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Understanding Light in Lightweight Fabric (ETFE Foil) Structures through Field Studies

Benson Lau*, Dawa Azad Aziz Masih, Abdulquadri Adesoji Ademakinwa, Siew Woon Low, John Chilton

Department of Architecture and Built Environment, Faculty of Engineering, University of Nottingham, Nottingham, NG7 2RD, United Kingdom

Abstract

This paper presents an experimental approach to investigate the luminous environment in lightweight fabric structures through field study. Buildings selected for the field study included the Engineering Science Learning Centre at the University of Nottingham and the Clarke Quay in Singapore.

By undertaking on site monitoring under different sky conditions in the chosen buildings with distinctively different site context, this research project explores how the typical homogeneously lit and rather dull luminous environment in lightweight fabric structure can be improved for enhanced visual interest, visual comfort, and three-dimensional modelling under both sunny and overcast sky conditions. Research data obtained from the subjective appreciation of the internal luminous environments and the quantitative spot measurement and mapping of light are compared and discussed.

This study concluded that selective use of transparent and translucent components in the ETFE envelope can offer architectural designers the opportunities to create well balanced, yet dynamic lit scenes. Also by combining single skin ETFE foil and the double or triple layered ETFE cushion and introducing ETFE cushions with different light transmittance to the building envelope can help improve the overall visual and luminous environment and enhance task illumination. The key findings from this research work are applicable to the design of light in lightweight fabric structure in general.

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Keywords: Lightweight Fabric Structures; ETFE cushion and foil, Luminous Environment; Field work.

* Corresponding author. Tel.: +44 (0) 1157484011; fax: +44(0)115 95 13159
E-mail address: Benson.Lau@nottingham.ac.uk,

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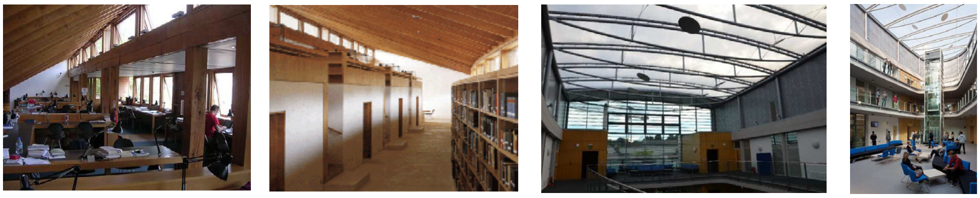
1. Introduction

Unlike more widely used heavy weight structures, which have perceptible brightness contrast in their internal spaces with relatively dark ceiling and brightly lit walls and floor (Figure 1 a & b), the luminous environment in tensile fabric structures is normally the opposite, with low brightness contrast and relatively uniformly illuminated ceiling, walls and floors (Figure 1 c & d). However, whether this kind of appearance is considered in itself to be good or bad will depend on the site context, the building programme and the function of the space. The perception and readability of the internal environment in these structures is dependent on the optical properties of the buiilding materials – the way they reflect, absorb or transmit visible light [1]. Thus, our understanding and design of the luminous environment in tensile fabric and ETFE foil-covered structures cannot be just based on the recommended illumination level alone. Designers need to understand the unique characteristics of the lit environment in these structures and strive to create interesting and well-balanced lighting conditions to suit the function of the space under the luminous roof and enhance task performance and visual comfort. By careful and well thought through manipulation of light, shadow and contrast, a lit scene which yields the required information and enhances visual perception can be created [2].



(a) (b) (c) (d)

Fig.1. (a & b) Darwin Library, University of Cambridge; (c & d) Engineering Science Learning Centre (ESLC), University of Nottingham.

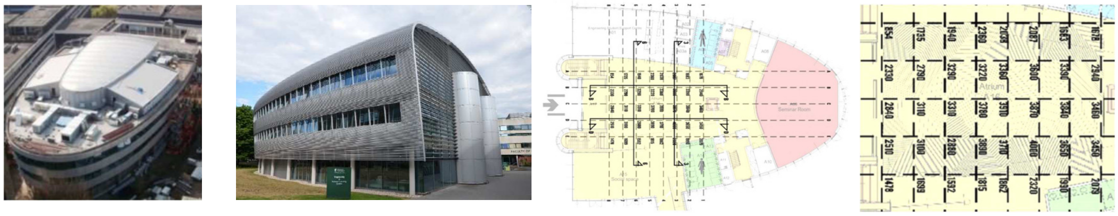
2. Field Studies

In order to have a better understanding of the luminous environment under the lightweight fabric enclosure, field studies through spot measurements and light mapping were undertaken in two buildings: the Engineering Science Learning Centre at the University of Nottingham and the Clark Quay in Singapore.

2.1. Case Study A: Engineering Science Learning Centre at the University of Nottingham

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

2.1.1. On site monitoring – Overcast Sky Condition



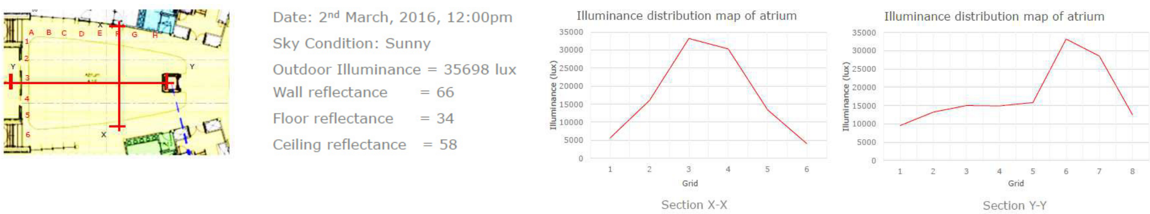
(a) (b) (c) (d)

Fig.2. (a & b) Aerial and side view of the ESLC Building; (c & d) daylight illuminance data measured under overcast sky condition

The measured daylight illuminance distribution pattern and data under overcast sky condition and on a measurement grid set at 800 mm above finished floor level is presented in Figure 2 c & d. The pattern shows high values in the central part of the atrium and relatively low values near the atrium edges. 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 homogeneous light zone in the center of the atrium, but non-homogeneous daylight distribution pattern across the section of the building. The low Uniformity Ratio of 0.3 also confirms this lighting condition.

2.1.2 On site monitoring – Sunny Sky Condition

The measured daylight illuminance distribution pattern under sunny sky condition is presented in Figure 3 c & d. Similar light distribution pattern was identified with a peak in the central part of the atrium and low daylight illuminance towards the atrium edges. The average internal illuminance at ground level was 12791 lux while the highest and the lowest value were 33180 lux and 4030 lux respectively compared to external illuminance of 35698 lux. This shows that the ETFE cushion roof transmits about 93% of the outdoor illuminance into the atrium, which brings in abundance of natural light in this space. Figure 2 shows the on-site monitoring details and illustrates the illuminance distribution curves in the atrium across section x-x and y-y respectively.

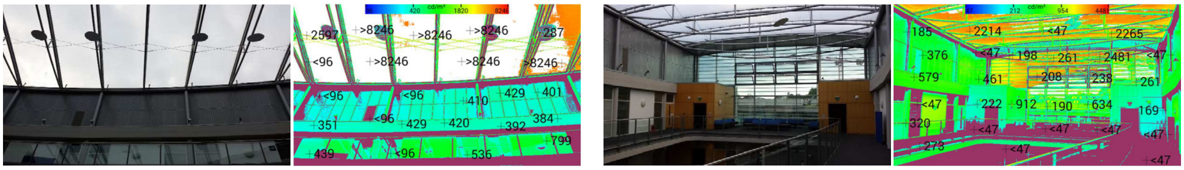


(a) (b) (c) (d)

Fig.3. (a & b) ESLC Building Plan with axis x-x and y-y; (c & d) daylight illuminance distributions in the atrium across section x-x and y-y

2.1.3. On site monitoring – Luminance mapping results and discussion

Luminance mapping of selected views inside the ESLC was conducted under overcast sky condition and Figure 4 shows the luminance distribution patterns measured in the selected view A and B. The luminance values were recorded by using Photolux, a luminance mapping software and measured in cd/m². As shown in View A, the luminace ratio between the ETFE roof and the wall surfaces underneath it is about 20:1. This indicates a high brightness contast which makes architectural details on the wall become invisible (Figure 4 a & b). In View B, the luminance distribution pattern is rather flat with poor modelling effect inside the atrium, which leads to a dull visual appearance. This is due to the side walls on the upper floors do not allow much daylight entering 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. In addition, the diffusing property of the ETFE roof further exaggerates the homogenous lighting condition, resulting in insufficient modelling in the field of view.



(a) (b) (c) (d)

Fig.4. (a & b) View A with luminance pattern and mapping data; (c & d) View B with luminance pattern and mapping data

2.2. Case Study B: Clark Quay in Singapore

The redevelopment of Clarke Quay consists of 2 distinctive areas; which are alongside Singapore River promenade, and the internal streets and central courtyard of Clarke Quay. Over 100 “Bluebells” created by 4m and 5m diameter PTFE canopies resembling flower covered the water front (Figure 5 a). A series of spiral truss columns are arranged zigzag along the internal streets leading to the Central Square; to support 18 numbers of huge “angle” ETFE canopies (Figure 5 b & c). The ETFE structure at Clarke Quay shelters four pedestrian streets with shops, bars and restaurants that are connected to a sheltered centre courtyard. The ETFE structures have 80% light transmittance at the centre (double skin cushion), and 98% around its periphery (Single skin ETFE foil canopy). The ETFE cushions consist of 2 layered foils: 200µm top layer with fritted leaf pattern and 150µm transparent bottom layer. Large gaps between the ETFE canopies and the roofs of the adjacent buildings were intentionally provided for more daylight admission and enhancing natural buoyancy ventilation. The single skin canopy edges overlap the existing building edges to offer rain protection.

(a) (b) (c)

Fig.5. (a & b) Aerial and street view of the ETFE structure at Clark Quay; (c) Clarke Quay ETFE structure at 15m above ground (source: Archinet)

2.2.1 On site monitoring – Luminance mapping results and discussion

By adopting similar on site monitoring procedure used in Case Study A, this field study focused on a more detailed luminance mapping. Images of view A (sheltered courtyard) and B (sheltered street) captured at 10am, 1pm, and 4pm on clear and overcast sky days were converted into luminance maps using Photolux to examine luminance distribution pattern (Figure 6 a). In this study, adjacent and non-adjacent surround were delimited by 2 cones of 60 and 120 degrees respectively to define luminance values to be considered for brightness contrast analysis. Object within 10˚ from the view point is considered task of the visual range [3]. Cones for task and adjacent peripheries are outlined in red in all luminance images in this paper (Figure 6 c, Figure 7&8). Contrast ratios of task to adjacent and remote surfaces at the existing environment are tabled and compared.

It was observed that overshadowing effect the existing buildings together with the amount of insolation attributed to lowest luminance value at 10am and the highest at 1pm under both clear and overcast skies. Lower luminance values were observed at view B (close-up view) than at view A (far distance view) at all times (Figure 7&8). This is because shaded environment was captured in close-up photos; while photos taken at far distance show more sun exposure. Brightness contrast between task to the adjacent darker surround, task to the adjacent lighter surround, task to the remote darker surfaces, sky to the adjacent surfaces, and ETFE foil to the adjacent surfaces were studied under both sky conditions. All luminance ratios were found within IES recommendation (Table 1).

(a) (b) (c)

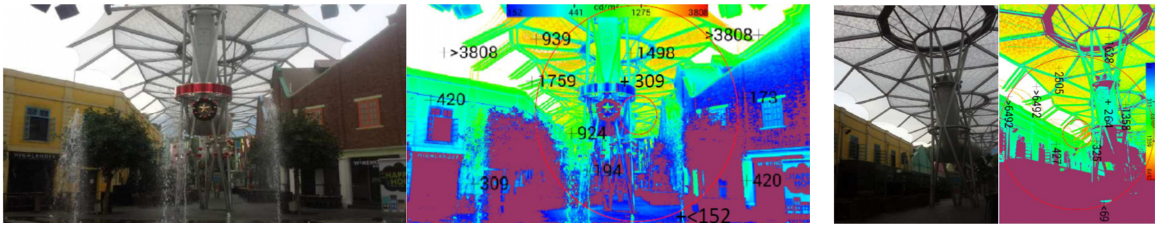
Fig.6. (a) Aerial view of the ETFE structure at Clark Quay with Viewing Angle A&B indicated on the photo; (b) Internal view of the ETFE canopy (c) Definition of Task, Adjacent surround and non-adjacent surround (source: redrawn by author after Robbins, 1986)

Table 1: measured luminance ratios derived from on-site monitoring under clear and overcast sky conditions

Luminance ratios	IES recommended maximum luminance ratios	View	Time on 22 December 2015 (clear sky)		
			10:00am	1:00pm	4:00pm
Task : Adjacent darker surroundings	3 : 1	A	1.4 : 1	1.6 : 1	1.8 : 1
		B	1.5 : 1	1.2 : 1	1.2 : 1
Task : Adjacent lighter surroundings	1 : 3	A	1 : 1.6	1 : 2.6	1 : 1.6
		B	1 : 3	1 : 2.7	1 : 1.3
Task : Remote darker surfaces	10 : 1	A	5.5 : 1	4.9 : 1	6.3 : 1
		B	5.5 : 1	5.4 : 1	5.1 : 1
Luminaries (sky) : Adjacent surfaces	20 : 1	A	17.2 : 1	18.2 : 1	14.8 : 1
		B	16.7 : 1	17.4 : 1	18 : 1
Luminaries (ETFE) : Adjacent surfaces	20 : 1	A	3.1 : 1	8.1 : 1	7.2 : 1
		B	8.1 : 1	12.2 : 1	7.2 : 1

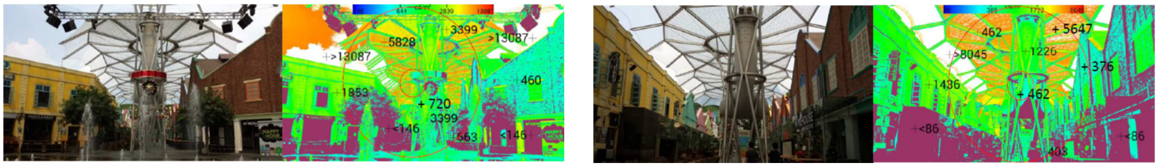
Luminance ratios	IES recommended maximum luminance ratios	View	Time on 24 December 2015 (overcast sky)		
			10:00am	1:00pm	4:00pm
Task : Adjacent darker surroundings	3 : 1	A	1.5 : 1	1.8 : 1	1.7 : 1
		B	1.3 : 1	1.2 : 1	1.4 : 1
Task : Adjacent lighter surroundings	1 : 3	A	1 : 2.3	1 : 3	1 : 2.7
		B	1 : 2.8	1 : 3	1 : 1.2
Task : Adjacent lighter surroundings	10 : 1	A	5.1 : 1	2 : 1	2.3 : 1
		B	6.1 : 1	4.7 : 1	6.4 : 1
Luminaries (sky) : Adjacent surfaces	20 : 1	A	14.1 : 1	12.3 : 1	11.5 : 1
		B	15.1 : 1	20 : 1	11 : 1
Task : Remote darker surfaces	20 : 1	A	6.3 : 1	5.7 : 1	5 : 1
		B	5.6 : 1	7.7 : 1	6.9 : 1

Highest luminance (13087cd/m²) was observed at the sky at 1pm during clear sky day (Figure 8); however people are more likely to tolerate high level of glare in an external daylight environment. Facade of buildings adjacent to the ETFE structure received close to 100% daylight through the perimeter foil (98% daylight transmittance); therefore the luminance ratio between the task and the adjacent lighter surrounding was about 1:3 (Table 1). Shading and low insolation at 10am attributed to low luminance at 28cd/m² (overcast sky); and 45cd/m² (clear sky). Luminance values under overcast sky were 70% lower than clear sky condition due to different cloud coverage (Figure 7). However luminance ratios during overcast day were lower by a fraction than clear sky. Brightness contrasts between the task and the sky at 10am, 1pm, and 4pm were high but within the tolerated ratio under both clear and overcast skies (Table 1); hence the visually interesting luminous environment are perceived under the ETFE canopy in Clark Quay.



(a) (b)

Fig.7. (a) View A at 1pm under overcast sky with luminance pattern and mapping data; (b) View B at1pm under overcast sky with luminance pattern and mapping data



(a) (b)

Fig.8. (a) View A at 1pm under clear sky with luminance pattern and mapping data; (b) View B at1pm under clear sky with luminance pattern and mapping data

3. Conclusion

The results from this study indicate that the ETFE roof with no variation in transparency as shown in the Engineering Science Learning Centre at the University of Nottingham tends to induce less interesting and homogenous luminous environment. For achieving an intended interesting lit scene, it will involve the exploration of different prototypes simulating the site condition on specific date, time, sky condition and direction of light. More importantly, it will require the designers to consider the composition and variation of transparent and translucent components in the building envelope so that more dynamic and visually stimulating indoor environments can be achieved. The ETFE structure at Clarke Quay has demonstrated that a mixture of single ETFE foil and double ETFE cushions with light transmittance of different percentage can improve luminance contrast and better modelling effect, as a result, enhanced visual experience can be perceived.

Homogeneous luminous environment is suitable for activities that require uniform daylight distribution; such as reading or painting, but for activities that demand visual interest and light contrast, non-homogenous daylight distribution can help produce visually interesting luminous environment. The results obtained from the field studies in Clarke Quay show limited improvement for enhancing visual comfort and perception is required. This may due to the design of the ETFE structure was well thought through; perhaps the daylight testing and simulations on different prototypes performed during the design stages help predict and improve the intended luminous environment at Clark Quay [4]. During the design process, it is crucial to conduct numerical and performative simulations so that the predictive outcomes could help verify to what extent varying parameters could influence the visual comfort in the proposed building.

For performing a task or tasks inside a fabric or foil-covered enclosure, other than the homogeneous lighting conditions, there are appropriate luminous environments under which we would ideally like to operate, and which would best facilitate and enhance the performance of the task. The consideration on visual interest, subjective perception and quality of light, not absolute quantity are essential for achieving a well-designed luminous environment in tensile fabric structures. The analysis and findings presented in this paper can be applied to the design of lightweight fabric structure in general.

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