Stage on Theatre Square

(Podium Schouwburgplein)
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1 INTRODUCTION

Architecture agency Lilith Ronner van Hooijdonk had approached Tentech in 2013 for this project. Tentech was looking for some way or someone to be able to work on this budget wise small but yet time consuming project. In January 2014 I finished my internship period at Tentech. Directly after this I could start working on this project that would be my graduation project. The project was a small project that would ask a lot of time and technical creativity. For me it was the perfect project, I could be there in almost all the steps of the process from form finding to actually helping to erect the structure on site.

2 ASSIGNMENT

The Theatre Square (fig. 1.0) in Rotterdam (Netherlands) is surrounded by three cultural institutions. These institutions are: The Pahté cinema, De Doelen Concert Hall and the Rotterdam Theatre. The square is designed by Adriaan Geuze in cooperation with West 8 Urban Design & Landscape Architecture BV, and meant to be a 35 cm raised stage with the Rotterdam skyline as backdrop and four big light installations as spotlights. The people on the square are the players in the spectacle.

Schouwburgplein, source: www.rotterdam.nl

Fig. 1.0: Pictures of Theatre Square

It is the task of the Foundation United Schouwburgplein to ensure that cultural activities are taking place during the summer months. This means involving local entrepreneurs in activities, reinforcing their own position as entrepreneurs by ensuring a steady flow of customers. This way the square's function as a cultural hub is being promoted.

During the renovation of the square in 2011 a round piece of street furniture/artwork (fig 1.1) by Wes 8 Urban Design & Landscape Architecture BV was added and because of its appearance earned the nickname "De Bult" (the bump).

Fig. 1.1: street furniture/artwork by Wes 8

In the past there have been events that have proven that putting a physical stage on Theatre Square, will give an extra flare to the events taking place. The Bump was an attempt to do this. The curved surface is original but not a very good surface for the performances that were supposed to take place on this structure. The Bump is a favourite spot for shoppers to have a beak. The stage discussed in this thesis is a second attempt to create a stage where performances can take place. The stage will be raised above the square deck to give the audience a better view. On top of this construction is going to be a membrane that will protect performers from rain and wind. And perhaps equally important the placement of the removable membrane construction will function as an announcement.

Architecture agency Lilith Ronner van Hooijdonk has been asked to give form to this idea (fig. 1.3) by the Foundation United Schouwburgplein. This architecture agency has experience in designing temporary constructions for public use.

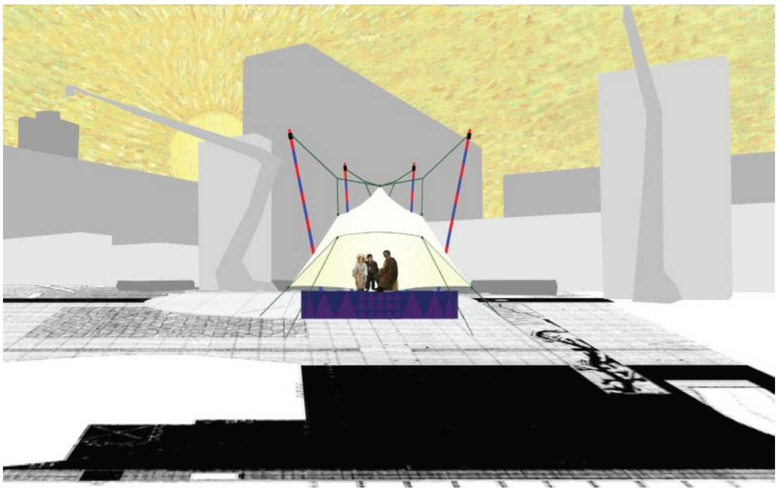


Fig. 1.3: Visualization by Architecture agency Lilith Ronner van Hooijdonk 1

The proposed design is based on the cheerful light-footed colourful world of the circus. Colour, motion and light are an invitation to imagination. A colourful layer of paint covering the construction in different shades of yellow represent colour. Pennants in the tops of the masts will move when the wind is playing with them. A lamp will be hanging in the centre of the masts will illuminate the stage at night, creating a feeling of intimacy (fig. 1.4).

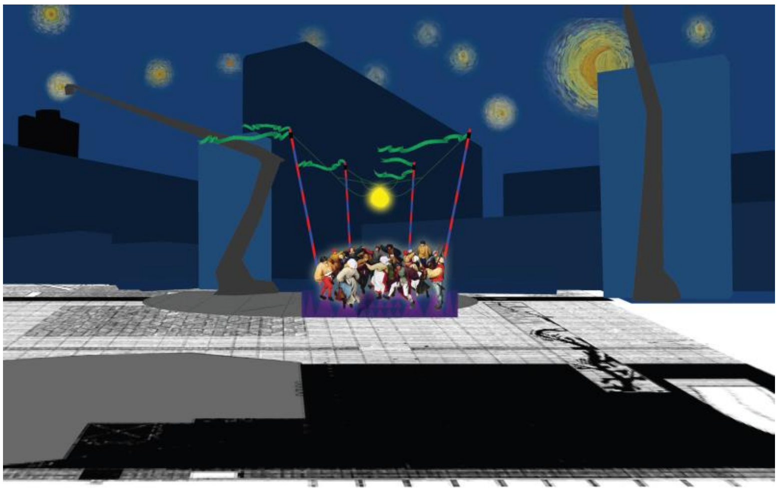


Fig. 1.4: Visualization by Architecture agency Lilith Ronner van Hooijdonk 2

The membrane and stage construction will be placed during the summer months from April to September. The stage construction will be build just once and will stay in place until the end of September. The membrane will be placed every weekend and when necessary on other occasions when there is an event. The stage will function as an announcement that there is a program of cultural activities. And the placement of the membrane will announce a performance is going to happen (or has happened) that day.

The stage is build out of wood and steel and will be robust enough to withstand the abuse of the young and bored up to some degree. When the stage is not in use for a programmed activity it functions as public furniture where people can sit and enjoy the surrounding activity on the square. The stage will contribute to a pleasant atmosphere and a bit of summer joy in the minds of is users. At the time of a planed activity on the stage it will really come to life. Slightly lifted above its surroundings it will enable performers to tell their story enriching the experience of visiting the Theatre Square of Rotterdam.

This is the idea Lilith Ronner van Hooijdonk came up with (fig. 1.5). My part in the process was to design a construction that resembles the idea of the architect as closely as possible.

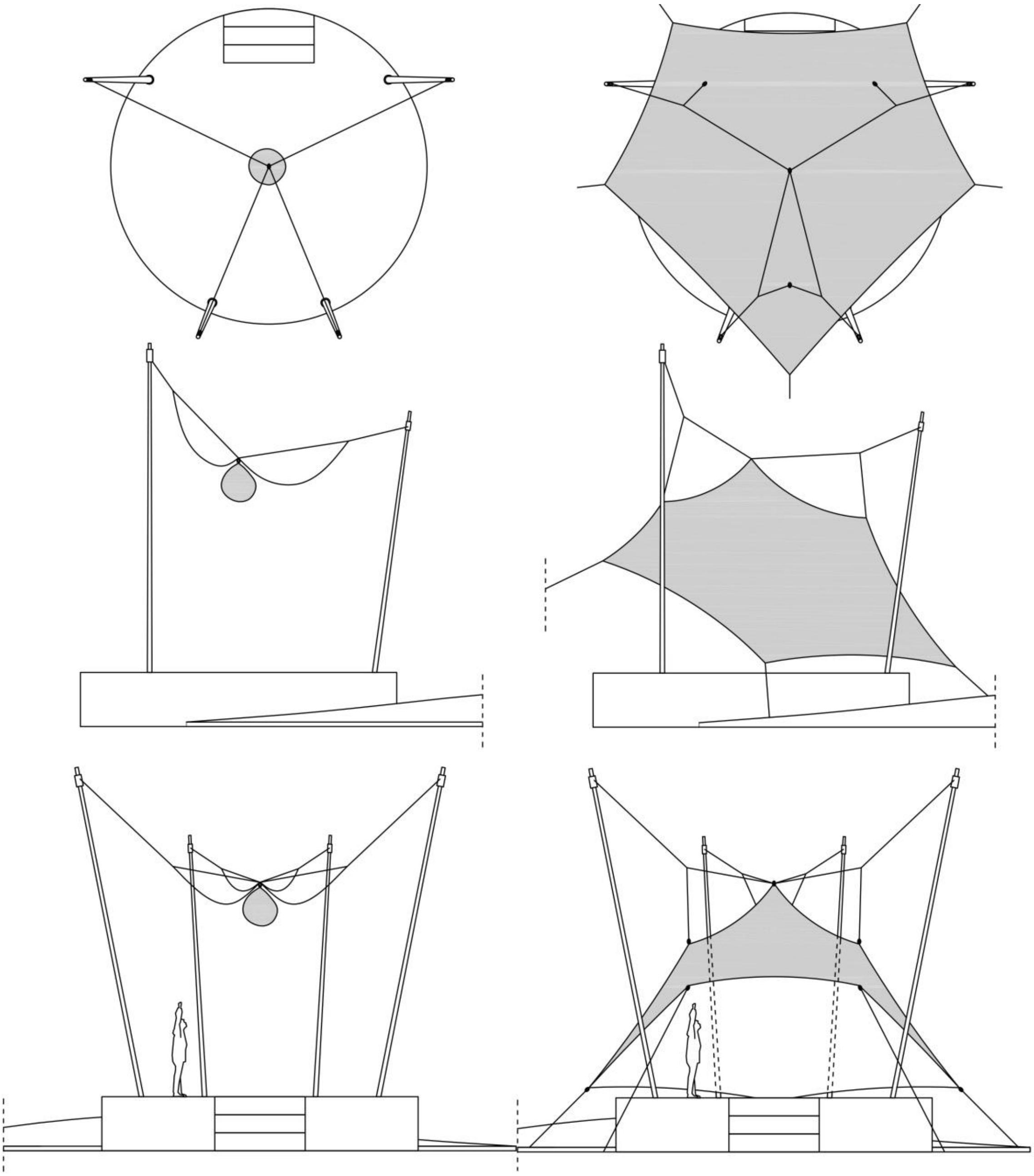


Fig. 1.5: Idea Lilith Ronner van Hooijdonk

3 TIME SCHEDULE AND COST CALCULATION

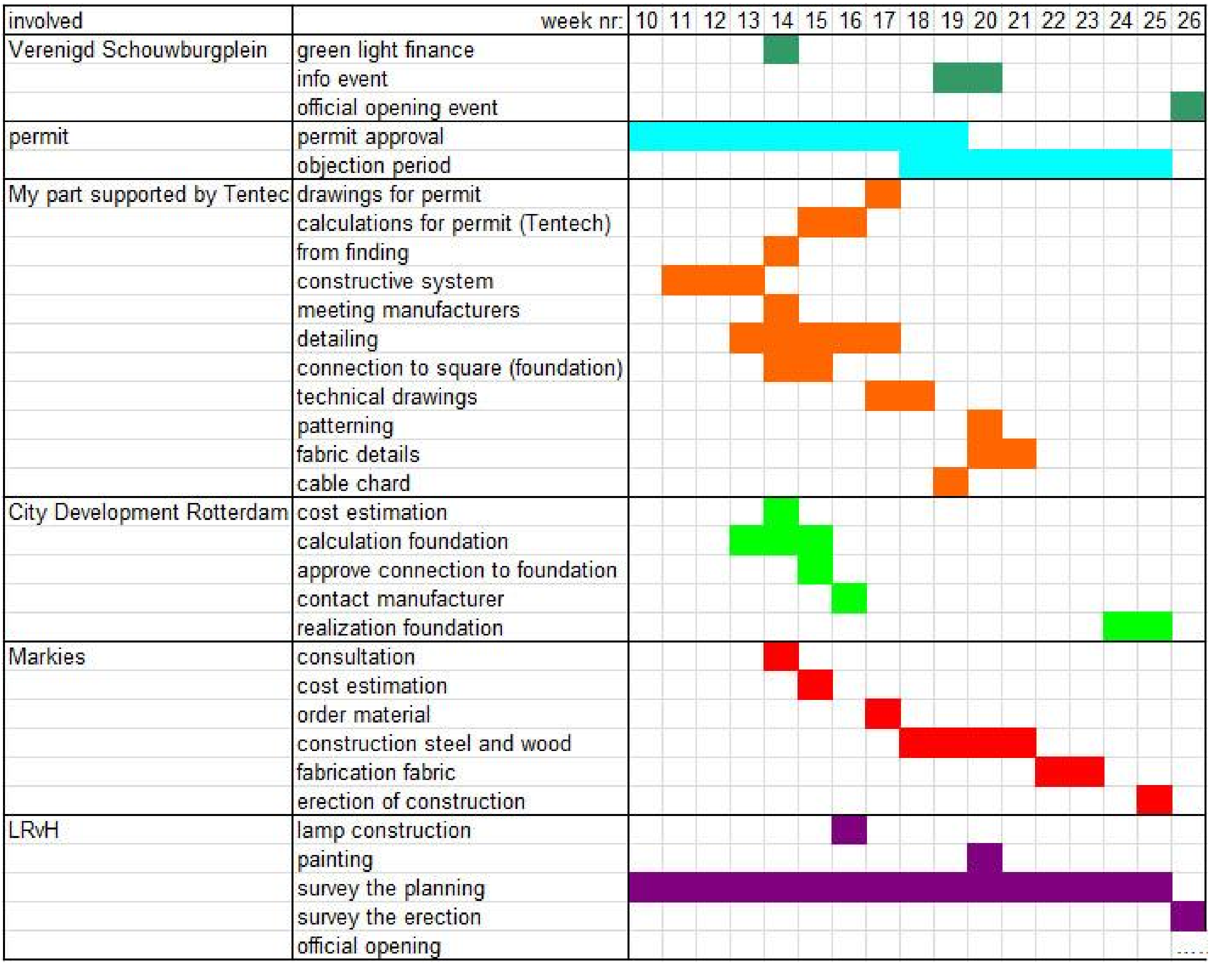
Because this is a relatively small project making a cost estimation using the amount of square meters membrane surface is not going to work. The cost calculation (tab. 1.0) for this project is kept as simple as possible.

cost sheet Theatre Square stage and tent construction:	excl. btw	**incl btw**
project mannagement		
architect LRvH	€ 4.520,00	€ 5.469,20
engeneering + calculations + and pattering		
Tentech bv	€ 5.000,00	€ 6.050,00
labour cost membrane:		
De Markies		
labor masts and stage construction:		
De Markies	€ 21.140,00	€ 25.579,40
material cost membrane		
material masts and stage construction		
transport		
painting	€ 1.400,00	€ 1.694,00
foundation (connection to square grid)	€ 12.000,00	€ 14.520,00
lamp (1 piece)	€ 2.000,00	€ 2.420,00
Totaal	**€ 46.060,00**	**€ 55.732,60**

Tab. 1.0: Cost estimation

Things that not represented in the cost sheet are the architectural design and sponsoring by Tentech in the form of guidance. The architectural design was done first and the technical design and realisation where seen as a new project.

The time schedule (tab. 1.2) is like the cost calculation kept very simple. In practice it took about thee months to realize the construction. The bureaucratic system worked took a little bit slower than we had anticipated. After several meetings between people from the architecture agency, Foundation United Schouwburgplein, Tentech and City Development Rotterdam the decision was made to continue the project without permit. If everything would go according to plan the permit would be given after the structure was fabricated but before erection on the square. There was a risk that if someone living in the surrounding area would make an appeal, the permit would not be given. If there is no permit there would not be any budget and there would be a problem. But there were no appeals and the plan worked.



Tab. 1.2: time schedule

4 BASIC STRUCTURE

This is where my part of the work begins. First the basic shape and mechanical system have to be determined. This is influenced by the possibility's on the location, the wishes of the architect and the materials available.
While reading this report note that the order the subjects is not necessarily chronological. In the process of designing this stage there where several developments going on at once that where all interacting with each other.

4.1 location

Before World War II this location was a densely populated area, already in a poor state of maintenance before being completely destroyed by a big fire caused by a bombardment in 1940.
In 1966 one of the first underground parking lots in the Netherlands was built underneath the square (fig. 4.0). The parking lot is not build on stacks to prevent it from moving witch is common practice in the Netherlands. It is a big concrete box that if floating on the soil beneath it. For this reason the force that could be absorbed in one particular spot was limited. At first we did not fully recognise the problems this would case.

Fig. 4.0: underneath the square

On top of the existing concrete is grid constructed of HEA 200 columns and horizontal IPE 200 beams bolted together with M16 bolts (fig. 4.1).

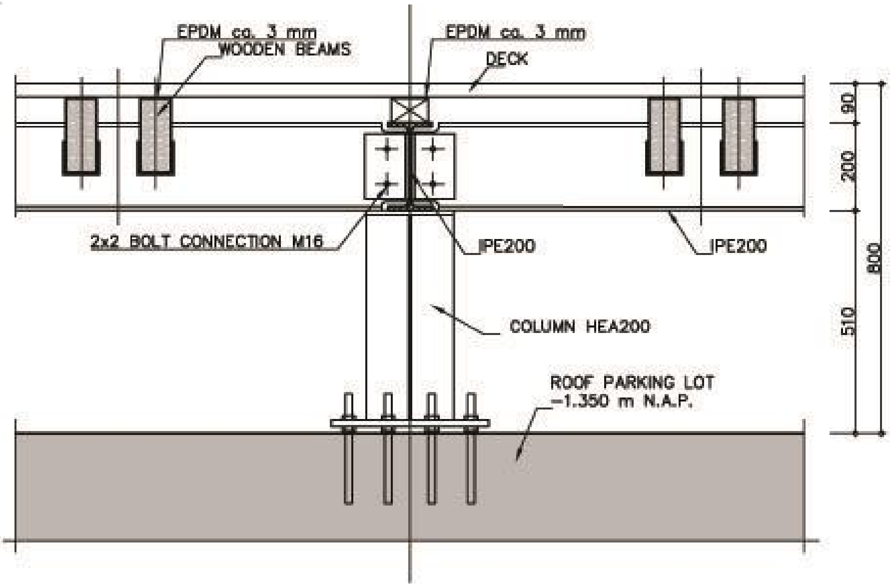


Fig. 4.1: Detail deck construction Theatre Square

The idea of the architect was to place the stage so it is partially on top of The Bump construction (fig. 4.2).

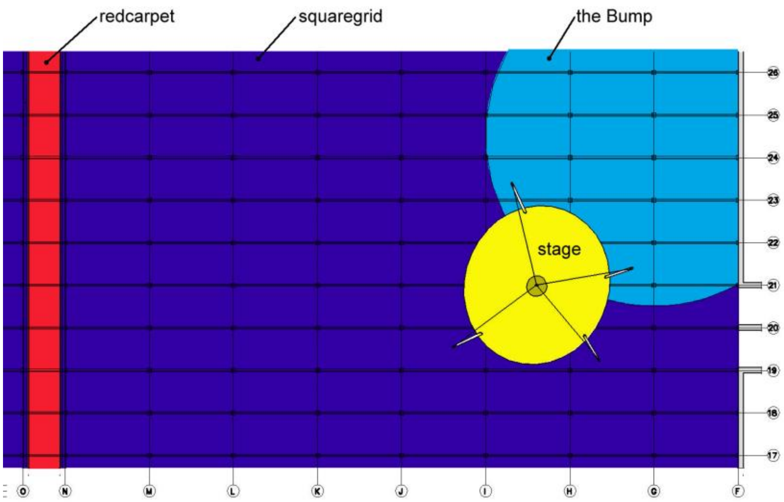


Fig. 4.2: Position of stage 01

Because the steel construction underneath The Bump was modified it would make the calculations more complex. These calculations had to be done by the engineers from Citty Development Rotterdam. Another issue here was that we did not know what the legal terms where for making adjustments to The Bump. After some research by the architect the decision was made the stage could be moved off The Bump construction (fig. 4.3).

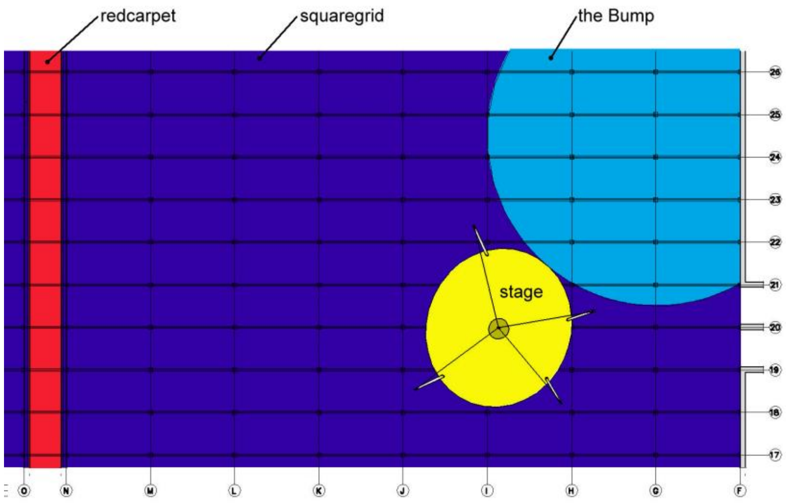


Fig. 4.3: Position of stage 02

Later in the process it became clear the force that grid could take was variable in different locations at the square. It was not possible to place the stage at the location right next to The Bump, unless the force was being divided over a bigger area. There was no budget and no time left to work on a solution to. So the stage was moved to the other side of the square (fig. 4.4). This had the advantage that the people passing the square could now clearly see the activity if one was taking place. The disadvantage of this location was that the way the stage had to be orientated the sun would be right behind it in the early afternoon. This would be the time that most performances would take place. The sun could be in the face of the audience during a performance. It was a risk the client was willing to take, so no precautions where taken.

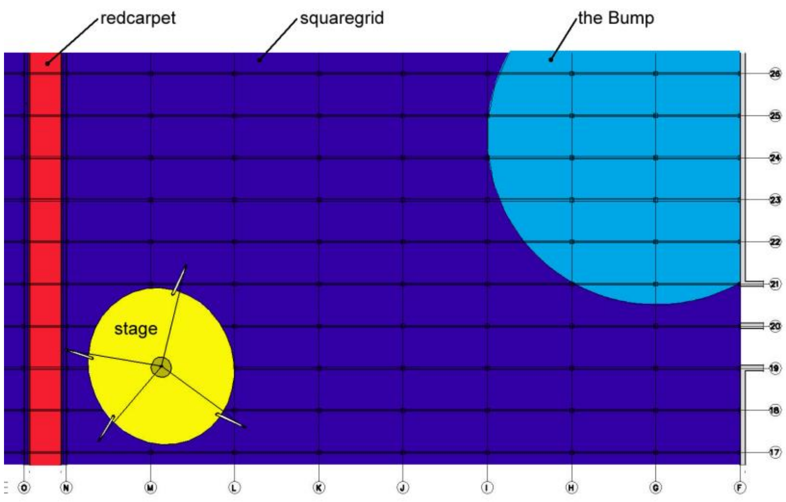


Fig. 4.4: Position of stage 03

In fig. 4.5 below an example of the square with the finished stage and a considerable live load on top of it.

Fig. 4.5: Live load on the stage

There are people crossing the square all the time in all directions. So guy cables from the construction to the square should be limited to a minimum. Especially when the membrane is not installed and the people passing by are likely not to pay attention to the construction and could possibly be injure themselves on guy cables.

4.2 elements

The structure has two states in which is has to be stable. When the membrane is hanging and when the membrane is not in position (fig. 4.6).

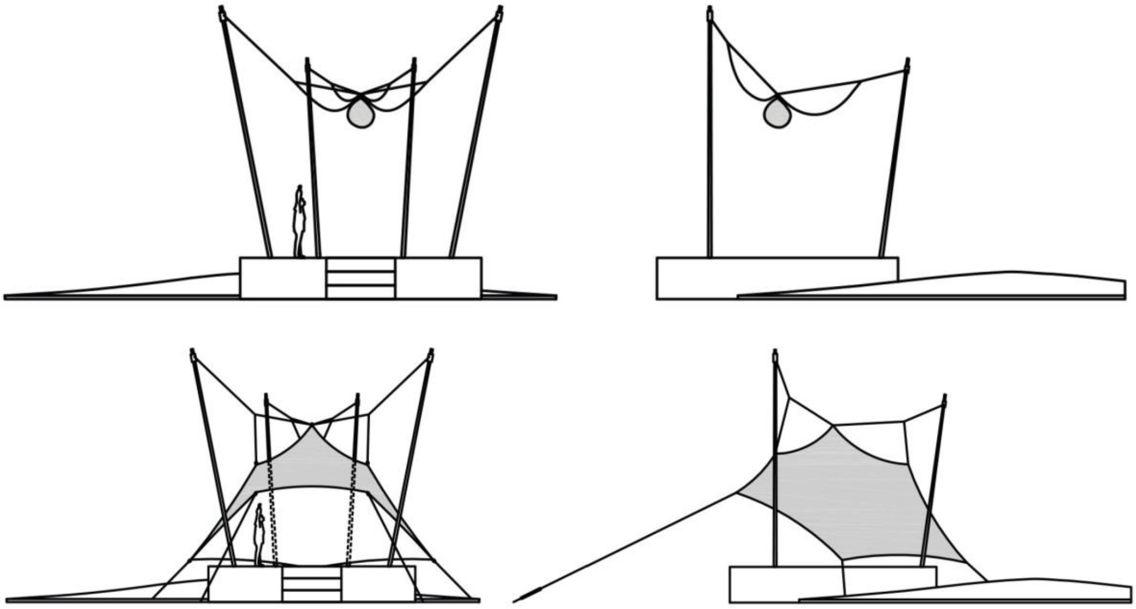


Fig. 4.6: Stage with and without membrane.

In the situation with the membrane installed the membrane is pulling because of the pretension. The masts have to take the downward force that is not only casing compression but also a bending moment. The front mast are about 7,5 m high and the back masts about 6,5m. The force of the membrane has to be taken by the masts. If no measures will be taken the masts will end up having a diameter and/or weight that would not be considered appropriate for this construction. A way to divert some of the force is through guy cables (fig. 4.7). There should be two guy cables per mast to stabilize it if the rest of the cables would stay the way they are right now.

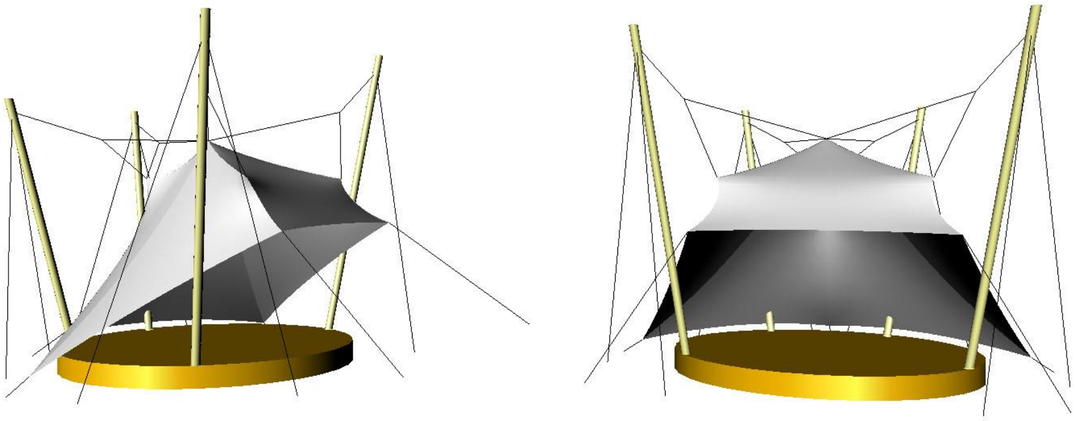


Fig. 4.7: Stage with guy cables

In the situation where the membrane is not installed, the pretension force of the membrane is no longer pulling on the masts. The cables that would been tensioned by the pretension in the membrane are now only tensioned by a lamp (fig. 4.6) hanging in the middle of the construction. This will likely not be enough to stop the mast from swaying outwards and damaging the construction. A solution for this problem could be to add a cable cross in between the masts (fig. 4.8).

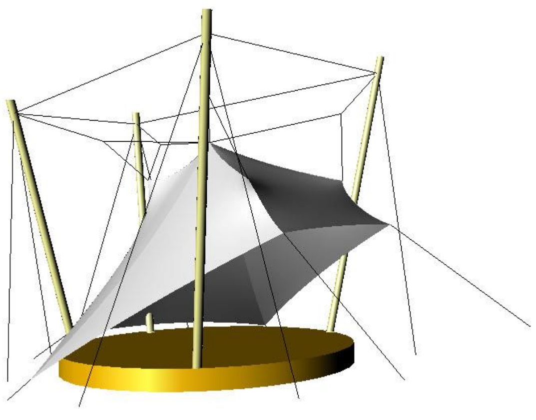


Fig. 4.8: Stage with cable between the masts

Another improvement would be to use separate cables to go from the mast to the fabric instead of splitting the cables in the middle (fig. 4.9). This would make the construction more stable once the membrane is installed it will also simplify and there by save cost on the details of the cables.

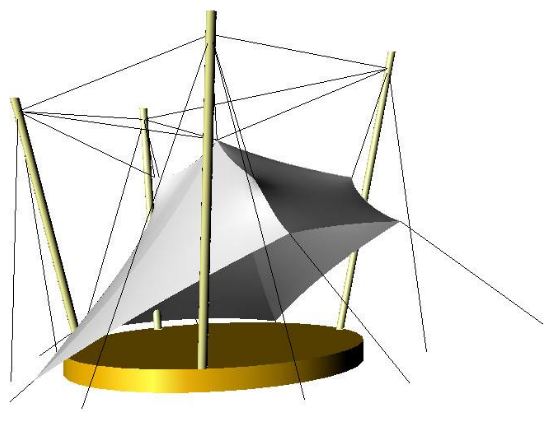


Fig. 4.8: Stage with individual suspender cables

In this construction only one guy cable per mast is needed once the membrane is installed. To stabilize the masts when the membrane is not installed there could be four cables between them. There was some arguing about this idea with the people from Tentech and the architect. After discussing this idea with the people from the Foundation United Theater Square the conclusion was drawn: any guy cables would pose too much risk. At an event where people are getting drunk they could to easily injure themselves on the cables. A second point was that we should keep modifications to the square to a minimum. Every modification to the square had to be calculated by an engineer of City Development Rotterdam. It also had to be approved for safety other than damage to the roof structure of the underground parking lot, and the visual impact it would have.

Permanent guy cables where no option here. Without these cables the bending moment in the masts would be unacceptably big, so another solution had to be found. We came up with a construction in between the masts that would fix the masts at the point where the cables leading to the membrane would be attached (fig. 4.9).

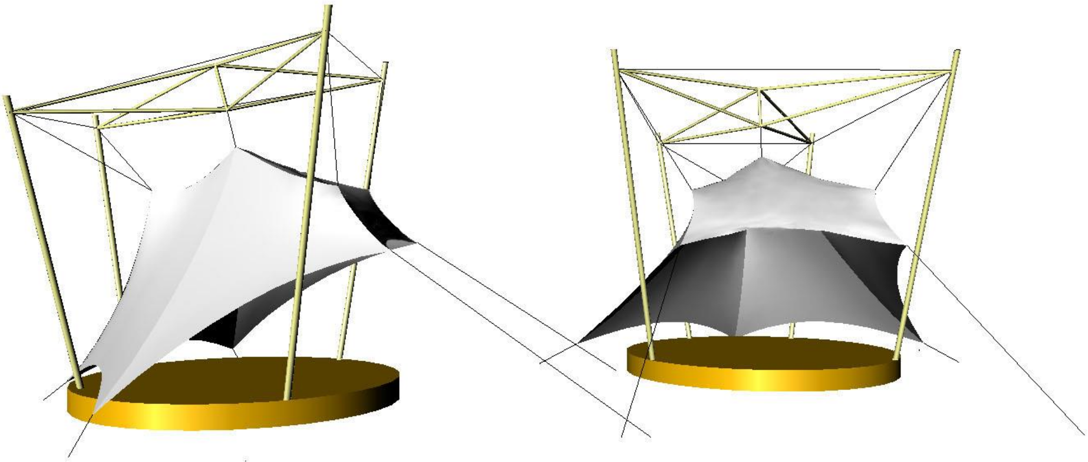


Fig. 4.9: Stage with fixed masts

This change would be a significant change to the appearance of the construction. Several attempts were made to make the mast more resistant to bending (fig. 4.10). Adding reinforcement ribs, the use of a conical tubes and the adding of struts. The use of conical tubes appeared to be plausible and visually acceptable. Tubes used to make lantern posts could possibly be used. The choice in wall thickness and diameter of these tubes is limited and new calculations would have to be made. It was very likely that if conical tubes could be used as mast would have to be custom made for this project. This would according to a quick internet research be very likely to go beyond the available budget. So the search for alternative solutions was stopped.

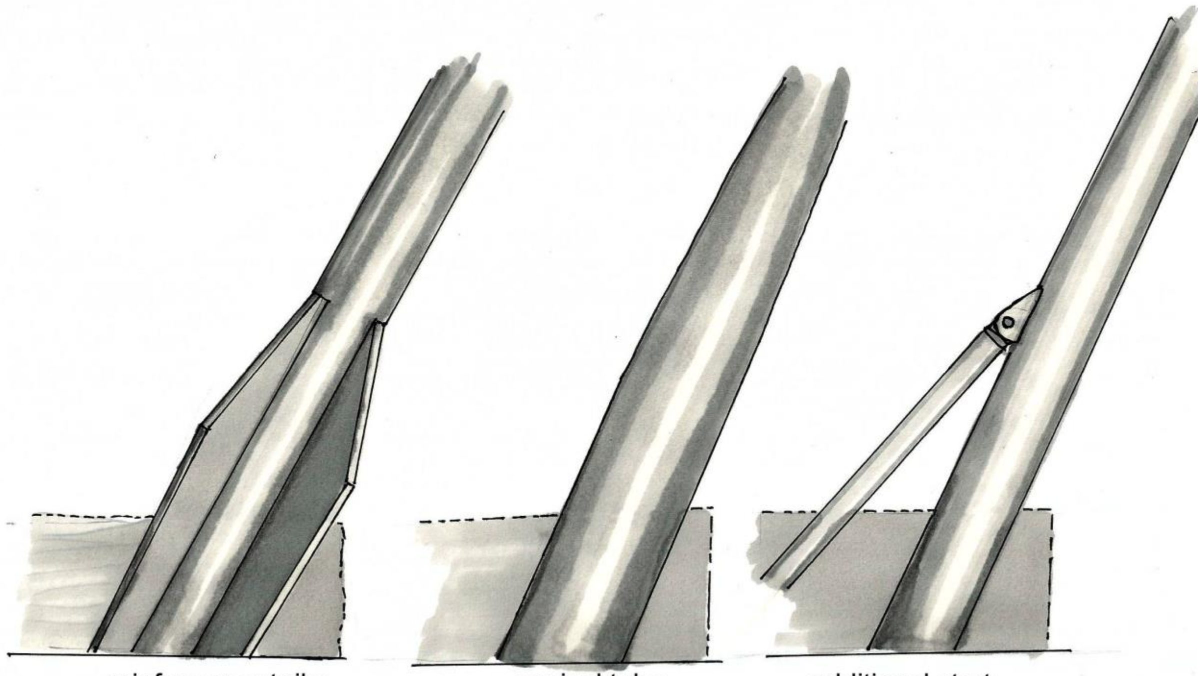


Fig. 4.10: Mast reinforcement options

The steel construction in between the masts is a serious change to the appearance of the structure but it has to be there to prevent the bending moment from becoming too high. Perhaps it could be made lighter by choosing the minimal diameter for the tubes. Another option was to replace some tubes by cables (fig. 4.11).

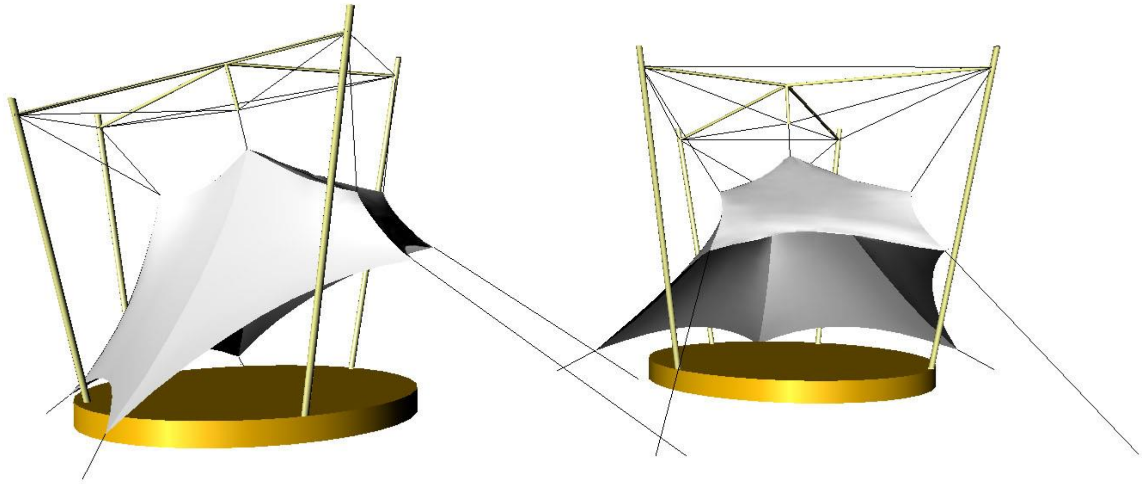


Fig. 4.11: Cables in the top construction

The cables are possible once the construction is completely installed but could pose a problem during the installation process. Therefore, the construction between the masts was made completely out of tubes. One final adjustment to optimise the construction was to lower the masts and the construction between the masts (fig 4.12). The membrane could now be attached directly to the construction.

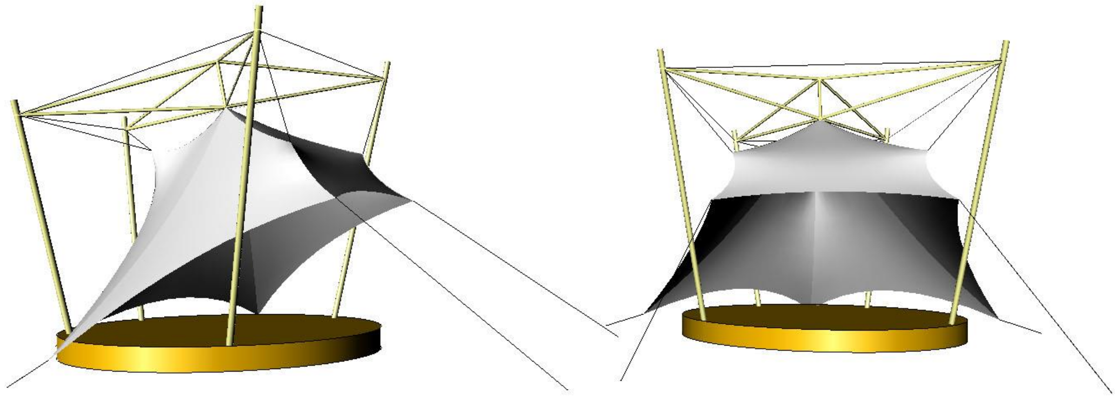


Fig. 4.12: Lowered top construction

4.3 membrane

The shape of the membrane is a ridge cable construction (fig 4.13). This means that the membrane is pulled up by cables to achieve the desired shape.

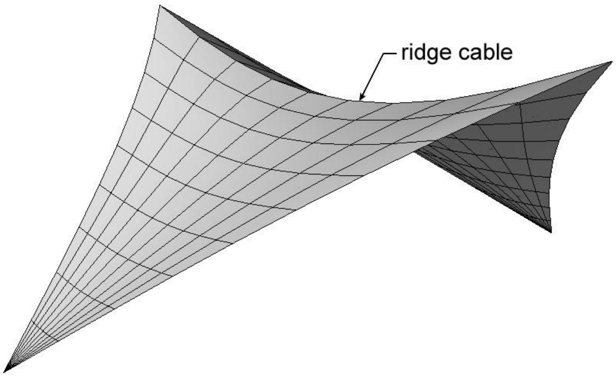


Fig. 4.13: Ridge cable

The positions of the masts where a given, the anchor points are at the intersection points of the grid steel grid underneath the square. To make the anchoring points symmetrical to the construction the construction was rotated 45 degrees on the grid. The cross sections closest to where the architect had designed her anchoring points were taken as fixed points. Putting the fixed coordinates where put in ixForten and form finding was done. In the centre top of the model the forces in the membrane accumulate but nothing extreme is happening here (fig. 4.14). The basic shape worked quite well the way the architect had designed it.

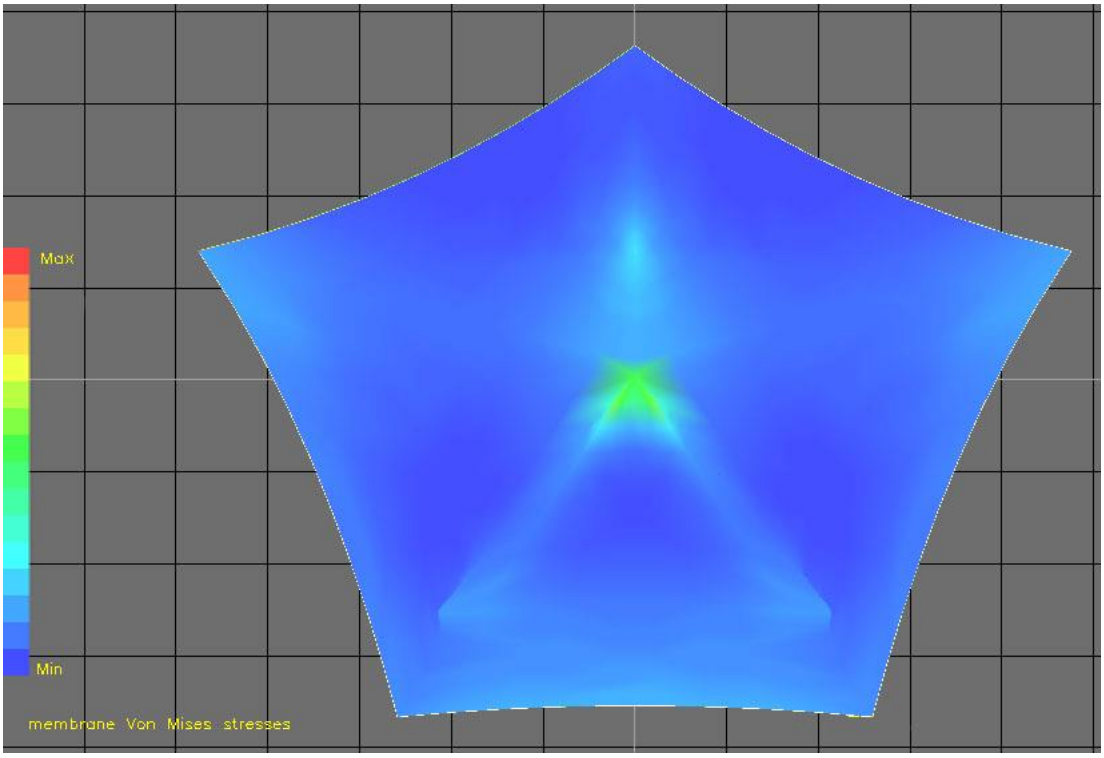


Fig. 4.14: Force in membrane

There were a few points that needed some attention. The “tail” was too close to the back of the stage (fig. 4.15) and the masts where intersecting with sides of the membrane (fig 4.16). The problem of the tail that was too close to the stage was solved by moving the back point of the membrane back and razing the C-value of the rear ridge cable. In the final construction the ridge cable was replaced by a TIR belt. Because there was more stretch in the TIR belt than there would have been in a cable the tail was touching the stage.

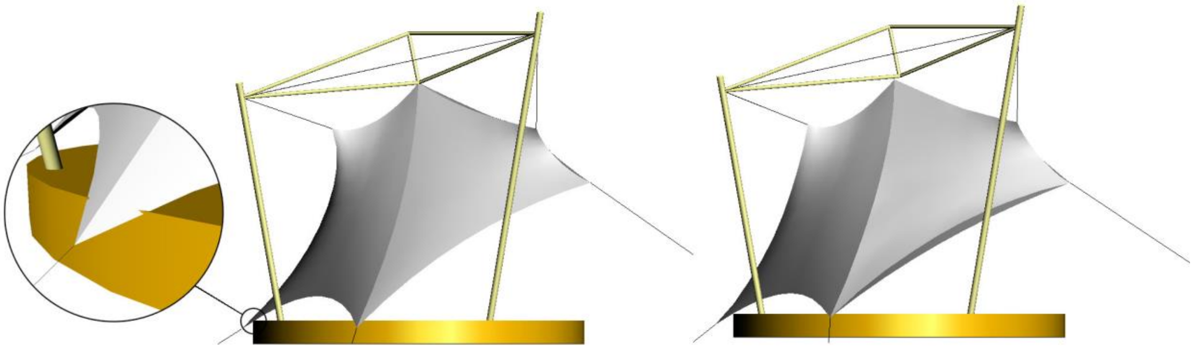


Fig. 4.15: Tail intersecting with the stage

To avoid the membrane hitting the masts the membrane was raised at the points where the mast passed it. This posed the problem that a space has formed between the membrane and the stage. The architect’s idea was the membrane would reach down far enough to protect the entire stage from the elements. There were going to be performances on the stage and the back of the stage was supposed to be a storage place to put equipment and personal belongings of the performers.

The membrane was supposed to prevent rain from getting to the stage and form a barrier to prevent easy access to the stored goods by thieves. After some attempts to change the form it became clear it would not be possible to close the gaps and stay clear of the mast.
Several ideas were proposed to try and solve the problem. The first idea was make holes in the membrane to let the masts go through it. This would have become too complex because the membrane had to be installed and removed on a weekly bases while the masts where kept in place. So there had to be a cut from the hole to the side of the membrane. This cut would go through the edge cable that had to be connected after the membrane was placed.
Another solution would be a flap of fabric underneath the membrane to connect the membrane with the stage. There would be various ways to make this possible by using a kedar, straps, zipper, cord or a velcro connection. The architect thought a connection would ruin the architectural statement the stage was supposed to make, so the idea was discarded. Another option was to raise the edge of the stage so it would form a barrier. At times the membrane is not installed these barriers could serve as benches. The idea was finally chosen was to make a hatch (fig. 4.16) in the stage so that would give access to the technical space below that could serve as a storage place.

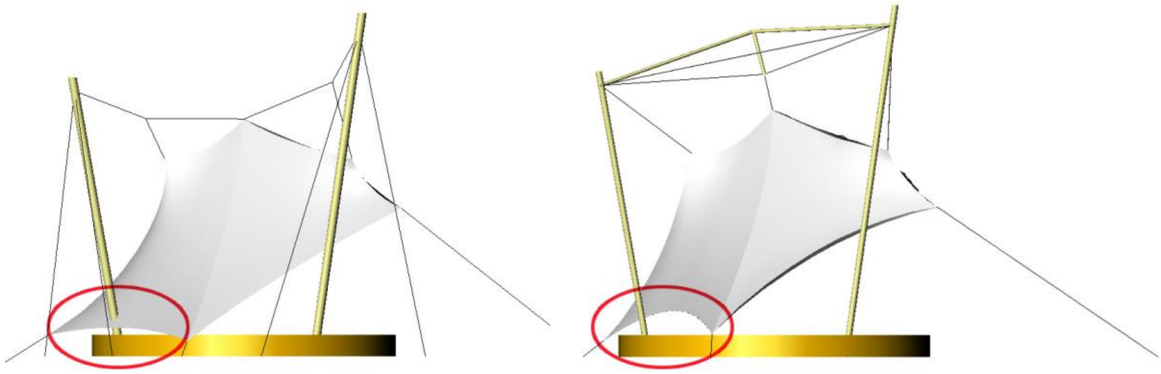


Fig. 4.16: Mast intersecting with the stage

Notice the construction is not the same in both pictures (fig. 4.16) because the process of developing the membrane was simultaneous with the development of the steel construction.

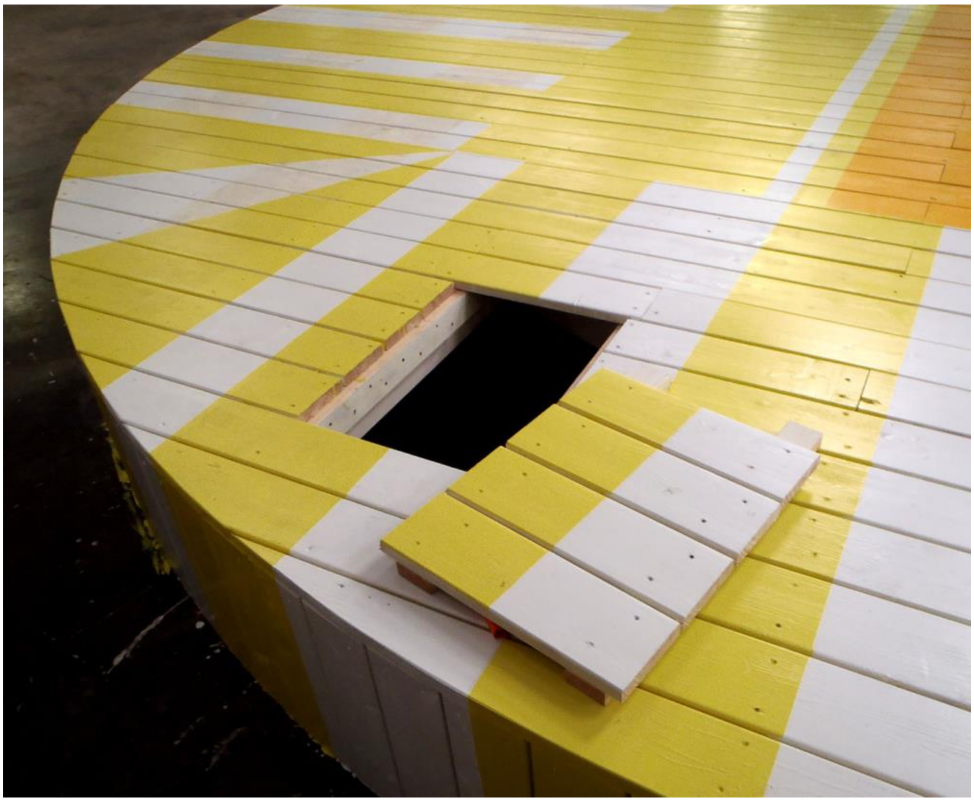


Fig. 4.16: Hatch

The construction has to be taken down and put up every week. To be stored it is folded so, the use of cables would not be practical and would also make details of the membrane to expensive. Therefore the ridge cables are replaced by TIR belts and the edge cables are replaced by ropes.

For the membrane material Ferrari Precontraint 602 opaque was chosen (fig. 4.18). Ferrari Precontraint 702 or 502 could also have been used if it would have been available in opaque. Precontraint means the top coats are applied to the fabric while the yarn is under tension (fig. 4.17). As a result of this pre-tensioning the fabric does not only stretch less under force, the stretch behaviour in warp and in weft is more similar than in a regular fabric. This makes compensating the stretch easer.

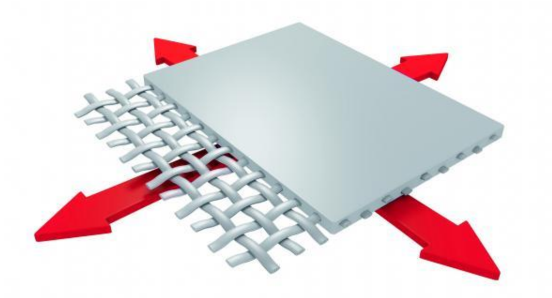


Fig. 4.17: Precontraint

Opaque was chosen because the fabric had to be folded and unfolded every time the membrane is installed. If translucent was chosen dirt and damaged spots would be more visible.

RESISTANCE UV

Les toiles Précontraint® Color Design gardent leur couleur dans le temps, fort de plus de 20 ans d'expérience dans les formulations d'enduction et la sélection de pigments résistants aux agressions des UV.

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GARANTIE 5 ANS
RESISTANCE UV
SECURITE INCENDIE

PRECONTRAINT®
602
OPAQUE

LAIZE : 250/267 cm | POIDS : 750 g/m²
PIÈCES* : ± 50 ml

GARANTIES ET LABELS

AVANTAGES

Technique Précontraint® Ferrari® :
- Stabilité dimensionnelle exceptionnelle
- Excellente soudabilité
- Durabilité supérieure

COLORIS & RÉFÉRENCES (COLORIS INDICATIFS)

602-8503 Blanc opaque

602-8504 Vanille opaque

CARACTÉRISTIQUES TECHNIQUES

	Précontraint® 602 opaque	Normes
Fil	1100 dtex PES HT	TERSUISSE
Poids	750 g/m²	EN ISO 2286-2
Largeur	250/267 cm	
Resistance rupture (chaîne/trame)	250/250 daN/5 cm	EN ISO 1421
Resistance déchirure (chaîne/trame)	20/20 daN	DIN 53.363
Adhérence	9/9 daN/5 cm	EN ISO 2411
Finition	Vernis Biface	
Réaction au feu	M2/NFP 92-507 • B1/DIN 4102-1 • M2/UNE 23.727	
Températures extrêmes d'utilisation	-30°C/+70°C	
Système de management de la qualité		ISO 9001

Les caractéristiques techniques mentionnées sont des valeurs moyennes données à titre indicatif et susceptibles de modifications.
*Nos conditionnements sont donnés à titre indicatif et sont susceptibles d'évoluer en fonction de nos contraintes de fabrication.

Fig. 4.18: Ferrari Precontraint 602

5 FORMFINDING AND LOAD CONDITIONS

Membrane software
To find the “right” form in of the membrane a computer model is made. By right is meant a form that is not only pleasing to the eye, giving the impression of the construction being in balance. The form is shaped in such a way that the internal forces are divided as evenly over the construction as possible within the given boundaries of the form.
A stamp of approval from a certified engineering company was needed, so an engineer from Tentech has done the calculations. The model I had created in Autocad was taken and the program Easy (similar to ixForten) was used to do this calculation. Afterward I have put the Cad model in ixForten and recreated the same simulation with the in order to learn something about it.

Force Density Method
The software in both ixForten and Easy uses the force density method to find the optimal form of the membrane, or at least approach the optimal form. A membrane is divided in squares by a grid (fig. 5.0). The grid lines are usually in the same direction as the warp and the weft of the material. There is a force in each segment of this structure that could be visualised as a cable net like structure.

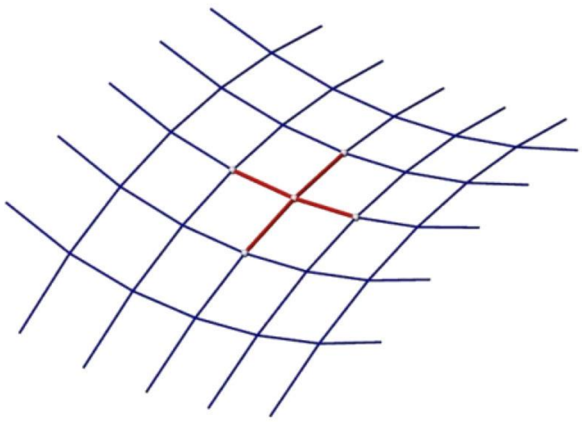


Fig. 5.0: Grid

The software uses iteration steps (fig. 5.1) to move towards a stabile situation. Each step of the process the points on the intersections of the grid are moved to a stable position. This results in the length ratio of the cables changing and, and if the cables are stretched the force increases. The same process can be repeated for the new situation. Changes will be smaller as the number of iteration steps increases. In theory it is possible to take an infinite number of iteration steps.

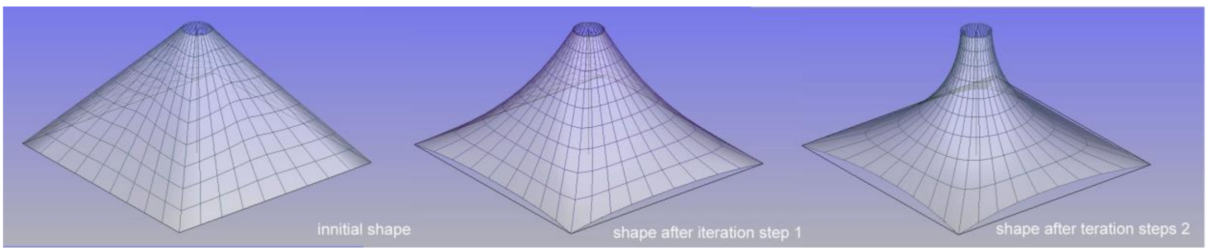
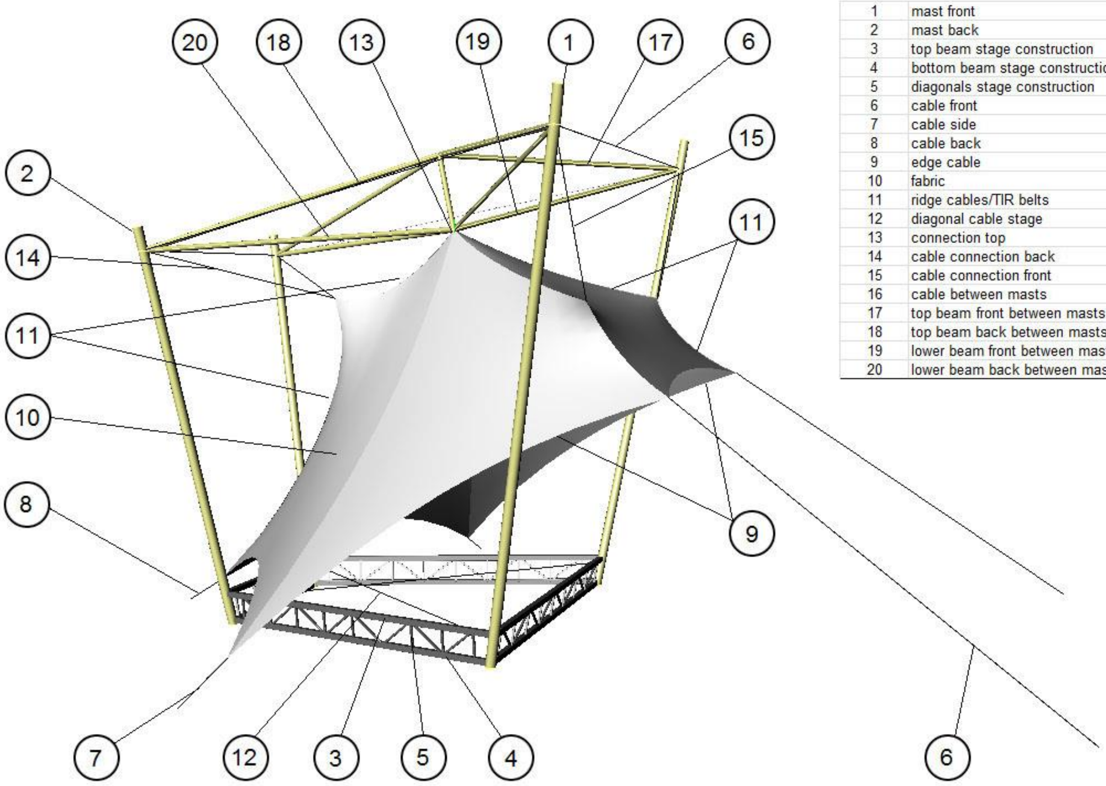


Fig. 5.1: iteration steps

5.1 load cases

To estimate the forces that could occur in the various parts of the construction a computer model is made. Several load cases are applied to the model and the highest force occurring in an element of the model in any load case will determine in minimal dimensions. In fig 5.2 you can see an overview of the elements, there location and the parts that are imported in the software.



1	mast front
2	mast back
3	top beam stage construction
4	bottom beam stage construction
5	diagonals stage construction
6	cable front
7	cable side
8	cable back
9	edge cable
10	fabric
11	ridge cables/TIR belts
12	diagonal cable stage
13	connection top
14	cable connection back
15	cable connection front
16	cable between masts
17	top beam front between masts
18	top beam back between masts
19	lower beam front between masts
20	lower beam back between masts

Fig. 5.2: Elements

5.2 self-weight and pre-stress

Self-weight and Pre-stress are always present in the construction even no external loads are applied.

The material fabric used for this construction is Ferrari precontraint 602. (type 2) The weight of this material according the information supplied by Ferrari is 75 kg/m^2. The membrane has a surface of about 88m^2 x 0.75 kg/m^2 + 10% for details is about 73 kg.

Weight of the steel excluding the (wooden) stage is about 1647 kg. The wooden stage is built on top of the construction is excluded. This is not a structural part of the construction, but it is important for the calculation of the load that is transferred to the deck of the square. The estimated load of the wood that was used in calculation was about 1500 kg.

The total weight of the construction (including wood) is about 3220 kg.

According to the European Design Guide for Tensile Surface Structures the pretention for a type 1 material should be 0.7 kN/m. Because this is a temporary construction it is tensioned by using hand operated belt ratchets, the pretention force is used for calculation is 0.5 kN/m.

5.3 wind loads

The first thing done while determining the wind load is to find the wind area according to the NEN-EN 1991-1-4 / NB is II (fig. 5.3).

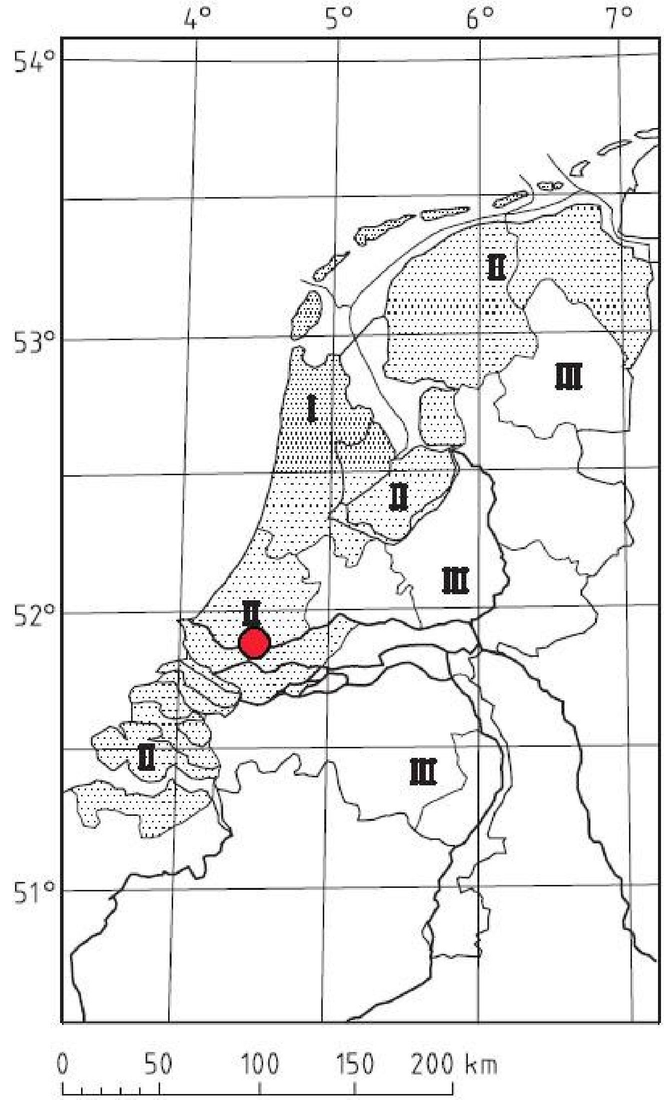


Fig. 5.3: Wind area's in the Netherlands

The construction is in the centre of Rotterdam surrounded by buildings (fig. 5.4).

location:	Rotterdam (centre)
wind area:	II
terrain factor:	urban
reference period:	10 year
height construction:	h = ± 7.5 m
reference height:	reference height compensation due to influence of surrounding buildings, according to NEN-EN 1991-1-4: 2005, annex A.4
average wind speed:	27 m/s

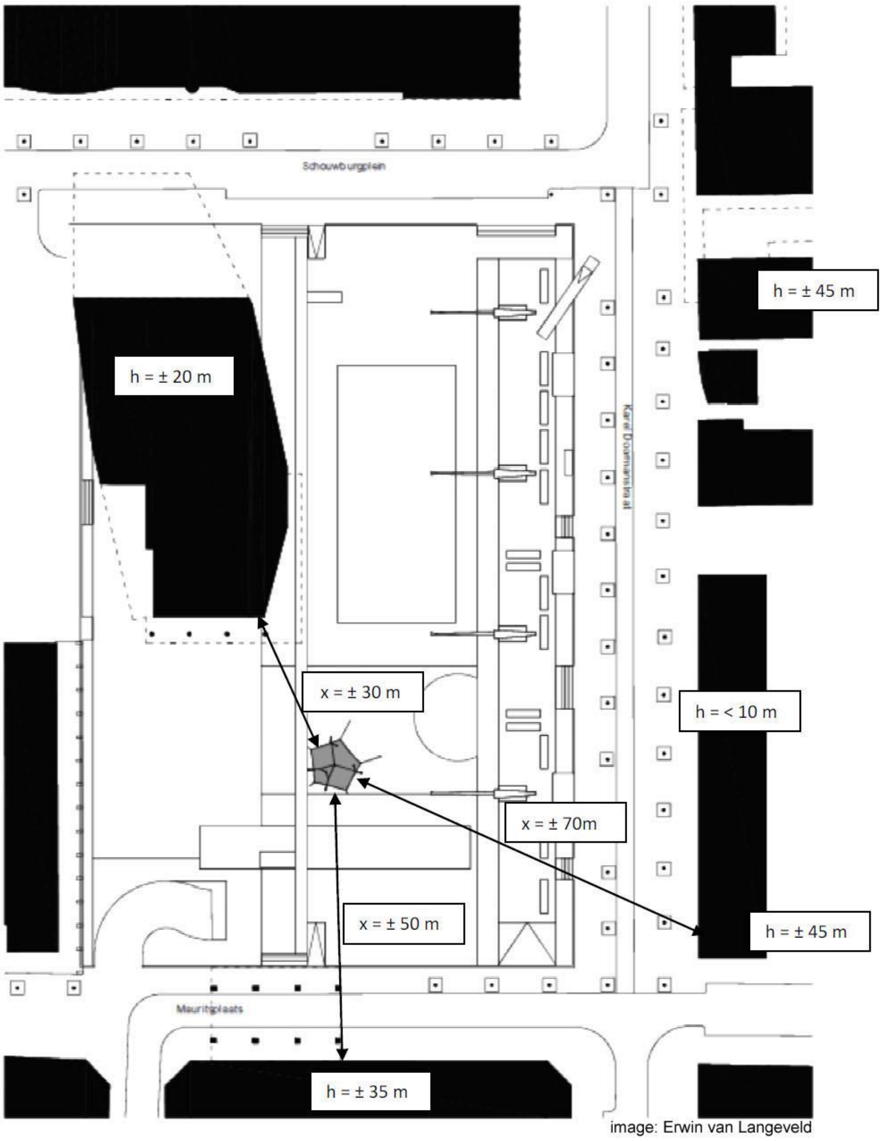


Fig. 5.4: Situation plan

The values below are derived from the plan of the square that was used for the calculation will be described in the following pages. A case could be created for every wind direction, so there would be a different value due to the variation in building height and distance to the structure around. To make the calculation less complex average values are used. If you really want to do it as accurate if possible a model should be made and wind tunnel test done. For a project of this scale this would be total overkill so the values below were used.

r = ±45m (surrounding building height)
x = ±70 m (radius from structure to surrounding buildings)

The next step is to calculate the wind pressure. This is done according to the NEN-EN 1991-1-4:2005 + NB:2007:

The basic wind speed (V_b) is the average wind speed will be there during a period of 10 min at a height of 10 m above ground level. The wind speed is measured independent of the wind direction.

The basic wind speed ($V_{b,0}$) is the average wind speed multiplied by the probability factor (C_{prob}). This factor can be calculated with the following formula.

$$c_{prob} = \left(\frac{1 - K \cdot \ln(-\ln(1-p))}{1 - K \cdot \ln(-\ln(0{,}98))} \right)^n$$

K = The shape parameter is dependent on the coefficient of variation of the extreme-value distribution. The value usually used for this is 0.2
n = The exponent. The value usually used for this is 0.5

$C_{prob} = 0.897$

$V_{b,0} = V_b \,.\, C_{prob} = 24.2$ m/s (basic wind speed)

ρ = The density of air on the height of Z_n (obstacle height) This can be found in a table given in the NEN-EN 1991-1-4: 2005 norm.

The terrain category can be taken from the following tab. 5.0.

terrain type	z0 (m)	zmin (m)
0 sea or coast with wind entering from the open sea	0.003	1
I lake of flat terrain with neglectabele or no obstacles	0.1	1
II open terrain with grass and/or obstacles with at least 20x the obstacle height between them.	0.3	2
III rural terrain with trees and/or obstacles with at least 20x the obstacle height between them.	0.5	5
VI area with at least 15% covert with buildings over 15m.	1.0	10

Tab. 5.0: Terrain type

The engineer from Tentech has taken a z0 of 0.5 m and a Z_{min} of 7m.

The roughness factor $C_{r\,(z)}$ has effect on the average wind speed at the location. The effect depends on the height above ground level, the roughness of the terrain on the windward side of the structure in the considered direction. The roughness factor $C_{r\,(z)}$ may be given in the National Annex of the NEN-EN 1991-1-4:2005 + NB:2007

$$c_r(z) = k_r \cdot \ln\left(\frac{z}{z_0}\right)$$

$$c_r(z) = c_r(z_{min})$$

Z_0 = the obstacle height in this case 0.5m

K_r = the area factor, and can be calculated with the following formula:

$$k_r = 0{,}19 \cdot \left(\frac{z_0}{z_{0,II}}\right)^{0{,}07}$$

In this case the engineer from Tentech did not use the standard value because he has taken an alternative value for $C_{r\,(z)}$. Although the obstacle factor ($C_{r\,(z)}$) is 0.75 in the table and the calculated value is 0.73 the fact there is only a difference of 0.02 is a mere coincidence.

The obstacle height (Z_n) is the height of the construction plus the added height due to the terrain factor. In this case 6m has been taken as the obstacle height and this is added to the Z_{min} of 7m. The masts are higher than 6m but the fabric is about 6m high and this is the part of the construction will catch the most wind.

Z_n = 13m

The turbulence intensity $I_{v\,(z)}$ at height z is defined as the standard deviation of the turbulence divided by the average wind speed.

$$I_v(z) = \frac{\sigma_v}{v_m(z)} = \frac{k_I}{c_o(z) \cdot \ln(z / z_0)}$$

$$I_v(z) = I_v(z_{min})$$

$K_{I(Z)}$ = the turbulence factor commonly taken as 1

$C_{o(Z)}$ = orography factor

Z_0 = the obstacle height in this case 0,5m

$$\sigma_v = k_r \cdot v_b \cdot k_I$$

The turbulent component of the wind speed has an average value of 0 and a standard deviation σ

The external pressure $q_{(z)}$ can be calculated with this formula.

$$q_p(z) = (1 + 7 \cdot I_v(z)) \cdot \tfrac{1}{2} \cdot \rho \cdot v_m^2(z) = c_e(z) \cdot q_b$$

ρ = the density of air during a storm, this depends on the altitude, temperature and air pressure. A commonly taken value is 1,25 kN/m^3

$C_{e(z)}$ = exposure factor

$$c_e(z) = \frac{q_p(z)}{q_b}$$

q_b = basic pressure

$$q_b = \tfrac{1}{2} \cdot \rho \cdot v_b^2$$

The values found:

V_b =	27 m/s	(average wind speed)
C_{prob} =	0.897	(probability factor)
$V_{b,0}$ =	24.2 m/s	(basic wind speed)
Z_0 =	0.5 m	(obstacle height 0)
Z_{min} =	7 m	(obstacle height min)
K_r =	0.22	(terrain factor)
Z_n =	13m	(obstacle height)
$C_{r(z)}$ =	0.73	(roughness factor)
$V_{m(z)}$ =	17.6 m/s	(average wind speed)
$I_{v(z)}$ =	0.31	(turbulence intensity)

$q_{(z)}$ = 0.61 kN/m² (external pressure)

There was not expected to be a risk of ponding but just to show that I thought about the possibility The Angele of the membrane in was checked (fig. 5.5). The slope on the membrane is about 35° to 60°. There is certainly no risk of ponding.

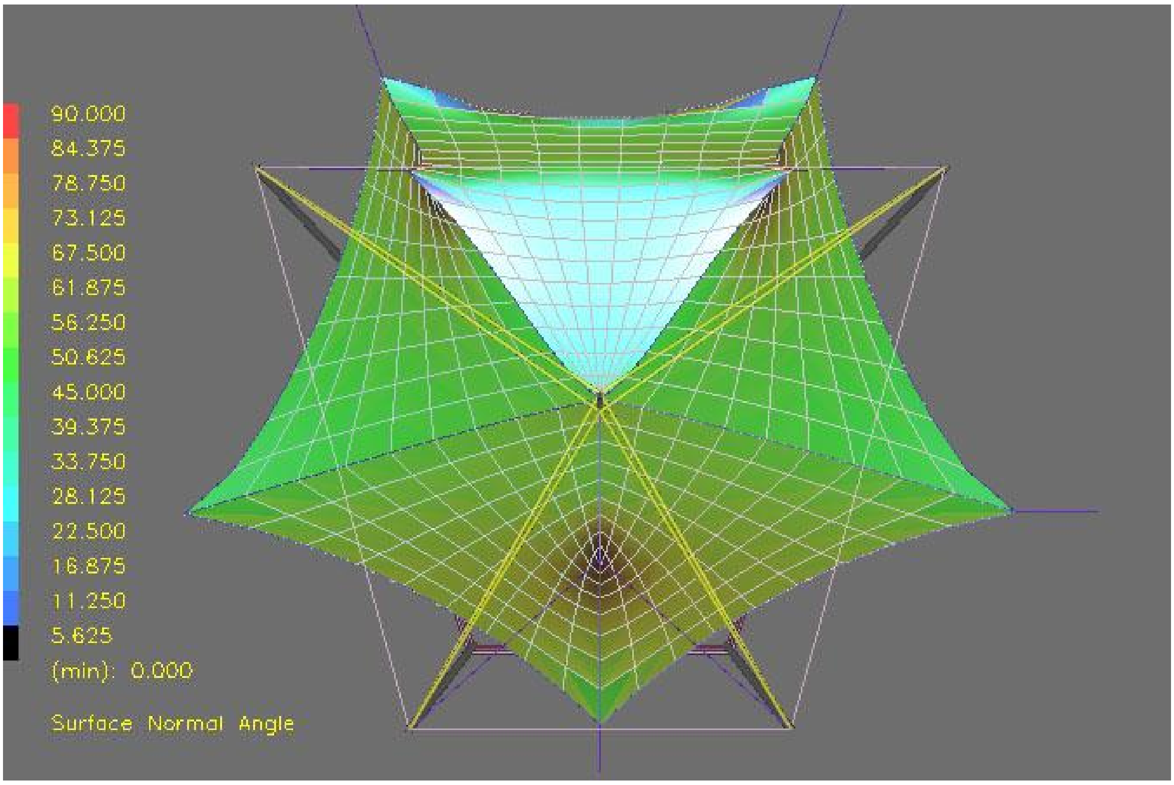


Fig. 5.5: Ponding check

The membrane surface is divided in several zones varying as the wind direction changes. The shape and C_p values of these zones are taken from the NEN-EN 1991-1-4 2005. I took a 2 sided sloped construction with a slope of + 30°.

Load cases to be considered:

1) Self weight + Pre-stress

2) Self weight + Pre-stress + wind suction (applied on the entire surface) (fig. 5.6)

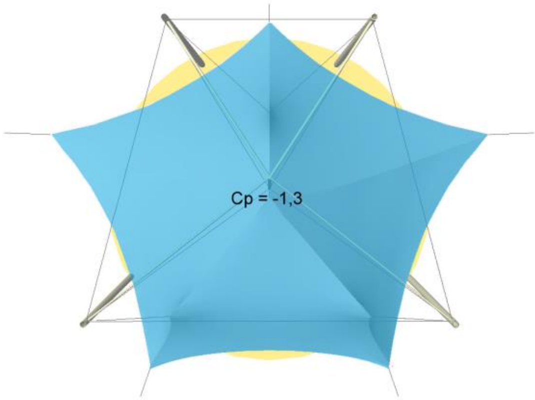


Fig. 5.6: Load case 2

3) Self weight + Pre-stress + wind front suction (applied on frontal surface) (fig. 5.7)

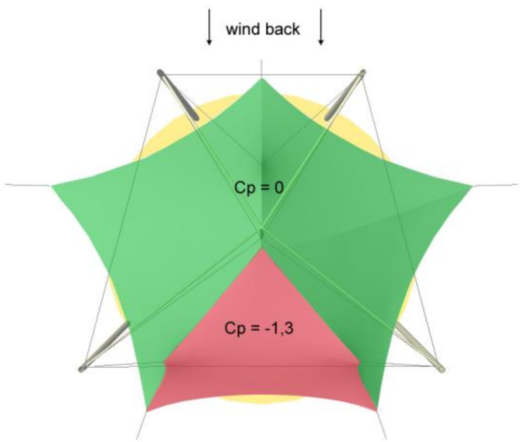


Fig. 5.7: Load case 3

4) Self weight + Pre-stress + wind front suction (applied on back surface) (fig. 5.8)

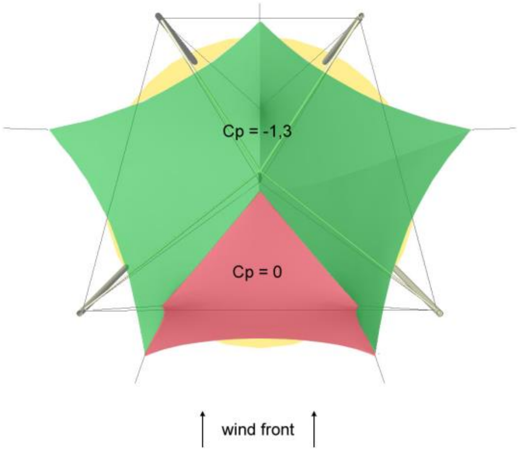


Fig. 5.8: Load case 4

5) Self weight + Pre-stress + wind side suction (applied on half of the surface) (fig. 5.9)

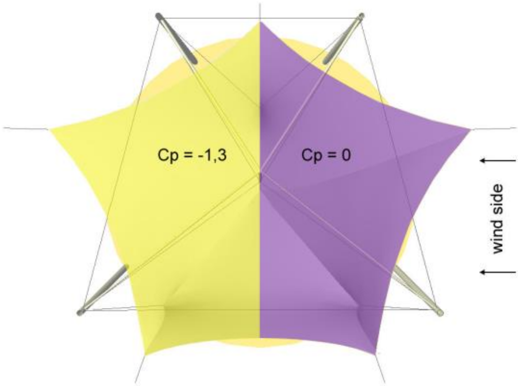


Fig. 5.9: Load case 5

6) Self weight + Pre-stress + wind pressure (applied on the entire surface) (fig. 5.10)

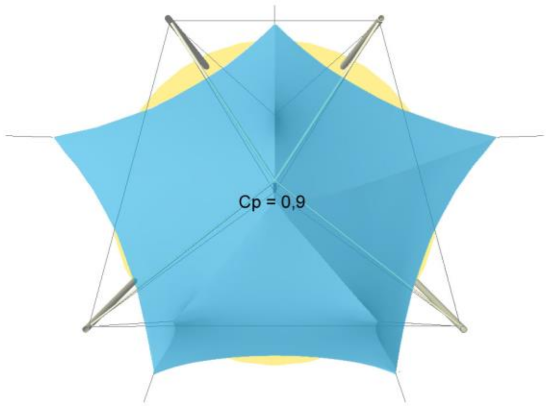


Fig. 5.10: Load case 6

7) Self weight + Pre-stress + wind front pressure (applied on frontal surface) (fig. 5.11)

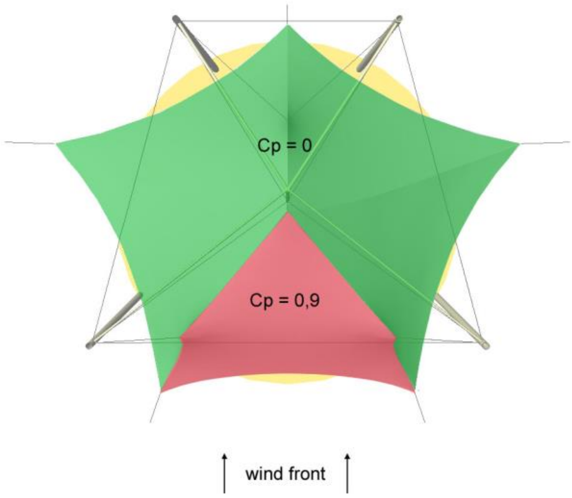


Fig. 5.11: Load case 7

8) Self weight + Pre-stress + wind front pressure (applied on back surface) (fig. 5.12)

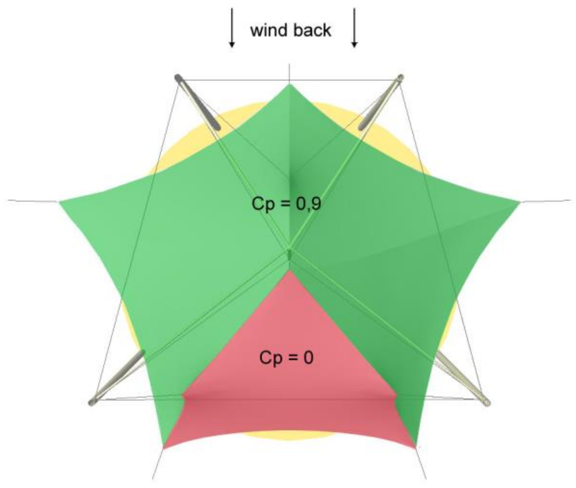


Fig. 5.12: Load case 8

9) Self weight + Pre-stress + wind side pressure (applied on half of the surface) (fig. 5.13)

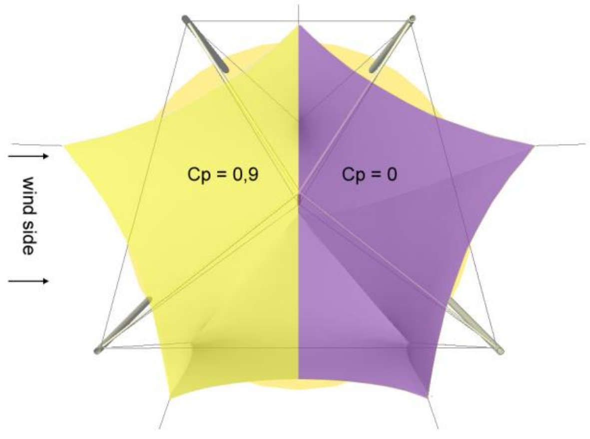


Fig. 5.13: Load case 9

Using these values load cases can be put in ixForten (tab 5.1).

load case	A	B	C	D	E	F	G	H	I
LC1	x								
LC2	x	x							
LC3	x		x						
LC4	x			x					
LC5	x				x				
LC6	x					x			
LC7	x						x		
LC8	x							x	
LC9	x								x

Tab. 5.1: Load cases

The membrane calculations are done by software, in a non-linear way. This means the results of the load applied are calculated after deformation has been taken into account. In most cases this works in a positive way reducing the reaction forces as deformation increases. To illustrate this (fig. 5.14), a cord tensioned between two points and a load is put on the cord. As the load is increased the deformation of the cord will increase.

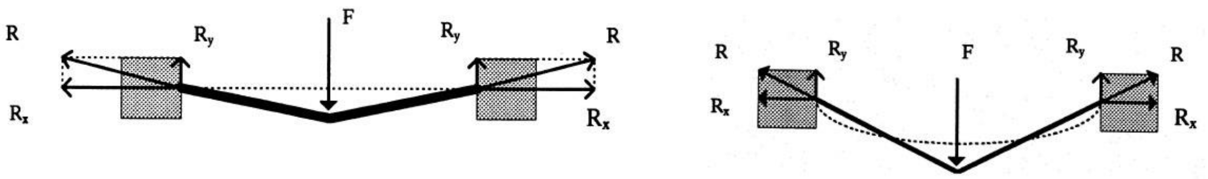


Fig. 5.14: Deformation

The calculation values applied are the ones found in NEN-EN 1990, par. 6.3.2.

5.4 results

All the load cases are calculated (tab. 5.2 and fig. 5.15) but only the most extreme cases are important for the actual construction because it will have to be able to withstand the forces occurring in these situations. Therefore I only have pictures of scenario 2 (LC2) wind pressure on the entire surface of the membrane and 6 (LC6) suction on the entire surface of the membrane.

			EG						wind suction						wind pressure					
			Fx	Fy	Fz	Fh	Ftot	α_{hor}	Fx	Fy	Fz	Fh	Ftot	α_{hor}	Fx	Fy	Fz	Fh	Ftot	α_{hor}
		position	[kN]	[kN]	[kN]	[kN]	[kN]	°	[kN]	[kN]	[kN]	[kN]	[kN]	°	[kN]	[kN]	[kN]	[kN]	[kN]	°
mast	mast back	1	2,5	1,3	8,3	2,8	8,8	71,2	2,9	0,6	21,2	3,0	21,4	82,0	9,0	5,8	30,2	10,7	32,0	70,5
	mast back	2	-2,5	1,3	8,3	2,8	8,8	71,2	-3,0	0,6	21,2	3,1	21,4	81,8	-9,0	5,8	30,2	10,7	32,0	70,5
	mast front	3	2,0	-0,7	2,8	2,1	3,5	52,9	4,1	-1,1	2,3	4,2	4,8	28,4	12,6	-2,9	5,3	12,9	14,0	22,3
	mast front	4	-2,0	-0,7	2,8	2,1	3,5	52,9	-4,1	-1,1	2,3	4,2	4,8	28,4	-12,6	-2,9	5,3	12,9	14,0	22,3
cable	cable side	5	-1,9	0,1	7,3	1,9	7,5	75,4	-16,2	-0,9	-8,5	16,2	18,3	-27,6	-17,7	2,8	-7,3	17,9	19,3	-22,2
	cable side	6	1,9	0,1	7,3	1,9	7,5	75,4	16,1	-0,9	-8,5	16,1	18,2	-27,8	17,7	2,8	-7,3	17,9	19,3	-22,2
	cabele front	7	-0,6	-1,8	5,4	1,9	5,7	70,5	-6,0	-18,0	-11,3	19,0	22,1	-30,8	-2,8	-8,4	-5,1	8,9	10,2	-29,9
	cabele front	8	0,6	-1,8	5,5	1,9	5,8	70,8	6,0	-18,0	-11,3	19,0	22,1	-30,8	2,8	-8,4	-5,1	8,9	10,2	-29,9
	cabele back	9	0,0	2,3	5,4	2,3	5,9	67,1	0,0	24,2	-20,1	24,2	31,5	-39,7	0,0	15,5	-8,6	15,5	17,7	-29,0

			wind suction front						wind suction back						wind suction side					
			Fx	Fy	Fz	Fh	Ftot	α_{hor}	Fx	Fy	Fz	Fh	Ftot	α_{hor}	Fx	Fy	Fz	Fh	Ftot	α_{hor}
		position	[kN]	[kN]	[kN]	[kN]	[kN]	°	[kN]	[kN]	[kN]	[kN]	[kN]	°	[kN]	[kN]	[kN]	[kN]	[kN]	°
mast		1	4,7	2,9	13,9	5,5	15,0	68,3	3,2	0,6	25,3	3,3	25,5	82,7	3,3	2,6	20,3	4,2	20,7	78,3
		2	-4,7	2,9	13,9	5,5	15,0	68,3	-3,2	0,6	25,3	3,3	25,5	82,7	-5,6	1,5	21,9	5,8	22,7	75,2
		3	5,4	-1,5	2,6	5,6	6,2	24,9	5,0	-1,4	2,1	5,2	5,6	22,0	5,8	-0,6	1,9	5,8	6,1	18,0
		4	-5,4	-1,5	2,6	5,6	6,2	24,9	-5,0	-1,4	2,1	5,2	5,6	22,0	-6,1	-2,6	3,2	6,6	7,4	25,8
cable		5	-8,9	0,9	-4,0	8,9	9,8	-24,1	-15,7	-1,1	-8,2	15,7	17,7	-27,5	-17,1	1,0	-7,5	17,1	18,7	-23,6
		6	8,9	0,9	-4,0	8,9	9,8	-24,1	15,7	-1,1	-8,2	15,7	17,7	-27,5	11,3	-1,2	-6,4	11,4	13,0	-29,4
		7	-2,2	-6,2	-3,8	6,6	7,6	-30,0	-6,2	-19,2	-12,0	20,2	23,5	-30,7	-4,7	-13,0	-8,2	13,8	16,1	-30,7
		8	2,2	-6,2	-3,8	6,6	7,6	-30,0	6,2	-19,2	-12,0	20,2	23,5	-30,7	4,2	-13,9	-8,6	14,5	16,9	-30,6
		9	0,0	11,8	-7,4	11,8	13,9	-32,1	0,0	23,3	-19,6	23,3	30,4	-40,1	-2,8	18,7	-14,2	18,9	23,6	-36,9

			wind pressure front						wind pressure back						wind pressure side					
			Fx	Fy	Fz	Fh	Ftot	α_{hor}	Fx	Fy	Fz	Fh	Ftot	α_{hor}	Fx	Fy	Fz	Fh	Ftot	α_{hor}
		position	[kN]	[kN]	[kN]	[kN]	[kN]	°	[kN]	[kN]	[kN]	[kN]	[kN]	°	[kN]	[kN]	[kN]	[kN]	[kN]	°
mast		1	4,7	2,7	16,2	5,4	17,1	71,5	7,6	5,4	25,3	9,3	27,0	69,8	7,0	4,7	19,1	8,4	20,9	66,2
		2	-4,7	2,7	16,2	5,4	17,1	71,5	-7,6	5,4	25,3	9,3	27,0	69,8	-6,3	3,9	24,0	7,4	25,1	72,8
		3	5,7	-1,6	1,8	5,9	6,2	16,9	11,8	-2,5	5,9	12,1	13,4	26,1	7,8	-2,8	2,8	8,3	8,7	18,7
		4	-5,7	-1,6	1,8	5,9	6,2	16,9	-11,8	-2,5	5,9	12,1	13,4	26,1	-9,7	-1,5	4,6	9,8	10,8	25,1
cable		5	-4,3	0,2	-1,8	4,3	4,7	-22,7	-17,1	2,7	-6,9	17,3	18,6	-21,7	-6,3	0,4	-2,7	6,3	6,9	-23,2
		6	4,3	0,2	-1,8	4,3	4,7	-22,7	17,1	2,7	-6,9	17,3	18,6	-21,7	15,8	2,7	-6,4	16,0	17,3	-21,8
		7	-1,9	-5,4	-3,3	5,7	6,6	-30,0	-2,1	-6,4	-3,8	6,7	7,7	-29,4	-1,9	-5,6	-3,4	5,9	6,8	-29,9
		8	1,9	-5,4	-3,3	5,7	6,6	-30,0	2,1	-6,4	-3,8	6,7	7,7	-29,4	2,4	-7,2	-4,3	7,6	8,7	-29,5
		9	0,0	5,4	-3,5	5,4	6,4	-32,9	0,0	14,6	-8,1	14,6	16,7	-29,0	-0,7	10,6	-6,3	10,6	12,4	-30,7

			maximum force			
			Fz	Fh	Ftot	α_{hor}
		position	[kN]	[kN]	[kN]	°
mast		1	8,3	10,7	32,0	37,8
		2	8,3	10,7	32,0	37,8
		3	1,8	12,9	14,0	7,9
		4	1,8	12,9	14,0	7,9
cable		5	7,3	17,9	19,3	22,1
		6	7,3	17,9	19,3	22,2
		7	5,4	20,2	23,5	14,9
		8	5,5	20,2	23,5	15,1
		9	5,4	24,2	31,5	12,7

Tab. 5.2: Calculation results

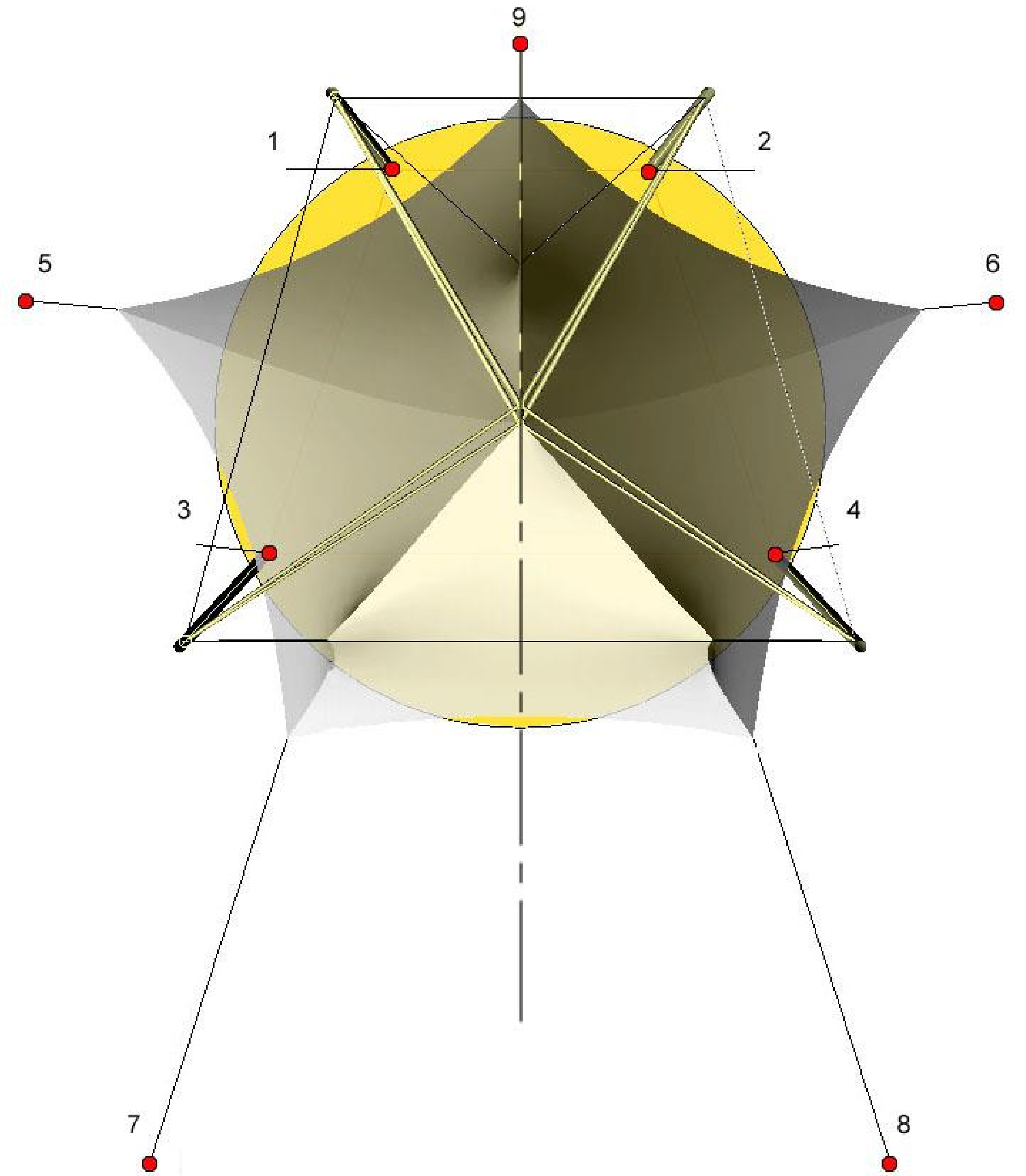


Fig. 5.15: Connection points construction to square

LC2 Membrane Tension Self weight + Prestress + wind suction (applied on the entire surface) (fig. 5.16)

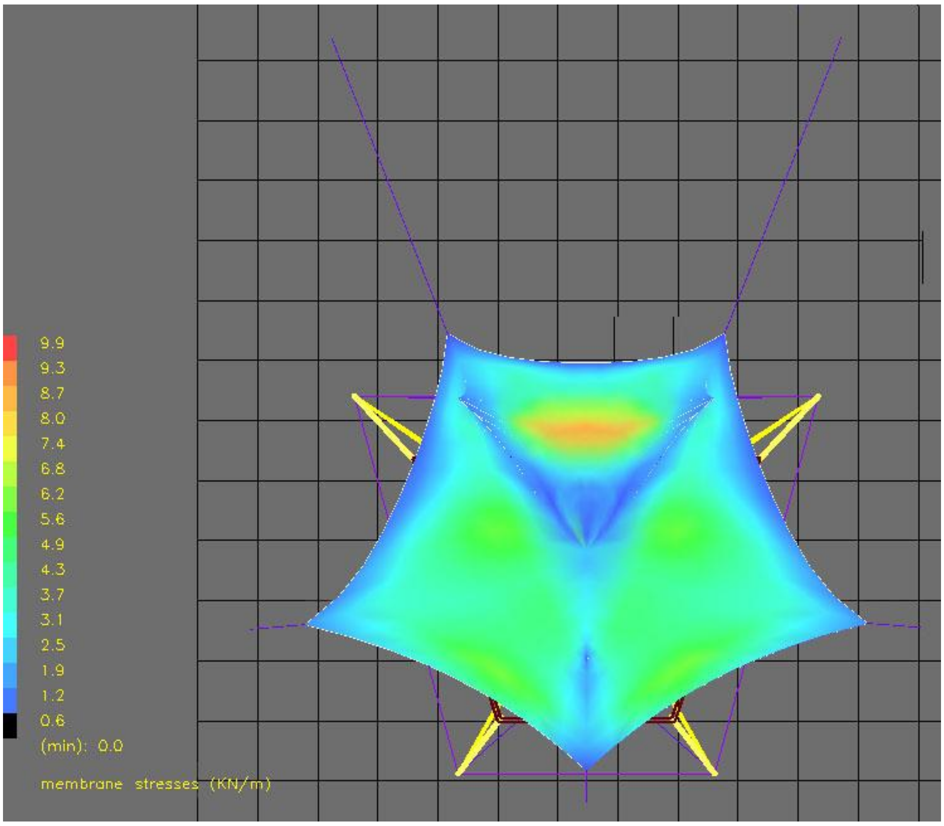


Fig. 5.16: Membrane stress load case 2

LC2 Cable forces Self weight + Prestress + wind suction (applied on the entire surface) (fig. 5.17)

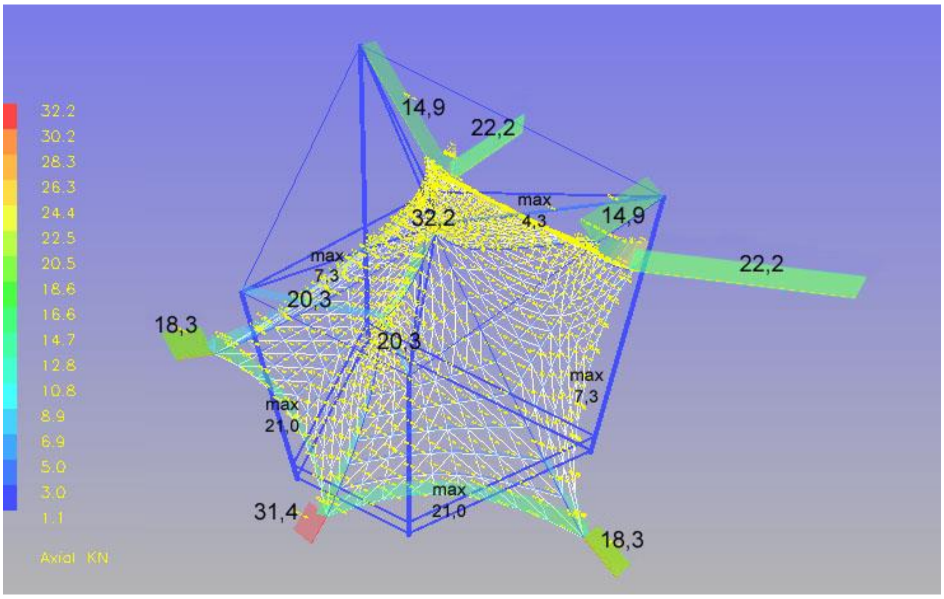


Fig. 5.17: Cables stress load case 2

LC6 Membrane Tension Self weight + Prestress + wind Pressure (applied on the entire surface) (fig. 5.18)

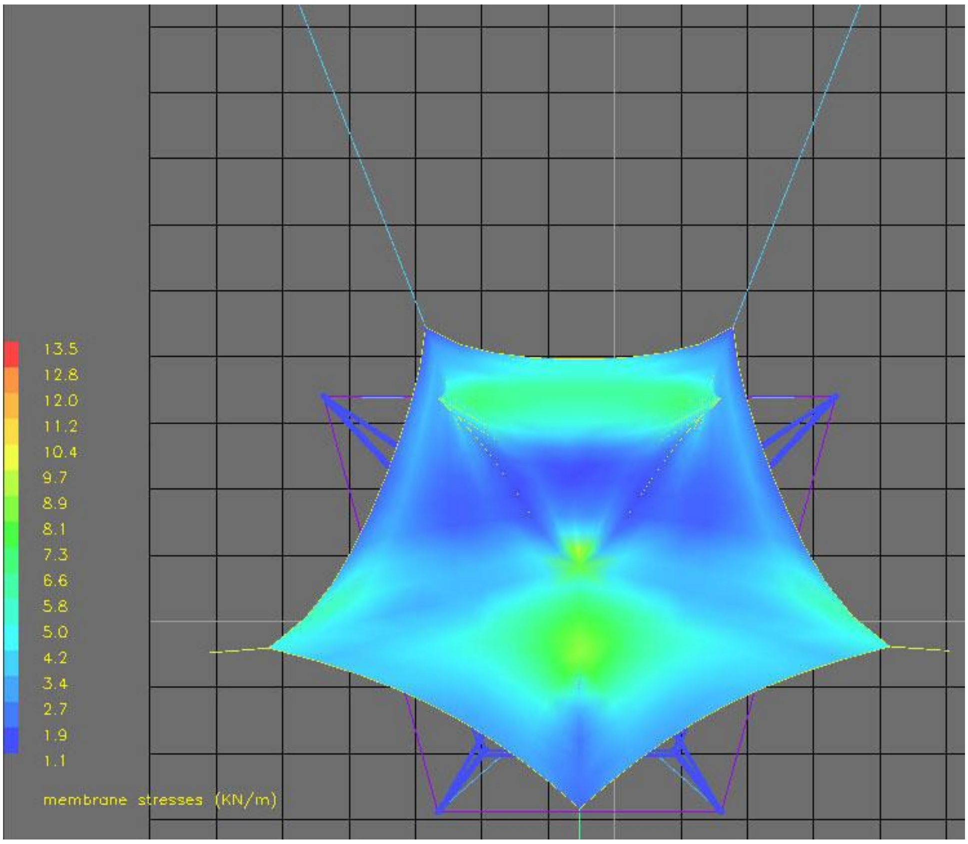


Fig. 5.18: Membrane stress load case 6

LC6 Cable forces Self weight + Prestress + wind pressure (applied on the entire surface) (fig. 5.19)

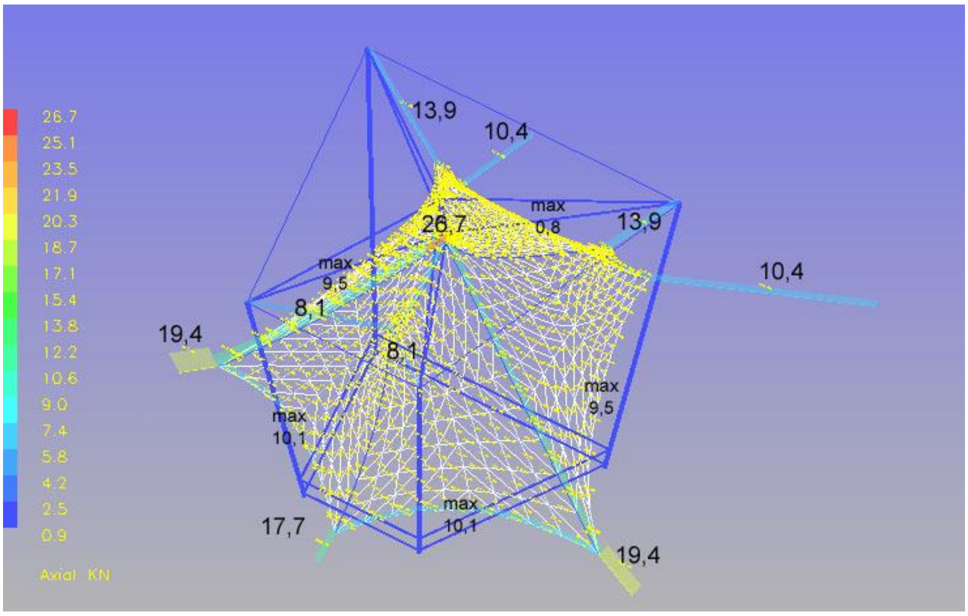


Fig. 5.19: Cable stress load case 6

6 STEEL CONSTRUCTION CHECK

The components (fig. 6.0) of the steel construction are checked by an engineer from Tentech.

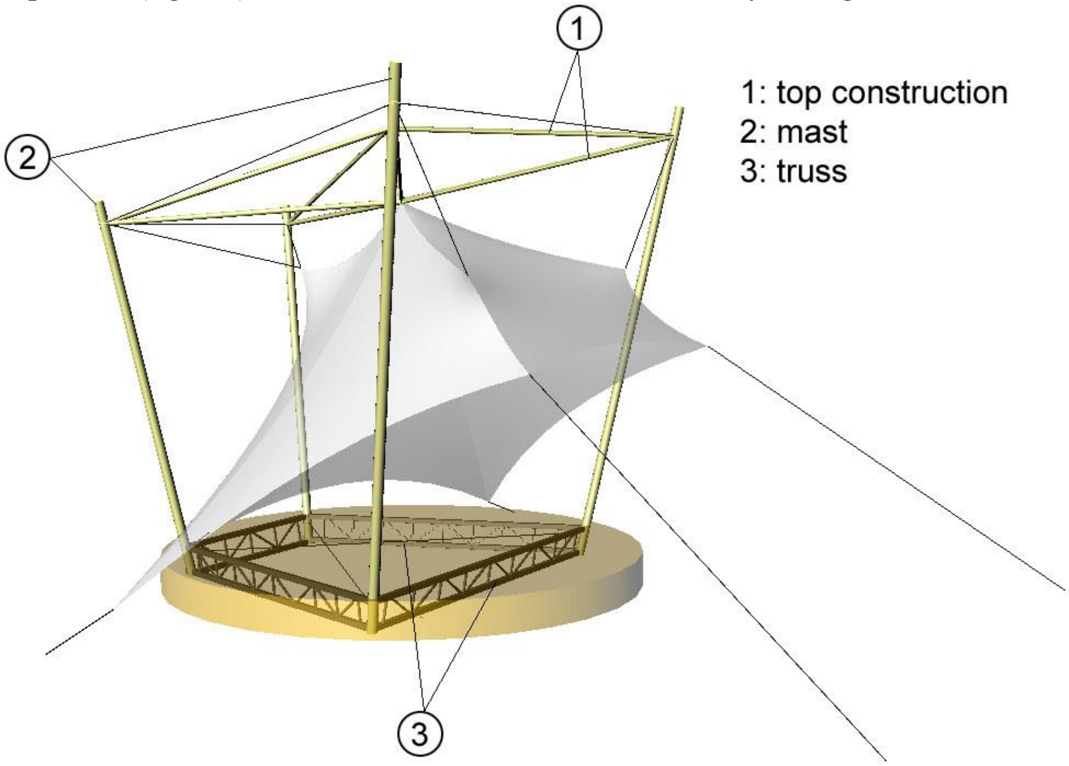


Fig. 6.0: Components

6.1 top construction

The top construction's function is to form a tridimensional cross to stabilize masts. The cross is being pulled down by the membrane. There is a compression force in the top beams and a tension force in the lower beams. In the computer simulation in fig. 6.1 you can see this.

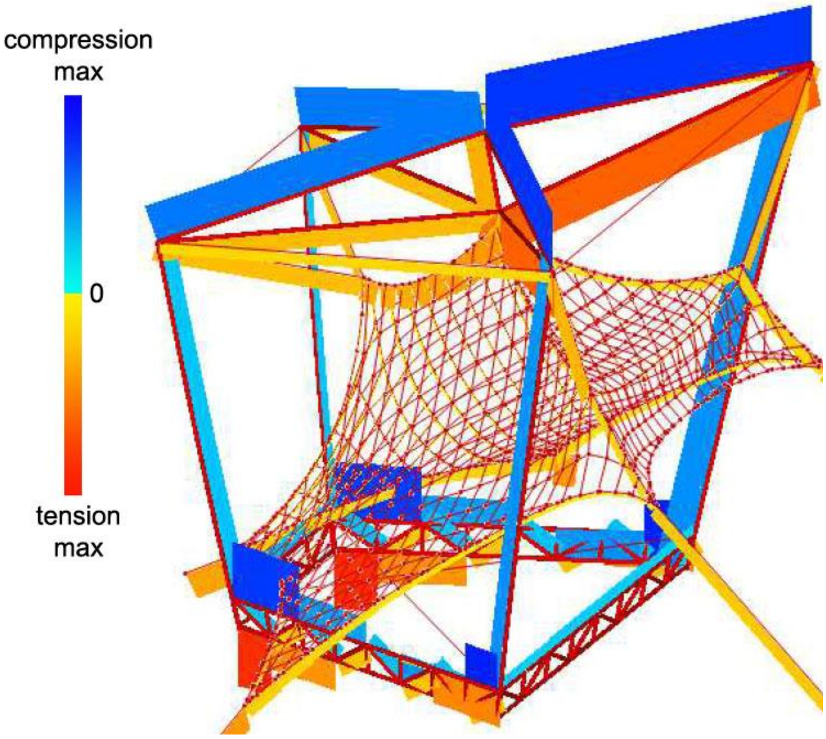


Fig. 6.1: computer simulation compression/tension forces

The fig.6.1 shows the model with a wind pressure load on the membrane. In case there is a wind suction load instead of pressure load. The connection link in the center will be slack because it is not capable to conduct a pressure load. So the force in the lower beams will always be a tension force. In theory the lower beams could be replaced by cables. During erection there could very well be a compression force on the lower beams. This would case the cross to deform. This could make the erection process more difficult so a beam was chosen over a cable.

Buckling check:
The top beams have to be checked for buckling. Buckling occurs when a long piece of material is put under pressure. Rather than being compressed the material will bend as in the example seen in fig. 6.2.

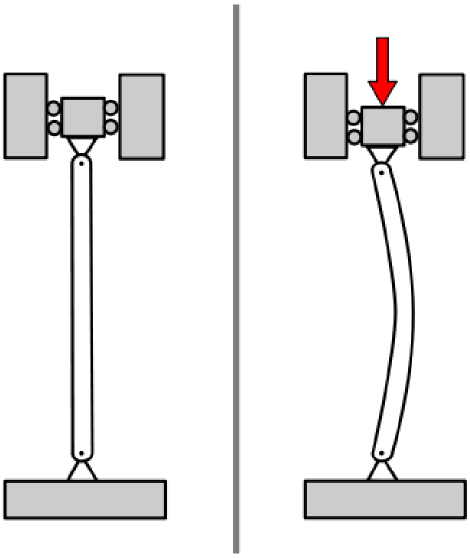


Fig. 6.2: Buckling (source: wikipedia.org)

$$F = \frac{\pi^2 EI}{(KL)^2}$$

F = maximum or critical force (vertical load on column),

E = modulus of elasticity,

I = area moment of inertia,

L = unsupported length of column,

K = column effective length factor, whose value depends on the conditions of end support of the column, as follows.

For both ends pinned (hinged, free to rotate), K = 1.0.

For both ends fixed, K = 0.50.

For one end fixed and the other end pinned, K = 0.699....

For one end fixed and the other end free to move laterally, K = 2.0.

KL is the effective length of the column.

Tube on top of top construction: CHS Ø 88.9 x 4 S235 JRH L = 4710 mm

The compression force on the tube is: Nc,Ed = 1.5 x 39.2kN = 58.8 kN

When the force (including a safety factor) is applied the tube is at 90% of the maximum force it can handle before buckling occurs so it is safe to use.

In case the chosen profile would not have passed there are a number of variables could be changed. The first variable is the moment of inertia (fig. 6.3) this is determined by the shape of the profile and the total surface of a section of the profile. As an example, it is easier to bend a tube with a thinner wall than one with a thicker wall. And easier to buckle a tube with a small diameter than one with a bigger diameter even if the total surface of the section is the same. The second value is the material.

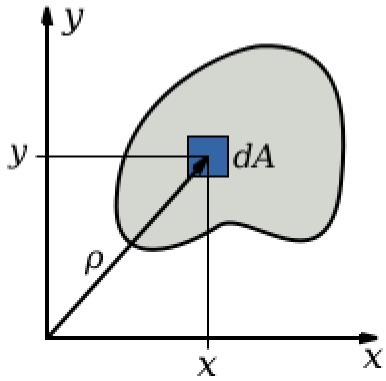


Fig. 6.3: moment of inertia

The second moment of area for an arbitrary shape with respect to an arbitrary axis BB is defined as

$$J_{BB} = \int_A \rho^2 \, \mathrm{d}A$$

$\mathrm{d}A$ = Differential area of the arbitrary shape

ρ = Distance from the axis BB to dA

The tube on bottom of top construction is only under tension.

The profile chosen for this is a:

CHS Ø 42.4 x 2.6 S235 JRH

The (tension) force on this element including safety factor is:

N_t, E_d = 1.5 x 30.8 = 46.2 kN

The force this profile can handle before it breaks is:

A = 325 mm²

$N_t,R_d =$ 325 x 235 = 76.4 kN

So the tension is only 60% of what it could be, this means it is safe to use this tube here.

As an alternative a cable could be applied in this position. The reason a tube is applied as mentioned before is that this will ease erecting the construction.

cable Ø 12
6 x 36 WS + rope core, galvanized

F_{break} = 84.1 kN

$N_t,R_d = 0.9 \times F_{break} / \gamma M = 0.9 \times 84.1 / 1.5 = 50.5$ kN (60% of the force it can safely handle)

6.2 masts

The masts are not only subject to pressure as can be seen in fig. 6.1. The masts are also being pushed outward by the cross construction that holds the membrane. This creates a bending moment as can be seen in fig. 6.4.

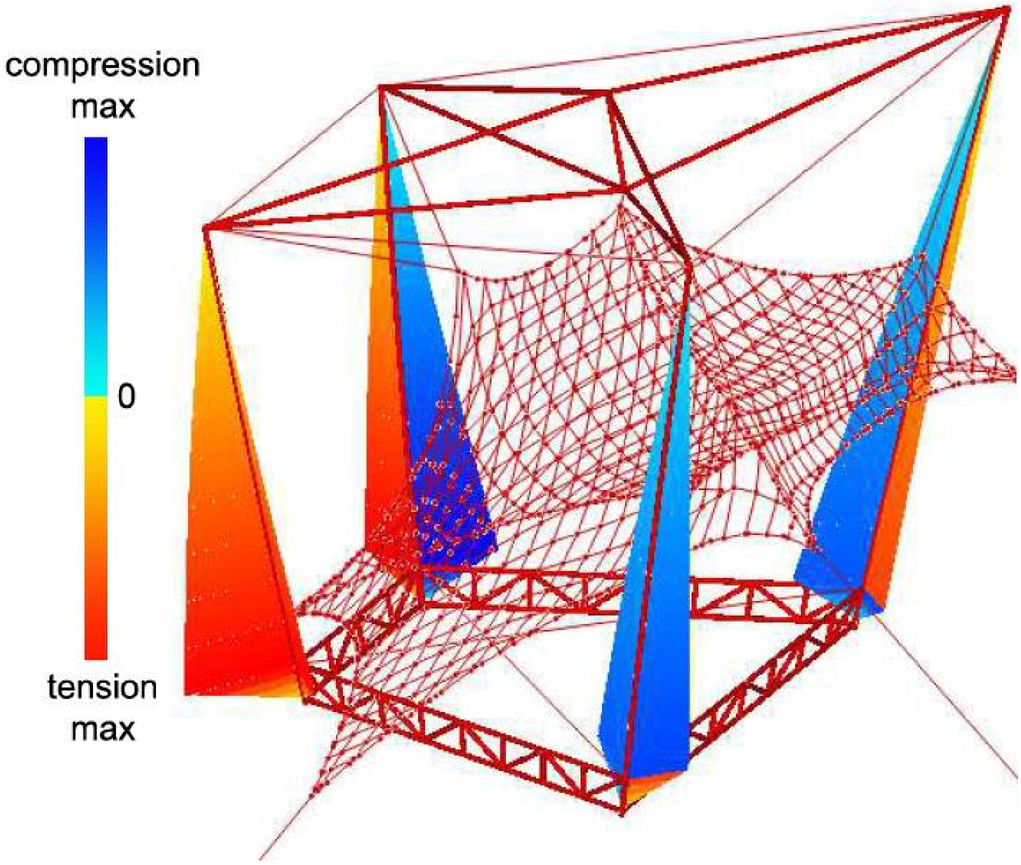


Fig. 6.4: Bending moment computer simulation

Mast: CHS Ø 139.7 x 6.3 S355 J2H

$N_c,E_d =$ 1.5 x 27.3 = 41.0 kN
$M_y,E_d =$ 1.5 x 13.4 = 20.1 kN
$M_z,E_d =$ 1.5 x 10.4 = 15.6 kN

L = 6450 mm

The masts are checked for buckling and they passed easily. There is only 24% of the force applied to them of what they could handle.

The next check is a bending moment check.

The bending moment is the force axial to the axes of the profile times the distance between where the force is applied and the point where the moment is measured (fig. 6.5).

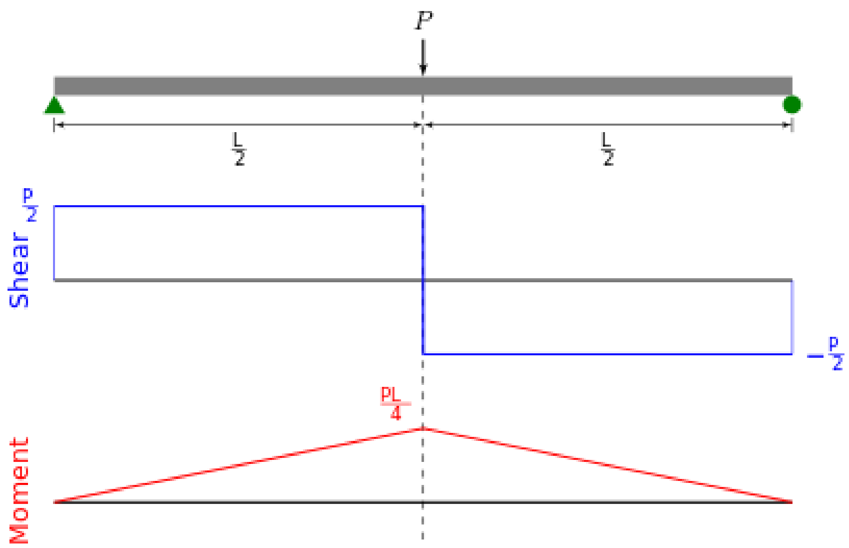


Fig. 6.5: Bending moment (source: wikipedia.org)

When a material is bent it is deformed, the inner part is compressed while the outer part is stretched (fig. 6.6)

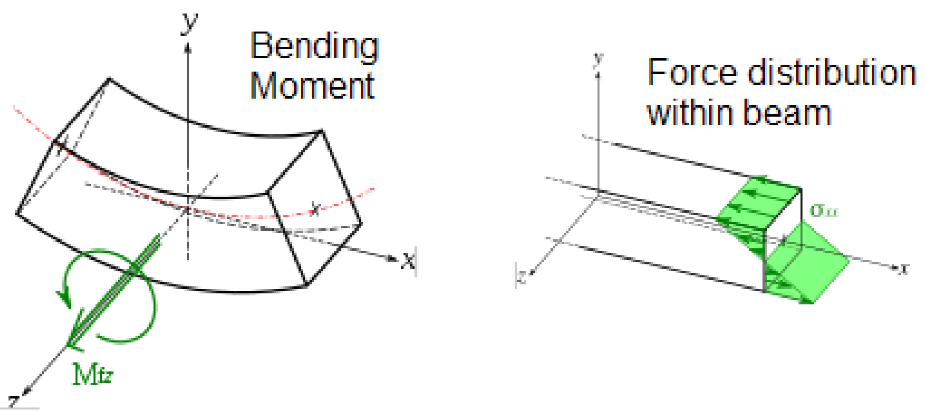


Fig. 6.6: Bending moment compression/tension (source: www.learneasy.com)

The bending stress can be calculated with the following formula:

$$\sigma = \frac{My}{I_x}$$

where

- σ is the bending stress
- M - the moment about the neutral axis
- y - the perpendicular distance to the neutral axis
- I_x - the second moment of area about the neutral axis x.

Without going in detail in material property's there is a limit to witch a material can deform without permanent deformation.

A strength check has been done by an engineer from Tentech with the following results:

tension resistance	Nt.rd	848.25	kN	(6.6) NEN-EN 1993-1-1
tension axial		-		(6.5) NEN-EN 1993-1-1
pressure resistance	Nc,rd	848.25	kN	(6.10) NEN-EN 1993-1-1
presure check		0.05<1.0	pass	(6.9) NEN-EN 1993-1-1
bending resistance (y-axe)	My,c,rd	35.88	kNm	(6.13) NEN-EN 1993-1-1
check bending (y-axe)		0.56<1.0	pass	(6.12) NEN-EN 1993-1-1
bending resistance (z-axe)	Mzc,rd	35.88	kNm	(6.13) NEN-EN 1993-1-1
check bending (z-axe)		0.43<1.0	pass	(6.12) NEN-EN 1993-1-1

The chosen profile CHS Ø 139.7 x 6.3 S355 J2H passes this test.

A stability check has been done by an engineer from Tentech. In this check the combined loads of bending and buckling are tested. The parts are also tested for their resistance against torsion.

$$T = \frac{J_T}{r}\tau = \frac{J_T}{\ell}G\theta$$

- T is the applied torque or moment of torsion in Nm.
- τ is the maximum shear stress at the outer surface
- J_T is the torsion constant for the section.

- r is the distance between the rotational axis and the outer surface.
- ℓ is the length of the object.
- θ is the angle of twist in radians.
- G is the shear modulus in gigapascals (GPa),

Stability check:

pressure resistance (buckeling)	$N_{b,y,rd}$	199.69	kNm	(6.47) NEN-EN 1993-1-1
buckeling check		0.21<1.0	pass	(6.46) NEN-EN 1993-1-1
torsion resistance (y-axe)	$M_{y,b,r,d}$	35.88	kNm	(6.55) NEN-EN 1993-1-1
Torsion check			pass	(6.54) NEN-EN 1993-1-1
check bending (dubble) + buckeling strong-axe		0.77<1.0	pass	(6.61) NEN-EN 1993-1-1
check bending (dubble) + buckeling weak-axe		0.74<1.0	pass	(6.61) NEN-EN 1993-1-1

The chosen profile also passed this check. The maximum applied force including a safety factor was 77% of what the profile could handle before failing.

6.3 truss

The beams of the truss inside the stage where checked for checked for pressure and buckling. The masts are connected to the foundation are pulled inward by the membrane construction. This creates a pressure force on the truss. If there is a crowd on the stage a pressure force will be passed form the stage to the truss construction.

The profile used for the top and bottom beams:

SHS 80x80x3 S235 J2H

The results of a strength check done by an engineer from Tenentech:

tension resistance	$N_{t.rd}$	192.44	kN	(6.6) NEN-EN 1993-1-1
tension axial		-		(6.5) NEN-EN 1993-1-1

pressure resistance	$N_{c,rd}$	192.44	kN	(6.10) NEN-EN 1993-1-1
presure check		0.59<1.0	pass	(6.9) NEN-EN 1993-1-1

Stability check:

pressure resistance (buckeling)	$N_{b,y,rd}$	125.19	kNm	(6.47) NEN-EN 1993-1-1
buckeling check		0.91<1.0	pass	(6.46) NEN-EN 1993-1-1

For the diagonals in the truss the same check was done by an engineer from Tentech.

The profile used for the diagonal beams:

SHS 30x30x3 S235 J2H

Strength check:

tension resistance	$N_{t.rd}$	68.18	kN	(6.6) NEN-EN 1993-1-1
tension axial		-		(6.5) NEN-EN 1993-1-1

pressure resistance	$N_{c,rd}$	68.18	kN	(6.10) NEN-EN 1993-1-1
presure check		0.39<1.0	pass	(6.9) NEN-EN 1993-1-1

The engineer from Tentech also did a stability check on the diagonals of the truss.

Stability check:

pressure resistance (buckeling)	$N_{b,y,rd}$	44.37	kNm	(6.47) NEN-EN 1993-1-1
buckeling check		0.61<1.0	pass	(6.46) NEN-EN 1993-1-1

6.4 cables

In fig. 6.7 you can see the location of the different types of cables.

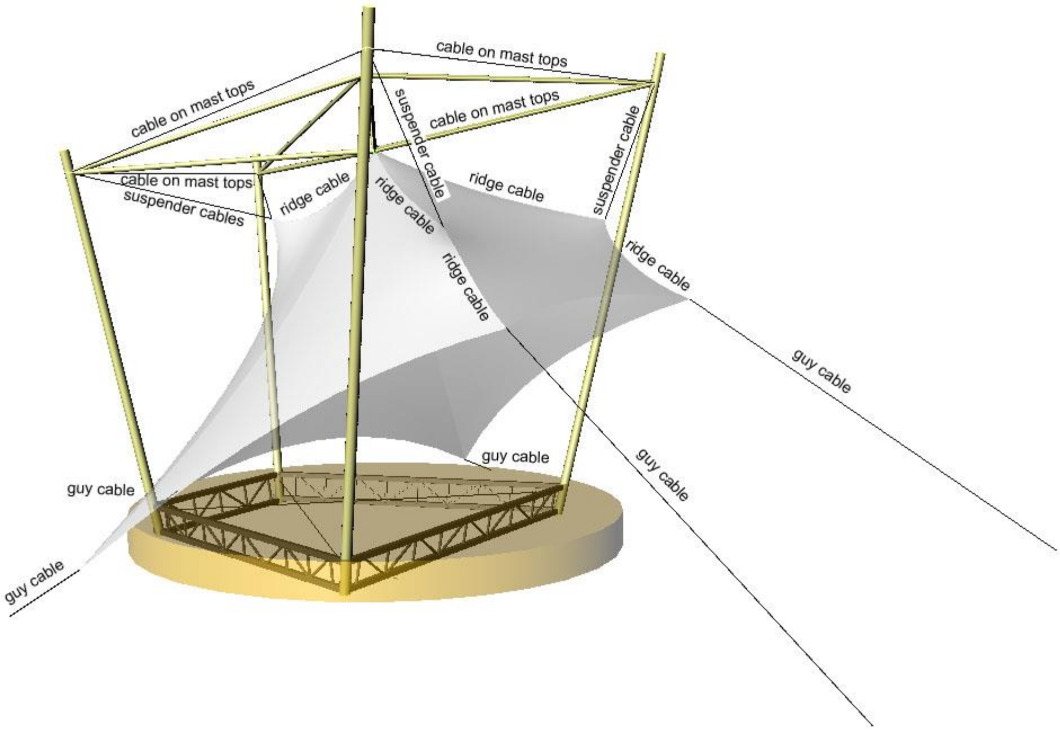


Fig. 6.7: cable types

Mast tops

Cable Ø 8 is taken on the mast tops. All cables are rope core galvanized 6 x 36 WS. The rope core gives the cable some extra flexibility over a steel core cable. The number of strains (6 x 36) is kept as high as possible within the standard assortment of cables. This is also done because cables with a higher amount of strains tend to be more flexible.

The first thing that is done is to add the safety factor of 1.5 on the maximum force that is applied to the cable. In this case 9.3 kN

$N_{t,Ed} =$ 1.5 x 9.3 = 14.0 kN

The breaking force of the cabele can be found in a table given by the manufacturer of the cable.

$F_{break} =$ 37.4 kN

The breaking force of the cable is multiplied by 0.9 because the cable could be weakened at the points where it is clamped to the end fittings. And the breaking force (x 0.9) is divided by a safety factor of 1.5 to get the force that is used in checking the cables.

$N_{t,Rd} =$ $0.9 \times F_{break} / \gamma M$ = 0.9 x 37.4 / 1.5 = 22.4 kN

The maximum force applied to this cable is 62,5 % of the maximum force it can safely handle so it can safely be applied.
The rest of the cables is done in a similar way.

suspender cables

cable Ø 10 6 x 36 WS + rope core, galvanized pass

$N_{t,Ed}$ = 1.5 x 18.7 = 28.1 kN

F_{break} = 58.4 kN

$N_{t,Rd}$ = 0.9 x F_{break} / γM = 0.9 x 58.4 / 1.5 = 35.0 kN

guy cables

cable Ø 12 6 x 36 WS + rope core, galvanized pass

$N_{t,Ed}$ = 1.5 x 31.4 = 47.1 kN

F_{break} = 84.1 kN

$N_{t,Rd}$ = 0.9 x F_{break} / γM = 0.9 x 84.1 / 1.5 = 50.5 kN

These cables are in the actual construction replaced by 50mm PES belts can handle a maximum of 60 kN including a safety factor of 1,5 this would be 40kN. This would mean when the maximum load would be applied the belts would receive 117,75% of what they could safely handle. So according to the calculations it would not be safe to apply them. If forces taken in the calculation do actually occur the square will be empty. The consequences it would have if the belts are breaking are acceptable.

suspender cable center

cable Ø 12 6 x 36 WS + rope core, galvanized pass

$N_{t,Ed}$ = 1.5 x 27.2 = 40.8 kN

F_{break} = 84.1 kN

$N_{t,Rd}$ = 0.9 x F_{break} / γM = 0.9 x 84.1 / 1.5 = 50.5 kN

ridge cables

cable Ø 10 6 x 36 WS + rope core, galvanized pass

$N_{t,Ed}$ = 1.5 x 21.0 = 31.5 kN

F_{break} = 58.4 kN

$N_{t,Rd}$ = 0.9 x F_{break} / γM = 0.9 x 58.4 / 1.5 = 35.0 kN

The ridge cables are replaced by TIR belts. The manufacturer has ensured me these belts would be safe. I have made several attempts to get technical data on these TIR bets but did not succeed at this.

The membrane is Ferrari precontraint 602 1100 dtex PES HT

f_{Ed} = 1.5 x 10.5 = 15.8 kN/m¹

f_d = 20 kN/m¹

The chosen fabric is stressed to 79% of it's maximum and is safe to use.

7 DETAILING

After the dimensions of the basic structure where determined the final detailing could be done. Dimensions of crucial details (fig. 7.0) where checked by engineers from Tentench to make sure there would not be any weak links in the construction.

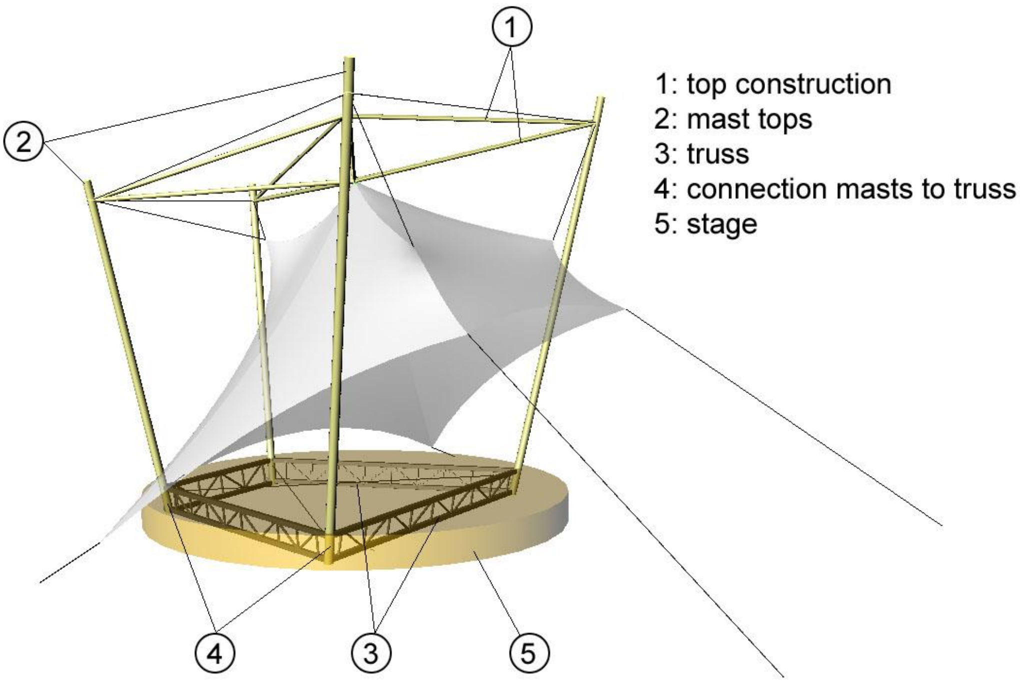


Fig. 7.0: Checked details

7.1 top construction

The first idea was to make 4 triangular pieces that would be connected by a central piece to form a cross (fig. 7.1). This would be a relatively simple solution that would enable the cross construction to be made out of just 5 separate pieces.

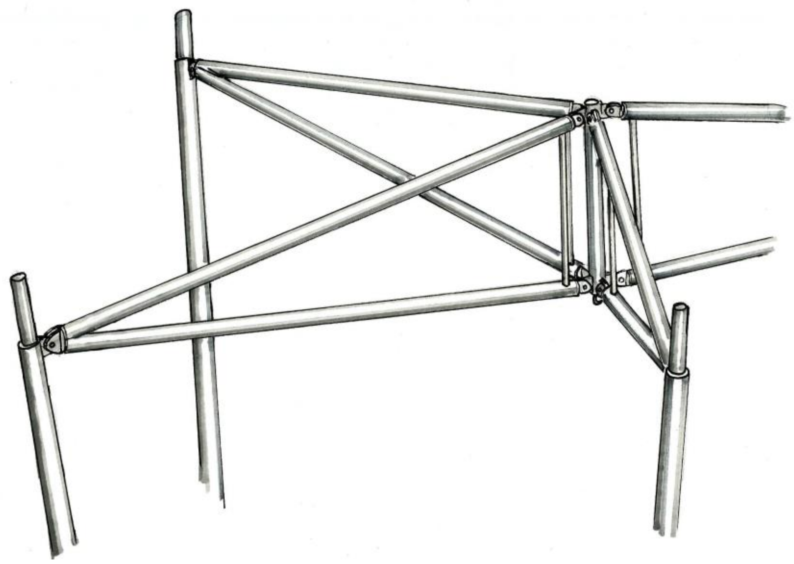


Fig. 7.1: Cross version 01

This construction (fig 7.1) would not look very elegant because of the bundle of vertical pipes in the center. The pieces would be rather difficult to handle and transport. It would also take quite a lot more storage space to store the triangular pieces than it would to store individual pipes and some connection pieces. So the construction was divided into separate pipes using a connection piece where the pipes would meet (fig. 7.2). The vertical pieces where mainly there to stabilize the construction during erection, transport and disassembly could be left out making the construction more slender looking.

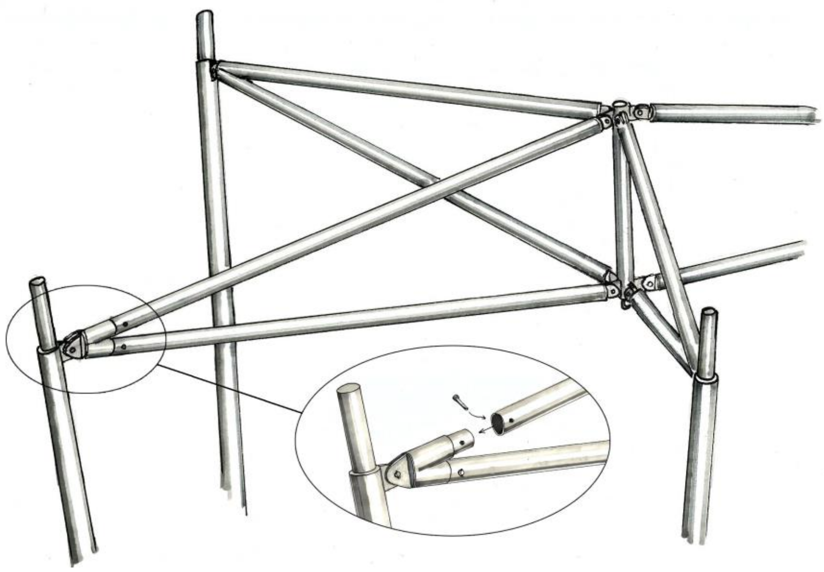


Fig. 7.2: Cross version 02

The top construction was added in a later stage in development of the construction. The construction had to be as light as possible, or at least look as light as possible. The calculation has shown that the lower elements could be cables. Because this could cause problems during erection the choice was made to use a tube. The lower tube could be much thinner than the upper tube because in theory it only has to take a tension force. The connection piece was replaced by a lug reducing the number of parts (fig. 7.3).

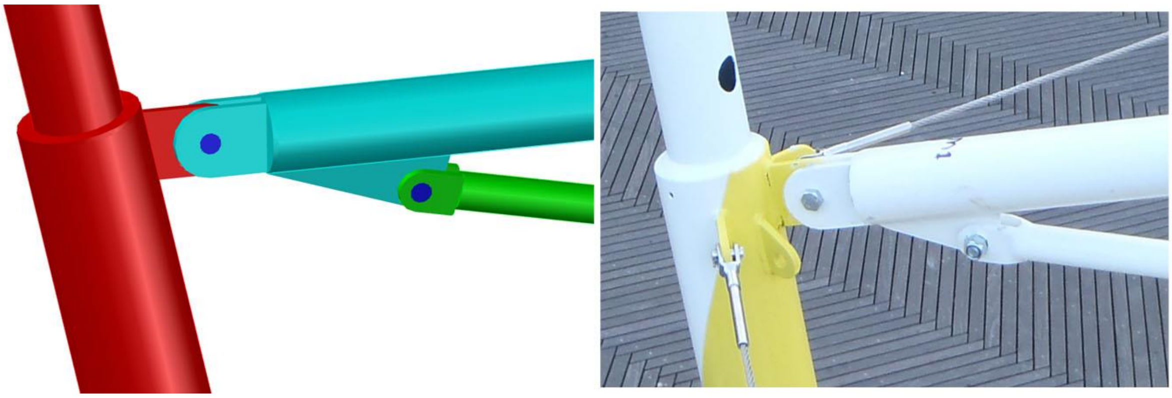


Fig. 7.3: Cross version 03

7.2 mast tops

In order to lift the cross construction a wheel had to be mounted on top of the masts. The first idea was to add a lug to the mast (fig. 7.4) so a wheel could be attached to the mast to guide the rope is needed to lift the cross construction. When lifted the construction would be attached to another lug (not shown in fig 7.4).

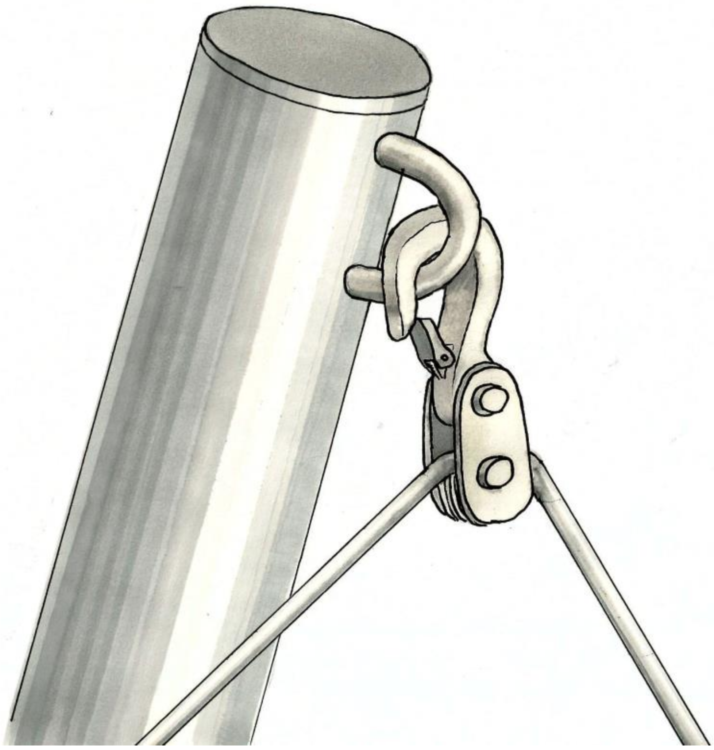


Fig. 7.4: Lifting wheel mounted on top of the masts

The second idea was to simply weld to lugs on top of the mast holding the wheel (fig. 7.5a right). A more complex but esthetically and structural better solution would be to put the wheel inside the mast tops (fig. 7.5a left). It would be more complex to build this but the welding company sad it would not be a problem.

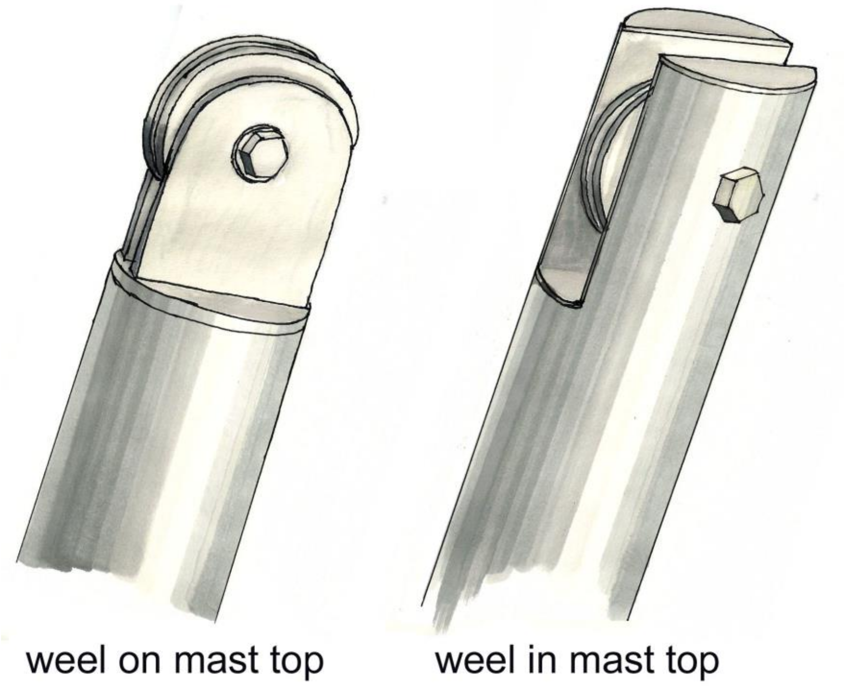


Fig. 7.5a

The idea was to use the small wheel so it would stay within the diameter of the tube (fig. 7.6b left). This was done to hide the wheel and protect it from damage during erection, disassembly and transport. In the real construction a bigger wheel was used to make an architectural statement (fig. 7.6b right). Because the wheel is bigger the bolt and nut also had to be bigger as you can se in the pictures below.

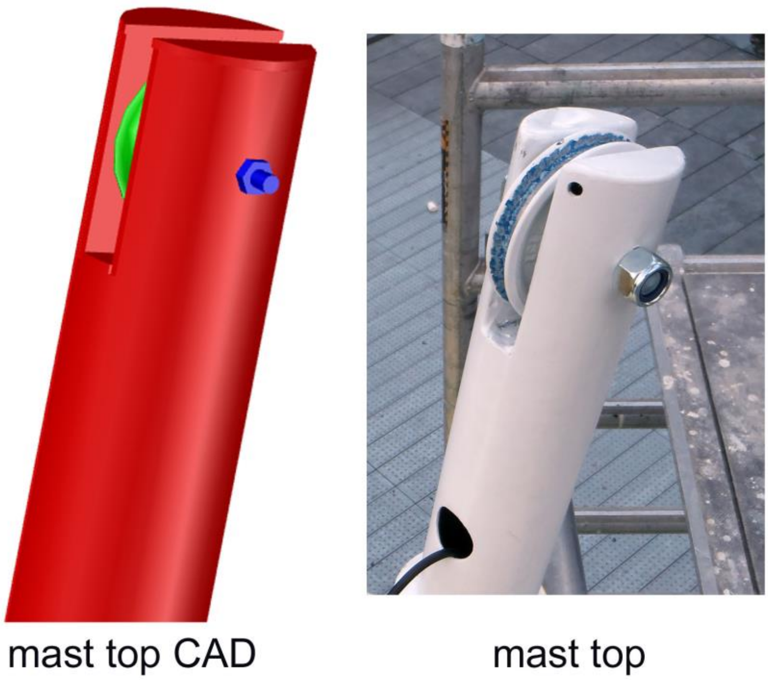


Fig. 7.5b

The cross construction and cables are both connected with lugs (fig. 7.6).

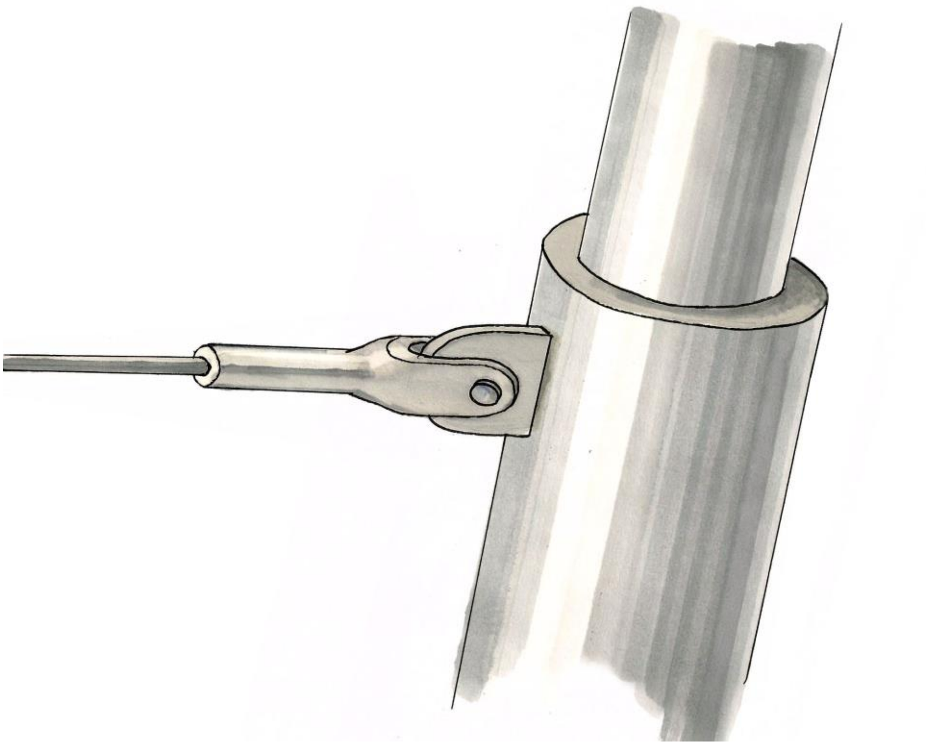


Fig. 7.6: Lugs on mast tops

7.3 stage

The initial plan was to have the stage be a structural part of the construction. Inspiration for the first construction idea was a carousel tent construction (fig. 7.7a and fig. 7.7b).

Fig. 7.7a: Carousel tent construction

center detail mast detail

Fig. 7.7b: Carousel tent construction

Because there are only four masts instead of ten the system would have to be stronger. The system used for the carousel tent would not work here because there is too much backlash and the parts have to be relatively heavy. The carousel tent has to be erected and disassembled more often than the stage at Theatre Square. To make assembly and disassembly more easily for at the carrousel tent some of the stability was traded for more assembly speed. In the second design a trapezium shaped truss frame was supposed to give stability to the masts. There could be a steel construction made of smaller beams in between the main trapezium shaped construction (fig. 7.8). Wooden plates could be screwed on to this frame with torque or allen head recessed screws (fig. 7.9). This would become a fairly complex puzzle.

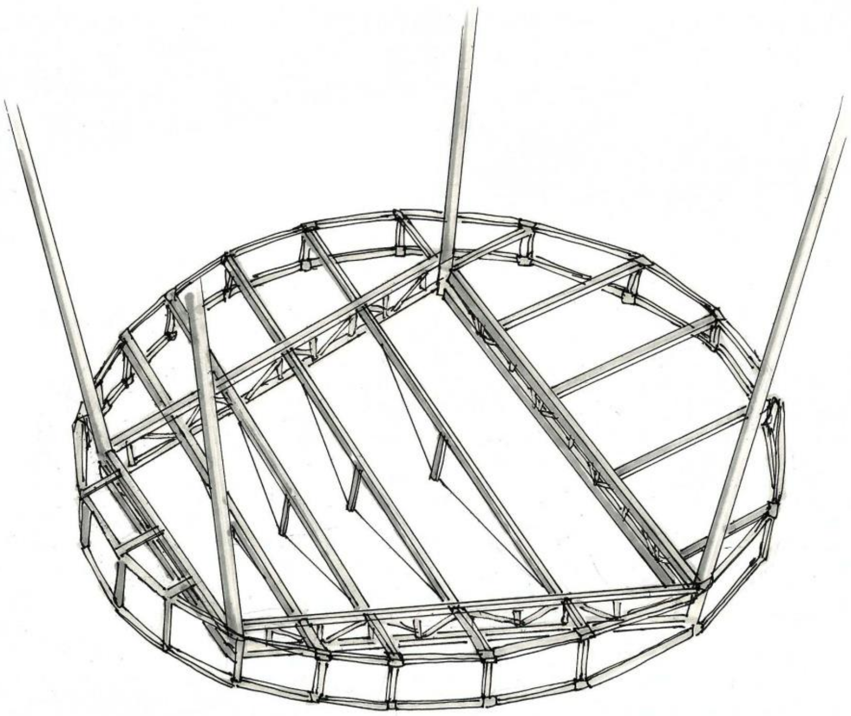


Fig. 7.8: Trapezium shaped construction

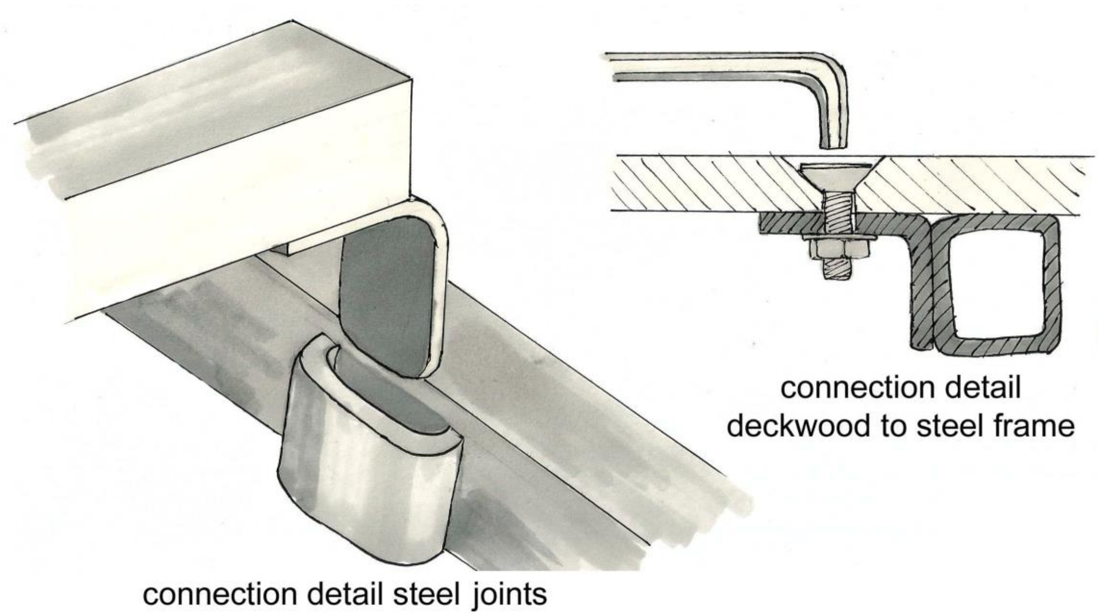


Fig. 7.9

A second option would be to make a wooden construction around the steel trapezium shaped truss. After talking with the fabricator the decision was made to go for a wooden construction. This wooden construction was not seen a structural part of the construction.

7.4 truss

The dimensions of the truss elements where determined in the calculations. The only point of discussion was if the truss had to be at an angle in order to be aligned with the masts. It would be more, easy to produce a truss that was straight. So the possibility was examined (fig. 7.10) but it would give more problems than it would solve. It would mean the hart line of the profiles would be moved outside of the system line of the construction. And the space around the bolt that is holding the mast would be smaller so it would be more difficult the get the bolt in.

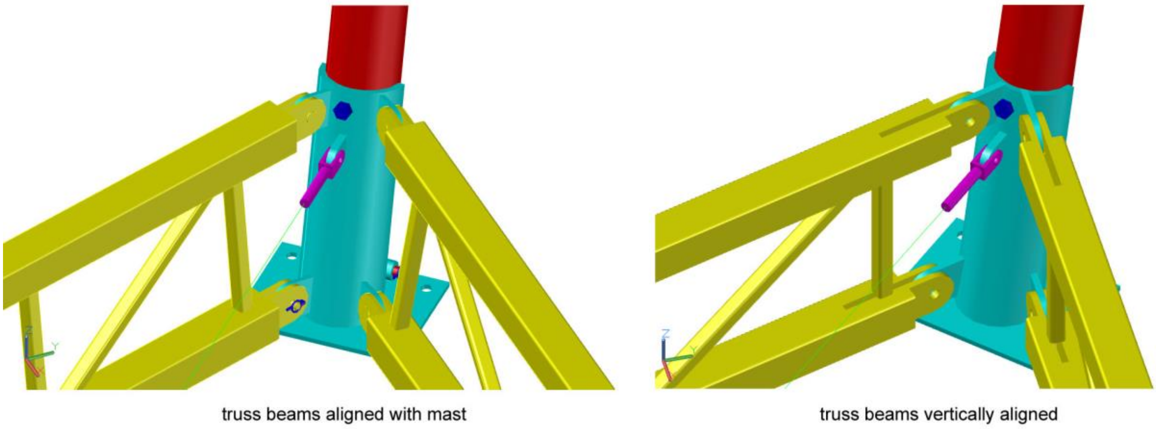


Fig. 7.10

7.5 connection mast to truss

The points where masts are located are also the points where force generated by wind and self-weight are transferred from the stage construction into the deck of the square. The first idea was to place the construction directly on the concrete floor that was the roof construction of the parking lot below. The masts would have to stick trough the deck and steel grid below. The masts would have a hinge point (fig. 7.11) to ease the erection since there are no cranes allowed on the square everything had to be done with hand tools.

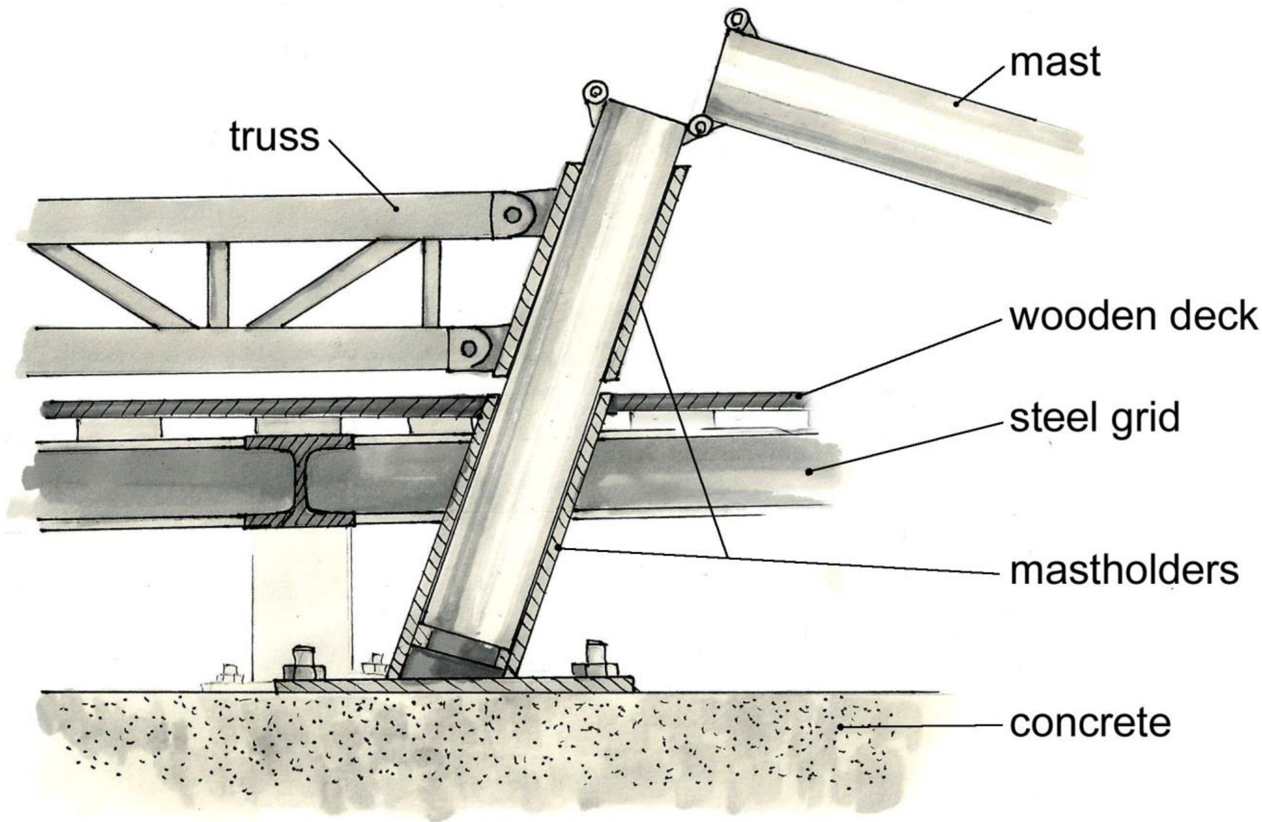


Fig. 7.11: Hinge point in mast

Later is in the process it became clear that the mast had to be attached to the steel grid. This made construction of the masts and connection with the rest of the construction easier. Instead of using a pipe to hold the mast half a pipe (fig. 7.12b left) is used, so the mast does not have to be split in two parts. The hinge point can now be on the floor level (fig. 7.12a and fig. 7.12b right).

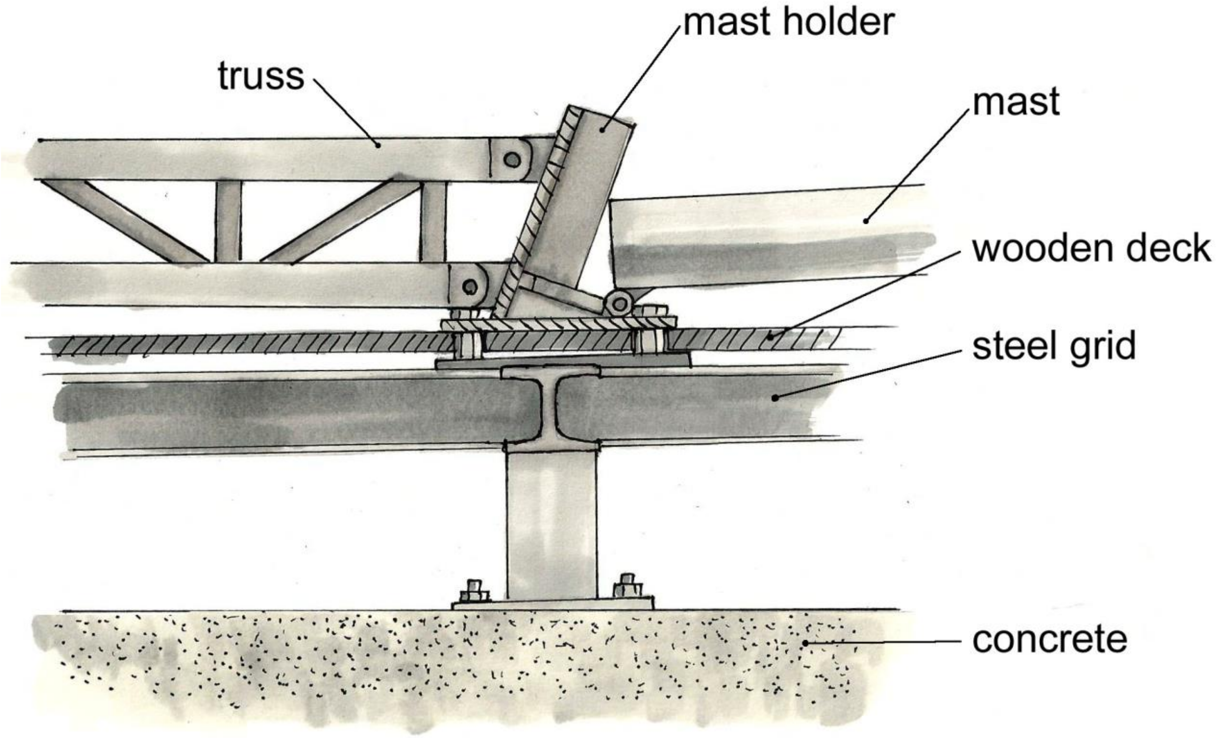


Fig. 7.12a: Hinge point at floor level

cutting a pipe in half lengthwise

mastholder installed

Fig. 7.12b

7.6 foundation

The construction is built on top of an underground parking lot as is mentioned in the chapter “basic structure”. The underground parking lot is one of the first ever build in the Netherlands and the construction is a concrete box that is floating on soil. There are no piles where the parking lot is resting on. Therefore the roof cannot subject to any significant point loads. This could case the concrete of the parking lot to crack. As we found out the Flore was covered with bitumen (fig. 7.13) to ensure that no water would be seeping into the concrete. Drilling holes in the concrete would surly break the seal.

Fig. 7.13: Flore covered with bitumen

One flaw in sealing the connection points for the stage construction could mean that water could seep through the bitumen. Over time the water could seep into the concrete and when frozen case the concrete to crack. Repairing this would be expensive so no one wanted to take the responsibility. The decision was made to Anchor the stage construction to the grid (fig. 7.14) that was built on top of the concrete to support the deck of the square.

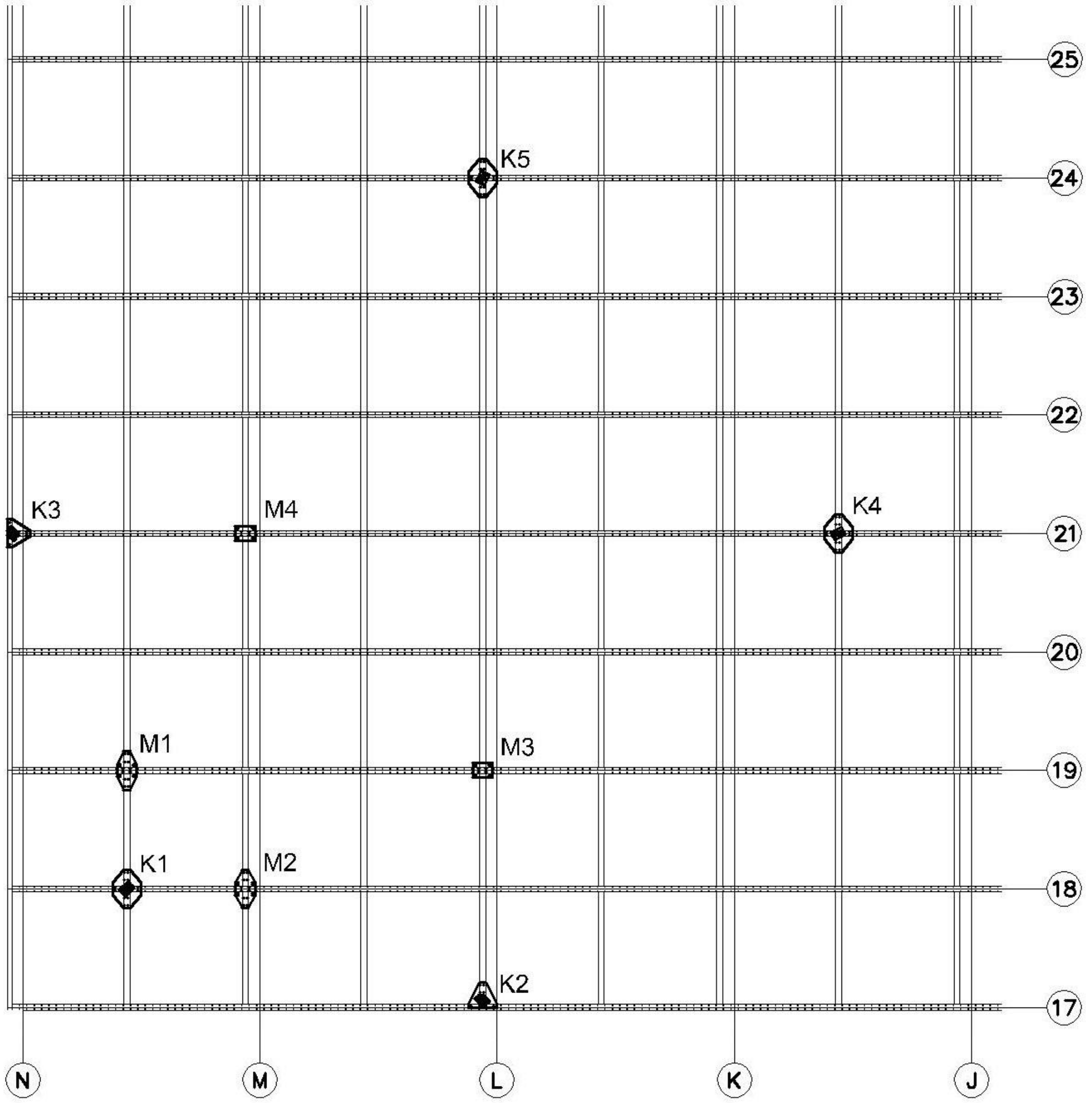


Fig. 7.14: Connection points to steel grid

The reactions forces that where calculated for the stage construction where send to the engineers from City development Rotterdam. The calculated what the effects of these forces would be on the square: see **appendix 01**

7.6 measurements

The cad drawing was based on a file that was provided by the architect. The architect had gotten the drawing from the company who had designed the grid. To be absolutely sure the grid really was built as according to the drawing, approval was asked to open the always busy deck of the square. The boards where removed and pictures where made of each point was selected as a connection point (fig. 7.15).

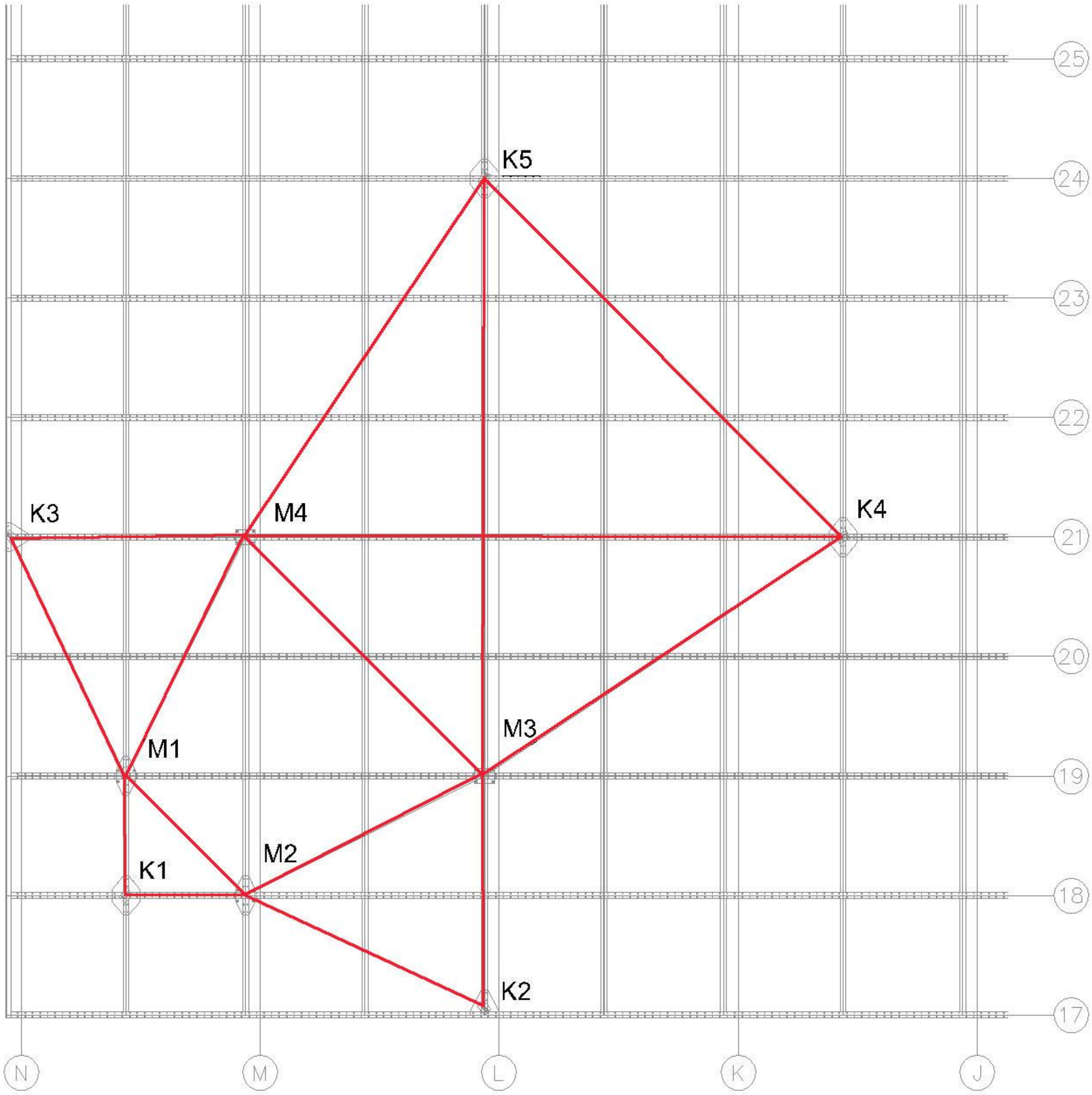


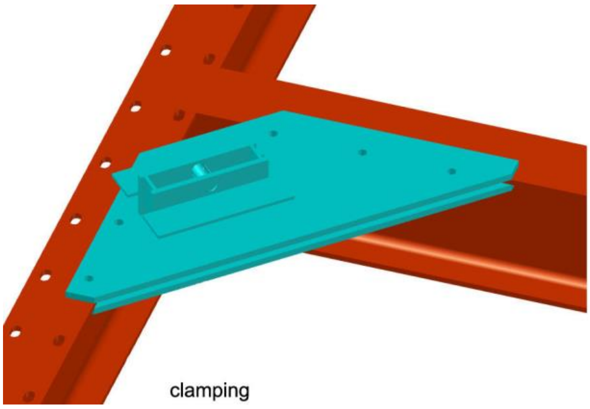
Fig. 7.15: Distance lines between connection points to steel grid.

7.7 attachment

The beams in one direction of the grid had a pattern of holes (fig. 7.16). The position of this pattern was checked on every point.

Fig. 7.16: Pattern of holes

These holes would be used to attach the connection details. At some points it would not be possible to use these holes. Because it was desirable to make as little changes to the existing construction as possible the first idea was to make a clamping construction (fig. 7.17 left). After consulting the City Development Rotterdam it was not a big problem to drill some extra holes in the beams of the grid construction. This would mean the details could be bolted directly to the grid and the construction of these details could be simplified (fig. 7.17 right).



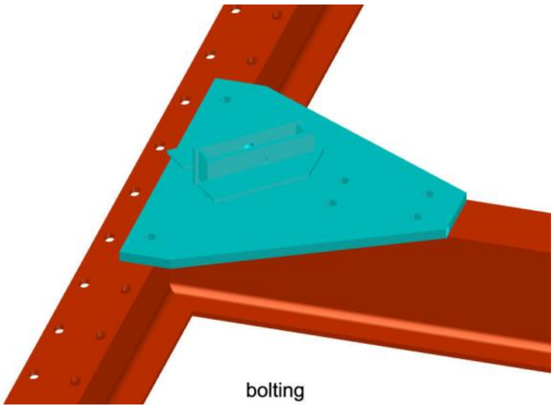


Fig. 7.17

The points where the masts would be attached to the grid would mainly direct a vertical force into the grid. The mast could be bolted on the grid by putting a plate on the grid and welding connection nuts on to it (fig. 7.18). There was enough space to use the standard M20 connection nuts.

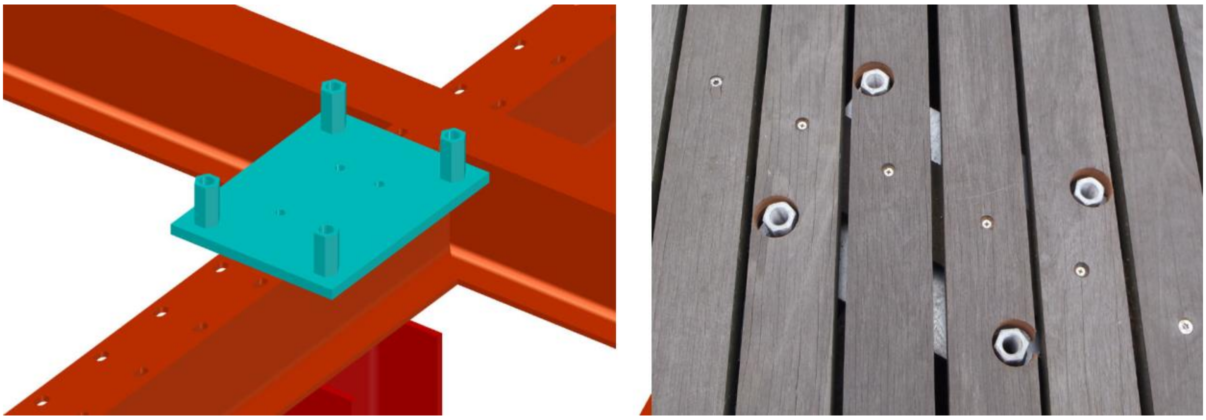


Fig. 7.18: Connection point mast

The connections for front masts are connected only to the beam directly placed on top of the support column (fig. 7.19 left). The columns in the positions where the rear mast are placed are in a less favorable spot on the concrete deck concerning the absorption of forces into the roof. Therefore a bigger plate is also connected to the beams that are placed in between the beams resting on the columns is used (fig. 7.19 right).

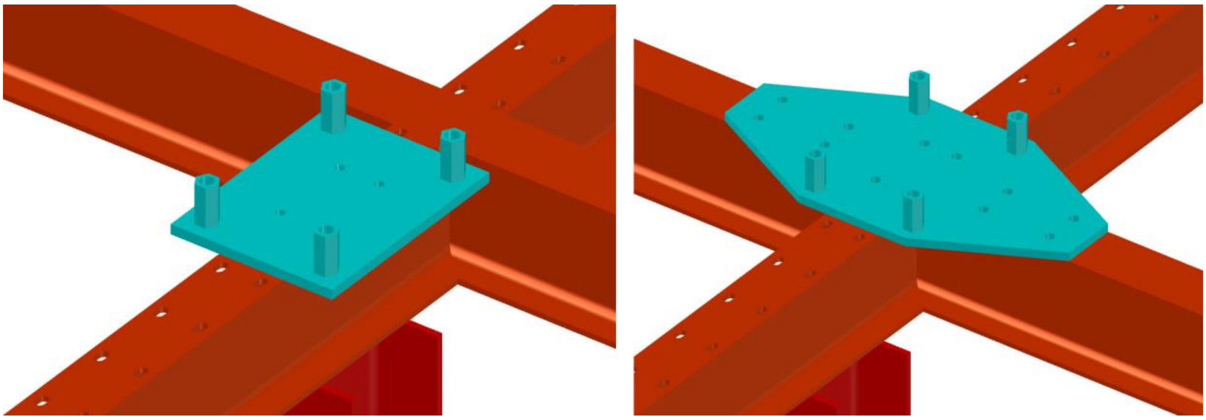


Fig. 7.19: Connections points masts

The cables, or belts used needed to be connected easily and quickly to the deck without the need of tools or lose screws or other small parts that could get lost or might be misused. The first idea was to make a slot in the deck with a pen horizontally crossing the slot. A hook could easily be hooked on and off (fig. 7.20a and 7.20b).

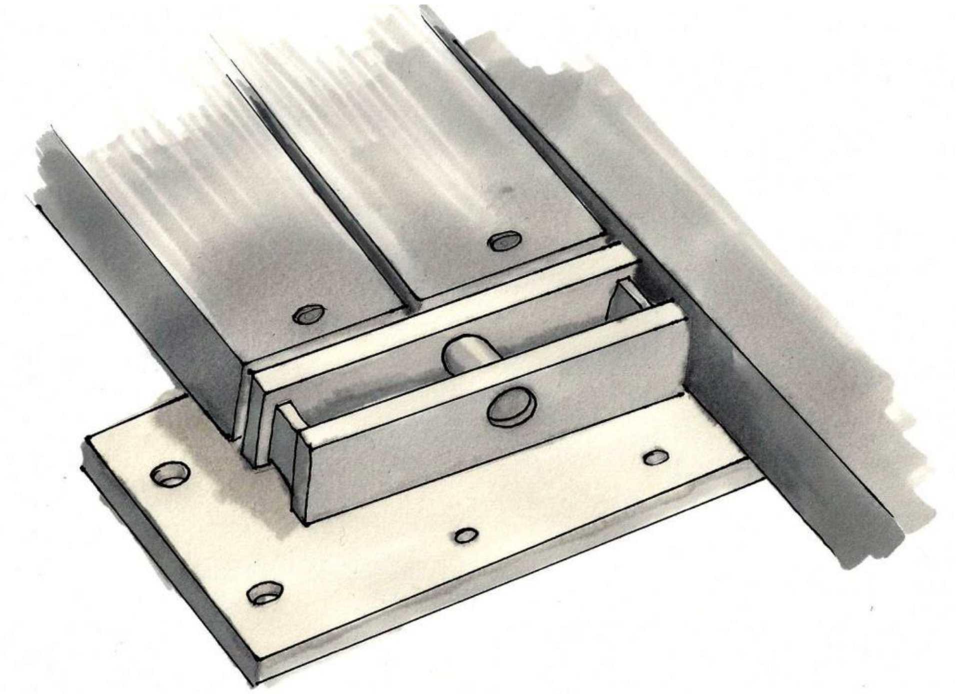


Fig. 7.20a: Cable/belt connection point

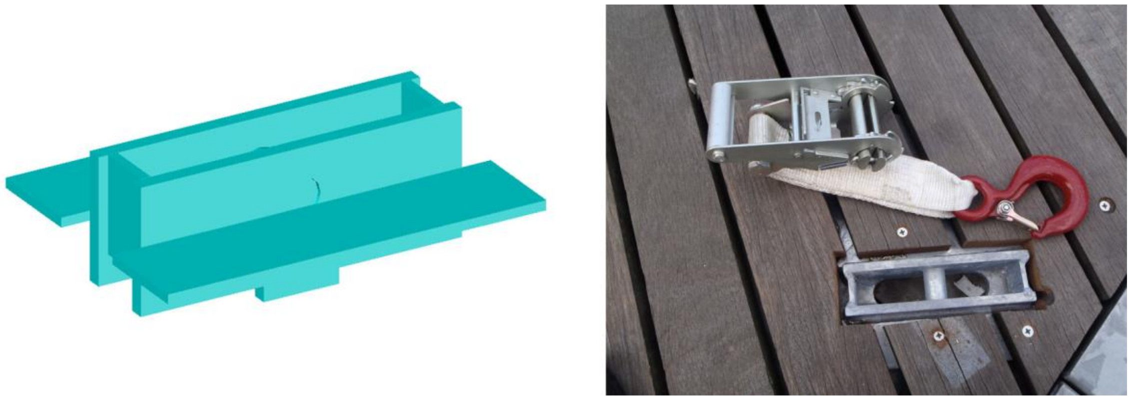


Fig. 7.20b: Connections points masts (left computer model, right photo)

A nut construction like the one in the masts was although easier to construct not used for a number of reasons. The thread could become dirty or even clogged with dirt. There would be a moment in the connection nut that could potentially case it to break of. It would be more favorable to use a different construction so the force could follow the system line. All the connection points for the cables are directed in the direction of the tension force on the cables. In connection K1, K4 and K5 there are no obstacles. K2 and K3 are at the edge of the wooden deck and the shape of the bottom plates had to be different. There was some space between the bottom plate and the boards of the wooden deck. To prevent the boards from moving when someone would walk over them pieces of strip where connected to the side of the slot construction. The boards could be screwed to these strips to secure them.

8 MEMBRANE

The membrane was designed using ixFoten. From ixForten it was exported to AutoCAD and imported in Easy. The patterning was done in Easy exported to AutoCAD for modifications. The details where delivered to the manufacturer as sketches.

8.1 patterning

The form finding for the model was done with ixForten. The patterning for final model was done in Easy and afterwards exported to AutoCAD. Easy was used because the model was used for calculations by people from Tentech was made in Easy. To prevent mistakes the same model was used for patterning (fig. 8.0a, fig. 8.0b and fig. 8.0c).

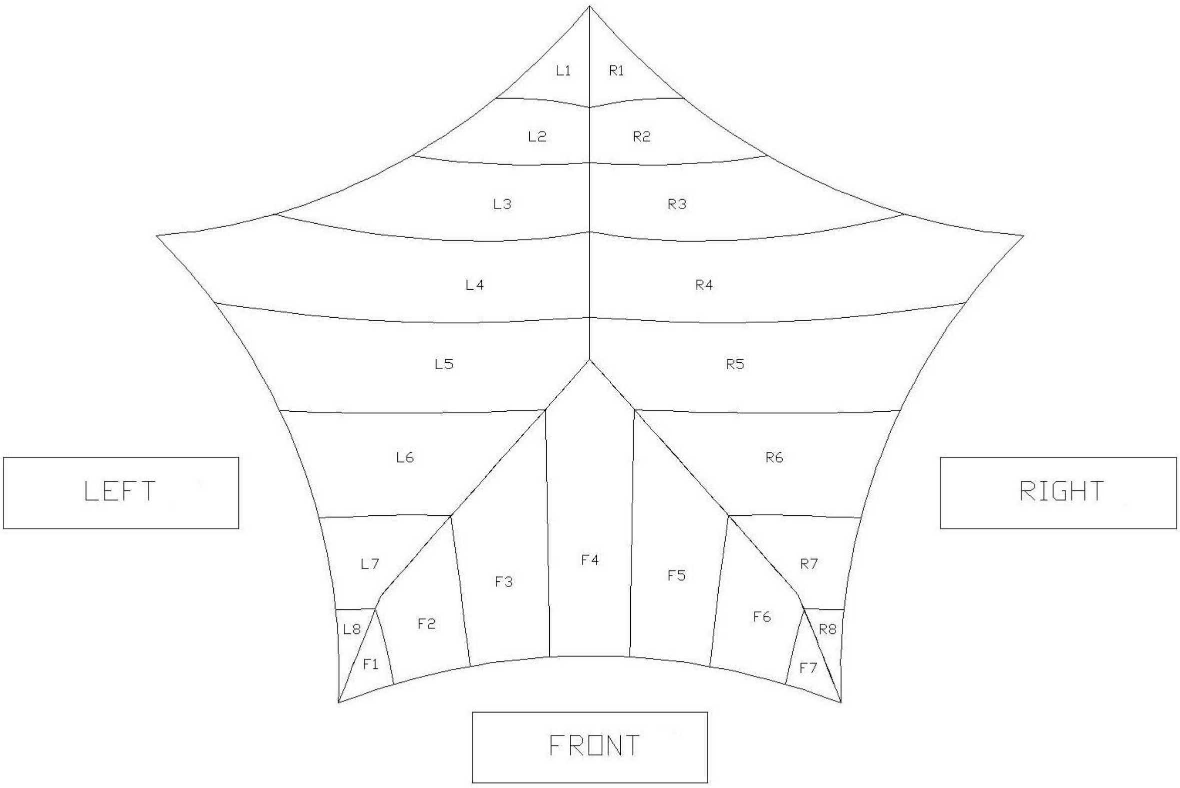


Fig. 8.0a: Patterns

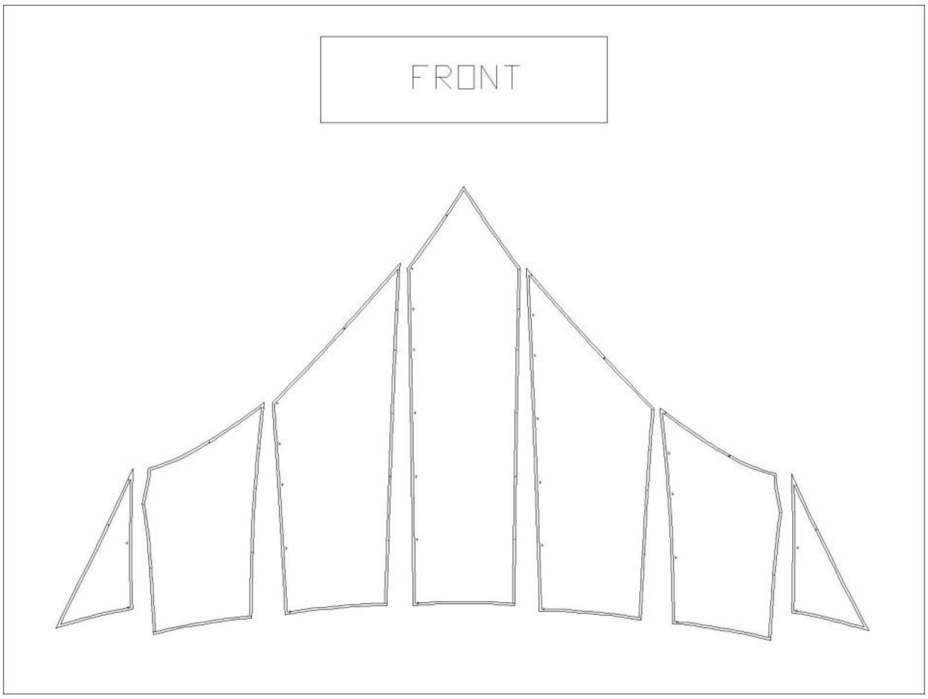


Fig. 8.0b: Patterns

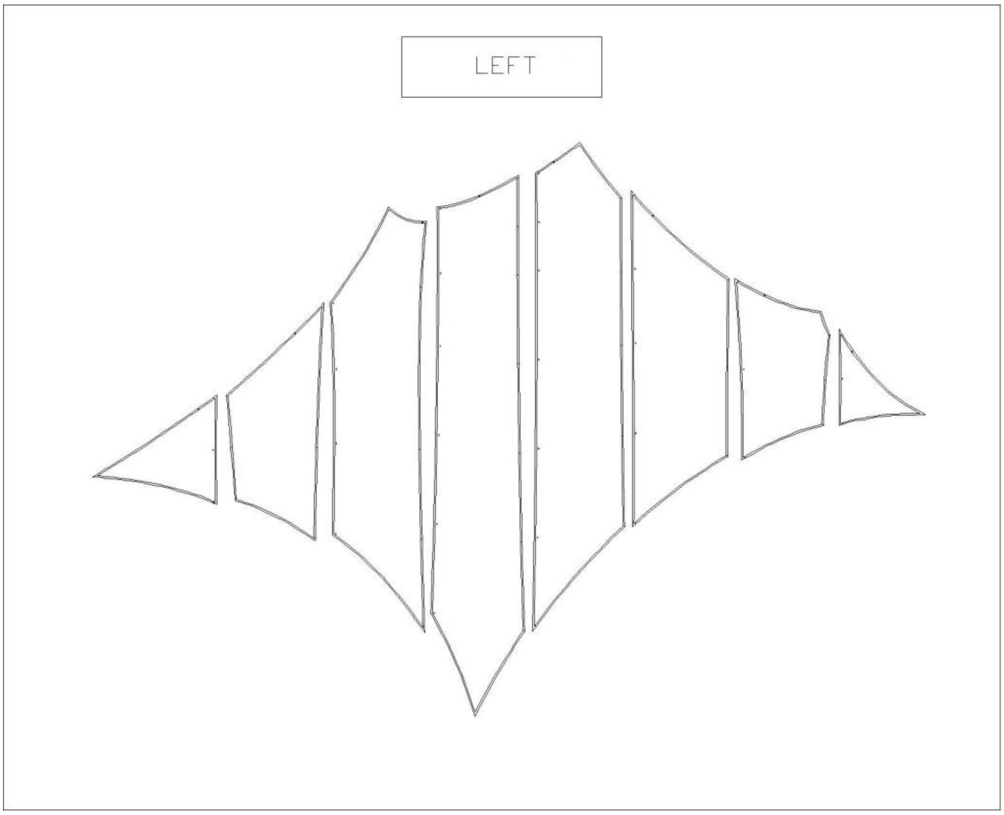


Fig. 8.0c: Patterns

The right side and left side have little differences due to round offs in the software. In the pictures I sowed only the left side because the differences are so small they will not be visible in the drawing, except for the fact the patterns are mirrored.

These raw patterns generated by the software where edited in AutoCAD (fig. 8.1) before send of the cutter.

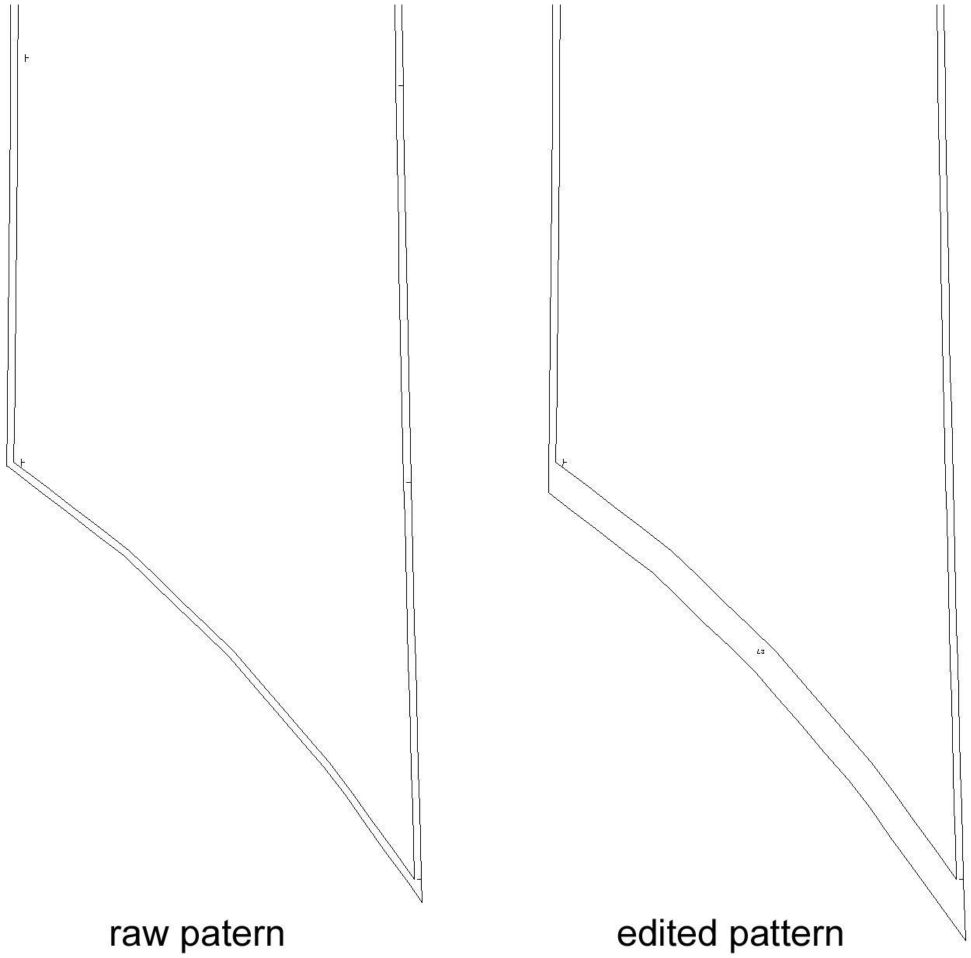


Fig. 8.1

The offset at the outer edge was enlarged with 80mm so there was some room for the edge cable/rope. Increasing or decreasing the offset within certain limits would not cause a problem as long as it is done in a consistent way over the entire set of patterns. It would just result in the entire membrane becoming a bit bigger or smaller. The length of the ropes could be adjusted to the length of the edge of the membrane instead of edge cables with a fixed length. The rest of the edges had an offset of 20 mm because the width of the welds would be 40mm. The pen marks generated by the software where deleted except for two of them on either side of the outside of the pattern. The rest of the pen marks was not necessary and would partially still be visible after welding witch is of course not desirable. The number of the patterns placed in a spot (not visible in the image) on the pattern was moved to the outer edge. This would ease the positioning of the patterns in the right location during welding. The numbers would be covered when the pocket for the edge cable/rope would be made. The patterns where nested on a strip of 2650mmleaving (fig. 8.2) an edge clearance of 50mm on either side. The orientation of the patterns was kept the same so that the warp and weft direction of the yarn would not be changed. When welded together the warp and weft direction should be orientated in the same direction trough out the membrane.

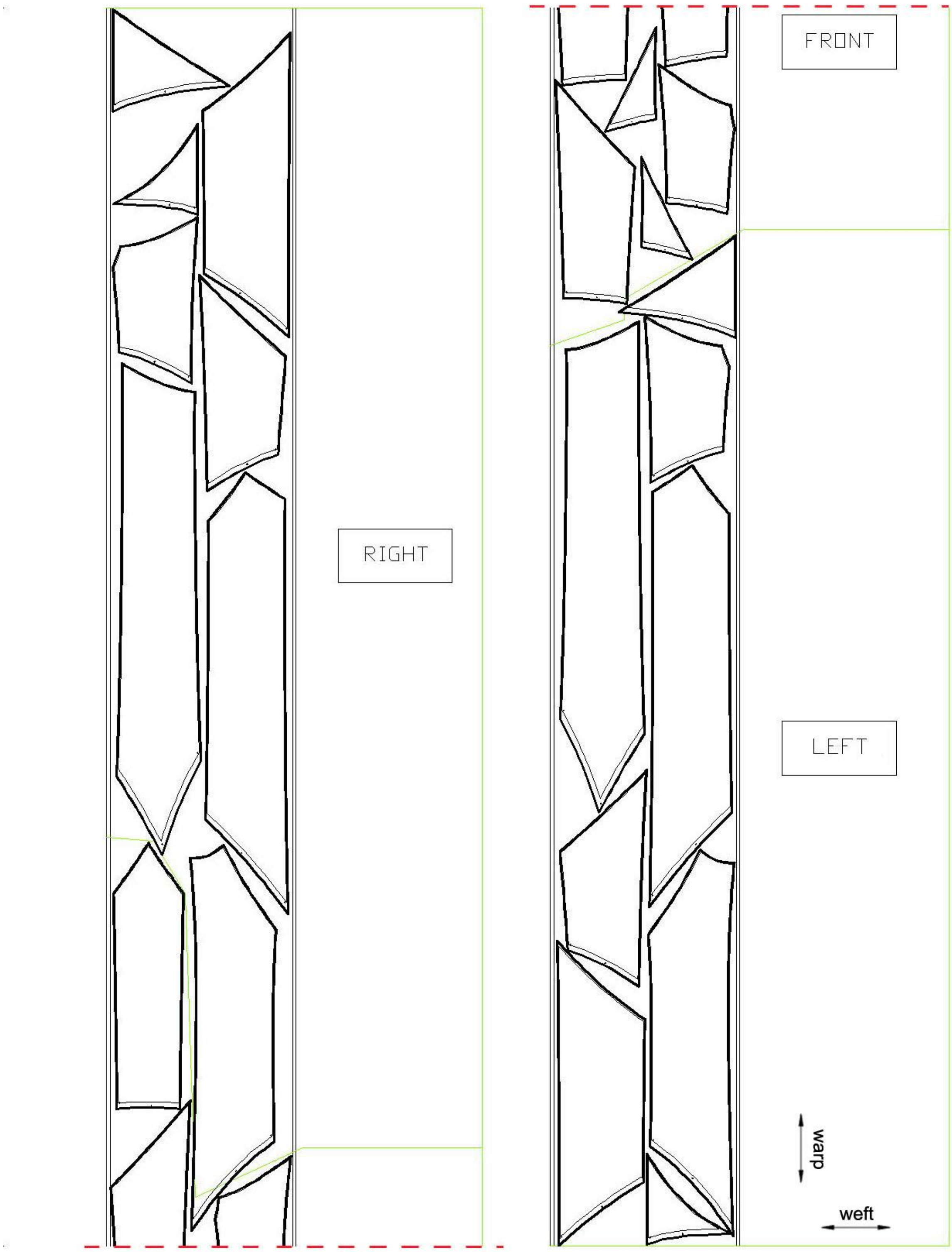


Fig. 8.2

8.2 detailing

There are 5 different types of details in the membrane (fig. 8.3)

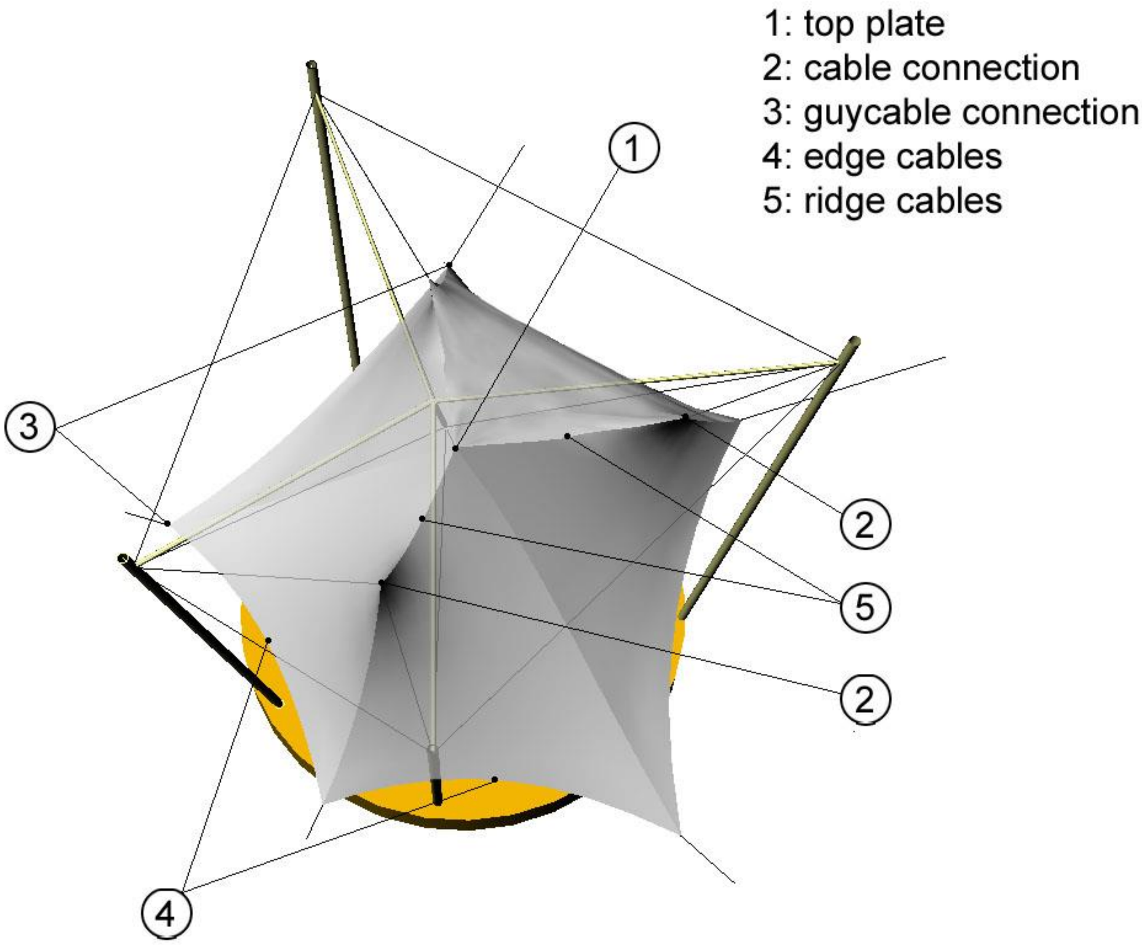


Fig. 8.3: Details in membrane

The first idea was to use cables in the edges and ridges. Because the membrane has to be installed, dismantled and folded, cables would not be the best choice here. The edge cables where replaced by ropes and the ridge cables by TIRbelts.

8.3 top plate

According to the calculation the top plate has to be capable of handling a maximum force of 50,5 kN. The first idea was to fold the belts together in some way. But after a bit of puzzling the manufacturer proposed to use components he could take of his shelf (fig. 8.4).

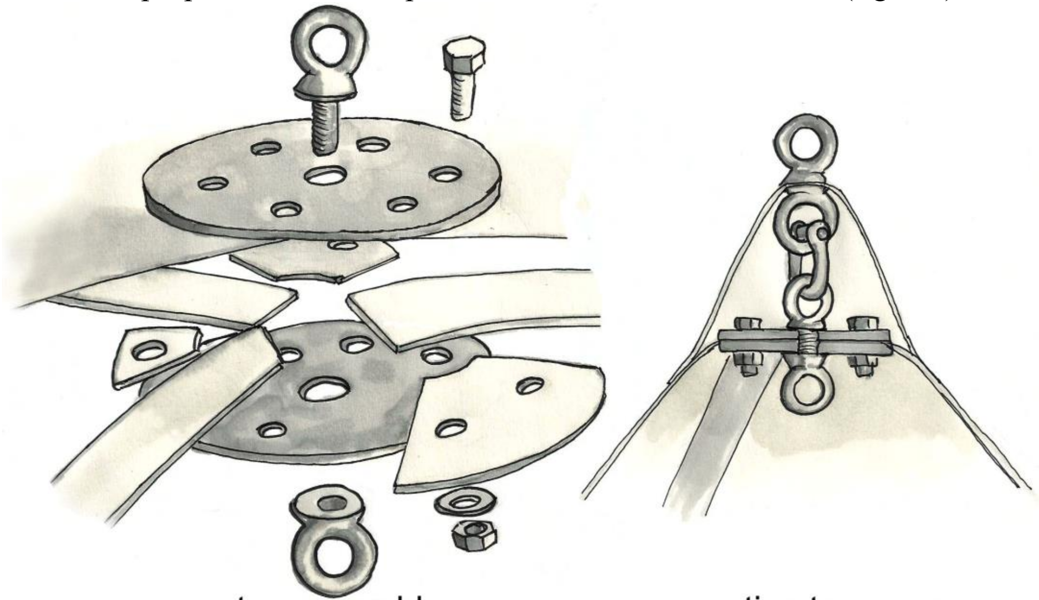


Fig. 8.4: top plate 01

The round stainless steel disks would be bolted together clamping the TIRbelts. The TIRbelts are welded on the membrane. Parts of the disk surface not covered by the TIRbelts can be filled out. The ring on the top of the membrane is shackled to another ring could be used to attach it to the frame. The rings and chopped off point are essential to the architectural statement the membrane is supposed to make. The shackles covered by an ornamental piece of fabric.
A problem with this system would be that it has to withstand a maximum force of 50,5 kN. The 50,5 kN is the most extreme and is in reality not likely ever occur. But still the disks of 2mm thickness would not even come close to taking the 50,5 kN without permanently deforming. The next idea was a similar solution with custom made parts (fig. 8.5).

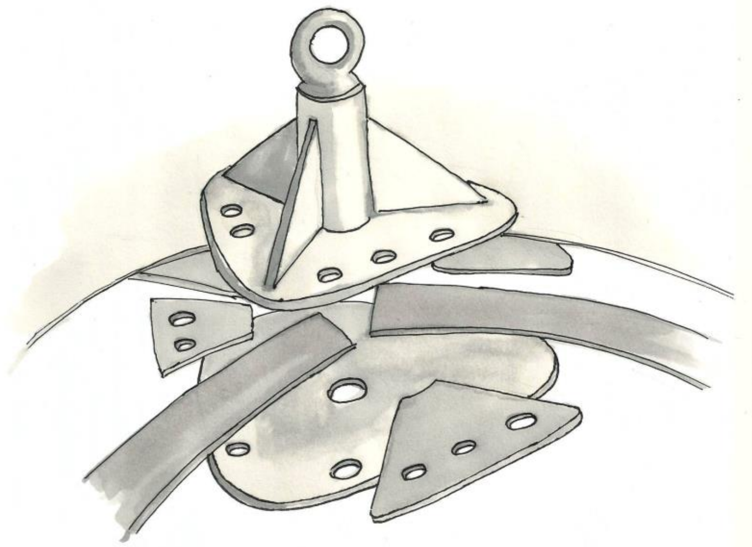


Fig. 8.5: top plate 02

The top plate has a pipe welded to it to create a distance between the ring and the plate (fig.8.5). Ribs are welded between this extension pipe/rod to guide the forces from the TIRbelts to the ring. The ribs would double up as replacement for the membrane “chopped” of the top. This solution is an improvement on the first solution in simplicity and capability to handle the 50.5 kN force. The clamping of the TIR belts that have a width of 50mm the top detail would have to become relatively big in compared to the rest of the structure. So a different solution that would make it possible to scale the detail to a more suitable size is desirable (fig.8.6).

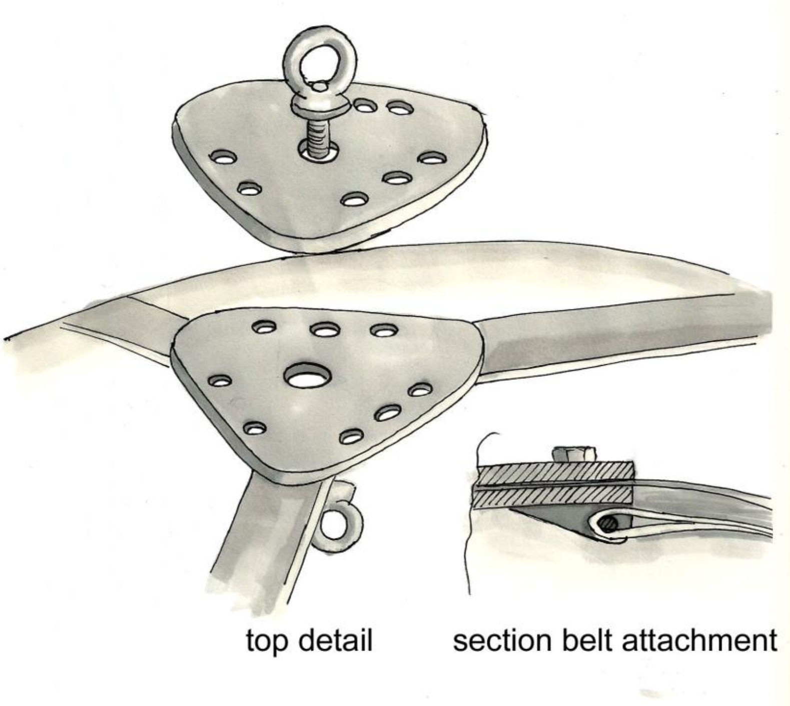
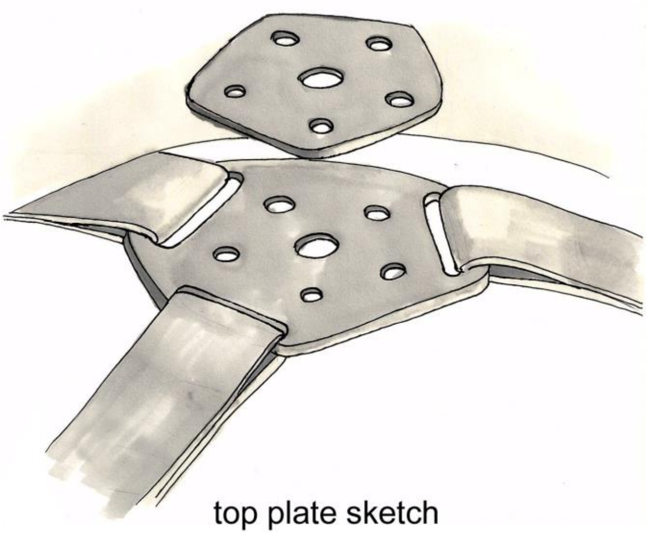


Fig. 8.6: top plate 03

The solution was to flip the TIR belts around a rod mounted on the plate so no extra length is needed for clamping. Although the top plate could now just be a straight plate the bottom plate would still require a bit more effort. So a final change to the design was made (fig. 8.7).



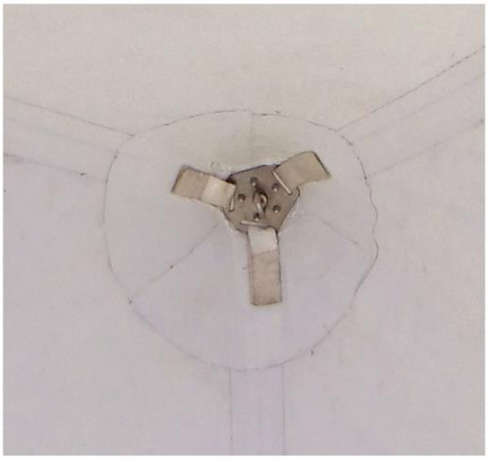


Fig. 8.7: top plate 04

The surface of the top plate was reduced so that the belts could be folded around gaps directly cut in the bottom plate. In fig. 8.7 you can see that the manufacturer did not connected the TIRbelts to the top piece but added extra PES belts on top of the TIRbelts. This has the advantage that the strip of membrane welded over the TIRbelt does not have to be broken. The covering strip has been left out in the sketches because it would make them too messy.

8.4 cable connection

In the points where the membrane would be hung from a single cable on the front side of the membrane or by a double cable on the back side the same principle could be applied (fig. 8.8).

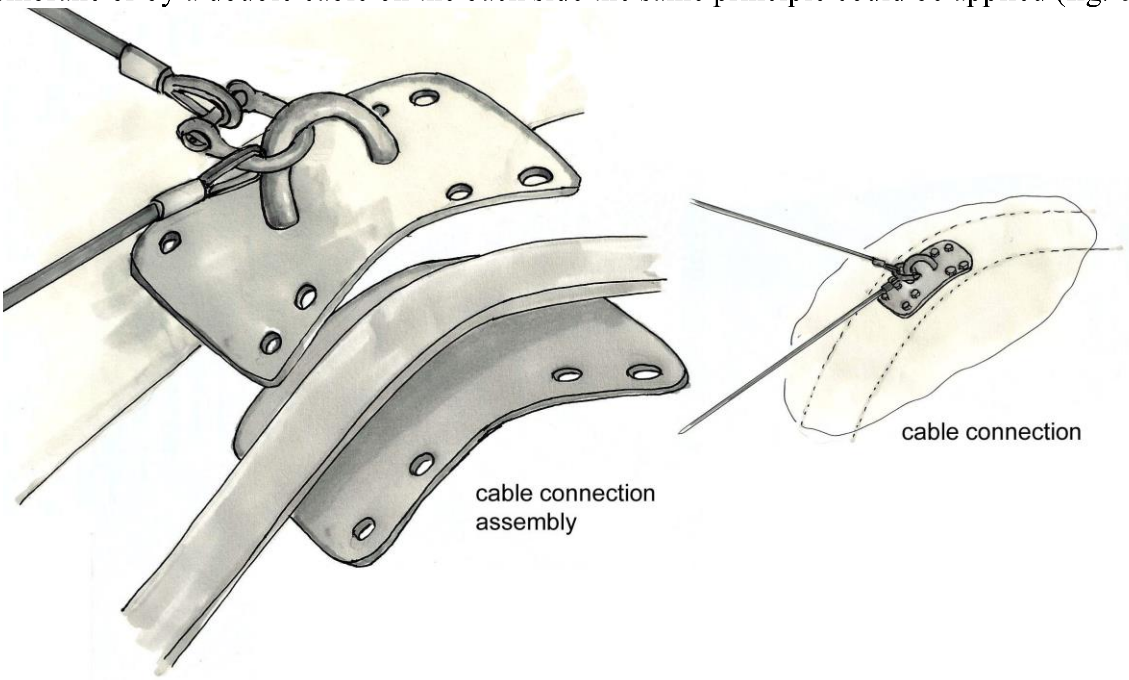


Fig. 8.8

A set of clamping plates bent in the shape of the membrane. The cable or in this case belt will be clamped and the cables could be attached to a lug or ring. In this case the membrane would be handled quite often this kind of detail would be sensitive to wear and tear. Unlike the top that could be flattened and properly packed without folding it. This would be more difficult for the cable connections so a more flexible solution would work better here (fig. 8.9).

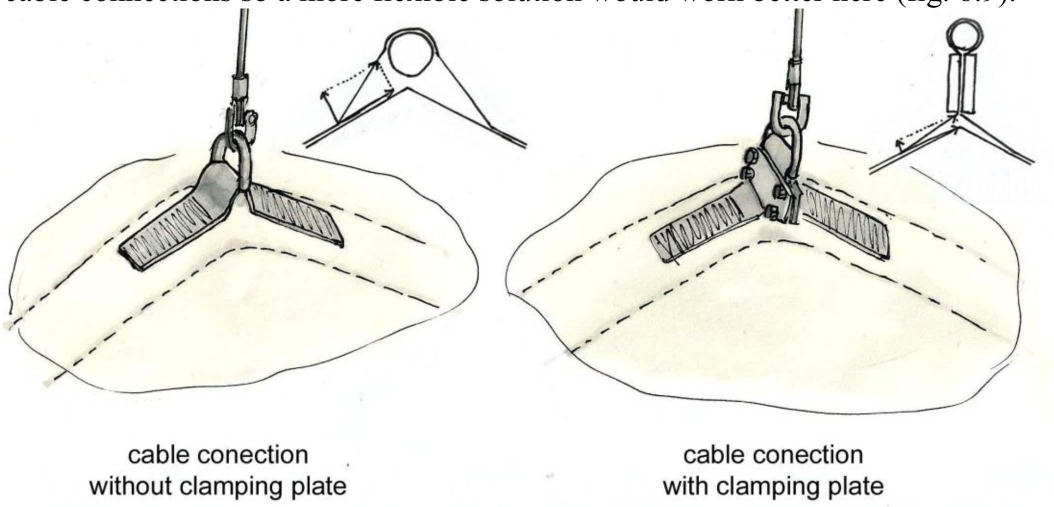


Fig. 8.9

8.5 guy cables connection

The guy cables are connected with standard connectors the manufacturer of the membrane had. This matches well with the circus inspired theme (fig. 8.10).

Fig. 8.10: guy cable connections

8.6 edge cables

The edge cables are actually not cables but ropes as mentioned previously in this chapter. The point with rope that kind of makes me wonder if it really works is that it stretches a lot more than most types of steel cable. But even if it does the pocked that holds the rope will double the membrane thickness on the outer edge of the membrane and locally increase the stiffness (fig. 8.11).

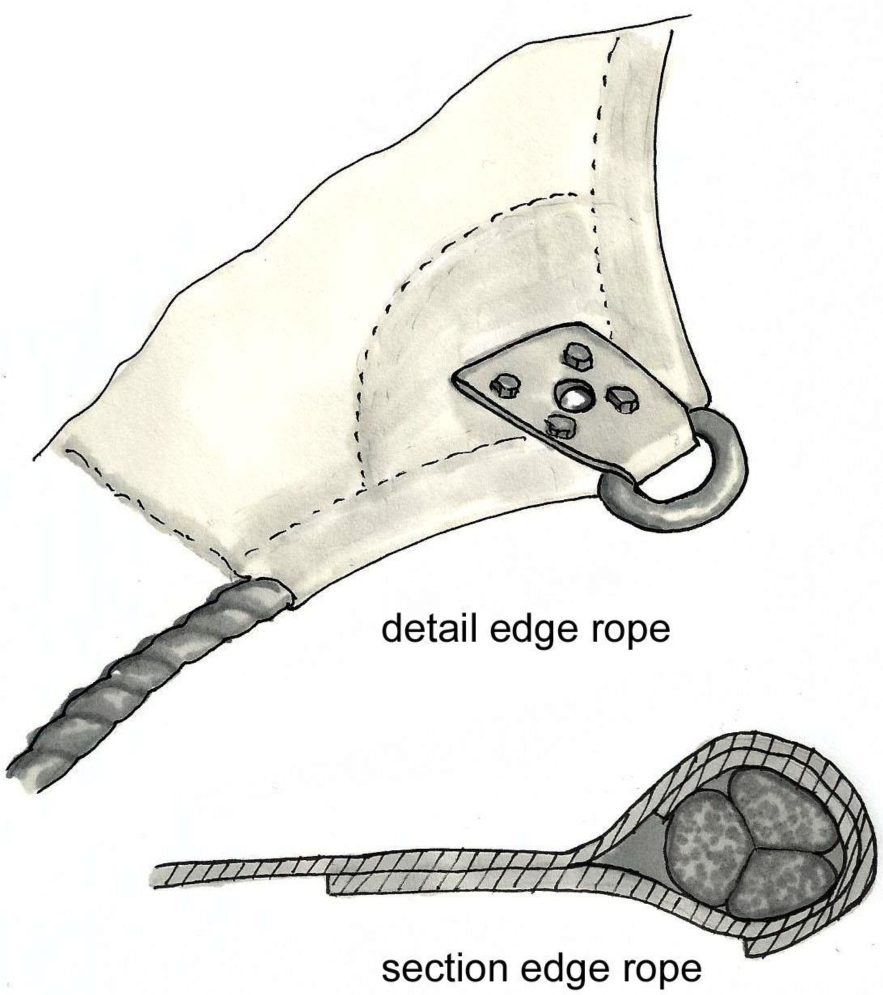


Fig. 8.11: guy cables

8.7 ridge cables

The ridge cables are replaced by TIRbelts. A TIRbelt is a polyester belt that is coated with PVC so that it can be welded on the fabric. The belts are than covered with a strip of membrane to give it a nice finish.

I have no technical data on this TIR belt. I did contact the manufacturer of the membrane about this but he has not replied until now.

9 DRAWINGS FOR MANUFACTURE

Because this is a small scale project the communication between the manufacturers and designer was direct or through very short communication lines. For the steel construction 4 technical drawings where made: see **appendix 02**
For the connection to the square a set of two technical drawings was made: see **appendix 03**
The patterning for the fabric was sent to the cutter as a CAD file and the details of the membrane where discussed with manufacturer via sketches and examples of actual details in the factory. The wooden stage was nothing but a few rough sketches before it was decided that it would not be part of the construction. Al the woodwork was done in the workshop. Perhaps the manufacturer made sketches of it but I never saw these.

10 MANUFACTURING AND ERECTION

The manufacturing was done by six companies: Lecon b.v.: steel, Van der Sneppen b.v.: cutting the membrane, De Markies: manufacturing the membrane, Lilith Ronner van Hooijdonk: painting, Duurt & c.o.: erection and City Development Rotterdam: modifications to the square.

10.1 steel work

Steel work was done by Lecon b.v.
Contact with the galvanizer was done by Lecon b.v. (fig. 10.0)

Fig. 10.0: Lecon b.v.

10.2 membrane cutting

Membrane cutting was done by Van der Sneppen b.v.
In fig. 10.1 you can see the cutting table and computer used to import the files from auto CAD to the cutting machine.

In fig. 10.2 can see a picture of the cutter head and a detail of the cutting table. The pattern of holes is connected to a pump and while cutting the pump creates a vacuum so the fabric will not move while it is being cut.

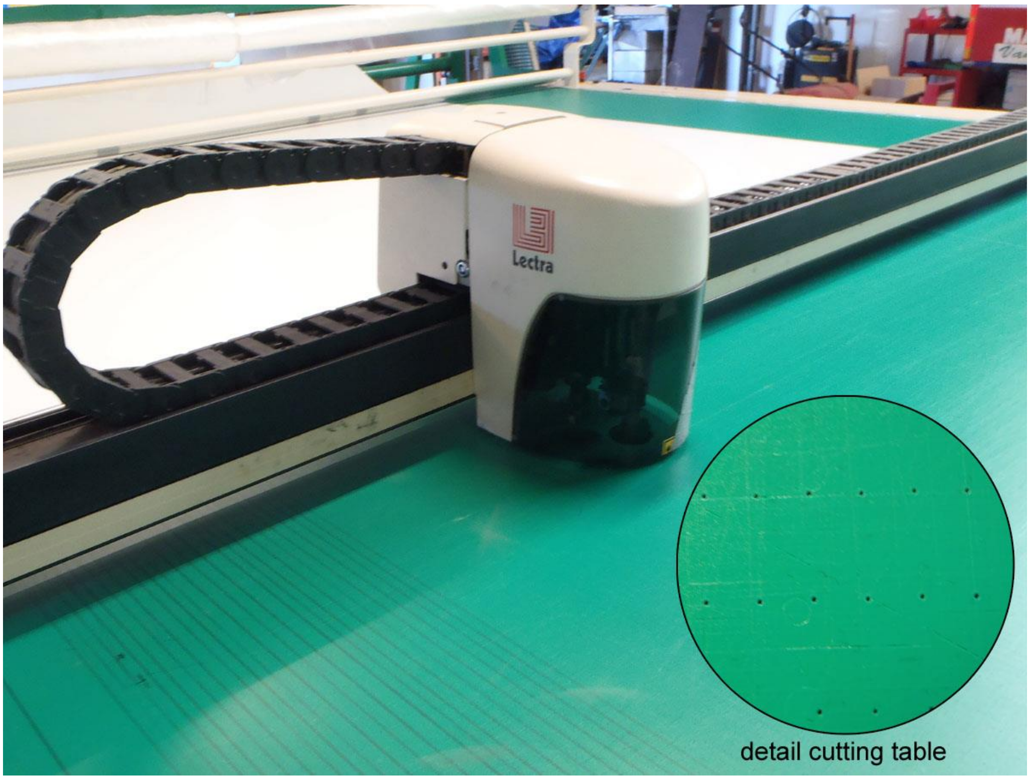


Fig. 10.2: cutter head

The cutter head has 2 pneumatic pistons that can be equipped with a cutting tool or a pen (fig. 10.3).

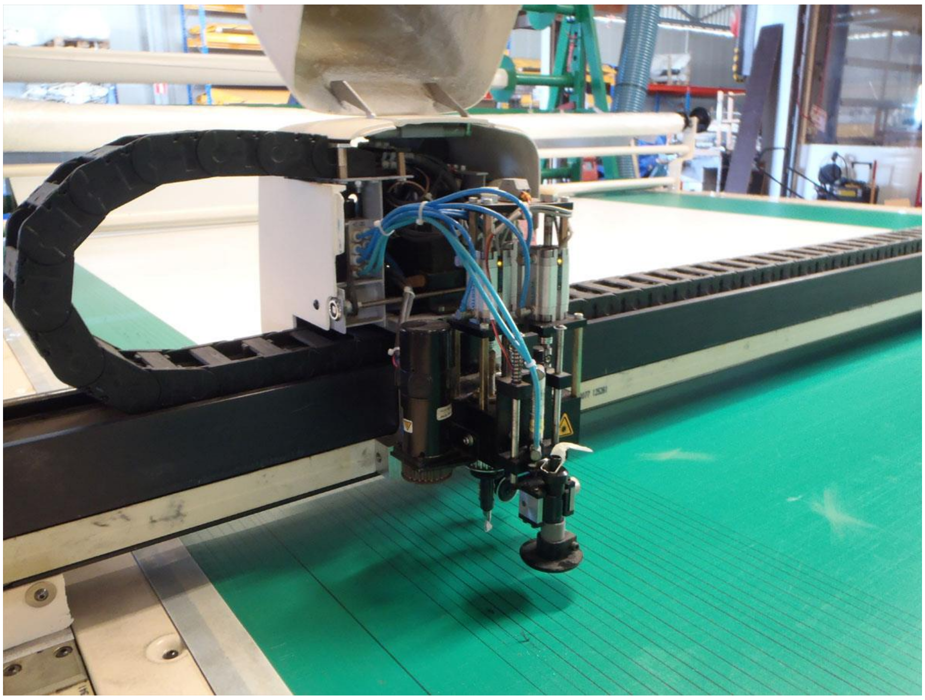


Fig. 10.3: cutter and pen

The patterns where layout on the Flore (fig. 10.4).

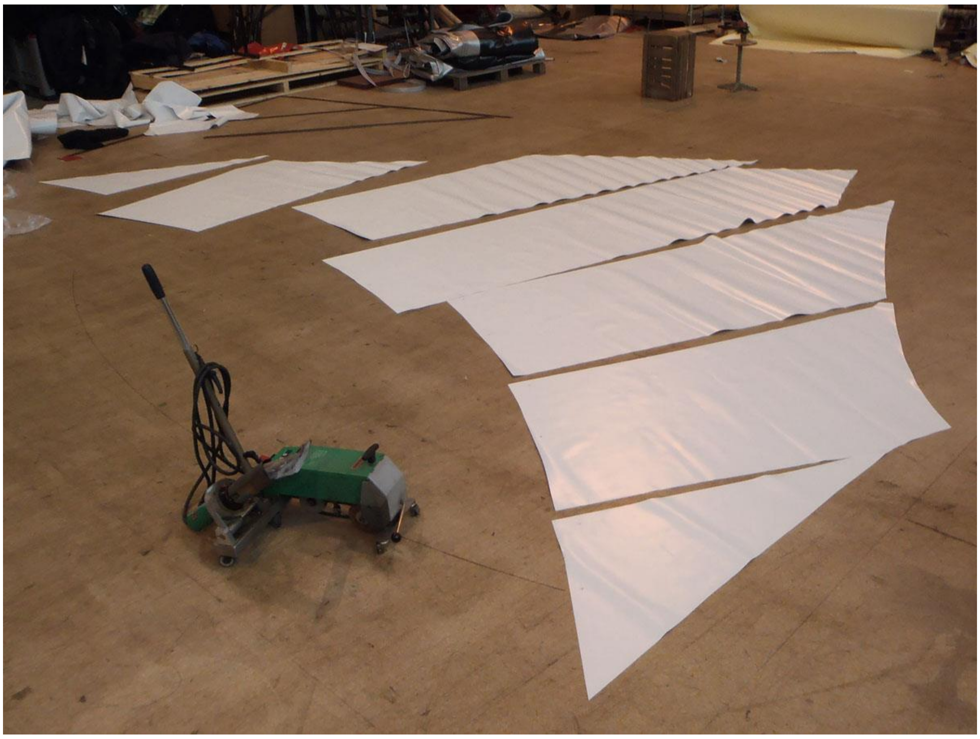


Fig. 10.4: Patterns on floor

The pieces of fabric are taped together at the right position and welded with a hot air welder (fig. 10.5). After the patterns are all attached together the details are done with a hand welder.

Fig. 10.5: PVC welding

10.3 erection

The erection of the construction on site took one day to complete. The whole construction was packed on the truck of Duurt & co (fig. 10.6) the day before and transported to Rotterdam from Nijmegen (about 120km).

Fig. 10.6: Construction on truck

After unloading the first thing that was done was to attach the mast holders to the anchoring points in the square. After the truss was mounted the mast is placed in there right position (fig. 10.7).

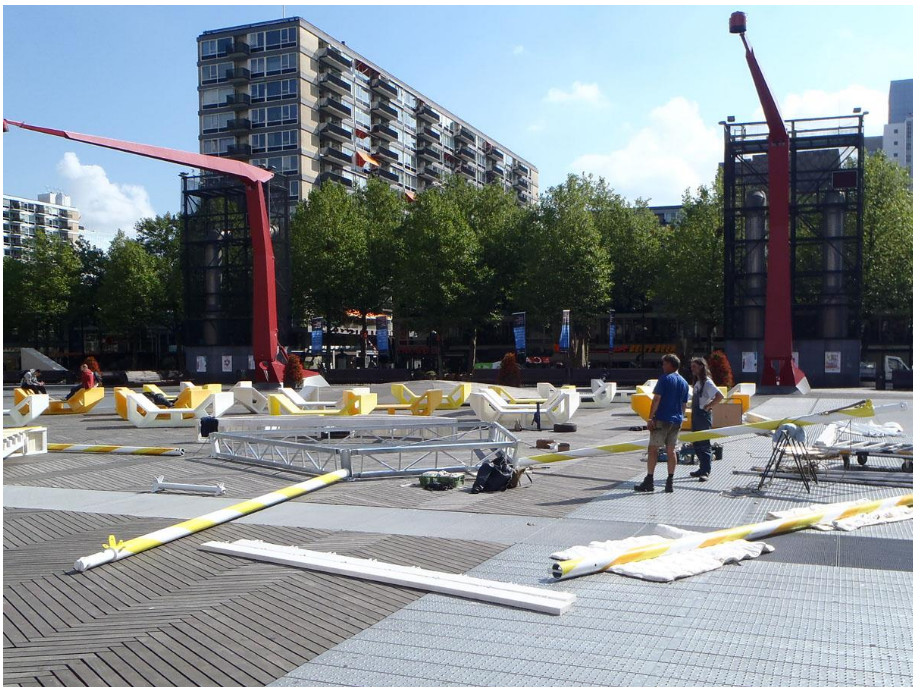


Fig. 10.7: Erection 01

The next thing was raising the masts (fig. 10.8 and fig. 10.9). This had to be done with tirfor's and bare hands because cranes where not allowed on the deck of the square.

Fig. 10.8: Raising the masts

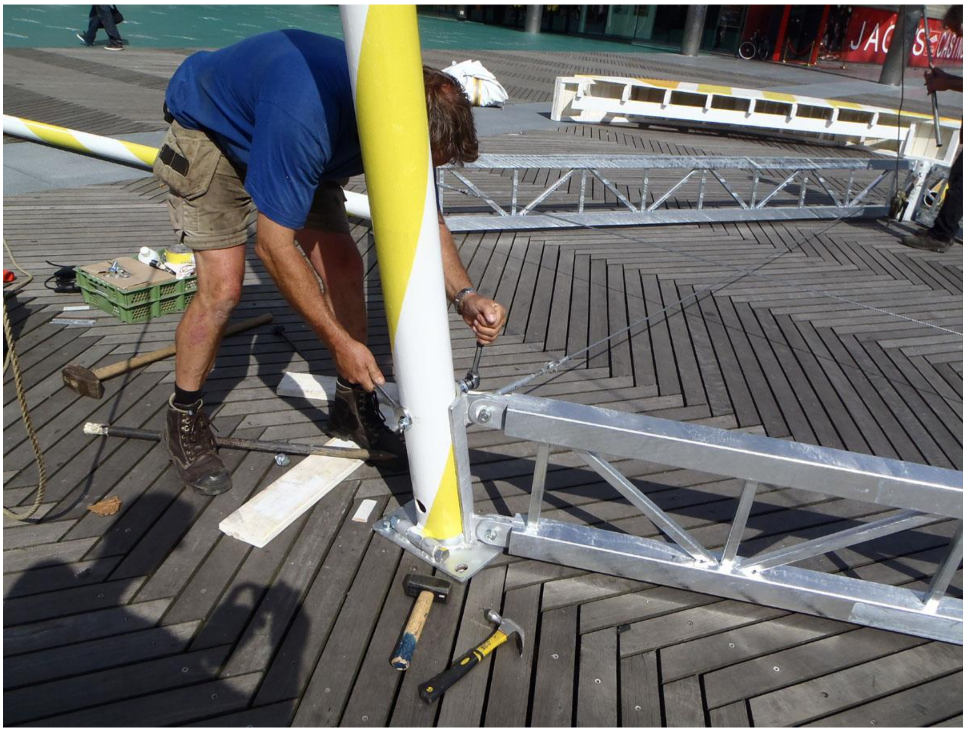


Fig. 10.9: Securing the masts.

Assembling the top construction, and lifting it in position (fig. 10.10)

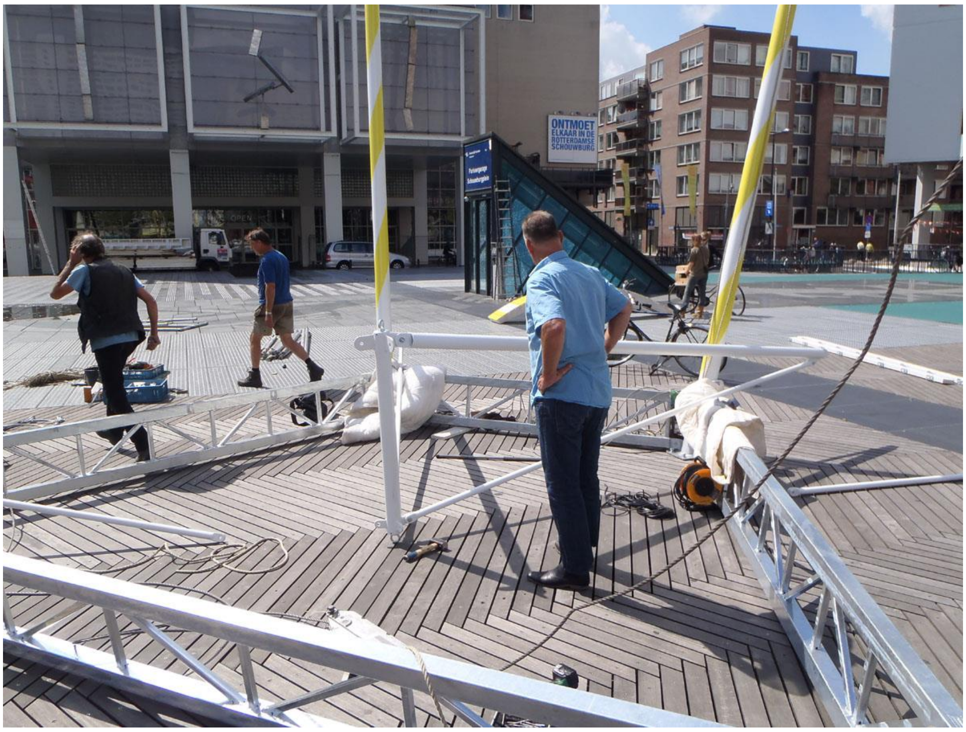


Fig. 10.10

Putting the stage construction together (fig. 10.11).

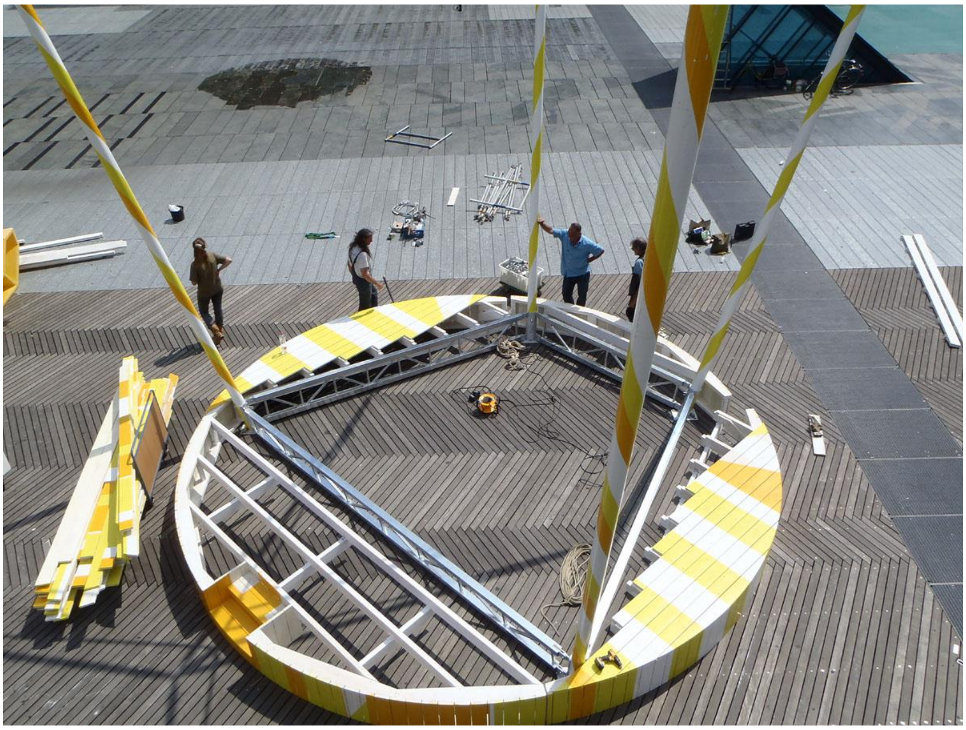


Fig. 10.11

Solving the puzzle of the stage deck and screwing the boards to the support construction (fig. 10.12).

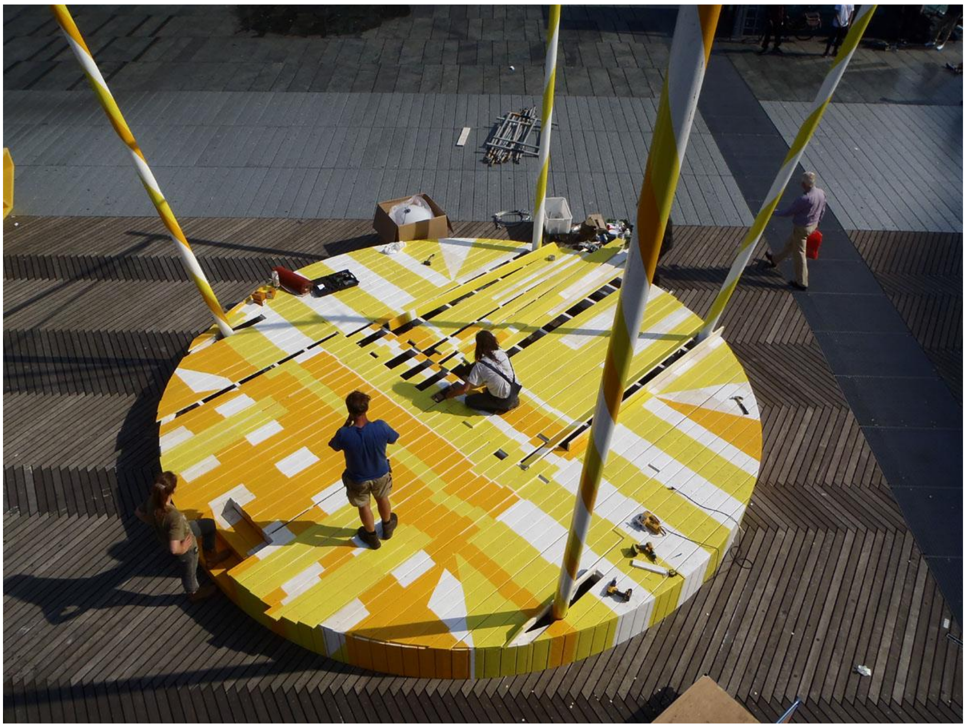


Fig. 10.12

Hanging the membrane on the construction (fig. 10.13).

Fig. 10.13

Attaching the guy belts and tensioning them (fig. 10.14).

Fig. 10.14

Looking at the finished work (fig. 10.15).

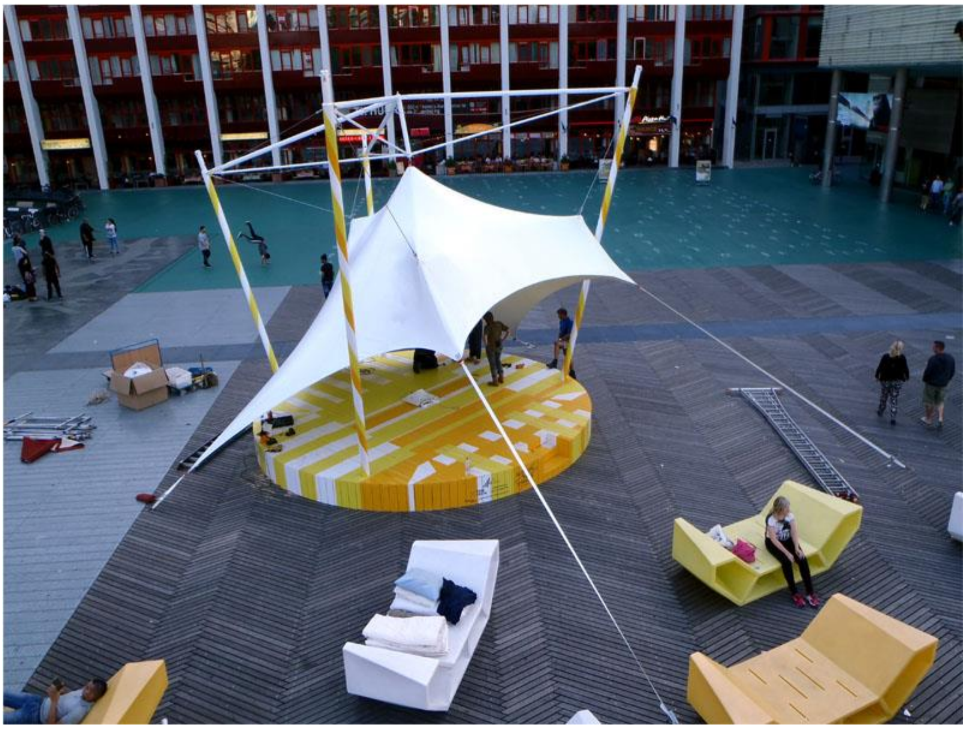


Fig. 10.15

Dismantling the fabric (fig. 10.16).

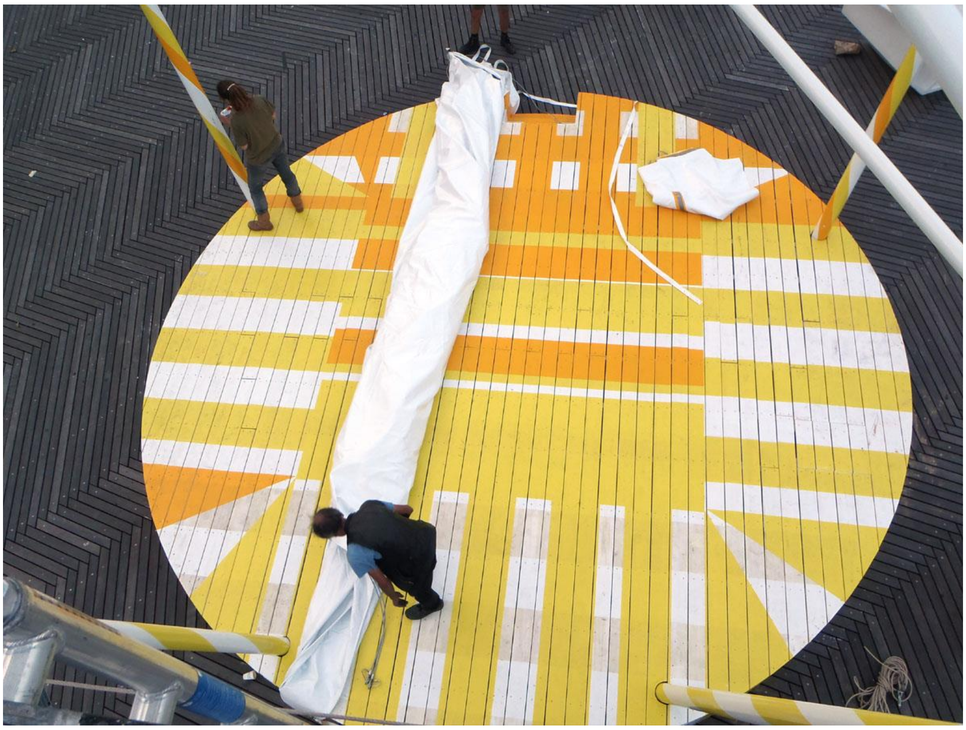


Fig. 10.16

Folding the fabric to a package ready for storage (fig. 10.16).

Fig. 10.17

11 CONCLUSION

At first I am positive about this project and the results. The main purpose of this project for me was to have a learning experience. And when it was finished I was amazed about how good it looked. I did see the entire process from the architectural design to the realization of the construction.

An important learning point was that the project was like a ship with 3 captains the architect, the people from Tentech (that includes me) and the manufacturer. All 3 parties where people with their own way of thinking and working. I learned a lot from all of them but at some times the organization of this project would become a bit chaotic. The main difference was between the people from Tentech who wanted things calculated, according to the norms and accurate. And the manufacturer who just wanted things done in a way that works for this situation. Especially replacing ridge and edge cables by rope and TIR belt was something that would likely not pass when calculated but it was practically a better solution than using cables in this case.

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