Superstructures of the CEVA Railway Stations

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Abstract

An innovative modular construction system is developed to design the superstructures of five railway stations on the new CEVA railway in Geneva, Switzerland. It involves large scale glass bricks façade elements supported by exposed slender steel structures that are integrated in the building envelope. The system adapts to each building particularities and environment to create unity among the five stations in the city. The glass bricks are large scale façade, roofs and floor glazed elements. The steel structure elements are welded built-up box sections with a constant width. Glass bricks and steel structure elements are designed with the same thickness to flash. This innovative modular construction system leads to many challenges in both façade and steel structure design to create a strong visual identity of the CEVA railway which is a "megastructure" composed of multiple bridges, tunnels, cut-and-covers and stations.

Keywords: CEVA project, glass façades, glass bricks, steel structures, welded built-up sections, 3D structural analysis, non-linear analysis, dynamic analysis

1 Introduction

The CEVA railway is a new 16km line that closes an historical gap between the Swiss Federal Railway and the French National Railway by connecting Geneva Cornavin main station in Switzerland to Annemasse station in France. This bidirectional mainly underground railway line connects the transborder Geneva area (Figure 1).

Structures such as bridges, tunnels, cut-and-covers as well as stations are located on this new line. They create a "megastructure" scattered on the territory for a total cost of 1.6 billion CHF. Station infrastructures are concrete load bearing structures such as diaphragm walls, basements, slabs and walls. Superstructures are the stations exposed structures, such as walls, roofs, floors and footbridges. The five new stations of Lancy-Pont-Rouge, Carouge-Bachet, Champel-Hôpital, Genève-Eaux-Vives and Chêne-Bourg are scattered in the city. Stations lengths range from 180m up to 450m while heights range from 5m to 25m.

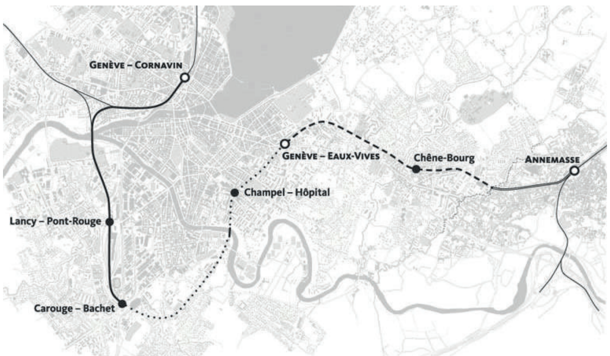

Figure 1. Overview of CEVA project

The client is the Swiss Federal Railways and Geneva Canton. It organised a competition in 2004 to design the superstructures of the five railway stations with the scope to create a unified architectural expression for the five stations. The winner of the competition is a team composed of the architects Atelier Jean Nouvel in Paris, EMA architects in Geneva and INGPHI Structural Engineers in Lausanne. The contractor is SHZ, a consortium composed of Sottas, Hevron and ZM companies in west-Switzerland.

After over ten years of planning and designing the superstructures construction started in 2015 and will be completed in 2019.

2 Innovative modular system

An innovative modular construction system is developed to design the superstructures of the five railway stations (Figure 2). This creates a strong visual identity and unity between five stations of various size and shapes. This system involves large scale glass bricks supported by slender steel structures. The glass bricks are intended to bring light down to the underground platform while pixelating, diffracting and recomposing the movements of trains and passengers. The slender steel structure elements are welded built-up box sections with a constant width. However, differently from traditional glass façade systems such as curtain wall and column-beam, the load bearing structure is integrated into the glazed façade plan. Glass bricks are inserted between steel structural elements. All glass bricks have the same dimensions and all steel elements are located on a grid. All elements are designed with the same thickness to flash and lead to a unified system.

Figure 2. Competition photomontage of the Chêne-Bourg station (AJN-EMA)

Moreover, the system is developed to adapt to all building elements in the five stations such as walls, roofs, floors, fireproofed floors and footbridges with multiple glass brick and steel section topologies.

3 Large scale glass brick

The large-scale glass brick is the central element of this innovative modular construction system and governs the architectural design process. It originates from the small glass bricks developed by Gustave Falconnier in 1893 in Nyon, which nowadays belongs to Geneva area. These small glass bricks were fabricated by a blowing process similar to bottle fabrication and sealed air-tight to provide enough resistance to be used like ordinary masonry bricks.

In this innovative modular system, these small glass bricks are scaled and magnified to reach the standard dimension of the large-scale glass brick: 5.40m by 2.70m. These dimensions create the grid of the five stations project. Trains, passengers as well as static images are pixelated, diffracted and recomposed by the glass bricks as illustrated in Figure 3.

Figure 3. Pixelated image(AJN-EMA)

However, these large-scale glass bricks do not work as real bricks. They are called "glass bricks" as they have the aspect of traditional glass bricks as illustrated in Figure 4. Since the glass bricks are façade elements, they do not carry loads. The steel structures are the load bearing structures.

Wall, roof, floor and fireproofed glass bricks are different. They are described below.

Figure 4. Large-scale glass brick

The wall glass bricks are made up of multiple glass panels as presented in Figure 5. Two square moulded glass panels are placed inside two front toughened laminated extra white glass panels. These four glass panels are glued to a steel frame. Wall glass bricks are waterproof and airtight. Since filters allow for inside and outside pressure balance, they are called breathing glass bricks. The pixelating effect is provided through light diffraction in both square glass panels.

The wall glass bricks are fixed to the steel structure through supports on the lower beam as well as lateral and upper fixations against the columns and the upper beam. Waterproofing between glass bricks and steel structure is provided by EPDM joints.

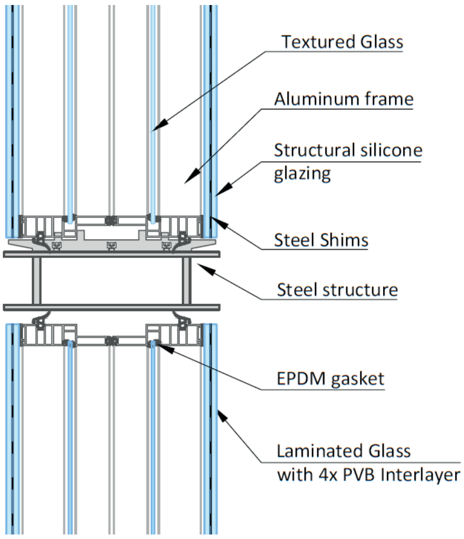

Figure 5. Composition of façade glass brick

The roof glass bricks are made up of a printed PVB interlayer toughened laminated glass panel glued on a steel frame. The frame is supported by roof beams and fixed on sockets that are welded on the top of roof beams. Both solar protection and pixelating effect are provided through square pattern printed on the PVB interlayer. Waterproofing between the glass bricks and the steel structure is provided by EPDM gaskets and silicon sealants.

The floor glass bricks are made up of a three-layer toughened laminated safety glass panel glued to a steel frame as illustrated in Figure 6. As for roof glass bricks, the frame is supported by floor beams and fixed on sockets that are welded on the top of floor beams. Waterproofing between glass bricks and steel structure is provided by EPDM gaskets and silicon sealants.

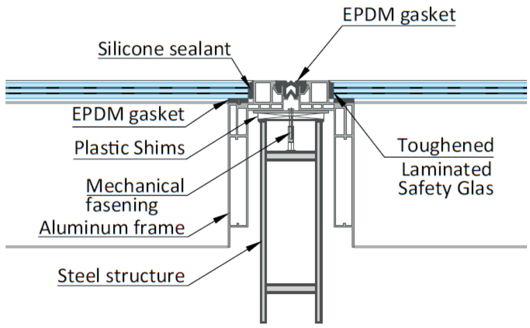

Figure 6. Composition of floor glass brick

Fire-proof floor glass brick are situated above rail tracks to prevent flames and smoke expansion in situation of carriage fire. Underlayer EI60 glass is added to the standard floor glass brick. This glass is composed of three layers of tempered glass with intumescent interlayers. Plaster layers are integrated to the glass brick to cover the steel structure elements.

The total façade, roof and floor areas cover 28'000m^2.

4 Steel structures

Longitudinal section and typical cross-sections of the 450m-long Genève – Eaux-Vives station are presented in Figure 7 and 8 as an example to illustrate the modular construction system that adapts to the five stations.

Slender steel structures carry the 5.40m x 2.70m glass bricks to create walls, façades, roofs and floors. Symbolically the steel structure is the joint between the large-scale glass bricks as mortar would be between traditional glass bricks. The main primary load bearing structure of the stations superstructures are steel frames with heights ranging from 6m to 25m and spanning up to 25m. They are placed on a 5.40m grid. Secondary structural elements such as façade, roof and floor beams are 5.40m long with 2.70m spacing. They are bolted to the steel frames. Stability is provided by stiff angles, anchoring against the reinforced concrete infrastructure and x-bracings.

Expansion joints are placed every 20m between two x-bracing layers. They are made by bolting secondary structure elements to the steel primary structures with oblong holes.

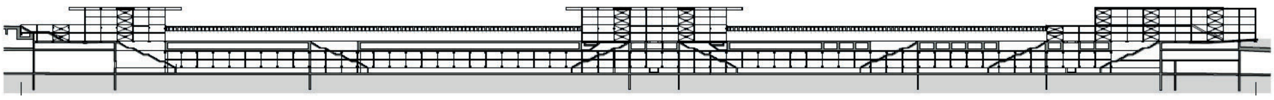

Figure 7. Longitudinal section of Genève – Eaux-Vives station

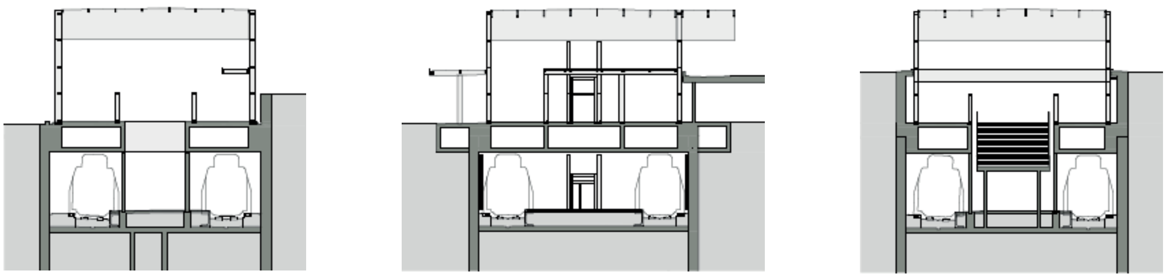

Figure 8. Cross-sections of Genève – Eaux-Vives station

Columns, roof beams, floor and footbridge beams as well as secondary structures have the same width of 120mm to build a modular grid in which glass bricks are inserted. The section is a welded built-up box section with a 60mm offset of the frontal plates, as illustrated in Figure 9 for multiple applications. Steel plate thickness and static height vary according loads and actions. Thick plates, reinforcement plates and solid steel are involved to design sections of highly stressed elements such as cantilevers and high columns.

The steel plates of the box sections are welded together in the 60mm negative offset of the section. Since internal stiffeners need to be welded on the four box sides plug welding are executed after closing the box to connect internal stiffeners to the fourth section wall. After welding, workshop retouching was required to control section geometry, as welding heat creates deformations such as shortening, bending and out-of-plan wall bending.

The anticorrosion treatment is a Sa 2½ sandblasting, and three layers of 80µm two-components painting.

The total steel tonnage is 3'300t of S355J2 quality steel.

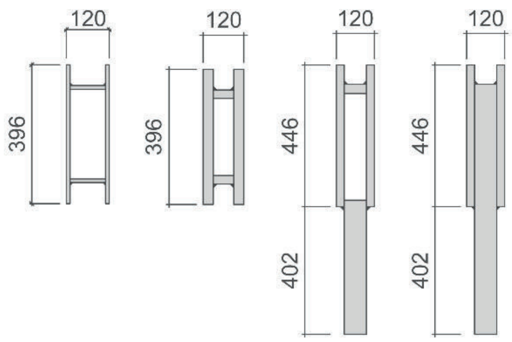

Figure 9. 120mm-wide box sections

5 Steel frames

5.1 Introduction

The main primary load bearing structures of the stations superstructures are steel frames. Among the five stations, the steel frame heights range from 6m to 25m and span up to 25m. They are made-up of 120mm wide columns and 3m-high, 120mm-wide roof beams, as illustrated in Figure 10. Roof beam section vertical walls are 10mm-thick plates. Therefore, frames are subjected to three non-linear effects that can lead to instabilities:

- Roof beam steel plates buckling
- Roof beam lateral torsional buckling
- Column buckling

Steel frame USL verifications are carried out through both active area method and geometrical, material non-linear calculation.

Figure 10. 3m-high and 120mm-wide roof beams

5.2 Active area method

Following [3], instabilities are considered in ULS verifications through strength reduction factors for each element, regardless of the stress level. The ULS verification method is chosen according to the cross-section plate slenderness.

Since the roof beam section vertical wall plates are slender, the cross-section belongs to class 4. Therefore, the *elastic-reduced elastic* method is used to verify roof beams. Forces are determined in elastic state and strengths are computed in elastic state on the active area of the section only, to consider the vertical steel plate buckling. The reduced cross-section is illustrated in Figure 11.

The design lateral torsional buckling resistance moment is calculated for the reduced cross-section with buckling length equal to secondary the roof beam spacing, 2.70m. Since the cross-section belongs to class 4, no uniform torsional resistance is available. The lateral torsional buckling elastic stress is equal to the nonuniform torsional component considering one third of the active compressed vertical webs.

For all stations, lateral torsional buckling factor is equal to 0.75 and lateral torsional buckling resistance moment is equal to 7'000kNm with slight variation between the situations.

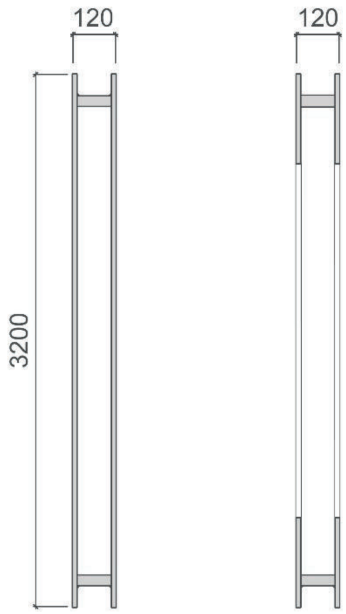

Figure 11. Roof beam cross-section and active area

Since column cross-sections belong to class 2, *elastic-plastic* method is used to verify columns. Steel frame column in-plane critical buckling length is computed from the Euler critical load of the frame. The Euler critical load is calculated using the linear instability method. Out of plane buckling length is equal to the 2.70m spacing between the façade secondary beams. Among the five stations, column design buckling resistance ranges between 2'000kN and 10'000kN depending on the situation.

5.3 Non-linear analysis

Instabilities as well as potential global instabilities are verified through a geometrical and material non-linear calculation. A single frame is analyzed using Ansys finite element analysis software.

Beams and columns are modeled with Shell181 elements that allow for material and geometrical nonlinear calculation. Dead load, snow and wind loads are applied on the frame. Load level is increased incrementally. At each time step, displacements and forces are computed and the stiffness matrix is updated considering geometrical and material contribution until load factor reaches 2.5. Although bubbles in the roof beam wall, lateral torsional buckling of the roof beam, as well as buckling of the columns are observed, the structure remain stable when forces equal 2.5 times ULS design load situation (Figure 12 and 13). No critical divergence is detected.

The non-linear analysis confirms the verifications that are carried out with the active area method for these steel frames that are made up of unconventional steel sections.

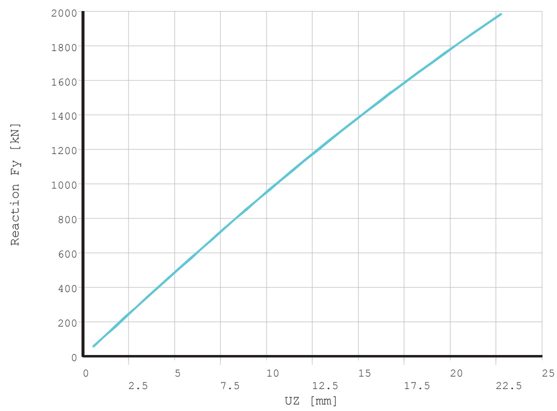

Figure 12. Load-displacement curve up to 2.5 load multiplication factor

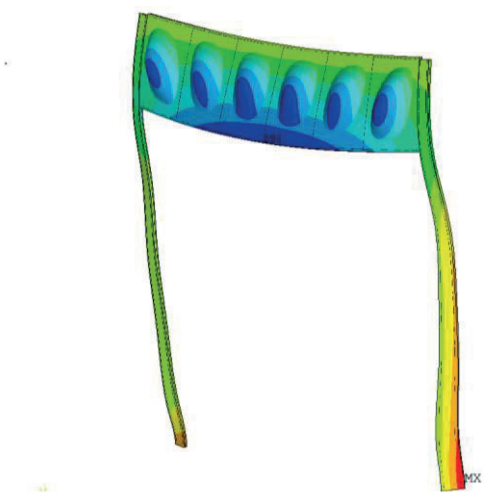

Figure 13. Transversal deflections under a 2.5 load multiplication factor.

5.4 Serviceability

Since these steel structures carry glass elements, the design is manly governed by serviceability to avoid fragile rupture of glass elements, fixation rupture and waterproof joint damage. The steel structures need to be stiff enough while keeping the 120mm-wide section and the 60mm-offset. Thick section walls as well as full steel sections are required for highly stressed elements such as cantilevers and high columns to satisfy the h/500 displacement limit imposed by [1].

6 Footbridges and floors

Footbridge and floor structures are designed for Champel-Hôpital and Genève-Eaux-Vives stations. These structures are subjected to resonance under pedestrian walking action. According to [2], natural frequencies lower than 2.5Hz for horizontal modes and 4.5Hz for vertical modes are in the discomfort range. While Genève-Eaux-Vives floor natural frequencies are higher than these limits, Champel-Hôpital floor first horizontal mode frequency is equal to 2.7Hz and first vertical mode frequency is equal to 3,4Hz (Figure 14), thus in the discomfort range. However, this vertical natural frequency is acceptable since the vertical acceleration is lower than 2,5ms^{-2} [4].

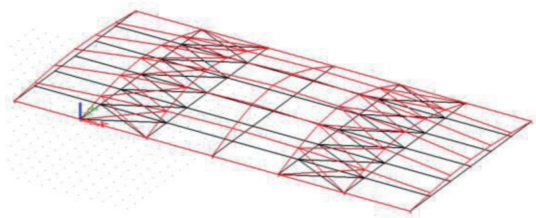

Figure 14. First vertical vibration mode of Champel-Hôpital mezzanine floor (3,4Hz)

7 Connection design

Connection design of exposed box sections is a challenging task since out-off-plan steel plate solicitations should be avoided and bolts should be hidden. Moreover, space is tight between the glass bricks.

Column footings are bolted to the reinforced concrete infrastructure as illustrated in Figure 15.

Figure 15. Column footing

Threaded rods are embedded in a blockout to hide connection elements. Diameter and position of the holes in the connection plate are adapted to fit with embedded threaded rods. After erection, position setting and bolt tightening, blockouts are filled with mortar.

Façade Column-beam connections are made through bolting the off-set beam vertical plate to two steel plates that are welded on the column (Figure 16). Oblong holes are executed on the two plates to create an expanding joint. Tightening torque is adapted to the connections type: x-bracings, expansive joints and standard connections.

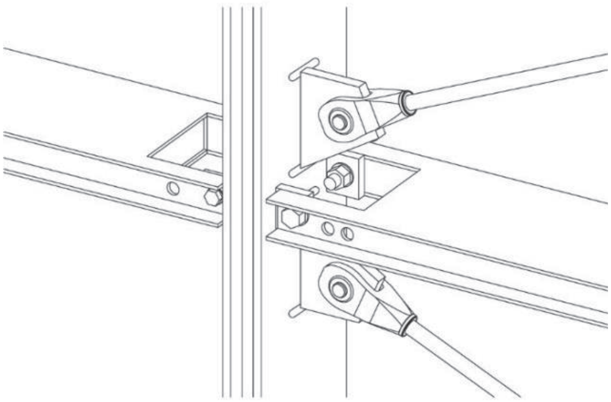

Figure 16. Column-façade beam connections

Roof beams and floor beams are connected to columns through on-site welding to create steel frames. Beam-column connections are made through on-site QB full penetration welding. During welding operations, columns and beams are tightened together with assembling jigs and clamps to ensure geometry. Anticorrosive coating layers interruption are staggered as seen in Figure 17. After visual, magnetoscopic and ultrasonic testing, welds are ground. Anticorrosive coating is then completed.

Figure 17. Beam-column on-site welding

Secondary roof beams are connected to primary roof beam by bolting. Upper and lower flanges of secondary roof beams are bolted on two steel plates that are welded to the primary roof beam. To avoid out of plan forces, the steel plates are welded to stiffeners inside the box section, as seen in Figure 18. Internal plates are welded in the box sections to create internal stiffeners. Since section walls are thin, they allow for load path while avoiding out of plan stresses. Other internal plates have a formwork function. They control the geometry of the sections. Therefore, openings are executed in the fourth wall of the section and it is connected to the stiffeners trough plug welding.

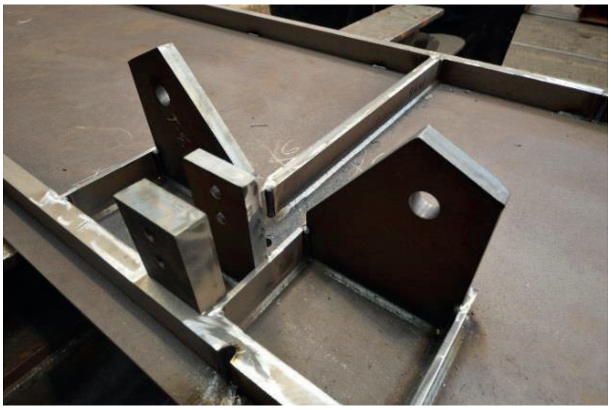

Figure 18. Column-façade beam connections before closing the fourth wall

Oblong holes are executed on the two plates to create an expanding joint. As for column-façade beam connections tightening torque is adapted to the connections type: x-bracings, expansive joints and standard connections.

X-bracings are made up of tie-rods. They are placed between two glass brick elements (Figure 19). Eccentricities are allowed in the connection to allow for waterproofing continuity.

Figure 19. X-bracings

8 Conclusions

An innovative modular construction system is developed to design the superstructures of the five railway stations of the new transborder CEVA railway in Geneva, Switzerland. It results in a strong visual identity of the five stations.

This innovative modular construction involves large scale façade, roof and floor glass bricks supported by slender steel structures. However, differently from traditional façade construction systems, load bearing structures are integrated in the building envelope.

The glass bricks are 5.40m x 2.70m glass wall, roof and floor elements. The slender steel structure elements are welded built-up box sections with a constant width. The glass bricks are inserted between the steel structure elements that are located on a grid. All elements are designed with the same thickness to flash. The system adapts to the five stations.

Glass brick design, fabrication and laying requires advance façade design. Steel structure stiffness, instabilities, dynamics and connection design, fabrication and erection are critical issues. 3D structural analysis, non-linear analysis and dynamic analysis are carried out to design steel load bearing structures. However, since the steel structures carry glass elements, serviceability is critical.

Moreover, the system is developed to adapt to all building elements in the five stations such as walls, roofs, floors, fireproofed floors and footbridges with multiple glass brick and steel section topologies. It leads to unity and familiarity among the five railway stations on the CEVA railway.

9 References

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