E3S Web of Conferences **22**, 00048 (2017)
ASEE17
DOI: 10.1051/e3sconf/20172200048

Dynamic environmental control mechanisms for pneumatic foil constructions

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Abstract. Membrane and foil structures have become over the last decades an attractive alternative to conventional materials and building systems with increasing implementation in different typologies and scale. The development of transparent, light, flexible and resistant materials like Ethylene Tetrafluoroethylene (ETFE) has triggered a rethinking of the building envelope in the building industry towards lightweight systems. ETFE foil cushions have proven to fulfil the design requirements in terms of structural efficiency and aesthetic values. But the strategies to satisfy increasing demands of energy efficiency and comfort conditions are still under development. The prediction and manipulation of the thermo-optical behaviour of ETFE foil cushion structures currently remain as one of the main challenges for designers and manufacturers. This paper reviews ongoing research regarding the control of the thermo-optical performance of ETFE cushion structures and highlights challenges and possible improvements. An overview of different dynamic and responsive environmental control mechanisms for multilayer foil constructions is provided and the state of the art in building application outlined by the discussion of case studies.

1 Introduction

The energy performance of the building envelope is becoming increasingly important since the building sector is held responsible for more than one-third of the worldwide energy consumption, according to the International Energy Agency. Dynamic environmental control mechanisms in building envelopes are a common strategy to balance between the reduction of solar heat gains and achieving good natural illumination while reducing energy consumption for cooling and artificial lighting at the same time. The integration and automatization of these mechanisms into complex fenestration systems and high-tech building facades has become a reality and opens possibilities for further optimisation of the energy performance and improvement of comfort conditions in the built environment. Responsive building envelopes can adapt to changing environmental conditions, or user demanded requirements and enhance the performance of the building. The developments in mechatronics, sensors and computer technology during the last decades, have made possible miniaturisation, mass production and successive cost reduction, which have

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allowed designers to integrate sensors and actuators into building elements making them truly responsive to the environment and occupant needs.

Pressurised multi-layered cushions of thin Ethylene Tetrafluoroethylene (ETFE) foil are increasingly applied in building envelopes and are now considered state of the art since the contributions of Frei Otto initiated the evolution of lightweight building over sixty years ago [1]. Lightweight and transparent materials play an important role in this development and ETFE is probably one of the most outstanding. ETFE has become a true alternative to glass and other transparent materials mainly because of its excellent material characteristics like low weight, flexibility, high translucency, tensile strength and good weathering performance. However, the thermal and optical behaviour of ETFE multilayer cushions is somehow still a topic of ongoing research, and the difficulty of predicting their energy performance has led in the past to reported problems of overheating of indoor spaces during summertime. Dynamic environmental control systems, including responsive shading mechanisms, could be a possible solution for the negative effects of overheating and glare, but despite their broad application in complex fenestration systems, they have not yet arrived at the same level of development in membrane and foil constructions. Advances in controlling the optical and thermal properties of the cushion system through, mainly, static adaptation measures are now common practice in the industry. Currently, the most widely used techniques are frit prints of reflective inks and combinations of different layer type compositions. However, these techniques are not sufficient during peak climatic conditions, and the integration of dynamic environmental control mechanisms into multilayer ETFE cushions remains a design objective alongside multiple approaches from the past. In search for technical solutions to respond to pressing environmental issues, new building techniques and materials are under constant development for more efficient and better performing building envelopes [2]. The following literature review is an attempt to provide an overview of the latest developments and state of the art in the building sector of membrane structures regarding the environmental control of multilayer foil constructions.

2 Building envelopes of ETFE

ETFE foil has been increasingly employed as a building material for building envelopes over the past decades [3]. Although used initially because of its high transparency only for temporary agricultural coverings and greenhouses, ETFE is now a recognised alternative for conventional transparent building materials such as glass [4]. The acceptance of the material among designers and the building industry can be attributed mainly to its excellent properties like transparency, flexibility, tensile strength and robustness towards weathering [5]. Since the first application of ETFE foil in a permanent building for the Mangrove Hall project in Burgers' Zoo, Arnheim, Netherlands in 1982 [6], important technological advances have been made. New form-finding methods and simulation software, as well as automated production and manufacturing processes together with a highly specialised design industry, have contributed to its widespread use in building envelopes. The absence of homogenised design codes and standardised testing methods remain as an obstacle, but ETFE coverings are now considered to be a reliable and safe solution for performance orientated building envelopes [7]. Recent iconic building projects like the Eden Project in St. Austell, UK (2000) (Fig. 1.), Allianz Arena in Munich Germany (2005) and the Water Cube swimming pool in Beijing China (2008) exemplify the outstanding performance and architectural attractiveness of ETFE as a building material [8, 9].

Fig. 1. Eden Project, St. Austell, United Kingdom (2000).

ETFE as a material for building envelopes is normally employed as an extruded thin foil in multilayer cushions which are pneumatically stabilised structural systems. The cushions can be composed of various layers of foil with air chambers in between. These foils are cut and welded together according to pre-calculated optimal shapes of equilibrium state. The foil cushion is clamped into a rigid frame system, typically of extruded aluminium profiles, inflated with air and maintained by means of a blower system at a predetermined pressure which enables the system to withstand external loads and maintain geometric stiffness. The number of layers of the cushion can vary in order to improve the structural or thermal resistance of the system. The foil thicknesses may also vary, according to the expected loads. Different tints or printed patterns can be applied, in response to the thermal and optical requirements [10].

Different building systems for ETFE foil are currently in use, but according to a case study from Moritz in 2007 [11], ETFE is most commonly employed in pressurised multilayer cushions systems (87%) and significantly less in mechanically pre-stressed single layer systems (10%), which however are getting used more often in recent years. According to the study ETFE is generally used in buildings related to occupancy for offices and housing (28%), swimming pools (18%), exhibition spaces and pavilions (15%). The building elements usually covered by ETFE are atria (35%), hall roofs (33%), canopies (14%) and building facades (8%) among others, ranging in a covered area between 100 and 10000 m². The predominant cushion geometry found in the analysed projects was reported as rectangular (60%) within a range of other hexagonal, triangular, circular or rhombic geometries. A comprehensive study by Schiemann [12] about the structural behaviour of ETFE foils proposed a classification of cushion systems according to the layer number and configuration which also is of interest to the understanding of the building physics regarding optical and thermal performance. Several experimental designs with different layer build ups and combinations of materials have been carried out so far [13, 14], including novel double layer ETFE panels which are pretensioned by heat shrinking and don't require an internal air pressure [15]. Nevertheless, few of these novel systems have been tested in any commercial construction so far.

Even though the majority of studies on ETFE have focused in the past on the structural efficiency of the building system, recently the interest in current research has been shifted increasingly towards the energy performance of ETFE envelopes.

3 Responsiveness in textile building envelopes

Active or responsive building envelopes are commonly referred to as shelter systems which can adapt autonomously, using sensors and actuators, to changing environmental conditions, or user and activity demanded requirements [16]. While the concept is not entirely new, as can be learned from several historical examples, like the Roman velarium or Venetian blinds, the idea of autonomously self-adapting buildings has emerged only recently [17], fulfilling the technological innovations envisioned by modernist scholars like Sigfried Ebeling almost a century ago [18]. The development of environment responsive membrane structures with automated mechanisms is indeed very recent and although several projects are reported in literature most of them are prototypes or of an experimental nature [19]. A schematic diagram of the functional relations of a responsive building envelope incorporating a dynamic shading mechanism within a multilayer ETFE cushion is shown below (Fig. 2).

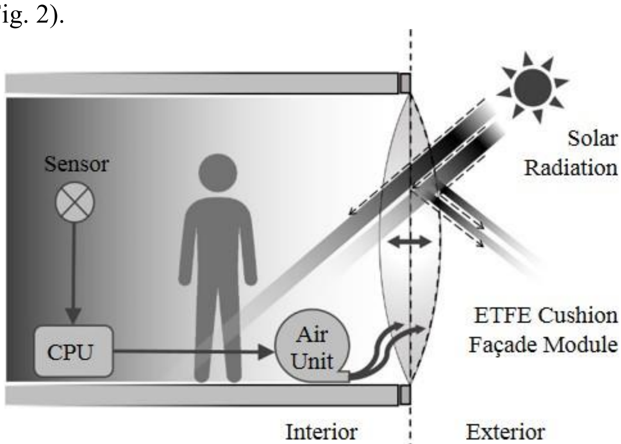

Fig. 2. Schematic diagram of a responsive building envelope incorporating a dynamic shading mechanism within a multilayer ETFE cushion.

4 Dynamic environmental control mechanisms for multilayer foil construction

True adaptability to indoor requirements and outdoor climate conditions is in this sense a relatively new approach as well for ETFE cushion systems considering the advances which have been made with other materials or building systems like, for example, retractable textile membrane structures, glass and complex fenestration systems. This could be owing to the fact that ETFE has been in use for only a relatively short period as a construction material but it is also related to its very distinctive physical characteristics which are still in the process of being investigated. A variety of different environmental control strategies have been developed for multilayer foil constructions (Fig. 3). But very few systems have been tested so far in commercial buildings.

The currently most widely used active mechanism for ETFE cushions is a triple layer system which employs positive and negative, reflective printing patterns on the middle layer and the inner or outer layer. These printed layers fit exactly when overlapped, covering a 100% of the cushion surface. The middle layer position can be moved by the control of the air pressure within the cushion chambers, making it geometrically overlap, either with the inner or outer layer. This allows adjustment to achieve a partial percentage of light translucence or total coverage, depending on the layer position (Fig. 4). This mechanism has been reported in several studies [3, 9, 10, 20–22] and was first employed in a building for the World Exposition pavilion “Duales System Deutschland (DSD) Cycle Bowl” in Hannover, Germany in 2000 [8, 9, 23]. The project comprised an 1800 m² active shading façade composed of a triple layer system with positive/negative frit patterns. In the same year another innovative building complex, the “Festo Technology Center”, an office building with a 2655 m² roof structure of triple layer ETFE cushions was constructed in

DOI: 10.1051/e3sconf/20172200048

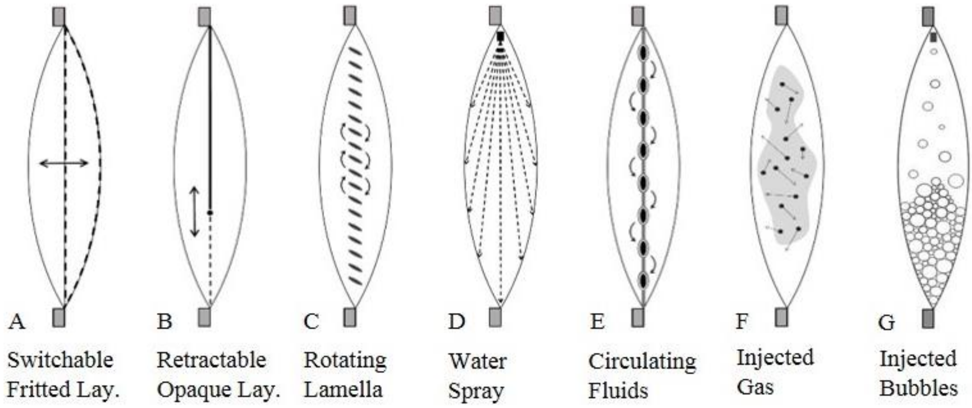

Fig. 3. Environmental control mechanisms for multilayer foil constructions.

Germany, and later in a scaled version for a branch project in France. A similar system as in the DSD project was employed, with the same mechanism of a switchable middle layer, but with a different frit pattern. In this case, the frit pattern was laid out as a squared checkerboard pattern. This project was followed by the "Kingsdale School" project in the UK in 2004, where a courtyard was covered with a dynamic ETFE roof which employed a rectangular frit pattern (Fig. 5). Several other projects incorporated the same or a similar mechanism in recent years and are listed below (Table 1). In addition to the mechanism mentioned above, very few alternative systems have been applied in commercial buildings. Retractable opaque middle layers have been employed in a 56 m² ETFE skylight of a gas-station in Munich, Germany in 2004 [24]. Venetian blinds have been incorporated into membrane envelopes only in a few built projects. One case is the Association for Medical Information (GFI) in Munich-Riem, Germany, built in 2003, which incorporates solar shading lamellas inside the air chamber of a triple layer cushion covering an area of 120 m² [25]. The Media-Tic building in Barcelona, Spain built in 2009 is an experimental building which integrated the above discussed dynamic triple layer shading mechanisms into the façade. In the same building, a novel shading mechanism based on gas injection was used for the first time, where the solar transmittance of the cushion was modified by pumping nitrogen into the air chambers of the ETFE cushions [9, 22].

Recently, there has been a spate of interest in the more unconventional mechanism, incorporating spray, liquids and bubbles as a strategy for dynamic environmental control mechanisms at an experimental stage. Mainini et al. investigated the influence of water spray on the thermal performance of a mechanically pre-stressed double layer ETFE panel as a strategy for reducing solar heat gains on building facades during summer climate conditions [26].

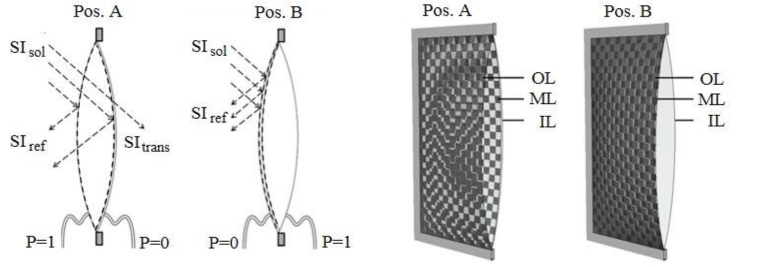

Fig. 4. Dynamic triple layer shading mechanism for pneumatic foil constructions, functional diagram and rendering of section in perspective view.

 DOI: 10.1051/e3sconf/20172200048

Fig. 5. Project Images: Duales System World Exposition Pavilion, Hannover Germany; Festo, Paris, France ; Kingsdale School, London, United Kingdom (left to right), source: © Vector Foiltec, http://www.vector-foiltec.com (accessed 30th April 2017).

Table 1. List of projects incorporating multilayer foil constructions with integrated dynamic environmental control mechanisms.

Project Name	Building	Application	Mechanism	Area m²	Year
Duales System World Exposition	Pavilion	Façade	A	1800	2000
Festo Technology Center	Office	Roof	A	2655	2000
Association for Medical Information (GFI)	Office	Roof	C	120	2003
Kingsdale School	School	Roof	A	5000	2004
Pasadena Art Center	Cultural	Skylight	A	690	2004
Allguth GmbH Service Center	Gasstation	Skylight	B	56	2004
The Mall Athens	Mall	Roof	A	-	2005
Archibald Vivian Hill Building	Research	Roof	A	547	2007
ZEP Leisure Park	Multiuse	Skylight	A	-	2009
JinSo Pavilion	Restaurant	Roof	A	600	2009
Lancaster University, ISS Building	University	Skylight	A	-	2009
Media-TIC Building	Office	Façade	F	2500	2010
St. Bartholomew's Hospital	Hospital	Roof	A	405	2013
RCS Pavilion EXPO2015	Pavilion	Skylight	A	72	2015
Urban Algae Folly EXPO2015	Canopy	Roof	A	-	2015
Mechanism Type (referring to Fig. 3): A – Switchable fritted Layer, B – Retractable Opaque Layer, C – Rotating Lamella, F – Injected Gas					

The effectiveness of different spray nozzles in relation to the thermal performance of the ETFE panel was tested. However, it was found that the system performance improvement was rather limited, as the water spray, while effectively reducing the surface temperature of the foil, had only a small influence on the mean radiant temperature. This was mainly attributed to the fact that water is a weak absorber of solar radiation. The effectiveness of the system was therefore strongly reliant on the volume of water sprayed on to the foil. Previously a study with a similar approach had been carried out [21]. The evaporative cooling effect of water on the middle layer of a triple layer foil construction was investigated. This study found great potential in improving the thermal behaviour of foil constructions with water. Numerical calculations and experiments under laboratory

 DOI: 10.1051/e3sconf/20172200048

conditions showed a reduction of the inner layer surface temperature of up to 5°C. Other research projects have explored the possibility of achieving environmental control of multilayer foil constructions with tinted fluids [27]. The fluids are circulated in pre-formed channels in-between the foil layers of the cushion. The system is switchable from a transparent to a translucent state. This is achieved by changing the tint concentration of the circulating fluid. The system is able to modify the light transmission but also has the capacity to absorb and remove heat from the cushion. A general U-value of 0.64 W/(m²K) was calculated for the system. The optical performance was tested according to DIN EN 410 and showed a absorption of 95.7%, a reflection of 4.3% and a solar transmission of nearly 0% using a 7.5% black tinted fluid. A similar system was used for a showcase pavilion construction at the Milan EXPO 2015 [28]. But instead of tinted fluids, an algae substrate was pumped through the ETFE panels. The algae substrate would filter eventually the solar radiation and absorb part of it and provoke photosynthesis of the algae. The growth of algae enhances a biological self-regulating effect on the shading performance of the canopy structure. Another highly experimental mechanism was tested for double layer foil constructions in greenhouses where for thermal and solar control soap bubbles where injected into the air chamber [29]. This allowed the system to be switched from the initial transparent condition to a highly insulated and light scattering state. Prototypes have been built and the thermal performance of the system was investigated. The results of CFD simulations showed that liquid bubbles can improve the performance of greenhouses. The temporary increase of the thermal insulation with liquid bubbles reduces the energy demand for heating in winter and the risk of overheating during the summer season [30].

5 Conclusions

A variety of environmental control mechanisms for multilayer foil constructions has been outlined and their function and application in building envelopes has been discussed through a range of case studies. It can be concluded that besides the perceived fascination in the public opinion about adaptive building envelopes and energy saving façade systems the topic of the dynamic shading mechanisms for multilayer cushions appears to be neglected by systematic research studies. Even though mentioned in several studies, the building physic aspects of dynamic foil constructions have not been addressed thoroughly. Nevertheless, they are continuously applied in new construction beside the vagueness of understanding of their influence on the energy performance of buildings. There have been very few published reports directly addressing the problem of the thermal and optical behaviour of these systems and their effect on the energy performance of buildings remains as a research objective. This represents a risk and opportunity at the same time, which needs to be addressed and which bears great potential for improving the system performance of both, building and envelope. It is believed that a thorough understanding of the systems' optical and thermal behaviour is indispensable to predict and assess their effectiveness in controlling the climatic factors, enhancing occupant comfort conditions and improving the energy performance of the building. Literature provides only limited information on the effectiveness of the reviewed systems. An explicit description of their optical and thermal properties and the complex physical mechanisms of light and heat transfer are available only to a very limited extent.

This initial review can only be the first step towards a broader understanding of dynamic environmental control mechanisms for multilayer ETFE cushions. More data from monitoring of operating buildings is required as well as new approaches towards the simulation of their dynamic behaviour with numerical calculation methods. Great potential is seen in these tasks for further research.

Acknowledgements

This work was supported by the Faculty of Engineering at the University of Nottingham through a PhD studentship awarded to Jan-Frederik Flor.

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