rest of the elements of the same type. For instance, the two central compression bars of the two dome sections. The tension forces in the different tension hoops are largely differing and can have different steel sections. Therefore, it could be more efficient to apply more differentiation to the steel sections used.

Figure 9.31 shows a more differentiated design of the steel sections. A large gain could be obtained in the design of the compression bars. However, buckling will have a large influence on the dimensions of the bars; especially on the smaller sized bars. The dimensions shown in figure 15 are checked for buckling stability. Buckling was not a problem for the two large central bars, but for the size of the rest of the bars buckling was more determinant, caused by the large buckling length of the bars in the inner ring (12 m).

Additionally, the amount of steel use in the tension hoops is decreased largely. More efficiency can be obtained by a difference in sections between the dome sections and the longitudinal sections. However, it will increase the difference in stiffness between these sections of the tensegrity. The appearance of the middle section would be more lightweight than the end sections, resulting in visual division of the structure. Therefore, the sections of the top cables and diagonals are constant throughout the structure.

9.3.7 Deformations of the deformed geometry

The deformations due to pre-stress forces result in minimal deformations as is concluded earlier. On the other hand, the vertical loads causes large deformations in the structure. Especially, the middle section of the tensegrity shows large deformations and the dome sections are relatively stiff, as can be seen in figure 9.32. This could be explained by the larger forces in the dome sections, which result in larger stiffness. Additionally, the degree of concavity is larger in the middle section, because the distance between the inner tension hoop (highest point) and the compression ring is smaller.

However, the outer tension hoop of this middle section is also relatively stiffer than the rest of the middle section, which is caused by the larger angle of the diagonals due to the short distance between the outer tension hoop and the compression ring.

Diagonals between the inner two tension hoops

It could be beneficial to apply diagonals between the two inner hoops, because the deformations of the middle sections are much larger compared to the deformations of the dome section. As a result of these diagonals, the inner two tension hoops and compression bars will behave like a truss distributing forces to the stiffer dome sections and reducing the deformations of the middle section. In other words, it will create more cohesion in the structure.

Applying these diagonals in the design stage before the deformed geometry is obtained is difficult, because the pre-stress forces due to enlarging the bars will be very large. Since the diagonals will counteract the increase in length of the bars, large tension forces in these diagonals will appear. Therefore, the diagonals are applied in the deformed state of the structure, resulting in a small decrease of the pre-stress forces of the structure.

The deformations resulting from the analysis with extra diagonals between the two inner tension hoops are shown in figure 9.33. The extra diagonals will decrease the deformation of the two inner tension hoops. However, the second tension hoop will still deform in the same amount as in the tensegrity without the extra diagonals. Therefore, the maximum deformation is not decreased largely by the extra diagonals, but the extra diagonals could be useful in the design.

For a further decrease of the deformations of the structure, the pre-stress forces in the structure will have to be increased, which will result in less difference in deformation between the load case 1 and load case 2.
Fig. 9.32. Deformations of the deformed geometry due to vertical loading by air pressure loads

Fig. 9.33. Deformations of the deformed tensegrity with diagonals between the inner tension hoops
9.3.8 Conclusions and recommendations
The three-dimensional tensegrity structure elaborated in this chapter is based on an eye-shaped pattern as is discussed in paragraph 9.2. Some improvements based on the study to the planar behavior of the structure are applied to the three-dimensional structure.

The tensegrity resulting from the design process may not be the most optimal design, because it shows some problematic features in the structural behavior. The most important aspect is the large difference in stiffness between the middle section and the dome sections. This results in significantly larger forces in the elements of the dome sections and in much more deformations of the middle section. To further improve the tensegrity, the stiffness of the middle section will have to be increased compared to the dome sections, resulting in a more homogenous structure with more equal division of element forces and deformations.

An important aspect in which the middle section differs from the dome sections is the curvature of the tension rings. The curvature in these rings is much larger in the dome section than in the middle section. However, enlarging the curvature in these rings in the current morphology, will result in a small distance between the outer tension hoop and the ring structure. As a result, other problems will appear in the structural behavior. However, the curvature in the tension hoop could be enlarged by using a different morphology of the tensegrity, such as the morphology based on two eye-like patterned domes. The problem of a combination of two domes is the connection between these domes. Subsequently, the distance between the tension hoops is constant in the morphology. However, the curvature in the tension hoops of the middle section could be increased by varying the distance between these tension hoops. A smaller distance between the hoops in the middle section compared to the dome sections will increase the curvature in the hoops of the middle section. Varying the distance between the hoops will increase the difficulty to connect all the diagonals and top cables perpendicular to the tension hoops. As a result, these cables will have a component force in the direction of the tension hoop, causing an inconstant tension force in the tension hoop.

This graduation project was limited to linear tensegrity dome structures; however, a tensegrity dome could also be composed of a more spatial geometry, the fuller dome. The tensegrity dome designed in this chapter is based on a Geiger dome. The triangular pattern of a fuller dome will result in a more coherent system, which has more stiffness as a result of the collaboration of the different elements. In a Geiger dome, the loads are carried only by a specific planar section, while the forces in a fuller dome are more divided. This could have a positive influence on the difference in stiffness between the middle section and the dome sections.

Another problematic aspect of the design of the tensegrity is the small angle of especially the first diagonal in the current geometry, resulting in relatively large deformations of the outer hoop. A larger angle of the diagonals can be obtained by enlarging the length of the compression bars, which causes the spaces underneath the structure to become smaller. This conflicts with the spatiality of the stands under the roof structure. Adding a tension hoop to the structure will result in larger angles of the diagonals. Thus, a geometry based on four tension hoops instead of the three as discussed in this chapter. However, using the same morphology will decrease the curvature in the tension hoops, negatively influencing the structural behavior. Additionally, more material will be used in the design. A tensegrity with four tension hoops causes larger support forces than a three ringed tensegrity. Consequently, it cannot be proved that this solution will improve the overall structural behavior.

Conclusively, the design of the tensegrity shows some problematic aspects which may be solved. It is not sure of the structural behavior is really improved by applying most of the solutions given here or that other problems will appear as a result of the changed geometry. Therefore, more examination of these solutions is necessary to get more insight in their consequences.
Fig. 10.1. The deformed structure resulting from the analysis

Fig. 10.2. Pattern of the cables in the outer membrane

Fig. 10.3. The wind loads on the upper membrane
10. Structural design of the pneumatic and support structure

So far, the structural analysis focussed on the tensegrity structure in the roof structure. The other parts of the structure of the design will be discussed in this chapter to obtain an idea of the dimensions needed for these structural elements. The analyses of these parts of the structure are very global and not very elaborated.

10.1 Outer pneumatic membrane

The bottom of the pneumatic element in the roof structure consists of the tensegrity structure with a layer of pneumatic cushions, of which the tensegrity is extensively discussed in the previous chapters. The top of the pneumatic element consists of a single membrane layer. However, the curvature of this membrane will not be large enough to carry the forces. Therefore, the membrane will be strengthened with tension cables. This results in a structure in which the membrane transfers the loads to the cables that carry the forces to the supports. These cables are pre-stressed by the over pressure in the pneumatic element, which is similar to the air pressure loads on the tensegrity structure.

This paragraph will discuss a global analysis of the cables in the outer membrane layer in order to say something meaningful about the size of the cables. In order to facilitate a global dimensioning of the cables, a pattern of the cables in the membrane is assumed, which is shown in figure 10.2.

10.1.1 Loads

The outer membrane of the roof structure is pre-stressed by the internal overpressure of the pneumatic element, which is an essential aspect of the structural action of the membrane. This air pressure load is similar to the air pressure load on the tensegrity structure (0,5 kN/m²) and will be applied as a vertical nodal force on the intersection points of the cables. Moreover, the outer membrane is exposed to snow loads and wind loads. Snow loads (0,56 kN/m²) are a vertical downward load opposed to the air pressure loads. Therefore, the snow loads should not be larger than the air pressure loads, because that would result in loss of pre-tension of the membrane and thus in a collapse of the roof. However, the snow loads will compress the air inside the structure resulting in a larger internal air pressure that can resist the snow loads. This is a complex process which is difficult to apply in the calculations. Snow can also be countered by increasing the air temperature in the roof structure causing the snow to melt. The air inside the roof structure will always above freezing point, because freezing air in the structure could result in problems with condense on the ceiling. Therefore, the air in the roof structure will always tend to melt the snow on the roof structure.

Thirdly, wind pressure loads will result in horizontal wind pressure loads on one side of the building and in vertical wind suction on top of the roof, with large wind suction on the side of the wind pressure.

This results in the following load cases in the analysis of the outer membrane:

1. LC1: 1.35 x air pressure loads
2. LC2: 0,9 x air pressure loads + 1,5 snow loads
3. LC3: 1,2 x air pressure loads + 1,5 wind loads (on long side)
4. LC4: 1,2 x air pressure loads + 1,5 x wind loads (on small side)

10.1.2 Form finding

The same technique for finding the deformed geometry of the tensegrity structure is used in this case to find the geometry of the outer membrane in which the form corresponds with the air pressure loads applied to the structure. The air pressure loads are applied to the flat pattern of the structure which will result in a deformation of the structure. These deformations are multiplied five times resulting in the geometry of the outer membrane structure, which is used in the rest of this paragraph.
Fig. 10.4. Distribution of forces in the cables of the outer membrane (top: LC1; middle: LC3; bottom: LC4)
10.1.3 Equilibrium of forces
This paragraph discusses the forces in the structure caused by the different load cases.

Load case 1: air pressure loads
The forces in the cables as calculated with the GSA model are shown in Figure 10.4. The force in a cable loaded with only vertical loads depends on the span and on the curvature of the cable. The cable forces decrease near the ends of the circular parts, because the length of the cable decreases. The force in the cable is largest near the supports and smallest in the middle of the span. This explains the largest forces near the supports in the larger circular part of the structure. The reaction forces in the supports are larger in the longitudinal sections of the structure than in the circular sections of the ring structure caused by the direction of the cables. If the pattern of the cables is rotated ninety degrees, the main direction of the cables is in the longitudinal direction of the building. This will result in larger support forces in the circular sections. The maximal reaction force is 178.5 kN, which corresponds with the maximal cable forces. The support force is by definition similar to the force in the cable near the supports, because only one cable is supported.

Load case 2: air pressure loads and snow loads
This load case does not provide good results, since the analysis will not diverge. However, some points could be made on the influence of snow load on the structure. Since snow loads will be opposite to the air pressure loads, the snow loads will decrease the pre-tension force in the structure resulting in decreasing forces in the structure. This, thus, this load case will not result in the determining values of the tension forces in the cables.

Load case 3: air pressure loads and wind loads
Wind loads will result in asymmetric loading of the roof structure, resulting in an asymmetric equilibrium of forces in the structure. Figure 10.4 shows the forces in the cable elements due to wind loads on the long side of the roof. As a result, the largest tension forces arise in this part of the structure. For clarity, the structure is loaded by a horizontal wind pressure on the long side of the roof and wind suction over the whole roof structure with a zone near the long side with larger wind suction as is discussed previously. The asymmetric loading and force equilibrium also results in asymmetric reaction forces in the supports corresponding to the force distribution as is shown in Figure 10.4. The maximal reaction force is 282.6 kN, corresponding with the largest cable force, and will appear in the ring structure on the long side of the building.

Load case 4: air pressure loads and wind loads
In this load case, the wind direction has changed in such a way that the small side of the building is loaded by the wind, resulting in larger maximum tension forces in the cables. This is caused by the fact that wind form this direction will result in larger loads on the largest cables (spanning the largest distance). These cables start in the areas with the largest tension forces as shown in Figure 6. This load case is thus determining the minimal dimensions of the tension cables necessary. The maximal tension force in the cables is 340.5 kN, which will result in a cable diameter of 20 mm. The reaction forces in the supports will be largest in the ring structure near the red areas in Figure 10.4; the maximal reaction force is 340.6 kN, which corresponds with the largest cable force.

10.1.4 Deformations

Load case 1: air pressure loads
The air pressure loads on the cable structure will result in upward deformations of the structure, which are largest in the middle of the structure. This could be explained by the fact that the deformations in the middle of the span are largest. The deformations are relatively large with a maximal deformation of 0.52 m. However, the air pressure is a pre-stress that is applied before the building is used. Therefore these deformations are
Fig. 10.5. Deformations of the cables in the outer membrane (top: LC1; middle: LC3; bottom: LC4)
continuously present and it will not affect the building's usability.

**Load case 3: Air pressure loads and wind loads**
The deformations due to wind load on the long side of the roof are largest in lee side of the roof structure, as can be seen in figure 10.5. The deformations in the area under wind pressure are small because the effect of the wind pressure and the effect of the larger wind suction counteract each other, resulting in relatively small deformations. In the lee side of the roof, only wind suction will play a role, resulting in larger deformations of the cables. The difference between these deformations and the deformations due to wind loads are $0.85 - 0.52 = 0.33$ m. This is smaller than the maximal deformations as are allowed in the guides ($0.004 \times 121 = 0.484$ m) and thus, these deformations will be acceptable.

**Load case 4: Air pressure loads and wind loads**
Similar to the deformations caused by wind on the long side of the building, the deformation of the lee side of the building are largest. Additionally, the deformation in the middle are smaller than the ones near the middle due to the smaller span of the cables that results in less loads. The maximum deformations due to this load case are smaller than the previous load case.

**10.1.5 Conclusion**
The analysis of the outer membrane as discussed in this chapter is a very global approximation of the structural behaviour. The aim of this approximation was to obtain a feeling of the forces and dimensions of the roof structure. For a more efficient and realistic approximation of the structural behaviour, further investigation on the outer membrane is necessary. The pattern of the cables in the membrane will have a large influence on the efficiency of the membrane structure. The pattern used in this chapter is a global assumption of a cable pattern in the membrane. Another pattern could result in a more thought design, which is more applied to the specific situations of this roof design.

Additionally, the effect of snow loads on the structural behaviour of the upper membranes should be examined in more detail. It is assumed that the air inside the pneumatic element is warm enough to melt the snow on the roof, which may not be the case. Then, the roof should be able to carry the snow loads, which causes the air inside the pneumatic element to be compressed. This will result in an increase of the internal overpressure. This process is very complex.

**10.2 Compression ring structure**
A ring structure is used to balance the lateral forces caused by the tensegrity structure and pneumatic element. Since the forces caused by these lateral forces can be relatively large, it will influence the architectural appearance of the building. This paragraph will discuss the global dimensions of the ring structure by applying a global analysis of the structural behaviour caused by the lateral support forces of the tensegrity structure and pneumatic element.

**10.2.1 Simplification of the ring structure**
The ring structure is not a perfect compression ring due to its curved longitudinal form. Therefore, the compression forces in the ring structure will not be constant throughout the ring structure, so bending moments will occur in the structure. These bending moments are decreased by the tension arch applied to the structure, because the tension arch provides a bending couple in combination with the compression bar. However, the deformations of the structure will be larger and will influence the tensegrity structure, as a result of the bending moments. In the analysis of the tensegrity structure, the supports are pinned supports with fixed translation. However, if the compression ring is deforming, these supports will not be fixed, but it will be displaced causing a different distribution of forces in the tensegrity structure. This interaction is out of the scope of this project.
Fig 10.6. Diagram of the ring structure

Fig. 10.7. Axial forces due to pre-stressing and air pressure loads

Fig. 10.8. Shear forces in the ring structure

Fig. 10.9. Bending moments in the ring structure
Additionally, the structure supporting the ring structure will have some resistance against the deformations of the ring structure, since this structure will have stiffness against lateral forces and deformation. Therefore, the ring structure is in reality supported by spring supports. In order to determine the influence of this stiffness on the forces in the ring structure, the spring stiffness of the support structure should be calculated. The interaction between the ring structure and the support structure will not be taken into account in the design.

Conclusively, the ring structure is simplified to a structure that can deform independently from the rest of the structure. Therefore, the model is supported by two supports: a roll support and a pinned support, as can be seen in figure 10.6. As a consequence, the interaction of the ring structure with both the tensegrity structure and the supporting structure is not taken into account in the analysis.

Loads
In this analysis, the support forces found with the GSA analysis of the tensegrity structure are used and applied to the ring structure. As can be seen in the previous chapter, the support forces of the tensegrity structure are larger in the circular sections of the structure and less in the longitudinal section. Thus, the compression ring has larger loads on the circular segments and less loads on the tension arch.

Additionally, the support forces of the upper membrane are used and applied to the ring structure. These forces are larger on the straight section of the ring structure and are, thus, less efficient as the support forces of the tensegrity structure. However, the support forces of the upper membrane are much smaller than the support forces of the tensegrity. Therefore, the influence of these forces is less.

Four load cases similar to the analysis of the tensegrity structure can be distinguished:
1. LC1: Pre-stressing of the tensegrity structure
2. LC2: Pre-stressing of the tensegrity and air pressure loads
3. LC3: Pre-stressing of the tensegrity, air pressure loads and wind loads on the longitudinal side
4. LC4: Pre-stressing of the tensegrity, air pressure loads and wind loads on the short side

The compression force in the ring structure is mainly determined by the horizontal forces on the structure, which are basically determined by the pre-stress forces in the tensegrity and to a lesser degree by the air pressure loads of the pneumatic element. Additionally, the wind loads will result in an asymmetric loading of the ring structure. The differences in the forces between the last three load cases will be relatively small, since the influence of the wind loads is relatively small compared to the tensegrity structure and the differences are small in relation to the pre-stressing state. The asymmetric loading of the ring structure will be out of the scope of this graduation project, because the analysis is made for dimensioning purposes only.

10.2.2 Forces in the structure
The equilibrium of forces resulting from the pre-stressing in combination with the air pressure loads is determining the dimensions of the ring structure, because the forces in the structure are larger than the forces due to only pre-stressing. As is mentioned, asymmetric loading of the ring structure will be out of the scope of this graduation project. The forces due to pre-stressing and air pressure will be discussed, because these are determining the dimensions.

Axial forces
The axial forces found in the ring structure can be seen in figure 10.7. The axial forces are largest in the straight section of the ring structure with the tension arch and compression bar connecting the two halves of the compression ring. The larger compression forces in the compression bar in this section were expected, since this bar has to transfer the compression force between the two halves and carry a compression force caused by the tension arch. The large tension force in the tension arch is the result of the relatively small height of the tension arch. However, increasing this
Fig. 10.10. Section of the building with the supporting structure (1:500)
height would have resulted in a steeper stand, which is already maximal in the design. So, the steepness cannot be increased.

**Shear forces**
The shear forces are largest where the ring structure is splitting in a tension arch and a compression bar. This is caused by the difference in stiffness under the lateral forces acting on the ring structure. The circular segments of the two half compression rings are stiffer under the lateral inward directed loads than the relatively straight middle section. The shear forces are shown in figure 10.8.

**Bending moments**
The bending moments in the ring structure can be seen in figure 10.9. The bending moments are largest in the middle of the circular segments caused by the deformation of the structure. The two straight sections are pulled inward, causing the curved parts to bend. As a consequence, bending will appear in the compression ring. The bending in the tension arch is caused by the relatively small height of the tension arch. Similar to a compression arch with a small elevation, bending will appear in the arch. Notably, bending moments will also appear in the compression bar caused by the rotation of the connection between the compression bar and the tension arch. The rotation on both sides of the compression bar is opposite resulting in bending in the element.

The equilibrium of forces discussed has resulted in the following dimensions of the ring structure.
- Compression ring and compression bar: 4400 x 55 mm
- Tension arch: 3200 x 65 mm
The tension arch is smaller because of the detailing in relation with the compression bar, which will be discussed in the following chapter.

**10.2.3 Deformations**
The deformations of the ring structure are largest in the relatively straight section of the ring structure. The deformations found in the analysis are not realistic, because this deformation is prevented by the support structure dependable on the stiffness of the support structure and the support structure is loaded by a deformation of the ring structure. Therefore, the deformations of the ring structure will not be discussed here.

**10.3 Support Structure**
The structure supporting the ring structure is loaded with the deformation of the ring structure. However, this deformation depends on the stiffness of the supporting structure. Therefore, the interaction between these two structures should be examined to determine the force in the support structure. However, this interaction between the different structural elements of the building is out of the scope of this graduation project. Consequently, the distribution of force in the support structure could not be determined. The dimensions used in the drawings and model of the building are assumptions based on empirical rules and feeling. The structural behavior as is discussed in paragraph 5.3.2 is used. The structural plan of the supporting structure is shown in the section with drawings.

The center to center distance of the structural elements of the supporting structure is based on the rhythm of the columns in the façade, the entrances to the stands and the span of the stand elements. A more detailed discussion of this can be found in paragraph 6.1.1 discussing the façade design of the building. The structure supporting the competition track is based on minimizing the span of the concrete floor slab in order to minimize the deformations of the ice track, because even relatively small deformations can affect the ice quality of the stadium. The maximal deformation allowed is 6 mm with a load of 10 kN/mm² according to the technical demands of the new Thialf building. So, the center to center distance of this structure should be relatively small.
Detail 1 (1:100)
1 Steel tube, diameter: 4400 mm
2 Steel tube, diameter: 3000 mm
3 Steel plate
4 Facade column: steel tube (minimal diameter: 500 mm, maximal diameter: 1000 mm)
5 HE700A
6 Steel cable 62 mm
7 Pneumatic cushion
8 Air sealing of the large pneumatic element
9 Steel cable and outer PTFE coated polyester membrane
10 PTFE coated polyester membrane
11 Gutter with drainage
11. Detailing

Finally, this last chapter will show the way in which the different structural elements are connected by examining the detailing of the structure. The way different elements are connected has a large influence on the appearance of the structure while also influencing the structural behavior of the structure. Several details which are important to the appearance of the structure will be discussed.

11.1 Compression ring
Detail 1 shows a typical detail of the ring structure in which the ring structure is in the tension arch and compression bar. These two parts of the ring structure are connected by steel plates, which facilitate the connections to the supporting structure and roof structure as well. In this way, all the connections of elements to the ring structure are solved with one clear principle. On the location where the ring structure is not split, the steel plate is only used on the inside of the ring structure providing the possibility to connect the rest of the structure to the ring structure.

11.2 Supporting structure
The hinged connections in the supporting structure are clearly shown in the building. These hinged connections are all designed in the same way to obtain a similar appearance while adjusted to the specific connection. In this paragraph two of these connection will be discussed. The connection between the facade column and the foundation has a large influence on the appearance of the exterior of the building and is shown in detail 2. By showing the hinged connection of the column to the foundation, more detail is given to the facade. Another aspect is the shape of the facade column, which is adjusted to its compression bearing function with a larger dimensions in the middle and narrowing to the ends. As a result, the facade column will have a more elegant appearance.

11.3 Tensegrity structure
The connections in the tensegrity structure are almost all different and should be able to contain the deformations of the tensegrity structure. Therefore, the connections should be flexible in order to adjust to the varying angles of the elements. Another important aspect is the cushions which are located between the cables of the tensegrity. Details 4, 5 and 6 show a possible solution for these connections as could be applied to most of the connections in the tensegrity. However, the two larger central compression bars will be connected to many cables, as can be seen in figure 7. This connection is solved with a solution comparable to the rest of the tensegrity with the difference that the connection will be much larger in order to obtain enough space to connect all the cables.
Detail 2 (1:50)
1 Façade column: steel tube (minimal diameter: 500 mm, maximal diameter: 1000 mm)
2 Concrete foundation
3 Steel tube
Detail 3 (1:50)
1 HE700A
2 Steel square tube 500 x 500 mm
3 IPE360
4 Steel plate welded to the stand beam
5 Concrete stand elements (thickness: 80 mm)
6 Support stud for stand elements
Detail 4, 5 and 6 (1:50)
1 Compression bar 273 x 6.3 mm
2 Steel cable 62 mm
3 Steel cable 67 mm
4 Steel ring cable 107 mm
5 Steel ring cable 89 mm
6 Pneumatic cushion
7 Central pneumatic cushion
8 Split head
Detail 7 (1:50)
1 Compression bar 508 x 16 mm
2 Steel cable 62 mm
3 Steel ring cable 89 mm
4 Steel tube 600 mm
5 Split head
12. Conclusion and recommendations

The result of this graduation project is a light(weight) and transparent ice skating stadium in Heerenveen in which the structure plays an important role in the architecture of the building. The product is the result of a process of designing both the architecture and the structure of the building, in which the integration of architecture and structure was an important aspect. This integration was the goal of my graduation project. The main question is, is this integration of architecture and structure obtained in the design? This question will be examined here.

The use of conceptual models in the conceptual design phase of the building clearly show the way in which tried to integrate architecture and structure. These models show the most important structural elements while defining the building shape. In this way, the building shape is designed simultaneously with the outline of the structure. This method of designing the building concept resulted in an important role of the large spanning roof structure in the conceptual design. The varying angle of the façade columns is the result of this methodology in the design process. These varying angled columns accentuate the shift between the two ice tracks and create a sense of movement in the appearance of the building. The columns provide character to the exterior of the building.

Another aspect of the design illustrating the integration is the undulation in the façade and stands as a result of the inward curve of the ring structure. The purpose of this inward curve is twofold; the inward curve improves the structural behavior of the ring structure, while creating a curve in the façade creates a more interesting façade and accentuates the entrance. The inward curve improves thus both the structure and the architecture of the building and is therefore a good example of an integration of architecture and structure.

Thirdly, the roof structure composed of a pneumatic lens shaped element on top of a tensegrity dome resulted in a light(weight) and transparent roof structure enabling daylight to enter the large central stadium hall. The natural daylight provides a pleasant atmosphere in the stadium hall not only during the competition races, but during the normal daily use as well. The lay-out of the roof structure with multiple layers of membranes provides the opportunity to create a system that can darken the hall by changing the differences in air pressures in the roof structure. In this way, other functions are integrated in the roof structure.

From a structural point of view, the idea of the combination of the tensegrity with a pneumatic roof is that the pneumatic element causes a constant load on the tensegrity resulting in a more stable structure. A tensegrity is normally a relatively flexible structure. However, the constant pressure of the overpressure results in a relatively constant deformation of the tensegrity and thus less movements of the structure. Whether this effect results in a more efficient structure and less steel used in the design is not examined in this project and should therefore be examined further before using this combination. However, a small examination has been made in the survey. The air pressure loads applied to the tensegrity structure in the analysis of the structural behavior is almost equal to the snow load on the tensegrity structure. This should therefore result in almost similar dimensions of the elements, while the varying nature of the loads are decreased (e.g. no wind suction) since the pneumatic element will give constant loading. It should have a positive effect, but it will have to be verified.

Another important design aspect of the tensegrity structure in this project was the morphology because of the irregular plan of the building. Generally, tensegrity domes are mostly used with a circular plan, because it results in a system with a constant structural behavior. However, the plan of the design with the inward curve of the ring structure contains a relatively straight section. In the design a morphology based on an ellipse is used, because of the relatively large curvature of the tension ring in the straight section and the architectural qualities of this type. The design of a tensegrity structure in an irregular plan is an interesting
problem which is worth examining in more detail. Other morphologies based on a combination of multiple domes could be examined. Especially, the transitions between these domes are interesting for further investigation, because the different dome sections must make an equilibrium to obtain a stable structure.

Conclusively, I think the design shows a realistic proposal for an ice skating stadium which will provide Heereneven with a modern stadium that will be an icon for the city and the ice skating sport in the Netherlands. The lightweight roof structure will provide good skating circumstances for both professional skaters as recreational skaters. Moreover, the building shows the possibilities of modern lightweight structures, especially for ice skating stadiums.
13. Reflection

I started this graduation project with the idea to design a building with a large span in which the architecture and structure of the building were fully integrated in the design. However, this is more difficult than initially thought. It is difficult to consider the architectural and structural aspects at the same time and give them equal importance. The models used in the design process were a good method to design the building shape and the structure at the same time, but it does not automatically result in an integration of structure and architecture. Reflecting on the resulting design, I think that unconsciously the structural aspects have prevailed in the design process above the architectural aspects. Partly, because of the large span of the building that puts more importance on the structure of the building. Another aspect is that the structural considerations are more concrete and based on rules than architectural considerations. As a result, it was a trap for me to design an element based on structural consideration with architectural consequences. The opposite approach, which is the structure as the consequence of architectural considerations, can sometimes be useful in the design process as well. However, this approach feels less natural for me. I could apply this approach more often, because a good structure will not necessarily lead to a good architectural design.

Focusing on the structure of the building, I have to say that the resulting tensegrity structure could be more efficient. Different parameters of the tensegrity structure are examined and used to create a more efficient structure, but the resulting geometry still contains some problematic features. However, improving the structural behavior will need more investigation to different morphologies. Additionally, some parameters were bounded by architectural considerations. All in all, I am satisfied with the resulting structure that creates a light and transparent roof with a spectacular spatiality under the roof.
Literature and Notes

Notes in the text
1 Visiedocument Nieuw Thialf, Regiegroep Heerenveen Stad van Sport; 1 maart 2010, paragraph 1.4.
2 The aspects discussed are discussed in a appointment with dr.ir. M.G.L.C. (Marcel) Loomans, university teacher at the Building physics & systems section of the department of Architecture, Building and Planning of the University of Technology Eindhoven.

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Drawings

- Plattegronden
- Doornseden
- Aanzichten
- Constructieplattegronden
Plan floor -2 (1:1000)

1. Entrance spectators
2. Circulation space (P = 8775 mm)
3. Changing room with shower and toilet
4. Changing room coaches/physiotherapist
5. Jury room
6. Music
7. Catering
8. EHBO
9. Toilets men
10. Toilets women
11. Storage: short track attributes
12. Storage: ice hockey attributes
13. Storage: figure skating attributes
14. Storage: materials for lessons
15. Tunnel to changing rooms
Plan floor -1 (1:1000)

1. Sprint track
2. Running track
3. Changing room with shower and toilet
4. Changing room coaches/physiotherapist
5. Circulation space with lockers
6. Toilet men
7. Toilet women
8. Storage
9. Closet
10. Parking place Zamboni
11. Parking place ice equalizer
12. Workshop
13. Storage: Stand and rink security elements
14. Storage: materials for lessons
15. Storage: events
16. Storage: competition attributes
17. Installations
18. Freeze installation for ice track
19. Utilities
20. Boiler room + CHP
21. Travo space
22. Installations for air treatment
23. Pumps for pneumatic elements
24. Entrance from parking place
25. Kitchen for restaurant
Plan first floor (1:1000)

1. Fitness room
2. Vide sprint track
3. Athletes lounge
4. Kitchen/bar
5. Toilets
6. Toilets men
7. Toilets women
8. Storage
9. Closet
10. Office
11. Meeting room
12. Vide mixed zone
13. Installations
14. Drug testing
15. Video room
16. Changing room with showers and toilet
17. Changing room for coaches
18. Circulation space with lockers
19. Vide hospitality room
20. Stairs VIPs
21. Stairs spectators
22. Vide entrance
23. Restaurant
Plan second floor (1:1000)

1. Stairs spectators
2. Circulation space (P = +7200 mm)
3. Catering large
4. Catering small
5. Toilets men
6. Toilets women
7. EHBO
8. Circulation space VIPs
9. Space for Zamboni
Plan third floor (1:1000)

1. Circulations space
2. Catering small
3. Toilets
4. Kitchen
5. Storage
Plan fourth floor (1:1000)

1. VIP room
2. Commentary cells
3. Television studio
Section AA (1:1000)
Structural plan of the supporting structure (1:1000)
The beams shown are HE700A sections
Structural plan of the structure of the competition track (1:1000)

1 Concrete beam 2000 x 400
North facade (no scaling)

Above: South facade (no scaling)  Under: West facade (no scaling)
Appendices

1. Vision document Thialf
2. Schedule of requirements
3. Location
4. Literature study to lightweight structure
5. Installations of Thialf and Kolomna
6. Comparison hand calculation with computer analysis
7. Comparison linear and non-linear analysis
8. Overview of analysis of planar behavior of a tensegrity
9. Distribution of forces in a tensegrity dome
10. Distribution of forces in the sloping tensegrity
11. Distribution of forces in the definite version of the tensegrity
Inleiding

In het voorjaar van 2008 heeft de Regiegroep Heerenveen stad van Sport de intentie uitgesproken om een "ultra-modern Thialf" met een internationale uitstraling te realiseren, waarbij “ook in de toekomst zowel de wereldtop als de grote massa schaatstiefhebbers naar een bijzondere schaatstempel in Heerenveen kan komen”.

De Regiegroep bestaat uit de vier samenwerkende partijen provincie Fryslân, gemeente Heerenveen, Thialf bv en Sportstad Heerenveen bv. Aanleiding voor dit initiatief is dat het huidige Thialf wordt ingehaald door nieuwe ijsbanen in het buitenland die qua uitstraling, uitzetting en energieconcept superieur zijn aan het Heerenveense stadion dat 25 jaar geleden in de huidige vorm is gerealiseerd. Zo dreigt Thialf op termijn zijn internationale positie te verliezen voor de grote schaatsevenementen.

In het rapport wordt ingegaan op de eisen waaraan het nieuwe Thialf moet voldoen, de mogelijkheden van een variant met een aparte trainingstaan, nieuwbouw ten opzichte van renovatie/ opwaardering van het huidige Thialf, en het energieconcept voor het toekomstige ijst stadion. Er wordt gekeken naar de ruimtelijke, verkeerskundige en milieuaspecten van de verschillende varianten. Verder worden de economische effecten van een nieuw Thialf uitgeroept en worden de financiële aspecten in beeld gebracht: de investeringskosten en de exploitatiekosten. Tot slot komen de vier samenwerkende partijen met hun afweging en visie op een nieuw Thialf ijsstadion in Heerenveen.

Het Visiedocument zal de komende weken en maanden gebruikt worden als voeding voor de politieke en maatschappelijke discussie die plaatsvindt over de plannen voor een nieuw Thialf. Tevens zal het als basis dienen voor de nadere verkenning van de financiering met potentiële subsidieverstrekkers en met marktpartijen.

1 Thialf ‘Een sterk merk’

Thialf staat voor zowel de topsport als de recreatieschaatsers symbool voor schaatsen in Nederland. Bij schaatsers en publiek is het de meest populaire baan ter wereld. Als Nederland zijn toonaangevende rol in de schaatssport wil blijven spelen en ook op de langere termijn verzekerd wil zijn van het accommoderen van de grote internationale evenementen, dan zal er een nieuw Thialf moeten verrijzen dat op het internationale podium zich de trots van Nederland mag noemen. De samenwerkende partijen hebben besloten zich hier maximaal voor te gaan inzetten. De KNISB heeft haar verloude steun voor het realiseren van een nieuw Thialf uitgesproken. Verder past een nieuw Thialf heel goed in het door NOC*NSF opgestelde Olympisch Plan 2028 waarmee het kabinet in juli 2009 heeft ingestemd.

De samenwerkende partijen hebben de volgende ambities verwoord voor een nieuw Thialf:

Ambitie 1
Het behouden en ontwikkelen van een internationaal topsportaccommodatie, ook voor de lange termijn. Tevens moet Thialf haar belangrijke functie voor recreatieschaatsen behouden en verder uitbouwen.

Ambitie 2
Het nieuwe Thialf moet een ultramodern stadion zijn met een bijzondere uitstraling. Het moet leidend zijn als het gaat om de aspecten ‘duurzaamheid’ (bijvoorbeeld in het gebruik van duurzame energie) en ‘innovatie’ (dit geldt voor het stadion zelf maar ook voor de trainings-, medische, wellness en leisure faciliteiten).

Ambitie 3
Het nieuwe Thialf moet onderscheidend zijn op zijn opzichte van andere top ijsstadiums in de wereld door de aanwezigheid van een tweede 400 meter baan, specifiek als trainingstaan voor de topsport.

Ambitie 4
Het nieuwe Thialf is een belangrijk onderdeel van het integrale programma Heerenveen Stad van Sport waarin ‘synergie’ en ‘integrale gebiedsontwikkeling’ belangrijke elementen vormen.

Deze ambities zijn vertaald in een gedetailleerd programma van eisen en in een accommodatienorm waar de belangrijkste accenten van de nieuwe accommodatie worden aangegeven. De samenwerkende partijen zien het als een uitdaging het geformuleerde ambitieniveau zo dicht mogelijk te benaderen.
De ontwikkeling van een nieuw Thialf biedt veel kansen en mogelijkheden aan duurzaamheid, energieverbruik en de zorg voor het milieu. Het nieuwe Thialf moet een (inter)nationaal voorbeeld worden op dit gebied. Overdekte ijssportstadions zijn grootverbruikers van energie. Wanneer genoeg aandacht wordt geschonken aan duurzaamheid en energie-efficiency is veel winst te behalen, zeker ten opzichte van het huidige Thialf complex. De kansen en mogelijkheden daarvan zijn op de Noordplot van het Sportstadgebied groter dan bij renovatie en realisering op de A7 locatie. Daar ontbreken de schaalvoordelen en de mogelijkheden om voort te bouwen op het in Sportstad ontwikkelde energieconcept. Bij de realisering van het Nieuwe Thialf wordt uitgegaan van een vergaande integratie tussen energieconcept, installaties, ontwerp en gebouw en het toekomstig beheer.

2 Vergelijking varianten en mogelijke locaties nieuw Thialf

Bij de verkennings van een nieuw Thialf is onderscheid gemaakt tussen een 1-baans variant (wedstrijd- en recreatiebaan) en een 2-banen variant met een aparte trainingsbaan gecombineerd met de schaatsploeg en topschaatsers.

Drie mogelijke locaties in Heerenveen zijn onderzocht: de huidige locatie (renovatie/opwaarderingen van het huidige stadion) en 2 nieuwbouwwelocaties. De ene locatie is de zogenaamde 'Noordplot' in het Sportstadgebied, de andere locatie betreft een perifere locatie aan de A7 (bij de 18F-afslag).

De verschillende varianten en locaties zijn toegelicht en vervolgens beoordeeld op de volgende aspecten:

- Ruimte: een nieuw Thialf is op alle locaties inpasbaar, hoewel de ene locatie meer randvoorwaarden stelt dan de andere. De ruimtelijke impact en betekenis voor Heerenveen zijn zeer uiteenlopend. De Noordplot locatie is qua inpassing het meest complex, maar deze locatie scoort het hoogst op betekenis voor de omgeving en Heerenveen als geheel.

- Verkeer en vervoer: een nieuw Thialf is op alle locaties mogelijk, mits er de juiste maatregelen worden genomen (onder meer met behulp van voldoende parkeerfaciliteiten). Bij de Noordplot locatie is uitgangspunt dat een schaatsevenement in Thialf niet gelijkzijdig plaatsvindt met een voetbalwedstrijd in het Abe Lenstra Stadion. Deze locatie is goed bereikbaar met het openbaar vervoer en daarnaast zou een shuttleverbinding tussen het trainingscentrum en het stadion een kansrijke maatregel zijn. De huidige Thialf locatie is bij evenementen wel goed bereikbaar met openbaar vervoer, maar in de dagelijkse situatie minder. Bij de renovatie- en A7-locatie is een shuttleverbinding met het NS station niet kansrijk.

- Milieu- en veiligheid: uit onderzoek op het gebied van ruimtegebruik, duurzaamheid en energie, verkeer en vervoer, wonen- en leefmilieu, bodem en water en integrale veiligheid blijkt dat de locaties op een aantal thema’s verschillen, maar dat deze verschillen niet significant zijn. Er is daarom vanuit deze invalshoek geen specifieke voorkeur voor één van de beoordeelde locaties.

- Synergimogelijkheden: de Noordplot locatie biedt de beste kansen voor synergie tussen het nieuwe Thialf en Sportstad Heerenveen. Bij de renovatie- en A7-locaties zijn de synergiekansen beperkt. Ook bij een keuze voor deze locaties kan de organisatorische samenwerking tussen Thialf en Sportstad worden versterkt en meerwaarde opbouwen.

- Integrale gebiedsontwikkeling: de Noordplot locatie heeft als voordeel dat het nieuwe Thialf zowel ruimtelijk als qua functies kan worden geïntegreerd in de doortoonontwikkeling van de huidige Sportstad Heerenveen. Daarnaast sluit deze locatie aan bij de beoogde integrale gebiedsontwikkeling van het gebied 'Heerenveen Centrum-Breed'.

3 Sportstad Heerenveen - 'Bouwen op een sterk fundament'

De samenwerkende partijen vinden dat de toekomst van Thialf niet los kan worden gezien van een integratie visie op Heerenveen als stad van sport en in het bijzonder de kans om de doorontwikkeling van Sportstad Heerenveen.

Sportstad Heerenveen is het nieuwste en modernste multifunctionele sportcentrum van Noord-Nederland en heeft ook nationaal gezien een voorbeeldfunctie. Het complex biedt een groot en gevarieerd aanbod van faciliteiten die direct en indirect gerelateerd zijn aan sport, deelnemen aan een groot sportcentrum, de Gezondheidsboulevard en het TopSport Medisch Centrum, de Lifestyle Passage, de BizzyFit Club, het Friesland College en het Abe Lenstra Stadion.

Sportstad Heerenveen is daarnaast recent aangewezen als één van de vier nationale Centra voor Topsport en Onderwijs (CTO) waar sportbonden hun talenten tot bloei zullen brengen. In het kader van het CTO zijn de sport- en onderwijsvoorzieningen en ondersteunende faciliteiten binnen Sportstad Heerenveen geconcentreerd. Eén van de speerpunten van Sportstad Heerenveen is haar beleid op het gebied van energie. In het hele Sportstadgebied worden aanzienlijke besparingen gedaan op het gebied van energieverbruik en CO2 uitstoot. Een andere belangrijke doelstelling is de sterke sportieve imago van Heerenveen optimaal te benutten ter ondersteuning van de economische ontwikkeling in de regio.

Er zijn plannen gereed voor een verdere uitbreiding van het Abe Lenstra Stadion van 26.000 naar 32.000 zitplaatsen. Als Nederland en België in 2018 het WK voetbal mogen organiseren, is Heerenveen kandidaat speelstad en zal het aantal zitplaatsen zelfs worden uitgebreid naar 44.000. Sportstad Heerenveen onderzocht de mogelijkheden voor een Sport Experience Centre, een grootschalige dagattractie op het gebied van sport, educatie en gezondheid. Ook worden de mogelijkheden voor het oprichten van een Wetenschappelijk Instituut voor Bewegingstechnieken onderzocht.


4 Economische effecten nieuw Thialf – vergelijking varianten

In het onderzoek naar de economische effecten is onderschied gemaakt tussen kwalitatieve uitstralingseffecten en de economische effecten van het nieuwe Thialf, waarbij gekeken wordt naar de (structurele) extra werkgelegenheid, toegevoegde waarde en jaarlijkse bestedingsimpuls.

Het nieuwe Thialf stadiion genereert belangrijke uitstralingseffecten die primair invloed hebben op Heerenveen en de regio. Dup afgezet van de werkgelegenheid die dit stadion creëert gaan er ook andere economische voordeelen van het stadion uit. De voornaamste uitstralingseffecten zijn verbetering bekendheid en imago (Heerenveen en Friesland), synergie met de omgeving en het geheel van Sportstad Heerenveen, verbetering op het gebied van energie en duurzaamheid. Ontwikkeling van een nieuw Thialf stadiion op de Noordplot genereert in beperkte mate grotere uitstralingseffecten dan renovatie of nieuwbouw op een andere locatie. Het grotere effect op de Noordplot locatie wordt met name veroorzaakt door de mogelijkheden van synergievoordelen binnen Sportstad Heerenveen, de bijdrage aan de ruimtelijke ontwikkelingen in het centrum en de winst die te behalen valt op het gebied van energie en duurzaamheid.
Het economische effect van een nieuw Thialf ligt in termen van structurele werkgelegenheid tussen de 60 en 80 extra arbeidsplaatsen (in totaal: lokaal, regionaal en nationaal), een toename in de toegevoegde waarde van € 3 à € 4 miljoen en een jaarlijkse extra besteding impuls van C3 à € 5 miljoen (voor circa 75% in Heerenveen en omgeving). Het gaat hierbij om 35% à 45% extra ten opzichte van de economische effecten van het huidige Thialf. De directe werkgelegenheids effecten komen vooral ten goede aan Heerenveen (zo’n 65%), de indirecte werkgelegenheids effecten slaan grotendeels neer in de regio (55%) en de rest van Nederland (35-40%).

De nieuwbouwvariant met een tweede baan leidt tot de grootste investering-kostenopstellingen (afgerond) 5.000-12.000 arbeidsjaren werk op, met een aparte trainingsbaan voor de topsport. Deze variatie tussen twee investeringskostenopstellingen gemaakt: een variant met de andere varianten; een variant met een aparte trainingsbaan voor de topsport.

De geop namede exploitatie in hoofdlijnen voor de verschillende varianten is als volgt (€ 1000):

<table>
<thead>
<tr>
<th>2014/15</th>
<th>Noordplot 2-baans</th>
<th>Noordplot 1-baans</th>
<th>A7 2-baans</th>
<th>A7 1-baans</th>
<th>Renovatie 2-baans</th>
<th>Renovatie 1-baans</th>
</tr>
</thead>
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<td>1.945</td>
<td>2.000</td>
<td>1.905</td>
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<td>2.008</td>
</tr>
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<td>965</td>
<td>1.155</td>
<td>965</td>
<td>1.155</td>
<td>965</td>
</tr>
<tr>
<td>commercieel en verhuur</td>
<td>2.250</td>
<td>1.850</td>
<td>1.740</td>
<td>1.340</td>
<td>1.320</td>
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</tr>
<tr>
<td>horsee</td>
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<td>1.600</td>
<td>1.600</td>
<td>1.600</td>
<td>1.500</td>
<td>1.500</td>
</tr>
<tr>
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<td>6.360</td>
<td>6.495</td>
<td>5.810</td>
<td>6.060</td>
<td>5.793</td>
</tr>
<tr>
<td>inkoop</td>
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<td>936</td>
<td>780</td>
<td>780</td>
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<td>824</td>
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<tr>
<td>bruto marge</td>
<td>6.109</td>
<td>5.424</td>
<td>5.715</td>
<td>5.030</td>
<td>5.236</td>
<td>4.993</td>
</tr>
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</table>

Bedrijfsresultaat: 331 401 94 294 408 1.018

Rentele: 211 225 224 220 220 214

Resultaat voor belasting: 120 176 -130 74 188 804

Belasting: 24 35 0 15 38 194

Resultaat na belasting: 96 141 -130 59 150 610

Door middel van een nieuwe organisatiestructuur kan de samenwerking tussen Sportstad Heerenveen en Thialf versterkt worden. Wat de locatie van het nieuwe Thialf ook wordt, zal gestreefd worden naar deze nieuwe structuur.
met nieuwbouw zal sprake zijn van verzwaa onderhoud en relatief hogere onderhoudskosten.

In termen van beoordeling in relatie tot het ambitieniveau wordt de volgende benadering gehanteerd:

• ‘Goed’: het nieuwe Thialf voldoet aan al de basiseisen voor het ijsstadion zelf
• ‘Beter’: het toevoegen van een aparte trainingsbaan die het Thialf van de toekomst een uniek voordeel geeft op ten opzichte van alle andere ijsstadions in de wereld
• ‘Best’: het nieuwe Thialf met een aparte trainingsbaan waar daarnaast de voordelen van synergie en integrale gebiedsontwikkeling in Heerenveen optimaal worden benut

Een nieuw Thialf met twee banen op de Noordplot van het Sport stadgebied voldoet het beste aan het ambitieniveau van de vier samenwerkende partijen. Deze variant komt overeen met de insteek ‘best’. Nieuwbouw op de A7-locatie ligt het minst voor de hand, omdat de investeringskosten van deze variant vergelijkbaar zijn met die van de Noordplot locatie terwijl de voordelen ten aanzien van synergiemogelijkheden en integrale gebiedsontwikkeling minder zijn dan op de Noordplot. Bovendien resulteert nieuwbouw op de A7 in een negatief bedrijfsresultaat. Renovatie/opwaarderen van het huidige Thialf biedt een goede oplossing voor het ijsstadion zelf voor in ieder geval de middellange termijn. De investeringskosten zijn aanmerkelijk lager dan bij nieuwbouw en het exploitatieresultaat is bij renovatie met één baan het meest omvangrijk. Er bestaat de mogelijkheid een extra trainingsbaan toe te voegen naast het huidige Thialf. Daarbij is ook sprake van een positief exploitatieresultaat. In de beoordeling moet worden meegenomen dat renovatie bij het aangegeven investeringsniveau veel minder ver reikt dan nieuwbouw. Ook zijn de synergiemogelijkheden hier duidelijk minder dan bij nieuwbouw op de locatie Noordplot.

**Planning**

De Regiegroep Heerenveen Stad van Sport heeft op 1 maart 2010 ingestemd met het Visiedocument. De Regiegroep biedt het nu aan aan de colleges van BBW en GS en aan de Raden van Commissarissen van Thialf BV en Sportstad Heerenveen BV.

Later in maart wordt de gemeenteraad van Heerenveen gevraagd om kennis te nemen van het Visiedocument (en de daaraan ten grondslag liggende documenten) en in te stemmen met het vervolgproces, waaronder het nemen van een definitief besluit later in het jaar. In april en mei van dit jaar wordt een maatschappelijk debat over het nieuwe Thialf georganiseerd en de komende maanden worden de subsidie- en financieringsmogelijkheden nader verkend. Het aflopen van het financieringstraject vormt het kritieke pad voor de definitieve besluitvorming.
## Appendix 2: Schedule of requirements

<table>
<thead>
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</thead>
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<tr>
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</tr>
<tr>
<td>Material C</td>
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<td>20%</td>
</tr>
<tr>
<td>Material D</td>
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<td>30%</td>
</tr>
<tr>
<td>Material E</td>
<td>350</td>
<td>20%</td>
</tr>
<tr>
<td>Material F</td>
<td>400</td>
<td>15%</td>
</tr>
<tr>
<td>Material G</td>
<td>450</td>
<td>10%</td>
</tr>
<tr>
<td>Material H</td>
<td>500</td>
<td>5%</td>
</tr>
</tbody>
</table>

### Appendix 3: Additional Notes

- Material A is preferred for projects involving heavy loads.
- Material B is recommended for indoor installations.
- Material C is ideal for outdoor applications.
- Material D is suitable for high-temperature environments.
- Material E is recommended for electrical control systems.
- Material F is preferred for industrial use.
- Material G is recommended for medical equipment.
- Material H is ideal for fire protection.
<table>
<thead>
<tr>
<th>Nr.</th>
<th>Plan</th>
<th>Aantal</th>
<th>Lengte</th>
<th>Breedte</th>
<th>Ronde ( \text{m} )</th>
<th>Ronde ( \text{mm} )</th>
<th>Vleugel %</th>
<th>Vleugel %</th>
<th>Vleugel %</th>
<th>Vleugel %</th>
<th>Lucht</th>
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<th>Lucht</th>
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<th>Lucht</th>
<th>Lucht</th>
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<th>Lucht</th>
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</tr>
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<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
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<tr>
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<tr>
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</tr>
</tbody>
</table>

**TOTALET:** 12.622

**TOTALET:** 12.622
There are three possibilities for the location of the new ice stadium, namely renovation of the current accommodation, a location adjacent to the Abe Lenstra Stadium and a location near the A7. These three location are shown in figures.

1 Renovation current accommodation
The current location of Thialf is in the south of Heerenveen adjacent to the railroad and industrial area ‘Heerenveen Zuid’. Around Thialf there are divers buildings accommodating a wide variety of functions, both commercial and recreational. Thialf is accessed by the Heremaweg to the south of the building, which is characterised by small-scale building along the road. This accessibility by car is good. The area between the Heremaweg and the building is a parking area for the daily use of Thialf. Another important access to Thialf is its own train station which is only used by events and important competitions; this is a large advantage top the other locations. However, the accessibility by public transport in daily situation is not very well, because Thialf is badly connected by bus with the train station of Heerenveen. The current accommodation has only one track, thus in order to create a second 400 metre ice track a second track should be build adjacent to the existing building. The north side of the complex is the best option for this new building, because the south side is of primarily importance for the accessibility of Thialf.

2 Sportstad Heerenveen
This location contains the area to the north of the Abe Lenstra stadium adjacent to the highway and relatively close to the centre of Heerenveen. The area is dominated by the Abe Lenstra Boulevard, which is a wide boulevard used as parking space and public space. The north of this area is formed by small-scale houses along a traditional road. The south-east is marked by an ensemble of three office building adjacent to the highway. The accessibility of the area is guaranteed by a link to the highway by the Stadionweg/parallel road. The location is in daily situation good accessible by more bus connections form the train station. In the future there will be a shuttle bus connection between the station and the stadium; this is also the solution for the accessibility of Thialf during events. This location has some opportunities. Firstly, the scale of the skating accommodation fits in the situation because of the large scale of the stadium. Moreover, the situation gives the opportunity of a relation with the Abe Lenstra Stadium and the other sport facilities in its direct surrounding. For instance, the parking space could be shared with the Abe Lenstra Stadium and the offices for an optimal use of space. Additionally, the proximity of the city centre of Heerenveen creates also opportunities for a more profound relation between Heerenveen and Thialf. Moreover, Thialf may improve the image of Heerenveen and could become an icon for the city. This is more obtained in this location than in the others. This location allows a north-south and an east-west orientation of the accommodation. Thus, there are enough possibilities to fit the new complex in the existing circumstances. The small-scale building in the north and the office towers adjacent to the highway should be taken into consideration in the design of the building in addition to the urban planning of the Abe Lenstra Boulevard and the stadium.

3 A7 location
This location is in the polder outside Heerenveen directly adjacent to the highway; of the two possibilities is the location south of the highway favourite, because the north location consists of a transmission line for electricity. There are no buildings in the direct surroundings giving restrictions to the design of the new Thialf. The accessibility of the location by car is very good, because the building is directly next to the access of the highway, in addition there is enough space to create enough parking spaces for events. The accessibility by public transport however is very bad, because the location is at a large distance of the train station and there is no existing bus connection to the location. During events there could be used a shuttle connection to the train station, but in daily situation this is not profitable.

Appendix 3: Location
Fig. 1 Current location Thialf

Fig. 2 Sportstad location adjacent to the Abe Lenstra Stadium

Fig. 3 Location near the highway A7
Although there is enough space to place the two 400 metre tracks next to each other, it is more economical to stack them above each other, because otherwise two hall structures have to be build and by stacking this could be combined. A disadvantage of this location is the lack of a relation with Heerenveen.

6.9.4 Consideration
Comparing the three locations, there could be concluded that the location near the A7 is less preferable than the other two locations, because it is badly accessible by public transport and it lacks a relation with Heerenveen. A newly build accommodation adjacent to the Abe Lenstra Stadium creates more opportunities than building the accommodation in the polder. Thialf could mean something for the city of Heerenveen when it is build near the stadium and the city centre. As a matter of fact, the stadium could become an icon for Heerenveen in this location, which is less possible on the location in the polder.

Consequently, there has to be made a choice between the current location and the Sportstad location. Renovation of the existing building would result in compromises to the requirements, and only solves the problems for a middle long term. A newly build complex should create an accommodation which could be used for a long period. Additionally, building a new complex creates more freedom to implement the ambitions to create the best skating accommodation of the world.

Both locations have a good accessibility by car and public transport during events, the only disadvantage of the current location is the bad accessibility by public transport in its daily situation. However, the accessibility during events is better than in the Sportstad location.

Because of the opportunity to create a relation with the Stadium of S.C. Heerenveen and the possibility to realize the ambitions of the initiators the location in the Sportstad area of Heerenveen will be chosen for this graduation project.
Appendix 4: Literature study to lightweight structures

1 Arches
The arch is an optimal structural form for a structure loaded with compression. This could be illustrated by a chain suspended between two points. A chain could only carry tensile forces and therefore shall take a form in which it is only loaded with tension, which is a curved form. Inversion of this form will result in a structure with pure compression. To design the form of a compression structure, a cable model could be used to find the form with pure compression. This could be found in the works of Gaudi and Frei Otto.

Important to fully exploit the benefits of the arch is the ability of the supporting structure to resist the horizontal lateral forces, because these forces will reduce the bending moments in the arch. Ideally, the bending moments will be prevented, resulting in the presence of only pure compression. When the supporting structure is not able to resist these horizontal forces, the arch will behave as a beam and is therefore loaded by bending moments, or the arch could burst dependably on the coherence of the structural elements in the arch. The horizontal forces could be resisted by a tension element between the two ends of the arch, buttresses as supporting structure or by balancing the forces with opposite lateral forces in adjacent structures.

The horizontal forces depend on the rise of the arch as could be derived from the equilibrium in the arch. This equilibrium also shows that the horizontal component only depends on the total vertical loading of the structure and not on the form of the arch. Thus, varying the rise of an arch will change the magnitude and direction of the forces in the supports. Arches with a relatively small rise will result in large supporting forces and arches with a large rise will thus result in small supporting forces.

An important concept for the understanding of the structural action of an arch is the pressure line, which could be defined as the tangent line of the pressure line in each point gives the direction of the pressure. For instance, a uniformly distributed load will result in a parabolic form of the pressure line and a structure with point load will result in a kinked line. Bending moments will appear when the pressure line deviate form the form of the
arch; this is for instance the case with asymmetrical loading. This contrasts with a cable, which will take another form corresponding to the asymmetrical loads. An arch could collapse when the pressure line deviate too much from the form of an arch, resulting in too much bending moments. In addition, an arch could also collapse due to instability resulting from compressive forces. Buckling out of the plane of the structure depends on the largest unsupported distance, buckling in the plane of the arch however is dependent on the form of the buckling shape which is determined by the static system of the arch. Most common static systems are the rigid arch, two-hinged arch and the three-hinged arch. This should be checked in the design.

2 Vaults

When arches are combined to create a more three dimensional structure, it will result in a vault. Vaults and arches are therefore closely related. A vault could be defined as a structural system composed of curved ribs and surface elements that distribute loads along ribs and planes, and have greatest efficiency when resisting evenly distributed loads. Vaults carry the loads primarily by compressive forces and obtain their stability from their three dimensional form. Commonly used as structural material are stone, masonry, reinforced concrete, steel lattice and timber frames. While the first three are homogeneous, the latter two are characterised as an assembly of elements. Generally, the forces in a vault will be transported to the ribs (except in continuous vaults with no ribs), which will transport the forces to the supports. An important design tool which could be used when designing a vault structure is a chain or hanging model. These models help to find the optimal form of the vault under its own weight and could be illustrated by the hanging models of Gaudi and Frei Otto.

Two important spatial forms of vaults are the barrel vault and the cross vault. Firstly, a barrel vaults refer to a vault distributing the forces along a continuous or braced surface and which have a linear character. Here, the non-homogeneous barrel vault, thus a braced barrel vault, will be discussed in more detail. This structural type is composed of elements connected to form a cylindrical shape. There could be distinguished varying types of bracing including the lamella type known from the buildings of Nervi and the hexagonal type. To obtain stability of the structure, end braces are needed in the open ends. Additionally, a barrel vault is sensitive to buckling out of its surface and has to be designed with enough buckling resistance. The buckling behaviour could be improved by using stiff joints or by using a double layer vault. Additionally, applying a double layer vault also decreases the stresses in the structure and, therefore, decreases the deflections of the roof. The sensitivity to buckling is influenced by the proportions of the barrel vault; a longitudinal vault is more vulnerable to buckling than a square vault. Therefore, single layer vaults are mostly used in a square or a short rectangular form. If the vault is more longitudinal, a double layer vault has to be used. A barrel vault could be strengthened by interweaving of two sets of lattices or by corrugating the vault, creating a stiffer undulating vault form. The IBM pavilion by Piano may be seen as an example of this type of vault.

Another example which should be mentioned is Nervi, who created a prefabrication system to economically create concrete braced barrel vaults. This is shown in the paragraph 4.5. Secondly, cross vaults are vaults in which the surface is subdivided in the form of a cross and in which the forces are distributed both along the surface and/or along the ribs subdividing the surface. Several variants on the cross vault are possible to increase the subdivision of the surface. In complex rib vaults the subdivision of the surface is further increased by introducing ribs and apex points to a pointed arch configuration. In fan vaults the vault is assembled from a set of curved ribs with same curvature and spaced equidistantly in a radial pattern describing a curved shell surface which is butted together with others resulting in
a flat surface between them for stability. The degree of surface subdivision is even further increased in curved rib vaults by replacing the ribs with a number of curves that distribute the lines of force. Finally, cellular vaults distribute the lines of force primarily along a highly subdivided surface that eliminates the need for ribs and distributes the loads along the surface of each facet.

3 Dome structures
A dome structure is designed to be loaded entirely with compressive forces and could be seen as a combination of arches rotated around their centre. The structural behaviour is similar to an arch. As a result, amongst other things, horizontal forces will appear at the basis, which could be carried by the supporting structure. A more economical solution is the application of a tension ring.

A dome has a spherical shape and could have a ground plan like a circle, ellipse, square or polygon form. A sphere form has the characteristic that it contains a maximum amount of space with a minimum surface. Basically, there could be made a distinction between two basic dome types, namely a solid dome, including concrete and brick domes, and a braced dome, which is composed of an assembly of elements. A braced dome could be composed either of curved members lying on the surface of revolution, or of straight elements with their connections lying on such a surface. To obtain an optimal type of braced dome is complex, since it not only depends on the minimum weight, but also on the amount of connections, type of covering, fabrication of the elements and the construction of the dome. All these elements influence the most suitable solution to a certain situation. There could be distinguished four types of braced domes: the single layer dome, the double layer dome, the stressed skin type and the formed surface type. These four types of domes will be discussed here.

The single layer dome (or frame or skeleton type) is a dome
composed of one layer of structure. The most simple variant is a ribbed dome, which is a dome consisting of a number of identical radial ribs interconnected at the top and supported at the foundation. Problematic in this type of dome is the top connection between all the ribs. Additionally, a ribbed dome is not very economical, because its lack of latitudinal rings and therefore of structural interaction between the rings. This could be solved by connecting the ribs with polygonal rings dividing the surface in trapezium like bays, which may be brace by either one or two diagonals. This type of dome could be defined as the Schwedler dome. The diagonals in this type of dome are necessary for carrying asymmetrical loading. If the connections of the Schwedler dome are stiffened instead of pin-jointed, the diagonals could be omitted. The resulting type of dome could be defined as stiff jointed framed dome. Another variant on the Schwedler dome is the plate type dome which is a Schwedler dome with a limited number of sides filled by bars in the same plane forming a triangular network. This type of dome could be used to span rectangular spaces. A network dome is also derived from the Schwedler dome by rotating each polygonal ring through an angle of π/n, in which n is the number of sides. This results in a dome composed of triangular planes and thus in a stable system without bracings. The Zimmermann dome is designed to be built on top of a building. Therefore the horizontal forces are resisted by the longitudinal direction of the supporting walls. Thus, the shape of the bracing depends on the lay-out of the supporting walls. Additionally, the dome should be designed so that each horizontal ring is composed of twice as many sides as the ring above. Lamella domes may be characterised by the diamond grid, which is formed by a few of the ribs running from the rim to the crown of the dome as meridional spherical sector dividers and the other ribs running as intra-sector parallel lines. This could result in flower like patterns of the elements, as could be seen in the lamella domes of Nervi. Another type of dome is the geodesic dome which is deeply related to Buckminster Fuller. A geodesic dome is formed by elements lying on the great arches of a true sphere creating a three-way grid comprising equilateral spherical triangles. As a result, all the elements are of approximately same length and the structure has thus a very regular network with uniform stress distribution. A geodesic dome could be obtained by exploding a polyhedron, for example an icosahedron, which divides the surface of the sphere in triangles. These triangles could be divided in elements in order to create more strength. Another pattern could be obtained by placing pentagons on the intersections of these triangles and fill the rest with hexagons. Since the compressive forces will increase by an increase of the span, the buckling resistance should also be enlarged. This could be obtained by a two layer dome, which has a much larger structural depth and is extremely rigid. An example of this type is the American Pavilion in Montreal by Buckminster Fuller. Stressed skin domes are domes in which the covering forms an integral part of the structural system. They could use the geodesic type of bracing, an example of this are many of Buckminster Fuller’s domes, such as Union Car dome. Another example is the temcor domes. These domes are composed of a single layer geodesic dome stiffened folded plates. The formed surface type is a dome composed of bent sheets which are interconnected along their edges to form the main skeleton of the dome. The basic type is the V-folded form.

4 Grid Shell
The braced vaults and domes discussed are bounded to a specific structural form. However, grid shells, which as a structural type are closely related to the braced vaults and domes, could be applied in more free and inventive forms. The use of double curved shapes is advantageous, because of a larger resistance to buckling unlike by a single curved shape. A grid shell could be defined as a single layer thin membrane shell with a triangular or square mesh. Moreover, grid shells are usually composed of flat bars of equal length forming a triangular or diamond-like pattern directly
Since the elements are rotation-free connected, the square mesh of a square mesh could be constructed by the mesh in the structure, in other words in which the cables are the primary structure, in other words in which a system of cables carries the roof load directly. Finally, the last type is a combination of cables carrying the covering elements, like glass panels, wooden elements or membranes. Even though all bars have equal lengths, the bars at the perimeter of the grid shell have different lengths dependant on the form of the building.

A grid shell is a form-active structure carrying the loads only by membrane forces, both compression and tension, and not by bending moments. Also shear forces will appear in the shell. Therefore, the material used should be able to carry both tension and compression. Consequently, steel and wood are commonly used.

It could be helpful in the design to use physical models, such as hanging models, in obtaining the structural form. As is illustrated by Frei Otto in the Mannheim building, hanging models could be inverted to obtain the ideal form. However, computer software is currently more commonly used to design the form of the structure and to calculate the exact length of the perimeter bars of the structure. An important design aspect is the balance between the amount of connection to the structural efficiency and material use. Among others, these aspects will eventually lead to a choice for a triangular or square mesh pattern.

A triangular mesh is the most efficient and stable one of the two, because of its relatively stiff triangles. As a result, it will deform less due to wind loads and other variable load patterns. An example of a grid shell with a triangular mesh is the roof structure of the British museum described in paragraph 4.8. A square mesh, however, could be glazed more economically, because the double curved glass panels are almost square; therefore, less material losses will occur than by a triangular mesh.

Since the elements are rotation-free connected, the square mesh could easily be transformed. Therefore, a grid shell composed of a square mesh could be constructed by pushing the mesh in a certain form three dimensional form. The diamond shaped mesh resulted is not rigid, thus the structure should be stabilised by diagonal cables. These are pre-tensioned in order to be able to carry both tension and compression. Since the cables run under the bars from one edge to the other along the whole structure, they could be easily pre-tensioned afterwards. Additionally, exact measurement of the length of the cable is unnecessary. Due to these cables, the structure deforms less due to variable loads than a mesh without cables. A square mesh could be stabilised by prevention of rotation of the connections, but this will result in bending and torsion in the bars. Additionally, the shear forces could be carried by the covering of the grid shell, for instance wooden panels.

For example, a timber structure is perfectly suitable for a grid shell structure. The lattice can be initially laid out on the ground and then pushed into the shape. Therefore a square grid has to be used with rotating connections between the timber elements. When the form is obtained, the timber grid shell should be stabilised to form a rigid structure. If the dimensions of the laths applied required by the span of the structure are too large to obtain the curvature of the shape, a double layer lattice could be used. A double layer lattice is obtained by imposing to meshes on each other. An example of a structure using this double layer grid shell is the Dowland Gridshell of Buro Happold.

5 Cable structures

The use of cables in structure is characterised by its inability to resist compression, bending moments and shear forces. However, cables could carry large axial forces; therefore, they are important in lightweight structures. Cables carry loads by deforming in a way that the internal tensile forces make equilibrium with the loads. For example, a parabolic line by an equally distributed load and a triangular form by a point load.

A distinction could be made between three types of cable structures, which can be classified as cable supported, cable suspended and cable-cum-air-supported roofs. A cable supported roof is a roof composed of girders or trusses supported on one or more points by cables. Since this principle is not really lightweight, it will not be discussed here. The cable suspended roof is a structural principle in which the cables are the primary structure, in other words in which a system of cables carries the roof load directly.
and pneumatic membranes. Here, this will only be discussed as a method to stabilise the cable structure, in the paragraph on pneumatic structure this type will also be discussed.

In cable structures, vertical supports are needed to provide the necessary height of the building, because these are the only elements able to carry compression. Additionally, the anchorages are needed to resist the tensile forces in the cables; this could be done by heavy foundations, pile foundations, part of the building, perimeter compression rings and interior tensile rings.

One single cable could not be a stable structure, for instance wind forces will cause the roof to flutter, which may induce damaging vibrations. Therefore, a cable structure has to be stabilised, five methods to stabilise cables could be distinguished:

- Stabilising the cable by applying mass
- Stabilising the cable by means of a hanging shell
- Stabilising the cable by means of a cable truss
- Stabilising the cable by means of a cable net
- Stabilising the cable by pneumatic pre-tensioning

5.1 Stabilising with mass
This method of stabilising a cable is based on the fact that a cable loaded with a heavy equally distributed load will deform less under a point load than a non loaded cable. This could be explained by the fact that less deformation is necessary to create a new equilibrium, in other words, the influence of the point load is decreased. Using this principle, the permanent load could be increased to the point that the deformations caused by the loads are small enough to meet the usability restrictions.

5.2 Hanging shell
Stabilisation of a roof with a hanging shell is a variant of the former method. The permanent loading of the concrete shell is larger than the variable loads. The shell also pre-tensions of the cables, because the lengthening of the cables is prevented by the concrete covering. Additionally, the concrete shell could also resist wind suction and local bending moments in the shell. The concrete shell also damps dynamic loads.

Although the structure behaves as a prestressed concrete shell structure, during construction of the concrete shell, thus when the dead load is applied, the structure will behave as a pure cable structure. The structure should thus be calculated as a concrete shell and as a cable structure.

5.3 Cable truss
A more lightweight solution to stabilise a cable structure is by a cable truss. In order to obtain stability it is necessary to apply double curvature, which could be achieved by applying two cables in opposite direction. These two cables could be curved outside with compression bars to tension them and to attain the distance between the two cables. On the contrary, the two cables could also be curved inside with tensile cable to push them together resulting in tensioning of the two cables. An example of this is the Jawerth cable system in which the tensile cables are diagonally configured resulting in stiffer structural behaviour of the truss.

These trusses could be placed on a repetitive interval in longitudinal direction with roof elements spanning the distance between two trusses. However, they could also be arranged in a circular lay-out resulting in the so-called bicycle wheel structure or lens shaped systems. In these kind of cable structures the peripheral horizontal forces are usually resisted by a compressive ring beam, possibly with a tensile ring in the centre of the circle. Similar to the trusses, these structures could have a convex shape (with compression bars) or a concave shape (with tensile cables).

5.4 Cable net
In this stabilisation method the cables are assembled in a net mostly with a double threading. The structural action of the net could be compared to membrane structures, discussed in the next paragraph. Stability is obtained by double curvature of the surface, because the intersecting cables pretension each other resulting in a more rigid structure.

The cable net should have an anticlastic form. An anticlastic form
has a surface with opposite curvature, thus positive curvature in one direction and negative curvature in the other direction. On the other hand, a synclastic form is defined as a form with same curvature in all directions, thus positive or negative curvature, for example the form of a dome. Stability of an anticlastic form is attained by pretensioning the system of cables, but a synclastic form should be stabilised by applying large permanent loads. One of the first cable net structures was the Raleigh Arena designed by Matthew Nowicki and Fred Severud, which has a saddle shaped roof hanging between two inclined parabolic concrete arches. Cable net structures are most used by Frei Otto, for instance the German Pavilion and the Olympic Stadium in Munich. A characteristic element of many of Otto’s cable net structures is the drop-like supporting cable by the masts; this cable is used to spread the forces from the supporting mast over more cables so that the tensile strength of the cables is not exceeded.

5.5 Pneumatic pretensioning
The last method to stabilise a cable structure uses a pneumatic structure to pre-tension the cable net resulting in a stable cable structure. This type will be discussed in the paragraph on pneumatic structures.

Usually the cable net is assembled on the ground and eventually assembled on site; to attach the last cable normally a high force is required, because these cables will pretension the whole system. A balancing construction planning could be necessary to prevent over tensioning of cables, for instance due to asymmetrical pretensioning of the system.

6 Membrane structures
Membranes are only able to resist tensile forces and could therefore be compared to cable structures, especially cable net structures. If compression appears in the membrane, wrinkles and folds will arise. When a force normal to the membrane is applied to the membrane, the membrane will deform in order to create equilibrium between the tensile stress in the membrane and the load. Additionally, tangential shear stresses will appear which also helps carrying the load. Thus, forces in two directions will arise. Consequently, a membrane applied as primary structure should be pre-tensioned to obtain a rigid and stable structure. Tent structures are mechanical prestressed by stretching the membrane between its supporting points. Large forces could be required to fix the membrane to the supports. The membrane canvas is incapable of carrying large concentration of stresses; therefore the supporting forces should be spread. Additionally, the supporting forces should be uniformly introduced in the membrane to obtain the desired evenly expanding of the membrane. The most common solution for both problems is applying a perimeter cable providing a uniformly distributed stress pattern in the membrane due to pretension. Additionally, the pretension in the membrane should be reintroduced as time passes due to relaxation of the membrane fabric. After a while, the pretension will decrease and therefore, the stability of the membrane will also decrease. The supporting structure mainly determines the structural form. The membrane will employ the form with the least pretension, thus a minimal surface form, similar to soap skins. The form could be adjusted by locally varying of the pre-tensioning. Similarly to prestressed cables, the surface of the membrane should be anticlastic, which is a surface with opposite curvature in perpendicular direction. This anticlastic surface is obtained by differences in the supports. Therefore, the form of a membrane structure could be modified by adjusting the height of the supports. Another aspect of the form is the curvature of the membrane. The smaller this curvature is, the larger the pretension forces should be to obtain a stable surface. A flat membrane should theoretically have an infinite pretension. Therefore an important design aspect is the balance between the span of the structure, the curvature of the membrane and the level of pretension. The form finding could be done with physical models, such as soap
Fig. 15 Examples of cable structures

Fig. 16 Different types of cable trusses

Fig. 17 Cycle wheel cable structures

Fig. 18 Peak tent

Fig. 19 Arched tent

Fig. 20 Bump tent

Fig. 21 Tent structure of Frei Otto for the Federal Garden Exposition
skins and models of a stretch fabric, as could be seen in the works of Frei Otto and Horst Berger. In addition, special software is available for the form finding process, the structural analysis process and the generation of cutting patterns. The fabric used in membrane structures are translucent, which means that light will partially shine through. This has influence on the architecture of membrane structures.

6.1 Basic types

There are four basic types of forms with an anticlastic membrane form. These forms are the saddle shape, the undulating roof, the peak tent and the arch surface. The saddle shape is formed by a direction of curvature between two high points and the other direction between two low points. These two should be perpendicular to each other, resulting in the characteristic saddle shape of the structure. A wide range of variants to these principles are possible, for instance by adding more low or high points, or by combining different saddle shapes.

The undulating roof is a variant on the saddle shaped roof. The difference is that cables between the two high points and between the two low points pre-tension the membrane resulting in sharp folds in the membrane. The direction of the opposite curvature is sequentially in longitudinal direction instead of perpendicular. Hanging cables are positioned between the two high points and spanning cables are positioned between the low points, these cables are in the membrane surface. The membrane between the two spanning cables result in a saddle form. The field cables cause problems in the membrane, but the advantage is that they decrease the membrane stressed. An example of this basic form is the San Diego Convention Centre of Horst Berger.

The third basic form is the peak tent, which is composed of a membrane spanning between a central high point and some vertices. This type could be seen as a circular saddle shape. The perimeter of the membrane is large, while the top of the membrane is small even though the forces should be similar, resulting therefore in high stresses in the top. This could for instance be solved using a steel cone or ring. If the difference between the differences in height is small, the membrane could also only pushed resulting in bumps creating the bump tent type used by Frei Otto.

The arch surface is formed by stretching the membrane over an arch. This introduces curvature in one direction; curvature in the other direction is obtained by the perimeter cables. The curvature of the perimeter is relatively small causing a weakness to wind loads. The arch is stabilised through equal load on both sides of the arch.

6.2 Supporting structures

Since the forces in the membrane are concentrated in the supporting structures, these structures often have large dimension. These supports are mainly compression elements to obtain the height of the building. The most common supporting structures are masts, arches and spatial structures.

Masts are mainly applied as a lean-on column, which are columns hinged on both sides, resulting in only axial forces. However, because the column is hinged on its foundation, it should be stabilised with cables, the membrane or a combination of both. The mast could also be fixed in the foundations, but this will result in bending moments in the column. Since they support the membrane on one point, large stress concentrations in the membrane will arise. These stress concentrations are decreased by an arch, which linearly support the membrane and defining the curvature of the membrane. The arch is almost uniformly loaded by the membrane forces, which will result in mainly axial forces in the arch. The membrane loads should therefore be in the same plane as the arch. Moreover, the arches should be stabilised against forces in the direction perpendicular to the arch. Commonly used stabilisation methods are membranes at each side of the arch, intersection of arches, stabilising with cables, or fixing the edge arch to a stable structure. The arch is often made of steel tubes, mainly trussed, but other materials and structural principles are possible, such as a pneumatic arch. Additionally, the arch could
be placed inside, outside or between the membrane canvases. The last supporting structures are spatial structures in which the membrane is used as a secondary structure. Since the supporting structure is the primary structure, the stresses in the membrane are minimal.

Sometimes, intermediate structures are used to transfer the forces from the membrane to the supporting structure. Commonly used are hanging structures, braced cable structures, flying mast structures and tensegrity structures. The hanging structure is similar to a hanging bridge; the membrane is connected to a cable hanging between two masts. A brace cable structure uses a cable connected to a stabilised mast. These cables are carrying the membrane. A mast could also be carried by a cable system causing the mast to ‘fly’; this mast carries the membrane resulting in a peak type surface. Finally, this principle could be developed further resulting in a tensegrity structure supporting the membrane.

7 Pneumatic structures

Pneumatic structures are membrane structures in which the membrane is pre-tensioned by a difference in internal air pressure and external air pressure. The structural form of pneumatic structures is characterised by double curved surfaces, mainly spherical or synclastic surfaces, in contrast to tent structures. Plane surfaces are impossible, because the internal overpressure will push the membrane outwards and will therefore always result in a curved surface. Additionally, similar to tent structures, the pre-tension forces should be infinite to create a plane surface. The basic forms of a pneumatic structure are the sphere, the cylinder and the torus (which is a closed curved cylinder). The form of a membrane structure could be influenced by the form of the membrane. The form of the membrane determines to which basic form a pneumatic structure will resemble. Thus, the design of a specific pneumatic form could be obtained by corresponding cutting patterns. The form of a pneumatic structure could also be influenced by using cables to push the structure in a specific form. The materials used in membrane structures are often similar to the materials used in membrane structures. A comparison of pneumatic structures with a soap bubble could be useful in the form finding process, as is illustrated by Frei Otto. However, also other forms than soap bubbles are possible. There are two main types of pneumatic structures, namely global pre-tensioned pneumatic structures and local pre-tensioned pneumatic structures. In global pneumatic structures the interior of the building is subjected to overpressure pressing the membrane outwards resulting in tensile stresses in the membrane. This type of pneumatic structure will not be discussed further here, because optimal skating conditions are attained with low air pressure, because the air friction is low. Thus, designing a building with overpressure is contrasting with good skating conditions.

Local pre-tensioned pneumatic structures are closed membrane structures pre-tensioned by an internal air pressure to form a structural element. These elements have internal force equilibrium; the foundations are therefore not subjected to upward forces as is usually the case by global prestressed structures. Moreover, the load carrying capacity depends on the volume of air inside the element, the internal air pressure, quality of the fabric and the form of the element. Since the elements are never completely airtight, the air pressure should be regularly restored depending on the size and air pressure necessary. The internal air pressure should fluctuate due to temperature changes, particularly elements with low air pressure will be subjected to this problem. Pneumatic could be used as primary structure and as secondary structure.

7.1 Pneumatic structures as primary structure

If a pneumatic structure is used as primary structure, a certain minimal rigidity will be required and relatively large forces should be carried. Since a larger internal air pressure will increase the curvature and tensile forces in the membrane, larger air pressures are required. As a result of this pre-tension, the structural elements are able to carry bending moments and compressive
forces. A disadvantage of a large internal pressure is the demand of constant air supply or regularly re-pressuring of the membrane. The most used basic form is the cylinder due to its linear character. Moreover, ideally the cylindrical element is applied as an arch, because the bending moments are minimised. However, they could also be used as straight beams and columns, as is illustrated by the pneumatic exhibition building of Festo. The pneumatic elements could also be applied as struts in a geodesic dome, as is done by Buckminster Fuller. These are examples of pneumatic structures as a replacement for structural elements which could also be made of other materials. A more specific application of pneumatic structures is a structure composed of a double layer on a supporting structure, resulting in a lens-shaped roof. This could be combined with other supporting structures resulting in hybrid structures.

7.2 Pneumatic structures as secondary structure
This application of pneumatic structures mainly concerns the use as façade elements. The elements will carry the loads directly to a supporting structure and therefore they do not contribute to the global rigidity of the building. Consequently, smaller internal air pressures are required. Recently, some prominent projects are built using pneumatic façade-elements including the Olympic Swimming Pool in Beijing and the Allianz Arena in Munich. Most of the pneumatic structures of this type are cushion-like elements, which could have a wide range of forms; for example, diamond-like as in the Allianz Arena or hexagonal like the cushions of the Eden Project in Cornwall. It is also possible to apply linear elements as façade elements, such as the elements in the National Space Centre in Leicester.

7.3 Pneumatic structures stabilised by under-pressure
Another possibility is to design buildings which are stabilised by internal under-pressure; an example of this is the floating theatre in Osaka Japan in the world expo of 1970. A large disadvantage is the larger influence of air leakages on the internal under-pres-

sure compared to overpressure. This type will not be discussed in more detail here.

7.4 Hybrid structures
Through the combination of different structural principles, the qualities of these principles could be combined to create a more lightweight structure. This includes the combination of different applications of pneumatic structures and the combination of pneumatic structures with cable structures. An example of the first is the acoustic barrier designed by Arjan Habraken, in which a pneumatic structure is supported by pneumatic arches. These arches support the inner membrane, the outer membrane is supported by air pressure between the two membranes. An advantage of this structure is the absence of overpressure in the interior of the building. Other potential structures are imaginable using a supporting structure composed of another material instead of a pneumatic arch.

Another example of a combination of different structural principles is a cable structure supporting the inner membrane. Cables support the inner membrane on some points through the outer membrane, resulting in a structure comparable to the previous example. The cable structure is on the outside of the building. These two examples illustrate the potential of hybrid structures, but other combinations are possible.

8 Tensegrity
Tensegrity structures could be defined as structures in which a set of discontinuous compression components interact with a set of continuous tensile components to create a stable structure, which is invented by Buckminster Fuller. The word tensegrity is a contraction of the words tension and integrity. In normal structures the compression elements provide the continuity to pass the forces to the foundation, in tensegrity structures however the continuity is provided by the tensile elements. The compression elements are thus not connected to each other. Consequently, the elements could be dimensioned according to
their function (tension or compression). Tensegrity structures are flexible and will largely deform due to loads, but also return to their original form after removal of the loads. Applying more pre-stress or more tensile members will decrease this flexibility. Thus, tensegrity structures should be pre-stressed. The calculation of the pre-tension required is therefore an important design aspect.

A comparison with pneumatic structures could be made to improve the understanding of the structural behaviour of a tensegrity structure, because the compressive struts push the tensile members (cables) outward similar to the air pressure pre-tensioning the membrane. However, tensegrity structures have an internal equilibrium and thus free standing structures, while pneumatic structures require large anchorages.

If the bars used in the tensegrity are relatively short, they are more resistant to buckling, but the small curvature in the dome causes the bars to interfere with one another. This could be solved applying large bars, which are more vulnerable to buckling. This consideration has to be made during the design process.

Stability could be obtained as each strut is connected with minimal three cables in a different plane or with two cables in the same plane as the strut. This last could only be pre-stressed in this plane and is therefore only stable in that plane. This could be found in tensegrity nets. If a tensegrity has less than five cables at a joint the pre-stressed structure can carry only a number of load configurations otherwise it will largely deform, while when it has more than five cables at a joint it could carry an external force in any direction.

Many tensegrity structures are based on simple elementary modules, which are a triangular prism made of 3 struts and 9 cables, a half-cuboctahedron with 4 struts and 12 cables, and an octahedron composed of 6 struts and 24 cables. These modules are shown in figure...

Three different patterns could be distinguished, namely the diamond pattern, in which each strut is surrounded by four tensile cables in a diamond like shape; the circuit pattern with a system of interconnected struts which do not touch each other; and the zigzag pattern, in which each opposite of the strut is connected with three tensile members defining a mirror image along it. Remarkably, this last pattern does not fit Maxwell's rule for stability (3J-6). Thus, a structure in this pattern is able to obtain stability with less elements than required in normal structures.

The standard tensegrity components, like the elementary modules or tensegrity nets, could be used to compose the desired structural form, for example domes and vaults. Additionally, the struts and tensile members could be replaced by other structural elements if these could carry the force, since the struts and elements represent the forces in the system. An example of this is a dome in which the cables are replaced by a membrane pre-tensioned by the struts.

One type of tensegrity structure is the cable dome, in which the loads are carried by a central tension ring through a series of radial ridge cables, tension hoops and intermediate diagonals and eventually by a perimeter compression ring. This type of domes has a highly nonlinear structural behaviour, because it is a statically determinate structure under snow load resulting in large deformations. Different variants on this principle are possible. Another dome structure using tensegrity is the tension strut dome. This type of dome uses a central lens-shaped cable girder, while the cable dome uses membrane material and a combination of diagonal cables and hoops. Additionally, the cable dome introduces tension to cable members which are connected to the top of the struts, while the tension strut dome introduces pre-stress in both the upper and lower chords, which are independent. Tensegrity domes could also be composed of tetrahedron-like modules.

Finally, the tensegrity principle could be applied in combination with another structural type to strengthen the qualities of both principles. For instance, a trussed dome could be strengthened by a tensegrity structure composed of hoop cables, radial cables and struts. This structure is developed by Prof. Kawaguchi and is called a Suspen-dome. Another application of tensegrity in com-
9 Tensairity

Tensairity is a hybrid structural type in which a pneumatic beam is strengthened by cables and struts. The word is derived from the words tension, air and integrity. The basis of this structure is composed of a cylindrical pneumatic element, a compression bar and a minimum of two cables spiralled around the beam and tightly connected to the compression bar. This combination of elements carries the loads on a conventional way by compression and tensile elements. The function of the pneumatic element is pre-tensioning the cables and stabilising the compression bar against buckling. Since buckling is prevented, this compression bar could have minimal dimensions in comparison to normal compression bars. In combination with the cables and pneumatic elements this results in extremely lightweight structures, while the load bearing capacity of the pneumatic structure is improved.

The cylinder is the basic form of this structural type, but the pneumatic element could also have other forms. Moreover, some other forms appear to have stiffer properties than the cylinder shape, for instance the cigar or spindle shape. Additionally, the spindle shape uses less fabric and is thus more economical than the cylinder form. Architecturally, tensairity beams can be made translucent similarly to conventional membrane and pneumatic structures, therefore there are opportunities for interesting illumination.

For a better understanding of the structural action in a tensairity, an analogy to a truss could be helpful. As is shown in fig 5, this analogy could also be used by the spindle form. There could be seen that the truss has an upper compression element and a lower tension element, which could also be found in the tensairity. The vertical and diagonal elements transfer the homogeneous loads to the tension element. In the tensairity structure, the function of these elements is fulfilled by the fabric and air pressure of the pneumatic element. Since this transfer depends on the air pressure, a relation between the air pressure and the load could be established. In the case of a cylindrical structure, the air pressure required seems to be proportional to the load per area and independent of the length or slenderness of the beam. In other words, the required air pressure in the structure is the same for small spans as for large span structures, such as the covering of a stadium.
Appendix 5: Installations in Thialf and Kolomna
Sneller door verse lucht

Tijdens de EK-aarvond dit weekinde op de Koreta ijsbaan in Kolomna (RUS) worden snelle tijden verwacht. De speciale constructie van de ultramoderne hal, de voortdurende stroom van verse lucht en het speciaal geprepareerde ijs moeten hiervoor gaan zorgen.

Unieke binnenboarding

Systeem in binnenboarding zorgt voor luchtstrom over het ijs.

1. Buitentocht wordt aangezogen.
2. Lucht gefilterd en droog gemaakt (gepolieerd).
3. Door gastjes in boarding wordt sfeer lucht de hal in geblazen.
4. Lucht wordt aangevoerd of terug geblazen in hal.
5. Extra installatie zorgt voor verse lucht van bovenaf.

Continu verse lucht

Door het speciale circulatie-systeem heeft de schaatsbaan meer zuurstof.
Appendix 6: Comparison hand calculation with computer analysis

Comparison between hand calculation and computer analysis LC1

Comparison between hand calculation and computer analysis LC2
Comparision between hand calculation and computer analysis LC3
Appendix 7: Comparison linear and non-linear analysis

Comparison between linear and non-linear analysis LC1

Comparison between linear and non-linear analysis LC3
### Appendix 8: Overview of analysis of planar behavior of a tensegrity

#### Minimal pre-stress force necessary

<table>
<thead>
<tr>
<th>Base variant</th>
<th>Total height</th>
<th>Shape top cable</th>
<th>Height above supports</th>
<th>Varying bar length</th>
<th>Distance between hoops</th>
<th>Varying distance between hoops</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-g-G-H</td>
<td>7500</td>
<td>24000</td>
<td>5800</td>
<td>1320</td>
<td>11000</td>
<td>8250</td>
</tr>
<tr>
<td>R-g-G-H-lager</td>
<td>10400</td>
<td>43000</td>
<td>7700</td>
<td>1450</td>
<td>12300</td>
<td>8600</td>
</tr>
<tr>
<td>H1-k-g</td>
<td>4350</td>
<td>5800</td>
<td>1180</td>
<td>13500</td>
<td>6000</td>
<td>5200</td>
</tr>
<tr>
<td>H2-k-g</td>
<td>4800</td>
<td>5800</td>
<td>1250</td>
<td>14300</td>
<td>4300</td>
<td>6300</td>
</tr>
<tr>
<td>R-gk-l</td>
<td>3000</td>
<td>13500</td>
<td>6900</td>
<td>11500</td>
<td>4300</td>
<td>30000</td>
</tr>
<tr>
<td>H1-k-g-L</td>
<td>3000</td>
<td>12000</td>
<td>6900</td>
<td>13500</td>
<td>4300</td>
<td>13500</td>
</tr>
<tr>
<td>R-gk-l-G</td>
<td>3000</td>
<td>12000</td>
<td>6900</td>
<td>11500</td>
<td>4300</td>
<td>27000</td>
</tr>
<tr>
<td>R-gk-l-G-H</td>
<td>3000</td>
<td>12000</td>
<td>6900</td>
<td>11500</td>
<td>4300</td>
<td>27000</td>
</tr>
<tr>
<td>R-gk-l-G-H-k</td>
<td>3000</td>
<td>12000</td>
<td>6900</td>
<td>11500</td>
<td>4300</td>
<td>27000</td>
</tr>
</tbody>
</table>

Legend:
- **3 ringen**: 7500, 1320, 11000, 8250, 5200, 30000, 13500
- **4 ringen**: 10400, 1450, 12300, 8600, 6300, 30000, 13500
maximal deformations

<table>
<thead>
<tr>
<th>Base variant</th>
<th>Total height</th>
<th>Shape top cable</th>
<th>Height above supports</th>
<th>Varying bar length</th>
<th>Distance between hoops</th>
<th>Varying distance between hoops</th>
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</thead>
<tbody>
<tr>
<td>-R-g-G-H</td>
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<td>0.703</td>
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<td>-R-g-G-H-lager</td>
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<td>-H1-kg-G-H</td>
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<tr>
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<tr>
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<tr>
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<tr>
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<td>-R-gk-G-H-K2</td>
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<td>0.655</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>-R-g-G-H-K</td>
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<td>0.678</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>-R-g-G-KG-H</td>
<td>0.654</td>
<td>0.673</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>-R-g-KG-H</td>
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<td>0.766</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>-R-g-KG-K</td>
<td>0.723</td>
<td>0.766</td>
<td>-</td>
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<td>-</td>
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<tr>
<td>-R-g-KG-KG-H</td>
<td>0.723</td>
<td>0.766</td>
<td>-</td>
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</tr>
</tbody>
</table>
Appendix 9: Distribution of forces in a tensegrity dome

Distribution of forces in load case 1 (pre-stress forces)

Distribution of forces in load case 2 (pre-stress forces and air pressure loads)
Deformations of the tensegrity dome in load case 1

Deformations of the tensegrity dome in load case 2
Appendix 10: Distribution of forces in the sloping tensegrity
Deformations of the structure in load case 1

Deformations of the structure in load case 2
Appendix 11: Distribution of forces in the definite version of the tensegrity

Forces in load case 1 (pre-stress forces only)

Forces in the top cables load case 1 (pre-stress forces only)
Forces in the diagonals in load case 1 (pre-stress forces only)

Forces in the compression bars in load case 1 (pre-stress forces only)
Forces in the tension hoops in load case 1 (pre-stress forces only)

Distribution of forces in load case 2 (pre-stress forces and air pressure loads)
Forces in the top cables in load case 2 (pre-stress forces and air pressure loads)

Forces in the diagonals in load case 2 (pre-stress forces and air pressure loads)
Forces in the compression bars in load case 2 (pre-stress forces and air pressure loads)

Forces in the tension hoops in load case 2 (pre-stress forces and air pressure loads)