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ScienceDirect

Procedia Engineering 155 (2016) 61 – 70

Procedia Engineering

www.elsevier.com/locate/procedia

International Symposium on "Novel structural skins - Improving sustainability and efficiency through new structural textile materials and designs"

Structural membranes used in modern building facades

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Abstract

Technology driven materials, designs and construction techniques play a major role in state of the art building facades. Textile membranes or foils are used more and more often in façades applications becoming an integral part of modern architecture. Today's diversity in lightweight façade options available is one of the key facts for its worldwide success. Membrane façades offer immeasurable opportunities for architectural expression, with free-form and complex geometries being structurally feasible and economically attractive.

The paper evaluates general demands on a façade system that can be used as a fundamental check list for the designer if membranes are a possible option for the façade system. Furthermore the paper presents and discusses material and system options, properties but also limits of membrane façades. The presented case studies show the variety of solutions including the typical material combinations. The examples cover all common materials and methods, including ETFE, Glass-PTFE, PVC Polyester, Glass-PTFE mesh as well as multi-layer insulated systems.

Peer-review under responsibility of the TensiNet Association and the Cost Action TU1303, Vrije Universiteit Brussel

Keywords: façade, lightweight, ETFE, ECTFE, mesh membrane, shading

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Peer-review under responsibility of the TensiNet Association and the Cost Action TU1303, Vrije Universiteit Brussel
doi:10.1016/j.proeng.2016.08.007

1. Introduction

The façade forms the outer envelope of a building and serves various purposes. Primarily, the façade protects the interior from environmental conditions such as wind, rain and sun, and it also separates the often intimate interior from views from the 'public' outside. Another key aspect of a modern façade design is to generate a unique appearance for the building, sometimes even creating a landmark that is well known in public.

A façade system usually consists of the façade cladding, a two-dimensional element that is supported by a primary and / or secondary structure. Various materials for the cladding have been used in architecture ranging from more traditional envelope materials such as glass, metal, stone, timber, concrete, etc. to materials that have been developed during the last decades such as glass fiber reinforced plastic (GRP), glass fiber reinforced concrete (GRC) just to mention a few. It is obvious that the use of textile membranes and foils as part of the building envelope is becoming more and more popular and several striking examples have been realized during the last years.

2. Façade systems and materials

2.1. Demands on cladding materials

Since the actual cladding is the main component of a façade system, the materials and project specific requirements must be evaluated and decided upon during the initial stages of the design process. Since building projects are very distinctive as well as their location and purpose, it is impossible to list all potential demands for each application on cladding material, but the following list intends to highlight the most significant ones:

- Protection from external environmental conditions (wind, rain, temperature, sun, etc.)
- Creation of private interiors
- Cladding has to withstand outer loads (wind, temperature, maintenance loads, etc.)
- Thermal performance
- Solar / light performance
- Fire behavior
- Durability
- Acoustic performance
- Aesthetic / surface appearance (translucency, color, etc.)
- Certain materials allow complex architectural geometries
- Material weight for substructure design
- Material costs
- Installation costs / time, modularity
- Maintenance requirements, and when required, replacement methods
- Recyclability, sustainability

2.2. Characteristics of high performance materials

Structural high-performance materials are characterized by a high ratio of structural strength to dead load. The application of these materials is optimal when they are under pure tension – using the full structural capacity by omission of bending moments and any stability issues. But the definition of high-performance is not limited to structural properties at all. High-performance means also, for example, that a material or composite of materials is designed and later on also produced to meet a certain specification such as transparency or translucency, air permeability, specific color, acoustic damping, etc. Moreover, selective coatings are sometimes part of high-performance material to directly influence the properties of a specific building requirement, for instance, of a low-e coating for improved interior climate conditions, or to enhance the self-cleaning behavior of a surface treated with nano-particles.

In architecture, adaptive or moveable elements also impose specific demands on materials. Sometimes they have to change their material properties or have to allow for a change in geometrical arrangements, which is the case of retractable shading blinds, for example.

The architectural appearance of a building is defined by contour, form, and appearance of the envelope, and while the pure thermal façade systems are relatively simple and well established in the market, with its traditional components such as glass, sandwich panels with insulation, or vertical coring bricks, these elements are all relatively heavy and / or limited in their variety in application. Using membrane materials in façade systems is a more economic alternative to the traditional cladding materials, especially when there are reduced requirements on the envelope system such as, for example, simple wind or visual barrier, pure shading or balancing of thermal peak loads.

3. Membrane facades

3.1. Material selection for membrane facades

Several different products have been developed in the field of architectural / structural membranes that can be also used for façade applications. In general two different types can be distinguished: On the one hand, there are textile membranes, a composite material consisting of a woven base cloth that is normally coated on both sides. On the other hand, there are foils, very thin extrusions with a thickness of less than 0,4 mm.

Due to the relatively low mass and thickness of single layer membrane systems, they are characterized by a relatively high U-value. Therefore the single layer structural membranes are mainly used as an exterior sun screen, for direct wind and rain protection, as skin for semi-air-conditioned zones (for example in stadia) or to generate a visual barrier between the interior and the exterior rather than acting as a thermal barrier.

Multi-layer membrane systems provide a better thermal performance with reduced U-values. The multi-layer systems are either inflated membrane cushions (2, 3 or even more layers) or a two-layer system with intermediate insulation. In case these multi-layer systems are the thermal envelope, the designer has to carefully verify that no condensation will occur for the chosen façade system.

The development of selective coatings that can be applied to architectural membranes started to grow over the last decade, with enhanced properties and increased possibilities in its application; for example, low-e coatings influencing the climatic conditions within a building, and TiO2 coatings can offer a longer lasting clean appearance of the surface under certain conditions. Since architectural membranes are becoming more popular, more selective coatings will be developed in the near future to further improve the products and widen their field of application.

3.2. Textile membranes

Different materials and material combinations are used for the textile membrane composites. Architectural fabrics are often woven from Polyester (PES) yarns that are coated with Polyvinylchloride (PVC) or from glass fiber yarns that are coated with either Polytetrafluorethylene (PTFE) or silicone. The reason for the coating is to protect the fibers of the yarns from environmental influences but also to allow individual membrane segments to be seamed together in terms of welding.

Uncoated fabrics are usually made of Polytetrafluorethylene (PTFE) or Polyvinylidenfluorid (PVDF).

The textile membranes can either be coated full-faced, creating a water and wind-proof fabric with translucencies between approx. 0 to 40% depending on the material, or the textile membrane is woven with explicit gaps between the individual yarns forming an open mesh membrane with a local coating of the yarns only. These mesh membranes are often used for sun screens but also to form an architectural building envelope that allows certain views in both directions. Various pattern of the meshes are available that also differ in size and arrangement of the open areas of the mesh.

Both glass/PTFE membranes and PES/PVC membranes are available in various colors. Some of the products are printable allowing a very individual appearance. Depending on the structural demands, different strength classes are available.

Over the last years also laminated open mesh membranes have been developed and are available in various combinations: glass/PTFE mesh membrane with a continuous lamination of a transparent Fluorpolymer (ETFE, PTFE, etc.). The advantage is relatively high transparency (> 50%) in combination with material strength of up to 60 kN/m.

Table 1.Common textile membranes

Category	Composition	Characteristics	Fire resistance (*)	UV Resistance	Expected Lifetime [years]	Translucency [%]	Colors
Closed mesh with full faced coating	PES cloth with PVC coating	Versatile applicable standard material	0	+	~20	0-25	Standard white, nearly all colors upon request
Closed mesh with full faced coating	Glass cloth with PTFE coating	High quality standard material	+	++	>25	4-25	Standard white, various colors upon request
Closed mesh with full faced coating	Glass cloth with silicon coating	Soiling behavior in exterior application could be improved	++	+	>20	10-20	Standard white, various colors upon request
Closed mesh with full faced coating	PTFE cloth with PTFE coating	Very high quality material with excellent foldability characteristics, durability and soiling behavior	++	++	>30	20-40	Standard white, limited amount of colors upon request
Open mesh, coated yarns	PES Mesh cloth with PVC coating	Different mesh sizes available, standard material	0	+	~20	Up to 90%	Several Standard colors, nearly all colors upon request
Open mesh, coated yarns	Glass mesh cloth with PTFE coating	Different mesh sizes available, high quality standard material	+	++	>20	Up to 90%	Standard white, some colors upon request
Laminated Open mesh	Glass mesh PTFE coated laminated with Fluopolymer-film	Few mesh sizes available, custom made material	+	++	~20	Up to 70%	Standard white, limited colors upon request
Closed mesh without coating	PTFE cloth uncoated	Very good durability and foldability for retractable structures, custom made	++	++	>30	Up to 40%	Standard white, limited colors upon request

Table 1 gives an overview of available textile membranes used for architectural applications.

3.3. Foils

Ethylen-Tetrafluorethylene (ETFE) are thin films with very high transparency up to 96%, however, compared to textile membranes ETFE has significantly reduced strength, and the material properties are more sensitive to elevated temperatures. The thickness of the ETFE foils in architectural applications ranges between 100 to 300 µm, and individual foil segments can be welded and seemed to form larger panels. Furthermore, ETFE foils allow printing in various patterns and colors, and some special coatings are available to improve the durability of the material, whilst other coatings can filter out certain wave lengths of the sun to avoid overheating the building.

An alternative to ETFE foils are Ethylene Chloro TriFluoroEthylene (ECTFE) foils. For architectural applications this is a relatively new product. Initially the ECTFE was manufactured in the USA and found its application in the aircraft industry, as front and back sheets of Photovoltaic as well as being used for special cable coatings. Key features of the ECTFE are abrasion resistance, excellent corrosion resistance (even acids under high concentration) and very good fire resistance. ECTFE has similar material properties to ETFE, thus the modulus of elasticity is higher at lower temperatures but also lower at high temperatures. The biggest advantage of ECTFE is that the material has higher solar transmission and clarity. It has very low haze and hence is more suited to applications where absolute clear transparency is required. The surface of ECTFE is very smooth which allows for easy printing and coating, thus increasing the possibilities of application. Film thicknesses of 100 to 400 µm are available. The material is weldable.

4. Case studies

4.1. Hazza Bin Zayed Stadion in Al Ain

The exterior palm bole façade of the Hazza Bin Zayed Stadium consists of a steel diagrid structure with 612 individual orientated membrane panels that achieve maximum shading whilst allowing view points from the inside (figure 2). Areas within the stadium that require comfort cooling have an additional thermal envelope consisting of a standard insulated glass or aluminum façade. The membrane panels of the exterior shading façade in combination with the primary steel structure pay homage to the palm bole - an emblem of the Oasis of Al Ain. A modular system has been developed in order to rationalize the façade and cladding system as well as to minimize construction time.

The shading panels of the palm bole façade comprise a steel frame with a pre-stressed glass-PTFE membrane, giving the façade the appearance of the segments the palm bole. An intermediate arch is used to form a saddle like shape to provide the membrane with sufficient curvature. The membrane panels are installed with varying inclinations depending on the local shading requirements and desired architectural appearance. They are supported in the diagrid frame nodes with a simple bolted clamp detail to speed up installation. This was possible due to the light nature of the panels (figure 1a). At night the white membrane panels are illuminated in various colors by LED units that are mounted to each diagrid steel node (figure 1b).

Fig. 1. (a) Glass/PTFE panel for external shading; (b) Illuminated membrane panels.

Fig. 2. Hazza Bin Zayed Stadium, Al Ain/U.A.E.

4.2. BC Place Stadium in Vancouver

The new BC Place Stadium in Vancouver is wrapped by a 9,500m² single layer ETFE façade. The continual 13m high façade is subdivided by three steel rings that form the substructure for the façade. In order to achieve an economical structural system in each of the 36 bays of the stadium, twelve vertical steel arches were used to create a 3D saddle shape made out of ETFE (figure 3). These ETFE foils have a printed fritting in grey color with varying density that allows the façade to be illuminated using LED lights that are mounted at the horizontal steel rings. The innovative façade system strikes with its transparent appearance during the day and a variety of colors at night (figures 4a and 4b).

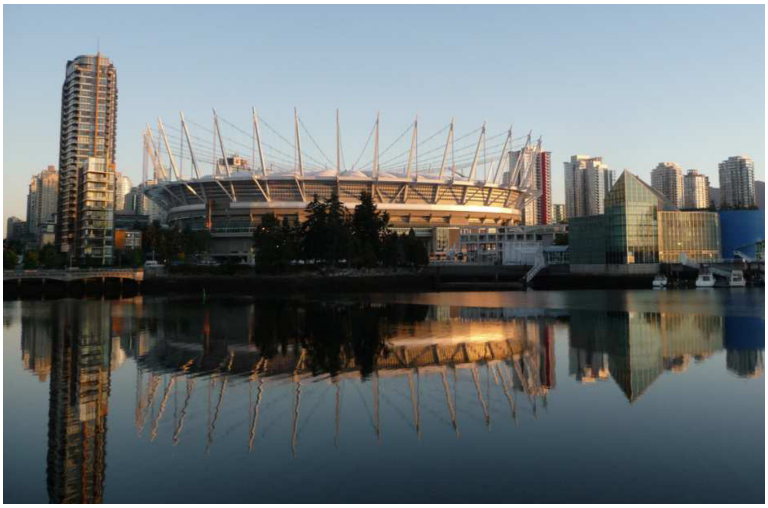

Fig. 3 BC Place Stadium, Vancouver/Canada.

Fig. 4. (a) ETFE façade, BC Place; (b) Illuminated ETFE façade, BC Place.

4.3. Greenpoint Stadium in Capetown

The Greenpoint Stadium was designed for the FIFA World Cup 2010 (figure 5a). The outer façade comprises a steel primary structure with vertical and horizontal elements that are braced to the concrete structure behind the façade. The horizontal beams that are curved in plan are set off the façade layer to the outside forming prominent fourteen horizontal lines. The actual cladding material is a silver-colored PTFE/glass open mesh membrane. Depending on the lighting conditions during the night and day, the appearance of the stadium is quite different; at night the interior is illuminated creating a transparent façade system that allows views to the interior while during the day, the façade looks more opaque from the outside (figure 5b).

Fig. 5. (a) Greenpoint Stadium, Capetown/South Africa; (b) open mesh membrane facade.

4.4. Mobile Spaces - Textile Pavilions for the Indo-German Urban Festival

The German artist Markus Heinsdorff developed several of the so-called "textile buildings" for the Indo-German Urban Festival 2012. Sixteen different lightweight system structures in the form of pavilions were designed to be wrapped by varying types of textile membranes, from solid and open mesh PVC to coated PES membranes, every pavilion could have a distinctive color, pattern or achieve an entirely different appearance solely based on the choice of material properties (figures 6a and 6b). The pavilions are designed as mobile spaces allowing for easy mounting, transportation and dismantling taking into account local skills, technologies and workmanship. The pavilions have been temporarily installed in several cities of India with different climatic and loading conditions (figure 7).

Fig. 6. (a) PVC/PES and open mesh membrane cladding for pavilions; (b) Mobile Spaces: Interwoven PVC/PES membrane strips.

4.5. Bamboo Pavilion for the Expo in Shanghai

The two-story membrane bamboo structure contains a total of 350m² of floor area. It was intended to present the German-Chinese Initiative at the 2010 Expo in Shanghai in a pioneering and an environmentally friendly building. The particularities of this art object lie in its design and the unique combination of bamboo rods, bamboo laminate, ETFE film as well as PVC/PES Membrane (figure 7a). The structure and all member connections were designed allowing the building to be taken apart and to be reconstructed elsewhere after the exhibition. All materials are either fully reusable or fully recyclable. In the event of repairs being necessary, each cladding element can be replaced individually. The transparent, single layer ETFE film has been arranged in folded plate geometry designed in the style of paper-folding techniques (figure 7b). The illumination of the façades also serves to light up the interior and the surrounding environment. Thanks to the fantastic transmission properties of single skin ETFE façade a lantern effect has been created which also makes additional light sources in the interior unnecessary. ETFE as a façade material has shown its outstanding combination possibilities with other traditional and unique materials.

Fig. 7. (a) Bamboo Pavilion for Expo in Shanghai; (b) Transparent ETFE façade, Bamboo Pavilion for Expo in Shanghai.

4.6. Olympic Swimming Facility Munich

A series of tensile structures have been designed for the Olympic Games 1972. Amongst those, the Olympic swimming pool features an enclosure made out of translucent and insulated PVC coated Polyester membrane that is suspended from the exterior cable-net roof. In 2007, the then over 30 years old membrane cladding has been replaced, since the material strength had become compromised due in particular to the prevalence of moisture and chlorine in the air. The re-design had to take into account the compliance with the latest standards whilst keeping the visual appearance of the heritage design in place. In order to fulfill the interior space's climate control requirements, the membrane is composed of – from bottom to top: load-bearing membrane of PVC-coated polyester fabric, 7cm polyester fleece insulation and transparent ETFE-foil sealing layer. On the advice of the executing contractor, a responsive ventilation system was installed in lieu of the lower moisture barrier. The measureable translucency of the roof assembly is approx. 1,5% and results in a high natural lighting of the swimming pool complex with a freeform tensile geometry (figure 8).

Fig. 8. Olympic Aquatic Center, Munich.

4.7. Memorial in Madrid (ETFE)

A glazed memorial at Atocha Station in the centre of Madrid serves as a reminder of the victims of the terrorist attack that took place there on 11 March 2004. On that day, 191 people were killed and 1,824 were injured in bomb explosions in four suburban trains.

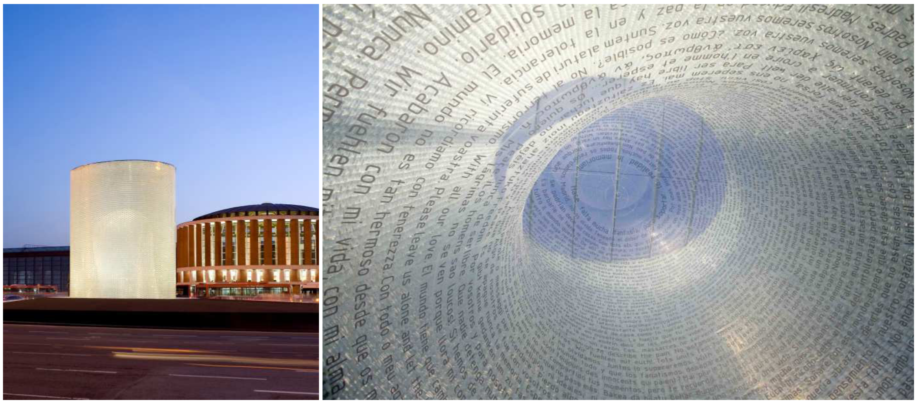

Fig. 9. (a) M11 Memorial in Madrid, solid glass blocks with inner ETFE foil; (b) M11 Memorial in Madrid, printed ETFE pneumatic structure.

The memorial consists of a glazed cylinder above ground and a commemorative space immediately below. Within the glass cylinder is a 150 μm thick ETFE foil stabilized by air pressure. Printed on the surface of this transparent inner skin are messages of condolence in different languages, written initially on pieces of paper by passers-by after the terrorist attack in Atocha Station (figure 9a).

The form-founded geometry is unusual for inflated structures, with both concave and convex areas. The membrane geometry was developed in conjunction with the stabilizing air pressure, so that in spite of different biaxial stress conditions, no folds occur. The complex process of determining the form of the 72 welded sections of the membrane took account not only of the elastic elongation of the material in two directions, but also of the spiraling layout of the messages, so that these could continue uninterrupted across the seams. Since the ETFE membrane is highly transparent, the underground memorial space receives natural light from outside during the day (figure 9b). Reflections and the formal interplay between the semitransparent glass structure and the amorphous membrane result in unusual visual effects and spatial impressions. At night, with its internal lighting, the glass monument is like a bright crystal. Light radiates out through the semi-transparent glass blocks, and one can discern the outlines of the ETFE bubble within.

5. Conclusion

The material summary shows the tremendous variety of today’s membrane materials. More combinations of fibers, coatings or laminates are still to come. Multifunctional materials, containing electro chromatic layers, selective coatings and energy harvesting elements will form the tool box of the future.

The guideline of sustainable designs: “minimizing the dead load of the structures” will be best followed by using the membrane materials. In addition, adequate design solutions for creating long span, lightweight and low cost solutions make this sector very successful in modern architecture. In the future we will see more and more of this and many of them in combination with retractable, foldable and adaptive arrangements.

Acknowledgement

Hazza Bin Zayed Stadium, Al Ain: Architecture by Pattern Design Ltd.
Greenpoint Stadium, Capetown: Architecture by gmp – Architeckten von Gerkan, Marg und Partner
Mobile Spaces, India: Architecture by Markus Heinsdorff and Büro Arch+
Bamboo Pavillion, Shanghai: Architecture by Markus Heinsdorff
Olympic Swimming Pool, Munich: Architecture by Behnisch und Partner, Auer und Weber
Memorial in Madrid: Architecture by estudio FAM

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Figure 6a, 6b: Markus Heinsdorff
Figure 7a, 7b: Germany and China - Moving Ahead together / www.kingkay.com

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