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## **POLYMERIC MEMBRANES IN ARCHITECTURE**

Principles and applications in temporary and permanent structures

EXTENDED ABSTRACT

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ABSTRACT:

Textile Architecture is as old as man itself. However, due to its temporary character it has not been developed and considered as a viable solution in the past. Nowadays, although technological advancements make tensile architecture possible, architects lack the knowledge and experience in this subject. With recent innovations in materials and techniques, sinuous and elegant forms are emerging, and membranes have proven to be suitable, not only for temporary but also for permanent constructions.

The aim of this dissertation is to inform architects on the most common varieties and respective qualities of modern-day polymeric membranes. This is achieved through the analysis of mechanical, thermal, acoustic, fire resistance and environmental impact properties. The most commonly used constructive details will be studied as well as all the methodology to follow, from form-finding process to patterning of the membrane. Two distinct projects were studied: The Shooting Arenas by Magma Architecture and the National Aquatics Center by PTW Architects. Both case studies aim to offer a practical understanding of the properties listed above and studied throughout this work, thus evaluating the main inspirations, challenges and solutions architects must face when dealing with tensile constructions.

To sum up, this work results in a reflection of membranes' potentialities in architecture from both aesthetic and technical points of view. The main assets and problems are addressed and through the application in the cases studies it is shown the reliability of this type of solutions.

**Keywords:** Polymeric Membrane, film, coated textile, Shooting Arenas, Watercube, National Aquatics Center.

## INTRODUCTION:

Membrane Architecture has been present since the early ages, mostly as a form of a tent. This first, yet primordial construction method provided mankind with shelter against climatic influences. Made from wood, cotton, or more initially from animal skins, these constructions set the roots of architecture and shared the same bases of present membrane structures: lightness and transportability. Due to their components, they were not as resistant as other construction materials, and consequently they displayed a short life span, diminishing their potential as a notable material in architecture (Berger, 2005 & Monjo-Carrió and Tejera, 2011).

In the 20th century, this paradigm starts to change with the industrial and social revolutions that led to the emergence of tensile architecture. First with the Walter Bird's first pneumatic radôme followed by the European Utopians and Visionaries, Frei Otto (1925-2015), David Geiger (1935-1989) and Horst Berger (1928-), membranes started to gain their importance, as a new way of construction in which the lightness and freedom went against the pre-war notion of architecture: heavy, solid, earthbound buildings (Knippers et al., 2011 & Nerdinger, 2005).

The new situation coupled with the new perspective found in the industrial development a way to improve membranes properties. With the introduction of polymers, membranes were able to expand to other areas besides protective envelopes, radar installations and pneumatic roofs. Their improved characteristics surpass those found in the natural components, and with the most recent developments, their usage has become more widespread.

With the advent of computerized programs, membranes achieved the freedom of form, and presently they are able to incorporate new materials and solutions almost without limits. Besides the incorporation of photovoltaic cells and various light options, smart textiles are being introduced, leading to an adaptive, responsive architecture, which is able to sense and respond to its environment.

## MEMBRANE'S MATERIALS:

The origin of the term membrane comes from the Latin word membrane, which is described "*as a skin, a flexible material that is very thin relative to its surface area*" (Knippers et al., 2011:100). This thin flexible material is usually made of woven yarns but can also be a film or foil.

When dealing with a textile solution, their properties will not only be a firm result of the weaving process, but of the type of fabric and coating (when applied). Uncoated solutions, regularly ETFE and cotton base fabrics, are not commonly used, as they only withstand small spans. Due to their exposed nature, the fabric is not very resistant to the UV radiation, fungi, bacteria and moisture enabling as well the passage of water. To overcome these issues, the fabric is often coated with a polymeric material to protect it, improving its performance and life span. According to Drew (2008:32) both PTFE-coated glass-fiber fabrics and the PVC-coated polyester fabrics are part of the 90% of materials used in membranes, however when dealing

with high light transmission, Silicone coated-glass fiber is commonly used. The PTFE-coated glass-fiber is the most expensive and durable solution with great self-cleaning properties and UV resistance, however due to the nature of flexing and folding weakness of the glass fibers, it cannot be used in retractable structures. For those, the recommendation goes to PVC-coated polyester, a less resistant and expensive solution with great mechanical and flex cracking characteristics that present a wider range of color options. Lastly, Silicone coated-glass fiber displays a very good translucency, as a result of the high translucency of both silicone and glass fibers, however due to its better maneuverability and tear resistance, it is more susceptible to the accumulation of stains and dirt (Drew, 2008, Armijos, 2008 & Huntington, 2013).

As films and foils lack a fabric mesh in their structures, they are unfitted to preform loadbearing, and consequently they are used in a form of multi-layer cushions. These types of membranes are used in high transparency applications, and ETFE foil is the most frequently used solution. This is due to the fact that ETFE is highly stable, making it suitable to outdoor usages, presenting a better self-cleaning ability and better transparency than glass, with countless printable options (Armijos, 2008).

#### MEMBRANES PROPERTIES:

As a heterogenic material membranes will perform differently, making it difficult to determinate their resistance against all influences. Therefore it is necessary to perform a series of tests in order to determine the most current behavior. Adding to the essential mechanical strength and stiffness properties of constructions materials, in membranes, the tear resistance is also taken into account. For the first, two types of tests are performed, a biaxial and uniaxial, defining the membrane's ability to resist the applied loads, evaluating the material's behavior through time. According to Pudenz (2004:62) the strength of the membranes' structures most commonly ranges from 0,04 KN/cm (light foils) to 2 KN/cm (coated fabrics). When dealing with tear strength, either tongue tear test or most commonly trapezoid tear test can be performed, defining the tear's propagation when the membrane is slit or cut. Film solutions are more resistant to tear than fabrics, and the most common cause of failure in a fabric's structure is indeed the tear propagation (Hungtinton, 2004).

When dealing with thermal properties, membranes present a low thermal insulation due to their low thickness value. However this can be improved by the creation of air gaps within membrane layers or by the introduction of insulating material or conditioned air in a double layer. Both solutions face some challenges, mainly with the appearance of microorganisms and the reduction of light transmission. Despite their low insulation, they exhibit a great light transmission, having solutions that can range from 0 to 95% translucency, enabling the use of controlled daylight and providing great glare control (Hungtinton 2013).

Membranes display little acoustic insulation as a result of their thin structure. At low frequencies (around 31.5-250 Hz) membrane solutions are almost 100% acoustically transparent, allowing the passage of low frequency sounds, and at middle to high values (500-8000 Hz) they will absorb a maximum of 30% of the sound, reflecting the other 70% into the surrounding area. Nevertheless, the tensioning of the membrane surface makes it vulnerable to vibration, creating a drumming in presence of rain or hail (Chiu, 2015).

In the case of coated solutions, flame-retardants are incorporated in the coating in order to ensure the extinguishing or removal of the flame. While PTFE-coated glass membrane is considered non-combustible, PVC/PES membranes melt away easily, producing holes that will release the heat and smoke from inside. Silicone rubber, for instance, withstands higher temperatures as well as lower temperatures than PVC, making Silicone-coated glass membranes perform similarly to PTFE-coated glass membrane. Lastly, when using an ETFE foil, due to their extremely low weight, all heat and smoke will easily escape from the inner environment (Chilton, 2010).

Despite PVC, polyester and PTFE being all thermoplastic materials, ETFE foils are more commonly recycled due to their simple composition that allows for their recyclability. Although recent developments are working to ensure the full recyclability of coated solutions possible, the reuse of membranes is always a viable option. With a service life of 25 to 30 years, membranes represent a great solution in terms of environmental impact, as their low weight characteristics maximize the material usage and reduce the whole structure's weight (Pudenz, 2004).

#### MEMBRANES' PLANNING AND METHODOLOGY:

The tensile behavior of membranes is the basis for the design and determination of the form. To begin it is important to know where all the fixed points are, and only after this is considered how the membrane will interact with the structure in order to define the kind of material and details that can be used. Therefore the design is based on the study of mechanical resistance against the external actions.

The form finding process aims to find the most efficient membrane surface for all the applied loads, and there are two ways of doing it, through a physical or numerical model. While the physical is commonly used in an early stage, the numerical method uses computer-aided software to calculate the optimal shape that will ensure equilibrium of forces at all the points and stages (Drew, 2008).

The geometry plays an important role in the form finding process, which is directly related to the repartition of the prestress defined by type of curvature used. When dealing with perpendicular double curvature, an anticlastic arises, commonly used for fabric solutions, and in the presence of same-direction double curvature, a synclastic form develops, commonly used in the pneumatic structures. The anticlastic shape, also known as mechanical surface, has a wider spectrum of shapes, as well as the possibility to be anchored in existent structures, providing an easy assembly/disassembly process with better acoustic performance and higher lifetime than pneumatic structures. On the other hand, the pneumatical surfaces are stabilized through the inflation pressure, not being part of the loadbearing's structure. While the anticlastic surfaces can be divided into four basic types: saddle and sails; ridge and valleys; high and/or low points; and arches, the pneumatic solutions can be either cushions or tube inflated (Maurin and Motro, 2012 & Knippers et al., 2011).

Despite the type of shape used, membranes solutions can only work in tension, and therefore supportive compressive elements are needed to transmit the loads onto their

surroundings and to apply the needed tension on the membrane. These elements can be either flexible or rigid, assuming the form of arches, cables, clamping/keder solutions or masts (Knippers et al., 2011).

Membranous materials are limited in size due to their manufacturing process: the whole membrane surface is divided into pieces to be assembled to form the final shape. This process of subdivision is named the cutting pattern, and it is one of the most delicate steps in the membrane planning, as a bad definition can result not only in a displacement of the edges, and consequently a projection of extra parts to compensate these errors, but also a bad load-carrying behavior (Monjo-Carrió, 1985).

The membranes' patterns are joined via seams. As an integral part of the membrane, they require the same high mechanical strength of the membrane's surface, as well as similar elongation and flexibility in order to unify all the surface behavior under the future load. When there are limitations in terms of size to fabrication, transport and erection of the membrane system, the available detachable seams can be laced, clamped or keder clamped, while in the permanent seams, the techniques used are welding, stitching, and although less often, gluing. The following table sums the most common used type of seam for each type of membrane material (Monjo-Carrió, 1985 & Llorens, 2015).

The finishing of the perimeter is made through the edge details, and sums up two types of systems available: the flexible and the rigid solutions. As flexible solutions for the edges there are the webbing belts, the edge cables in pockets, and the separated edge cables, whereas in a rigid proposal laced systems, clamping bars or keder rails are used. In both cases, the edge details will transfer the normal and tangential forces to the membrane's surroundings, and therefore the most suited one should be chosen not only regarding the membrane material, but also the stress calculation (Knippers et al., 2011).

Membranes' edges don't have to be necessarily rectilinear, and in most cases the supportive points coincide with the membrane's corner. These corner details must carry not only the weight structure and forces, but also restrain all the tangential forces, allowing the flexibility of movement, and in some cases the attachment of the tensioning systems, within different angles' acuteness. According to the type of edge detail adopted, there are different solutions available dealing with edge belts or cables (Knippers et al. 2011).

#### THE SHOOTING ARENAS BY MAGMA ARCHITECTURE:



Figure 1: Photo of the Artillery Barracks in Woolwich. (Diehl, 2012)

In 2010, Magma architecture was commissioned to design the 10-, 25-, and 50-meter ranges for the London 2012 Olympic and Paralympic shooting events, in the background of the Royal Artillery Barracks, in Woolwich. According to the Olympic Delivery Authority ODA, the project had to be a temporary construction that should not only follow the principle of reduce, reuse and recycle, but also be easily dismantled in order to leave no trace of the venue post-Games (Kleinheinz, 2013).

The concept envisions the buildings as bivouac tents inspired by the Royal Artillery Barracks' military heritage, where the experience and precision of the shooting sport is invoked through the use of tensioned fabric with colorful apertures (*Figure 1*). These holes were more than decorative, and it was through them that the membrane was stretched, reducing the need of steel for about 55%, when comparing to a building made out of the same material but in a continuous way, and less 40% if it was pulled only in the corners (Gundlach, 2014 & Pottgiesser, 2013).

The pavilions were constructed with modular, standardized, steel-truss frames, easily found in several companies, over which the membrane material was tensioned, making it possible to achieve large enough spaces to accommodate the visitors without any obstacles. Not only steel-truss frames were reused, but also the driven piles, which were made from reclaimed oil and gas steel pipelines. Creating mobile, rather than just temporary buildings, lead to a cautious design of all the connections so that they could be disassembled and re-assembled in other locations (Kleinheinz, 2013).

With an outer and inner PVC-coated polyester membrane the venues were able to maximize the use of natural light, reducing the need for artificial light. This entrance of solar radiation was also beneficial to the thermal properties of the venue, since it was possible to heat the intermediate space between the inner and outer membrane. In the summer, the heated air is conducted outside, and in the winter it is used to heat the inner environment of the venues.

The hot-cold air circulation is ensured by the entrance and exits of air to the exterior through the colorful perforations, which not only gave strong visual reference to bullets holes for each building (blue 25m range; magenta: 10/50 m range; and orange for the finals), but also display the main entrances when located in the lower part.

Despite this, it was also through these holes that the membrane was tensioned and consequently they were the main consideration in the cutting pattern. All the PVC-coated polyester panels were pre-welded in factory via high frequency welding and after installed in site firstly to the truss frame structure and after in the clamping bar system present in the holes ring, one façade at the time.

Due to the use of such a system, it was possible to correctly tension the membrane creating the necessary curvature in order to avoid the tearing of the fabric, the standing water that can lead to soiling, wrinkles and surface soiling. The rainwater was not an issue as well, as it was collected through PVC manholes and redirected to soakaway crates. The only problem faced was an act of vandalism in the lower section, which was easily removed due to the washing capabilities of the membrane.

This case study illustrates the opportunities that membrane solutions can bring to temporary structures. Through the use of a tensile material, it was possible to drastically reduce the weight of the whole structure, and consequently minimize not only the materials and resources used, but also the time of construction and dismantling. Adding to this, with the use of a membrane solution, it was possible as well to establish controlled lighting and ensure the correct ventilation and comfort temperature inside. Although Magma Architects faced some limitations regarding the design process, they were able to find a solution that was both aesthetically pleasant and mechanically reliable.

#### THE NATIONAL AQUATICS CENTER BY PTW ARCHITECTS:



Figure 2: National Aquatics Center, "Watercube": PTW Architects, Beijing, 2008. (Bosse, 2008)

For the Beijing 2008 Olympic Games, PTW architects designed a project whose concept envisioned *"water as a structural and thematical leitmotiv" with the square, the primal shape of the house in Chinese tradition and mythology* (Pohl, 2008:58), the watercube (Figure 2).

Even though, the inspiration came from nature, PTW used computerized software to achieve a solution that was both natural and innovative, redefining the typical building elements such as walls, columns, windows, etc. With the cooperation of Arup Engineers, it was possible to develop a three dimensional model resembling soap bubbles, in which the repetition of different kinds of bubbles gave the illusion of a random and organic arrangement (Pohl, 2008).

The structure was the key element of the proposal, and composed of 22,000 steel members and 12,000 nodes, this allowed the required ductility for the high seismic area of Beijing. Subdivided into three main groups of structural elements: the inner and outer members, and the corner elements, the structure is quite flexible weighting only 100 kg/m<sup>2</sup> only, and measuring 175 meters on each side and 35 meters in height (Pohl, 2008 & Hill, 2008).

ETFE (Ethylene Tetra Fluoro Ethylene) film cushions were used for the skin of this steel structure, as they present a great life expectancy (25 years) with a very low weight, providing great transparency and being resistant not only to UV radiation but also to the site's atmospheric pollution. Constituted by more than 3 000 cushions restrained in aluminum extrusions and

supported by the steel structure, the project was at its time the largest structure made by a transparent plastic film (Pohl, 2008).

Ranging in size from 1x2 meter to 8x11 meter modules, these cushions were made from 1.5m wide ETFE foils that were putted together via thermal welding, keeping a vertical orientation in the façade, and a random display in the roof. In site, their pre-installed edge ropes were clipped to the aluminum frame, establishing the connection to the primary structure.

The external ETFE cushions are composed of several layers of blue and transparent ETFE film, and can change the facade's shading with the use of a dual ETFE solution, (an envelope inside of the inner cushions) blocking or transmitting the sunlight to the inside of the building. The internal cushions are composed of interior foils with reflective and low emissivity frit which varies from 10 to 60%, according to each space requirement, that can be opened or closed by means of air pressure. Both systems work together to take the maximum advantage of solar gains, and use solar energy to efficiently heat the inner space in winter and the water pools all year long. To accomplish a Low U-value, three layers of ETFE were used for the external cushions in the walls, four for the roof, and six to eight layers in the inner cushions, that in combination with a similar vented cavity system used in the shooting arenas, ensured a comfortable interior temperature all year (Pohl, 2008 & LeCuyer, 2008)

The high translucency of the membrane allows the projection of light that not only advertises the activities inside but also reduces the risk of vandalism, due to the high presence of the building, even in the night environment. Regarding the other common problems of membranes, the ETFE cushions were designed to withstand the loads coming from rain, wind and snow, and when pillow inversion occurs all the layers will work together, distributing the stresses to the surrounding area and avoiding the collapse of the cushion. Despite the flat roof, standing water and soiling problems were solved due to the use of a perimetric gutter throughout the roof cushion.

The Watercube in Beijing was the largest structure in the world of ETFE cushions. The use of ETFE had already showed major advantages in lighting, and the way such a light and thin material can be a better thermal insulator, more transparent, and not as brittle as glass, opened major possibilities in architecture.

#### CONCLUSION:

It is clear that membranes structures are a viable option not only for temporary but also for permanent structures, as the evolution of materials is leading towards increasing strengths, which consequently renders these types of structures into everlasting options. As membranes demand a great collaboration between architects and engineers, their use brings a new approach to architecture, where the construction is born both artistically and scientifically. The unique features of membranes enable solutions of interesting appearances that not only meet construction requirements, but also provide solutions of great foldability and lightness, where the interior spaces can be adapted to many kind of uses. As Dame Zaha Hadid eloquently put it back in 2004:

*"Fabric is both a traditional and a high-tech material whose form is directly related to the forces applied to it – creating beautiful geometries that are never arbitrary. I find this very exciting"* (McManus, 2014).

Membranes solutions have the great potential of improving architecture's future, and therefore it is imperative to encourage their use with a better promotion of the correct detailing and a better cooperation between all involved areas.

Their usage today, is still in an initial stage as consequence of their limited lifespan. The materials are highly exposed, making it crucial to invest in further research so as to improve their resistance, not only their behavior under continuous stress, but also their UV resistance. Another important factor is the high maintenance of these types of structures. Furthermore, no studies so far evaluate the environmental impact and the financial cost from a long term point of view - starting from their initial investment to the maintenance expenses. Finally membranes should be studied in other constructions areas, such as conservation and restoration of cultural heritage, as they can provide means to minimize the impact during the works.

## REFERENCES:

- Armijos, S. (2008). *Fabric Architecture: Creative Resources for Shade, Signage, and Shelter*. New ed. W W Norton & Co, New York.
- Berger, H., (2005). *Light Structures - Structures of Light: The Art and Engineering of Tensile Architecture Illustrated by the Work of Horst Berger, 0002 ed.* AuthorHouse, Bloomington, Ind.
- Chilton, J., (2010). "Textile structures – textile for architecture and design" in Pohl, G. (ed.),. *Textiles, Polymers and Composites for Buildings*. 1 edition. ed. Woodhead Publishing, Oxford ; Philadelphia, p.351-374
- Chiu, S., (2015). "Acoustics in architectural fabric structures: the case of ETFE pillows" in Llorens, J.I., (ed) *Fabric Structures in Architecture*. Woodhead Publishing, Boston, MA, p.241-256
- Drew, P., (2008). *New Tent Architecture*. New ed. Thames & Hudson, New York.
- Gundlach, S., (2014). "Berlins neue Baumeister" in *Berliner Morgenpost*, Sunday Edition 26 October, p. 16-17
- Hill, T., (2008). *Solutions for a Modern City: Arup in Beijing*. Black Dog Architecture, London, UK.
- Huntington, C.G., (2004). *The Tensioned Fabric Roof*. American Society of Civil Engineers, Reston, Va.
- Huntington, C.G., (2013). *Tensile Fabric Structures: Design, Analysis, and Construction*. American Society of Civil Engineers, Reston, Virginia.
- Kleinheinz, L. (2013). "Built for the Moment: Designing for a Fast-Paced World in The Economy of Sustainable Construction" in Ruby, N. janson E.I. & A., *The Economy Of Sustainable Construction*. Ruby Press, p. 310-325
- Knipppers, J., Cremers, J., Gabler, M., Lienhard, J., (2011). *Construction Manual for Polymers + Membranes*. Birkhäuser GmbH, Basel.
- LeCuyer, A., (2008). *ETFE*. 1 edition. ed. Birkhäuser Architecture, Basel ; Boston.
- Llorens, J., (2015). "Detailing for fabric architectural structure" In Llorens, J.I.. (ed) *Fabric Structures in Architecture*. Woodhead Publishing, Boston, MA, p.241-256
- Maurin, B., Motro, R., (2012). "Architecture Textile" in Motro, R. (ed) *Les Matériaux Composites Souples en Architecture, Construction et Intérieur*. Birkhäuser Verlag GmbH, Basel p.26-38
- Maurin, B., Motro, R., (2012). "Architecture Textile" in Motro, R. (ed) *Les Matériaux Composites Souples en Architecture, Construction et Intérieur*. Birkhäuser Verlag GmbH, Basel p.26-38
- Monjo-Carrió, J., (1985) *La Arquitectura Textil, Informes de la Construcción*. Vol 36, No 367, p.5-29
- Monjo-Carrió, J., Tejera, J., (2011). "The use of textile materials for architectural membranes" in Figueiro, R., (ed) *Fibrous and Composite Materials for Civil*
- Nerdinger, W., (2005). *Frei Otto. Complete Works*. 1st ed. 2005. 2nd printing edition. ed. Birkhäuser Architecture, Basel ; Boston.
- Pohl, E.B., (2008). *Watercube: The Book, Bilingual edition*. ed. DPR, Barcelona.
- Pottgiesser, U., Ashour, A. (2013). "Design vs. development: neue ansätze" in *Innovative Fassadentechnik 2013*. Berlin: ernst & sohn special, September
- Pudenz, K., (2004). "Materials and Workmanship" in Koch, K.M., Habermann, K.J., (ed.) *Membrane Structures: Innovative Building with Film and Fabric: The Fifth Building Material*. Prestel Verlag, Munich ; New York, p.46-65