Composite steel-glass fins for the lobby façade of Iberdrola Tower

Núria Guitart

Summary

The Iberdrola Tower in Bilbao, designed by Pelli Clarke Pelli architects, features a lobby entirely enclosed by two sculptural glass walls with a length of 66 meters each forming a softly rounded triangle in plan. The variable surface curvature of the façade is achieved by means of cold-bent insulating glass units supported by vertical composite glass fins.

The fins, with heights ranging from 8 meters to 17 meters, are designed as hybrid elements which combine the use of glass and steel.

The structural solution adopted comprises two solid steel flanges joined to a laminated glass web by a high-strength friction grip connection. Laminated glass with ionoplastic interlayer guarantees a suitable post-breakage behaviour. However, the use of friction grip connections together with laminated safety glass is technically demanding due to the creep behaviour of the interlayer. Therefore, in the areas of load transfer through the thickness it is is replaced by an stiffer material. This structural system poses several challenges with regard to design and fabrication and demand appropriate testing, although it offers a significant load-bearing capacity after failure of the glass web.

The design, simulation, testing and fabrication of the structural elements of the façade are discussed in the paper.

Keywords

structural glass, steel, friction joint, cold bent glass

Theme

Structural & Architectural Design - action engineering/wind-glass and steel

1. Introduction

The Iberdrola Tower, located in the city center of Bilbao, measures 165 meters and has a shape of a triangle prism with slightly curved sides. The office skyscraper, designed by Pelli Clarke Pelli architects, features an enormous lobby entirely enclosed by a sculptural glass pavilion (fig.1 and fig.2).

The complex changing curve of the wall façade is achieved by means of cold bent insulating glass units with different inclinations. The structural support of the façade consists of vertical glazed fins of up until 17 meters high and 0.5 meters deep spaced approximately 1meter apart along the wall façade. The upper part is a cantilever of maximum 4.5 meters above the roof line. These elements are designed and developed in collaboration with the architect, exploring for structural solutions which combine the use of two types of materials, glass and steel. The solution eventually adopted use a composite structure consisting of steel flanges bolted to a glass web.

The glass façade weight is transferred at the base of the fins while the wind loads are supported by the tridimensional structure of the roof and the base. The roof structure, trapezoidal in section, consists of a tapered steel lattice designed with circular hollow sections ramped from Ø 323.9 to Ø139.7 mm. This spaced frame is fully supported at one end to the main concrete tower structure and 23 meters apart by two columns which define the main entrance to the building. After this point, the lattice is extended as a cantilever 15 meters to form the entrance pavilion.

The present paper focus on the design, simulation and testing of the elements of the wall façade.

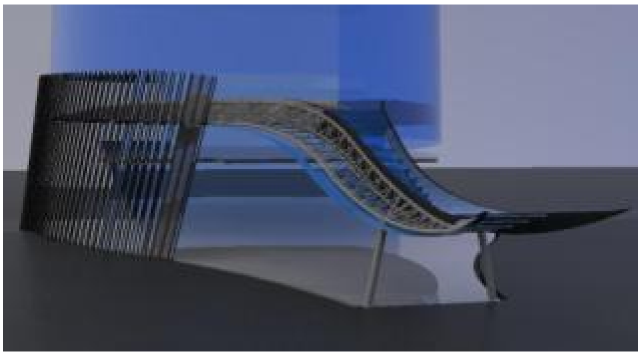

Figure 1: Render of the lobby of Iberdrola Tower Iberdrola Tower

Figure 2: View of the lobby of

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2. Steel-glass fins

2.1. Definition of the solution

The architecture tendency is the use of lighter and slender structures which implies the use of glass as structural element. The combination of glass with other materials opens up even more possibilities for achieving such slender structures with a high load carrying capacity and adequate post-breakage behavior.

For the lobby glazed fins, two types of hybrid constructions were investigated to arrive at the optimum solution in terms of architectural intent and safety design.

2.1.1 Option 1: Plate girder

The glazed fin consists of a composite section made of two circular solid steel S355 flanges 120 mm diameter connected to a toughened laminated glass web by means of a high-strength friction grip connection with tension control bolts, grade S10T M20 (fig.3). Bolts are located at 300 mm centers. The structural solution is inspired by the construction of built-up sections: the steel flanges transfers compressive and tensile forces while the glass web takes up primarily the shear forces.

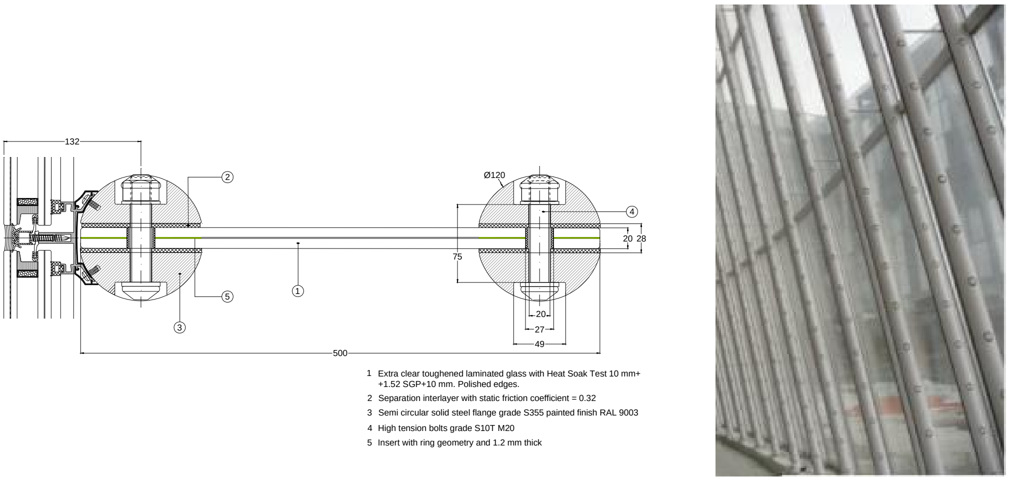

Figure 3: Plate girder fin

The magnitude of the normal, shear and bending stresses that the friction grip connection can carry depend directly on the contact pressure and the friction coefficient of the surfaces. Therefore, a high friction coefficient for the interlayer material between glass and steel is required. The friction grip connections are located close to edges in order to transfer effectively compressive and tensile bending stresses.

The loads in-plane are not directly transmitted between the edge of the glass hole and the side of the bolt and the use of oversized holes causes less stress concentrations on the glass surface. The shear forces are resisted by the frictions forces between the components of the joint.

From the aesthetic point of view, this design avoided the use of the metallic connections between the glass panes, so a great transparency could be achieved in the joints.

2.1.2 Option 2: Lattice girder

The alternative glazed fin is composed of two steel S355 circular hollow sections Ø121x25mm with triple laminated glass plates connected to them by means of steel chromosome-shaped web members which allow the glass to work as a membrane shell (fig.4). The contact between the glass and the steel cross is performed by means of an epoxy resin permitting only the transmission of compression forces. The structural system has the classical features of a typical truss beam: the glass elements replace the function of the diagonal struts acting in compression and the horizontal members placed in the glass joints carry possible tension forces.

In order to ensure a satisfactory bracing of the beam, the height of the truss glass elements should be half the height of the plate girder glass elements.

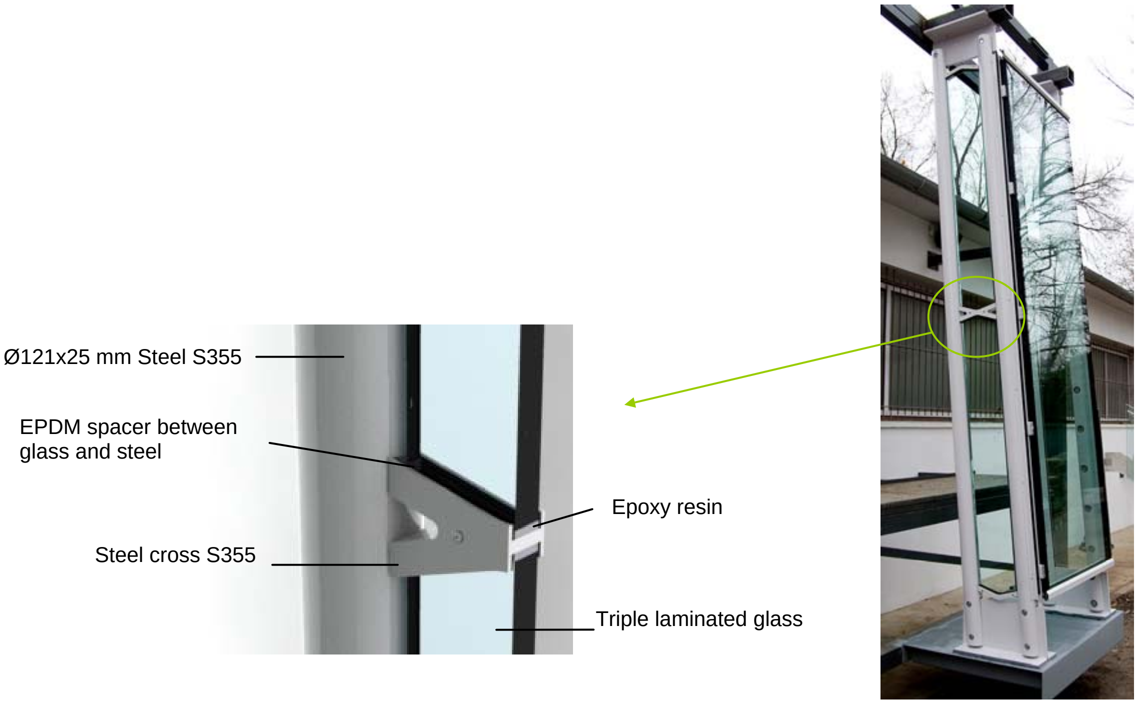

Figure 4: Lattice girder fin

2.1.3 Comparative performance study

The structural behavior of both types of glazed fin was found to be satisfactory under the most significant wind loads according to the wind tunnel test. The middle span deflection encountered for the lattice girder was approximately 50% larger than the plate girder deflection. Differences in deflection were due mainly to the contribution of the glass web members, which work as diagonals only in compression, to the global deflection of the truss beam in contrast with the plate girder where shear deformations are negligible. Concerning stresses, it was observed that the steel elements of both fins were not highly loaded whereas the glass elements were less stressed in the truss beam case principally due to the absence of holes.

Since the load carrying capacities of slender elements depends also on their local and global stability, structural buckling studies were performed. In order to prevent lateral buckling when the fin is subjected to the peak negative pressures, the bottom connection was designed as a fork support having the form of a shoe fabricated from flat steel plates and the top connection was laterally stabilized by a couple of stainless steel rods. Likewise a bracing system was provided at the top of the cantilever as a lateral restraint. On the other hand, the vertical loads from the façade should be considered as compressive forces having the capacity to induce compression buckling of the fin. The analysis showed that for both types of fin no buckling occurs under any load case.

Regarding the post-breakage behavior, it is noted that the structural redundancy of the lattice girder is higher since it has twice the number of plate girder glass webs. In comparative terms, it was considered the collapse of one glass element for the composite beam and two glass elements for the truss beam.

Figure 5 shows the overall deflections. Due to the chromosome-shaped rods located in the horizontal glass joints, the response obtained for the truss beam was the most satisfactory with respect to deformations and shape stability whereas the girder beam experimented an abrupt change in the geometry of the chords although within the admissible values. The calculations showed that the displacements obtained in the middle of the span for the composite beam had increased about 66% whereas for the truss beam about 26%.

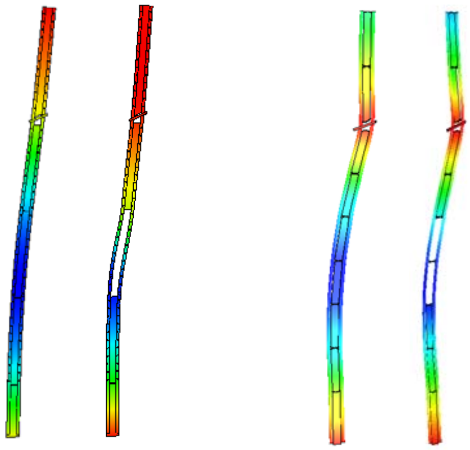

Figure 5: Plate girder and lattice girder deflections, pre- and post-glass breakage

The stress utilization factor of the composite beam steel chords was nearly doubled but was still lower than 100% whereas the resultant stress of the glass part had increased significantly without exceeding the maximum allowable stress. Otherwise, the stresses of both steel and glass part of the truss beam had not changed considerably.

2.2. Fabrication challenges of the solution adopted

The structural system eventually adopted was the composite steel-glass beam. This selection was based exclusively on aesthetic judgment since the both types of fin fulfilled the structural requirements.

For laminating the extra clear tempered glass panels the interlayer DuPont ™ SentryGlas® was chosen mainly for its high transparency, significant post-breakage behaviour and delamination resistance when exposed to the environment. However, the creep behaviour of the ionoplastic interlayer leads to the relaxation of the bolt pretension unless it is replaced in the areas of load transfer by an stiffer material. From the structural point of view, the post-breakage behavior in case of fracture of the two tempered glass plates was of special concern. For this reason, the SentryGlas® interlayer was replaced solely in the zone near to the bolt subjected to compression. Traditionally, and angle of 45º was considered.

One of the main aspects in terms of glass fabrication was to prevent the formation of air bubbles during the lamination process in the autoclave taking into account the presence of discontinuous elements each 300 mm made from different material than SentryGlas® interlayer. The glass manufacturer abilities played a major role in achieving this objective. Several options regarding the material were investigated: aluminium EN-AW5754 H111, stainless steel grade 1.4301 and composite material (glass fiber, rock wool, modified phenol resin, rubber). The selection of the right interlayer material entailed the fabrication of a series of samples and real scale prototypes for visual inspection and testing. As a result, constant adjustments in both the production method and thickness of the inserts were carried out. The inserts of friction composite material 1.2 ± 0.02mm thick with annular geometry and smoothed surfaces were finally used for this application since no defects were observed in the laminate even when exposed to temperature changes. The composite material showed also good chemical and mechanical compatibility with SentryGlas® (fig.6).

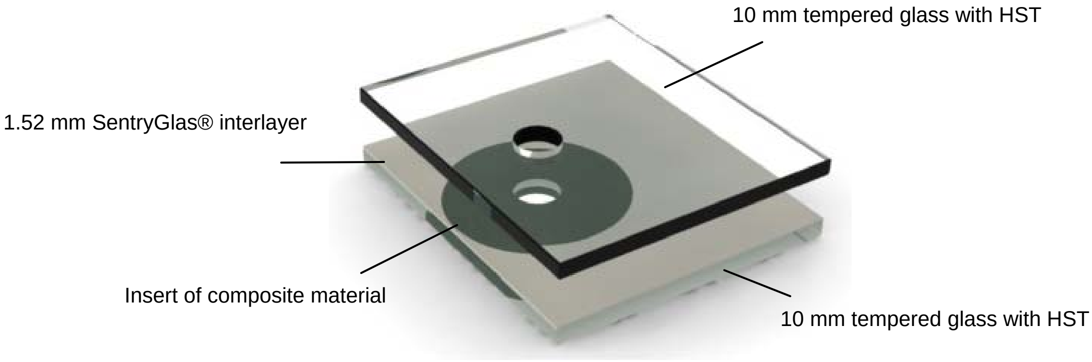

Figure 6: Glass web detail

Given the brittleness behavior of the glass coupled with the transmission of very high forces by the large number of friction grip connections along the fin, it was vital for success to avoid stress concentrations points on the glass surface, above all near the holes, when the bolts were tightened which would lead to fracture. Based on the experience acquired during the manufacturing of the preliminary prototypes, strict fabrication tolerances were requested before allowing the pre-assembly of the fin, listed below (fig.7).

A. Bar straightness tolerance on edge of 1mm/1000 mm and on flat of 0.10mm/300mm.
B. Bar twist tolerance of 0.05mm/total length.
C. Maximum allowable values for total and local warping of the glass of 0.0015 mm/mm and 0.3 mm/300 mm respectively measured according to the norm UNE-EN 12150-1.
D. Maximum offset of 2 mm between individual plies of the laminate.

E. Thickness tolerance of the insert ±0.02 mm.
F. Concentrity tolerance between the diameters of the ionoplastic interlayer hole and the insert hole in the laminate ±2 mm.
G. Painted steel contact surface irregularities up to 0.015 mm should be smoothed out.
H. Surface flatness of the mechanical intermediate joint between flanges ±0.5 mm.
I. Preload tolerance $^{+2}_{-2}$ kN.
J. Tidy finish of contact surfaces should be achieved.

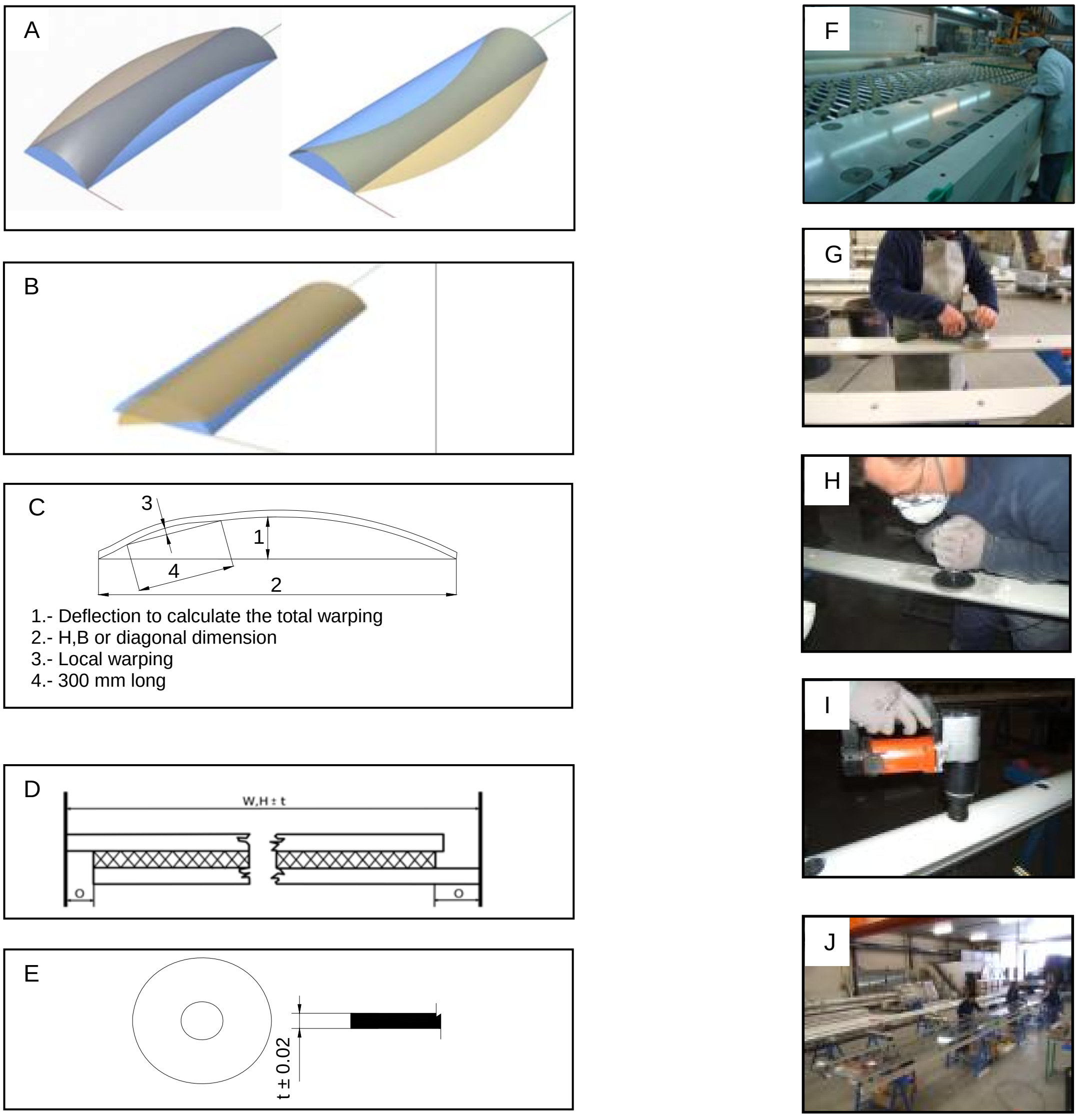

Figure 7: Factors influencing the glass stress state

Taking into account the complexity and the manual method of production, it was essential to prepare an strict fabrication and quality control manual for all parties involved in the fabrication process in order to avoid unwanted circumstances and thus respect the delivery terms.

The pre-assembled fin was maintained at a temperature of 30ºC for 12 hours and afterwards at a temperature of 60ºC for 4 hours by means of infrared lamps in order to evaluate his adequate performance under the creep deformation of the ionoplastic interlayer (fig.8).

Figure 8: Conditioning of the fin by infrared heating lamps

2.3. Testing

For proper material selection of the separation interlayer, the static friction coefficient should be determined by testing. The tests were carried out following the principles of the norm ASTMD 1894 [3]. Prior to testing, the 5 samples are to be conditioned at 48 hours at 23ºC ±2ºC, with a relative humidity of 50 ±5 percent. Furthermore, the test specimen and the glass base were kept in touch during a minimum of 30 minutes.

The friction joint composed basically by glass fiber, rock wool, modified phenol resin and rubber showed the best results. The resulting static friction coefficient was of 0.32 (fig.9).

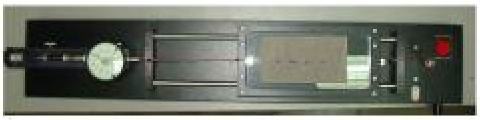

Figure 9. Device used to determine the static friction coefficient of the elastomer interlayer

Due to the creep behaviour of the elastomer material, a creep test of the preloaded connection was also performed. This test allowed to obtain the loss of the bolt pretension force with the time and thus determine if an additional tight of the bolts is necessary once the lobby façade is assembled.

For this purpose, two strain gages were installed on the bolt and connected to a Half-Bridge circuit, one active strain gauge and one passive. The high-strength friction grip connection was loaded at 172 kN and conditioned at 25ºC in the climatic chamber during 190 hours. As a result, an exponential creep curve was observed with a decrease of the pretension force about 4%. Afterwards, the temperature of the chamber was increased at 60ºC, the maximum expected service temperature, during 65 hours and the pretension force was decreased at 157 kN (fig.10).

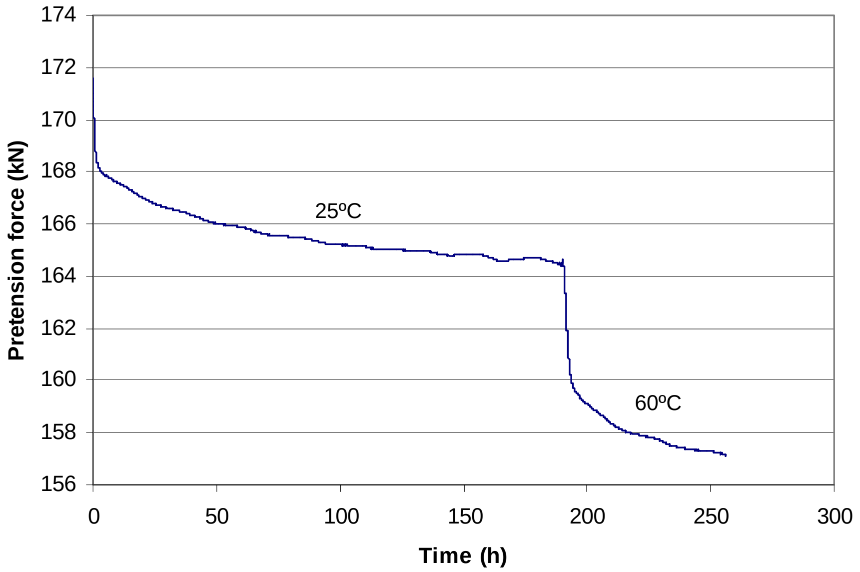

Figure 10:

Creep test pretension force pretension vs. time

In order to assess the structural behaviour of the composite fin and validate the numerical simulations, full-scale tests with 4 m span were carried out, a four-point bending test and a three-point bending test. The tests were conducted using a loading frame prepared specifically for this purpose and were monitored with stress and deflection control over the metallic and glazed parts by means of strain gauges and a displacement transducer. The load was applied statically with an hydraulic jack secured to the loading frame. Lateral supports were provided at the end of the beam to exclude lateral torsional buckling during load application.

The fin demonstrated substantially linear behaviour under proof test load. Strains and middle span displacements were reasonably in accordance with those predicted with the FEA model.

The failure load obtained for the four-pont bending test (fig.11) was considerably higher than the design load under the worse service conditions, 212 kN compared to 80 kN. It was observed that the glass failure occurs in the area between end supports and load applications points, where shear forces are located. It must be emphasized the high residual strength of the fin of 130 kN as well as its stability, thereby confirming a very satisfactory post breakage behaviour.

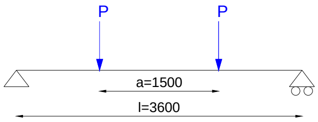

Figure 11: Full-scale four-point bending test set-up

The specimen subjected to the three point bending test included the joint of 8 mm between two glass panes since the glass web of the actual fin could not be achieved in one piece of glass. Results gave a shear resistance of 170 kN, significantly higher than the service design load of 40 kN. The beam also fulfilled the requirements regarding stability and post-breakage behaviour (post-failure load bearing capacity of 105 kN).

In addition, it was verified by testing the resistance of the cantilever beam connection and the mechanical intermediate joint of the flanges at the ultimate loading state.

3. Cold bent IGU

3. 1. Description

The cladding of the two façades of variable height, inclined and curved of the lobby has been performed by means of 1876 m^2 of cold bent glass composed of two 6.6 high strengthened laminates. Due to the long rectangular shape of the glass panes, they are easily twisted on site at ambient temperature forcing one corner of each plane out-of-plane to a maximum displacement of 44 mm. Each glass pane is about 3.5 m high and 1 m wide and is simply supported on 4 edges: the two short edges by the transoms via a cover capped system while the two long edges by the glazed fins via a toggle system (fig.12).

Figure 12: Lobby façade with cold twisted glass

3.2. FEA analysis

A dynamic transient finite element analysis was performed by means of ANSYS software in order to determine the magnitude of stresses due to cold bent process. Glass is supposed to be elastic while the PVB plastic interlayer is considered viscoelastic. The thermal and time dependent behaviour of the PVB is described with the mathematical model of relaxation (generalized Maxwell model). The data made available by Dupont allows to compute the shear modulus at any time and temperature by means of a shift function (William-Landel-Ferry).

Immediately after bending, the laminate behaves monolithically since full shear transfer in the interlayer takes place. The maximum principal stress obtained was 4.4 MPa. The figure 13 a shows the stress distribution in the plate applying the out-of-plane displacement of 44 mm at the right top corner during 3 seconds. However, one year later, a reduction of stresses is computed due to interlayer creep deformation. The figure 13b shows the maximum principal stress drop to the half approximately. Afterwards, a design load of 3.5 KPa and an additional climatic load due to the difference of height from installation and manufacturing place and temperature difference was applied to the model.

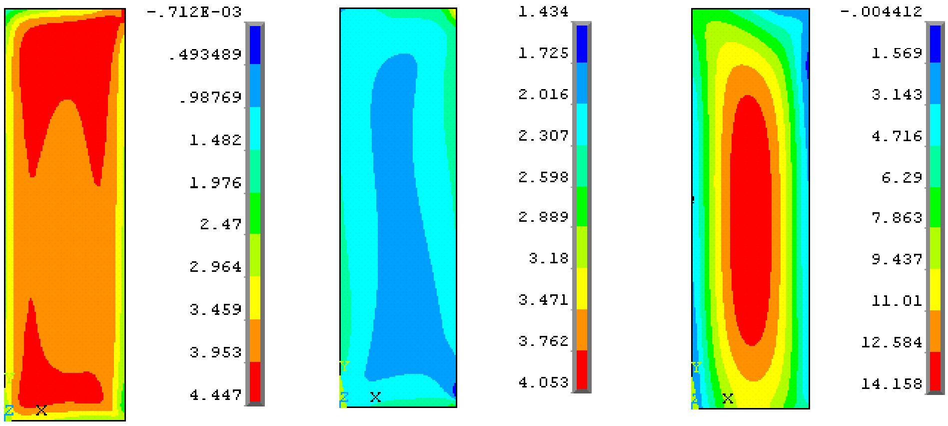

Figure 13 a,b, c: Maximum principal stress distribution after 3 seconds bending at 20ºC, after 1 year at 40ºC, after applying wind and climatic loads (MPa)

From the results obtained, it was observed that the contribution in the global stress due to the cold bent process was not critical since the glass curvature is small.

3.3. Testing

The main concern of the warped glass pane was the adhesion and tightness of the outer leaf of the IGU bonded along the two long edges by the structural silicone. The ageing resistance of the perimeter silicone sealing as well as the butyl joint, even when exposed to moisture and increased temperature over a long term period was proved by testing according to the EN 1279-2 [4]. An average index of moisture penetration of 0.11±0.02 was obtained, well below the limit value of 0.20.
Once selected the best appropriate design and construction solution, it was created a full size prototype of the façade system including all the support elements in order to inspect visually the finished quality and interface items. After approval of appearance, the mock up was subjected to a series of tests aimed at demonstrating the conformity of the product according to EN-13830 [5]. The test sequence included the following points:

- Measurement of air permeability at peak positive test pressure up to 600 Pa.
- Water penetration resistance at static pressure up to 600 Pa (fig.14).
- Wind resistance- serviceability test under the design wind load (fig.15).
- Air permeability test. Repetition .
- Repetition of the test of water tightness at static pressure up to 600 Pa.
- Water penetration resistance-dynamic test at a pressure of 600 Pa.
- Wind resistance-safety test at a peak pressure equal to 1.5 times the design wind pressure.
- Self weight test.
- Impact resistance test (fig.16).

The results demonstrated compliance with the requirements provided for the performance characteristics associated with air permeability, water tightness and resistance to wind load of curtain walling.

Figure 14: Water penetration test

Figure 15: Wind resistance test. Displacements transducers

Figure 16: Impact test

4. Conclusions

The façade composite steel-glass fins of Lobby Iberdrola permitted to achieve the geometrical requirements, length up to 17 m and 0.5 m deep, with high structural efficiency. The design incorporated the characteristics of a typical built up section making use of high strength friction grip connections for joining the glass web and steel flanges. However, the brittleness of the glass presented a major challenge in terms of engineering, manufacturing and safety.

In addition, the cold bent IGU glass skin in front of these steel and glass mullions made the whole façade structure to be design-driven by the limited glass knowledge and experience.

Appropriate testing and redundancy were keys to assess the structural behavior as well as the post-breakage stability.

5. Acknowledgement

Client: IBERDROLA

Architect :	Pelli Clarke Pelli architects	Axel Zemborain
Façade engineering consultant:	Buro Happold	Francesca Madeo
Structural engineering consultant:	IDOM	María del Mar Mayo
Project manager:	Technical office Iberdrola	Elena Lázaro
Design and construction:	Bellapart	Francesc Arbós, Joan Colom, Sergi Plana, Jordi Vilà Carles Teixidor

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