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Structural Glass Fin Façade St. Davids Hall, Cardiff

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The remodelling of the entrance of St. David's Hall in Cardiff features an array of translucent and partially pigmented structural glass fins with artistic lighting. The fins are composed of 2 x 10 mm toughened glass incorporating a red screen frit and acid etching. The fins are 300 mm deep and up to 5 m long, supported by a stainless steel shoe bracket at the bottom and a fork bracket in the upper zone of the fin. Only by using a stiff Ionoplast interlayer the fins could be designed to suit the load bearing capacity of the existing structure. The robustness and safety of the design was demonstrated by a series of impact tests.

Keywords: Glass Fin, Ionoplast Interlayer, Bracket Design, Impact Testing

1. General

1.1. Background

St David's Hall comprises the National Concert Hall and Conference Centre of Wales and is located in the city centre of Cardiff in Working Street. The building was designed by Seymour Harris Partnership and opened in 1982. It features a concrete primary frame and precast concrete cladding (see Figure 1). In connection to the refurbishment and new development of the St. David's Shopping Centre the entrance of St David's Hall is undergoing a remodelling featuring glass fin cladding and artistic feature lighting.

Cardiff City Council employed Benoy Architects and the lighting designer Peter Freeman to develop the design of the glass fin façade. Arup was appointed to provide the structural engineering and the detail design of the glass fins and their supporting brackets. Following the tendering phase the work was commissioned to the Spanish Specialist Contractor Bellapart in July 2009. The works will be completed in springtime 2010.

1.2. Design Intent

The intent of the scheme is to be modest and unobtrusive towards the existing architecture but at the same time to strengthen the public appreciation and the communal character of the building by accentuating the entrance during day and night time. Another aspect of the scheme is to visually integrate the logo of St David's Hall and the LED screen that had been installed 2008 for the Commonwealth games.

The geometric arrangement of the fins and their materiality allows a changing perception of the entrance area when approaching the building from different sides. When looking in line of the fins they visually disappear and the original facades of St

David's Hall are revealed. When approaching from the side the flanks of the fins shall create a veil catching the reflections of the sky during daytime and in this way dissolve the massiveness of the existing building. During night time a similar effect is achieved through the artistic lighting with LED placed at the bottom between each fins allowing a "lightwash" of the fins. Playing with natural and artifical light, colour, translucency and reflectivity the scheme strengthens the ephemeral character inherent in the material glass [1].

Figure 1 (left): existing entrance of St David's Hall, Figure 2 (right): Scheme Design © BENOY

2. The scheme

2.1. Setting out

Following on a series of studies investigating various fin arrangements and spacings (see Figure 2) the design features an array of glass fins that wrap around the outline of the first floor façade and terraces. The glass fin façade redefines and smoothens the cladding line by bridging over two 45° notches between the existing terraces. In plan the fins follow a polygonal line with a total length of 25 m. The 66 fins in total are spaced at 400 mm centres. Where the fins extend over the full length of the first floor elevation they measure 4950 mm in length (Fin Type 01), in the zone where they are located underneath the LED screen they measure 1095 mm in length (Fin Type 02). The bottom edges of the fins are approximately 4275 mm above ground (see Figure 3).

2.2. Structural arrangement

Each of the Type 01 fins is supported individually by a pair of stainless steel brackets (grade AISI-316). The dead load of each fin is taken by a shoe bracket at the bottom, while the fork bracket located approximately at three quarters of the height provides a lateral restraint. All brackets connect with bolt fixings to a carbon steel substructure consisting of a RHS beam grade S275 (200/100/6) that runs continuously along the first and second floor slab edge bridging the notches between the terraces. The RHS box sections of the substructure are fixed with torsion stiff connections to the existing concrete slabs. Fins of Type 02 feature a bottom bracket only which is identical to Fin Type 01 providing an encaster for the cantilevering glass.

2.3. Lighting

Centrally between each bottom support brackets a LED uplight is located (Type Colorblast), supported by an individual console (see Figure 8). The LED features a lens for a 10 degree beam to ensure that the light is travelling up the fin. The wiring for the LED are integrated in the RHS box section.

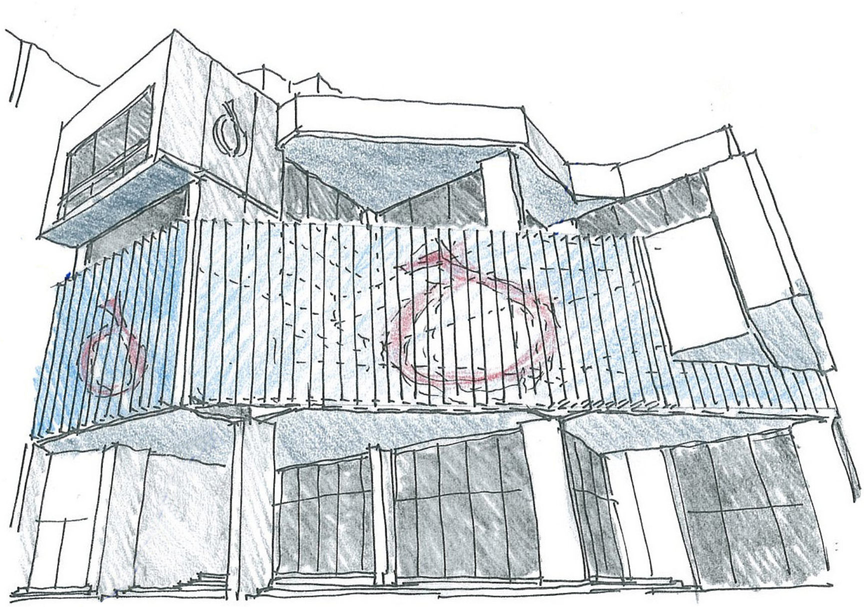


Figure 3: Design Sketch showing arrangement of fins, © Stephen Gill, BENOY

3. Glass composition and build up

3.1. Visual requirements

As the fins are to be illuminated at night, the build-up needs to incorporate a translucent layer, either as a frit or as an interlayer, to diffuse the light. In addition a large scale mono-chrome logo of St David's Hall was to be integrated in the laminate. It is essential that the fins have the same visual appearance seen from either side. For a clear, neutral colour of the glass the use of low-iron glass was specified.

3.2. Structural requirements

Due to the limited load bearing capacity of the existing structure any additional load along the first floor slab edge was limited to max. 3.6 kN/m. Due to this requirement an in depth analysis had to be carried out to determine the glass thickness and to proof the feasibility before tender.

The effective wind speed for the Cardiff Region was calculated to be ca. 38 m/s following BS 6399-2 corresponding to gusts of 5 m length (approx. load duration of 1 s), leading to a net surface pressure of ca. 1.8 kN/m² for the glass fins. The deflection limit was set to be equivalent to a span/100, corresponding to 39.5 mm for Type 01 and 10.95 mm for Type 02. The natural frequency of the glass screen was specified to be over 4 Hz so that the fins do not display harmonic oscillation induced by the wind.

Due to the location of the glass fins straight above the entrance of one of the most frequented public buildings in Cardiff the safety, robustness and post fracture integrity of the design was of superior priority. A monolithic build-up not addressing these issues was therefore ruled out.

The weight restrictions of the fin in conjunction with the given wind load lead to the necessity to take a composite action between the individual glass plies of the laminated glass fins into account by using a stiff PVB or Ionoplast interlayer. The required amount of composite action of the laminated glass needs to respect the temperature of glass and interlayer.

3.3. Warp of fins

As the fins are very slender (height to depth 16.5/1) tight tolerances for straightness were specified. After lamination the warp of the fin does not exceed half the thickness of the overall build-up of the fin if placed on the ground and measured against a plane surface (see sketch below).

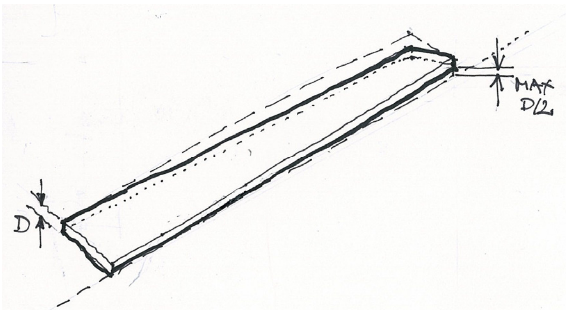


Figure 4: Tolerances for warp of fin

3.4. Option 1: 2 x 15mm with PVB-Interlayer

With the use of PVB the build-up was calculated to consist of 2 x 15 mm heat strengthened glass plies. A shear modulus of 0.4 N/mm² for wind with 3 s load duration was taken into account.

By using a translucent PVB interlayer the requirement of light diffusion is achieved. For same visual appearance from both sides of the fin both flanks of each ply facing the interlayer feature an identical frit pattern. Due to orientation of the fritted surface towards the interlayer, the reduction in strength due to the fritted surface has no consequence for the structural performance of the fin. With this build-up there are certain concerns regarding the durability of the laminate due to the equal orientation of the roller waves and the adhesion of the fritted glass surface with the PVB. This build-up leads to an additional total loading of approx. 4 kN/m and therefore does not comply with the structural requirements as it exceeds the given weight restrictions.

3.5. Option 2: 4 x 6 mm with Ionoplast Interlayer

By using a stiffer Ionoplast interlayer a similar appearance to Option 1 can only be achieved with a quadruple laminate of 6 mm plies as currently no translucent Ionoplast interlayer is available.

The partial red frit pattern is located on surface 2 and 6, while the full surface translucent frit is located on position 4 within the build-up. This build-up leads to an additional total loading of approx. 3.5 kN/m and therefore complies with the given weight restrictions. However the visual quality of the multi layered edge did not match with the architects' expectation.

3.6. Option 3: 2 x 10 mm with Ionoplast Interlayer

For a double laminate featuring an Ionoplast interlayer a different approach was taken to incorporate both translucency and a partial red frit pattern. With a laminate of two 10 mm toughened plies the partial red frit is located on position 2. Both surface 1 and 4 feature a homogeneous acid etching over the whole surface. This build-up leads to an additional total loading of approx. 3 kN/m and therefore complies with the given weight restrictions.

The toughening of the glass compensates for the loss in strength due to the mechanical processing of the glass surface. The perception of acid etching depends on the condition of the glass as a wet surface reduces the effect. In addition the red frit is taken back in its presence as it is located in between the translucent layers. Reference projects as the "Kunsthaus Bregenz" have demonstrated that an external acid etched surface can be maintained clean over time. A sample could demonstrate that this build-up strengthens the desired ephemeral quality both during day and night time. Therefore this build-up was chosen for the glass fins.

4. Glass Design

4.1. Basis of the design

The fin is 4950 mm long and 300 mm wide. The restraint points are at the bottom end and approximately 1000 mm away from the top end. The fin consists of 2 plies of 10 mm toughened glass with a 1.52 mm Ionoplast interlayer.

For the Ionoplast interlayer SentryGlass ® Plus (SGP 5000) was chosen. A shear modulus of approx. 8 N/mm² is taken into account for load duration up to 3 sec and an interlayer temperature of 60 °C [2]. The analysis follows the principles of the prEN 13474 [3].

4.2. Analysis pre-tender

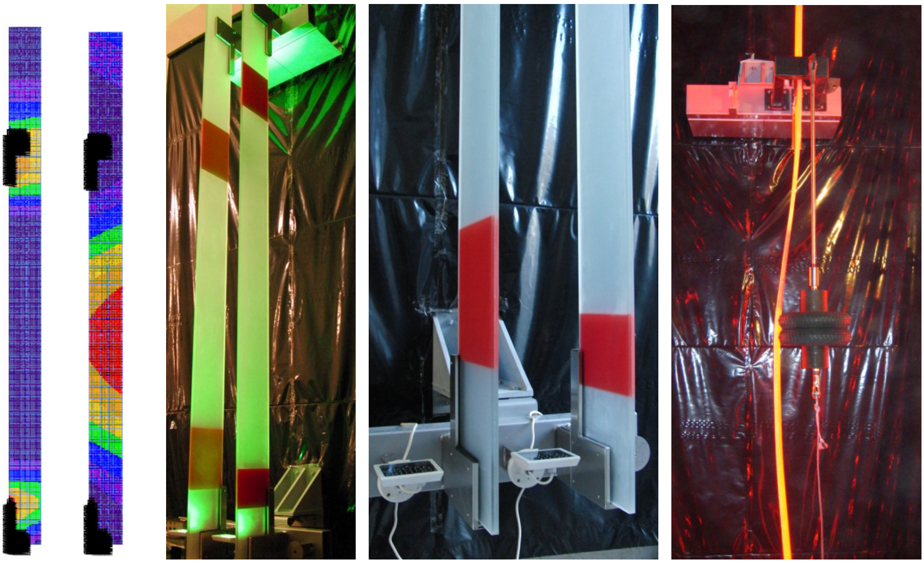
To validate the feasibility of the design Arup Materials Consulting completed the detail design and carried out a detailed structural analysis before tender. A finite element software Oasys GSA was used for the calculations.

The deflection of Fin Type 01 was calculated to be 29 mm between the two support points, with a maximum stress of 27 N/mm² close to the top support bracket. Its natural frequency was calculated to be around 5 Hz (see Figure 5, 6).
The deflection of Fin 02 was calculated to be 8 mm at top of the cantilever with a max. stress of 10 N/mm².

4.3. Analysis post-tender

The calculations carried out by Bellapart as the successful tenderer were based on a more accurate and detailed model, however the results show a good match to the original assumptions. The calculations were carried out using COSMOS/Design Star.

The deflection of Fin Type 01 was calculated to be 35 mm between the two support points, with a maximum stress of 28 N/mm² close to the top support bracket. Its natural frequency was calculated to be 5.5 Hz. The deflection of Fin 02 was calculated to be 10 mm.



Figures 5-9 (from left to right): Stress analysis, Deflection analysis, Visual mock up © Bellapart, Impact testing stage 3 © Bellapart

4.4. Impact testing

To proof the robustness of the design a series of three impact tests was specified and conducted by the specialist contractor under the surveillance of an independent testing authority.

For the whole duration of the impact stage of the testing and for six hours following the final impact the glass surface was maintained at a temperature of 40°C ± 3 °C by means of infrared lamps. Following that the specimen was maintained at ambient room temperature. The impactor and impactor rig used for this test was in accordance with BS EN 12600.

For Test 1 the impactor with a drop height of 1200 mm swung at 15° to the front edge of the fin, at the mid height point and close to the bottom gravity support bracket. As both plies of the fin were unbroken after Test 1, one pane was deliberately broken by a centre punch applied to the glass edge.

For Test 2 the impactor with a drop height of 450 mm swung at the same locations noted for Test 1. As both plies of the fin were not broken after Test 2, the remaining ply was deliberately broken by a centre punch applied to the glass edge.

For Test 3 the impactor with a drop height of 190 mm swung at the same locations as noted for Test 1 and additionally perpendicular against the side of each fin at mid height (see Figure 9). After the final impact the fin was observed for 72 hours. The fin remained in place and less than 40 grams of fragments were released during all stages of the testing, thus the design was considered to be robust and safe.

5. Detail

5.1. Bottom bracket design

The stainless steel bottom support bracket is transferring the full dead load of the glass fin and a proportion of horizontal loads to the substructure. The bottom shoe bracket is fabricated from 8 mm and 10 mm thick plates. A horizontal plate supports the bottom edge of the glass fin and the two vertical plates on each side provide lateral restraint. These plates are tied together by a vertical plate parallel to the back edge of the fin and a blade in plane of the glass fin providing the structural connection to the substructure. The bolted connection between the shoe bracket and the console of the sub frame provides a moment stiff connection. The bottom brackets are extended by approximately 400 mm along the back glass edge to increase the lateral stiffness of the glass support reducing deflections.

Setting blocks between the bottom edge of the fin and the shoe bracket provide a controlled transfer of the dead load and an in-plane vertical position of the fin; EPDM pads on the sides of the shoe define the vertical position of each fin.

The edges of the bracket are sealed against the glass with a continuous structural silicone seal carried out in the workshop to protect the shoe bracket from ingress of rain water. In addition the horizontal plate of the shoe bracket features weep holes to drain any water should the weather seal fail.

To hold the fin in position and to prevent the fin from sliding out of the shoe bracket towards the front (also in case of glass breakage) each glass fin has a mechanical interlock with the bracket. A pair of structural silicone bonded aluminium strips at the bottom of the glass interlock with folded stainless steel clamps. The clamps (one on each side of the fin) are bolted into the shoe bracket to ensure the glass fins are mechanically restrained (see Figure 10).

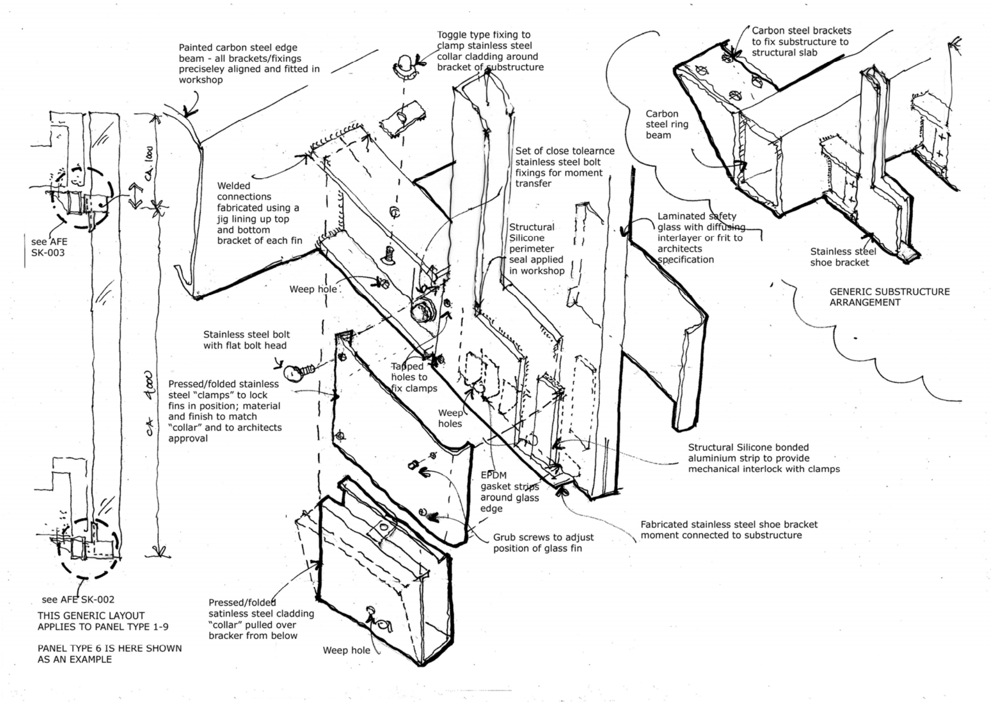


Figure 10: Design Sketch showing bottom bracket arrangement

5.2. Top Bracket

The design and appearance of the fork bracket at the top of the fin corresponds directly to the bottom support bracket, however there are two distinctive differences. The top brackets only provide lateral restraint for the glass fins. The connection to the substructure needs to accommodate for all vertical movement such as thermal movements and slab edge deflections. The mechanical interlock between glass and bracket provided by the pair of stainless steel clamps stop the glass also from sliding vertically should the fin lose its bending stiffness in case of breakage.

5.3. Assembly

To allow an even and vertical setting out of the fins, all brackets are positioned and fixed to the glass fin in the workshop. All consoles to the substructure are positioned, aligned and welded in the workshop to minimise tolerances occurring on site.

6. Summary

The laod bearing capacity of the existing concrete structure limits the additional load imposed to the slab edge by the glass fin assembly to 3.6 kN/m. Only by using a stiff Ionoplast interlayer the glass fins could be designed to meet this criterion. The fins that are up to 5 m long with a free span of approx. 4 m are featuring two plies of 10 mm toughened glass with a 1.52 mm interlayer. The use of this type of interlayer that is currently not available in translucent impacted on the visual apperance and the overall design of the glass build-up. Acid etching on the outer glass surfaces was employed to provide translucency, the red logo of the St. David's Hall was incorporated by partial fritting.

The Ionoplast interlayer also allows the use of toughened glass, which is generally not advisable due to its low post fracture stability. However in this instance the robustness was demonstrated by a series of impact tests, showing that a fully broken fin remained in place for the specified period of 72 hours.

7. Acknowledgements

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8. References

[1] Wurm, Jan, *Glass Structures – Design and Construction of self-supporting glass skins*, Birkhäuser, Basel, Switzerland, 2007

[2] DuPont, *Technical Datasheet SentryGlass® Plus (SGP 5000)*, 2008

[3] pr EN 13474-1:1999, *Glass in building – Design of glass panes – Part 1: General basis of design*, CEN, 1999