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Original scientific paper

TENSILE MEMBRANE STRUCTURES AT WORLD FAIRS

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Abstract. *World Fairs provide the opportunity for all nations to show their achievements to the rest of the world. In addition to state of the art developments in science, technology and culture, Expos also became the showcase for architecture. The history of application of tensile membrane structures at Expos started in 1958 in Brussels and continues until today. This paper researches the progress of tensile membranes through the structures built for World Fairs.*

Key words: *tensile membrane structures, world fair, expo, lightweight structures, tension structures*

1. WORLD FAIRS

The history of World Fairs started in 1851. Although not intended as an architectural showcase, the Expos became one of the most important architectural events in the world. Some of the most significant architectural landmarks such as the Eiffel's Tower, Atomium, and Habitat 67 were built for the World Fairs.

First world exhibition happened under the big influence of industrial revolution. However, after the second world war, the idea of the technological revolution has totally changed, first of all because of using technological achievements in a destructive way without the social and political responsibility. World exhibitions are becoming events that promote progress of human kind and multi-cultural dialogue as well as current topics of that time. Some of them are "Progress and Mankind" 1958, in Brussels, "Man in the Space Age" in Seattle 1962, "Man and His World" Montreal 1967. From the beginning of the 21st century Expo started promoting the sustainable development and its importance for the mankind. Despite the promotion of current topics, Expo has always provided architects with the opportunity to showcase their new ideas and use this big event as a creative laboratory for testing their innovations in design and technology of building.

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Fig. 1 The famous object made of membrane structure at World Fairs

The research that was conducted and partially presented in this paper revealed that tensile membrane structures had an important role at World Fairs. Their being one of the newest structural types, makes it possible to follow their progress and improvements through the structures built for Expos. As membranes evolved some of their properties became superior to other structural types and they became one of the leading structures at Expos. This is especially notable in the past decade, where some of the dominant structures at World Fairs were built as tensile membranes. This paper shows only a few selected membrane structures built at World Fairs and discusses their progress over the years (Fig. 1).

2. TENSILE MEMBRANE STRUCTURES

Tensile membrane structures emerged as the successor of traditional tents. Characterized by their light weight and tension they became popular mostly due to the attractive double curved form they attain. Membrane material is extremely thin, about 1 mm, and has a decisive role in defining the structural behavior [10,11]. Fast erection and inexpensive transport reduce the total construction price, while complex production and unique design process impede a more frequent use of membrane structures.

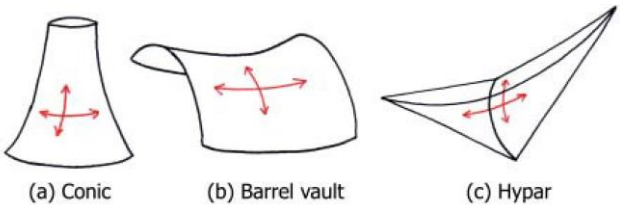

Fig. 2 Shapes for double curvature[10]

The regulations on designing tensile membranes in Europe are still not complete. Currently, there is a Design Guide [8] and a Prospect for European Guidance [9], while the Eurocode for Designing Tensile Membrane Structures is expected to be published in the next few years. Wind and snow loads combined with the membrane prestress are dominant actions on membrane structures, although recent researches also showed the importance of point load actions [13,14]. Up to date, thermal properties remain the critical issue of the membrane structures [15,16] which are therefore best used for covering of open spaces. In cases where space needs to be enclosed, multi-layer membrane of air-cushion structures are preferably used. Some of the membrane properties will be highlighted in the following analyzed examples.

3. Connection between Tensile Membranes and World Exhibitions

The relation between the tensile membranes and Expos starts in 1958 when a minor and relatively insignificant membrane was used to cover a stage. Only a few years later in Lausanne membranes got a much more prominent role. In 1967 at Montreal Expo, one of the most famous membrane structures was erected. At Osaka Expo several attractive membranes were designed and erected. For the recent Expos in Shanghai, Milan and Dubai some extraordinarily big tensile membrane structures were built.

3.1. Bruxelles

First world exhibition after world war was held in Brussels 1958. In addition to the great importance for global community and reuniting the world, Expo 58 has its big importance because of membrane constructions. Even though in the first plan of this exhibition we have imposing constructions such as Atomium, US Pavilion, USSR Pavilion, Philips's Pavilion, one small podium covered by membrane construction represents the beginning of a new era in history of pavilion architecture.

This podium was projected by architect Oger Schomblood and engineer André Paduart. Although several important cable net structures were erected at the World Fair in Brussels, the bandstand appears to be the only double-curvature cable-and-textile structure built for the event. The bandstand (Fig. 3) had a rounded wedge plan form (13.91 m long, 15.04 m wide) and consisted of an anticlastic cable net tensioned between an inclined mast at the

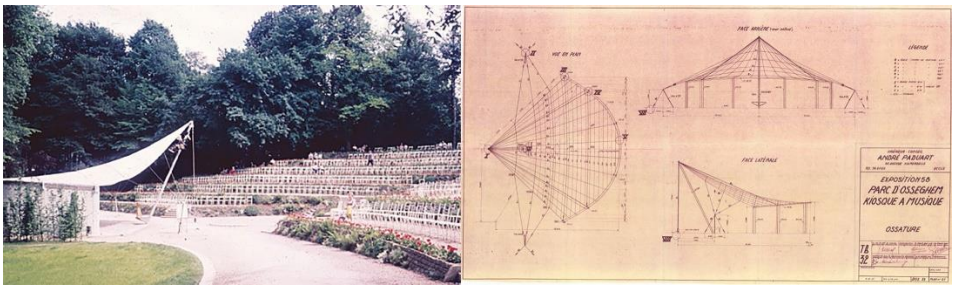

Fig. 3 The bandstand at Expo 58 and plan of the steel members for the bandstand by Paduart, Dec 1958 [1]

front, 7.50 m high, and a curved wall with varying height (2.82–3.22 m) at the back [1]. Although this was the first membrane covered structure, because of its small dimensions it was not as attractive at the exhibition as its successor. In this example, the membrane has a secondary role where it accepts the external loads and transmits them to the primary load bearing cable net.

3.2. Lausanne 1964

World exhibition 1964. (Expo 64) was held in Lausanne, precisely in Vidi on the coast of Geneve lake. For the duration of Expo 64 the visitors could see a big number of technological achievements, some of them are the "Spiral" tower, the Mésoscaphe Auguste Pisccard, symphony of exchanges.

In architecture, this exhibition we remember because of the idea of Marc Saugev, Swiss architect. He used large multi-coloured tents to imitate Alps, their snow and rock. After creating the basic shape of the structure and initial plans, Frei Otto has joined the project and his task was to define the definitive geometry and solve structural problems.

In proximity of a small harbor 24 pavilions were set up with their sides touching and overlapping. A huge number of pavilions were basically simple saddle-shape with four points of support, but with a large diagonal span of 36 m between the lowest and highest point. The biggest challenge but also an attraction was the pavilion intended for a restaurant in the north eastern part of the port. This pavilion was formed by multiplying three large saddle tents supported in 4 points, each of which had 2 smaller saddle-shaped tents with supports in 3 points. In perfect harmony with angled slim lattice masts, the elegant architectural look has been achieved (Fig. 4).

Fig. 4 Exhibition Pavilions in Lausanne 1964.[2]

Structurally the pavilions are not at all usual membrane structures but prestressed equally meshed steel cable net structures, covered with cotton fabric as a weather skin. The cables of the net are disguised in lipped PVC-pouches which continuously are sewn on the fabric. All main stresses are taken by the cable net whose deformation under load is much smaller than for the fabric [3]. Once again, like in Brussells, this is not a typical membrane structure, but rather a combination with the cable net. Nevertheless, some advances are still present. Most notably, the span of the structure was doubled. This allowed for the creation of more impressive structures. In addition to this the multiplication of structures with some variations of each one led to showing what architecture can achieve with light, playful membrane construction even though pavilion looks are repeating themselves.

3.3. Montreal 1967

World exhibition in Montreal 1967 has been considered as one of the most successful exhibitions in XX century. Big number of countries participants had its very own pavilion designs. Among these pavilions are the Montreal Biosphere designed by Buckminster Fuller, the modular Habitat 67 housing complex designed by Moshe Safdi and the pavilion of the Federal Republic of Germany designed by Frei Otto (Fig. 5).

In collaboration with architect Rolf Gutbrod, Frei Otto designed the exhibition pavilion of the Federal Republic of Germany, a tent structure representing his experiments, in the field of lightweight membrane construction, to an international audience at the time.

The pavilion was located in the eastern part of the island of Ile de Notre-Dame and covered almost 8000 m^2. The entire area was covered by a single membrane of irregular plan and varying heights. Its contours were determined by the high points of the masts and low points where the membrane was drawn, funnel-like, down to the ground. Eye loops filled with clear plastic material accentuated these points and the saddle surface they created. The prestressed membrane consisted of a translucent skin hung from a steel wire net, which, by eye, ridge, and edge ropes, was connected with the mast heads and anchor blocks. Membrane construction was relying on 8 masts, height from 14 to 38 meters, while the maximum span was from 105 to 130.

Fig. 5 German Pavilion in Montreal 1967. [www.archdaily.com,www.arch.mcgill.ca]

Compared to the previous two examples, this membrane is even bigger in size. However, more importantly the membrane is here separated and distanced from the cable net. This was a very important step towards implementing exclusively membranes as both supporting and covering element. The German Pavilion is a technologically sophisticated, conceptually simple solution that, with its elegant irregular shape, arouses the admiration of observers who were in post-war modernism. As well as the first building of this size in the architecture of light constructions.

3.4. Osaka 1970

There are various aspects of Expo ’70 in Osaka that should be highlighted in terms of the historical development of membrane structures whose stability is based on pneumatic principles. In the first place, emphasis should be placed on the individual value of certain pavilions, both due to the structural-typological innovation they reflect and the large

spans they achieved. Two pavilions stand out in this sense; the U.S. Pavilion and the Fuji Group Pavilion.

The U.S. Pavilion was made up of a low-pressure pneumatic vault reinforced with cables covering a space with a super-elliptical shape of exponent 2.5 measuring 83.5 x 142 m (Fig. 6). The low-profile vault was only raised 6.5 m above the ground and was encircled by a reinforced concrete compression ring, while the exhibition space remained half-buried. The super-elliptical shape was chosen for aesthetic reasons.

Fig. 6 U.S. Pavilion in Osaka 1970. [www.davisbrodybond.com]

When dealing with the pneumatic pavilions in Expo ’70 in Osaka that had acquired an individual value both in terms of structural innovation and size, reference has to be made to the Fuji Group Pavilion. Created by the engineer Mamoru Kawaguchi and the architect Yutaka Murata, it was the largest high-pressure pneumatic structure ever built, as well as displaying a brilliant design of organic inspiration (Fig. 7). The structure was made up of 16 tubes 72 m long and with a diameter of 4 m filled with pressurised air. The tubes arched and were inter-connected by 50-cm-wide strips placed every 4 metres. The plan of the tube bases formed a circumference with an outer diameter of 50 metres. Each tube was connected at its base to a metal ring anchored to circular pile caps. All the tubes were the same length, while the central ones were semi-circular and the others were progressively raised the closer their bases were situated [17].

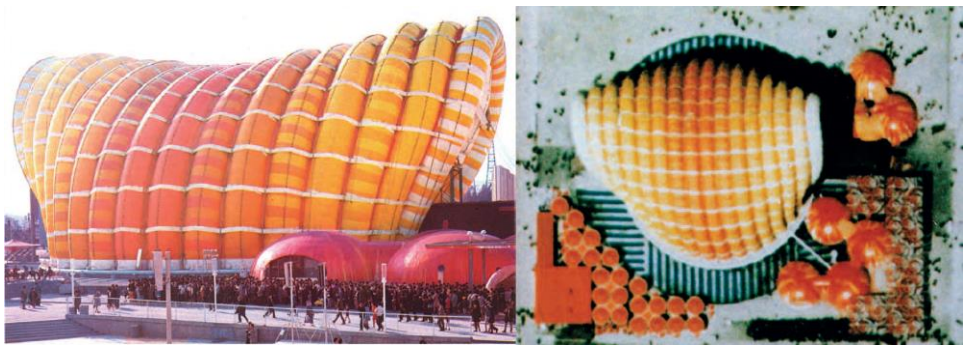

Fig. 7 Fuji Group Pavilion in Osaka 1970. [17]

3.5. Shanghai 2010

After the Beijing Olympics, the World Exhibition in Shanghai was the largest international event in China. The theme of "Better City Better Life" has put the life in 21st century cities at the center of this world exhibition. 246 countries and international organizations exhibited on 5.28 km^2. Expo 2010 is the most expensive and largest world exhibition in history.

Fig. 8 Expo Boulevard in Shanghai 2010. [www.archdaily.com]

In addition to all the pavilions, the Expo Boulevard stood out (Fig. 8), a structure that was 100 m wide and 1 km long and was the largest and most important building in the exhibition. Positioned to form the central part of the entrance and provides over 350000m^2 for all necessary facilities. The size and short construction period led the designers to use the membrane construction as a roof covering.

The Expo Boulevard is covered by a membrane roof with a total surface of 65,000 m^2, the currently largest of its kind world-wide. With a free span of almost 100 m, it sounds the limits of technical feasibility. The roof is carried by 19 interior and 31 exterior masts and by six funnel shaped framework shells consisting of steel and glass. It has a height of 45 m and a free projection of 80 m. The applied PTFE-glass membrane is of the sturdiest type V and has a tensile strength of 8,000 N/5cm, which is equivalent to 16 t relating to a strip of 1 m width [4].

This megastructure has once again proven the potential of membrane material, not only when it comes to large ranges and low cost, but also when it is necessary to create a sophisticated, elegant solution that goes beyond the stereotypical cubic form.

Two more pavilions have appeared in Shanghai, whose roof construction is made of membrane material. One of them is the Norwegian pavilion, which is made of wooden constructions and membrane material as a cover, while the other Japanese pavilion was made of a combination of steel and membrane.

Norwegian architects Helen & Hard, guided by the idea of “The Nature of Norway”, designed a pavilion of 15 separate trees that multiply to form a single space, but can also exist separately (Fig. 9). All 15 trees are basically rectangular in shape, covered by a simple saddle-shaped tent construction with a diagonal span of 16 m and a vertical difference of 3 m between the lowest and highest point of support. A translucent PTFE membrane by the name of Gore™ Tenara® 4T20HF Architectural Fabric was chosen. This fabric is highly flexible, non-flammable and non-dripping. The complex membrane structure is prestressed on site and connected to the timber arm ends. This introduces

considerable forces to the timber structure [5]. Norwegian pavilion has shown very interesting combination of wooden and membrane constructions and it really showcased spirit of Norwegian landscapes.

Fig. 9 Norway Pavilion in Shanghai 2010. [www.archdaily.com]

Japan also presented a large number of its technological achievements at this world exhibition, and one of them represents their pavilion. The pavilion is officially named "zi cao dao" ("purple silkworm island"), which best describes its shape and color of the pavilion (Fig. 10).

Fig. 10 Japanese Pavilion in Shanghai 2010. [www.designboom.com]

Structurally very simply constructed from steel lattice girders whose facade is a two-layer membrane material filled with air, the facade itself is a series of innovative technological systems. The semi-circular 'breathing organism' makes an efficient use of natural resources, incorporating solar energy collection batteries and a double-layer membrane that filters sunshine coinciding with its interpretation of how technology can better our lives. Energy-saving technologies are displayed and performances are also being staged, highlighting the role of ecological technology in helping humans achieve a more comfortable life and confidence in the future [6]. This pavilion has proven that membrane material is not only used for large ranges, but it is also possible to form energy efficient facade systems.

3.6. Milan 2015

EXPO 2015 in Milan showcases the theme “Feeding the Planet, Energy for Life”, offering answers to the major future challenges of human nutrition. In the context of a conceptual master plan, this world exhibition introduces a clear paradigm shift by dispensing

with prestigious monumental buildings, and by presenting itself rather as a "sustainable AgroFood Park" [7].

After Shanghai, which reminded the world public of the importance of membrane constructions, in Milan we had the opportunity to see membrane material in a slightly larger number of pavilions than before. Starting from Cardo and Decumano streets, main streets on Expo, and the German pavilion where the membrane is also used as sun protection, the pavilions of Kuwait and Mexico where it has the function of an aesthetic element on the facade and the pavilions of China, Malaysia and COPAGRI using membrane material as a roof structure (Fig. 11).

Fig. 11 Exhibition Pavilions in Milan 2015 [www.archdaily.com]

Of all these pavilions with a membrane construction, the largest, but also the most important, was Cardo and Decumano. Cardo and Decumano occupied a central position among the other pavilions and formed a covered connection between them. These two streets which together are around 1,700m long with a covered surface of 65,000 m2. This structure represents one of the largest membrane structure roofs in Europe (Fig. 12). In addition to the membrane material that acts as a roof covering, this megastructure is composed of more than

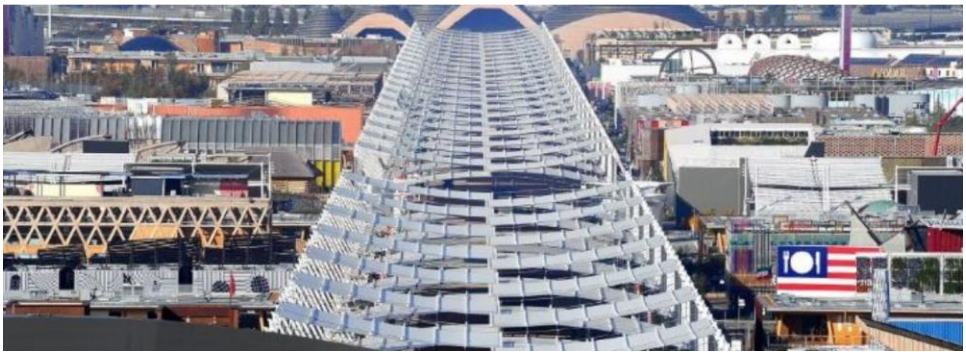

Fig. 12 Top view of Decumano [18]

400 steel columns of 17m height; supporting and stabilizing cables are connected to the columns and more than 2000 steel beams were installed between the cables in order to support the membrane [18].

Cardo and Decumano best show how membrane megastructures progressively occupy a central position at world exhibitions, primarily because of their constructive features, but also because of the visual effect of elegance achieved by their application.

3.6. Dubai 2020

The first Expo to be held in the Middle East, Africa and South Asia with many reasons to be counted as one of the most important in exposition history. The main site of Expo 2020 Dubai was a 438-hectare area located between the cities of Dubai and Abu Dhabi, near Dubai's southern border with Abu Dhabi [19].

Considering the size of the space it occupies as well as the climatic conditions of the location itself, membrane structures appeared at this world exhibition in the form of structures that protect visitors from the sun along communications between pavilions, but also as a facade cladding of individual pavilions (Fig. 13). Within this paper, several pavilions with membrane construction will be presented.

Fig. 13 Membrane structure at Expo 2020 [23]

The Spanish Pavilion at Expo 2020 Dubai is composed of a series of interlaced membrane structures, which create a series of sub-spaces with diverse experiences. When people are strolling through the designs of various countries, the Spanish Pavilion will provide resting seats and shade for the weary viewers. This design expresses welcome and friendliness to visitors. Therefore, this building does not want to be a shopping mall or a commercial center, but to create a space that is within reach, friendly, and full of a warm atmosphere like home [20]. This ambience was achieved by multiplying and varying the dimensions and colors of the fringed cups that make up the Spanish pavilion. The main construction of the grooved cups is represented by steel profiles of circular cross-section, while the membrane construction serves as a sheath and has no bearing role in this joint (Fig. 14).

Fig. 14 The Spanish Pavilion at Expo 2020 [20]

The Opportunity Pavilion was designed by AGi architects for Expo 2020 Dubai. The pavilion also includes a membrane structure that floats 32 meters above the ground, symbolizing the dream that people desire to realize (Fig. 15). The structure is formed by covering the metal frame with fabric, like clouds, shielding the square from direct sunlight. The membrane structure is very clever in the use of transparency, light and color, and they will constantly change with the time of day, sunlight and people's movement [21]. The membrane construction of this pavilion is not in the function of the main supporting structure, but only has the function of a roof covering.

Fig. 15 The Spanish Pavilion at Expo 2020 [21]

The Brazil Pavilion at Expo 2020 Dubai provides visitors with a rich sensory experience about Brazil's biome and cultural heritage. The structure was envisioned in steel, both in the roof of the pavilion and in the space beneath. The pavilion presents a tensile structure with large trusses on its four facades, from whose upper edges are stretched the fabric of the roof, tensioned so as to take the form of a concave impluvium of four faces that converge in a circular water spout positioned slightly off-center. The fabric is reinforced with steel cables that form the ridges of the impluvium and which, passing through a traction ring are taken down and tied at a single point to the ground, inside the water mirror. The resulting geometry, as in any tensile structure consisting of elastic elements, is not entirely flat, with the ridges curving upwards from their center (along with the steel cables) with a curve of the order of 5 percent along their length, while the fabric tensioned between the cables curves almost imperceptibly downwards (Fig.16). In the horizontal plane along the top of

the trusses of the facade is envisioned a compression ring, formed by the beams of the facade and by two more beams inserted in the former, rotated and crossed over each other so as to form struts between the nodes of the facade trusses [22].

Fig. 16 The Brazil Pavilion at Expo 2020. [22]

The fabric is a Precontrant fabric by Serge Ferrari, which features a flexible structure of high tenacity PET micro-cables coated with several layers of polymers and finished with a dirt-resistant surface treatment, offering low solar factor translucence and avoiding excessive heat gains. The internal volume has trusses in both of its longitudinal facades, each supported by two pillars, resolving in a rational manner the large proposed cantilevers [23].

4.CONCLUSIONS

The information given in the paper shows that membrane structures have often been used at World Fairs. At the couple of last Expos membrane structures had absolutely dominant place at the exhibition site, which shows the importance of these structure for today's architecture. By comparing first membrane structures to the newest ones we can also monitor their progress through time. From being dependant on cable nets they became one of the structures with highest spans. Pneumatic structures were also developed from tensile membranes.

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MEMBRANSKE KONSTRUKCIJE NA SVETSKIM SAJMOVIMA

Svetske izložbe pružaju prilikumu nacijama da prikažu ostatku sveta svoja dostignuća. Pored najnovijih dostignuća u nauci, tehnologiji i kulturi, Expo je takođe postao i podijum za arhitekturu. Istorija pimene membranskih konstrukcija počela je na Expo-u 1958. godine u Briselu i traje i dan danas. Ovaj rad istražuje konstantni napredak membranskih konstrukcija kroz paviljone izgrađene za Svetske izložbe

Ključne reči: *membranske konstrukcije, Svetksa izložba, Expo, lake konstrukcije, zatezne konstrukcije*