Review Article:
ETFE: New Sustainable Material

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Abstract

ETFE, a synthetic fluoropolymer, has been widely used in the construction industry for a few decades and is gaining more popularlity due to its versatility. This article aims to review the applications of ETFE foils in buildings as a sustainable construction material. According to literature reviews found that using of ETFE in construction can reduce the amount of raw material used, reduce building time, and reduce building costs. ETFE cushions also provide highly light-transmittance, less weight and more thermal insulation compared to glazed roofing. Examples of built projects and applications of ETFE foils are presented to show the potentials and challenges in order to improve the environmental performance of a building which may reduce the overall energy consumption.

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Keywords: ETFE foil cushions, Environment, Sustainable, Pneumatic structure

Introduction

ETFE (Ethylene tetrafluoroethylene) a lightweight material, has been known of since the 1940s when a US patent for the substance was granted to Du Pont (Schier, 1997). Architectural interest in ETFE was sparked by the first oil crisis in 1973-1974, when Europe began to focus on harvesting solar energy to replace fossil fuels. Extruded ETFE film was developed and used as a replacement for glass in greenhouses and for thermal collectors (Le Cuyer, 2008, p. 301).

Due to its high daylight transmittance (95%), ETFE was initially found to be used on projects such as zoological gardens, botanical gardens, swimming pools, and exhibition spaces. The first applications were for plant houses at Burgers' Zoo in Arnhem in Netherlands, 1981. As a result, it has been used in various buildings predominantly in the United Kingdom, Germany and other parts of Europe. Beside the most common textile membranes, ETFE is used in the application of pneumatic structures by assembling it into cushions which are inflated. ETFE cushions can provide thermal insulation, with reduced initial cost investments and fewer supports compared with a glazed roof (Robinson, 2005). Although the ETFE have a very high solar radiation transmittance (up to 0.8) which cause the primary structure below the cushions to have a high temperature, this problem can be modified by printing silver dots and increasing thickness. Furthermore, ETFE film also has a range of outstanding properties such as self-cleaning, flame retardant and a long life expectancy. It can be easily dismantled and recycled, with 100% of the used material being recycled into useable ETFE materials and products.

Nowadays, as modern membrane technology has been developed, ETFE foils have had a number of applications in buildings. The use of this kind of material is understood as sustainable design, not just in structural terms but also regarding their embodied energy, especially when compared to conventional construction.

ETFE as Sustainable Material

The advantegous physical properties of ETFE foils are outstanding; its behaviour is extremely complex and differs from other textile membrane materials (Schiemann & Moritz, 2010). In recent years, several researches were carried out to evaluate ETFE as a smart building material compared to glass. The obvious advantage of ETFE is that it is extremely lightweight (0.35 kg/m^2) and it requires less structural steel to support it. For the Eden Project in Cornwall, designed by Nicholas Grimshaw (Figure 1), each ETFE foil pillow weighs approximately 2 – 3.5 kg/m^2, which means less than 2% of equivalent glass cladding, while the entire pillow system including aluminium connection and steel frame support weighs between 10% and 50% of conventional glass-façade structure (Robinson, 2005).

Figure 1. Eden Project, Cornwall, UK. (Source: http://grimshaw-architects.com/project/the-eden-project/)

Besides the weight of material, three main aspects are focused for defining the sustainable material : lighting transmission, insulation, and embodied energy.

Lighting transmission: ETFE transmits 94 – 97% of visible light higher than those in ordinary 6-mm single glazing which is only 89%.

Insulation: ETFE foil roofing has a better rating for insulation with U value at 1.9 W/m^2K in comparison to single glazing at 6.3 W/m2K or even in double glazing 3.2 W/m^2K (Robinson-Gayle, Kolokotroni, Cripps & Tanno, 2001). The physical properties of ETFE foil compared to glass are shown in Table 1.

The another indicator to define the sustainable aspect is embodied energy (EE), as referred to Robinson-Gayle et al., the EE amount of 1 kg ETFE is 27.0 MJ/m^2 while for 6-mm float glass is 300 MJ/m^2 (Table 1). However, the obtained value for the energy embodied during the cushion manufacturing phase is about 210 MJ/kg (Monticelli, 2009), 173 MJ are due to the generation of the new materials, 28 MJ due to the polymerization process and 9 MJ for the extrusion ETFE pellets in thin films. The estimation of ETFE foil's EE is varied, as shown in Table 2, the most recent value is over ten times that stated by Robinson-Gayle, Kolokotroni, Cripps & Tanno in 2001.

Table 1. Physical properties of ETFE and glass.

Properties	ETFE foil (0.2 mm)	Glass (6 mm thk.)
Ultimate tensile strength (N/mm^2)	40 - 46	50 – 100
Yield stress (N/mm^2)	30 – 35*	-
Visible light transmission	95%	85%
Weight (kg/m^2)	0.35	14.40
U-value (W/m^2K)	1.9	6.3
Thermal Resistance (m2 • °C/W)	0.16	0.16
EE (MJ/m2)	27.0	300

*Yield stress is temperature-dependent.

Table 2. Comparison of published values of embodied energy for ETFE foil. (Source: Chilton, Pezeshkzadeh & Afrin, 2013)

Source	Embodied Energy (MJ/kg)
Robinson-Gayle et al., 2001	26.5
Fernandez, 2006	120 – 130
Ashby et al., 2007	100 – 120
Monticelli et al., 2009	210
EPD Texlon®, 2001	337.3

Towards the Sustainable Architecture

At the present time, designers have become increasingly committed to ecological concern within the built environment. Construction materials are being reassessed and redesigned to be more sustainable. ETFE foils can play an important role in sustainable architecture, according to its outstanding properties. ETFE foils offer an alternative application to building envelopes and is being considered as one of the most sustainable building material available. Hertzsch and Lau (2010) investigated the contribution of textile facades to energy efficiency and its practical application to buildings in Australia. The result revealed that ETFE offers benefits to energy-efficient building design. A comparison of the attributes of fabric materials and glass is shown in Table 3.

Attributes Sustainability issues	ETFE inflated cushions (triple layered)	PTFE coated fiberglass fabric	PTFE fabric	Double glazed unit
Light transmittance	Approx. 90% max. (83-88% of UV; scattered light 12%)	7-29%, depending on fabric thickness. Typically 65-75% is reflected and up to 8% absorbed.	20% (variable)	78% (81% single glazing)
U-value	1.9 W/m^2K (5.1 W/m^2K for a single layer system)	4-5 W/m^2K (additional layers can decrease the U-value)	4.6 W/m^2K	2.7-3.1 W/m^2K (5.5 W/m2K for single glass) horizontal application
Embodied energy	27 MJ/m^2	All architectural fabrics have been found to have a lower embodied energy compared to traditional materials	All architectural fabrics have been found to have a lower embodied energy compared to traditional materials	300 MJ/m^2
Recyclability	Yes	Yes	Yes	Yes
Weight	1 kg/m^2	1 kg/m^2	1 kg/m^2	30 kg/m^2
Primary structure (steel)	25-35 kg/m^2	30-40 kg/m^2	30-40 kg/m^2	45-65 kg/m^2
Cleaning	Self cleaning	Self cleaning but degrades over time as surface texture holds dirt	Requires regular manual cleaning	Not self cleaning
Durability	Approx. 35–40 years	20-30 years	15 years	15-30 years

Table 3. Comparison of the energy-efficiency attributes of ETFE, PTFE and double-glazed units. (Source: Hertzsch & Lau, 2010)

The study of the environmental effects of ETFE used for building cladding, conducted by Brunel University in Middlesex and Buro Happold Consulting Engineers in London, indicates that ETFE foils can improve the environmental performance of a building from two points of view; to reduce the overall environmental burden incurred by the construction process itself and is to reduce the burden of the building during its lifetime (Robinson-Gayle, Kolokotroni, Cripps & Tanno, 2001, pp. 323-327). ETFE cushions can also improve energy efficiency in buildings. High light transmission characteristics can reduce the need for artificial light during daytime, while the excellent insulating properties contribute to a building making it easier to heat and cool.

An interesting example is the Gerontology Technology Centre in Bad Tölz, Germany. The building has a double-skin façade made of ETFE film curving in two directions and spanning over four storeys (Figure 2).

The façade creates a buffer between the building and the exterior. In winter, this zone is heated up by solar radiation and diminishes the heat losses, whereas the additional screens protect from excessive solar gains and the sensor-controlled vents open during the night to cool down the activated concrete slabs of the walkways (Jeska, 2008, pp. 394-406).

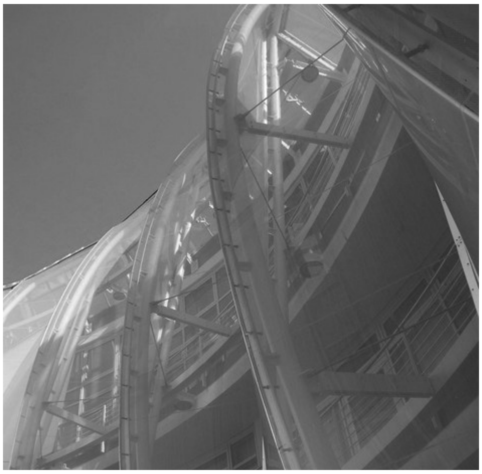
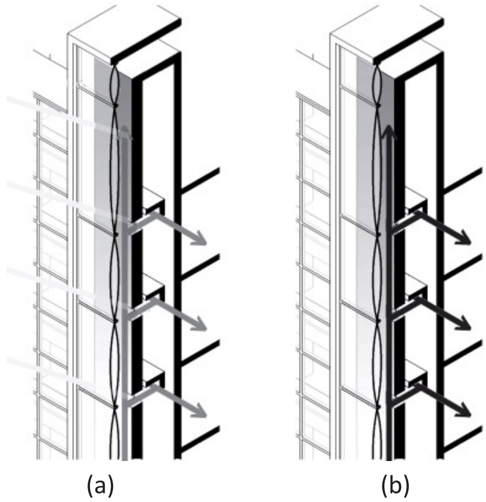


Figure 2. Gerontology Centre, Bad Tölz, Germany. (Source: Cremers, 2010)

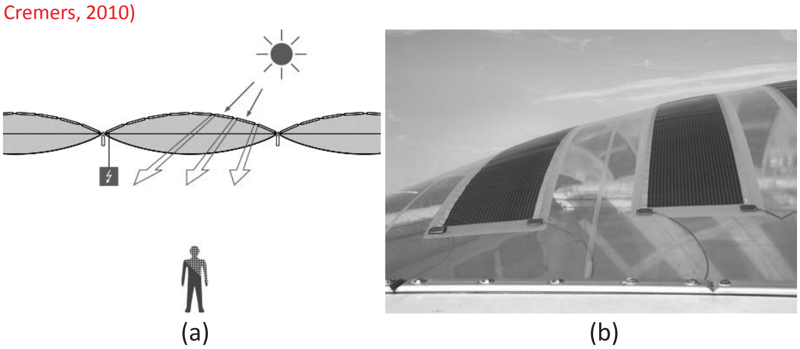
Figure 3. Proposed solar chimney for the RMIT, Melbourne, Australia. (a) solar wall; (b) heat sink (Source: Hoe, 2009)



Another inspired idea for a sustainable design solution is the solar chimney, a type of passive solar heating and cooling system that uses the sun's heat to provide cooling by using the stack effect. Due to the extremely high light transmittance of ETFE, a solar chimney can be covered with this material as shown in the proposal for a refurbishment of a RMIT University building in Melbourne, Australia (Figure 3).

The solar radiation heats up the air in the cavity, inducing the rise of the air to the upper air outlet. The use of ETFE foils can reduce the amount of glass in the façade thereby diminishing the cooling load. In winter, the system would be closed and the accumulated heat helps to reduce the heat loss, while in summer the system would be opened and the heated up thermal mass can then buffer temperature peaks and act as a heat sink as shown in Figure 3 (Hoe, 2009).

Figure 4. Flexible photovoltaic integrated into ETFE foil. (a) PV integrated in the top layer of ETFE cushion, providing shading and electrical power (b) Flexible photovoltaic integrated in an ETFE cushion of 5x5 m(Source: Cremers, 2010)



Moreover, with the current technology, ETFE films are not only providing a more sustainable alternative to glass but also a new way for self-sufficient performance. The high light transmittance of ETFE foil and long-span ETFE cushion roofs indicate that a cushion integrated photovoltaic/thermal system could have a great potential in solar energy utilization (Hu, Chen, Yang, Zhao, Song & Ge, 2016, pp. 40-51). This technology is based on extremely flexible, amorphous silicon thin-film solar cells (a-Si) laminated in the outer layer of the cushion (Figure 4). The output forecast for PV in foil is significantly more complex than for standard PV arrays because of the vary in shape in each project; the anticlastic surface which PV has to follow and the complex three-dimensional shapes that affect the shading effects (Cremers, 2010). Some recent projects were AWM carport roof and Japan Pavilion in 2010 Shanghai World Expo where a-Si PVs were integrated on ETFE cushions. This system could generate electricity for system use and provide a way of collecting thermal energy.

According to the research conducted by Jianhui Hu (Hu, Chen, Zhao & Song, 2014, pp. 394-406), a series of tests were conducted under winter and summer weather conditions to evaluate the solar energy utilization. It was found that the average stored electricity was 61 Wh and the average ratio of consumption of electricity to output electricity under sunny conditions was lower than that under sunny to cloudy conditions. Whereas, an average temperature difference between air temperatures inside and outside of the cushion was 18.1 °C. This study provides a way to expand the application of building integrated photovoltaic/thermal to cushion structures.

From an architectural perspective, photovoltaic elements do not only generate electricity, but they also provide shading which reduces heat gains in the building and helps to minimize cooling-loads and energy demand in summer. This was indicated in a report by the International Energy Agency (IEA) which gives an estimation of the building-integrated photovoltaic potential of 23 billion square metres. This would be equivalent to approximately 1000 GWp at a low average efficiency of 5% (International Energy Agency [IEA], 2004).

Conclusion

ETFE foil is a widely used material in architecture nowadays. It's applications can be used as building's envelope in single or multi-layer cladding. All structural applications of ETFE foils are subjected to tension force through pre-tension or inflatation, in order to be able to resist the external loads. The most used ETFE cushions are designed for skylight and atrium where glass would traditionally used. Nevertheless, ETFE foil has several advantages over glass, it is much lighter and requires less support structures which means less energy consumption. Furthermore, ETFE cushion not only allow more transmission of visible light, but are also better insulators than glass panels because of the air pocket(s) contained between the layers of foil.

Several techniques of design and research are carried out, such as the application to solar chimney or technical integration of the PV-ETFE cushion structure system, in order to improve the environmental performance. Most of the studies indicate that ETFE foils can reduce the overall environmental burden of buildings where sustainability is becoming increasingly important. There are three distinct sectors in which sustainability can be effected and enhanced: environmental sustainability, economic sustainability and social sustainability (Maywald & Riesser, 2016). For environmental sustainability, the ETFE foil can be considered as a more ecological solution than glass because it requires much less energy than glass production and needs fewer structure materials to support the whole system. While the use of ETFE as cladding system contributes to cost savings due to reduction in structure, maintenance and installation costs which can be considered as economic sustainability. ETFE cladding structures also offer social sustainability by creation of large and comfortable environmental inner spaces for people to meet and work. Therefore, dealing with ETFE in terms of sustainability is a new approach towards future development and particularly challenging for the construction industry.

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