Bellapart

THE NEW GLASS FLOOR AND GLASS BALUSTRADE FOR THE RENOVATION OF THE EIFFEL TOWER'S 1ST FLOOR AND THE PAGODA'S GLASS FAÇADES FOR THE ELEVATORS

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Abstract

The new first floor of the Eiffel Tower, designed by Moatti-Rivière architects, features a transparent glass flooring and balustrades around the central open space giving an extraordinary view of the city below and of the tower itself. The glass floor, located 57 meters above the ground, is made of three layers of laminated safety glass with an anti-slip top surface. The slightly inclined glass safety balustrade protects the interior perimeter of the opening and includes a hinge mechanism to allow cleaning at both sides of the barrier. The use of glass in this application required comprehensive testing and structural redundancy. Curved glass was used to create a variable transparent surface sheltering the North and West lifts. The substantial dimensions of the glass units and the confined work space required great skill and care in its installation. The design, testing, fabrication and installation of the glazed elements will be discussed in the paper.

Introduction

On 6th October 2014 the mayor of Paris inaugurated the newly renovated first level glass floor of the Eiffel Tower, designed by Moatti-Rivière. One of the most crowd-pleasing elements is the glass skywalk which encircles the central opening of the tower providing a new perspective on the city of Paris (Figure 1). The new glazed floor allows visitors to walk 57 meters above ground and gradually increases transparency from the interior towards the central space providing an impressive experience whereas the glass balustrades of 2.6 meters in height provide adequate fall protection. The refurbishment also incorporates the North and West lift shafts. The façades have a square base with round angles and follow the obliquity of the tower´s piers. Double curved glass was used to achieve the desired transparent surface. This paper concentrates on the design of glass elements, where real-scale tests were an essential part of the process.

Fig. 1. View of the Eiffel Tower's glass floor and balustrade

Glass floor

The new 120 m2 glass floor surrounding the central space area has been the subject of a technical assessment of experimentation (ATEx) by CSTB.

The 32 mm thick tile is made up of laminated safety glass of three layers and has dimensions of 3.87 m x 0.7 m with a load-bearing capacity of 6 kN/m2. Low iron glass was used to reduce the green appearance as much as possible. The sacrificial top lite is toughened for better impact resistance and not included in the stress calculations although has been considered for deflection. To provide the most effective post breakage behaviour the lower two sheets underneath the anti-slip lite have been heat strengthened.

The SentryGlas® interlayer was selected for its superior structural features allowing to minimize the overall laminate thickness and therefore to comply with the current weight restriction applied on the existing main structure of the Eiffel Tower. Moreover, the interlayer does not add any color to the laminate and offers delamination resistance when exposed to the environment. Above all, this interlayer provides significant structural performance in case of accidental glass breakage.

The glass floor assembly ensures water tightness and has a slope between 1-2% in order to guarantee that the water flows properly towards the existing gutters to avoid rain in the Eiffel Tower Square. Each floor panel is clamped between the structural beams and the brass cover plates and bolted together through a non standard pig nose brass screws to avoid public removing them. To ensure the right position of every panel, elastomeric gaskets of adequate thickness and width were placed on top of every beam. Top layer pane position has been considered a bit retracted with regards to the structural panels in order to guarantee an aligned image between the cover plate and the top surface. With this action a flush appearance is achieved. (Figure 2).

Glass panels are linearly supported on all four edges under downward loads and restrained on the two long edges against uplift. Analytic formulas were used to make structural calculations as specified in section 2.2 of the Technical Assessment (Avis Technique) of SentryGlas® [1] for the equivalent thickness and the specifications defined in CSTB's book nº3448 [2]. On the other hand, non-linear finite element analysis were also performed for every load case taking into account the real properties of the ionoplastic interlayer.

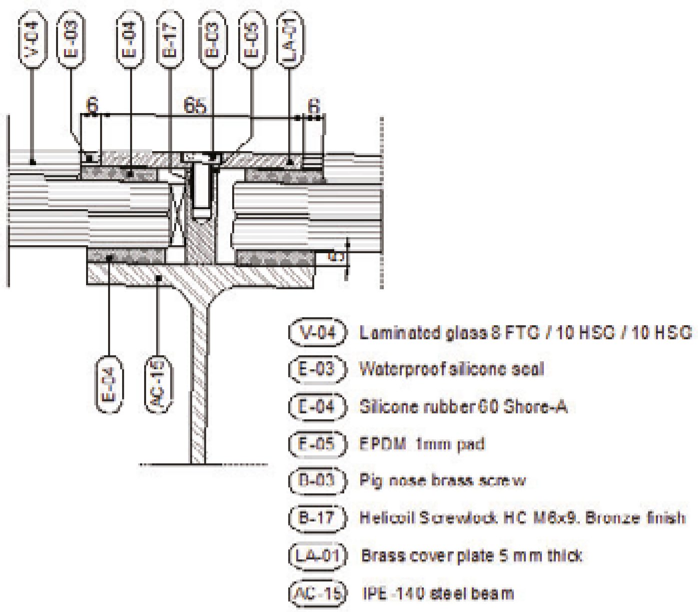

Figure 2. Detail of the glass floor

The results obtained following both methods, analytical and finite element, were satisfactory in terms of deflections and stresses. In order to assess the structural behaviour of the glass floor panels and validate the calculations, the following tests were undertaken:

- Hard body impact test with a steel ball of 1 kg dropped from a height of 1 meterproducing an energy of 10 Joules (Figure 3).

- Punch test on the sacrifice layer applying a concentrated load of 2 kN around a 25 mm diameter surface according to NF P06-001 [3].

- Point loading test of 2 kN applied in the worst point location in a 40x40 mm area. The load was applied with an hydraulic jack during 1 day (Figure 4).

- Uniform loading test to simulate the specified live load of 6 kPa under ULS using sandbags. The sacrificial layer was deliberately broken prior to the test since it had not been considered from a structural point of view. (Figure 5).

- Post-breakage test. One structural glass component was broken in order to check the overall glass pane stability.

All tests carried out confirmed that the glass floor was capable of supporting without failure the designed loads and had sufficient redundancy to provide adequate safety in case of glass accidental damage. A bespoke anti-slip treatment (LiteFloor XtraGrip) was especially developed by the glass supplier in order to ensure the most transparent appearance but at the same time to guarantee a safe walking surface for the public. The slip resistance of this silk-screen print applied on the top surface was tested according to ASTM 1679-04 [4] obtaining a slip resistance coefficient of 0.8 under wet conditions and according to EN-12633 pendulum test method description [5] resulting in a slip resistance value Rd of 45. In order to check the aesthetics and mechanical durability, an abrasion test was performed according to EN 14411 [6]. The preventive maintenance program also includes periodic testing to verify that the anti-slip resistance is still within the agreed range.

Fig. 3.Hard body impact test

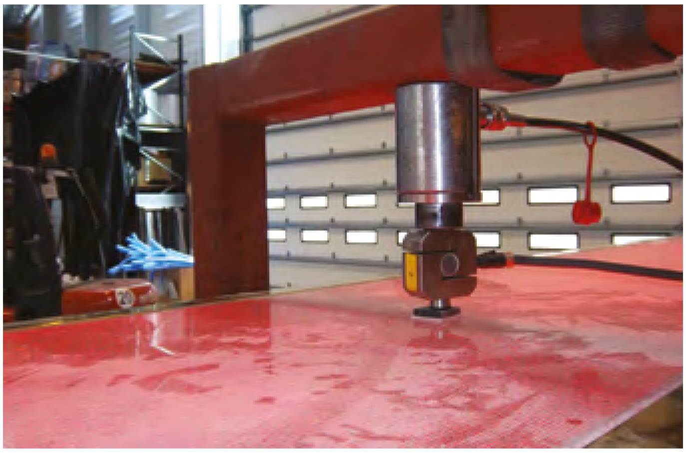

Fig. 4. Point loading test of 2 kN

Fig. 5. Load bearing capacity test on the glass panel under ULS (9 kPa)

Glass balustrade

The inclined safety glass balustrade of 2.6 meters in height is aligned with the interior perimeter of the first floor's central void. The structural support of the balustrade is made of tapered T-shaped beams fixed to the perimetral floor steel beam each 0.95 meters through bolted connections.

The bottom part of the glass balustrade is composed of two lites of heat strengthened glass with a thickness of 6 mm and one lite of tempered glass with a thickness of 6 mm laminated together with a 1.52 mm SentryGlas® interlayer. This bottom pane is continuously clamped to its supports through 3 of its edges with a capped system leaving a frameless top edge. The cover plate was specially designed to fit a light system (Figure 6).

Several physical tests were performed on a real-scale mock up according to NF P01-013 [7] and the CSTB's book nº3034 [8]. The static load test verified the strength and - 21 - GPD Glass Performance Days 2015 Glass in Structural Applications remaining deformation performance of the balustrade when applying the considered horizontal load for public spaces of 3 kN/m during 3 minutes to the balustrade. The remaining displacement of the top edge was less than 3 mm. The balustrade provided adequate load bearing capacity even to withstanding an horizontal factored load of 9kN/m (Fig. 7).

The balustrade was also subjected to soft body impact test at an energy level of 900 J resulting in no damage. Afterwards, a hard body impact test of 3 J was also carried out to the glass

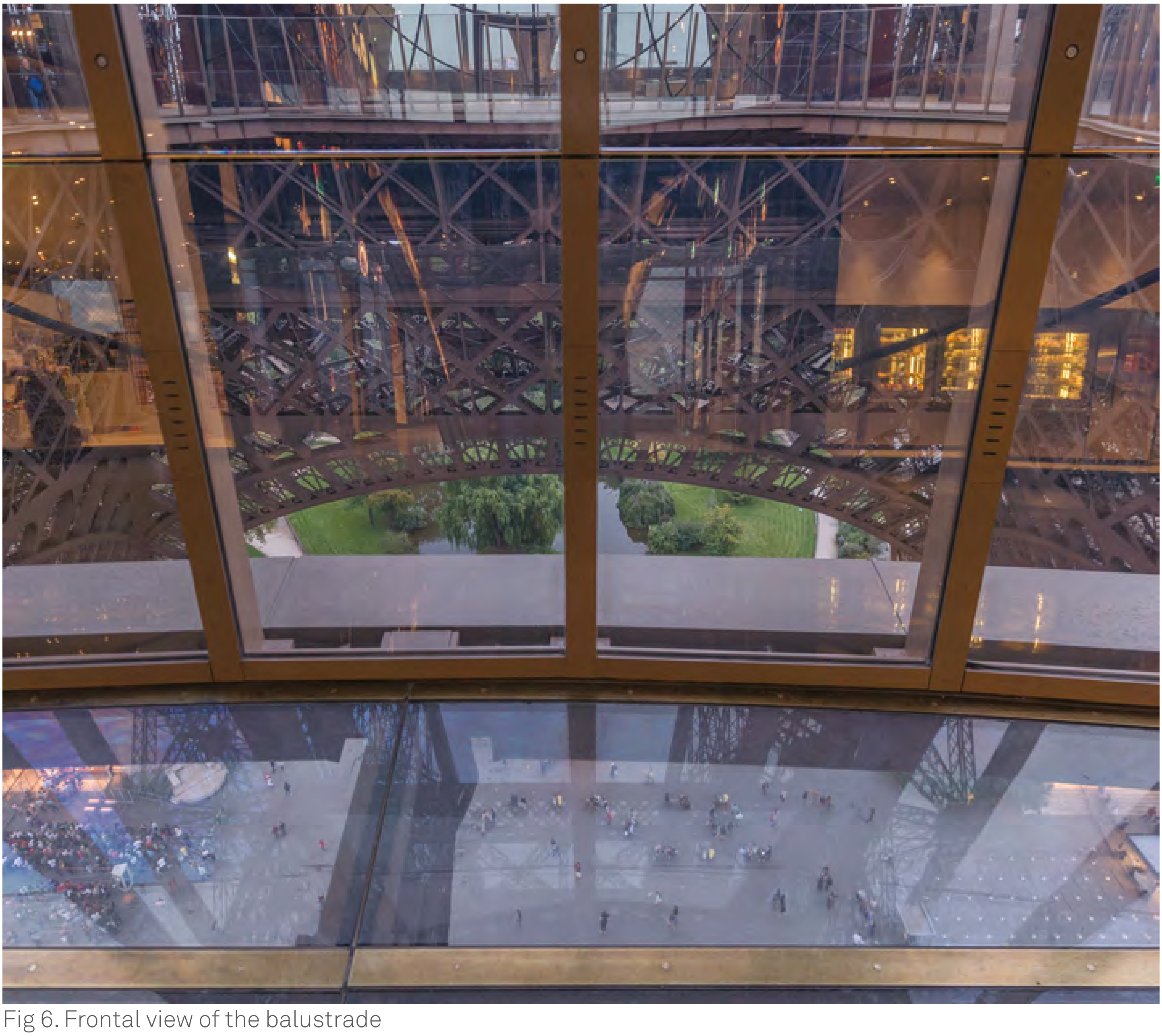

Fig 6. Frontal view of the balustrade

Figure 7. Application of an horizontal factored load of 9 kN/m

pane noting no visible damage on it. Finally, an impact energy test of 10J was applied onto the glass finalizing with the break of one of the glass components without compromising the integrity of the assembly. Moreover, no fragments of glass were detached from the ionoplastic interlayer.

The upper part of the balustrade includes a hinge mechanism detail, designed with a stainless steel gas spring system to allow cleaning on both sides of the barrier. In addition to this, a serrated top edge is included to prevent climbing and is also used as a bird deterrent. These elements are secured enough with concealed fixings specially designed in close collaboration with the architect in order to achieve a lighter appearance. Furthermore, static and dynamic wind loading tests were performed on a real scale prototype of the window to check its resistance against uplift (Figure 8).

Pagoda's glass façades

The north and west elevator shelters, where visitors wait for the cab, create an oblique volume comprising two floors of which the base is a square of 10x10 m with round angles and the axe follows the inclination of the Eiffel Tower's piers. The top of the cylinder is cut by an inclined plane resulting in second floor glass panel heights ranging from 1.8 to 3.3 meters. The inclined transparent façades incorporate three entrance doors. The doors are vertical and always located inside the cylinder envelope for both positive and negative tilt angles of the façades with respect to their verticality. The voids created between the door and the façade are covered by fitted metallic triangular sheets. A 3 D model was used for the design development in order to define the constructive geometry of all the façade components avoiding any interference with the supporting structure. The flat and single curved glass panels are

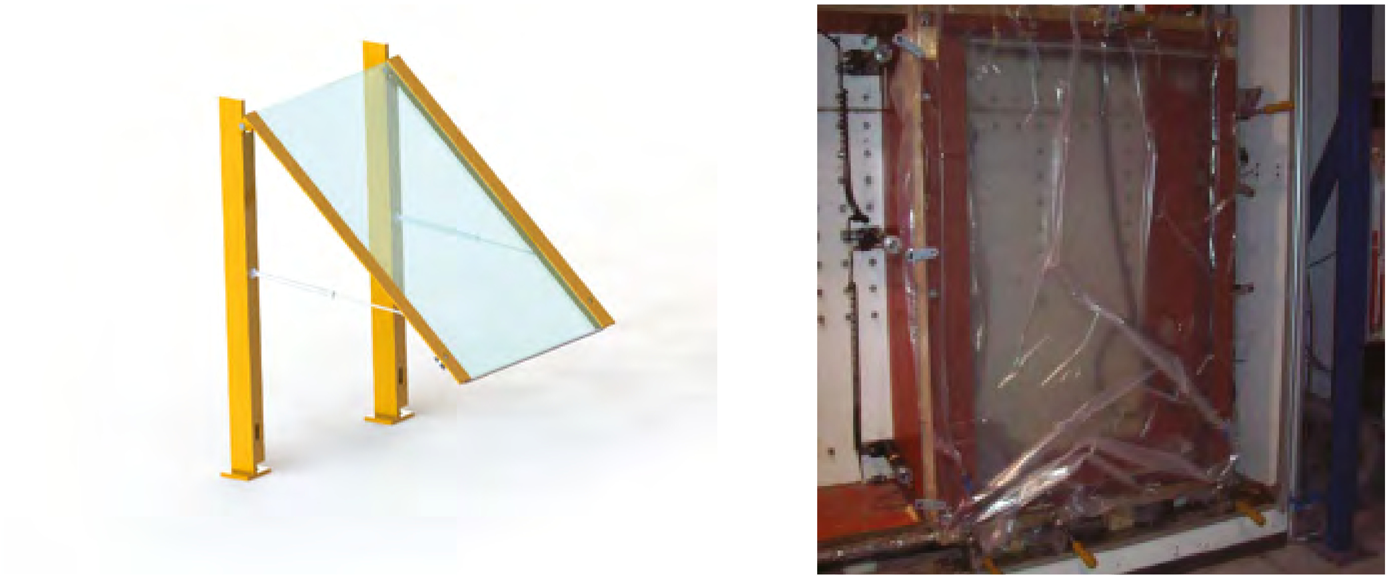

Fig. 8. 3D model of the window mock-up and wind loading test performed on it

composed of two heat-strengthened layers 8 mm thick laminated together with a 1.52 mm SentryGlas® interlayer.

The top and bottom edges are continuously supported whereas Figure 7. Application of an horizontal factored load of 9 kN/m Figure 8. 3D model of the window mock-up and wind loading test performed on it clamp fixings are used at the vertical edges. Double curved float glass was used to achieve the smooth transition between the different inclination of the façades at the second floor (Figure 9).

Fabrication and installation

The glass floor's supporting steel structure was integrated inside the existing structure of the Eiffel tower avoiding any interference with it. The geometry was designed in such a way that all the triangles and elliptical parts had the same size following the most restrictive gap tolerances defined in the site survey. As a result, the number of references were minimised simplifying the manufacture and installation processes. Once the main structure responsible for supporting

Fig. 9. Pagoda's glass façades for the elevators

the floor planks was manufactured, it was pre-assembled on the workshop in order to ensure an accurate position of each element following the designed geometry. (Figure 10).

The nature of the project implied a number of limitations during the construction progress. The installation was undertaken on a site really close to the Eiffel Tower structure and works of demolition were carried out around the area, so a high-precision and well coordinated execution was essential during this stage. Lifting and positioning works of the main structure, with a total length of 12 m and a weight of 2.2 tons, was carried out by a bespoke lifting system in a really small place were a spider crane did not fit. Since The Eiffel Tower is protected as a historical monument, welding to the existing structure was not allowed. Clip systems or bolted connections were employed to attach the new structural elements and special attention had to be taken to prevent interference with the large number of existing rivets. However, despite the specific site constraints the tower was never closed to the public during installation.

Conclusions

The recently renovated first level of the Eiffel ower enhance the visitor's experience by providing a new way to explore the city of Paris and the tower itself. The use of laminated safety glass with ionoplastic interlayer was a key element to achieve the impact resistance, load capacity and residual strength required for this project.

During the installation phase, additional challenges were faced such as site access, material logistics and execution accuracy.

Fig. 10. Glass floor structure fitted to the existing Eiffel Tower's structure

Fig. 11. View on the glass floor

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