

# The New Roof of the Olympic Stadium in Berlin

Das neue Dach des Berliner Olympiastadions

*Herrn Dr.-Ing. Gerhard Kiefer (1934-2005) zum Gedenken*

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# THE NEW ROOF OF THE OLYMPIC STADIUM IN BERLIN

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## ABSTRACT

The paper presents the structural design and the construction of the new roof of the Olympic Stadium in Berlin . The stadium was completely modernised in view of the next World Football Championship and the work is already completed. The paper describes the design concept of both architect and structural engineer, which has had to comply with the requirements set by the client while optimising the design from all points of view, i.e. aesthetic function, cost and safety. Details on the realisation of the steel structure of the roof are also given within the paper.

*Keywords: roof, stadium, steel structure, textile membrane*

## INTRODUCTION

In 2006 Germany will host the World Football Championship. Several stadia had to be modernised or even completely re-built in order to cope with the FIFA regulations and the latest requirements for a modern sport complex. The Olympic Stadium in Berlin has been designed by the architect Werner March for the Olympic Games from 1933 and is the largest stadium in Germany [1], [2]. The construction is listed as protected monuments.

Fig.1 gives an aerial view of the sport area. The stadium oval is interrupted by the Marathon gate allowing the Bell tower to be seen from inside the stadium (Fig.2).The oval is 300 m long, 215 m wide and the grandstand has a maximum height of 15 m above the surrounding ground. The upper and lower terraces are separated by a inner gallery (Fig. 3).The grandstand was built with reinforced concrete (prefabricated step units and cast-in-place radial frames, Fig.4). The columns of the outer and the inner galleries are made of stone blocks.



Fig.1.View of the Olympic Park from 1933.



Fig.2. Marathon Gate with view of the Bell tower

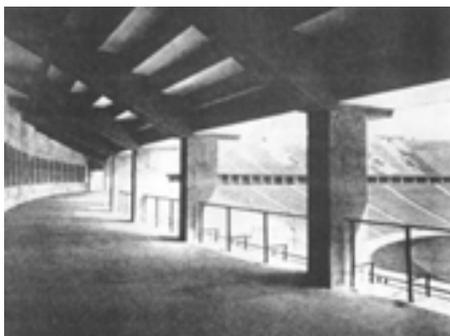


Fig. 3 View of the stadium from the circumferential inner gallery.



The upper and the lower terraces are structurally completely independent from each other. In tangential direction dilatation joints were provided every 3 or 4 radial frames (i.e. at a distance of 15 to 20 m); they were realised by using brackets. Most of the damages that occurred within the reinforced concrete construction during the 65 years were located at these joints.

In preparation for the World Football Championship from 1974 the two main opposite grandstands were partially roofed with a MERO system (Fig.5). The roof was carried by very slender massive steel columns placed inside the upper terrace and by the existing outer stone columns. Steel anchors had been bored inside the stone columns in order to be able to balance the tension forces from the roof by activating the self-weight of the outer gallery.

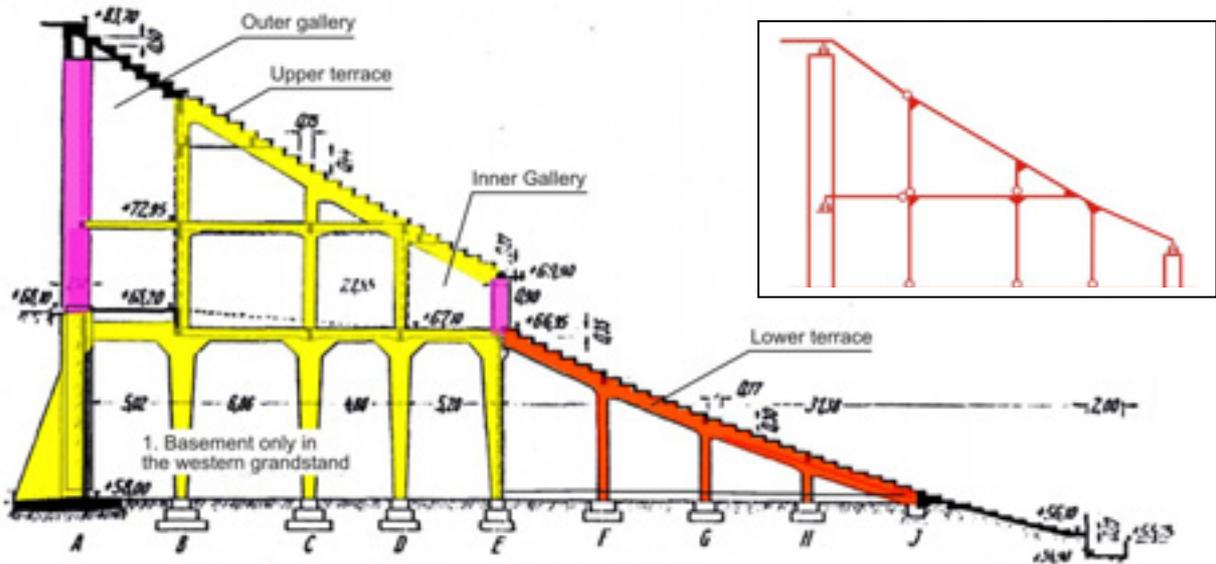


Fig. 4. The grandstand and the structural model of the upper terrace [3].

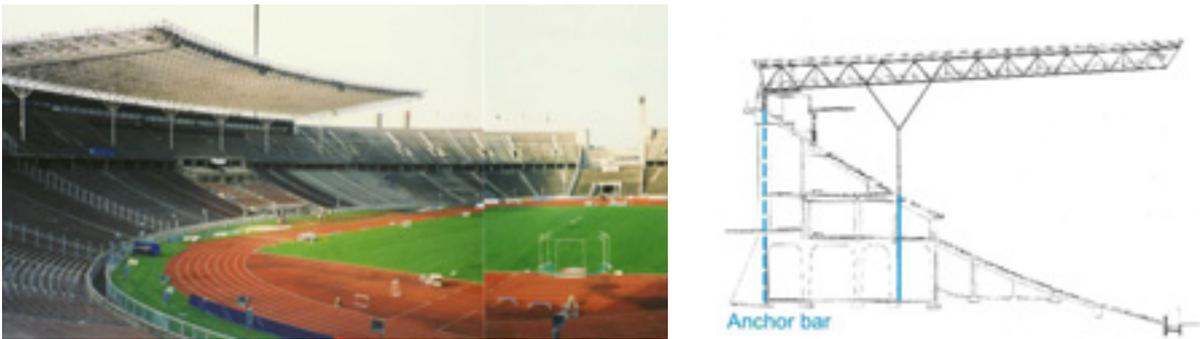


Fig.5 The roof from 1974 and the load carrying system.

Due to its inappropriate state the stadium could not have been used properly for the world event from 2006. Indeed the construction of the grandstand was in a very poor condition with large zones of reinforcement bars without concrete cover and serious damages of the concrete and stone parts. Further the new FIFA regulations require a complete roofing of the terraces. Consequently the city council of Berlin decided in 1998 to completely retrofit and modernise the stadium; the reinforced concrete and the stone construction were to be completely restored, the old partial roof from 1974 was to be replaced by a complete roofing of the whole spectator area, new premises inside the grandstands as well as constructions outside were to be realised, to optimally accommodate the multiple

functions of a modern sport arena. An architectural contest was called upon. The call of tender particularly specified, that the new concept should preserve as much as possible from the historical appearance of the stadium and that a special attention should be given to the main architectural features of the complex with its pregnant east-west axis (containing the Marathon gate and the Bell tower). Furthermore the construction work had to take place without any interruption of the sport activities but the normal seasonal pauses.

Ten teams participated to the contest. Winner was a team led by the famous German architects *von Gerkan, Marg and Partners* [4],[5]. Structural engineers were *Krebs & Kiefer Consulting Engineers* [6].

The winner’s design concept included a complete new roof, a complete retrofitting of the upper terrace with added structural elements to carry the roof, the replacement of the lower terrace through a new construction, the lowering of the sports ground by 2,65 m with a new construction of the reporter trench , the extension of the 1st basement over the whole circumference of the stadium with new constructions outside the stadium to accommodate different functions. The total costs were expected to be about 270 Millions Euro. A major role in the jury decision for the winning concept has played the design of the new roof. Its structural concept and construction are presented within this paper.

**2. THE STRUCTURAL CONCEPT**

The choice of the structural system was crucially influenced by the three requirements set by the client, i.e. (i) keep the Marathon gate open to allow a free view from inside the stadium towards the Bell tower, (ii) design a roof which will optically not affect the outside appearance of the stadium and (iii) make possible the erection of the roof without any interruption of the sport activities. On these accounts we have decided to give up any concept of a suspended roof. Such a roof would have needed closed outer and inner rings which had impeded the view from stadium through the Marathon gate even if the roofing itself were to be interrupted there. Furthermore either of the two possible suspended roof systems have had also other inconveniences. The one system with two outer compressed rings had needed a height (distance between the upper and lower ring) of at least 25 m, which was not to be overseen from outside the stadium The other system with only one outer compressive ring had needed a similar height between the two tensile rings situated at the interior of the stadium and therefore the lower cable grid could have had impeded the view from one upper terrace to the opposite, if the outer compressive ring were to be placed not too high above the attic of the stadium.

The structural system that we have finally chosen is depicted in Fig.6. The steel structure is a spatial truss

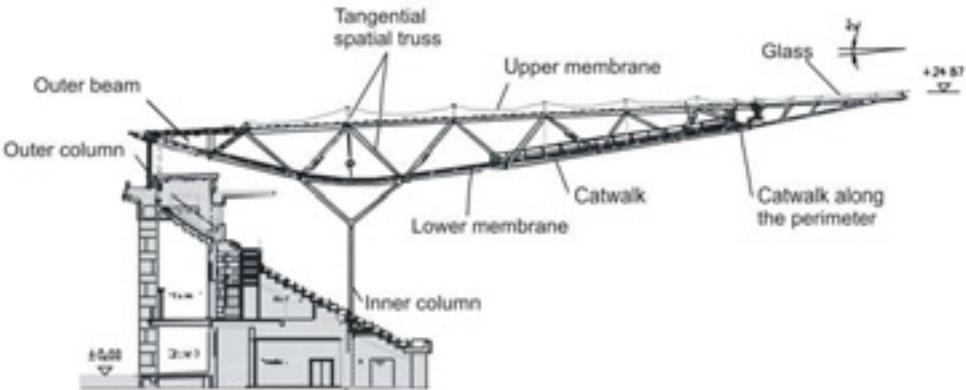


Fig.6 The chosen structure

sustained by inner and outer columns. The length of the roof in radial direction is about 68 m. The lay-out in-plane<sup>2</sup> has the shape of a horse shoe, there is no roof above the Marathon gate. The total roofed area is about 43300 m<sup>2</sup>. Placing the inner column within the upper terrace was not only an unorthodox decision for a modern stadium but also a very risky one in view of the possible verdict of the jury. It has been however taken after carefully analysing the pros and contras.

The advantages were

- (i) the roof will hardly be perceived from outside if it has a sharp edge only few meters above the stadium attic,
- (ii) there is no problem to interrupt the roof at the Marathon gate, so that the view towards Bell tower will remain completely free,
- (iii) it is possible to build the roof sequentially, so that there will be no disruption of the sport activities.

With respect to the disadvantage of having columns within the grandstand studies carried out by the architects have shown that the inner columns were less hindering as initially feared. Of course the number and the diameter of these columns were to be reduced as much as possible. Preliminary calculations have shown that the roof can be sustained with 20 steel columns having a diameter of ca 27cm. The initial concept has foreseen an inclined inner column.

The inclination has had advantages from both architectural and structural point of view: from the architectural because it had brought a certain dynamic to the whole concept, the columns have had looked like 'hands' carrying the roof, from the structural because the cantilever span could have hence been reduced. However the inclination of the inner column yields an horizontal reaction force even under vertical loading (Fig.7a). The resulting compressive force between the two supports could not be carried by the existing inclined beam of the terrace frame, so that it would had to be strengthened. On the other hand the outer columns have had to carry larger bending moments. Hence to avoid large changes within the existing construction and to keep the outer columns slender it was finally decided to design a vertical inner column.

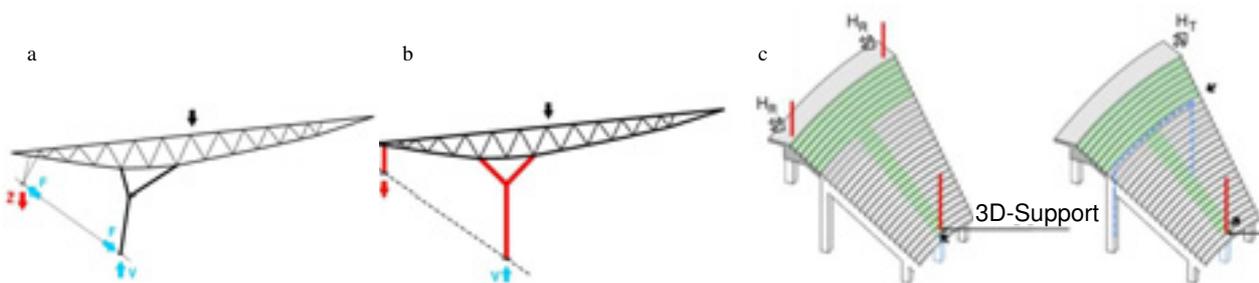


Fig.7 Reaction forces under vertical loads by an inclined inner column (a) and by a vertical one (b) as well under horizontal loads (c).

The design concept has following additional features (see Fig.6)..

- (1) The roofing comprises two textile membranes placed above and beneath the steel structure. The upper membrane carries the snow and protect against rain. The slight inclination of the upper flange of the steel truss towards outside allows a natural drainage. The lower membrane acts as a ceiling: a huge wing-shaped box is therefore created in which both structure and the necessary technical equipment could be incorporated.
- (2) The outer side of the roof is designed as a triangular-shaped box. The sharp exterior edge has the effect that the roof appears from outside as a line floating above the facade. In order to underline this effect and also to create a surface reflecting light during the nocturnal activities inside the stadium, it was decided to cover the

lower side of the box with metal. The box has also an important structural role. Its weight was to be so optimised that the resulting compression in the existing stone columns could balance the maximal tensile force yielded by the roof (Fig.7b).

- (3) The outer columns were placed above every facade column. They were to be very slender to have a minimum impact on the outside view of the stadium.
- (4) The inner side of the roof is designed as a glass surface sustained by a visible 'Vierendeel' girder made of cast steel. The resulting height at the joint between the glass roof and the double membrane made possible the realisation of a catwalk along the whole roof perimeter, in which the nocturnal lightening of the sport ground as well as other technical equipment were to be accommodated.

The final design concept as prepared by the architects and presented to the contest is shown in Fig. 8 and 9.



Fig.8. Views of the stadium (models).



Fig.9. Views of the stadium without roof (a) and with the new roof (b)

### 3. THE STRUCTURAL DESIGN

The structural system and components are depicted in Fig. 10. There are tubular radial and tangential truss girders with welded nodes. There are 76 radial truss girders, i.e. one for every two stone facade columns. They are vertical two-flange trusses and are carried by two tangential members: a spatial, three-flange truss sustained by the treed inner columns and an outer spatial beam sustained by the outer columns. Further there are two other tangential structural members. At the side of the roof in the vicinity of the joint between the membrane and the glass surfaces there is an inclined two-flange truss, which has the role of equalising the vertical displacements at the ends of the radial girders. In between the described members there are tangential tubular bars linking the upper nodes of the radial girders and respectively the lower nodes. Their role is to stabilise the radial girders by carrying the horizontal tangential forces to the bracing. All bars with the exception of the lower flange of the radial truss over the bright of

the three flange tangential truss are straight. The curved lower flange of the radial truss is stabilised vertically by means of a steel cable (see Fig.6).

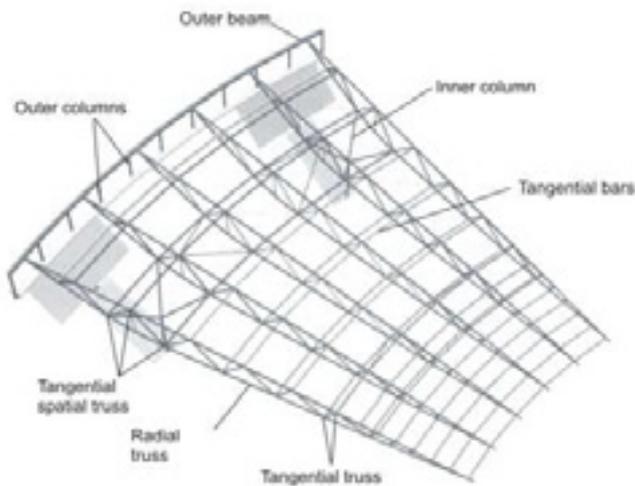


Fig.10. Detail from the computational model of the structure [8].

The radial truss has a maximal height of 5.5 m and its cantilever span is about 49 m. The radial distance between the inner and the outer columns is about 17.5 m. The distance between the inner columns in tangential direction varies between 32 and 40 m. The nodes of the tangential truss are cast. The inner column has to carry a maximal force of 12 MN. Its vertical branch has a length of 8,5 m and a diameter varying from 250 mm (lower end) to 350 mm; its cross section is massive and made of a high strength forging steel. The four inclined branches of the inner column have a massive diameter of 290 mm. The node between the vertical and the inclined branches are made of high strength cast steel.

The outer beam with triangular cross-section has a width of 8.5 m and is made of reinforced concrete partially prefabricated. In the vicinity of the radius containing an inner column the triangular cross-section is full, in order to become enough weight to balance the tensile reaction force.

The horizontal stiffening in radial direction is realised by means of the frames made of an inner column, the two corresponding radial trusses and the four corresponding outer columns (see Fig.10). 20 radial frames are available. In tangential direction there are two framed lines available: the one made of the inner columns and the spatial tangential truss, the other made of the outer beam and the outer columns. Additional braces are necessary in tangential direction to horizontally stiffen the roof. Their location is dependent on the dilatation joint which were provided in order to reduce the internal forces caused by the deformation under temperature variation. The position of the dilatation joint and of the braces is depicted in Fig.11. The outer beam is built continuously (without any joint) over the whole perimeter of the stadium. There are three dilatation joints inside the range between the outer beam and the tangential in-plane (two flanged) truss at the tip of the radial trusses and there are six dilatation joints inside the range made with glass. This range is stiffened in tangential direction by the horizontal frame made of the radial and tangential girders. Consequently only the middle ranges between the three dilatation joints are to be stiffened in tangential direction. Four braces are necessary. Their location is depicted in Fig.11. Each brace uses two radial trusses adjacent to an inner column as flanges, while diagonal bars link the upper nodes of one girder with the lower nodes of the other in an alternating way. The diagonal bars are designed as tensile members and are made of pre-stressed high-strength round bars. This concept originates from the architect's wish to become a regular rectangular grid of the structure to be seen through the lower textile membrane - see Fig. 12.

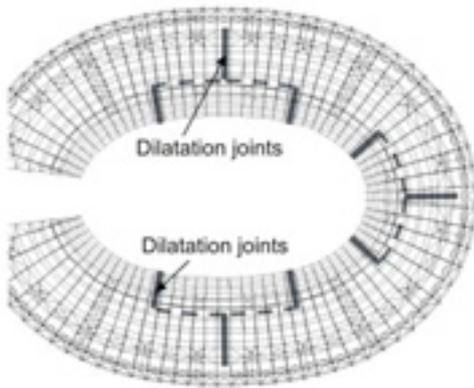


Fig. 11. The dilatation joints and the tangential bracing.

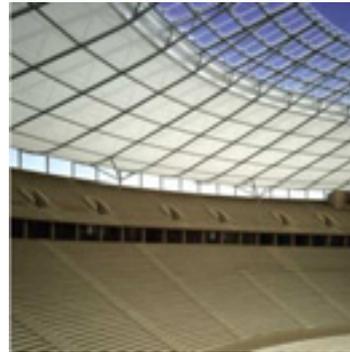


Fig. 12. View of the roof from beneath.

The roof reaction forces had to be further carried through an existing construction which was made of a very poor concrete. Indeed measurements of the concrete strength have shown values between 5 and 25 MPa (Fig.13). Moreover there were no reinforcement drawings available. Consequently it has been decided to use the existing construction for carrying – as before – only the loads coming from the grandstand itself and to design a new system for the loads induced by the roof. This new structural system had to be independent of the existing grandstand or modify it as few as possible bearing in mind that the stadium is a protected architectural monument. The structural concept of this system is shown in Fig.7c. It is a statically determinate system. Its construction is depicted in Fig. 14. It is made of reinforced concrete and consists of the following parts.

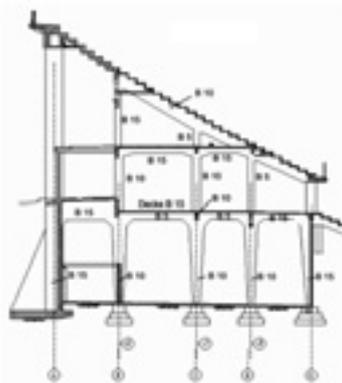


Fig.13. Measured concrete strength [7]



Fig.14. The structural system carrying the roof loads

- (i) The main structural part is a spatial frame with four columns in the axes C and D, which has the role of carrying the vertical loads from the inner column and the horizontal loads in radial direction. At the same time it represents one of the two supports for the horizontal loads in tangential direction. The concept of this frame has also had to take into consideration that there are different situations within the grandstand to cope with. For instance at certain locations the inner column had to be supported vertically by a beam since otherwise it would go through a corridor linking the inner and the outer galleries.
- (ii) The second support for the horizontal loads in tangential direction is provided by structural walls in axis B. These walls are cast-in at the inner face of the existing façade.
- (iii) To carry the horizontal reaction forces in radial direction from the outer column to the spatial frame described under (i) parts of the existing inclined diaphragm between the axes A and B (monolithic terrace) was completely

new replaced and additionally a new link between the axes B and D underneath the terrace units had to be built.

(iv) Above the existing stone columns in the facade and inside the stone attic beam a new reinforced concrete beam was cast. Its role is to distribute the horizontal tangential force coming from the outer roof columns to the diaphragm described under (iii). At the same time it was possible to cast-in the supports of the outer roof columns in this beam. Furthermore a special attention has to be paid to the dilatation joints within this beam since the beam crosses many of the dilatation joints existing in the old construction of the grandstand.

#### 4. THE STRUCTURAL ANALYSIS AND CONSTRUCTION

The structure was analysed by means of a complete 3D model of the roof (see Fig. 10). The wind loads were determined by testing a model in a wind tunnel and numerically evaluating the gust factors. The first period of vibration is about 3 s and the corresponding form is a general horizontal rotation about the central vertical axis of the whole roof. The gust factors are 1,3 for the horizontal and 1,1 for the vertical wind forces while the static wind pressure is about  $1.25 \text{ kN/m}^2$ . The vertical displacement at the inner end of the roof under snow is about 25 mm. The computed relative displacements in the roof joints under a temperature variation of  $35^\circ \text{C}$  are 60 mm in the middle joints and 35 mm in the joints within the glass construction (see Fig. 11). On account of the column slenderness there are very small internal forces to occur from the different deformations of the roof and the grandstand [8].

The erection of the steel structure has always started at a radius with inner column. Following steps were used. Firstly came the outer columns and the steel and pre-cast R/C elements of the perimeter beam. The inner column was then erected and temporarily supported. Afterwards the assembly made by the parts of the radial trusses adjacent to the inner column and lying between this column and the outer beam was erected. All spatial parts were welded outside the stadium and were already equipped with the steel arches, which had to carry the upper textile membrane (Fig.15). At this stage the structure became self stabilized, there was no longer need for the temporary support of the inner column. After ballasting of the outer beam the erection continued with the tangential spatial truss linking the inner columns, the rests of the radial and tangential steel structure and so on.



Fig.15. Erection of the steel structure



Fig. 16. Detail of the outer beam before ballasting

The textile membranes were designed by the consultant civil engineers Schlaich, Bergemann and Partners [9]. The upper membrane is supported by steel arches and has a double negative curvature (Fig. 17). The lower membrane is open on the perimeter, plane and pre-stressed by means of small springs (Fig. 18). A detailed description of the roof construction is given in [10].

Following German companies were involved with the design and erection of the roof: *von Gerkan, Marg and Partners (gmp)* as architects, *Krebs & Kiefer Consulting Engineers Ltd* as structural engineers, *Schlaich,*

*Bergermann and Partners* as designer of the membrane roofing and of some cast nodes, *Wacker Engineers and Institute for Industry Aerodynamic Aachen* for the Wind Engineering, *Institute of Steel Construction (University of Aachen)* as expert for special steel, *Dillinger Stahlbau Ltd* for the steel construction, *B&O Hightex Ltd* for the membrane construction, *MERO Ltd* for the glass construction and *Prof. M. Specht* as proof engineer. For the design of the roof gmp and *Krebs & Kiefer* have received the Special Award of the German Association of Steel Construction 2004.

Within the design team of *Krebs & Kiefer* the main technical responsibilities were ensured by *the author* (for architecture contest and preliminary design), by *Dr. Stroetmann* (for final design and structural analysis) and by *Dr. Kiefer and H. Müller* (for load carrying structure inside the existing grandstand).



Fig.17. The upper membrane.



Fig.18. The lower membrane. (View inside the roof box)

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## Abbildungen und Fotos

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