EMPHASIZING THE 'GREEN' PROPERTIES OF ETFE FOILS AND VISUALIZING ITS SPECTRUM OF IMPLEMENTATION IN ARCHITECTURAL BUILDING ENVELOPES

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ABSTRACT

ETFE (Ethylene Tetrafluoroethylene) membranes or differently called the transparent foil is a new material in architectural applications which makes it moderately explored by the professionals and academy. Recently it has been the selection of many pioneers that seek various alternatives in materials and techniques for increasing the building's efficiency and their Green impact on the environment. ETFE as a very light material attracts the attention of many designers for integrating them in the building. Apart from the lightness of the foil that asks for less heaviness on structural support some other properties that makes it relatively a Green selection are the lesser maintenance cost and time through their lifetime, it's 100 % recyclability, lighting transmission properties, its expanded lifetime that has increased recently by many manufacturers, its high resistivity to degradation from severe outdoor conditions etc. These up-mentioned properties have been illustrated and displayed by the case study approach and are concluded in the later sections for highlighting further those characteristics and putting into observance the parameters that need to be improved deeper for achieving a wider applicability in architecture.

KEYWORDS: ETFE (Ethylene Tetrafluoroethylene), Green, transparent foil, light material, recyclability

INTRODUCTION

The consumption of energy for the build environment is covering ⅓ of the total consumption of energy in the world. Meanwhile investigating the energy consumption for specific building cycles, figures out that 85-95% of the total energy used by building is consumed during its operation phase which raises the concern of this phase in the forefront. (K. 2010)

The material selection is a key step for improving the energy efficiency by the built environment and this selection can be measured upon the environmental impact of the material, cooperative properties among selected materials, lifespan and certainly without dimming the maintenance requirements.

ETFE results as a new material in architecture with its own limitations that is still being worked on for their improvement but doubtlessly providing its enhanced characteristics when used adequately in the building systems. They have been initially developed by DuPont in the service of aerospace industry in 1980's. (www.birdair.com 2017). Its first implementation as a building envelope started as covering for greenhouses. The first prominent buildings using ETFE foils as main covering envelope are Eden zoo project in Cornwall in 1998 than in 2006 is the construction of Allianz Arena soccer stadium in Munich, Germany and then the "water cube" in Beijing Olympics in 2008. (www.wikipedia.com 2017)

Figure 1: Eden Zoo in Cornwall, 1998 (www.pinterest.com 2017)

Figure 2: Allianz Arena Stadium in Munich (www.to-experts.com 2017)


Figure 3: Beijing swimming pool hall (www.constructionphotography.com 2017)

To all of the up-mentioned projects the quality of space and energy efficient approach are key generators of designing with ETFE cushion membranes. (www.birdair.com 2017) Some of the key characteristics of the membranes are: lightness, slenderness of supporting materials in need, complexity of the structure solved effortlessly, colourfulness, 100% recyclability, high transmissivity, high thermal insulation properties when arranged in more than one layer (inflated cushions), high temperature resistivity, low maintenance cost and low embodied energy. (K. 2010), (Kowalski W. 2016)

The objective of the study is to highlight the characteristics of the ETFE foils for acquiring energy efficiency and Green performance on the applied building. For achieving the expected outcome from the study a review on the provided literature and a thorough extraction of the fundamental properties from various implemented projects is endeavoured to be achieved. The expectation is displayed in a

retrospective paragraph referring to past literature and accomplished implementations.

OVERALL CHARACTERISTICS OF ETFE FOILS IN ARCHITECTURE PERSPECTIVE

ETFE is the abbreviation of Ethylene Tetra Fluoro Ethylene so it is fluorine-based plastic. It has been manufactured for possessing properties such as resistance to relatively high temperature variance, corrosion resistance, electrical resistance, chemical resistance and radiation resistance. (www.wikipedia.com 2017)

STRUCTURAL AND INSTALLATION CHARACTERISTICS

For the application techniques and installations there is need for a specialised group of workers. The integration of the membrane with the supporting skeleton or structure is realized by specialized labour forces which makes the unique joint connection happens. For the membranes to fit perfectly on the supporting skeleton there is need for precise design and calculations through the manufacturing process to preparation of individual elements and assemblage in the site.

The elements vary according to the character of space they are covering performance which is pretended to be acquired in the final product. They can be a single layer of ETFE membrane, double layer, triple layer, 4-layer and 5-layer membranes. From 2 layers to 5 the membrane is provided in cushion form or in stretched condition which is rarely used due to its complicated calculation on form finding. (Lombardi S. 2015), (Wu M. 2011) For the cushion elements to be constantly pressurized there is need for some helping appliances such as sensors and air pump. (Wu M. 2011)

ETFE reaches the same span dimensions with the equivalent glazing at a weight of less than 1%. Due to this feature the weight of the supporting skeleton is reduced drastically and the span between the supporters is increased enormously, approximately four times the glass covering. (Wu M. 2011) The lightweights of the membrane are associated with less time consuming through the mantling process. (Kowalski W. 2016)

OPTICAL PROPERTIES

ETFE membranes possess very high sun light transmissivity and IR radiation which enhances the greenhouse effect in the indoor space and need for advanced strategies is emerged. In the case of multiple membrane cushions optical characteristic is dependent on the

curvature of the last ETFE layer of the multi-layered membrane. (Lombardi S. 2015) The intensity of solar radiation can be controlled by: multi layered cushions, printing on film, colour in the mixture of polymers and additional shading elements installed between the layers. ETFE has ability to transfer long wave radiation of electromagnetic waves (IR), a feature which is not possessed by the glass, so due to this reason it behaves differently compared to the glass and there is no calculation machines that provide results for the effect of IR into them. (Lombardi S. (2015) Combination and optimization of opaque surfaces and transparent ETFE membranes would enhance the qualities of the space in terms of lighting. (Masih D. 2015)

THERMAL PROPERTIES

ETFE as a thin material possesses low thermal resistance as its thickness varies from 0.1-2 mm. (Lombardi S. 2015) Providing air cushions of ETFE would reduce the heat transmittance to acceptable levels. A Triple layer of ETFE cushions perform close to the glazing characteristics by improving the U-value to 20%. In the tables below are displayed the ETFE thermal transmittance properties when the layering of the cushion changes and glazing topologies & characteristics as a matter of comparison.

Table 1: U-value of different layer cushions (Lombardi S. (2015)

ETFE layer cushions	**U-value (W/m2 K)**
2 layer	~2.95
3 layer	~1.96
4 layer	~1.47
5 layer	~1.18

Table 2: U-value of different glazing types (www.yougen.co.uk 2017)

Glazing layers	**U-value (W/m2 K)**
Single layer	~5
Double layer	2.2 - 1.2
Triple layer	1 - 0.6

The two factors that affect the thermal resistance of the cushions are the convection (heat transferred through air circulation) happening within cushions and surface resistance of each of the layers towards the thermal flow. By printing on surface of ETFE the total g-value (solar radiation transmitted by a material in this case the ETFE foil) can be reduced to a level of 0.48 and by using triple layer of ETFE it is reduced to 0.35. (Lombardi S. 2015) In the figure 4 are shown some different printing textures on membranes which possess specific lighting transmittance coefficient.

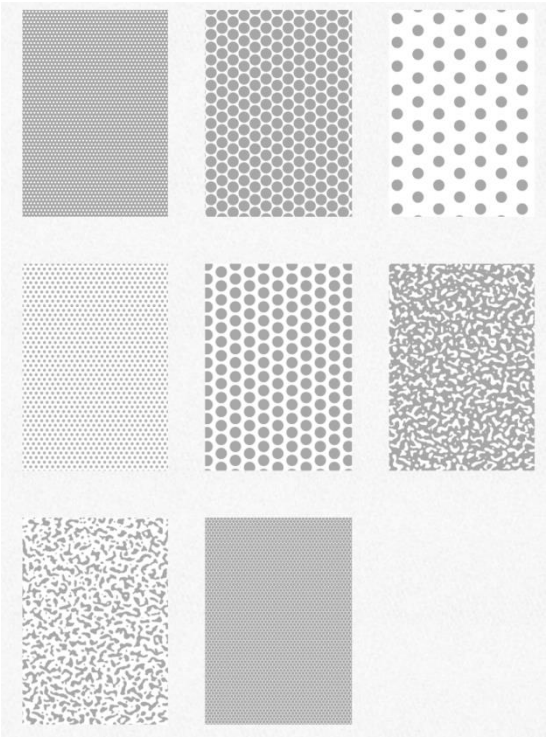


Figure 4: Printing textures on membranes

ACOUSTICAL PROPERTIES

At low frequencies ETFE fully transmits the sound while at middle and high frequencies it absorbs at most 30% of the sound generated and reflects most of it. It has deficiencies in many aspects while the sound that is produced from within the ETFE covered space can be easily transmitted to the nearby facilities and buildings and the sound

generated outside can rapidly penetrate through. Also, the raindrops cause drumming noise within the space which has been an important challenge for manufacturers to be fixed. In general, the drumming effect is reduced by rain shield noise suppressors which in general are applied on outermost layers. In the figure below is shown the application of sound suppressors in ETFE cushions.

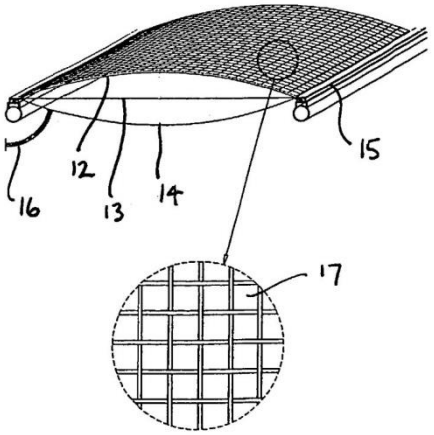


Figure 5: Influence of acoustical suppressors in rain drop damping. (www.google.com 2017)

In the figure 6 is shown the effect of the sound suppressors in the acoustical performance.

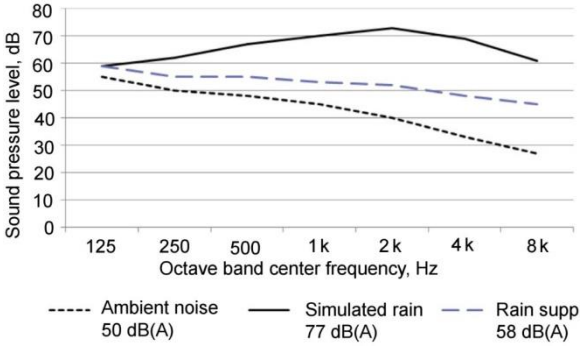


Figure 6: Influence of acoustical suppressors in rain drop damping.

In some cases, the manufacturers are producing triple layered cushions where a plexiglass and an interior perforated pillow is incorporated within the ETFE cushion system. Past researches have

shown that ETFE membrane with noise suppressors for the rain drumming effect is highly approaching the performance of glass surfaces in terms of acoustics reflectance and absorbance. (Chiu S. 2015)

In spaces with background noise such as environments with a couple of machines working within, helps in reduction of background noise because of being acoustically transparent, this works in low frequency noises. (Chiu S. 2015)

The main milestones to be accomplished at some of the implemented projects is the reduction of the noise caused by the raindrops by analysing the rain flow rate, droplet size, surface area of the acting rain and velocity of the droplet. Some of the currently experimented solutions that would fix the acoustical effect induced by rain droplets are the addition of an extra covering layer, adding an insulating layer in the middle of the air filled cushions and reducing tension to the outer most layer by increasing damping. Some of the factors that should be taken into account from acoustical point of view during the design of the ETFE membrane are the transit systems such as aircrafts, vehicular, rail, watercraft. The reaction of the membrane to the noise acting on it is directly related to the design of the membrane. (Chiu S. 2015)

APPLICATION OF ETFE IN ARCHITECTURE, A SERIE OF REPRESENTATIVE REALIZED PROJECTS

DOLCE VITA TEJO LISBON, PORTUGAL

Dolce Vita Tejo Shopping Center after construction completed in 2009 was the biggest shopping mall in Portugal in city of Madeira and the first shopping center where ETFE is been used. Designed by RTKL, London in co-partnership with Promontorio, Lisbon this project has a building area of 46000 m2. (www.facadeworld.com 2017), (www.architizer.com 2017) The structure of the building is reinforced concrete covered with an ETFE roofing membrane, the integration of the system was one of the objectives of the project. There are totally used 346 cushion elements with approximate dimensions of 10m x 10m. Is been used 200000 m2 of different ETFE membranes for the whole covering. (www.ptprojects.co.uk 2017), (www.gravidade.pt 2017) To realize the objectives of having an inside well enlightened space and good performance on heat exchange the designers proposed distinctive coating systems (high performance selective filters) on ETFE inflated cushions integrated with low-E treatments of the layers. The north light

was preferable for this project and the need for shading elements was provided by well-coordinated coatings. (K. 2010) By maintaining the design integrity a considerable reduction in cost was achieved. By the three dimensionality of the cushions and several different coatings and treatments the principle for achieving the “north light” was fully realised and eliminating the direct unwanted light and glare effect was met (Lombardi S. 2015) One of the effects of the interior is that it gives the impression as the walk is happening outside in the natural air and light due to the effects of the lighting strategy and slenderness of the structure.

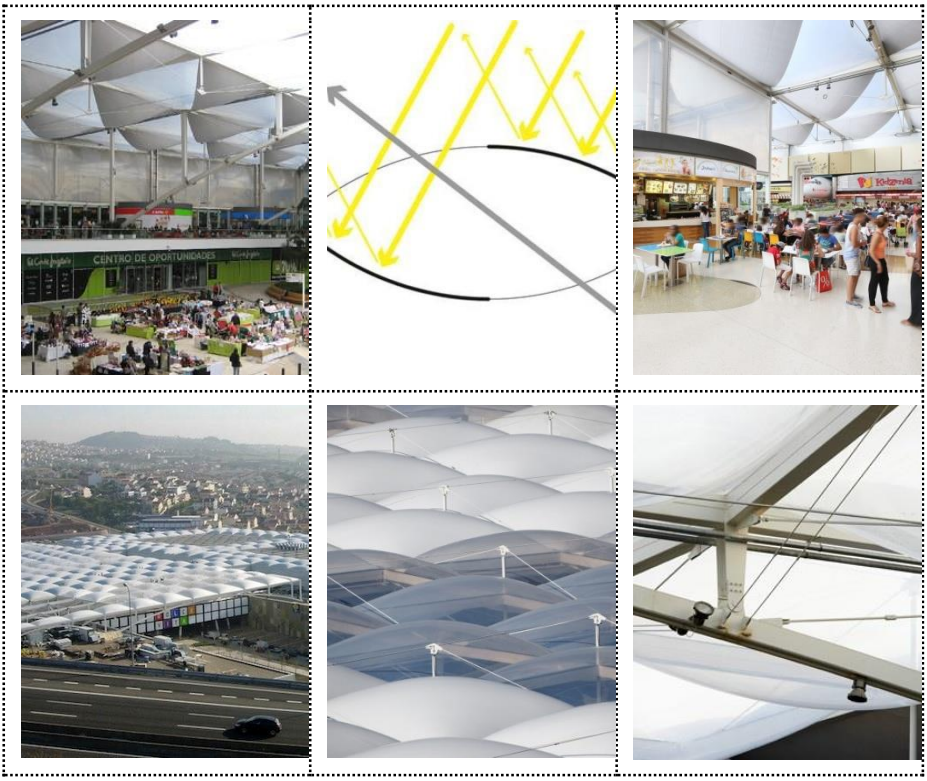


Figure 7: images of Dolce Vita Tejo shopping mall from the interior, exterior, joint details, from the top and sketching showing the special properties with respect to daylight control. (www.pragma.pt 2017)

GERONTOLOGY TECHNOLOGY CENTRE, BAD TOLZ

Located in South of Germany the Gerontology technology centre is the first building where is been used in facade a single layer of ETFE transparent film constructed in 2003. It is a spiral building which is

comprised by a shopping area on the ground floor and office space on the upper floors. One of the most inspiring characteristics of this building is the walkway between the outer facade made of ETFE and the glazing of the interior. The space between the glazing and ETFE acts as a buffer zone with its own physical characteristics. The space can be ventilated by the upper and lower parts of glazing.

Figure 8: Figures of Gerontology technology center in Bad Tolz from inside and outside the double skin facade. (www.kochmembranen.com 2017)

The total area of the ETFE facade is 1550 m2 and is completely a pre-stressed layer supported by very slender elements. Apart from being the first case that a single layer of ETFE is used in building facade it is also the first case that an ETFE film is been used as the outer skin of a double facade system. The sun protection and light scattering is provided by the silver dot fritting surface applied on the foil. The life of the membrane is expected to reach more than 20 years if the material is treated as on specification. The ETFE is flame retardant and due to

the minimal thickness, that accompanies the material the danger for elements falling in case of fire is diminished. The optical impact provided by the membrane is impressing and possessing unique characteristics. (Knaack U. 2009), (www.kochmembranen.com 2017)

NEUES GYMNASIUM BOCHUM, BOCHUM, GERMANY

Construction finished in 2012. The atrium consists of an under-floor heating system and is lit from above by 1000 m2 roof doom. The covering is made by triple ETFE layers spanning on very slim steel structure. To be protected from much sun and from glare effect generated on sunny days the outer film of the membrane was printed from inside without reducing the lighting properties of the atrium. The triple layer possesses very good thermal insulation properties which makes it an appropriate material for this specific case.

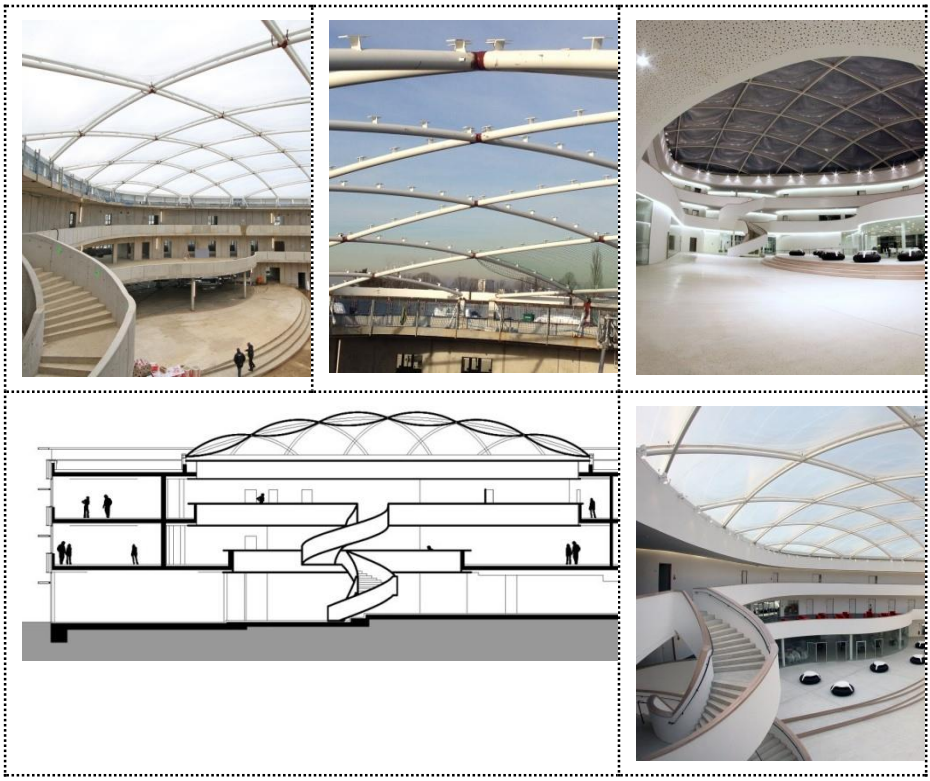


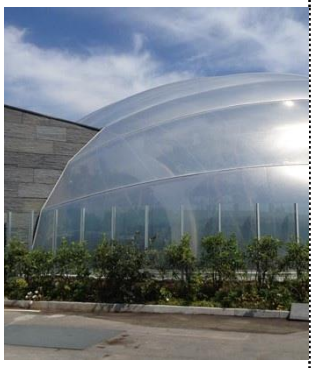
Figure 9: Figures and section of Neues Gymnasium Bochum in Bochum from outside showing the structure of the atrium foils. (www.neues-gymnasium-bochum.de 2017)

MULTIPURPOSE DOME AT FORUM HOTEL IN VERONA

It is a multipurpose dome shaped building at the forum hotel in Verona. It is a building where the state of art of automotive systems is been used for increasing the energy efficiency in the indoor environment. This is one of the first cases of buildings totally covered with ETFE cushions in Italy. The main purpose of the area is for meeting hall or just for relaxation. The winter garden has an ellipsoidal shape and a curved envelope. The structure of the building is composed of concrete foundation where the wood arches are fixed on. Over the wood structure is been fixed the tubular steel profiles where the ETFE membrane is sticked on with the help of aluminum profiles. The distance between the arches is 4.5 m and the maximum span of the arches is 27.2 m and they cover a total area of 625 m2. On the two sides of the ellipse are concentrated the technical room and in the other side the entrance as the two poles of the structure where the steel secondary structure ends up.

The ETFE structure is inflated by a suitable machine that adjusts the pressure into the cushions according to the climatic conditions. The cushions are made of 4 foil layers.

Cushions are also printed differently according to their position in the structure for controlling better the internal climate. The cushions positioned at the top of the structure have a very dense printing concentration and they reduce while they fall aside till the last element that is positioned at the lower base that is perpendicular which is fully transparent. To arrive in this solution engineers and architect have done several experiments for optimizing the printing on the ETFE membrane. On the top of the whole structure are provided openings for natural ventilation as skylights in case of very high temperatures.



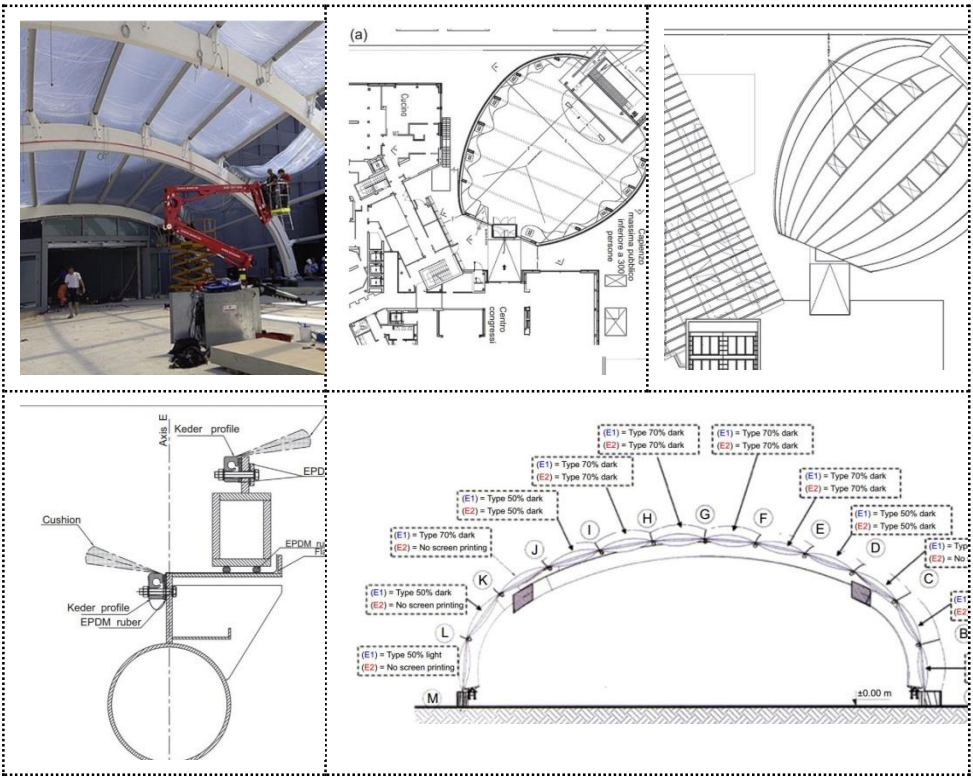


Figure layout 10: Figures and drawings showing the interior, exterior, the application details and structural member positioning. (Lombardi S. 2015)

The represented projects are shown intentionally to highlight the potentials of ETFE foil material that can be managed through several different techniques and structural combinations. Starting from its first implementations in architecture the ETFE foils found space only on greenhouse coverings then spread exponentially in larger projects when the foil inflated cushions were discovered. In the first Dolce Vita Tejo shopping mall the characteristics of ETFE are the managing of the overall covering with ETFE which would require slender supportive structure and the integration of the foils with several treatments for enhancing the comfort parameters of the space and providing a diffused enlightened interior space far from glare effect. In the second case study the characteristics of the foils are tended to be emphasized by their application as the outer layer of the double skin facade where the intermediate space acts as a buffer zone with its own characteristics. In the third case the structural benefits and the controlled light which penetrates through the foil are the issues that characterize remarkably

the project. For the last case the purpose of selecting among others is that it is an overall representative of the application of ETFE on buildings because every part of the structure is covered by the foil and the performance of the material in an enclosure is comprehended thoroughly.

DEFINING THE SPECTRUM OF APPLICABILITY BY RETROSPECTIVE ANALYTICAL APPROACH

Referring on the literature provided for the ETFE foil (single layer and cushion forms or other techniques for assembling together multiple layers), the limitations which convoy the transparent membrane applications restrict the vast implementation of the material for several purposes and in different building with any various character of usage. Its limitations for providing good acoustical insulation and optical clearance in single layer and cushion applied forms, keeps it away from applicability on housing facades, office buildings and any other building character where the visual communication with the outdoor environment is fundamental. Due to these reasons the implementations are seen in large roof coverings and facades where the visual qualities have not been the primary issue for the edifice. In many cases for obtaining the best qualities in the indoor environment and dimming the greenhouse effect that is a characteristic of the materials with high U-value, the integration with other transparent glass which possesses enhanced characteristics from the optical point of view and opaque surfaces is seen as the best solution for many applications for achieving the required performance from the design selections.

Focusing on the implementations already mentioned in the previous paragraphs the ETFE transparent foils find its spectrum of applicability in enclosures where the need for reduction of the supporting materials is very essential such as the shopping malls where the huge covering of the roof top can easily be affordable and it would double the reduction of the cost of supporting structure. This not only would reduce the cost but also would give the sense of freedom to the space escaped from the massive elements that a glass supporting structure would require. By treatments of the foils with different printing techniques and integration of other systems for controlling of thermal, acoustical and lighting comfort, the energy efficiency can be increased hugely. The treatments can afford for the indoor space a diffused lighting distribution which would reduce the glare effect and overheating from direct radiation. Application of the membrane as the outer skin of the multiple layered facades happens rarely by applying a single foil

which would not reduce the optical quality if the interaction of the space with the outside environment is required.

The resistance to severe climate conditions makes the ETFE foil a good choice as an outer skin. Meanwhile the ETFE is been used as an outer envelope for many building typologies the integration of the systems with artificial lighting makes them visually attractive and this kind of systems is been used for promotion purposes related with the activities of the building. In this chapter is merely discussed about the possibilities of application of ETFE foil as an outer envelope for enclosures where the need for thermal, lighting and acoustical comfort is required and referring to these parameters is argued about the performance of the foils and their possibilities to be integrated in the system with their bads and goods and the issues for further improvement are positioned in the forefront. While the target is given on structures that need to perform as sheltering base, the ETFE foil is really a smart choice made by the designer because the performance in terms of thermal, acoustical and lighting comfort is demanded on a reduced scale upon the function of the shelter. Due to this reason the focus is concentrated on the lightness of the structural members, its maintenance and installation of the element and opportunities for applying various striking forms in the building envelope.

As a sum up in the table below is shown the adoptability of applying ETFE foils in various building topologies.

Table 3: U-value of different layer cushions (Lombardi S. 2015)

Adaptability level	**Type of building structure**
high	Roof top coverings (Atrium covering, transitory spaces between buildings, greenhouses)
	Large spanning structures (terminals, shopping malls, stadia, swimming pool hall)
	Outside sheltering structures
medium	On vertical multi layered facades as the outer layer of the buffering zone
	As material in advertisement facades integrated with lighting devices

low	On facades of housing, offices, and any other building facades where the activities last longer during the day

DISCUSSION, CONCLUSION AND FUTURE PERSPECTIVE

The spread and extension of ETFE membrane textile usage in architecture is increasing by leaps and bounds. Its 100 % recyclability makes it a very friendly material with the environment. Its cautious footprint helps a lot all the branches of design and engineering that do take part on a project to derive on much effective solutions in terms of the cost but also in the space values that are achieved by the exclusive characteristics demonstrated by ETFE membrane foils.

Exploration for lightly materials especially for high span structures and vast space coverings makes it one of the very first selections of the designers and this concern is shown in prominent examples like gaming stadiums such as Allianz arena in Munich and water cube in Beijing Olympics in 2008. Providing air inflation for the cushions that are comprised of more than one foil is a task to be executed through the usage of active devices such as air pumps, sensor etc, but new systems are being tested and performed which work completely passively by relying on exploration of the tensile strength and elastic modulus of the material.

The material's properties only by focusing in its simple form of application and treatments perform low with respect to thermal and acoustical comfort and display enhanced properties with respect to lighting, nevertheless the integration of the material in its simplest form with other systems and constellations appraise the last by-product to a high rate with special distinctive properties in the market. Recently the applications are concentrated on the rooftops or skylights where no optical performance is required and the direct light is controlled properly by the diffusive parameters of the ETFE foils induced by the air inside the cushions and the treatment (fritting, printing or coloring during production phase of the material). For improving the thermal resistance without preventing the light penetration through the ETFE layers, researches are concentrated on transparent insulation materials that would augment thermal insulation properties.

For understanding the role of the ETFE in the near future the selected projects that have been explained above are intentionally chosen for understanding the spectrum of implementation in the future of this kind of material. So the selection's objective is to display the

potentials of implementation that go beyond the roof topping or skylight for sport hall coverings and integrating them in more delicate design structures such as in double skin facades, main envelope on gathering halls, in spaces where the artificial air conditioning is a crucial issue to be solved such as shopping malls etc, so for purposes that go beyond the provision of shelter against rain and wind. As envelopes for outside structures where no parameters for thermal and acoustical comfort are required ETFE foils have been more extensively incorporated in the structures where their benefits for seeking more slender supportive elements are obviously comprehended.

Application of intelligent systems integrated in the foil structure is very compatible due to the lightweights and flexibility of the polymeric foil. In general requiring half of the elements compared with a normal glazing supportive structure makes the ETFE foil membranes to rise in the forefront of the selection pool for specific cases. As an overall by applying the ETFE transparent foils in relation to the context and in proper systems of the buildings would result in really Green solution due to the enhanced properties of ETFE for particular characteristics.

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