A Spoked Wheel Structure for the World’s largest Convertible Roof – The New Commerzbank Arena in Frankfurt, Germany

Knut Göppert, Managing Director, Schlaich Bergermann und Partner, Stuttgart, Germany; Michael Stein, Vice President Operations, Schlaich Bergermann and Partner, New York, USA

Introduction

The roof is a lightweight structure consisting of three major parts:

- the edge panel supporting the compression ring (6000 m²);
- the fixed main roof (27,000 m²) using radial cable trusses and two tension rings and;
- the retractable inner roof (8,000 m²) supported by radial cable trusses.

In the plane of the roof, the three components structurally exploit the principle of the spoked-wheel. In order to adjust the roof geometry at the outer corners of the stadium bowl, the circle was modified to create a more rectangular form.

44 pairs of radial cables are connected to the compression ring. To achieve an out-of-plane stiffness for the roof, the radial cables are spread vertically, leading to two tension rings at the inner edge of the fixed roof portion. The structure for the inner roof follows the same principle.

The retractable roof can be unfolded by pulling its outer edges towards the lower tension ring. Sitting in the world’s largest convertible greatly improves the spectator’s experience at the stadium (see Fig. 1a and 1b).

Keywords: cable truss; retractable folding fabric; compression ring; lightweight translucent stadium roof systems.

General

As at the beginning of the seventies, a series of new football arenas were built between 1998 and 2005 after the successful German bid to host the Football World Cup. This move coincided with a new direction in the design of stadiums. The design moved from stadiums designed to host football and track and field events to stadiums designed as multifunctional arenas or purely to host football matches. With this development, the proximity of the spectators to the pitch, the elimination of the track for athletic events and the optimal arrangement of VIP and Press boxes were achieved.

A significant change in the structural form is the result of the increasing orientation towards football stadiums. A rectangular central space and rectangular roofing edge are becoming more common along with a closer orientation of the exterior form to the playing field. What at first appears to be a contradiction, can actually be combined: the football stadium and the spoked wheel principle.

Development of Spoked Wheel Roof Structures

Roofing structures relying on the structural behaviour of a horizontal wheel with inclined spokes have been in use for many years. These structures have been employed for circular systems such as Madison Square Garden or the Zaragoza Stadium.2

With the erection of the Gottlieb-Daimler Stadium in Stuttgart, the spoked wheel principle was greatly expanded (see Figs. 2a, b).2

- Instead of one compression ring with a central spread hub, two compression rings were employed with the inclined spokes running to a central point.
- Instead of connecting all the spokes to one point, these are led to an inner tension ring.
- The circular form became oval.

Following the construction of the Stadium in Stuttgart (Fig. 3a),3 numerous other stadiums have been designed by the Authors’ office with similar spoked wheel roofing that are referred to as cable ring structures.

The Malaysian National Stadium in Kuala Lumpur4 and the Nigerian National Stadium in Abuja consist of one compression ring and two spread tension, all with an oval form. The Kuwaiti National Stadium has a single, radial-tangential cable net. The difference in elevation along the compression ring creates the “structural depth”.

The World Cup Stadium in Hamburg (Fig. 3b)5 was the first approximation of a rectangular opening for a cable ring roof. The forces caused by directional change at the ring cables are in equilibrium with the forces due to directional change in the “rim”. The force of directional change at the inner tension ring corners are each transferred by the three cables to the compression ring with more constant curvature.

Fig. 1: (a) Aerial perspective (b) Inside view of stadium
(a) Photocredit: Max Bögl (b) Photographer: Martin Stahl

In order to eliminate any important bending stresses in the rim under self weight, the following conditions must be met:

- The self weight of the light structure has a negligible impact on the forces in the supporting elements.
- The form of the tension and compression chords are funicular with respect to one another.

The possibilities opened up by this construction principle can be further developed and combined. Two current examples of this further development, in Durban, South Africa and Delhi, India, are currently being designed and executed in close collaboration with the architects.

**The Stadium Roof Structure**

The compression ring along the circumference of the stadium bowl forms the rim of the cable ring system. The central hub is replaced by a cable ring in which the tension forces are carefully balanced with the forces of the compression ring. Radial cable girders make up the spokes and connect the rings.

In elevation, several combinations of compression ring(s) and tension ring(s) have been explored. The results of detailed analysis led to a system having one compression ring above the outer edge of the bowl with radial cables spreading out towards the inside of the stadium and ending in two parallel tension rings running on top of each other. From there the radial cables of the inner roof start and meet at the centre of the stadium at – theoretically – one point. The vertical components of the upper and lower tension ring are balanced by means of vertical struts.

The complete roof structure is supported by slender vertical columns of 8.5 m height in each axis. The roof therefore appears to be floating almost weightlessly above the stands (see Fig. 4a, b).

The roof cladding consists of a combination of four different materials:

- The metal cladding at the outer edge hides the slightly different curvature of the stadium bowl and compression ring. More curvature is necessary for the compression ring to create a viable structural system with moderate forces. The edges of the metal cladding are arranged parallel to the bowl’s edges.
- The material of the fixed roof is a PTFE (Polytetrafluoroethylene) coated glass fabric, which is located on the lower cable level reducing the vertical distance to the stands.
- To improve the interior lighting situation, a 15-m wide area of polycarbonate sheets is arranged parallel to the tension ring. These sheets have a high level of translucency (85%) whereas the roof achieves 15%. The polycarbonate also closes the catenary-shaped gap between the inner and outer fabrics.
- The material of the retractable roof is PVC (polymer of vinyl chloride) coated polyester with additional PVDF (Polyvinylidene Fluoride) coating on the upper side. It is situated at the lower cable level of the inner roof.

In standard spoked wheel structures, ring geometries and ring forces are strongly dependent on each other and cannot be chosen freely. The inner roof of the Frankfurt Stadium helps to overcome this design limitation.

The structure of the inner roof follows the same principles as the outer roof, resulting in two interlocked spoke wheels with one outer compression ring, two tension rings and the central hub. This combination allows a choice of the geometry of the tension ring freely as the balancing forces for the compression ring could be assigned to the tension ring or the hub.
respectively. Not only the horizontal position could be adjusted but also the vertical shape of the roof, leading to several architectural options as well as the possibility of arranging the drainage in the corner areas of the roof.

Structural Analysis

All primary structural members, i.e. columns, compression ring, radial cables and ring cables of the inner and outer roof and the flying struts, were simulated in one computer model. Using a high end software package, this model was analysed using geometrically non-linear solvers as recommended for all major tensile structures.

The columns and the compression ring were modeled as beam elements, the flying masts as strut elements and all cables including the bracing diagonals as cable elements. The covering as secondary element was not considered in the global model.

The most important step at the beginning of the analysis of a tensile structure is the form-finding in which the geometry and forces of the primary elements are coordinated in the most efficient way under a chosen loading condition. The results of this iterative process, i.e. geometry and forces, constitutes the basis for all the following calculations (see Fig. 5).

DIN German Standard was used to define the standard loading provisions. The wind loads on the roof were derived in a wind tunnel test considering local topography and urban environment. The retractable roof was designed to withstand summer loading conditions only as the roof should only be deployed between May and October of each year. However, as extreme summer conditions like hail storms had to be considered in the design, the load could only be reduced to 65% of the full snow load. During the moving
operation itself the loads due to wind or rain were restricted to a practical minimum. This requires responsible operational management to close the roof for one event and includes contacting the local meteorological institutions for specific weather forecasts. As the moving operations take 15 minutes, these provisions were found to be practical.

One of the most challenging parts of the structural analysis is the stability check for the compression ring, as standards or other provisions are hardly applicable. The well-established process, which was used for the compression ring here, is to calculate maximum stresses in the ring under factored loading including imperfections. The imperfections should be adopted by using the scaled deflections under the first eigen-frequency of the system. Special attention is required to scale the deflections carefully and coordinate them with the specified tolerances. As a final step, a standard buckling check was carried out for each compression ring element.

Several sub-models were created to account for secondary structural systems such as the structure of the inner and outer roof, the catwalk including the support structure for the polycarbonate cover and the video cube.

Special attention was given to the central node, where a total of 96 cables are connected in the minimum possible area. The maximum total force which was introduced into the hub was 30,000 kN from both main axes of the stadium. One quarter of the node was reproduced with a finite element model using a Software and analysed, considering the main cable forces from the global model. Special welding and erection procedures were developed to guarantee the safe transmission of the predicted forces.

Retractable Roof

The retractable roof can be unfolded along the inner radial cables. The non-deployed position of the roof is folded up in the central video cube of the stadium. The video cube and its roof have to be designed properly to withstand all possible loading conditions during the entire year and to protect the membrane package from severe environmental conditions (Fig. 6).

The fabric is connected by means of polyester straps to gliding steel trolleys in distances varying from approximately 6–9 m. The steel trolleys are hooked to the primary steel cables of the inner roof. These are double cables spaced 250 mm apart to provide stable gliding conditions. To avoid any direct gliding of steel on steel, the trolleys are equipped with hard-wearing blocks of synthetic material at the contact zone to the steel cables.

At the outer edges of the fabric, the driving trolley is connected to an endless steel cable which is guided along each radial cable and looped around a winch located near the tension ring. Using a motor-operated winch, the cable can be moved, and so can the driving trolley. When deploying the roof, the driving trolley pulls all gliding trolleys, as they are connected via the fabric. Folding the roof together the driving trolley pushes the other trolleys by direct contact (see Figs. 7 a,b).

The motor-operated winch allows fast traveling, but cannot be used to introduce the prestress into the fabric, required to provide a stable load carrying system. For this reason the driving trolley is mechanically locked to a stressing device at the very end of the deploying process. The stressing device consists of a pair of hydraulic cylinders. These cylinders introduce high local forces at the outer edge to stress the entire fabric properly and to withstand the concentrated local forces under loading conditions.

The travelling process requires coordination between the 34 inner roof axes to avoid uncontrollable side-effects due to uneven driving velocities or local interferences. The mechanical devices and the software had to pass extensive long term tests at the fabrication site.

before the system was approved by the authorities and the engineers.

The required volume of the video cube to store the folded package of the inner fabric was investigated in three different ways:

− The physical model of the inner roof, to get a deeper understanding of the complex geometrical processes during folding of the membrane (Fig. 8a).

As for most scaled models, it is necessary to find a material with the correct weight and the correct bending stiffness as the folding is strongly dependent on both parameters. Ultimately, special fabrics from the apparel industry were used to obtain useful results.

− Computer model using software of the automobile industry (airbag folding).

To gain practical results with computer models, very detailed finite element systems are required. The finite elements must be defined as contact elements, simulating the folding process, not a standard software in the construction industry. To reduce the necessary calculation time, only half a bay was modeled and calculated first. This calculation proved the results of the scaled physical model, so bigger computer models were unnecessary.

− Mock-up of one eighth of the roof checking the folded condition (Fig. 8b).

The final step was the 1:1 model with part of the actual roof itself at the fabrication site. This final check has proved that the chosen volume of the video cube could be considered as sufficient. Some uncertainty remained as the influences of temperature and the repeated folding and unfolding on the volume of the fabric package could not be estimated exactly. Now, all testing operations have certified the design volume as adequate.

Fabrication and Erection

As the complete renovation of the stadium was performed while the stadium was in service, well-coordinated erection procedures, not only for the stands but also for the roof, were crucial for the successful completion of the project. Increasing the amount of prefabrication and reducing the required time at the site during erection, proved...
to be the right approach to the coor-
dination problem. This led to unique
fabrication and erection methods.

To meet the assumptions of the struc-
tural analysis, the compression ring has
to be fabricated following strict toler-
ance requirements both in the length
of each element and angular deviation
of the end plates. One effective meth-
od, also applied in previous stadium
projects, is to sequentially machine the
end plates of each compression ring
element and to perform immediate
trial assemblies at the fabrication site.
Intolerable deviation at one element
can be settled by correcting adjacent
elements. This approach, which might
sound complex and costly with respect
to the fabrication, pays off during erec-
tion. The compression ring elements
can be quickly erected one after the
other and fixed together, after the col-
umns and linking girders are installed
and temporarily fixed. The placement
is very precise and major surveying
during erection can be avoided by the
attention during fabrication, saving im-
mense time and money at the site.

The complete compression ring must be
finished to start with the installation of
the cable structure. The cables are com-
pletely pre-fabricated, cut to extremely
tight tolerances, connected with the end
sockets and delivered at the site.

In the next step, the cables are laid out
on the stands and the field. All cables
are connected to each other with cast
steel clamps and ring connectors, pro-
ducing one single cable net. The radial
cables are connected by means of tem-
porary strands to lifting jacks fixed to
the compression ring. By pulling these
temporary strands, the complete cable
net can be lifted off the floor towards
its final position (Fig. 9a).

As all 44 axes are pulled at the same
time the jacks have to be carefully coor-
dinated from a control panel, checking
geometry and the corresponding forces.
After a certain height is reached, the
flying masts are installed and the lifting
of the cable net completed (Fig. 9b).

During the complete lifting process the
cable net represents a stable structural
system. After the cable net is installed,
the arches and the fabric are erected
bay by bay, following structural and
operational requirements. The cat-
walk, including the polycarbonate roof,
is erected in parallel. In the middle of
the roof the steel skeleton of the video
cube is connected to the central hub of
the cable structure and all mechanical
devices are installed and tested.

Finally, the inner roof is installed. It
was delivered in a single piece of ap-
proximately 8,500 m². After waiting for
low winds and reconfirming the weather
conditions, the raising of the entire
inner roof is begun by connect-
ing the polyester straps sequentially
to the trolleys located near the central
hub. The procedure is finished after an
uninterrupted construction period of
approximately two days.

Conclusion
The roof of the Commerzbank Arena
was a technical challenge requiring
the innovative solutions of all project
participants. Described as “the world’s
biggest convertible” it has proved itself
over the last two years in a series of
sports and other events including the
football World Cup in 2006.

The roof demonstrates that light-
weight designs with modern materials
are definitely attractive alternatives to
standard structures. The final layout of
the structural members proved again
the tremendous adaptability of cable
supported roof structures.

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