

# Erection of the Moses Mabhida Stadium Roof, Durban

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## **Abstract**

Building the Roof for the Moses Mabhida Stadium in Durban, South Africa PFEIFER Seil- und Hebetechnik GmbH has succeeded in realizing a most complex structure to its Client's satisfaction. This paper describes the installation and assembly of the steel and cable structure of the stadium roof.

## **1 Introduction**

The Moses Mabhida Stadium in Durban being one of five completely new structures for the Soccer World Championship 2010 in South Africa is truly the most iconic one. The impressive bowl is covered by an even more remarkable roof structure. This roof consists of a steel arch which spans over the playing field and a cable net with membrane cover.

The way to combine steel works with a lightweight cable net as it has been done in Durban is quite unusual for such a wide span structure. This has presented the responsible structural engineers, fabrication managers and installation experts of PFEIFER Seil- und Hebetechnik GmbH with the need to overcome exceptional difficulties. The stadium roof of Durban can be constituted one of the most demanding steel structures of the world in recent times.



**picture 1: Aerial view of Durban Stadium**

## **2 The Project**

### **2.1 Overview in figures**

The Moses Mabhida Stadium offered 75,000 seats on three tiers during the period of the Soccer World Championship. After the games the capacity has been adjusted down to 50,000 by disassembling temporary seating. Parking decks supply 10,000 spaces for the spectators. The VIP-area with separate entrance and VIP-club comprises 150 boxes. The whole stadium complex has been built as an insitu-concrete structure out of 80,000 cubic meters reinforced concrete with added precast components such as the lower parts of the columns.

The stadium roof features the following figures:

Covered area: 42,000 sqm  
Perimeter of the Compression Ring: 830m  
Span of the Arch: 350m  
The Arch: 2,700 tons of steel  
Temporary structures: 1,200 tons of steel  
The Compression Ring: 2,800 tons of steel  
Cable Structure: 18,000 m cables, 150 tons of castings  
Membrane: 48,000 sqm PTFE-glasfibre  
Cladding: 10,000 sqm aluminium sandwich panels

## 2.2 The Roof

The roof of the Moses Mabhida Stadium is a unique combination of steel and cable structure. The most distinct element, the arch, is not free standing in transverse direction. It has to be supported by the cable net. The cable net itself works similar to a bike wheel. The compression ring on the outer circumference acts as a rim. The radial cables are like spokes. The inner ring cables act as the hub of a wheel. Such spoked wheel systems are pre-tensioned and do not need further support except vertically. In this special occasion the cable net is suspended from the arch, thus stabilising the arch itself. Connecting every second radial cable and introducing additional front ridge cables provides a three-dimensional fanning out of the radial cables. The upper and lower radial cables are building up stabilised areas for the membrane cover and enable sufficient drainage of the roof surface.

The arch can be walked on by stairs from both sides. A cable car provides access from the north side to a glazed visitor's platform on the top.

## 3 The Structural Steel Elements

### 3.1 The Arch



picture 2: The arch

### 3.1.1 Structure

The arch is split into two sections on the south side and has this way two foundations. The two sections join within element 21 to a single section. Free span of the arch is about 350m. Its peak is 106m high. From elements 4 to element 36 there is no vertical support to the arch. Underneath these elements the arch is supported by lattice columns.

The arch consists of 56 welded box elements with head plates each side. After welding and surveying of the elements the head plates were machined. Connection of the elements has been developed as a full contact and friction joint with high torque bolts.

On the level of the compression ring the forces from tensioning the cable net are lead through the arch element. In this location the compression ring is supported by the arch through specially engineered bearings. These bearings allow for smaller twisting angles of the compression ring due to torsion forces. The compression ring is completed by rung 1 which is situated between the two sections of the arch in the south. At the interface to the arch it has bearings similar to those used for the compression ring.

Rungs 2 to 6, also built in between the two arch sections on the south side, are not all serving structural but also architectural needs.



picture 3: South arch with rungs

### 3.1.2 Fabrication and Delivery

Production of such large size steel box elements with dimensions up to 5m / 5m / 11m requires the highest fabrication standards in terms of areas, tolerances and jigs. At times of construction the capacities of the South African steel workshops had been fully booked. Because of this situation it became necessary to supply the steel work from Germany. Transport routes had to be checked and approved for the element sizes. The elements were brought from the plant to Brink harbour in Hannover by low bed trucks. They were loaded onto canal barges which shipped them to Hamburg harbour. In Hamburg the elements were transferred to break bulk vessels regularly servicing South Africa destination.

Depending on weather conditions and schedule of the vessels the elements arrived in Durban harbour after a journey of 4 up to 5 weeks. To manage the final 10 km to site they

would again be loaded to low bed trucks which within South Africa needed special police escort.



picture 5: Loading of element from barge to vessel in Hamburg



picture 4: Off loading of elements in Durban harbour

### 3.1.3 Engineering for Installation

Already at times of tender it became clear that the erection of the steel arch would be the most difficult part of the roof construction works.

Conditions to be taken into consideration:

- No final wind load investigations for the installation process of the arch were available. These should be within the responsibility of the contractor by intent.
- Requirements for tolerances were defined as 30mm deviation max. within three dimensions for each and every point of the structure.
- Installation steps and the necessary temporary structures for the steps were not finally defined. Right at the start of the contract it became apparent that in addition to three temporary towers further four support towers would be needed to service the structural needs of the arch during erection.

The integration of the arch into the spoke wheel system of the cable net resulted in manifold interfaces between the different structural elements. These influenced heavily engineering, procurement and fabrication of the arch elements and had to be accommodated at the earliest time possible.

Key issues during engineering:

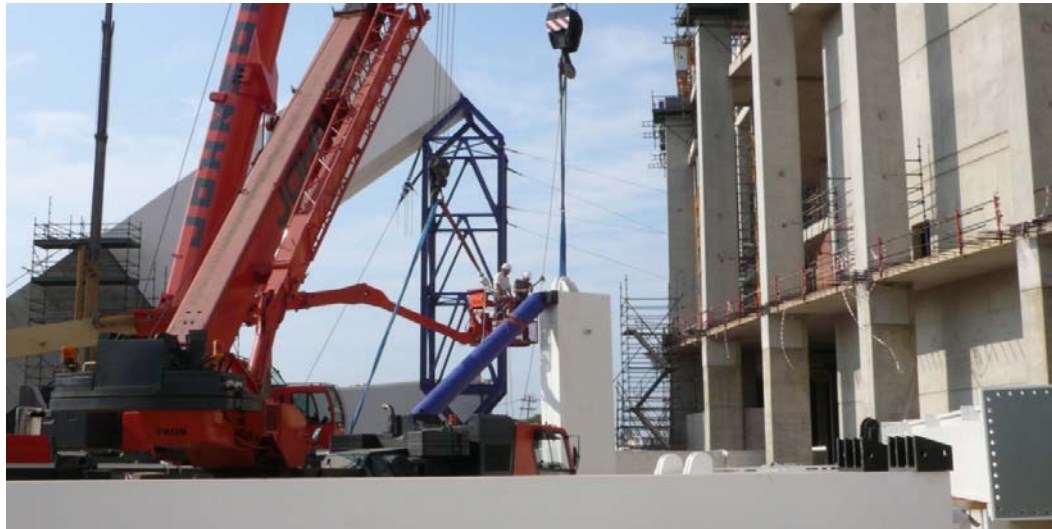
- Provide three-dimensional adjustment at the foundation point during erection period.
- Developing a 3d-model of the arch for the purpose of: a) comparison of trial assembly data from the fabrication plant against set values, b) comparison of on site survey data against set values of the individual installation steps.
- Enable an independent erection process for arch and compression ring. This resulted in a temporary bracing of the arch on the south side.
- Clarification of interaction between temporary towers and arch structure at the earliest possible time to achieve an independent engineering process for both structural elements.

- Engineering of the temporary towers as a reuseable structure.
- Ensure a safe installation process, including dismantling of the temporary towers situated underneath the arch.
- Reduce steel weight and max. support loads of the temporary towers by ways of changing the intended structural system: from a cantilevering tower to columns with hinged connections.
- Achieve a maximum of adjustability during installation by suspending the arch from the large temporary towers, not supporting it underneath.
- Having the top part of the temporary towers acting independently from the arch in order to avoid further bracing for the back stay support of the arch.
- Development of adjustable suspension gear for individual positioning of arch elements during installation.
- Minimising the number of necessary crane configurations.
- Definition of a survey concept for an integrated monitoring and control of all installation steps.

### **3.1.4 Installation**

A 600ton crawler crane was used for the installation of the arch. This plant provided the sufficient height under hook combined with high load capacity within the necessary working range. Erection started with placing the arch columns. These needed temporary stabilisation to the concrete structure of the bowl, which had to be adjustable. At the same time pre-assembly of the four start elements of the spliced arch was proceeding in areas outside the stadium. The assembled units with a total weight of 260tons each were then positioned to the shear keys on the foundations and on top of the arch columns. To enable this activity it needed very sensitive adjustment devices for the elements angles in 3d. This was provided by specially designed PFEIFER chain rigging device with hydraulic adjustment. Additionally, an adjustment with hydraulic jacks was possible at the lower foundation. The gap between foundation and the face of the first element was grouted with high strength mortar afterwards and the connecting bolts pretensioned.

At the northern end of the arch, the single arch side, the arch elements near the foundation could only be lifted in pairs because of their weight and limited crane access. An additional temporary column outside the bowl was therefore necessary for the works.



**picture 6: Temporary column north side; in front: installation of columns**

Some of the most challenging steps during erection have been the installation of the rungs, situated between the two spliced arch ends. The first rung had to be delivered in three pieces because of the sheer total weight of 220tons and the length of 45m. The three pieces were pre-assembled and then welded outside the stadium. Surveying was done and adjustment of length followed by ways of machined shim plates. The rungs 2 to 6 were connected to the neighbouring spliced arch elements by friction connection with pretensioned high torque bolts.



**picture 7: Rung 1 has been installed**

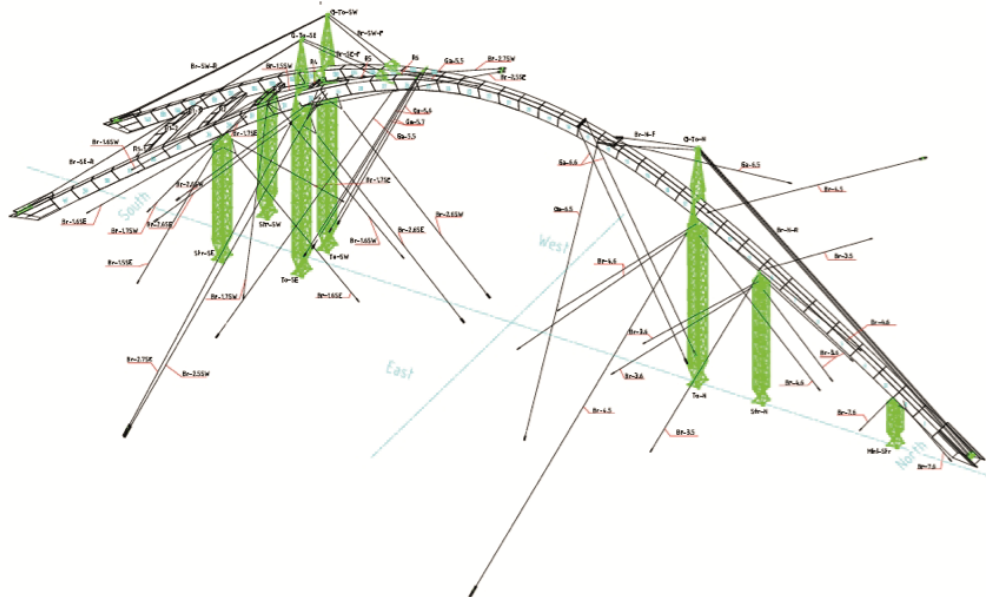
Before the arch installation could continue to cantilever out over the pitch, first a transversal support had to be supplied. In the north the compression ring with its bracings was used for

this purpose. In the south PFEIFER choose a temporary cross bracing between the two spliced arch legs, done with fully locked cables diameter 95mm.

In general all arch elements that arrived on site would be cleaned completely, damages to the corrosion protection repaired and the final top coat applied before installation. Because of the exposed situation of the building (less than 500m to the sea) a specially designed polysiloxan coating system with 320µm overall thickness was used.

All arch elements situated above the bowl were installed piece by piece. Each piece would be placed onto the shear keys of the previous one. Bolting of the elements was done with hydraulic devices which provided excellent tabling of the pretension forces achieved.

The longer the cantilever, the more difficult became the temporary measures during installation process. All in all six further temporary towers with heights up to 85m were erected and later, at a further erection status, dismantled.



**picture 8: Overview temporary systems**

The temporary towers were designed in an elementary system, which would enable re-use in the various towers needed in different steps of installation. Because of the height of the towers and the high level of vertical forces transversal bracing had to be designed and executed. In order to have a sufficient stiffness for the bracing 92 pcs of 15,2mm diameter parallel strands, each pretensioned, were used. Forces on the lower end of these bracings were initially thought to be anchored to the concrete structure of the bowl, but were too high. Therefore individual, temporary foundations outside the bowl had to be erected and later to be demolished.



**picture 9: Temporary towers with bracings and suspension**

In order to cope with deformation of the arch during the various steps of installation hydraulic adjustment devices were included on top of the temporary towers. Although the arch was able to have a free cantilever of two elements beyond the last tower, it was necessary to have a suspension system based on strand bundles and an extension of the highest tower above the arch. The strand bundles were anchored to the final foundations of the arch itself. This suspension system provided a very fine adjustability for the arches geometry.

The installation steps in the middle part of the arch (the arch cantilevering from both sides) were very sensitive against wind. During several steps the structural capacity of the arch only allowed for a max wind speed of 10m per sec. Two weather forecasts each day provided the safety for following a meticulously engineered installation sequence.



**picture 10: The keystone element**

The temporary suspension system was used to widen the gap between southern and northern half of the arch in order to slide in the keystone element effortlessly. This last step went smoothly.

Being a real highlight in the structural works of the stadium the installation of the last piece of the arch lead to a complete standstill of the site a road blockages in the neighbouring streets. Everybody, workers as well as Durbanites wanted to be part of this moment.

## **3.2 The Compression Ring**

### **3.2.1 Structure**

The compression ring runs along the outer circumference of the stadium bowl in an undulating geometry. It is designed from box section elements 1,6m / 1m / max 16m, connected with headplates, bolted together with pretensioned high torque bolts. The ring is not taking forces being on its own. It needs the cable net similar to a bike wheel to be stabilized.

The concrete structure of the bowl ended on the so called level 6. In most areas the outer columns were inclined. These columns then received extensions built from steel work (box section 1,6m / 0,8m) to supply the bearing points for the compression ring. Because of the undulating geometry the length of the steel columns and their inclination vary, lengths roughly varying between 8 to 16 meters. The columns have hinged connections with lugs and

pins on the upper and lower end. At the lower end a shear bracket is added to limit torsional deflection.

In order to stabilise the system of columns and compression ring in horizontal direction cross bracings were applied between 22 columns, using fully locked cables . These cables are pretensioned.

### 3.2.2 Fabrication and Delivery

The fabrication of the columns and the compression ring elements was done in Johannesburg, South Africa.

All columns and compression ring elements have been welded airtight in fabrication. The headplates on each side of a compression ring element were machined and pre-connected to the box. Only after trial assembly of three elements and the appropriate survey the headplates were finally welded to the element.



picture 11: Compression ring element in delivery

Delivery of the steel structure was done by truck. Because of the lengths of the elements special police escort was needed during delivery once more. Such special transport only received permission for daylight hours in South Africa.

### 3.2.3 Engineering for Installation

As mentioned before the structural system of columns and compression ring was not self-supporting, neither in any erection status nor in finals status. Thus called for elaborated engineering and temporary measures. Geometrical adjustments during erection were limited to the upper and lower connection point of the columns. Key aspects of engineering were:

- Columns and their bearing points: In this location only tolerances of the concrete structure underneath could be compensated. After in situ survey of the cast in plate

the exact geometry for the connecting lug and the shear bracket was calculated. These connection parts were then fabricated just in time and delivered to site.

- Temporary supports / bracings: After connecting at the lower end the columns had to be adjusted to a definite inclination. Readjustment after further erection steps was needed. This has mainly been done by connecting PFEIFER bracing cables to the upper end of the columns, to inner and outer side. Calculating the resulting forces from all erection steps resulted in the necessity to brace the columns of the curved areas with pressure props to the inside. Anchor points to existing structure had to be established and engineered.
- Compression ring elements: During erection the elements had to be positioned in 3d with very low tolerances. For this purpose a lifting suspension gear was developed with four adjustable chains. Three dimensional coordinates for the connecting lugs on the elements were given to the fabrication plant. On site all angles were adjusted directly after lifting off from the ground, before rigging to the final location on top of the columns.
- Bearing point of the compression ring to arch: In situ survey of the installed compression ring and the arch. Calculation of the exact geometry for a shim plate, followed by just in time fabrication of the plate.
- Survey: The geometry of the compression ring had to be verified in all erection steps. The next action had to wait for comparison of measured against set values of the preceding erection step. Only after necessary adjustment had been done installation could proceed.

### 3.2.4 Installation

Installation of the compression ring started at the northern end. To ensure the transversal stability for the arch both sides of the compression ring, east and west had to run simultaneously. For lifting the elements a 250ton hydraulic crane was used on each side. To handle the works further smaller hydraulics and fork lifts were needed. A total number of eight installation crews served the different, interrelated erection activities.



picture 12: Weld on lug for a column

Preceding to placing the columns themselves all just-in-time-fabricated lugs and brackets had to be welded to the cast in plates. Since the progress of the concrete works was always on or beyond the critical path, this put the installation process under immense pressure.

After placing of the columns they were braced with cable elements, or where applicable with pressure props. Two columns were followed by one compression ring element.



A separate survey followed after all compression ring elements had been installed. The just-in-time fabricated shim plates at the bearing points to the arch were slid in. Only after this step the bracing of the columns to the outside could be released and dismantled.

The temporary bracing to the inner side could only be released during the tensioning process of the cable net, this way the cable net taking over the stabilisation within the bike-wheel-system.

**picture 13: Lifting a compression ring element**

## 4 The Cable Net

### 4.1 Structure

The cable net is the central connecting and bracing system for this stadium roof. The cable net only connects steel arch and steel compression ring which are not self supporting.

The cable net consists of a tension ring and radial cables. The tension ring is made from six fully locked cables with diameter 80mm which are connected with casted elements at each node point with the radial cables. Where the tension ring runs along underneath the arch the small bending angles resulted in high deviation forces. These were anchored to the arch with tie back cables. At the connection point of the tie backs to the tension ring large casted elements were needed with weight up to 3,5tons per piece.



picture 14: Ring cable connector at tie backs

Half of the radial cables (valley cables) are connecting the compression ring directly to the tension ring at 52 grid lines. The balance of the radial cables, 52 grid lines (the ridge cables) are connected to compression ring and arch. Flow of forces is completed by connecting the tension ring and the ridge cables with so called front ridge cables. The relevant upper pickup points on the ridge cables have to provide further hinged lugs to connect two so called catwalk hangers. These catwalk hangers in return are connected to the valley cables. These lower pickup points are supporting the catwalk. All this resulted in a very elaborate and complicated 3d-geometry of the casted pieces, being different in nearly each and every grid line.

The task for the cable net to stabilise the arch leads to a complex structure with many degrees of freedom. These had to be handled during erection. Over and above the structural necessities the cable net supports the membrane cover. The three dimensional situation of

ridge cables, valley cables and catwalk hangers provides the necessary ups and downs for placing the membrane panels.

## **4.2 Fabrication and Delivery**

Fabrication of the cable net elements has been completely done in the works of PFEIFER in Memmingen, Germany. The cables were tear- or non-destructively tested according to specification in the works. The cables were pre-stretched, marked, cut to length and completed with their end connections. All engineering and workshop drawings for cables and castings and most important all 3d-modelling for the castings was done in house at PFEIFER offices.

A total number of 748 cables with a total length of approx. 18 km and a total weight of approx. 400tons had to be fabricated. Diameters of the cables ranged from 31mm to 90mm. Types of cables used for the primary structure were PG (spiral strand, DIN EN 12385 – Galvan coated, see PFEIFER catalogue chapter 3 p. 42ff) and PV (fully locked cables – Galvan coated, PFEIFER catalogue chapter 3 p. 54ff). Additionally used were cables of smaller diameters between 10mm and 24mm for the suspension of the catwalk and catenary cables of the membrane. End connections varied over open swaged fittings with or without turnbuckle, open spelter sockets, conical sockets. Delivery to site was made by packing the elements in container wherever possible. Where the diameter of the coils had been too large special timber boxes provided protection for the cable elements during shipment. Breakbulk vessels brought the goods to South Africa.

Starting from the types of the casted connectors given in the tender the elements had to be developed in detail in 3d. Thus enabling each piece to deal with the varying angles and different connecting elements. This resulted in a number of 90 different types for the ring cable connectors only. The same kind of variety applied to the upper and lower pickup points. At arrival of the casted pieces in our plant in Memmingen a meticulous quality check has been done. After assembling of main bodies with clamp covers and further completion with hinged parts the connectors were packed in containers and delivered to site by ship.

## **4.3 Engineering for Installation**

As the Durban roof system is a one where all structural elements are well interacting with each other, the main subject of engineering has been to determine this interaction in all erection steps. Important tasks amongst all were:

- Developing special connection devices to the arch lugs for lifting the net.
- Securing structural integrity for arch and compression ring. Re-checking the temporary towers since it turned out that they had to stay to the end of the lifting process.
- Engineering the laying out geometry and defining the necessary scaffoldings.
- Defining concrete seating protection.
- Analysis of lifting and tensioning forces for sizing the strand jacks.
- Providing solutions for access to all cable connection points to the steel work. On the arch they were positioned to the side of the box elements – in heights of up to 100 m.
- Engineering and fabrication of all kinds of temporary devices for laying out, positioning and connecting the cables.
- Analysis of all steps for lifting and tensioning.

- Determining the structural status for dismantling the transversal bracings of the temporary towers.
- Determining the structural status to disconnect the temporary towers from the arch. At this point in time they were braced against the now stabilised arch and dismantled only later.
- Determining the structural status for dismantling the temporary bracing of the compression ring.
- Analysis of the installation forces for the bracing cables between the columns.

Having done the first investigations decision had been made to lift and tension the cable net up to the arch. This way the hydraulic jack climbed to the arch step by step. Advantage of this procedure has been that only half of the radial cables had to be equipped with tensioning devices, 52 pieces. As a disadvantage it turned out that access to the hydraulic elements for maintenance was difficult with using crane and basket only.

The chosen way to tension the cable net triggered requirements for the pre-installation of the net on the ground. Solutions had to be found when and how the 102 cable ends would be connected to the compression ring. The ridge cables were chosen to be connected directly after uncoiling. This could be done without any force. To do so the ring cable had to be laid out in a large diameter. The necessary gap in the ring cable was positioned on the south.

#### **4.4 Installation**

The ring cables were pulled out from the coil using a turntable and winching systems. After placing them exactly on the engineered geometry situated on a scaffold track two of the three coupler locations were closed. The ring cable connectors were installed. Now the radial valley cables were laid out with elongations in direction to the compression ring. They were finally connected to the ring cable connectors and temporarily connected to the compression ring. Afterwards the ridge cables were uncoiled. The ridge cables were finally connected to the compression ring. The other ends were connected to the lifting and tensioning equipment which in return received the strand bundles on which they would climb to the arch. Laying out the cable net was completed by installing as well the front ridges between upper pickup point and ring cable connectors as the catwalk hangers between the upper and lower pickup points. After positioning all cables the strand bundles of the radial ridge cables were lifted by crane to the arch and connected to the final lug plates.

The bracing cables that stabilised the compression ring had been tensioned to a set value before lifting the cable net. This should have resulted in achieving the correct pretension forces in these bracing cables after the lifting process of the net. But in the real world the bracings had to be checked and again tensioned to the correct forces.

The lifting process of the cable net started with closing the gap in the ring cables. Electrical winches combined with block and tackle were used, with capacity up to 400 kN. Because the ridge cables were already finally connected to the compression ring the cable net lifted some 15m above ground during this closing procedure of the ring cables.



**picture 15: Hydraulic jacks have climbed to the arch**

Within the next step of the installation sequence the ridge cables were pulled to the arch with the hydraulic tensioning equipment. Installation analysis had indicated a discrete status during the ongoing lifting process in which the distance between the valley cable ends and the compression ring would be minimum. In this status the final connections were made with the help of electrical winches and specially designed tension devices, forces being below 200 kN.

A small number of radial cables were in collision with the transversal bracings of the temporary towers. The erection sequence allowed for these radial cables to be slack until a certain status of stability for the arch was achieved. By then the bracings to the temporary towers could be disconnected and the balance of the radial cables brought to the tensioning level already achieved for all other cables. Special care had to be taken for the pressure props that stabilised the compression ring to avoid any overloading of these elements.

A fine-tuned, sequenced procedure lead to the final connecting and pinning of the cables to the arch lugs. Surveys at certain hold points had to be compared with the set data from the 3d model. Planned forces at the time of pinning the cable and real forces measured were only 3% apart at max.

After having finalised all cable connections a total of 1500 tons of temporary steel work had to be dismantled and transported off site. This cleared the structure for the installation of the membrane panels. The membrane only gave the final tensioning status for the complete roof. Installation of secondary elements like the catwalk and the inner gutters completed the roof.



**picture 16: Membrane panels in place**

## **5 Perspective**

The roof on top of the Moses Mabhida Stadium in Durban is an awesome structure. The Client, the Ethikwini Municipality, now owns a landmark asset. It will be a tourists focus point long since after the World Championship 2010 has ended. The roof has been awarded the South African Steel Award in 2009.

This roof in Durban has been executed by Pfeifer Seil- und Hebetchnik GmbH in the most reliable and professional manner. It is a milestone reference in its position as a General Roof Contractor – beyond their proven expertise in Cable Structures.

Nearly simultaneously to the works in Durban PFEIFER has been the responsible General Roof Contractor for the roof of the Capetown Stadium (Greenpoint).

Leight-weight, wide spanning structures will be in demand for further roofs during championships and games all over the world. To make their stadium unique more and more owners and clients are searching for structures of very distinguished design and engineering. The roof in Durban is such a piece of art.



**picture 17: Cable net of Durban**

### **Parties involved in construction**

Client:	Ethikwini Municipality (City of Durban)
Structural Engineer Roof:	Schlaich Bergermann und Partner
Architects:	gmp Gerkan Marg und Partner
General Contractor Roof:	Pfeifer Seil- und Hebeteknik GmbH

Fabrication Steel Structure Arch:	Eiffel Stahltechnologie, Hannover, Germany
Fabrication Steel Structure Compression Ring:	DSE Structural Engineers and Contractors, Johannesburg, South Africa
Erection of all steel structures:	Pfeifer Seil- und Hebeteknik GmbH
Fabrication of cables and castings:	Pfeifer Seil- und Hebeteknik GmbH
Erection of the cable net:	Pfeifer Seil- und Hebeteknik GmbH
Fabrication and Erection of Membrane:	Birdair Inc.