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Daylighting Performance in an Atrium with ETFE Cushion Roof and in an ETFE-Encapsulated Panel Structure

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Abstract

This paper presents the results of the field work on the luminous environment conducted in an atrium enclosed by an ethylene-tetra-fluoro-ethylene (ETFE) cushion roof and a test structure constructed with ETFE-encapsulated panels. In addition to the on-site monitoring, theoretical parametric studies using a scaled physical model of the ETFE panel structure were undertaken to further investigate the lit environment created by changing the transparency of the test structure envelope. The aim is to explore how the typical homogeneous and dull luminous environment can be improved. Subjective appreciation of the lit scenes and quantitative analysis results are compared and discussed. This study concluded that selective use of translucent and opaque components in the ETFE enclosures can offer opportunities to create well balanced, yet dynamic lighting conditions. Also selective positioning of these components in different parts of the ETFE structures can help improve modelling effect and enhance visual perception.

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Keywords: ETFE cushion and encapsulated panel envelope, field study, theoretical parametric analysis, luminous environment, visual comfort.

1. Introduction

In recent years the application of lightweight transparent/translucent membrane and ETFE foil in buildings has increased and diversified. ETFE foil is increasingly being applied in the form of multi-layer inflated cushions or single and double-layer tensioned surfaces as either primary or secondary building façades where the associated

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lighting conditions and visual environments need to be better understood. In comparison to more conventional glazing materials, ETFE foils are in general highly transparent and more responsive to external environmental stimuli like incident solar radiation. Structural behavior and material properties of ETFE foil have been well researched. However, its impacts on the visual and luminous environment are relatively unexplored. This paper aims to fill this research gap.

2. Description of buildings and the building envelope

2.1. Case Study A

This three-storey Engineering and Science Learning Centre (ESLC) at the University of Nottingham containing student support office, graduate center, learning and teaching spaces and a multi-functional central atrium was designed by Hopkins Architects, UK, and completed in 2011. The atrium roof consists of three-layer ETFE cushions with fritted top layer (200µm), transparent middle layer (150µm) and bottom layer (150µm), which are edge clamped in extruded aluminum frames connected to the primary steel truss structure. The geometry of this building has an arc-shape in plan with a central atrium of 330 m^2. The atrium roof provides daylight for all the internal spaces. A glazed aperture on the top part of the south west façade offers supplementary daylight and the building envelope is protected by horizontally attached louvers that help to reduce both solar gain and glare on the glazed façades (see Fig. 1).

Fig. 1. The external and internal views of the ESLC Building

2.2. Case Study B

The test structure with ETFE-encapsulated panels (two-layer 150µm ETFE foils) as external skin was built at the garden of a detached house near Grantham, UK, and it is being used as ‘an outdoor room’ and a greenhouse for plants throughout the year. This structure is supported by an aluminum structural frame infilled with ETFE panels of different sizes and it measures 6.5m in length by 4.1m in width (see Fig. 2).

Fig. 2. The external and internal views of the Test Structure with ETFE encapsulated panels

3. The on-site monitoring process and findings

3.1. On-site monitoring for Case Study A – The Engineering and Science Learning Centre

The field work was carried out under mainly overcast sky conditions. The objective is to, firstly, investigate the daylighting performance in the atrium covered with ETFE cushions and secondly, to find out the luminous characteristics of this atrium in terms of visual appearance and brightness contrast. A hand-held digital illuminance meter was used to measure the internal and external daylight level at 1 meter above finished floor level for calculating the Daylight Factor (DF) and generating the DF isolux contour map. For the luminance distribution and contrast analysis, a digital camera was used to capture the images of the lit scenes and then the images were converted into luminance maps by using a luminance conversion software.

3.2. Results and Discussion on the daylighting performance and visual perception for Case Study A

The measured daylight illuminance shows high values in the central part of the atrium and relatively low values near the atrium edges (see Fig. 3 c). The average internal illuminance was 2736 lux in comparison to the external illuminance of 4500 lux, while the highest value inside the space was 4000 lux and the minimum value was 854 lux. This significant brightness variation is due to the fact that the side walls surrounding the atrium do not allow daylight ingress. The average daylight factor in the ESLC atrium is 60.8% which indicates an excessively daylit space. The high central luminous zone and low peripheral luminous edges here indicate a non-homogeneous daylight distribution pattern and this is confirmed by the low Uniformity Ratio of 0.3.

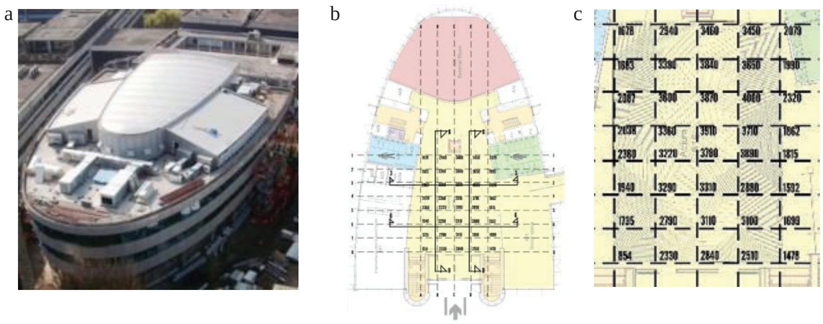

Fig. 3. (a) Aerial view of the ESLC Building; (b) ESLC Building plan with measurement grid; (c) Daylight illuminance data measured on site.

Luminance mapping of selected views inside the ESLC was conducted under overcast sky condition and Fig. 4 indicates the luminance distribution patterns measured in the selected views a and b. As shown in View a, the luminace ratio between the ETFE roof and the wall surface underneath it is about 20:1. This indicates a high brightness contast which makes architectural details on the wall become invisible. In View b, the luminance distribution pattern is rather flat and this does not enhance either the visual interest or modelling effect inside the atrium. As a result, a dull visual appearance is perceived. This is mainly caused by the fact that in the atrium of the ESLC building, the side walls on the lower floors do not allow much daylight to enter the hub of the building. The transparent ETFE roof brings in large amount of directional top light which makes it difficult to perceive the architectural details inside the atrium. Also the diffusing properties of the fritted ETFE roof further exaggerate the homogenous lighting condition, resulting in insufficient modelling in the field of view.

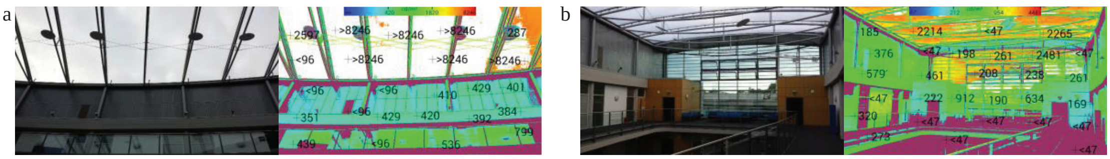

Fig. 4. (a) View looking at a part of the top floor and the ETFE roof; (b) View looking at the top floor

3.3. On-site monitoring for Case Study B – The ETFE-encapsulated panel test structure

The field study was carried out during the summer of 2014 by following the same on-site monitoring procedure used in Case Study A. The daylight illuminance readings were taken in the afternoon between 5:00 and 6:00 PM under overcast sky conditions.

3.4. Results and Discussion on daylighting performance and visual perception for Case Study B

The measured daylight illuminance values and the associated daylight illuminance isolux contour map is shown in Fig. 5. It was observed that the maxiumim illuminance value inside the test structure was 1171 Lux and the minimum value was 478.7 Lux. The average illuminance was 919.5 Lux, and the average DF was 56.4%, which also indicates an excessively daylit space. The calculated Uniformity Ratio is 0.7 which indicates a homogeneous luminous environment inside the test structure.

Fig. 5. The Daylight Isolux Contour Map and the internal view of the Test Structure with ETFE-encapsulated panels

Luminance mapping of selected views inside the test structure was conducted and Figure 6 indicates the luminance distribution patterns in the selected views under overcast sky conditions. Both images show relatively homogenuous luminance patterns in the field of view which again, indicate a rather flat visual appearance and relatively small luminace range. The perceived low brightness contrast in the field of view also indicates inadequate modelling effect. The results from the above two case studies support the previous research findings that the perception of objects in three dimensional sense is closely related to the modelling effect of light flux and that the diffusing properties of the translucent building skin tend to cause insufficient modelling effect in the ETFE structures and produce an uniform lighting condition [1,2]

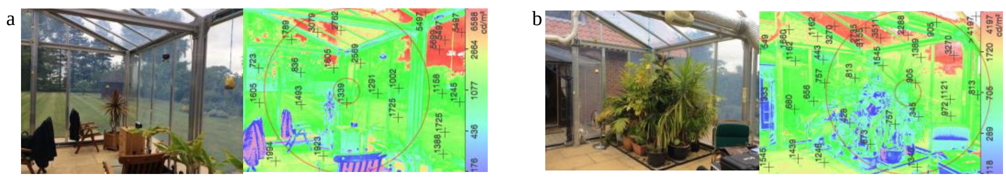

Fig. 6. The internal views a and b of the Test Structure with luminance maps showing selected luminance values (unit: cd/m²)

4. Parametric study by physical modelling to improve the luminous environment in the test structure

In order to explore how the visual environment inside ETFE-enclosed structures can be improved, a 1:20 scale model with the same dimensions as the existing ETFE-encapsulated test structure was constructed and tested under both overcast sky condition and sunny sky conditions. A comparative study based on 10 different types of roof and wall combinations were tested to identify the best performing option and then this was compared against Case 1 (existing test structure) in terms of daylighting performance and three dimensional modelling of the objects positioned inside the test structure model. Fig. 7 shows the selected 4 cases and the last case (Case 4) has been identified as the best case for daylighting performance and modelling effect.

Fig. 7. The selected 4 cases out of the 10 tested cases. Case 1 is the existing test structure, and Case 4 on the far right is the best performing case

4.1. Results and Discussion on improving the luminous environment inside the test structure

Although the daylighting performance in Case 1 and Case 4 show a similar trend, the luminance pattern in Case 4 shows a much wider luminance range, and the subjective visual appearance and the modelling effect of the objects in this case (especially the two cylindrical columns positioned at the far left hand corner of the test structure) are significantly better than that of the Case 1 (see Fig. 8). This improved luminous environment is mainly due to the selective application of combined translucent and opaque components in the test structure which bring in top light and sidelight and the interaction of these two key light sources creates a dynamic, yet balanced luminous environment.

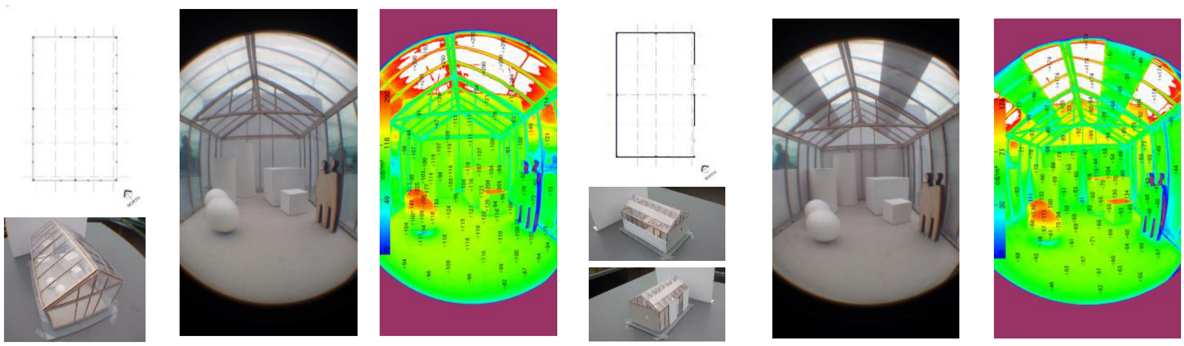

Fig. 8. The plan, top view, internal view and the luminance map of Case 1 and Case 4

5. Conclusion

The on-site monitoring data obtained from the field study provide quantifiable evidence to assist the understanding of the subjective visual appearance of the dull and uninteresting luminous environment inside the ETFE enclosed structures. The typical homogeneous lighting condition may be useful for some general activities, but for performing a special visual task, better visual clarity and modelling are required. Also visual interest created by controlled brightness contrast can enrich the occupants' visual experience. As demonstrated in the parametric studies undertaken in this study, by careful manipulation of the transparency and opacity in the ETFE structures, much enhanced visual perception and modelling can be achieved, For performing a special task or tasks inside an ETFE-covered enclosure, other than the typical uniform lighting condition, there is a need to design appropriate luminous environments under which we would ideally operate, and which would best facilitate and enhance the performance of the task [3]. Flexibility and quality of light, not absolute quantity, are the essentials of achieving this goal.

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