

## The Berkeley glass pavillion

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### Abstract

The Berkeley hotel in Knightsbridge, London, is scheduled to be under refurbishment in the near future. As part of the works, it is planned to build a new entrance canopy / glass pavillion designed by Rogers Stirk Harbour and Partners. This paper describes the design, testing and construction of the pavillion, focusing on its carbon fibre composite structural members and its innovative glass-honeycomb sandwich panels that were specially developed for this project.

**Keywords:** Carbon fibre, composite, glass, honeycomb, stainless steel.

### 1. Introduction

The Berkeley hotel in Knightsbridge, London, will undertake some refurbishment works in the near future. The main part of these works is the demolition of the current entrance area and its adjacent rooms, and the construction of a new glass pavillion designed by Rogers Stirk Harbour and Partners.

As shown in Figure 1, the pavillion consists of a 28.5 m x 10.0 m glazed roof and canopy covering the entrance area and the extensions of the Blue Bar and Caramel Room, both clad with glass walls.

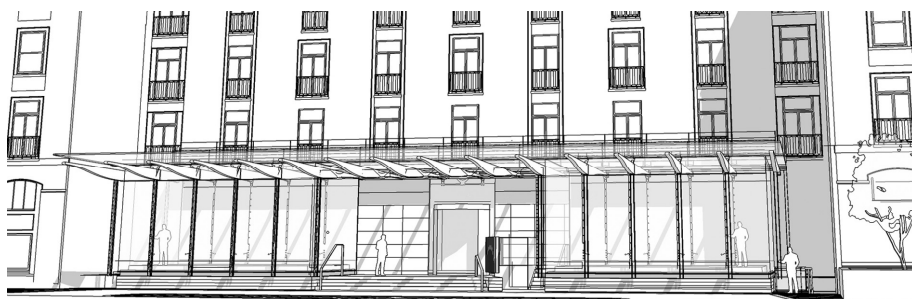


Figure 1: Sketch of the pavillion (courtesy of RSH+P).

All roof and lateral wall cladding is composed of glass-honeycomb sandwich panels specially developed for this project, whereas front walls are cladded with conventional insulating glass units.

The glass-honeycomb sandwich panels consist of two thin glass skins structurally bonded to an aluminium honeycomb core, obtaining a stiff and relatively light panel with a peculiar translucent look. Triple glazing is used in both wall and roof cladding enclosing internal spaces in order to neutralise the thermal bridge caused by the honeycomb.

All glass panels are supported by a simple isostatic structure made up of beams and columns. However, it must be pointed out that some of the main structural members were designed in carbon fibre reinforced polymer (CFRP) with a high quality surface finish.

## 2. Structure

The pavillion structure consists of sixteen free-form CFRP beams, measuring 10 metres in length, that are connected to the building at one end and to a stainless steel (SS) column at their mid point, creating a 5 metres cantilever over the car stop. In the entrance area, the SS columns are replaced by a 9.5 metres long truss formed by two stainless steel chords and a set of CFRP V-shaped brackets acting as diagonal members (see Figure 2).

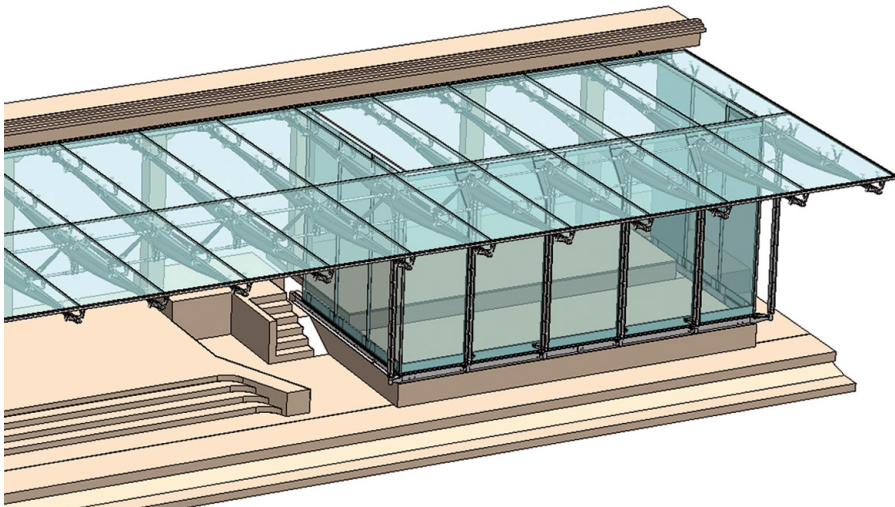


Figure 2: Structure of the pavillion.

The CFRP beams are spaced 1.9 m centres and cover both the canopy area and the internal spaces. Therefore, all front wall glass panels are cut in a special shape that allows the CFRP beams to cross the front walls through glass joints. This shape also permits the front wall panels to tilt inwards without any collision to any structural member, which is essential for future glass replacements.

The bottom of the columns is supported by a number of stainless steel fins welded to a continuous stainless steel channel which extends along the perimeter of the two rooms.

This channel is in turn supported by an internal carbon steel structure which also supports the floor of the Blue and Caramel rooms, at an approximate height of 1 m above the street level.

Bracing is entirely provided by the front wall and roof glazing. In fact, four front wall glass panels are structurally connected to the roof glazing and to the bottom channel and columns, acting as shear walls which impede the pavillion to swing in longitudinal direction. Swing in transversal direction is not possible as the CFRP beams are directly connected to the concrete structure of the building. Finally, bracing in the plane of the roof is provided by the roof and canopy glass panels.

The accidental situation in which one corner column and its adjacent shear wall panel are lost (i.e. due to a car accident) was analysed in order to determine its impact in the lateral stability of the structure and in the behaviour of the central door truss.

### 3. Carbon fibre composite beams and brackets

The CFRP beams (see Figure 3) were designed to carry significant permanent and imposed loads according to BS 6399 [2,3,4] with relatively small deflections. Therefore, the top and bottom areas of the beams were designed as 17.6 mm thick chords composed of unidirectional carbon fibres oriented in longitudinal direction ( $0^\circ$ ) whereas lateral areas are 7.6 mm thick laminates with fibres oriented in four different directions ( $0^\circ$ ,  $\pm 45^\circ$  and  $90^\circ$ ). An epoxy matrix was used in all areas. In order to provide the required high quality surface finish, the complete beam was covered with a carbon fibre weave.

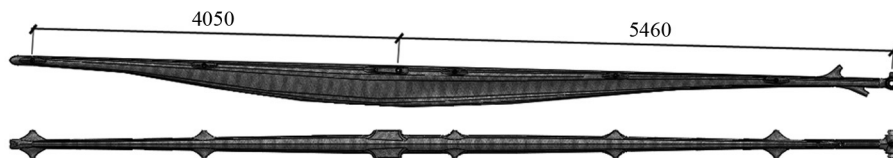


Figure 3: Sketch of a carbon fibre composite beam.

The connection to the stainless steel structure was solved by using threaded stainless steel inserts bonded to the beam with a specific epoxy adhesive. The total weight of the 10 m long beam is 162 Kg (128 Kg without SS inserts).

The beams were fabricated by means of a manual lay-out of the carbon fibre prepregs on two 10 m long carbon fibre moulds, each corresponding to one half of the beam plus overlap flaps. Then, the two moulds were joined together and a plastic bag was inserted in the empty space inside the beam. Vacuum was created between the bag and the moulds and the whole assembly was cured in an oven for 18 h at  $70^\circ\text{C}$  and an additional 6 h at  $95^\circ\text{C}$ . Temperature in the thicker areas of the laminate was monitored and used as an input signal by the computerised control of the oven.

After that, the beam was removed from the mould, the SS inserts were bonded on it and a final post-curing thermal cycle in the oven was carried out in order to reach the desired

mechanical properties and glass transition temperature of the laminate. Finally, the beams were polished and coated with a satin-finished transparent varnish.

The fabrication of the CFRP V-brackets was similar, although these elements were cured in an autoclave at 95 °C and 2.5 atm for 10 hours, approximately.

The design of the CFRP elements was performed in accordance to Cripps [5]. The resistance of the beams in ultimate limit state was verified using a combination of the Tsai-Wu, maximum stress and maximum strain criteria, while maximum deflections in service conditions were agreed with the client's consultants using BS 5950 [1] as a reference. In addition, 10% of the layers in the beam unidirectional top and bottom chords were oriented in  $\pm 45^\circ$  and  $90^\circ$  directions in order to guarantee that no creep would occur according to MIL-HDBK 17 [7].

The structural performance of the CFRP beam was assessed by carrying out three different loading tests on the full-size prototype beam. This prototype was instrumented with strain gages and beam deflections were measured using computerised depth gages, as shown in Figure 4. Test results were compared to predicted values obtained from the finite element models used for design and showed a reasonably good agreement. In addition, loading tests were also carried out for the CFRP V-brackets.



Figure 4: Full-size prototype beam during testing.



#### **4. Glass-honeycomb composite panels**

The required thickness of façade and roof glass panels is defined by their maximum stresses and deflections which in turn are function of their stiffness. This is specially important in roofs, where self-weight deflections might be determinant for the thickness. Therefore, it is always interesting to find a way to increase the stiffness of a glass panel without increasing its weight.

On the other hand, for privacy or design reasons it is sometimes interesting to use translucent glass panels which allow light to enter in a building while not showing what is happening in it.

The glass-honeycomb composite panels are intended to solve these two problems. They are composed of two sheets of glass structurally bonded to a microperforated aluminium honeycomb core by means of a continuous layer of UV-curing transparent acrylic adhesive, creating a true structural composite panel with a peculiar translucent look, as shown in Figure 5.

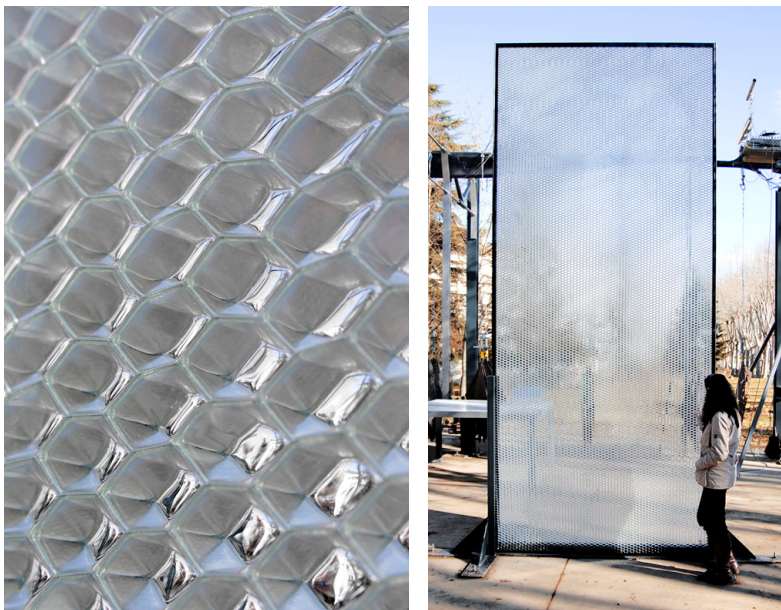


Figure 5: Glass-honeycomb composite panel.

In fact, during fabrication the liquid adhesive climbs on the honeycomb by capillarity creating a concave meniscus in each honeycomb cell that is solidified during curing. Therefore, the cured panel is composed of an array of acrylate lenses, two per cell, that distort the images transmitted through the panel (see Figure 6).

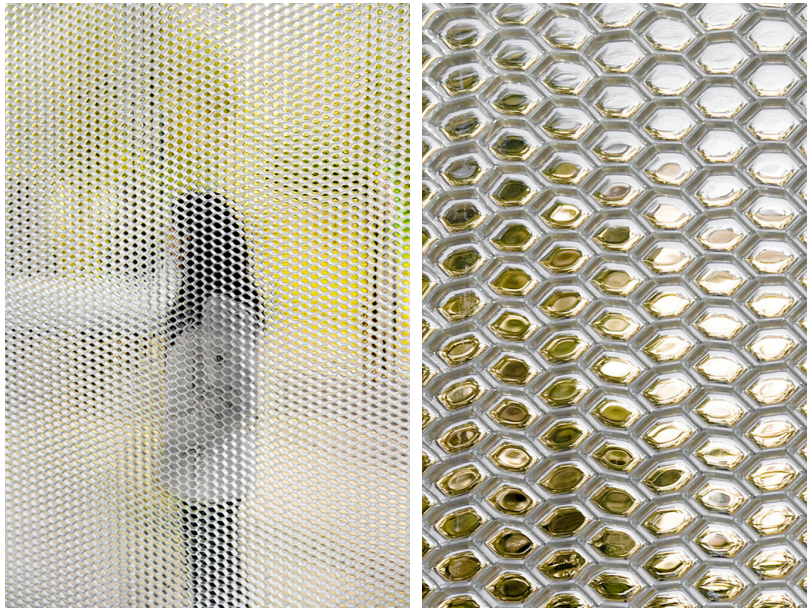


Figure 6: Maximum transparency is obtained by looking through the panel perpendicularly.

The structural advantages of the glass-honeycomb composite panels are remarkable. The bending stiffness of the panel increases significantly due to the fact that the two glass skins are 25 mm apart, with an intermediate aluminium honeycomb allowing an effective shear transfer. Therefore, both deflections in the centre of the panel and stresses around point fixings decrease compared to a conventional insulating glass unit.

These lower stresses permit heat strengthened glass (for point-fixed panels) or annealed glass (for perimetally supported units) to be used. After breakage, the relatively large glass fragments remain attached to the honeycomb thanks to the acrylate adhesive, which allows designers to use monolithic glass components in many situations which would require the use of laminated glass if a conventional IGU was to be installed. Despite this good post-breakage behaviour, laminated glass was used in all internal glass components of the Berkeley pavillion in order to skip the tests required if monolithic glass panes were used.

The light and solar transmission of the glass-honeycomb panels is high (reliable test-based values are not yet available) as the crossed reflections between the honeycomb, adhesive and glass cause that most incident radiation is transmitted through the panel as diffuse light, thus avoiding glare. Therefore, coatings are required for an effective solar protection.

On the other hand, the thermal performance of these units is lower than a similar conventional IGU due to the thermal bridge caused by the aluminium honeycomb. Therefore, in the Berkeley pavillion an argon-filled air chamber and an additional laminated

glass component with a Low/E coating was added to all panels enclosing internal spaces (see Figure 7).

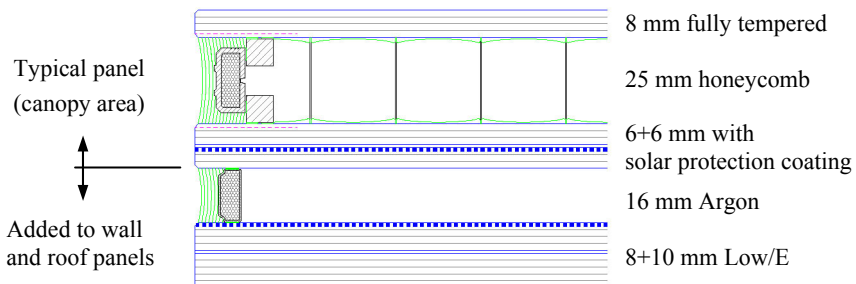


Figure 7: Cross section of typical glass-honeycomb panel.

The fabrication of the glass-honeycomb panels is a manual process that requires skilled personnel and a clean environment (pressurised room) to avoid dust being trapped in the adhesive layer. At the moment, glass panels measuring 4.60 x 1.90 m have been successfully fabricated, as shown in Figure 8, while the Berkeley pavillion requires panels up to 4.85 x 2.30 m.

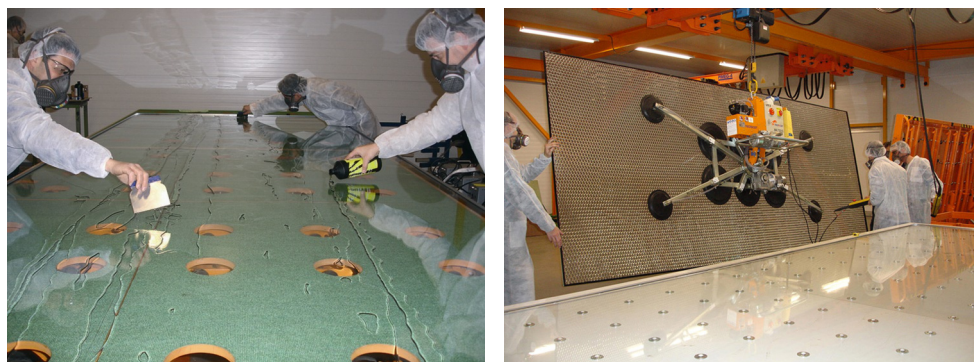


Figure 8: Large glass-honeycomb panel during fabrication.

Another important point for fabrication is to use the right adhesive. Apart from the adhesive structural and visual properties, viscosity and vapour emissions during curing are important factors that must be taken into account when choosing an adhesive. The more viscous an adhesive is, the more difficult it is to remove the air bubbles that are formed when spreading it. However, low viscosity adhesives tend to emit higher quantities of vapour during curing which might create condensations that cause undesired permanent textures and tears in the adhesive layer.

In addition to all calculations, the structural properties and durability of the panels for the Berkeley pavillion was assessed by testing. A number of tests are being performed at the time of writing this paper, which are intended to check the following points:

- Yellowing of adhesive specimens after a 2000 h irradiation in a sunlight simulator.
- Chemical compatibility of the acrylate adhesive with all perimetral sealing materials.
- Fogging of units under sudden temperature changes.
- Moisture ingress through the perimetral seal and/or pneumatic conduits.
- Effect of cyclic temperature variations on the glass-honeycomb bond.
- Tensile resistance of aged glass-honeycomb specimens.
- Compression resistance of glass-honeycomb specimens.
- Bending resistance of aged glass-honeycomb specimens.
- Cyclic bending resistance of glass-honeycomb specimens.
- Long-time bending behaviour of the glass-honeycomb sandwich (creep).
- Post-breakage behaviour according to CWCT technical note no. 42 [6].

Depending on the results of the tests, it is possible that the glass-honeycomb bond cannot be considered strong enough to bear the internal pressure load caused by the expansion of air in the air chamber under temperature variations. Should this happen, a system of pneumatic conduits connecting all glass panels to a battery of six breathers was designed in order to allow the release of any significant pressure variation within the honeycomb cells. These breathers are equipped with adequate filters to avoid dust entering in the panels and sufficient quantity of self-indicating silica gel dessicant to allow a minimum replacement period of 1.5 years.

## **5. Conclusions**

The paper has shown how the use of carbon fibre composites permitted to design and fabricate 10 m long beams with the free-form shape desired by the Architect and a high structural efficiency. In fact, the weight of these beams is approximately half the weight of an equivalent variable-depth carbon steel I-beam with the same bending stiffness.

On the other hand, glass-honeycomb sandwich panels are able to meet the structural and privacy requirements of the project and to provide a unique visual appearance to the cladding of the pavillion.

The use of innovative materials in construction can provide creative solutions to specific problems, although they must be carefully analysed and tested to guarantee their durability and suitability for the intended application.

## **Acknowledgements**

To all project participants, detailed in Table 1.



Table 1: Project participants

Owner	The Berkeley	Norman Mc.Kibben
Architect	Rogers, Stirk, Harbour + Partners	Amo Kalsi, Paul Thompson, Davide Costa
Structural engineering consultant	Expedition	Simon Pierce
Façade engineering consultant	Arup Façade Eng.	Graham Dodd, Felix Weber
Project manager	Rainey & Best	Mark Allen
Design and construction	Bellapart	Francesc Arbós, Carles Teixidor, David Linares
CFRP manufacturer	Nexus Projectes	Bernat Calpé
CFRP engineering	Mira Tecnologia	Adrià Roca, Eduard Ferreró, Lluís Raurich
CFRP consultant	University of Girona	Joan Andreu Mayugo, Albert Turon, Daniel Trias, Sergi Ortiz

## References

- [1] BS 5950-1:2000, *Structural use of steelwork in building. Code of practice for design. Part 1: Rolled and welded sections.*
- [2] BS 6399-1:1996, *Loading for buildings. Part 1: Code of practice for dead and imposed loads.*
- [3] BS 6399-2:1997, *Loading for buildings. Part 2: Code of practice for wind loads.*
- [4] BS 6399-3:1988, *Loading for buildings. Part 3: Code of practice for imposed roof loads.*
- [5] Cripps A., *Fibre-reinforced polymer composites in construction.* CIRIA, 2002.
- [6] CWCT Technical Note No 42, *Safety and fragility of glazed roofing. Guidance on specification and testing.* Centre for Window and Cladding Technology, 2004.
- [7] MIL-HDBK-17-3F, *Composite materials handbook. Volume 3: Polymer matrix composites. Materials usage, design and analysis.* US Department of Defense, 2002.