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The National football stadium in Warsaw

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Анотація. У даній роботі представлені нові тенденції розвитку у проектуванні спортивних споруд. Основна увага приділяється проектуванню мембран, які підтримуються тросами та мають форму, подібну до велосипедного колеса. Принцип велосипедного колеса прийнятий та застосований для конструкції навісу Національного стадіону у Варшаві. Надаються та демонструються у вигляді креслень основні концепції використаних конструктивних рішень, створених проектувальниками. Також у роботу включено додаткові ескізи та фотографії, у тому числі такі, що демонструють монтаж вибраних елементів конструкції.

Аннотация. В данной работе представлены новые тенденции развития в проектировании спортивных сооружений. Основное внимание уделяется проектированию мембран, которые поддерживаются тросами и имеют форму, подобную велосипедному колесу. Принцип велосипедного колеса принят и применен для конструкции навеса Национального стадиона в Варшаве. Предоставляются и демонстрируются в виде чертежей основные концепции использованных конструктивных решений, созданных проектировщиками. Также в работу включены дополнительные эскизы и фотографии, в том числе такие, которые демонстрируют монтаж выбранных элементов конструкции.

Abstract. This article presents new development tendencies in the design of sports facilities. The main focus has been put on design of cable supported membranes shaped according to bicycle wheel principle. This principle has been adopted and applied in stuctural design of the National Stadium's roof in Warsaw. The core concepts of the solutions applied there are presented and illustrated with drawings and descriptions made by the designers. Additional sketches and photographs, including those presenting the assembly of selected elements of the structure are also included.

Key words: membrane, structure, type bracing, covering.

The technical and technological progress and development of new and improvement of existing methods of structure analysis are necessary conditions for development of forms and methods of shaping, construction and delivery of facilities.

Sports facilities are covered by particularly intensive development. Construction of new stadiums and thorough rebuilding of existing ones applies, most of all, to countries, which are hosts to Olympic games, world or continent cups. Such behaviour became a rule as early as at the end of the previous century. Application of this rule is imposed upon by international, organisations and main organisers of the events, who impose increasing standards upon the facility contractors. Among various facilities, demand for football stadiums is dominant. As far as football stadium designs are concerned, initially there was a

trend to build stadiums with covered stands on the entire circumference. In the 90s of the 20th century, they started to build closed facilities with opened roofs or sliding walls as multi-functional facilities [1]. The first such type of the facility is Civic Arena erected in Pittsburgh (USA) in 1961. Another facility was erected as late as after nearly 30 years and it was Sky Dome (presently referred to as Roger Center) in Toronto (Canada) in1989. four years later the Japanese erected a multi-functional hall with a football pitch and opened roof. Next, the Dutch erected two football halls with horizontally sliding parts of the roof, which cover the football pitch: Amsterdam Arena in 1996 and Gerledome in Arnhem with an extendable reinforced concrete plate with a football pitch in 1998.

In the next years, the Japanese and Germans erected a lot of opened facilities. Mobile parts of roofs are usually covered with a light membrane made of coated fabrics of high strength and flexibility and suitable for use in most weather conditions. Japanese solutions are dominated by opening by way of sliding or rotating of appropriate segments of the enclosure. However, suspended covers with a centrally foldable mobile part of the roof into a suspended container, a so-called "garage" are most often used in Germany. A team of designers, namely schlaich bergermann und partner (sbp), specialised in designing of numerous varieties of the solution and designed the structure of cover of the stadium with an opened roof in Warsaw and numerous stadiums worldwide. However, the dominant trend is still to design stadiums without roofs above football pitches, but with canopied stands on the entire circumference, as is the case of stadiums in Ukraine and Poland.

The structures of German solution are often based upon a principle of a bicycle wheel. This principle has been known and applied for a long time. Zbigniew Makowski in [2] presented several facilities of the type, including the cover of a large pavilion of the USA found in the World Exhibition in Brussels in w 1958 (Fig. 1).

However, it was only with the possibility of use of membrane covers made of contemporary fabrics that qualities of covers improved and they could be used for covering of, among others, the above-mentioned stands and halls. One of the first and larger contemporary applications of the above-mentioned principle for the purposes of covering of stands on the entire circumference of the athletic stadium is Mercedes Benz Arena located in Stuttgart and designed by schlaich bergermann und partner (sbp) in1993, (Fig. 2). An outline of structure used in this stadium is presented in Fig. 3.

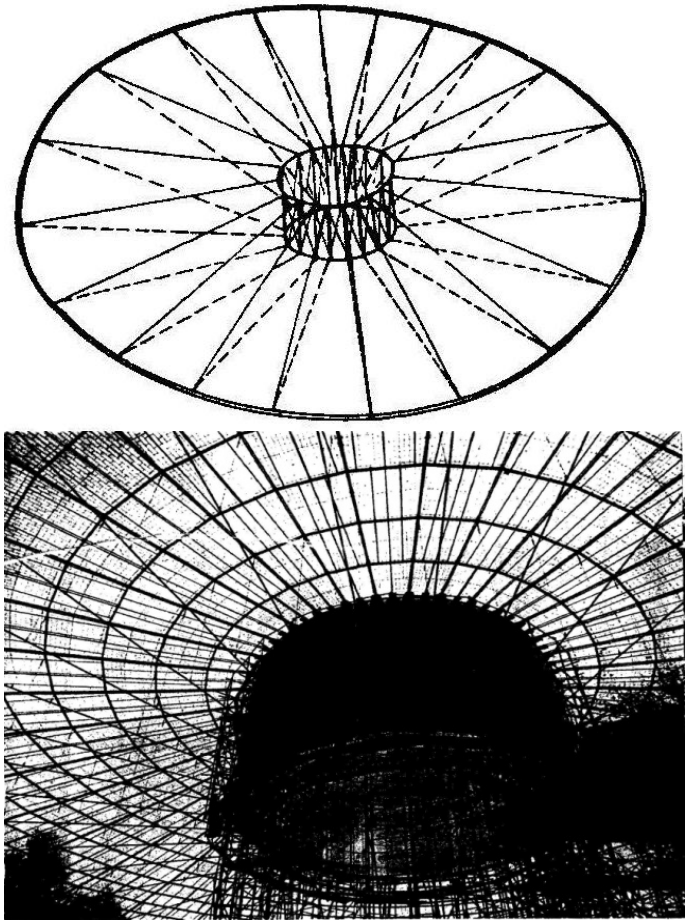

Fig. 1. An outline of a bicycle wheel-type structure used for covering of a large hall [2]

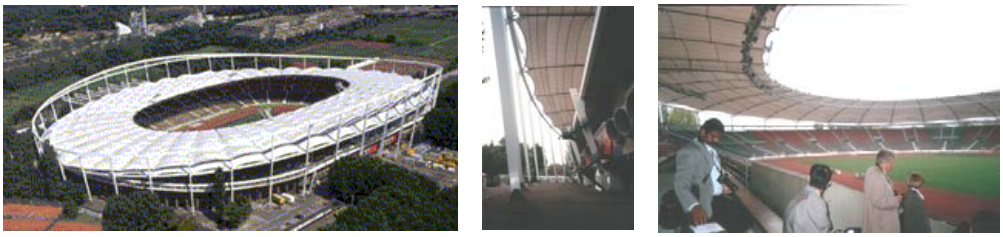

Fig. 2. Cover of the stadium stands in Stuttgart:
a) general view (Google: Stuttgart stadium), b) support structure with a bottom ring,
c) extendable line internal ring (Fig. 3b, c – photo: A. Reichhart)

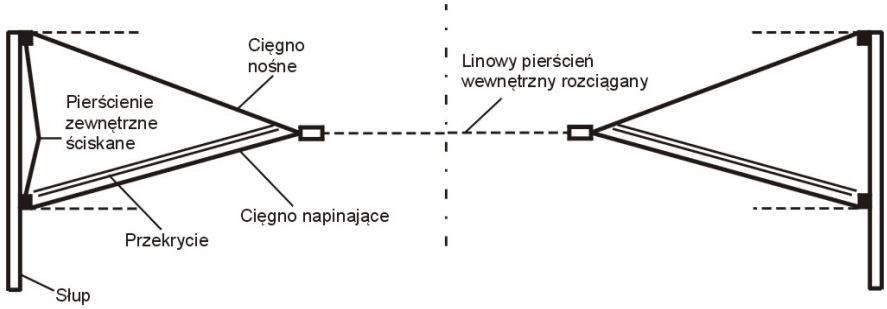

Fig. 3. A diagram of a single system of suspension strings balanced with external and internal rings

General description of the National Football Stadium in Warsaw. The National Football Stadium may hold approx. 58 thousand fans, it consists of a football pitch surrounded by stands on the entire circumference. The height of stands changes gently on the entire circumference – the highest stands are found in the middle of the pitch, the lowest stands are located at the corners and a little higher stands may be found behind the goals. This solution causes the upper edge of the stands slightly wave, which is repeated at the compressed ring of the main bearing structure of the stadium enclosure. The space under the stands has been used for various purposes (Fig. 4, table).

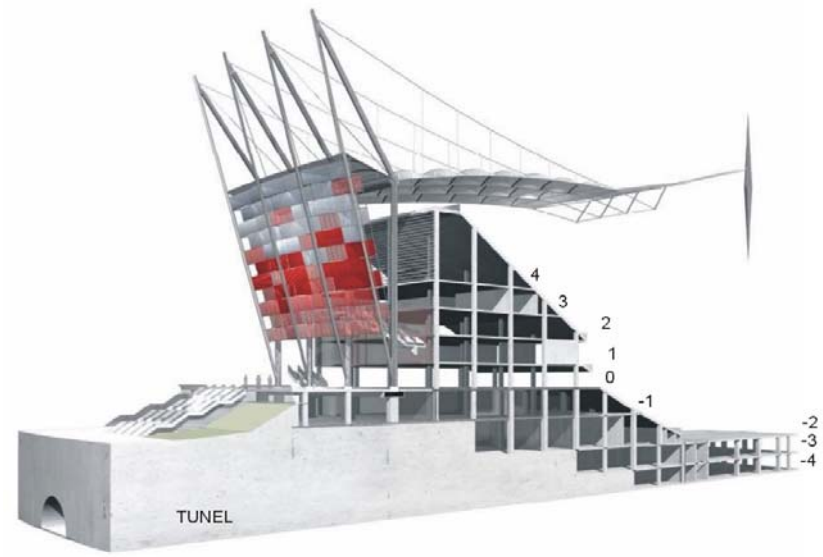

Fig. 4. A section of the facility and its use [4] - ©Konsorcjum Projektowe Stadionu Narodowego in Warsaw (J.S.K. Architekci Sp. z o.o. /grup International architects and engineers/ schlaich, bergermann und partner (sbp)

Table 1

Use of the space under the stands of the National Football Stadium

Level -4 and -3	Two-level car park for approx. 2000 vehicles, located under the football pitch
Level -3	Main entrances into the stadium from the Vistula River, a chapel, VIP reception desk and technical rooms
Level -2	The football pitch with natural heated and hydrated grass. Entrances with direct access to the football pitch. Cloakrooms for football players, a zone for warm-up for players. A press centre and car par for VIPs.
Level -1	A sports café, shop and fan club as well as restaurants and rooms for media
Level 0	The main promenade with shops, toilets, usable spaces and catering points suitable for the disabled. There is also a business club and restaurants.
Level 1	Office rooms, conference rooms, VIP lounges, including a lounge for the president and corporations. The command centre for security guards in the stadium. Rooms for commentators and media and restaurants
Level 2	Fitness club and conference spaces with a view of the nearby park. There are also VIP lounges, cafes and offices.
Level 3	The upper promenade with catering points, toilets and first aid points
Level 4	The highest part of the stands with a restaurant with the area of 1300m^2, at then height of 40m above the surrounding area, with a view of the Vistula and Old Town.

The structure of the stadium enclosure and fragments of its assembly. The whole of the stands constitutes an oval closed building. Together with the football pitch and stairs it is covered with an oval enclosure, which is not structurally connected with the building and includes a structure supporting a permanent roof above the stands and, with the aid of the roof, supporting a foldable roof above the football pitch. It was assumed that the cover would be designed in accordance with the bicycle wheel principle. The line structure of the permanent roof consists of 72 radial string girders, each of which is made of an upper bearing line and bottom tensioning line as connected by hangers and tightened by internal rings.

The stands are surrounded by an open-work white and red façade wall (fig.5).

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Fig. 5. A view of the National Football Stadium in Warsaw

In the initial phase of the design it was assumed that enclosure of the stands would be made similar to a closed wicker basket. This concept allows for erection of a lighter structure, but it requires different structural solutions. In order to achieve similarity to a basket, they decided no to use an upper compressed ring. This made it necessary to convey force extending each bearing string to a lower compressed ring as well as the pole and foundations supporting the ring. The force was conveyed via a compressed brace based upon a junction connecting the ring with the pole and extended stay of the façade. Each brace has to be stabilised with a pair of stays connecting its summit with adjacent junctions of the compressed ring. The stay is imitated by a wicker straw and makes it possible to fasten elements of the façade (Fig. 6). The described modification did not change the essence of the support structure of the cover, although forces within the structure are directed to other ways.

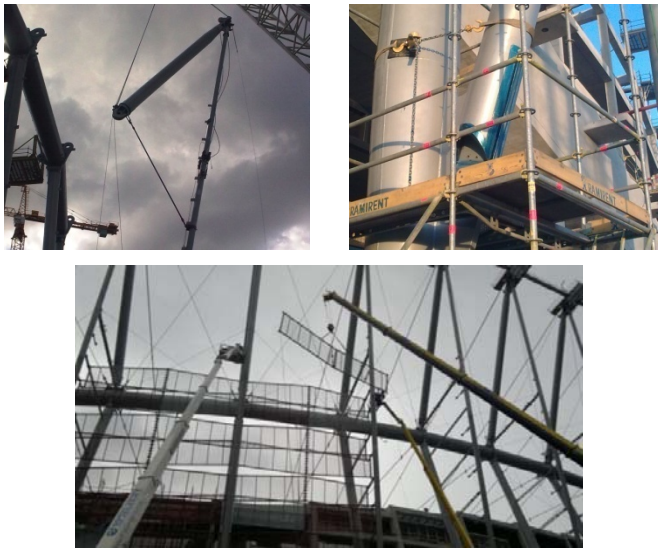

Fig. 6. A brace with stay ready for a bolt connection and bottom of the stay ready for welding; assembly of façade panels, stays stiffened by connections with poles

The basic steel bearing structure consists of a compressed ring ate the level of tensioning strings based upon 72 poles as well as the already mentioned braces and stays. The system of the above-mentioned poles has only four pairs of fields between the poles with X type bracing. They were placed in the corners of the football pitch in order to eliminate undesired effects of wind load (Fig. 7).

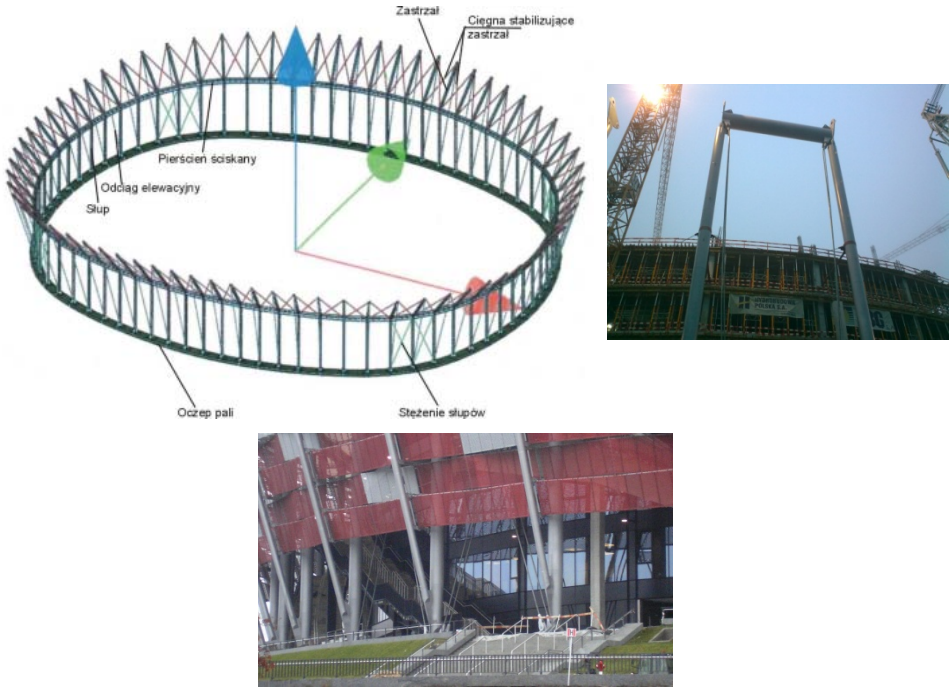

Fig. 7. The main bearing system of the suspension string structure of the roofs [4] – schlaich, bergermann und partner (sbp); the first field before bracing and the field braced in the facility

Use of an opened roof covering the pitch required further modifications of the basic structure of cover of the stands as compared to the structure of an open cover as in Stuttgart (Fig. 2). In the vertical axis of symmetry of the entire roof a suspended mast with an icicle was inserted in order to enable fastening of bearing lines of the foldable roof (Fig. 8).

In order to tie the roof lines above the pitch with the permanent roof lines as well as suspend the mast, they doubled the internal extendable ring and put is closer to the mast. The obtained two extendable rings were envisaged for balancing of forces in the permanent roof strings and the lower ring was to be used for suspension of the mast and the upper ring – for fastening of 60 bearing lines of the foldable roof. Line girders located on the opposite sides of the mast are mutually balanced (Fig. 9 and 11).

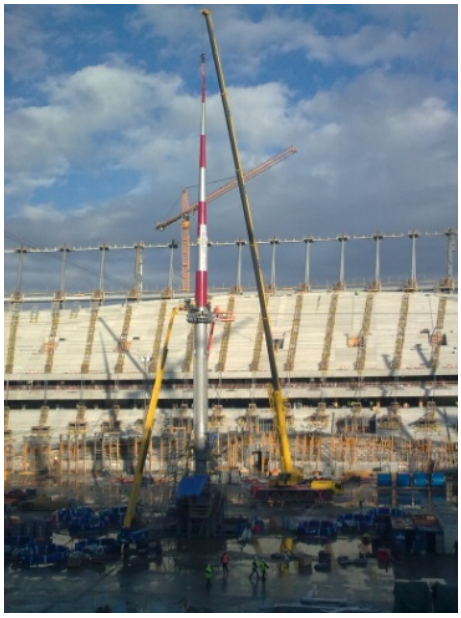

Fig. 8. The mast is composed of three parts: the bottom part with holders for suspension with the use of 12 lines, the medium part with two rings in the top part for anchoring of 60 lines of the foldable roof and; the entire structure before suspending

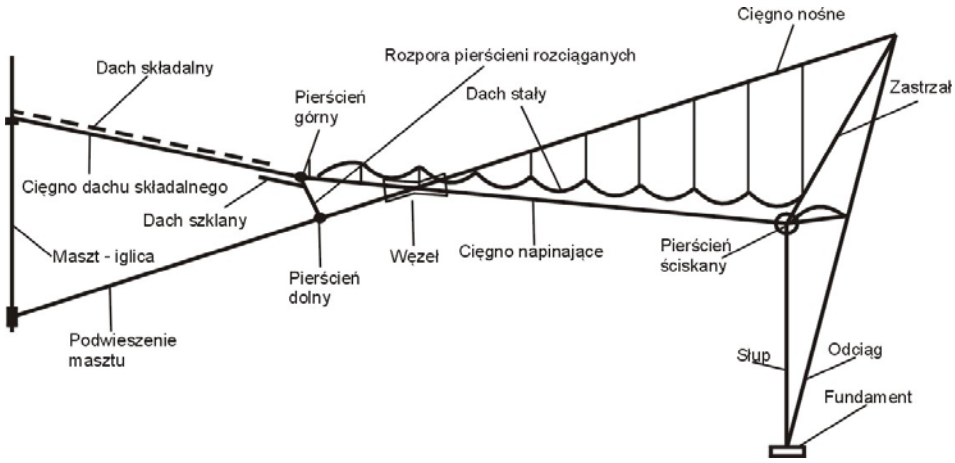

Fig. 9. An outline of line structure of a single girder of the permanent stadium roof cooperating with the foldable roof at the level of lines, which suspend the mast

The distance between the lower and upper internal line ring is maintained by spreaders (fig.10).

Fig. 10. Connection of lines of the permanent and foldable roof and tensioning of the lines, two rings with spreaders and three lines for suspension of the mast

The mutual stability of both rings is ensured by X type bracing, with two bracings on longer sides and one bracing on shorter sides.

The internal roof was assumed as a roof in a tent form with a centrally suspended icicle mast and its view resembling that of a rectangle. The rectangular shape was given by connecting four girders of the permanent roof in four points above the pitch corners. In these points, four sets of three lines for mast suspension were fastened (Fig. 11).

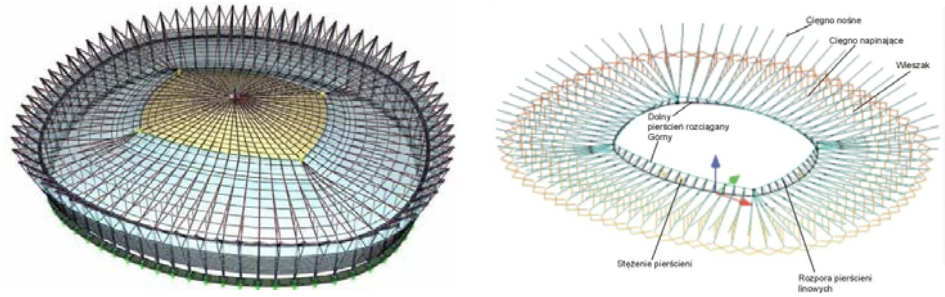

Fig. 11. A view of a complete rod and line system of the stadium enclosure structure and presentation of all strings suspended under the bearing structure, with exception of the internal roof; visible accumulation of strings in corners suspending the mast [4] – schlaich, bergermann und partner (sbp)

At the level of the extendable upper ring, bearing bracket elements of the glass roofs were fastened to the spreaders. The roof enables laying of the bottom edge of the membrane, which covers the pitch and pouring of water down the glass roof into a circumferential gutter. The bearing structure of the foldable roof is composed of 60 radial lines fastened in the upper part of the mast to two rings located at the distance of half a meter vertically from each other and to the upper extendable ring above the glass roof in the distance enabling extension of the suspended membrane to the bearing line (Fig. 12).

Fig. 12. Assembly of the glass roof brackets; above the glass roof there are visible lines of the foldable roof and anchoring elements; under the lower ring there is a visible connection of bearing strings with the strings, which suspend the mast

Anchoring of the foldable roof lines to the mast at two levels causes that waving of the fabric adjacent to the mast gradually disappears to disappear completely on the glass roof. During unfolding and folding, the membrane is fastened to the lines and moved appropriately with the use of sliding trolleys. The roof is unfolded and folded automatically and lasts approx. 18 minutes. The “garage” is closed at the top and lowered or raised as needed (Fig. 13).

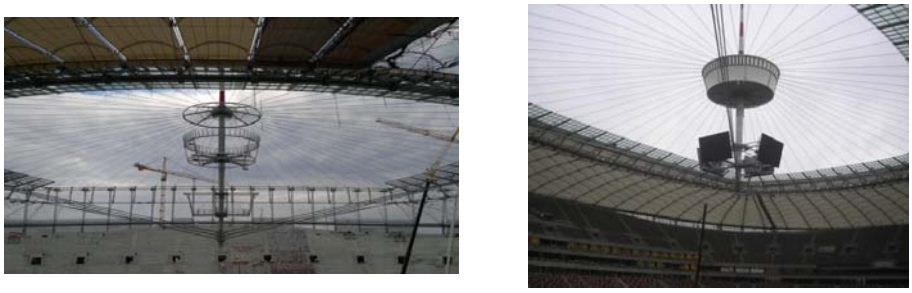

Fig. 13. A view of a partly covered permanent roof and mast with an icicle and rod structure of the garage; below telebims during construction and upon completion of construction with a closed foldable roof

The membrane of the foldable roof is made of polyester fabric in PVC coating with appropriate parameters. The foldable structure of the roof is made of a flexible fabric, which is creased when folded as a result of moving of the fabric along the tensioned radial lines. Due to hardening of PVC, it is prohibited to fold or unfold the roof at minus temperatures. The permanent roof was made of a glass fabric in PTFE coating . To the bottom tensioning line they fastened arcs with a stay giving the necessary curvature to the membrane coat of the permanent roof spread on the arcs. Both membrane roofs are connected via a glass bracket roof, which creates a transparent glass ring (Fig. 14).

Fig. 14. Suspended arcs with stays tensioning the fabric and folding of the fabric – staff is visible

Regardless of the mentioned benefits, splitting of the extendable ring makes it possible to create circumferential communications with four accesses and to distribute the installation. Water from the roof unfolded above the pitch pours down the glass roof, into the circumferential gutter and along the roof pavements into external drain pipes and container located inside the building (Fig. 15).

Fig. 15. One of the suspended bridges leading to the circumferential pavement with water gutters; permanent roof drainage in the vicinity of the main junction of the compressed ring with the pole and tensioning string

The façade is made of drawn and cut aluminium sheet in the form of open-work panels fastened with staggered joints to the pipe lattice. The wavy line of façade panels reach a little above the facility roof. The façade stay taking over wind load is connected with a stiff main pole (Fig. 16).

Fig. 16. Cascade stairs between the bearing structure and stands; wind-proof fixing of the stay, which supports the façade

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