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Concept, design and realization of the Moses Mabhida Stadium, Durban, South Africa for the Football World Cup 2010

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Abstract

As part of the City of Durban´s redevelopment program the projected World Cup stadium was chosen to create an icon for the KwaZulu Natal region and Durban, being the 2nd largest city of South Africa. The ambitious plan to gain international attention enabled the lead architects von Gerkan Marg und Partner, Berlin, the lead structural engineers Schlaich Bergermann and Partner, Stuttgart and BKS, Durban to design an outstanding stadium of unprecedented scale and beauty and therefore won the design competition. The multipurpose stadium with a possible capacity of 85,000 seats features a unique roof structure of 46,000m² of Glass/PTFE membrane being prestressed against a cable net. The cable net is tensioned against two steel compression rings along the perimeter of the stadium and a major arch structure with 103m height and 360m distance between its foundations.

Keywords: conceptual design, form finding, steel structure, cable net, membrane structure, wind simulation, fabrication, installation

Fig. 1 Stadium in close proximity to beach front and city centre

1. Architectural Design

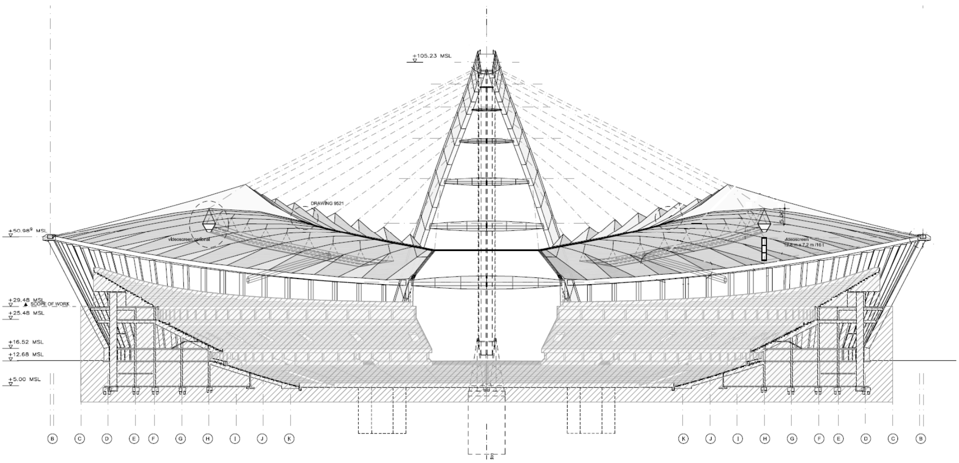


Fig. 2 Cross section through stadium

To be able to use the stadium after the World Cup on a regular basis, the design team developed a stadium scheme for different sporting events. Therefore, the stadium is designed to host major athletic events as well as rugby and other sports. The running track is pushing the first seating row outwards in plan, leading to less steep triple tears compared to common football only stadiums while maintaining the same quality sightlines. For the legacy mode the third tear of approx. 20,000 seats, which is built temporary, is removed, because for most regular events a capacity of 55,000 seats is sufficient. However, the stadium is enclosed by a roof and facade structure capable of providing up to 85,000 seats.

While there is a common believe that the arch spanning the short way over the football pitch would create a shorter and more efficient span the opposite is actually true. In order to clear the highest seating row of an undulating stadium bowl, creating better views along the long sides of the pitch, the span over the main axis leads to a shorter span.

The two upper tears of the stadium are opened up on the south side to draw the attention from the outside into the stadium and to enable views from the inside onto the "People's Park" and Durban´s city centre [Fig.1. Fig. 2.].

To create more revenue for the stadium and the surrounding sport facilities, the stadium is fitted with several retail areas, a cable car travelling to the top of the arch and a swing bungee jump connected to the underside of the arch soffit.

From the early concept scheme [Fig. 3], developed for the design competition, a comprehensive design process was undertaken to derive the final form of the stadium's roof and facade mainly driven by structural and form finding aspects.

Fig. 3 Roof shape Competition Entry

2. Structural Concept, Form-finding

The self-contained system of the spokes wheel roof has been adopted successfully for different stadia applications worldwide, consequently the structural system of the new Durban roof was initially developed as two separate elements: The arch and the perimeter compression ring being structurally independent [Fig.4a].

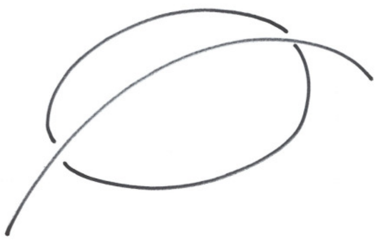


Fig.4a Separate system

Fig.4b Three arch system

With the ongoing structural development [Fig. 5.] and the evaluation of the architectural aspects and requirements resulting out of the build ability, the "three arch system" [Fig.4b.] evolved. The new system does not rely on the same geometrical constrains. The horizontal arches are therefore bearing pinned against the vertical arch. The horizontal thrust at this location is then equilibrated by the tension ring ties Fig. 6., which creates a fundamentally different structural behaviour, leading to minimised deflections of the horizontal arches and therefore to a greater efficiency.

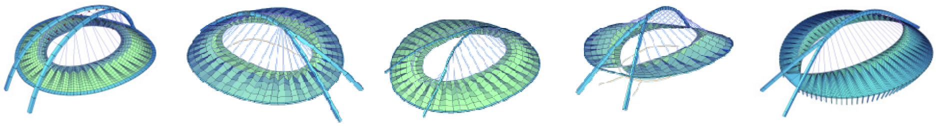


Fig5. Analysis Model Evolution (small selection)

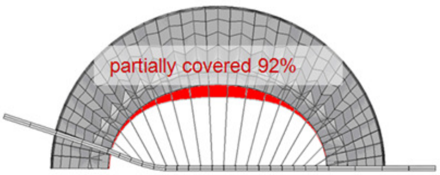


Fig.6a Separate system seats coverage

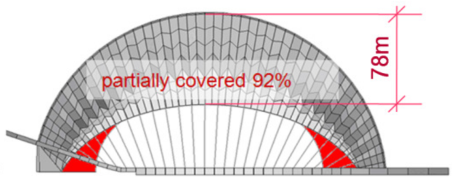


Fig.6b Three arch system

The fundamental requirement of concentrical geometrical distances between the compression ring and tension ring on the inner edge ring for the separate system leads to less cover for the best spectator seats located along the side of the pitch [Fig.6a]. The Three Arch System does not rely on the same geometrical principles and, therefore, achieves a much better cover while matching the surface area in plan. Further the Three Arch System also spans a great roof depth of 78m [Fig 6b.].

The geometry of the complete structure including arch, cable net and elements of the compression ring had to be form found simultaneously being an integral system. Some few form finding parameters are named here:

- Architectural Appearance
- No Bending under prestress and self weight
- Maximum height of arch 100m (system line)
- Defined clearance heights of arch at stadium bowl
- Maximum weight limitation of individual arch elements
- Even cable net spacing
- Cable distance (span of membrane panels)
- Small differential forces at tension ring connections
- Natural slope of roof to the outside (no drainage pipes required)

The form-finding process was a semi-automatic step by step process in which analysis output data, deflections and element forces were evaluated and used reformatted as an input for the next geometry input and prestress forces. After convergence of the form-finding process, the structure was loaded and studied using typical environmental loads. The results were evaluated and in many cases the shape of the structure adjusted and form found again to create a new more efficient structure. Even though driven by ecological concerns, some shapes and form-finding results have been excluded from further processing due to the fact that the visual appearance of the structure should be one of the key topics.

3. Wind loading

While South Africa is not affected by catastrophic hurricanes, the coast line has high wind speeds with some unusual effects that were evaluated using the local wind data and statistical analysis: The average high wind speeds have a clear daily pattern with the peak in the early afternoon and calm conditions usually overnight. The wind is predominately driven along the coast line, offshore and onshore winds are insignificant [Fig 7a.].

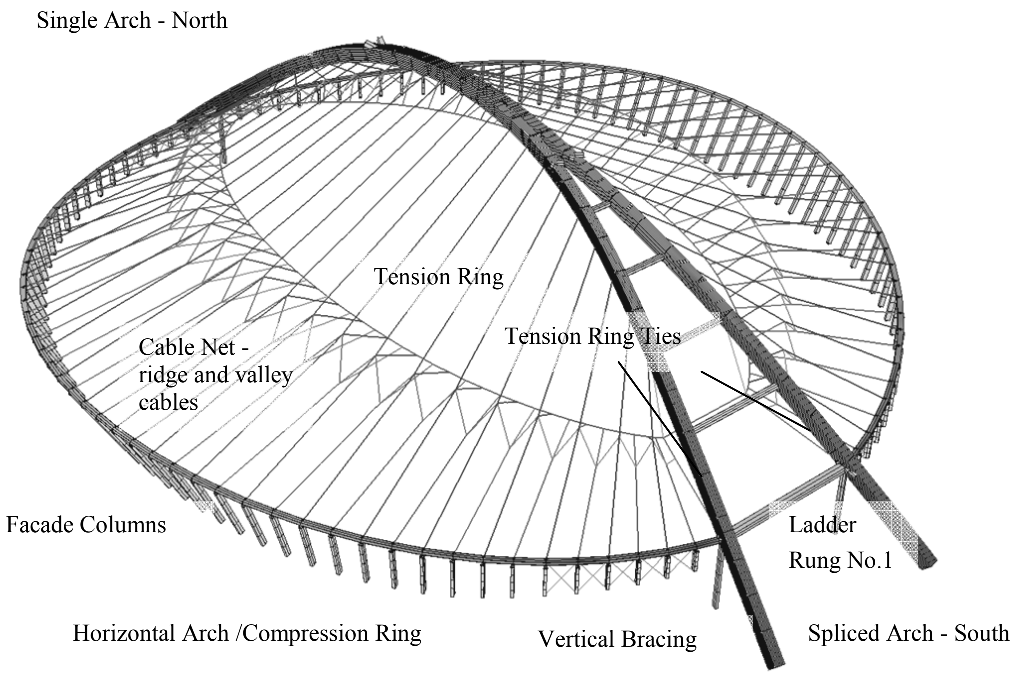
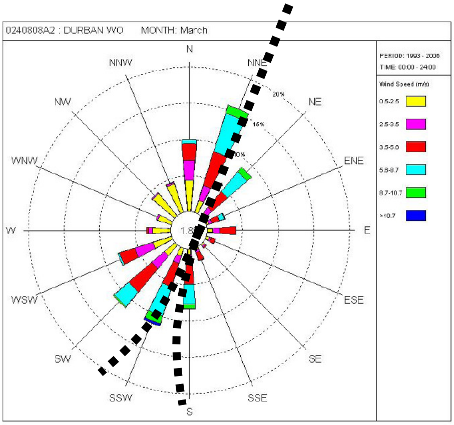


Fig. 6. Main structural elements



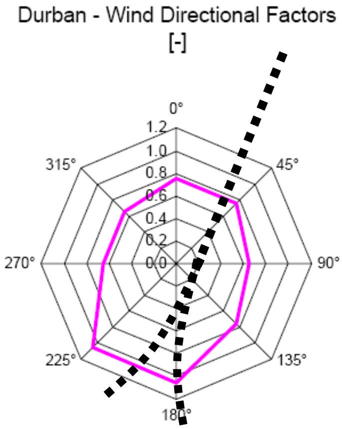
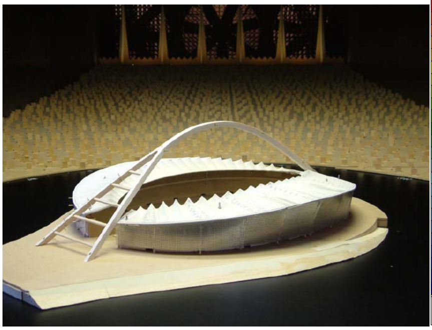


Fig.7a. Wind statistic Durban March Fig.7b. Wind directional factors

The Durban stadium roof structure is exerted to enormous wind loads due to its arch height and the generally high elevation of the cable net and membrane roof of up to 65m. Due to the steep roof inclination at the perimeter of the roof edge [Fig.2.] the wind suction form coefficients (cp) are very high. Usually the high cp factors for edges of horizontal roofs are small in area, dissimilar to the New Durban Stadium where high cp values can be found over a long distance into the roof depth. In addition the ridge and valley shape leads to a funnelling effect also resulting in increased wind suction loads.



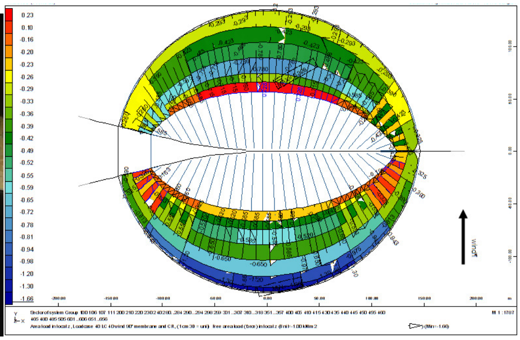


Fig.8a. Wind tunnel model Fig.8b. Wind loads 135°

The roof structure is due to the vast windage area exposed perpendicular to the arch wind sensitive. Also the deepest roof area is exposed to the oncoming wind and the resulting high wind loads out of the same wind direction. Because of this the wind directional design method was established using statistical wind analysis [Fig. 7b.] reducing the wind loads for the most critical wind directions up to 65% of the factors stipulated by the South African code SANS.

4. Design of elements

The structural system was analysed as an integral system on a geometrical non-linear basis. All support conditions of arch foundations, columns and vertical supports were input as springs with their relevant spring stiffness and settlement values. The analysis model was programmed on a numerical basis. To decrease analysis times and output data, the element mesh density was changed accordingly at the relevant element under investigation. Several of the thin walled arch elements have been studied in separate analysis models [Fig.9.] to assess local stress concentrations and plate buckling.

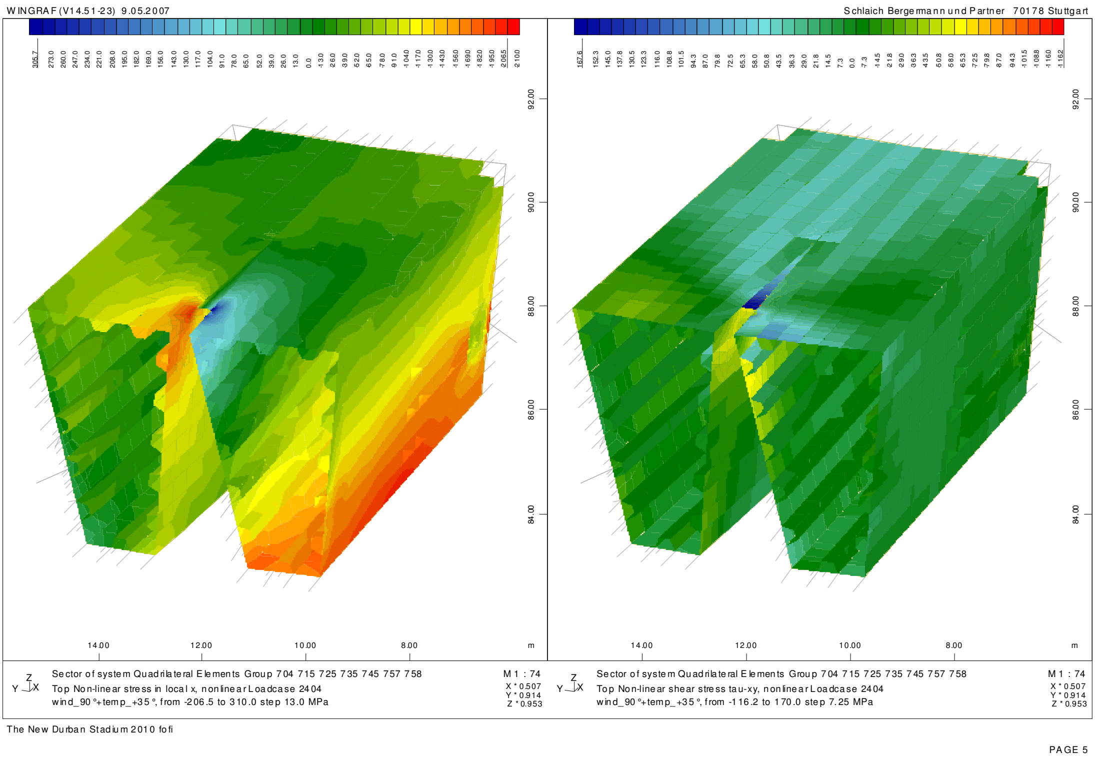


Fig. 9. Detail FEM analysis model of Y-section – principal stresses

Generally the steel grade S 355 was sufficient; however, at critical locations with high stress concentrations at cable connections S 460 was used.

For the cable net structure fully locked galfan coated cables with diameters from 31mm to 95mm are used. For thinner cables below 30mm stainless steel cables are used in order to gain better corrosion protection.

The European Design Guide for Tensile Structure of 2004 stipulates a new safety concept for the design of membrane structures. Therefore, the design concept for the Glass/PTFE Durban Stadium was adopted for design strategy, safety factors and prevention of tear propagation.

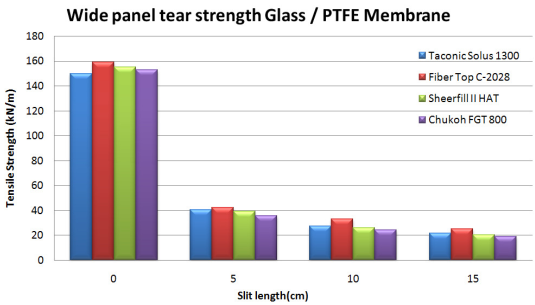


Figure 10a. Biaxial wide panel tear test   Figure 10b. Test reduction due to slit length

The new design strategy is based around the idea that the common safety factors resulting out of various individual factors (biaxial, long term, temperature etc.) cannot be lower than the failure mode resulting out of a 10cm wide tear. Being crucial for the design, the tear strength for various materials were investigated [Fig. 10b.[. The reduction of the virgin strength material of around 150 kN/m is reduced to approx. 30 kN/m due to a 10 cm long slit and therefore has an impact on the design strategy to be followed. Being a failure mode, the reduced stresses are compared to design stresses resulting out of reduced wind loads.

5. Details

Due to the complex geometry nearly all elements were designed with 3D analysis tools and drawing packages. At several locations, especially at the cable connections, high strength steel castings with a yield strength of up to 700N/mm² (Material number 1.6759) were used in order to minimise the dimensions of the connection. A further advantage of the castings is that complex geometries especially for cable grooves can be cast and do not require additional machining processes.

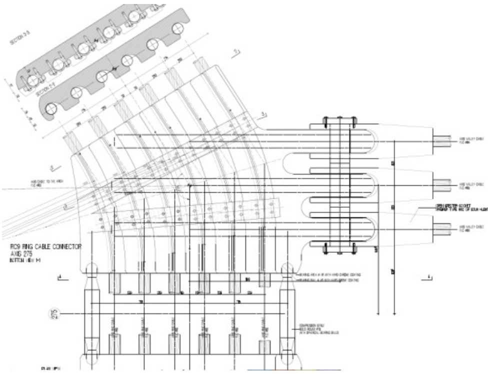
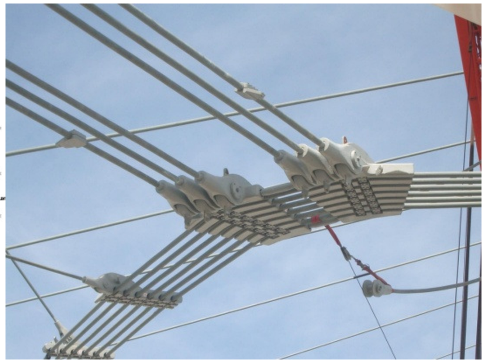



Figure 11a. Simplified detail drawing   Figure 11b. Casting at tension ring of 3 tons each

6. Manufacturing

All roof elements were manufactured compensating their elastic stretch or compression. Based on 3D workshop geometries all steel elements were manufactured to extremely tight tolerances. The end connections were manufactured over length and machined of to achieve accuracy and load transfer via smooth contact surfaces. After several elements were manufactured, the correct geometry was confirmed with a trial fit procedure [Fig. 12a.].


Figure 12a. Trial fit of Y-section   Figure 12b. Shipment from Hamburg to Durban

The coast of Durban is one of the most corrosive environments in the world due to the elevated temperatures, the humidity, the steady winds and the constant spray of salt water. Therefore, utmost care was needed for the corrosion protection and surface preparation. To improve the protection and to decrease the maintenance intervals, a polysiloxane based system was applied.

7. Installation

The installation process for a structure of that scale requires careful consideration by the contractors and the engineers. So the planning of all works was analysed in great detail for all parts of the structure. The installation process for the arch and the membrane were also assessed in additional wind tunnel tests.

All compressive members were fitted with survey targets to ensure that all installation processes can be monitored and follow exactly the pre-analysed installation steps.

The complete structure has no allowance for any kind of tolerance adjustment due to occurring site inaccuracy. Therefore, the installation steps of the first four arch elements on each side were very crucial and were adjusted several times, before the lowest arch elements were grouted into position onto the foundations [Fig.13.].

Figure 13. Big lift of first four arch elements and accurate positioning onto supports

The installation analysis ensures that none of the elements are overstressed either during the time of erection or by the relevant environmental loads. While all main structural elements and their connections are designed to take enormous compressive forces and compressive stresses, the tensional capacity of all elements and especially their connections are very limited. So during the arch erection e.g. all temporary support elements are fitted with active control elements in order to reduce bending. The control elements are accurately adjusted hydraulic jacks which were fitted to the towers and the backstays [Fig. 14.].

Figure 14: Arch structure supported by towers and backstays

After the cable net was installed and prestressed the membrane installation started by pulling the large glass/PTFE panels off a roll supported at the horizontal arch. After securing the panels in position, the membrane is tensioned towards the ridge and valley cable [Fig. 15.].

Figure 15: Installation of membrane panels between ridge and valley cables

8. Conclusions

The New Durban Stadium is of similar size and can host the same sporting events as the recently built Olympic Stadium. While all these stadia are seen as achievements and icons, the African stadium uses only a small fraction of steel and resources. The Moses Mabhida stadium is one of the prime examples demonstrating that iconic buildings do not have to be a waste of resources, however, this requires close collaboration between architects and engineers.

Careful consideration of the local environment is the key for a successful project. The detailed studies undertaken to design the stadium using a wind directional method saved plenty of resources and minimised costs.

To build an outstanding complex structure, technical skill, competence and experience are compulsory. Considering the given task and the short time period to build the New Durban Stadium, actually plenty of courage was required, too. I would like to thank herewith all contractors mastering this project.

Schlaich Bergermann und Partner Team: Knut Göppert, Markus Balz, Roman Kemmler, Michael Werner, Peter Schulze, Tobias Waldraff, Bernd Ruhnke, Jürgen Schilling, Uli Dillmann, Lorenz Haspel etc.

Specialist Roof Contractor: Pfeifer, Memmingen

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