УДК 624, 691

Supporting structure and roof diaphragm of the Warsaw National Stadium

Leszek Miara, Przemysław Ziemczyk

National Sports Centre, Poland

Анотація. Коротка інформація про особливості зведення національного стадіону (Варшава). Приведені основні будівельні об'єми, даний опис виду, роботи і процесу виробництва і зведення основних несних конструкцій. Також, даний опис центральної опори, що підвішеної над центром поля і несе увесь рухливий дах. Особлива увага приділена виробництву і доставці елементів, а так само перевіркам антикорозійного захисту і контролю зведення конструкцій.

Аннотация. Краткая информация об особенностях возведения национального стадиона (Варшава). Приведены основные строительные объёмы, дано описание вида, работы и процесса производства и возведения основных несущих конструкций. Также, дано описание центральной опоры, подвешенной над центром поля и несущей всю подвижную крышу. Особое внимание уделено производству и доставке элементов, а так же проверкам антикоррозийной защиты и контролю возведения конструкций.

Abstract. The brief information about the Warsaw National Stadium erection peculiarities. There are given the total structural volumes of the erection process, the description of the shape, work and the manufacturing and erection processes of the main bearing structures. Also the description of the central mast is given, which is suspended over the center of the playground and supporting the whole movable roof. Special attention is applied to manufacturing and delivery of elements and to the inspection of antycorrosion protection and structure erection.

Key words: Warsaw National Stadium, central mast, cables.

General information. The latest construction solutions and materials were applied at the realisation of Warsaw National Stadium. The cubage of the whole stadium exceeds 1,1 million m^3 and the lengths of its main axis are 314 m and 279 m. According to UEFA standards it attains the fourth highest class.

The State Treasury represented by the Ministry of Sport and Tourism is the owner of the Stadium. The National Centre of Sport Ltd appointed by this ministry was responsible for stadium construction. The individual erection technology of stadium elements was employed. During the whole process of construction the safety and quality of work were treated as priority factors.

The stadium is located in the basin of the former Tenth Anniversary Stadium (see drg. 1), on the plot limited on the south by Poniatowski avenue, on the east by Zieleniecka street, on the north by the railway line (with “Stadion” stop situated in the vicinity of the Stadium), on the west by Wybrzeże Szczecińskie street. The mentioned streets are two-lane streets (in each direction). Near the Stadium the underground station will be finished in 2014 year.

Fig. 1. The Tenth Anniversary Stadium (birds view)

The decision of Stadium construction was undertaken in April 2007. The preliminary design was approved in February 2008. In June 2008 the design with all documents necessary for obtaining building permit were submitted to the Warsaw Governor and the building permit was issued on the July 22, 2008.

Fig. 2. The new National Stadium in Warsaw

The first stage of the National Stadium construction, the piling for foundation was started in October 2008. It was carried out by Pol-Aqua SA. 7 000 prefabricated piles were performed, ca 6 700 gravel and concrete piles and 900 large diameter piles. The piling was finished in March 2009.

In May 2009 the second stage of work was started (after contract awarding) in May 2009. It comprised concrete works, foundations and concreting of the first three storeys of the stadium construction.

In January 2010 the first element of the compressed ring was delivered to Warsaw enabling to start the erection of the steel structure. The consortium: Alpine Bau Deutschland AG, Alpine Bau GmbH, Alpine Construction Polska Sp. z o. o., Hydrobudowa Polska SA, PBG SA was appointed as general contractors of the second construction stage.. This Consortium entrusted the specialised works including delivery and erection of steel structure to Cimolai SPA which organized another consortium: Cimolai SPA, Mostostal Zabrze Holding SA, Hightex GmbA. In this consortium Mostostal Zabrze was responsible for the erection of the total stadium steel structure, the cable roof and for the delivery and erection of the glass roof and the façade. The basic data concerning the steel structure, façade and the roof of the stadium:

- compressed ring diam. 1820 mm, wall thickness g = 80 mm, 72 segments each 12,6 m long, the total length of the ring 907 m;
- columns supporting the compressed ring diam. 1016 mm, wall thickness g = 30 – 70 mm, 29 – 34 m high;
- angle struts diam. 1016 mm;
- fasade tie diam. 508 mm, wall thickness g = 25 – 45 mm;
- weight of main steel structure 12 000 t;
- weight of auxiliary steel structure with the mast (needle shaped) 2 400 t (must with equipment 190 t);
- weight of steel cables with connectors 1 700 t;
- total length of the cables 37 000 m;
- outer aluminium façade ca 22 000 m^2;
- surface of fixed roof over the tribune ca 50 000 m^2;
- surface of outer roof ca 6 000 m^2;
- surface of closed roof ca 10 000 m^2;
- surface of glass roof ca 4 000 m^2.

Top view and cross section see Fig. 3.

The contractors were obliged to present the suitable production capacity to manufacture steel structure, cables and diaphragm. The updating of the information submitted by the contractors could not exceed five years. The working documentation was delivered by the orderer, the National Centre of Sport. The contractor prepared the workshop documentation with necessary calculation, technical specification of delivered elements and materials, quality material certificates and results of material tests. The important part of the delivered documentation was design of method statement.

Static diagram – load distribution. Different arrangements in the form of the so called spoke wheel are creating one complicated structure. In section the inner roof over the play ground is easy to recognize as spoke wheel with one band and one central hub. The band consists of two stretched rings of the outer structure. The mast (needle shaped) acts as a central hub. In horizontal projection the four bundles of lower radial cables supporting the mast settle down as the diagonal of the play ground. The conception of spoke wheel in the outer part structure was realized by means of two compressed rings and two stretched rings connected by crossing radial cables. The upper compressed ring was replaced by the façade tie of the carrying cable which by intermediation of the inclined angle strut rest on the lower compressed ring. The whole radial force originating from lower and upper radial carrying cables was transmitted to the compressed ring and as horizontal component of radial force to the foundation. Between two stretched rings there were inserted compressed struts which together with 10 m long cantilevers compose the support of the glass roof and simultaneously compose the roof inner edge. In this way the span of roof structure attains 91 m.

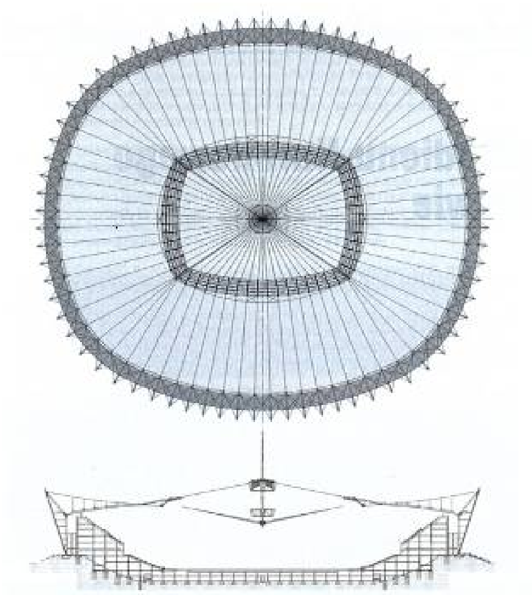

Fig. 3. Top view and cross section

The snow load causes increase of force in upper radial cables and simultaneously decrease of prestressed force in lower radial cables. In case of load caused by wind suction the principle is opposite. Both types of loads exert influence as well on vertical as on horizontal support reactions.

Workshop design – establishing of geometry. In the construction system there is no possibility to correct geometrical deviations of cables or steel items. Structure prestressing is based exclusively on workshop geometry of manufactured items and corresponding tolerances.

The length of cables was determined taking into consideration the influence of cone slide and so called cable creeping. In case of big diameter cables additionally had to be taken into account the tension by the first loading. Due to limited possibilities of pulling equipment the cables could not be subjected to preliminary stretching with total work load. In the frame of tests there was determined the summary total value of cable plastic elongation by reaching the primary work load which was subtracted during marking and cutting the cables. The whole series of tests due to lack of time were carried out simultaneously at Trento University, in FMPA Stuttgart and in DMT Bochum[1].

Often determination of steel structure workshop geometry was reduced to preliminary elongation of compressed ring and columns and to preliminary shortening of stretched items in order to get the demanded geometry after imposing the full load on erected items. But in this case the geometry according to workshop design had to take into account the influence of restraining. The columns (a) and the inclined angle struts (b) together with façade ties (c) compose a triangle. This elements are shown on Fig. 4.

Fig. 4. Triangle of the main pipe elements

In the final position the façade ties are stretched and two remaining items are compressed. The façade tie is connected with adherent column and angle strut by welded joint executed on site (bolted or pin joints were impossible to execute on account of large stretching forces). Before applying load on the structure those joints are forcing moments appearance in triangle corners, which can be totally eliminated only by the repeated opening. The lower triangle corners were released from moments in the process of welding by previously placing in the

[1] FMPA - Material Prüfungsanstalt – Universität Stuttgart, DMT – Bochum – Zerstörungsfreie und Zerstörende Seilprüfstelle.

triangle the connecting beam – the façade upper angle strut. The upper corners will be released from moments after full loading.

The supports were initially horizontally appropriately shifted according to rigidity of particular foundations and horizontal supporting forces in order to equalize shifting under the influence of full load.

Steel structure. Items of steel structure anchoring cable system (column bases, columns, compressed ring, angle struts, façade ties) were manufactured by Cimolay company in Italy. Particular problems created fabrication of compressed ring pipe: bending and welding (wall thickness 80 mm) produced of steel S460. Frontal sheets for pipe items were prepared with thickness allowance and were machined before welding in the zone of welded joint to smooth the sheet roughness and to equalize the thickness tolerances. After welding of frontal sheets to pipe elements, but still before machining, the pipe segment were precisely positioned with application of Laser Track device in order to get accurate position and correct connection angle. These segments were supported in order to eliminate deflection or deviation at the ends under their proper weight. As complementation to precise measurement of single items in workshop, 5 sequent segments each time were initially assembled together on supports regulated hydraulically by servo-motors in order to equalize deflection originating from proper weight.

Hanging items of structure were manufactured in Poland by Mostostal Zabrze (struts of stretched rings, glass roof and diaphragm arches) and by Zakłady im. Cegielskiego in Poznań (needle shaped mast).

The central point of the inner roof is the central mast (needle shaped), suspended over the center of the play ground and supporting the whole movable roof. From this mast bundles of roof cables radiates and this mast support diaphragm garage in which the roof diaphragm is stored in closed position. The lifting devices with hoisting cable winches permit to lower video screens nearly to play ground level. Automatic interlocking system with hydraulically actuated pins is fastening screens on the mast. To prevent destruction of inner roof carrying items in case of fire all video-screens were equipped with automatic anti fire devices.To assure transport to service platform by videoscreen there is the manlift from level of playground to platform. Simple-hanging lift is integrated with video-screens supporting structure in order to enable access to the mast during conservation works. Starting from the design and finishing on execution the whole mast structure dead weight (together with diaphragm garage and video-screens - total weight 190 t) should be incessantly controlled to avoid surmounting of permissible forces in the cables supporting the inner roof.

On the upper tip of the mast carrying structure is situated the central knot where on the possibly smallest surface 60 radial cables are fastened. (Fig. 5 and 6). To diminish the knot diameter the anchored cables were split into two layers. Before starting knot manufacturing the trial model was executed to determine welding technology and feasibility of execution of welded joints with difficult access. Part of knot horizontal sheets unnecessary from the static point of view was removed in order to reduce the weight. As a result an interesting geometry was received, optically resembling to rosette which will be visible by opened diaphragm garage.

Fig. 5. Central knot, for 60 radial cables forten (rosette)

Fig. 6. Central knot seen downwards

From each of the four corners of the main roof 3 cables lead to the mast lower knot (drg. No 18). In corner knots of the stretched ring these cables are in horizontal position, however at connections with the mast they change the position to vertical. Due to this fact each cable has a different angle connection and the easiest method of obtaining such position was to apply a casting.

The casting of lower knot weighing 18 t is the heaviest connector of the cable system. Together with connectors of the stretched rings and cable clamps they were manufactured in Cividale SPA foundry in Italy. Castings, see drg. 7, with complicated geometry were modeled and spatially analysed by applying program Nastran.

Organisation of inspection and supervision. To guarantee the high quality of stadium roof steel structure and its conformity with technical specification the method of control and supervision was worked out. Inspection process was carried out according to construction stages.

The technical specification was elaborated by sbp designers and it composes part of the working documentation. It concerns the delivery, erection anticorrosion protection of steel structure, roofing, complementary works, organisation of inner work taking–over, programme of production and expedition.

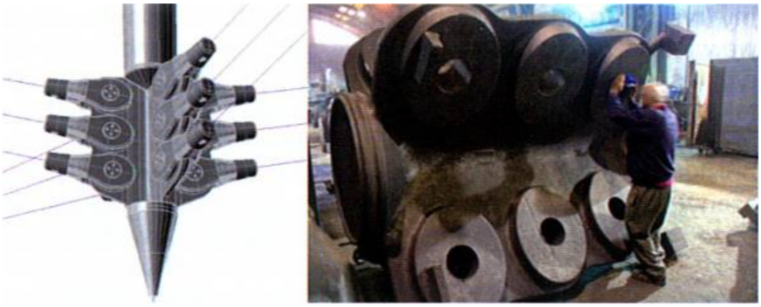

Fig. 7. Cast steel footing – the heaviest connector of the cable system – weight 18 t

Manufacturing and delivery of elements. The sequence of particular elements manufacturing of was coordinated with the erection demands. This coordination was indispensable to maintain the erection continuity and to conform demands imposed by static conditions, relating to all stages of erection works. Insufficient surface of storing area and necessity of maintaining roads mobility on the building site necessitated to respect strictly delivery sequence. It should be noted that on the building site there were carried out simultaneously several different types of works: earth works, reinforced concrete works, erection of steel structures. The weight of prefabricated steel structure main items attained 60 t, its length 30 m and its width 15 m.

For erection works even 60 cranes with capacity up to 600 t were simultaneously used. The works were carried out round the clock, seven days a week.

By acceptance of materials the following procedure had to be verified:

- conformity of delivery with sequence, time schedule and its completeness;
- eventuality of transport damage (deformation, defect of anticorrosion coating);
- documents of delivery;
- notification of eventual remarks to the manufacturer and assurance of proper unloading and storing on right places.

Before starting the erection process the following procedure had to be noted:

- checking of foundations or supporting structure – this facts had to be certified in due reports with enclosed survey statements;
- construction site and access roads handing over taking into account subsoil load capacity and pressure exercised in the process of structure prefabrication and in erection process;

— informing the teams working in the vicinity about dangerous conditions connected with erection activity, possibility of its exclusion or reduction.

Method statement design. Before starting the erection or prefabrication works the contractor was obliged to submit the method statement design accepted by the construction designer and by the supervision of National Centre of Sport. The structure stability had to be checked in different stages of erection as well as the strength of heavily loaded elements to assure the safe conditions of work (scaffoldings, safety devices, ect.). From the beginning of production process through all its stages up to erection, adjustment, intermediate and final acceptance of works there were checked all conditions determined by the designer in technical specification.

The required accuracy of manufacturing and erection of steel structure required all elements to be erected under geodesy surveing, by contractor and designer participation. Erection deviations were analysed taking into consideration tolerances determined in design and standards and later according to designer's directions were corrected or accepted in relation to supposed conditions. In fabrication plant the main structure elements were subject to trial assembly and after satisfactory result of the test were subject to finishing (Fig. 8). Dimensions and complicated shape of these elements disabled to correct them on the building site. In Cimolai SPA plant all 72 pieces of the compressed ring were subject to trial assembly: pipes diam. 1 800 mm, g = 80 mm (wall thickness), 12,5 m long, weight ca 50 t, with different angle of flange to connect ring segments. The accuracy obtained by applying technology and manufacturing conditions resulted in achieving the tolerance plus minus 2 mm on the total length of the compressed ring ca 900 m long.

Fig. 8. Trial assembly of the compression ring

Inspection of anticorrosion protection and structure erection. An important factor of inspection was anticorrosion protection of steel structure and cables. Because in reception documents delivered by the manufacturers included protocols of execution of anticorrosion protection coating (surface preparation, weather conditions during painting process, reference surfaces, measurement of coat thickness), checking on the site was limited only to transport damages, protection of welded erection connections, coating defects due to impact or friction. Efforts were undertaken to eliminate direct contact of carbon steel structure with stainless steel structure. Clamping items fastening different elements against damaging anticorrosion coating had do be equipped with different spacers protecting structure and cables.

Erection correctness of steel structure fragments and assemblies was currently checked. The inspection enclosed:

- completeness and correctness of bolt connections;
- completeness and correctness of welded connections;
- compatibility of element's geometry and location with design and calculation model.

Foundation settlement was initially measured in two weeks intervals, later in one month intervals and finally every three month. The results were compared with previous measurement. In 2011 when construction load increased the uniform settlement of 2 mm per year was observed. The geodesy measurement of foundation settlement are carried on all the time.

Safety of work was analysed and controlled during the whole erection process. It referred to erection technology, risky and hazardous activity. In particular the subject of control contained:

- permission of work for workers employed 1 m above the ground level certified by special medical examination;
- good quality of utilised scaffolding and equipment to prevent accidents
- validity of material and element certificates;
- proper qualification of workers engaged to assembly protecting devices;
- schooling of workers in such a way as to enable them to understand the necessity of applying safety devices;
- cooperation of "alpinists" (erectors working with alpinist equipment) with other erectors;
- marking of dangerous zones and precluding access of persons not engaged in erection activity.

Above mentioned activity was constantly supervised by management and industrial safety services.

General technical specification of execution and acceptance of construction works. Specification was worked out by designers of elevation wall steel structure and steel cable roof structure: JSK Architekci, GMP and sbp. It contained detailed description of stadium structure cover. This solution is described by spb authors in this copy "Inżynieria I Budownictwo".

Erection of steel structure. As the first step of Steel structure erection was erection of steel columns supporting the compressed ring. These columns were temporarily fastened to concrete construction. The temporal support was carried out in such a way that columns were initially outside deflected what enabled erection of compressed ring elements, manufactured with suitable initial elongation (see workshop geometry). By closing the ring the supports of nearby items were set in a way assuring in early morning hours the gap ca 50 mm wide – exactly so to enable inserting of missing element of the compressed ring. After centering the item and inserting the bolts the gap 50 mm wide disappears due to ring items elongation caused by temperature increase.

Fig. 9. The closing ring

Fig. 10. The gap by closing ring

Having closed the compressed ring it was possible to start the erection of already earlier prepared and connected angle struts and façade ties.

Their weight caused serious outer deflects of the ring. By leaving some of the temporary supports the overload of ring items was eliminated. Simultaneously the support configuration had to be incessantly checked to enable free thermal deformation of the ring. It excluded temporary overload of supports and reinforced concrete structure.

Previously prepared items, connected angle struts and façade ties were fastened to compressed ring by pins and welded on the site to column bases. During this operation the control points fixed on top of the each façade tie were continuously monitored with respect to ambient temperature and position of compressed ring. The correct geometry necessary for the execution of welded joints was set by applying hydraulic equipment, which by pushing the façade ties upstairs caused the turn of the whole assembled item round the pin and in this way enabled adjustment of its position.

Fig. 11. erection of the angle strut and facade tie

Both the method statement design of cable structure and its execution in December 2009 when the temperature reached – 20 ^{0}C demanded from the designers and the contractors the highest professional standards.

The whole proper weight of the inner roof rest on four corner knots of the lower stretched ring. After lifting up of the mast the cables which directly did not carry its weight were loaded only in the final faze of the stretching process. To maintain the suitable balance of radial forces on the compressed ring during cable system erection, proper technology of prestressing had to be worked out which in result of application the cables different stretching speed in particular axis assured equalization of forces transmitted from the inner roof.

The initial geometry resulted from the starting position of upper central knots (needle shaped mast) on the one hand and from the limited flexibility of stretched ring thick cables on the other hand. To enable the assembly of cables near the ground level and taking into account the play ground plate load capacity it was decided to set the mast initially at the bottom of the underground garage. Execution of suitable hole in play ground plate enabled the immersion of the mast with upper central ring on a depth permitting setting cables of lower stretched ring partially from the lower tribune level. The geometry of cable configuration was set in such a way that cables of stretched ring arranged ca 1,5 over tribune steps simultaneously complied with their geometry. In case of upper ring cables scaffoldings 5 m high were indispensable. Stretched rings struts were inserted in gaps between scaffoldings. Due to this fact during the faze of structure lifting up no horizontal cable shifting was possible. The accuracy of cables geometrical arrangement on the site played an important role and had to be strictly observed. Owing to such solution it was possible to lift up the cable system from the scaffolding nearly vertically. Repeating changes in load carrying by cable system during stretching process resulted that some of the cables temporarily were visibly hanging down.

Fig. 12. Preparation of the cable roof to Big Lift

Fig. 13. Big Lift

The stabilization of needle shaped mast by radial cables of the inner roof nearly devoid of forces. Prestressed forces which value resulted out of design appeared in them and in the upper stretched ring only after nearing to final position at the end of stretching process.

To assure the necessary state of safety during diaphragm erection the calculations were carried out taking into consideration the suitable erection fazes of roof covering. In connection with this analysis there were made tests in the aerodynamic tunnel considering the erection critical stages. The erection process was determined in a way eliminating in possibly highest degree the wind load on diaphragm free edge which reduced risk of diaphragm destruction during erection. Moreover it was revealed that snow load on the roof diaphragm partially covered may cause high tension in wind braces.

To enable obtaining proper form of stadium roof spatial steel structure and of aluminium net outer elevation it was indispensable to respect strictly conditions and prescriptions imposed by the designer and to adhere dimensions in conformity with permissible deviations. One must note that taking into account the shape of the structure not all deviations were determined in standards. Due to this fact some problems had to be solved by the designer.

In the first stage of erection many items had to be initially shifted in relation to theoretical axis. Only after imposing the load by erected items they could take the proper position. As an example it is possible to mention the columns supporting the compressed ring. In the first stage of erection those columns were initially set up as radially shifted outside. By manufacturing and erection the ambient temperature was taken into consideration causing element elongation. By structure regulation as fiducial temperature +8 ^{0} C was assumed.

The regulation of main or closing items (lateral bracing, compressed ring, ring supporting columns) was carried on in designer's presence, who analysed deviations confirmed by geodesic measurement and their conformity with calculation model. Measurement protocols were enclosed to acceptance documents after works finish.

Structure geodesic measurement undertaken were during the erection activity and observation of foundation settlement under the columns and formed the complete real image of the object and its location.

Manufacturing of steel cables cooperating with steel structure and supporting stadium roof diaphragm was a different problem.

Steel cables designed by sbp in the frame of the working design were manufactured by Redaelli Tensotec Engineering in Gardone Val Trampe in Italy.

Cables diameters varied from 17 mm to 150 mm depending on localisation and loads. The thickest cables are carrying radial roof cables (diam. 140 mm), cables supporting the mast (diam. 145 mm), cables supporting lateral bracing (diam. 100 mm) and compressed ring cables (diam. 125 mm). for cables manufacturing there were used round wire and zed shaped wires. All cables used for stadium construction were certified by Research Institute of Roads and Bridges in Poland.

The important problem was the anticorrosion protection of cables to guarantee the effective safeguard during the whole life service. Round wires were galvanized according to DIN 2078 standard and zed shaped wires were coated with galftan in hot-dip process (galftan composition: zinc-aluminium-composite metal). Quality control of cables enclosed dimensions, tension and zinc coating adhesion.

By cutting the cables on suitable length segments the contractor took into consideration the elongation determined on the base of test results and temperature influence. The exact length of cables, points of anchorage were calculated after achieving examination results. On the base of delivered points system lengths of cables were calculated, determined location of fixing points on cable's ends and only having finished these action the decision of cutting the cables was undertaken. This activity was very important because later there is no possibility to change the final length of cable with endings. The tolerance of total cable length attains 0,01 % and permissible deviation of clamp fixing is 2 mm. Length deviation of 10 m long cable can not exceed 2 mm (0, 02 %)

Steel GS18 was applied for production of cable seats, anchorage and connectors. Seat systems for cable connectors must be approved by independent institution.

Stadium roof and central mast (needle shaped). Parameters describing materials of roof diaphragms are specified in the table below.

Table 1

Information concerning materials for roof diaphragms

Parameter	Fixed roof	Closed roof
Type of fabric	Glass fibre coated by teflon (PTFE)	Polyester coated by PVC
Manufacturer	Saint Gobain USA fabric produced in France, diaphragm produced in Thailand	Fabric produced in Ferrari in France, diaphragm produced by KFM in Edersleben near Leipzig
Trade name	Scherfil II	Precontraint 1302
Information concerning incombustibility	ITB – 11.03.2010	French institute and ITB 21.12.2010
Classification of fire resistance	Incombustible, non ignitable, non flaming droplet	Incombustible, non ignitable, non flaming droplet
Range of work temperature	- 30 + 70 ^{0} C	- 30 + 70 ^{0} C
Specific weight	1150 g/m^2	1950 g/m^2
Light permeability	12 = 14 %	8 %
Noise damping	15 dB	

The main roof – over tribunes, all around the whole stadium. Its surface attains 50 000 m ^{2}. The roof diaphragm was produced of fabric glass fibre coated by PTFE. Is incombustible, non ignitable and non flaming droplet fabric. It consists of 72 fields stretched on arch construction supported by 72 carrying cables. Drainage is carried out by cavity on roof surface in radius axis (cables in these axis are inclined by ca 10^0). Water is evacuated through pipes situated near the compressed ring.

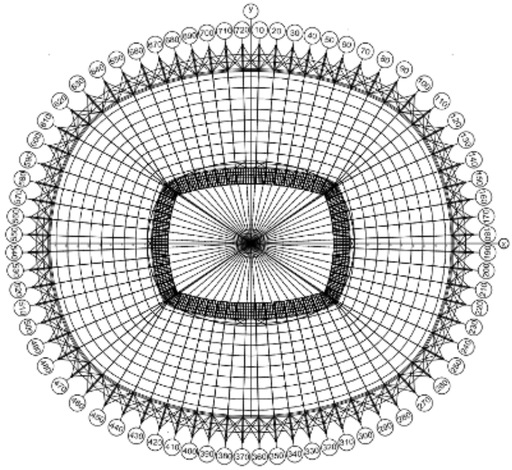

Fig. 14. Top view of the roof

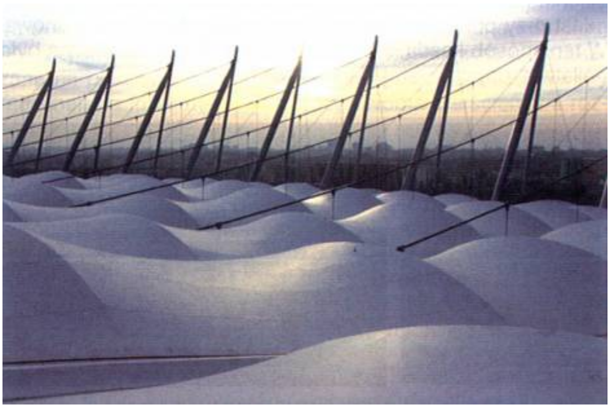

Fig. 15. The main roof – glass fibre cated by PTFE

The outer roof – from the compressed ring to outer aluminium façade. The same material was used as for the fixed roof. The roof surface attains 6 000 m$^{2.}$ and is 6,75 m wide. The diaphragm is stretched on the structure in the same way as the fixed roof.

The glass roof – on the border between tribunes and the sport ground is ca 10,8 m wide with the surface of ca 6 000 m^2 Double layer adhesive glass VSG was used as roof material. Each layer is 8 mm thick. The roof is inclined in direction of gutters placed at roof outer edge to enable the drainage.

The inner roof – rectractable roof: closed covering the sport ground and opened (hidden in the shelter). Roof surface ca 10 000 m^2 The material used for its production is PVC.

The roof is suspended by means of slide carriages on 60 cables diam. 60 mm and diam. 55 mm. The drainage is achieved due to slope of radial suspension of diaphragm on cables (inclined by 12^0).

The roof is shut and opened by means of driving system consisted of 15 slide carriages and 1 driving carriage fixed on all 60 cables. Driving carriages are travelling together with the rope pulled by system of rollers. The rope is coiled on hoisting winch of the driving unit.

Fig. 16. Inner roof closed

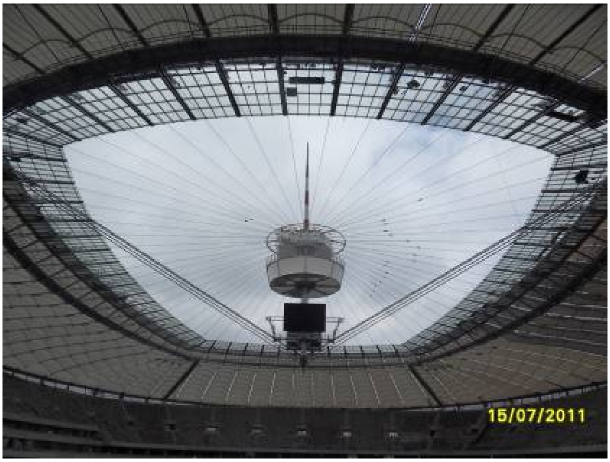

Fig. 17. Inner roof opened

Because length of cables are different in different axes and the roof diaphragm should be uniformly unfold the speed of driving carriages and consequently the speed of coiling cables on drums has to be synchronised. This is one of the function of the computer program operating roof shutting and opening.

Safety reasons and factors influencing durability of diaphragm coating forbid (according to manufacturer's instruction) the following activity:

- roof spreading in temperature below 0^0 C: taking into consideration practical reasons as limiting temperature should be taken as +5 ^{0}C;
- roof spreading when wind speed exceeds 7 m/s, the roof is stable if it is fixed after spreading, during the process of spreading it is sensitive to wind activity;
- opening and shutting of roof during rainfall.

The computer program operating roof shutting and opening does not permit to start this activity in dangerous conditions. Information concerning temperature, rainfall, wind velocity are transmitted from weather station situated on the roof. It is advisable to get information about weather forecast one hour before beginning of roof shutting or opening.

An important element of roof covering structure is the mast (needle shaped). Its lower end is situated ca 30 m above turf level and upper end ca 100 m above turf level. The main part of the mast (needle shaped) is the stem (pipe like) Its shape is adjusted to its function.

The lower part to which the cables are connected (4 bundles, 3 cables in each bundle, diam. 145 mm) is the footing supporting the whole mast. The footing is manufactured as cast steel item (Fig. 7 and 18). Due to its importance it was checked by three independent research institutes.

Fig. 18. Cast steel forting supporting the central spire

The lower part of the cone stem mast with diameter from 1 070 mm to 1600 mm. in its upper part it changes its shape to cylindrical with wall thickness 30 mm. In the middle of the mast the ring is situated (see drg. No 5 and 6) to which cables of roof middle part (60 cables diam. 55 mm and diam. 60 mm) are fixed.

The garage is situated on the mast where roof can be stored. This garage is vertically displaced on mast guides. In the lower part of the mast the supporting structure of four large screens (6x9 m) is situated.

Façade. The façade consists of red-silver alternately arranged panels manufactured of cut drawn anodized alunminium sheets fastened to steel truss placed just behind these sheets. The truss from one side is connected by articulated joint with main façade tie from the second side suspended to upper panel. This untypical chain brings to an end on the height of the one before the last panel where forces by means of hangers are transmitted to façade tie. The whole system creates flexible, light structure permitting to assure the transparency condition.

The structure supporting façade is connected in an interesting way with the diaphragm small roof covering cascade stairs and promenade.

Fig. 19. Erection of the facade elements

For quick-acting connection of panels produced of cut-drawn anodized alum inium sheets is used the specially designed clamp. As material for this clamp was applied anodized aluminium sheet. This fastening detail had to fulfill production tolerances demands foreseen for drawn sheets.

In façade and panel calculation had to be taken into consideration panel meshes caused by icing what seriously influenced the value of wind load.

Conclusions

The stadium construction proved that the responsibility for the total designing process containing not only the full working design but for erection calculation, checking of workshop documentation, author's, investors and contractor's supervision during production and erection faze is the key factor contributing to final success of such enterprises.

The inner movable roof with only one cables layer adapted to winter conditions, glass bracket roof fastened to the flexible inner edge of cable roof and inspiring span of the main roof is the milestone in designing and construction of light prestressed structure of roof cover. One can say that the National stadium in Warsaw is an important contribution to modern stadium architecture.

(Some parts of the article are based, with authorization of the authors, on the article by K. Göppert, L. Haspel).

Надійшла до редколегії 22.08.2012 р.