Air Inflated Cushions – Recent History

Karsten Moritz, March 3, 2020

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1. Construction Methods

Membrane constructions are divided into two basic types, pneumatically and mechanically pre-stressed constructions. Both types differ in their appearance, their load-bearing behavior, in the failure mechanisms and thus also in the safety considerations [1].

The term "pneu" has its origin in the Greek word "pneuma", which means wind or breath. In architecture, the term is used, for example, for "pneumatic constructions". Pneus are components which, in relation to their ambient pressure, are stabilized against external loads by an over- or under-pressure of the enclosed air volume. This also means that the individual membrane systems, which enclose the air volume, are curved and wrinkle-free due to the pressure difference resulting from over- or under-pressure.

With elastic membranes that enclose the air volume, pneumatic constructions are able to transfer loads (wind and snow) via tensile forces into a substructure, into a primary structure or directly into the foundations.

Pneumatically pre-stressed constructions are generally divided into the three categories tubes, air halls and air inflated cushions. The cushions can be stabilized with positive or negative pressure (Fig. 1).

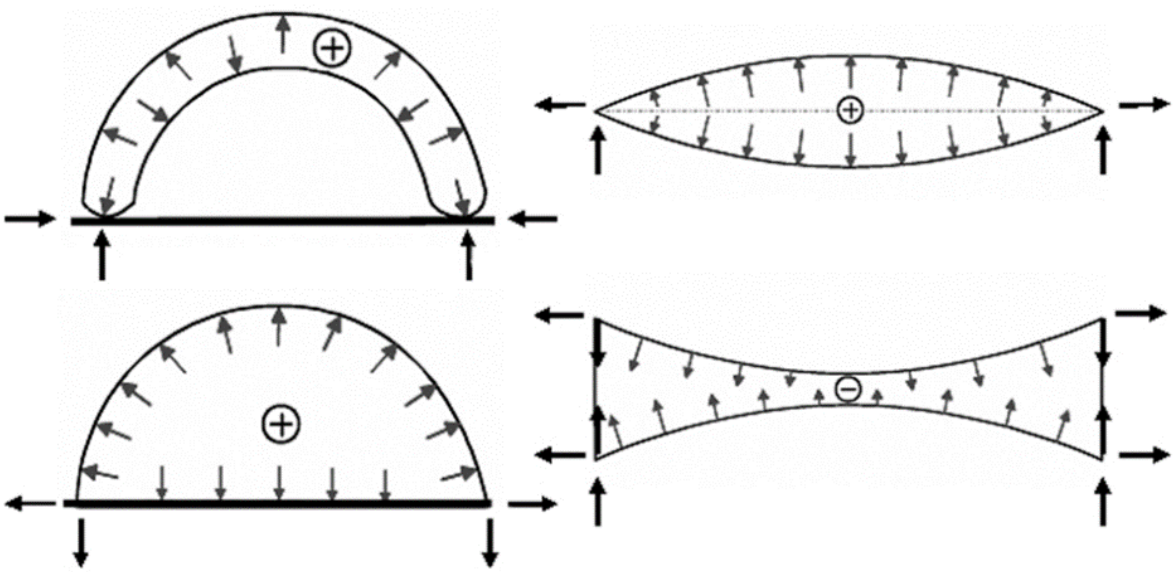

Fig. 1: Subdivision of the pneumatic constructions: a) tubes, b) air halls and air inflated cushions c) with positive pressure, d) with negative pressure (source [1], see also [2]).

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2. Pressure Management

Since the under-pressure-cushions have disadvantages with regard to the high edge support required and the difficulty of air filtering, overpressure cushions are almost always used to this day.

In order to keep the air volume enclosed in the cushion free of condensate, it is flushed with dried air as standard. The flushing rate depends on the ambient conditions in the building interior (temperature, air humidity). It is usually 1-4 times the cushion volume exchange per day. For example, in cases of envelopes for tropical gardens or swimming pools with high air temperature and humidity a higher flushing rate may be required.

The nominal overpressure in the cushion is approximately 250 to 600 Pascal, depending on geometry and external loads. For increased stability against wind and snow loads, the overpressure is temporarily increased to about 1000 Pascal depending on the project. In the context of the structural analyses of the membrane, it should be noted that the internal pressure of the cushion usually determines the maximum horizontal support load at its boundary.

The membranes and their connections must also be dimensioned for the maximum design value of the overpressure and for the highest temperature to be assumed. This applies in particular to the use of foils where the maximum foil tension must be examined taking into account the maximum temperature dependent on the load case in order to rule out inadmissible or excessive creep deformations.

Air-inflated cushions can be made from foils, preferably made of ETFE, or from almost airtight technical fabrics, such as PVC-coated polyester fabrics. If the span of the cushion exceeds the load-bearing capacity of the membrane material or its connections, pneumatic overpressure cushions can be supported using cables or cable nets. Cables on the surface of the cushion are avoided wherever possible in order to avoid dirt deposits and thus visual impairments.

The pre-tension in the membranes can be regulated depending on the cushion curvatures via the set blower pressure. It can be adapted to a certain extent to the calculated effects (wind, snow). The overpressure in the cushions fluctuates between the adjustable maximum and minimum pressures. The pressure in the cushion is usually measured and controlled by three sensors, the min pressure sensor, the max pressure sensor and the nominal pressure sensor. The sensors supply the pressure data to the electronics of the blower station, which increases or decreases the air supply as required. The maximum output of the blower determines the maximum possible amount of air, which is required or makes sense especially in the event of large damage (leaks) to membranes or air ducts, but also during commissioning (initial filling) of the cushions.

It is state of the art today that each blower has two redundant fans. The two fans alternate in rotation during normal operation, for example every two weeks, so that wear parts are protected and the functionality of both fans is checked automatically and regularly. Only in exceptional cases, i.e. in the case of the above-mentioned leaks or when the cushions are blown up initially, do both fans run at the same time in order to call up the maximum performance of the blower unit.

Efforts are made to set the overpressure in the cushion during operation to be as high as statically necessary on the one hand and as low as possible on the other hand so that creep deformations and the associated changes in geometry are as small as possible. Creep deformations mean an increase in the amount of stitch on the film in the case of the pneu-cushion. For this reason, the maximum

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pressure, which can also be set in addition to the nominal pressure, is only increased when wind or snow loads (at low temperatures) require it. It is important to know that creep, more specifically, relaxations, in mechanically pre-stressed membranes can lead to a reduction in tension or a loss if there is no tensioning device. With a pneumatic preload, moderate creep deformations only lead to a slight increase of the sag. As a result, the curvature increases slightly, the film thickness and the pre-tension force decrease slightly. Since the decrease in the films thickness and the increase in the cushions curvature have an opposite effect, the film tension remains approximately constant. The overpressure is not influenced by creeping processes. However, the level of pretension is chosen so that creeping does not occur or leads maximal to negligible deformations.

Due to the overpressure in the cushion, a synclastic surface is created in many areas, i.e. curved in the same direction in both main directions of curvature. The positive Gaussian curvature is $k > 0$ in all points of this surface. Only in the corners, depending on the shear rigidity of the membrane, locally anticlastic, i.e. oppositely curved areas with a negative Gaussian curvature ($k < 0$) can occur. Such corner areas can be avoided if necessary by suitable cutting of the membrane sheets welded together.

3. Multilayer Cushions

Especially when using ETFE foils, one or more so-called middle layers are used today. There are two variants:

Flat middle layers

Three-layer cushions are often made with a thinner, evenly stretched, middle layer. This serves to divide the enclosed air into two (usually coupled) volumes and thus to improve the thermal insulation. To keep the flat middle layer free of wrinkles, it is provided with a mechanical pretension. The support loads resulting from the flat middle layer are small in comparison to those of the outer foils, but must nevertheless be considered statically. The restoring force of the flat central position is usually not used arithmetically. Snow or water pond loads can lead to plastic deformation of such a central layer if the air supply fails (malfunction). The risk of the case to be classified as a usability criterion is usually minimized by a redundant air supply (e.g. emergency power supply and second fan).

Curved middle layers

Due to the risk of plastic deformation of a flat middle layer, multi-layer cushions are increasingly provided with one or more middle layers, which are cut to size and have a synclastic curvature. The two air volumes decoupled in the case of the three-layer cushion re fed with different pressures in order to stabilize the middle layer by means of a pressure difference.

Multi-layer cushion systems with curved middle layers also offer advantages for load transfer: On the one hand, an outwardly curved middle layer can take a part of the often dimensionally relevant wind suction load, which relieves the outer layer or increases the possible span of the cushion. On the other hand, in the event of a snow or water load in case of a malfunction (e.g. failure of the air supply), a curved central position is not overstretched as quickly as a flat one.

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4. Milestones

At the beginning of the 1970's, pneumatically supported cushions were already used in building construction. In his impressive book "Pneumatic Constructions - Buildings from Membranes and Air" Thomas Herzog documented and analyzed a number of pneumatic constructions, including pneumatic cushions, as early as 1976 [2].

At first, these were mainly experimental buildings. They consisted either of translucent fabrics (e.g. PVC-coated polyester fabrics) or of transparent but not permanently UV-stable multi-layer PVC films.

The 10,000 m² Plaza Pavilion at the Expo in Osaka 1970 is an impressive example of the design of the air inflated cushions. They consist here of up to 5 layers of transparent PVC film. The square air inflated cushions arranged in a grid already had an impressive edge length of 11m (Fig. 2).

Fig. 2: Plaza Pavilion at the Expo in Osaka, Japan, 1970, 11 x 11 m cushions made of several layers of PVC film, architect: Kenzo Tange et al. [2], photo/source: Japón cultura y arte [3]

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The mangrove hall in the Burger's Park, the Arnhem Zoo in the Netherlands, is considered as the first permanent air inflated cushion structure made of ETFE-Foil s. The pneumatic cushion roof made of HOSTAFLON ETFE-Foil from the manufacturer Hoechst was built in 1982 by the company Vector Foiltec in Bremen. It wasn't until about three decades later that ETFE-Foil cushions had to be replaced due to a hail event. Otherwise, the ETFE-foil was still intact and not changed significantly in its optical and mechanical properties (Fig. 3).

Fig. 3: Mangrove hall in Burger's Park in Arnhem, 1983, client: Arnhem Zoo, architects: ABT, Arnhem, structural engineer (ETFE-Foil cushion structure): Dr. Grotkop and Partner, Bremen, execution (ETFE-Foil cushion structure): Vector Foiltec, Bremen, photo/source: Isenmann, Volker [5]

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The convertible (removable) roof of the arena in Nimes, France, which was built in 1988, also represents a milestone in the history of building with air inflated cushions.

The large cushion construction developed by the engineering office Schlaich Bergermann und Partners forms an area of around 5,000 m² in the winter months a roof over the interior of the arena. In the summer months, the air can be released from the cushion, which is made of PVC-coated polyester fabric, and the entire construction can be dismantled (Fig. 4).

The air inflated cushion is stabilized by a pressure ring, which rests on 30 supports at a height of approximately 10 m. The ring is slightly "sunk" in the arena, so that the cushion is not visible from the outside. The upper membrane has a stitch of 8.20 m, the lower membrane, supported by a cable net, only 4.20 m. The membranes are made of PVC-coated polyester fabric.

Fig. 4: Ancient arena in Nimes, France, 1988, client: Ville de Nîmes, architects: LABFAC, Paris (Finn Geipel, Nicolas Michelin), Schlaich Bergermann and Partner, Stuttgart, execution (air inflated cushion): Stromeyer Ingenieurbau, Konstanz, photo/source: TensiNet [6]

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In 1994 the predator house in Hellabrunn Zoo in Munich was another milestone in the construction with pneumatic cushions.

The roof made of two-layer ETFE-Foil cushions curiously forms an overall anticlastic shape. This is due to the pre-tensioned cable network, which is supported by two masts, and the long, spatially curved cushions that are attached to the cable network.

The film cushions stretch between the meridian cables and lay on the ring cables of the network. The top layer of film runs from the eaves to the ridge, thus reaching a maximum field size of approximately 2 x 20 m. The lower layer of film forms approximately square fields (approx. 2 x 2 m), which transfer inward loads to both the ring and meridian cables. Cushions and cable network form a harmonious, soft overall system (Fig. 5).

Fig. 5: Predator house in Hellabrunn Zoo, 1994, client: Munich Hellabrunn Zoo, architects: Herbert Kochta, Munich, structural engineer: Schlaich Bergermann und Partner, Stuttgart, structural analyses (air inflated cushions): IPL, Radolfzell, execution (ETFE-Foil cushion structure): Koit / Koch Hightex, Rimsting, photo/source: TensiNet [7]

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The lifting lens in the Munich Olympic Park from 1996 represents a further milestone in pneumatic construction. The semi-transparent pneumatic cushion functions as a movable lifting roof. The lower layer of the large cushion is made of ETFE-Foil . It is supported by a cable network. The top layer of the air inflated cushion consists of a glass fiber mesh fabric laminated with PTFE (Fig. 6).

Fig. 6: Lifting lens in the Munich Olympic Park, 1996, client: Munich Olympic company MOG, architects: Behnisch und Partner, Munich, structural engineering: Posselt Consult, Übersee, Tensys Ltd. Bath, version (air inflated cushion): Koit / Koch Hightex, Rimsting, photo/source: K. Moritz [8]

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In 2001 an iconic representative of the air inflated cushions with under-pressure was designed and built. The temporary structure called Dynaform was created to present the new BMW 7 series on the IAA exhibition in Frankfurt. It included a cladding of PVC-PES membranes, but also double-layer ETFE-foil cushions at the gable side of the s-shaped pavilion. The form of the under-pressure cushions is synclastic, as for the over-pressure cushions, but the constellation of both foil-layers is concave (refer to Fig. 1), instead of convex (Fig. 7).

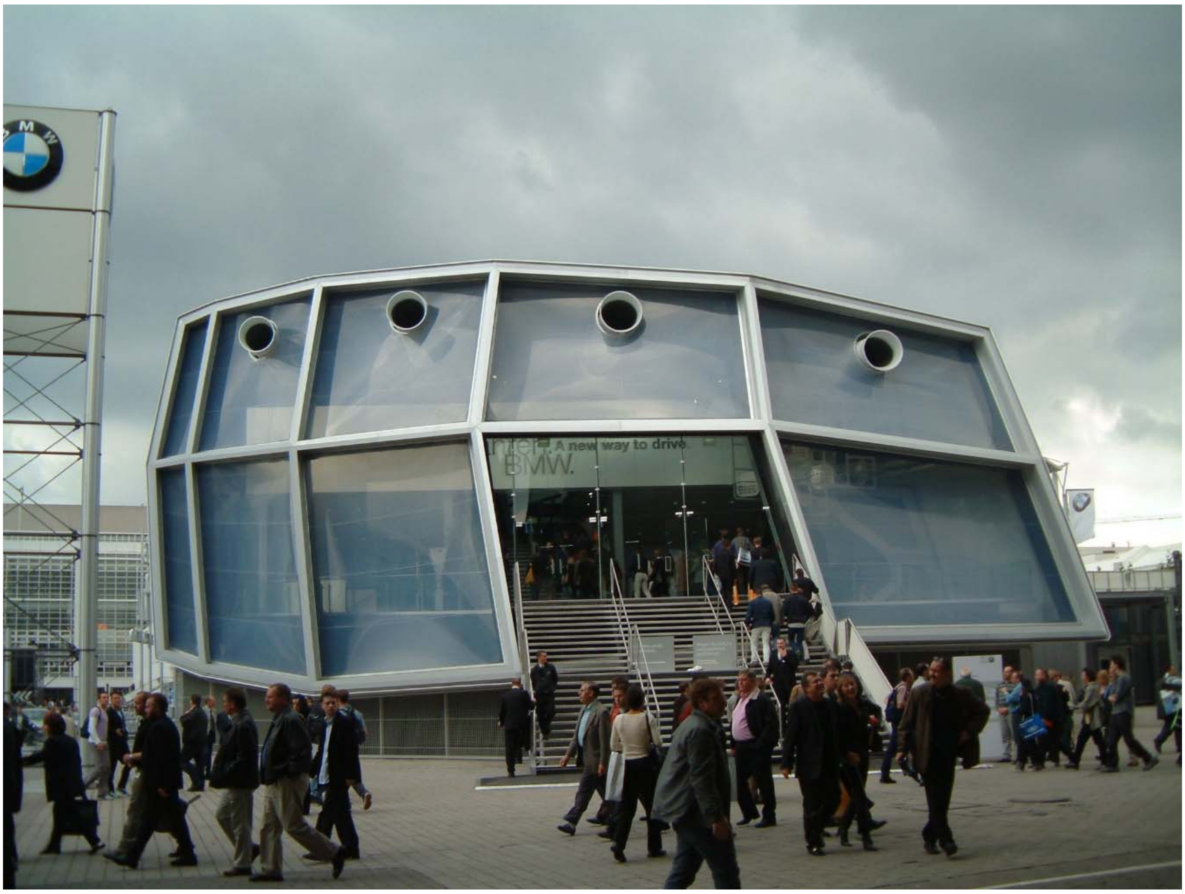

Fig. 7: DYNAFORM, BMW-pavilion on the IAA in Frankfurt/Main, 2001, client: BMW group, architects: Franken Architekten, Frankfurt/Main, structural engineer: : IBZ and Bollinger + Grohmann, Frankfurt/Main, execution: skyspan, Rimsting, photo/source: Karsten Moritz [8]

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Another lifting lens was built in 1999 over the Vistalegre bullring in Madrid. The roof is formed by a circular steel roof structure with a diameter of 100 m. The middle section is a vertically movable, pneumatically supported membrane roof with a diameter of 50 m. The air inflated cushion consists of a steel pressure ring and two membranes, between which the air is blown. The upper membrane consists of a translucent fabric, the lower one is a transparent ETFE-Foil , which rests on a cable net. In the “parking position”, the cushion lies on the fixed roof ring and forms a rainproof room for the arena. In the open position, the air inflated cushion hovers 10 m above the ring of the fixed roof (Fig. 8).

Fig. 8: Vistalegre bullring, Madrid, 1999, client: Palumi S.A., Madrid; Arturo Beltrán, architects: Jaime Pérez, Ayuntamiento de Madrid, structural engineer (air inflated cushion): FHECOR Ingenieria S. A., Ingenieros Consultores, Schlaich, Bergermann und Partner, Stuttgart, execution (air inflated cushion): Skyspan, Rimsting, photo/source: Tensinet [9]

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The temporary “Cycle Bowl”, an exhibition pavilion of the “Duales-System-Deutschland GmbH”, was erected at the EXPO 2000 in Hanover. Pneumatic shading was used here for the first time, in which the outer layer and the middle layer of the three-layer ETFE façade cushion were printed alternately. If you increase the pressure in the inner cushion chamber and lower it in the outer one, the middle layer attaches to the outer layer. The two prints of both layers complement each other to form now an almost opaque cover. For the first time, the light transmission of the building envelope was designed to be variable and controllable with the help of two different chamber internal pressures of a three-layer cushion (Fig. 9).

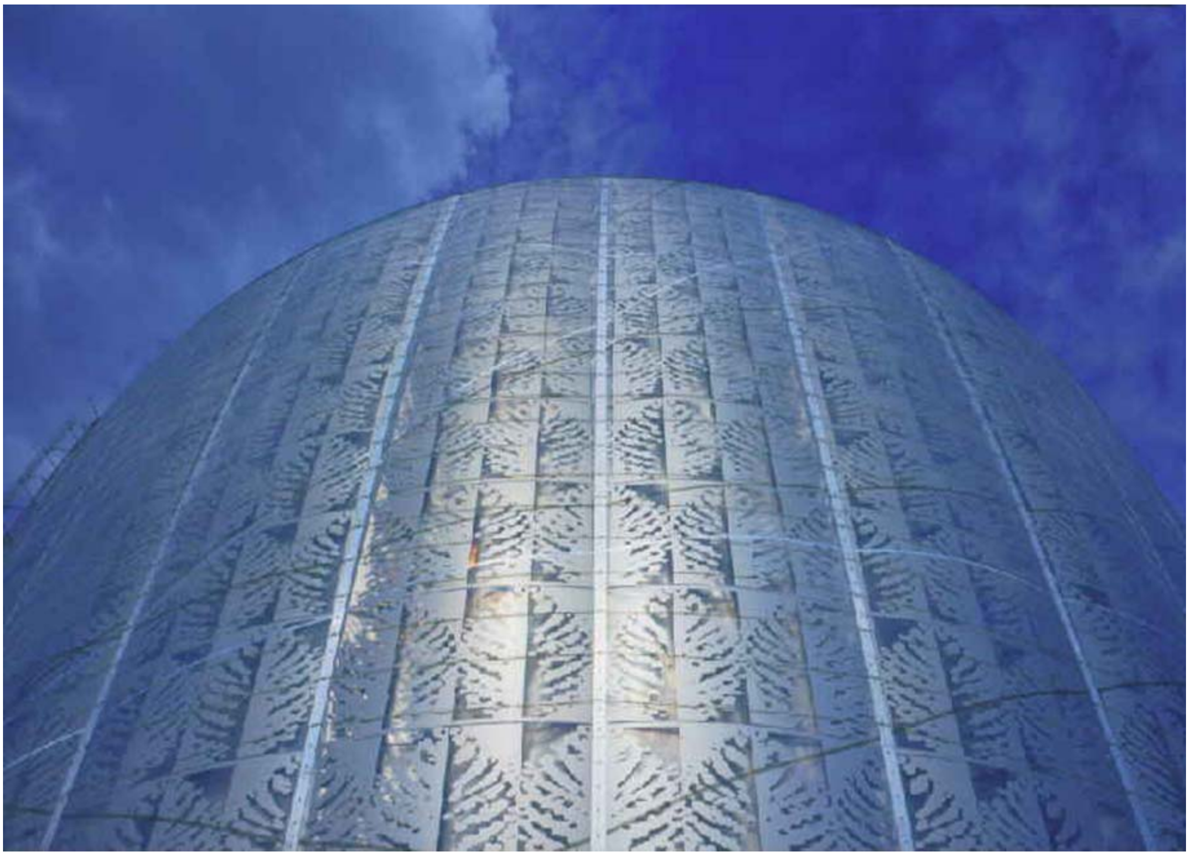

Fig. 9: Cycle Bowl, Expo 2000 Hannover, client: “Duales System Deutschland GmbH”, architects: Atelier Brückner, Stuttgart, structural engineer (ETFE-Foil cushion structure): Dr. Grotkop and Partner, Bremen, execution (ETFE-Foil cushion structure): Vector Foiltec, Bremen, photo/source: K. Moritz [8]

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Also in 2001, the “Garden of Eden” project – “Eden Project” for short – created the shell for a botanical garden in Cornwall (UK). With a total area of approx. 30,000 m² (625 ETFE-Foil cushions), in terms of its dimensions and aesthetics, it outperformed all constructions made in this way (Fig. 10).

Fig. 10: Eden Project (Garden of Eden), St. Austell, UK, 2001, client:, architects: Sir Nicolas Grimshaw & Partners, London, UK, structural engineer: Anthony Hunt & Associates, execution (ETFE-Foil cushion structure): Vector Foiltec, photo/source: Tensinet [10]

The envelope of the Masoala rainforest was built in Zurich almost at the same time. The cover was initially planned and built with three-layer ETFE-Foil cushions. The hall houses the flora and fauna of the Masoala peninsula in Madagascar (Fig. 11).

The rectangular cushions span between Virendeel beams of the arched support structure. Their maximum span is 3.90 m, their maximum length from eave to eave is 106 m. This makes these cushions probably the longest ETFE-Foil cushions worldwide.

The Masoala rainforest was also the first ETFE cover, with which a fourth ETFE-Foil was later added. This additional layer serves as a hail protection layer. It also provides improved thermal insulation.

The subsequently added outer ETFE-Foil was not welded to the other three film layers, but was attached to the standard clamping profile with a second profile (System Membrane Plus, covertex), so that it can be replaced in the event of damage caused by hailstorms without the underlying three-layer cushion open, expand or even destroy. In fact, the hail protection membrane in the hail-prone region has been damaged and replaced twice by hailstones (up to a diameter of about 75 mm) over the decades.

Fig. 11: Masoala Regenwald, Zurich, Swizzerland, 2002, client: Zurich Zoo, architects: Gautschi + Storrer, Zurich, structural engineer (ETFE-Foil cushion structure): Engineering + Design Linke and Moritz, Rosenheim, execution (ETFE-Foil cushion structure): Covertex , today seele cover, Obing, photo/source: K. Moritz [8]

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The Allianz Arena in Fröttmaning near Munich represents another architectural milestone in the construction of air inflated cushions. The 2864 two-layer ETFE-foil cushions form the roof and the façade. They cover a large part of the stadium. The illumination of the ETFE-Foil envelope made of fluoropolymers is also impressive. Originally achieved with fluorescent tubes of different colors, light-emitting diodes with low power consumption now radiate the envelope from the inside in many colors (Fig. 12, 13).

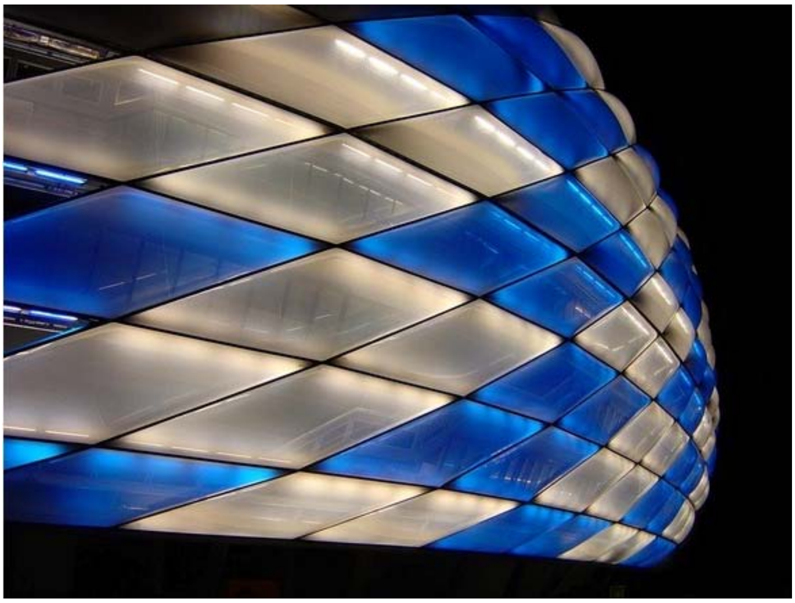

Fig. 12, 13: Allianz Arena, Fröttmaning near Munich, 2004-2005, client: München Stadion GmbH, architects: Herzog & DeMeuron, Basel, structural engineer (ETFE-Foil cushion structure): Engineering + Design Linke and Moritz, Rosenheim, execution (ETFE-Foil cushion structure): Covertex , today seele cover, Obing, photos/sources: Tensinet [11]

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With a roof area of 100,000 m², the Water Cube in Beijing in 2008 not only set new standards in building with ETFE-foil cushions. It also shows for the first time a design with two cushion levels one above the other (Fig. 14). The roof and façade consist of approx. 4000 ETFE-Foil cushions.

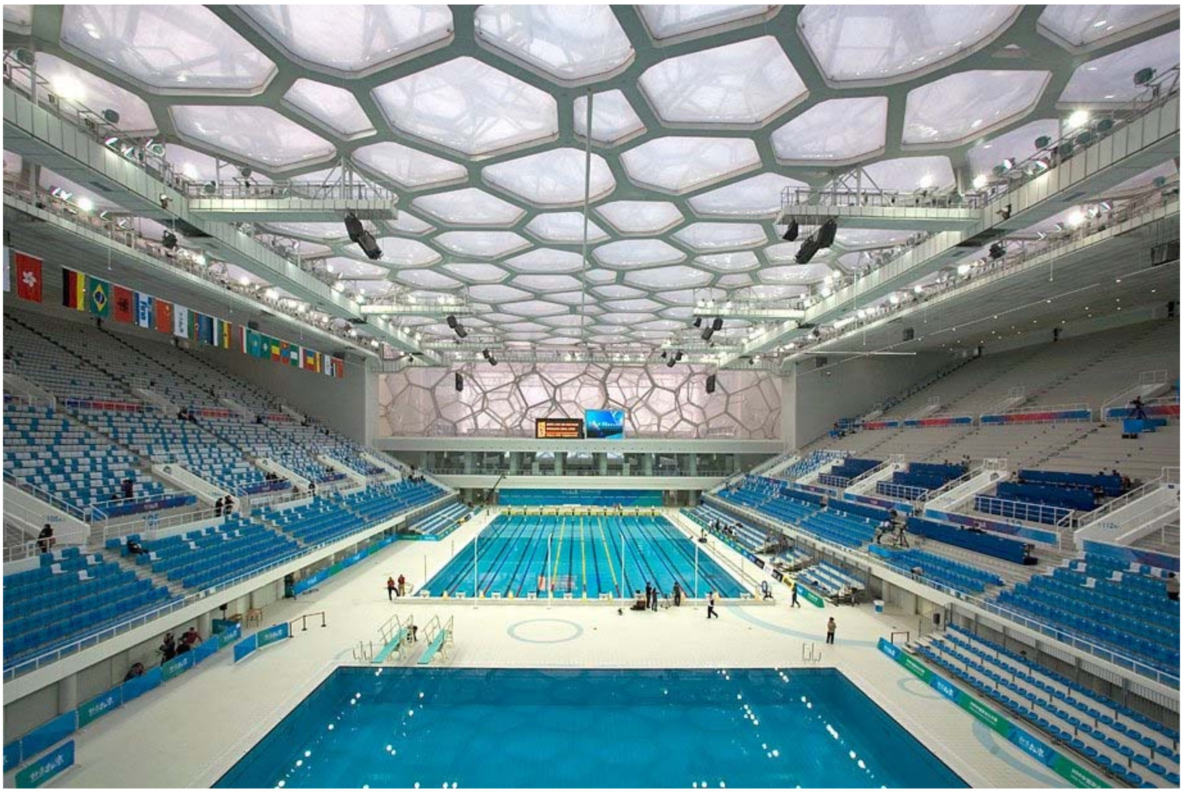

Fig. 14: National Aquatic Center "Water Cube", Beijing, China, 2008, client: Beijing State-Owned Assets Management Co, architects: CSCEC & DESIGN, Arup Pty. Ltd, Peddle Thorp Walker Architects, Beijing, structural engineer (ETFE-Foil cushion structure): Arup, execution (ETFE-Foil cushion structure): Vector Foiltec, Bremen, photo/source: Arup [12]

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With a roof area of approximately 10,000 m², the carpark AWM in Munich is the first permanent large ETFE-foil cushion roof worldwide with flexible photovoltaic-modules integrated. The PV-plant was connected to the electricity-grid in November 2011. It consists of 2,640 flexible thin-film PV-modules, fixed on the middle layers of the 220 triple-layer ETFE-foil cushions. The project impressively shows the possibilities ETFE films and PV offer to generate solar gains in future. (Fig. 15)

Fig. 15: AWM Carpark for waste disposal vehicle services, Munich, 2011, client: City of Munich, architects: Ackermann Architects, Munich, structural engineer (ETFE-Foil cushion structure): Christoph Ackermann, Munich, execution (ETFE-Foil cushion structure): Taiyo Europe, Sauerlach and Konstruct AG, Rosenheim, photo/source: Taiyo Europe [13]

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Due to increasing demands on the thermal insulation of building envelopes and the energy consumption of buildings, cushions with four layers of ETFE-Foil were planned and built since around 2012.

The ARC River Culture Pavilion in Daegu, South Korea is a museum and an architectural and structural masterpiece. It interprets the connection between nature, technology and space in a spectacular way. The air inflated cushions made from intensely printed ETFE foils are carried by the harmonious grid shell on the underside of the building. (Fig. 16)

Fig. 16: ARC River Culture Pavilion, Daegu, South Korea, 2012, client: Kwater Korea, architects: Asymptote Architecture, Hani Rashid, New York, structural engineer: Knippers Helbig, Stuttgart, Withworks, South Korea, structural analyses (ETFE-Foil cushion structure): Konstruct AG , Rosenheim, execution (ETFE-Foil cushion structure): Taiyo Europe, Sauerlach, photo/source: Taiyo Europe [13]

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The large cushion made of ETFE foils above the atrium of the Lilienthalhaus in Braunschweig, completed in 2017, is an iconic example for air inflated cushion technology, too (Fig. 17).

Here the idea of a cushion-drainage developed, patented and applied by covertex many years ago for the Allianz Arena for the first time was taken up again. In case of the Allianz Arena, stiff drainage tubes had been placed in all cushions of the horizontal area of the large stadium roof. These tubes shall drain the referring cushions from rain water or melted snow. Such situations may occur only, when the air inflation breaks down (despite the redundancy of the air fans) or if the snow exceeds the over-pressure of the cushion. Fortunately such situations are very rare in practice. Without such a drainage system, water ponds may occur, that are able to generate a big water load in a quite short time. The large cushion of the Lilienthalhaus shows instead a number of integrated flexible drainage-hoses for this purpose. This approach considers, that such a large cushion filled with water cannot be supported by an economically planned primary structure.

Fig. 17: Lilienthalhaus, Braunschweig, 2017, client: Volksbank, BraWo, architects: Rüdiger, Braunschweig, structural engineer (ETFE-Foil cushion structure): FormTL, Radolfzell, execution (ETFE-Foil cushion structure): Temme // Obermeier, Raubling, photo/source: Tensinet [14]

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The transparent roof of the Oxigeno recreation and shopping center in Francisco de Heredia near San José, Costa Rica, from 2018 also represents a large cushion. With a diameter of 45m and a surface area of 1,600 m², it is currently the largest ETFE-foil cushion in the world. Since the load-bearing capacity of the thin ETFE foils does not allow such spans, the cushion is supported on both the top and bottom by cable nets. If, despite the redundancy of the fans, the air supply to the cushion fails and the cushion collapses and may even run full of water, the opening valves located near the center in both membranes should drain the water pond. It is also interesting here that the top layer consists of an IR cut ETFE-Foil, which largely converts the solar radiation in the infrared spectrum into thermal energy, which the film releases in both directions with a time delay. IR-cut foils should ensure that the interior heats up less in summer and releases less energy to the surroundings in winter (Fig. 18).

Fig. 18: Oxigeno, San Francisco de Heredia, San José, Costa Rica, 2018, client:, GC: 3dtex, architects: Jerde, structural engineer (ETFE-Foil cushion structure): z3rch, execution (ETFE-Foil cushion structure): Lonas Lorenzo (installation), Novum, Membranes (manufacture), photo/source: TensiNet [15]

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As the River Culture Pavilion in Daegu (Fig. 16) has already shown, the number of ETFE-Foil layers of the air inflated cushions is constantly increasing due to energy savings. In 2019, cushions consisting of five layers of film were used for the first time at the Center Commercial Balexert in Geneva, Switzerland. With a dense print, you can achieve an Ug value of around 1.0 W / (m²K) (Fig. 19).

Fig. 19: Center Commercial Balexert, Genève, Switzerland, 2019, client: Center Balexert SA, Genève, GC: Hevron, architects: S + M Architectes SA, Le Lignon, France, structural engineer (ETFE-Foil cushion structure): Massimo Maffeis, Solagna, Italy, execution (ETFE-Foil cushion structure): Taiyo Europe, Sauerlach, photo/source: Taiyo Europe [13]

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