TUDelft

Glass-Honeycomb Composite Panels

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The bending stiffness of insulating glass units can be significantly improved by including an aluminium honeycomb core continuously bonded to both glass panes. This arrangement also offers a number of additional advantages, ranging from an improved post-breakage behaviour to a particular translucent look. This paper provides an overview of the structural, thermal and visual advantages and drawbacks of glass-honeycomb composite panels and also describes its development, testing and fabrication method. Finally, a design method is proposed.

Keywords: Glass, Honeycomb, Composite, Sandwich, Adhesive, Acrylate

1. Introduction

The required thickness of façade, floor and roof glass panels is defined by their maximum stresses and deflections which in turn are function of their stiffness. This is specially important for floors and roofs, in which 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 (fig.1).

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. The result is a relatively light but stiff glass panel with good post-breakage stability and interesting visual properties.

2. Development and production method

The glass-honeycomb panels were originally developed for the new glass pavillion of the Berkeley hotel in London (UK) which is planned to be built in the near future. In this project, the Architect and his consultants challenged the façade contractor to use glass-honeycomb sandwich panels to clad the whole roof and approximately half the façade area of the pavillion.
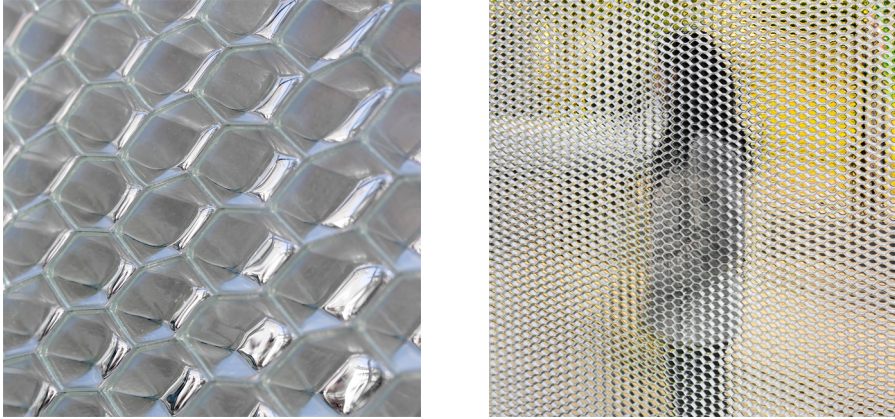
Figure 1a and b: Glass-honeycomb composite panel.

According to the Architect, the panels should show a similar look to polycarbonate-honeycomb panels that are currently in the market for interior design and furniture applications. However, they should be able to have a longer service life and to resist the solar radiation, temperature and humidity variations related to an external environment. In addition, due to their large size and support conditions these panels should show a true composite action between their two glass skins.

After some preliminary research on available adhesives, it was clear that acrylates were the most appropriate products in terms of yellowing resistance, transparency and mechanical properties. Initially, four candidate adhesives from different manufacturers and with different viscosities were considered.

The development phase of both the panels and their production method was an iterative test-and-error process consisting in fabrication tests followed by performance tests on the samples obtained. Feedback from the tests resulted in constant changes and adjustments in both the production method and panel design.

It was soon noticed how important it is to choose the right adhesive. Apart from its structural and visual properties, viscosity and vapour emissions during curing are the main factors that must be taken into account. 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 (fig. 2).

Based on the experience acquired during the development phase, two candidate adhesives were chosen which were subject to an extensive test battery as described below. Tests results provided enough information to make a decision on the final adhesive to be used for this application.
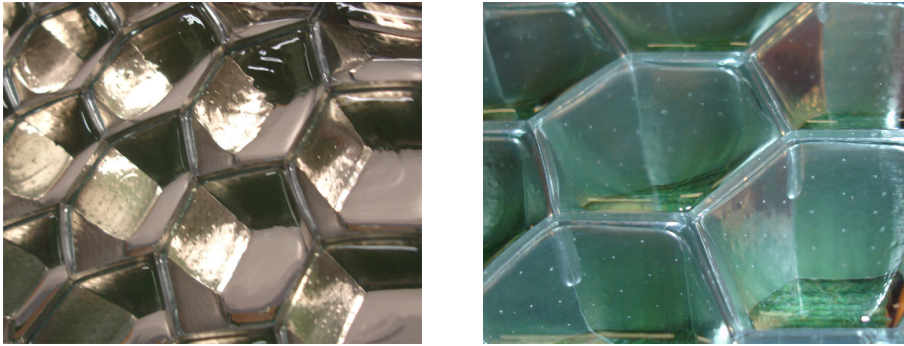
Figure 2a and b: Textures and tears in the adhesive layer related to wrong adhesives and wrong production methods.

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 (fig. 3). At the moment, glass panels measuring 4.60 x 1.90 m have been successfully fabricated (fig. 4) whereas the Berkeley pavillion requires panels up to 4.85 x 2.30 m.

3. Advantages and drawbacks

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 some distance apart (usually 19÷25 mm) with an intermediate aluminium honeycomb providing an effective shear transfer. Therefore, both deflections in the centre of the panel and stresses around point fixings are smaller than in a conventional insulating glass unit.

These lower stresses permit heat strengthened glass (for point-fixed panels) or annealed glass (for perimetrally 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.

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. 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, providing a U-value of 1.2 W/m^{2}K

4. A critical point: Expansion of air in the honeycomb cells

When a conventional IGU is heated (e.g. by sun radiation) the air or gas in its chamber expands. This expansion is accomodated by a slight deformation of the two glass panes which increases the volume of the chamber, together with a small internal pressure increase. A volume reduction also occurs when an IGU is cooled down or when atmospheric pressure drops.

The glass-honeycomb panels can be regarded as a conventional IGU in which the two glass panes are connected along all their surface by the honeycomb core. Therefore, volume changes in the air chamber are impeded by the honeycomb core which results in important internal pressure variations and the related damage risk on the glass-honeycomb bond.

Tests suggest that breakage of the bond in a fresh panel would occur for temperatures above 80ºC mantained for 10 hours approximately (the panel is considered to be fabricated at a temperature of 18±2ºC). However, regardless of these test results it is interesting to release any important pressure rise in the air chamber so that the mechanical strength of the bond is used for shear transfer only.

To do so, the glass-honeycomb panels are composed of a microperforated aluminium honeycomb that allows some air circulation between the honeycomb cells and a pneumatic connection incorporated in the perimetral seal that connects the air chamber to a breathing device (fig. 5) through conventional pneumatic conduits.

The breathers are industrial devices commonly used to prevent significant internal pressure changes in electric transformers and outdoor hermetic cases containing electronic equipment. They are composed of a set of mechanical filters to avoid dust entering in the system and a transparent container filled with self-indicating silica gel dessicant which removes moisture from incoming air. This dessicant is partially regenerated by warm air out flow. An active carbon filter is also required between the dessicant and the glass unit in order to avoid acrylic vapours released by the adhesive to reduce the moisture adsorption capacity of silica gel.
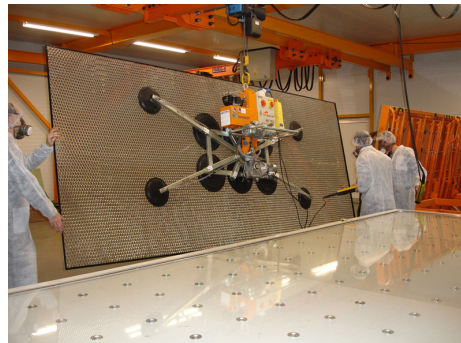

Figure 3a and b: A large glass-honeycomb panel during fabrication

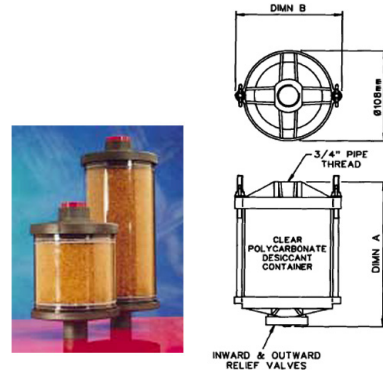Figure 4: Glass-HC panel measuring 4.60 x 1.90 m. Figure 5: Breather-dessicator.

Self-indicating silica gel changes its colour when it becomes saturated, thus it is always clear to the user when the dessicant needs to be replaced. A safe estimation of the replacement period for a typical dessicant charge in London is 1÷2 years.

5. Testing

A comprehensive test battery was carried out in order to check whether the panels were adequate to be used as permanent cladding in buildings and also to establish their mechanical properties and wheathering resistance. A brief description of the most relevant tests follows.

5.1. Yellowing test

Yellowing tests consisted in determining the *L, a* and *b* colorimetry parameters of 1.5mm thick adhesive specimens before and after exposing them to a 2000 h radiation using a light source which irradiates a spectrum similar to sunlight. The radiation intensity was 70 ± 10 W/m^2 UVA and specimens were considered to be yellowish for *b*-values higher than 5. The average *b*-value of test specimens after a 2000 h irradiation was 3.63, significantly under the limit value.

5.2. Chemical compatibility test

Chemical compatibility between the adhesive, the aluminium honeycomb and all components of the perimetral seal was checked by carrying out colorimetry measurements on adhesive specimens that had been in contact with the second test materials for 55 days. No colour difference was observed between exposed specimens and reference specimens stored in the dark for the same time period.

In addition, shear strength tests were also carried out on glass-adhesive-glass sandwich specimens which had been in contact with the perimetral seal materials at 60 ± 2 ºC for 676.5 hours and then 10 days at 25ºC. No significant differences in shear strength were observed between exposed and reference specimens.

5.3. Fogging

All acrylate adhesives release some acrylic vapour when heated that is readsorbed when the adhesive is cooled down. However, the adhesive layer might not be able to adsorb vapour quickly enough when the panel is submitted to a sudden temperature drop and some acrylic vapour condensation on the adhesive layer might occur, resulting in a foggy look of the unit. In order to check that fogging would not occur under the worse service conditions, a panel sample was successfully tested by heating it to 80ºC and suddenly submerging it in water at 12ºC.

5.4. Outgassing

In this test, the maximum mass of vapour emitted by the adhesive during its service life was estimated and it was determined how much this vapour emissions might interfere with the moisture adsorption capacity of dessicants used in the perimetral seal and the breathers. Although the total vapour emissions in 25 years are expected to be small (1.18 % of the liquid adhesive mass) it was found that they might completely saturate both dessicants. Therefore, remedial measures were included in the fabrication method in order to remove as much acrylic vapour as possible both during and after curing the adhesive layers. In addition, the moisture adsorption capacity of the dessicant in the perimetral seal was considered only to remove the initial moisture content of fresh air in the chamber immediately after closing the unit, and breather dessicant was protected from acrylic vapours by means of an active carbon filter.

5.5. Moisture ingress through the perimetral seal

The standard test method described in [4] with slightly modified test samples was used to determine the amount of moisture entering in the unit through the perimetral seal and pneumatic conduits. An index of moisture penetration of 0.04±0.02 was obtained, well below the limit value of 0.085.

5.6. Cylic temperature variations

Three glass-honeycomb samples with a weak perimetral seal were submitted to 56 twelve-hour temperature cycles similar to those detailed in [3] with a special temperature range of -10±2 ºC to +61±2 ºC. The thickness of samples was controlled in five points along its surface before and after the thermal cycles were applied. No damage in the glass-honeycomb bond was observed after the cycles and the max. observed thickness increase was 0.21 mm (less than 0.15 mm in most points). Therefore, it was concluded that panels are not sensitive to the expected temperature variations in the event that the breather system gets blocked, thus no emergency breather system is necessary.

5.7. Tensile strength

The tensile strength of the glass-honeycomb bond was determined with a conventional tensile test on eighteen glass-honeycomb samples measuring 105x105 mm previously submitted to different ageing and radiation cycles (fig. 6). Test results were used to determine the design method described below.

Figure 6: Tensile strength test.

Figure 7: Punching strength test.

5.8. Compression (punching) strength

The mechanical resistance of glass-honeycomb panels under compression loads transmitted by bonded point fixings was investigated by carrying out a number of compression tests on 500x320 mm samples (fig. 7) with the actual glass composition to be used in the Berkeley project (8 ESG + 25 HC + 6.6.4 TVG). Test results were used to determine the design method described below.

5.9. Bending strength

The bending strength of 1100x300 mm samples composed of two 8 mm annealed glass skins and a 25 mm honeycomb core with and without a previous ageing was investigated by means of four-point bending tests (fig. 8). Bond breakage was not observed in any case and an extesive shear buckling of the honeycomb occured prior to glass breakage. Test results were used to determine the design method described below.
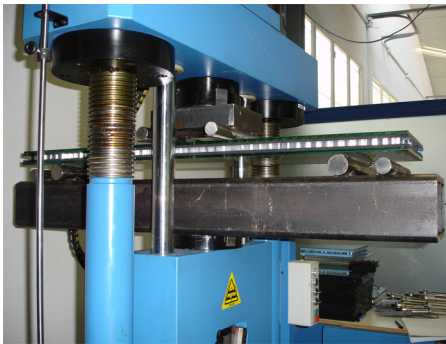

Figure 8: Bending strength test.

Figure 9: Hard-body impact test included in the CWCT-42 test sequence.

5.10. Cyclic flexural loading test (low-cycles fatigue test)

The low-cycles fatigue resistance of the glass-honeycomb bond was investigated by submitting three 1100x300 mm samples similar to those used in the bending strength tests to a three-point bending test with the cyclic loads defined in [1] and a max. force of 1762 N. The thickness of samples was controlled in five points along its surface before

and after the cyclic load was applied. No damage in the glass-honeycomb bond was observed after the cyclic load and the max. observed thickness change was 0.08 mm.

5.11. Long time bending test (creep test)

Creep in the glass-honeycomb bond was investigated by submitting a 1100x300 mm panel sample to a four-point bending test with a constant load of 1585 N for 1291 h at room temperature and registering the central deflection every 24÷48 hours (fig. 10). Deflection measurements continued for 669 h after removing the load.

The measured elastic deflection was 0.71 mm and creep deflection after 1291 h was 3.07 mm (432% of the elastic deflection). 669 h after removing the load, the remaining creep deflection was 1.93 mm (63% of the max. creep deflection). Fitting an exponential curve to the unloading phase registers it was possible to estimate the long time remaining deflection which was around 50% of the max. creep deflection. This data was used to determine the shear transfer of the glass-honeycomb bond for different loads with different durations, as shown in the proposed design method described below.

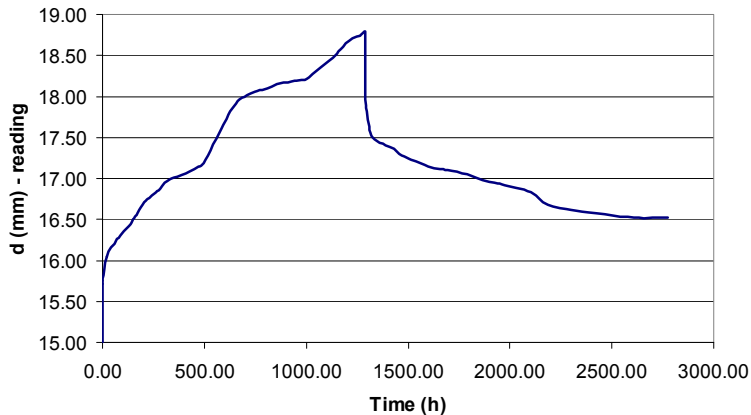Additional long time creep tests in an outdoor environment are in progress since December 2008.

Figure 10: Creep test midpoint deflection vs. time.

5.12. Impact resistance and post-breakage behaviour

A full size panel measuring 4.60 x 1.90 m with the glass composition to be used in the Berkeley project was tested according to the procedure shown in Annex 3 of CWCT-42 [2] with successful results (fig. 9).

6. Proposed design method

Based on the previous tests, the following design method is proposed for glass honeycomb panels supported by bonded point fixings. Some of the numerical values shown below may need to be revised for glass compositions different from the one used in the Berkeley project.

6.1. Simplified finite element model of panels

A rough but reasonably good approximation to the behaviour of glass-honeycomb panels can be obtained with a finite element model of the sandwich in which the honeycomb core is modeled as a linear isotropic material with the mechanical properties shown in table 1. These properties were obtained from creep test results and are valid only for 25 mm thick aluminium honeycomb with a cell size of 25 mm.

Table 1: Equivalent linear isotropic properties of 25x25 mm honeycomb bonded on two glass skins.

Load	Young modulus [MPa]	Shear modulus [MPa]	Density [Kg/m^3]
Short time loads (wind, etc)	144	48	0 (negligible)
30-days snow load	22.5	7.5	0 (negligible)
Long time load	Layered. No shear transfer through honeycomb.		0 (negligible)

6.2. Bending strength check

- Glass failure: $\sigma_1 < \sigma_{adm}$
  $M_b \cdot \gamma_{M,glass} / M_{bk,glass} < 1$
- Extensive honeycomb shear buckling: $V_b \cdot \gamma_{M,HC} / V_{bk,HC} < 1$
- Glass-honeycomb bond breakage: Not expected

where:

σ_1	max. principal stress on each glass ply
σ_{adm}	max. allowable stress according to a relevant glass design standard
M_b	max. ULS bending moment in the panel
V_b	max. ULS shear force per unit length in the panel
$M_{bk,glass}$	95% fractile bending strength of panels (3.26 kNm/m for an 8 mm annealed / 25 HC / 8 mm annealed panel)
$V_{bk,HC}$	95% fractile honeycomb shear buckling resistance (8.33 kN/m for an 8 mm annealed / 25 HC / 8 mm annealed panel)
$\gamma_{M,glass}$	material factor for glass (1.10)
$\gamma_{M,HC}$	material factor for the aluminium honeycomb (1.10)

6.3. Local resistance check for panels on bonded point fixings

a) Point fixing under tension
  - Glass-honeycomb bond breakage: $F_t \cdot \gamma_{M,bond} / F_{tk,bond} < 1$
  - Glass failure: Not expected
b) Point fixing under compression
  - Extensive honeycomb buckling: $F_c \cdot \gamma_{M,HC} / F_{ck,HC} < 1$
  - Glass failure: $\sigma_1 < \sigma_{adm}$
  - Glass-honeycomb bond breakage: Not expected

where:

F_t	max. ULS tensile force transmitted by a point fixing
F_c	max. ULS compression force transmitted by a point fixing
$F_{tk,bond}$	95% fractile tensile resistance of the bond

$F_{ck,HC}$ (7.84 kN for a Ø60 mm stainless steel fixing bonded on t>8 mm glass)
95% fractile extensive buckling resistance of honeycomb
(9.00 kN for a Ø60 mm stainless steel fixing bonded on t>8 mm glass)

$\gamma_{m,bond}$ material factor for the bonded connection (2.34 according to [1])

7. Conclusions

This paper has shown how glass-honeycomb composite panels are able to meet the structural and privacy requirements of many façade, floor and roof applications and to provide a unique visual appearance to the cladding of buildings.

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.

8. Acknowledgements

9. References

[1] BRE Digest No. 346, The assessment of wind loads. Part 7: Wind speeds for serviceability and fatigue assessments, British Research Establishment, London, UK, 1989
[2] CWCT Technical Note No 42, *Safety and fragility of glazed roofing. Guidance on specification and testing,* Centre for Window and Cladding Technology, Bath, UK, 2004.
[3] EN 1279-2:2002 *Glass in building. Insulating glass units. Part 2: Long term test method and requirements for moisture penetration.*
[4] EN 1279-6:2002 *Glass in building. Insulating glass units. Part 6: Factory production control and periodic tests.*