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An ETFE canopy above IGR metro station

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Abstract

Gustave Roussy Institute (IGR) station is an emblematic station at the junction of Line 14 (extended south to Orly Airport) and the future Line 15 of the Grand Paris Express network.

Geological and topographical constraints (the station is located on a hill and the two lines intersect at a 90° angle) dictated the tunnel layout, resulting in a deep circular station 63 m in diameter and 45 m deep.

The initial concept developed by Dominique Perrault Architecture (with whom Setec worked as civil, structural and MEP consultant) is that of an underground pantheon illuminated by a central oculus at the top of a dome. The dome being materialized by interior floors becoming less hollow as one approaches the surface.

The emergence, very flat, adjoins a park and conceals the extent of the underground space occupied by the station. It consists of a 4,200 m2 canopy made of three distinct elements. Two large circular canopies intersect above the station's central void (41m in diameter). The void itself is covered by a transparent ETFE membrane attached to steel radius tensed between two outer compression rings and a central tension ring.

This canopy being part of a large-scale civil engineering project, almost 10 years elapsed between the first sketches and completion. This article aims to describe the evolution of the technical and architectural design during the different phases of the project, and how it was informed by the technical design of the station itself (including fire safety requirements).

Keywords: Canopy, ETFE, membrane, bicycle wheel structure

1. Introduction

In 2009, an exhibition at the *Cité de l'architecture et du patrimoine* presented the results of an international urban design consultation on "a new comprehensive development project for Greater Paris". A year later, the Société du Grand Paris was created to develop its public transportation component: 200 km of new lines, mainly underground, and 68 new stations.

Line 15 south and the southern extension of line 14 are the first lines for which the Société du Grand Paris (SGP) launched a tender for design. They will be inaugurated in summer 2024 for line 14 and in 2025 for line 15 south. **setec** leads the two consortia responsible for the design of these infrastructures.

The Institut Gustave Roussy (IGR) station is located at the intersection of these two lines.

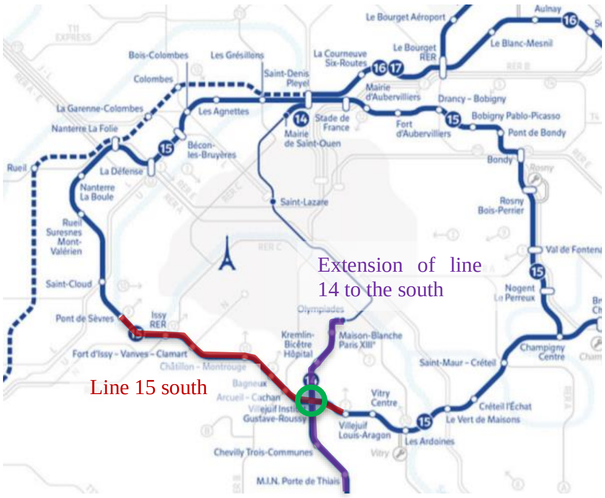

Figure 1: Location of the IGR station in the Grand Paris Express network

2. Presentation of the station

IGR is a deep underground station: the tracks of line 15, the lowest one, are located 50 meters below ground level. 12m higher, perpendicular to line 15, line 14 crosses the station in a box girder bridge.

This layout is dictated by the local topography: the station is perched on a hill and the longitudinal profile of line 15, constrained by the level of Arcueil Cachan station to the west and the passage under the A6 motorway, could not be raised any higher.

A large cylindrical shaft with an internal diameter of 63m accommodates the escalators and elevators used to bring passengers to and from the station, as well as the necessary technical rooms required to operate the station. Four underground galleries house the ends of the platforms of both lines.

Regarding fire safety, which is a very strong constraint for these structures, the shaft, because of its great width, is considered an open-air space. In other words, once passengers have exited the platforms, i.e. very quickly, they are considered to be in a naturally ventilated 'disaster-free' zone. This is a strong point of the design that cleverly addresses the safety of individuals. The large dimension of the opening on the ground floor and the permeability of the roof were key elements in allowing this fire strategy.

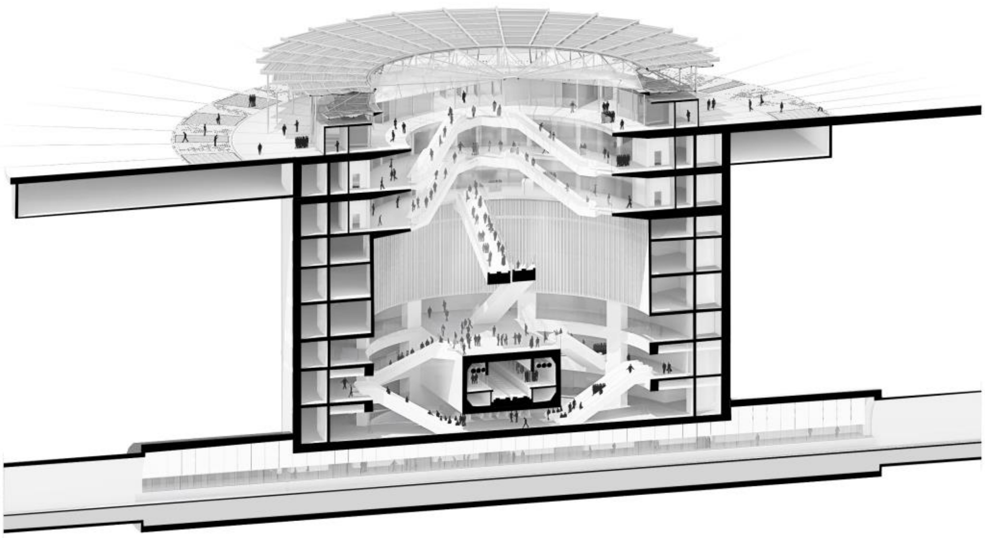

Figure 2: Axonometry of IGR station [credit DPA]

3. The canopy, from first sketches to final design

3.1 Architectural vision

In order to launch the long and complex works on the stations as quickly as possible, civil engineering studies have been anticipated. For the IGR station, the various phases of studies took place between 2013 and 2015. The functional and architectural design of the station crystallized during this period, before being refined and detailed during the subsequent design of finishing works (2016 to 2018).

The station roof is significant as it serves as the signal, the image of the station. However, it is also a very secondary object compared to the civil engineering of the shaft. Its definition thus progressed very gradually during the civil engineering studies and continued during the finishing studies. The design of this roof spanned, in a very discontinuous manner, nearly 6 years.

During the architectural competition for this emblematic station, Dominique Perrault used the image of an underground Pantheon, whose upper floors formed a dome. From the outset, a transparent oculus was intended to crown the ascent to open air, bringing light into the depths of the shaft.

The station is very deep and voluminous, and the architect wanted a station without any above-ground construction except for a large, very flat canopy, which would open up to the Hautes-Bruyères park to the south of the station, as well as to the built environment to the north.

Early on, DPA proposed a roof made up of two off-center discs at different altitudes (+9.10m on the street side and +5.55m on the park side). At the intersection, a large central disc (1 295 m2), made of transparent material, covered and brought light to the station shaft.

Initially, the peripheral roofs were two thin mirror-polished blades [figure 4.a]. The part over the shaft, on the other hand, was to be perfectly flat at the level of the upper disc.

The disc above the central void, 41.5m in diameter [figure 5], could only be supported around its perimeter, and the architects wanted it to be as thin as the peripheral roofs (themselves supported by a forest of columns). In order to lighten the structure, DPA very quickly proposed that this transparency be achieved through ETFE cushions.

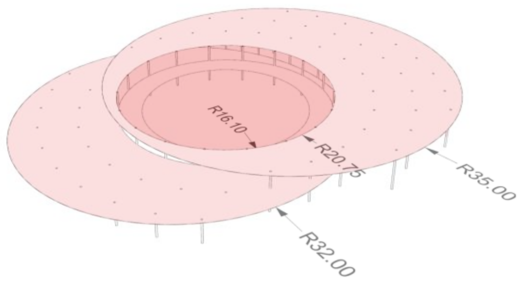

Figure 3: Schematic axonometry of the roof

3.2 Structural and architectural iterations

Multiple structural solutions were explored:

- Extending the edge columns to suspend the central roof with cables. However, this disrupted the flatness of the structure, especially since the roof is highly visible from above, from the Gustave Roussy hospital and surrounding buildings.
- Cable structures [figure 4.1]
- Radial cable beams, with a deflection corresponding to the thickness between the two peripheral discs and supporting a very light structure made of ETFE cushions. A bicycle wheel, with a central traction hub [figure 4.2].
- A low-profile dome supporting ETFE cushions held in place by a traction ring at the edge [figure 4.3].

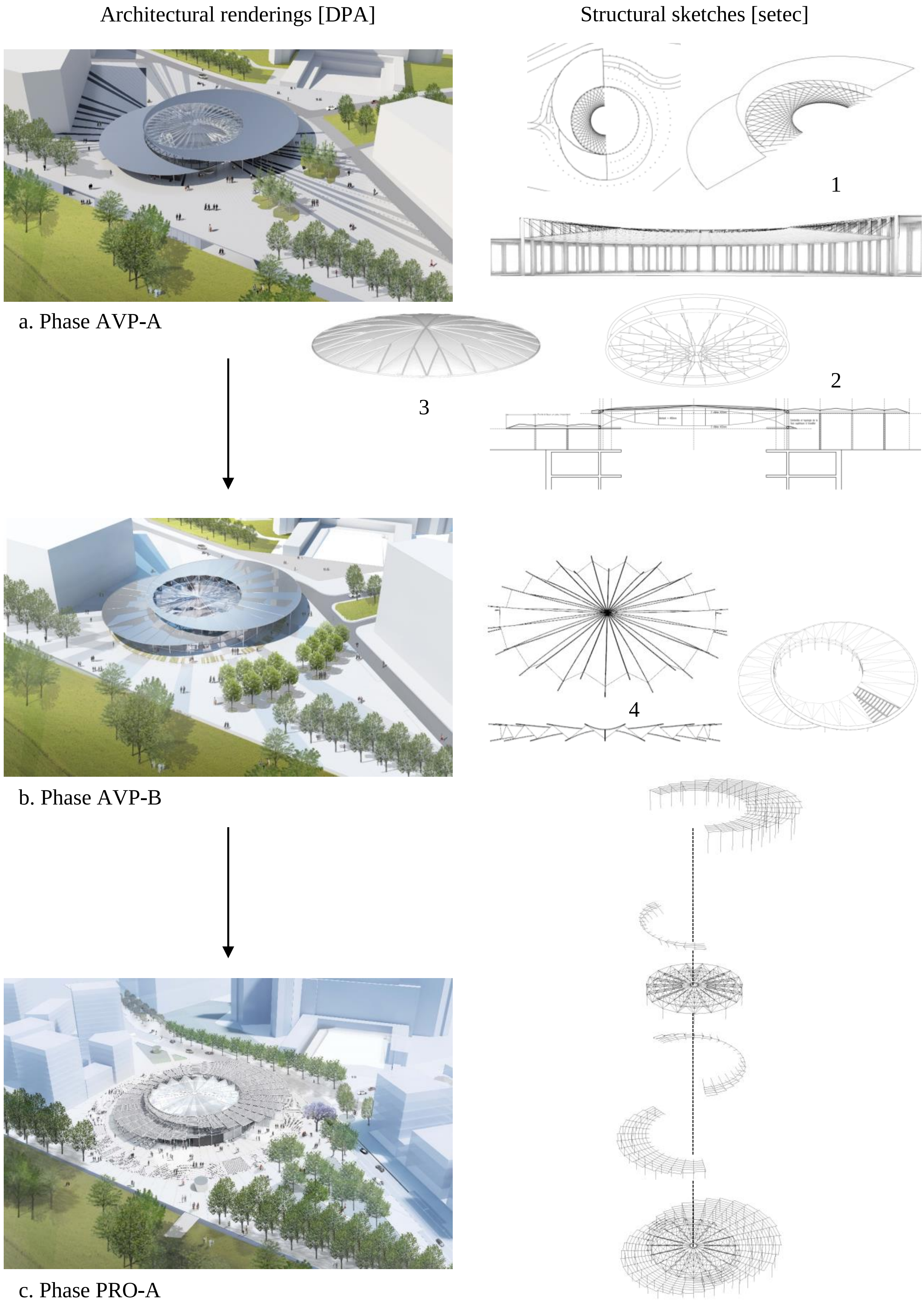

Figure 4: Architectural and structural evolution of the roof during the initial study phases

But DPA envisioned a transparent and flat disc. A substantial structural thickness was nevertheless indispensable to span the void. Folding [figure 4.4] reconciled these two antagonistic constraints: the form resistance provided by the folding allowed for thin and transparent panels while taking advantage of the structural height given by the difference in altitude between the peripheral roofs. The idea immediately appealed to DPA, who tried to make the perimeter roof respond by slightly pleating it too.

A peripheral circular Warren truss beam supports this central cover (with diagonals following the slope of the folds). Due to the available height between the two levels (3.50m), it was not worth supporting it at each low point: given the stiffness of the truss, small differential deformations would lead to very high stresses in the columns and their anchors. It was therefore decided to only have 9 structural columns. 9 other 'false' columns, desired by DPA, are used to lower the rainwater collected at the edge.

ETFE cushions or membranes are generally held at the edge by a "Keder" hem held in a groove profile itself held in an aluminum extruded profile. The first ETFE suppliers consulted advised us against a cable solution, too flexible to support these profiles. A steel structure supporting the ETFE was therefore designed based on this geometry.

During design phases of finishing works, T/E/S/S proposed to re-explore the idea of a structure in tension between two compression rings.

3.3 Peripheral roofs

The perimeter roofs are covered with undulating GKD metal mesh of variable density, tensioned (at 5 kN/ml) over ortho-radial CHS beams (diameter ranging from 168mm to 219mm). These profiles are fixed to radial beams (IPE 450) supported by 8.50m and 5.00m high columns (diameter of 219mm).

4. Final ETFE canopy technical details

4.1. General description

The circular sky opening of Villejuif IGR underground station is sheltered by a transparent ETFE roof, supported by a self-tensioned metal structure. In plan view, the construction is dividing the circle into 18 angular sectors of 20°. Each sector consists of two inclined panels along the radii of the circle, alternately generating high ridges and low valleys that collect rainwater.

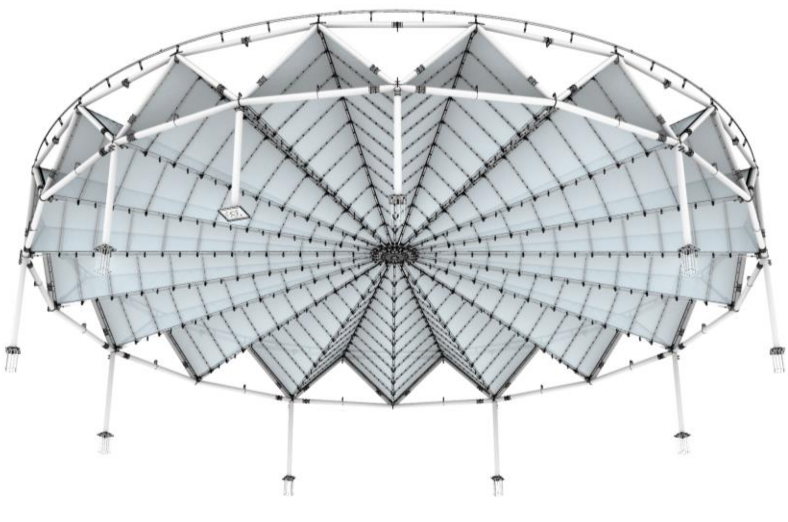

Figure 5: Axonometric view from below of structure and ETFE roof
[credit: MAP3 / TAIYO construction 3D model]

This structural option was chosen for the visual lightness of the central load-bearing elements, which proved to be much more efficient than bending members. The tensioned elements are indeed intrinsically stable, avoiding the need for large sections against buckling (as needed in the first truss solution).

Additionally, the roof needed quick installation to avoid disrupting the work schedule of the underlying operations requiring a watertight enclosure. The tensioned structure and its ETFE covering also proved to be very efficient in terms of assembly time and limiting task overlaps.

One of the major technical challenges of the chosen solution is to ensure its compatibility with the fire safety requirements of the Station. In order to avoid resorting to conventional fire protection for the supporting cables, which would have significantly compromised the slenderness and architectural quality of the whole structure, an original technical arrangement has been developed for the key radial elements of the structure to make them compatible with calculations according to Eurocode 3 Structural Fire Design.

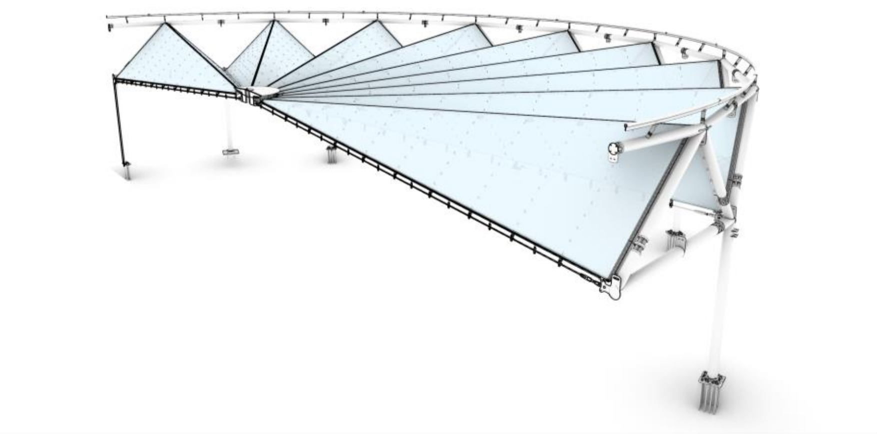

Figure 6: Semi- Axonometric view from above [credit: MAP3 / TAIYO construction 3D model]

4.2. Structural design

The ridge catenaries (shown in red in figure 8) consist of straight, solid 100x40mm rectangular steel bars, S460 grade. They are delivered as single pieces, without axial splicing, between the outer truss and the central node. The flat rectangular section of the catenaries also allows for optimal integration of sealing details accommodating aluminum profiles receiving the KEDER edge of ETFE modules.

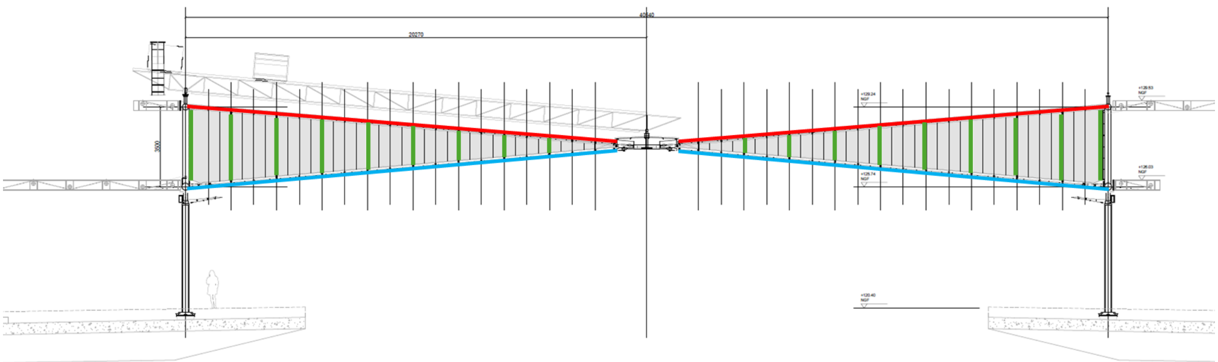

Figure 7: 2D section of structure and membrane [credit: T/E/S/S tender drawings]

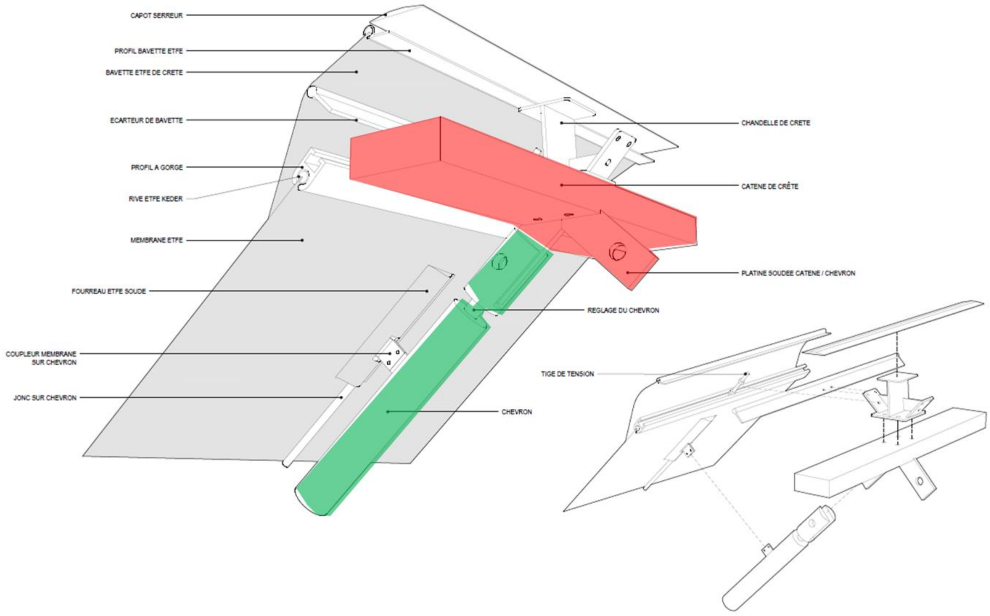

Figure 8: Axonometric ridge details [credit: T/E/S/S tender drawings]

The valley members (shown in red in figure 9) are full locked cables made of high strength steel Z wires coated with a zinc-aluminum corrosion-resistant protection. They are considered inactive at high temperatures because the mechanical properties of the cables, especially at the end fittings, are not compatible with fire temperatures.

The rafters (in green in figure 8 & 9) are S460 steel tubes connected at their ends by machined female threaded fittings. The rafters are designed to allow for length adjustment during the life of the structure, from the underside of the roof and without dismantling the ETFE membrane. They help maintain the distance between the ridge and valley and provide transverse support to the ETFE membrane.

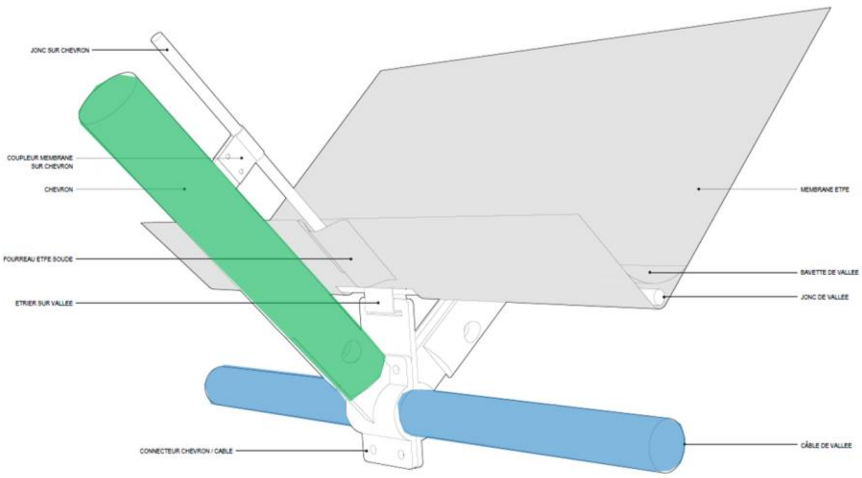

Figure 9 : Axonometric valley details [credit: T/E/S/S tender drawings]

All ridge catenaries and valley cables are converging to the central node, a mechanically welded steel piece, weighing approximately 3 tons.

Figure 10: Axonometric details left – site construction right [credit: T/E/S/S]

4.3. Structure erecting on site

Due to their lightness and flexibility, all tensioned elements (ridge catenaries, valley cables, and central node) could be installed in a single crane operation lasting a few hours. The structure found temporary stability as soon as the first three catenaries, spaced at 120°, were connected. Subsequently, the other catenaries were fixed, and finally, the main cables were connected to the truss. Pre-tension was introduced into the system solely through the cable tension, using temporary screw jacks. The catenaries were then tensioned by reaction.

Figure 10: Drone flight above construction site - central structure installation [credit: Bouygues]

4.4. Envelope design

The single-layer ETFE membrane is stretched over the central structure, conforming to its ridge and valley geometry. It ensures rainproofing of the opening. Rainwater is collected by the slopes, directed into the valley lines towards the peripheral gutter. The ETFE covering has a safety impact resistance of 1200J.

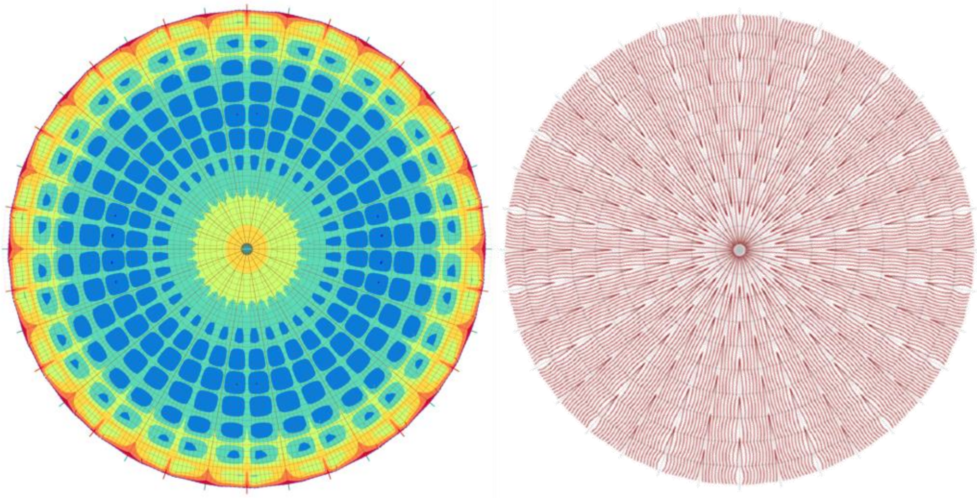

Figure 11: Left: vertical translation contours – Right: water ponding check by contour on deformed geometry [credit: T/E/S/S tender calculations]

The ETFE membranes are fabricated in large continuous modules, covering a single angular roof sector of 20°. They consist of membrane strips assembled by continuous watertight welding. The welds between strips are aligned parallel to the rafters. In plan view, the weld lines form concentric faceted circles with regular spacing. The two triangular slopes of each module are fixed and tensioned on the structure's spokes. Therefore, the membrane of a module forms an uninterrupted watertight surface between the ridges.

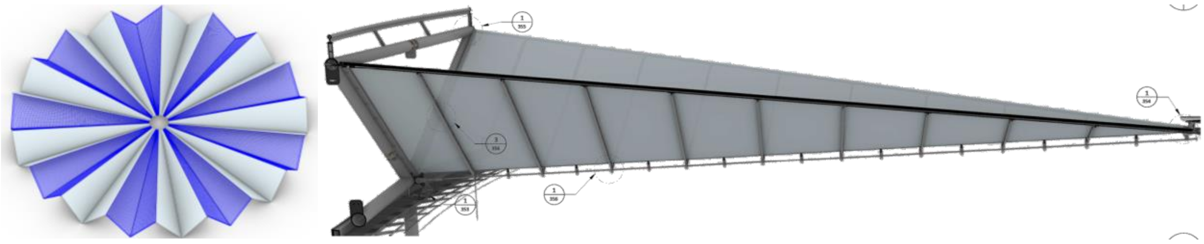

Figure 12: ETFE modules arrangement [credit: T/E/S/S tender package and MAP3 / TAIYO execution drawings]

The membrane panels rest out-of-plane on the underlying rafters through a hemmed bar in the membrane regularly linked to the rafters by stainless steel connectors.
The ridge is the sealing joint line between two continuous ETFE modules through an extruded aluminum groove profile.

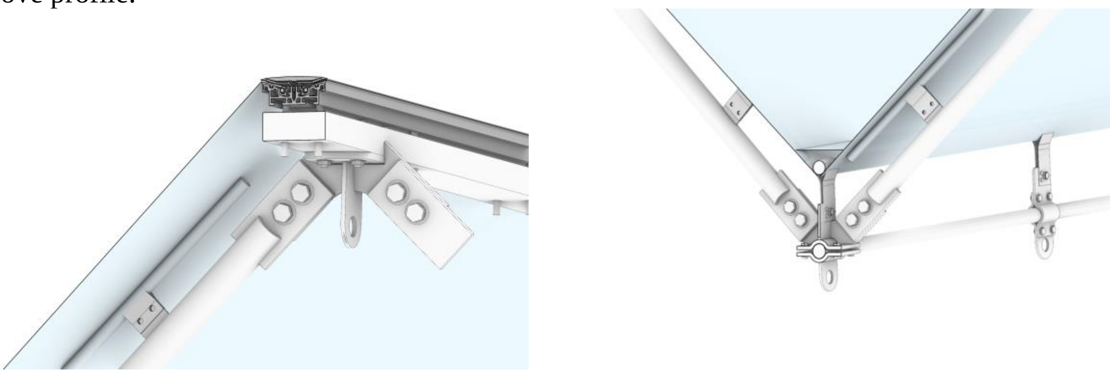

Figure 12: ETFE ridge and valley detail [credit: MAP3 / TAIYO execution drawings]

On the underside, a hemmed valley bar in an ETFE pocket welded to the running membrane allows for tensioning of the slopes through adjustable stirrups exerting vertical traction.

Construction site closeups – Left: valley detail – Right: ridge detail [credit: T/E/S/S]

4.5. Maintenance design

A polar maintenance beam has been designed to carry out routine cleaning and maintenance operations on the roof. It consists of a rotating spatial truss beam in the orthoradial direction, pivoting at the center of the roof, and supported on a bogie rolling on the upper member of the truss. On the beam, a movable basket provides radial translation and allows two operators to access the entire roof.

Figure 13: Installation of the polar maintenance beam, drone flight over construction site [credit: Bouygues]

For exceptional operations, the underside of the beam is equipped with a rope access rail, allowing secure movement of operators walking along the valley lines.

4.6. Conclusion

The upcoming station of the new transportation network in the Parisian region will soon welcome tens of thousands of commuters and see millions of train passengers passing through each day. Thanks to its structural efficiency and transparency, the new roof will provide them with abundant natural light, enough to illuminate the spaces up to the 8th level underground.

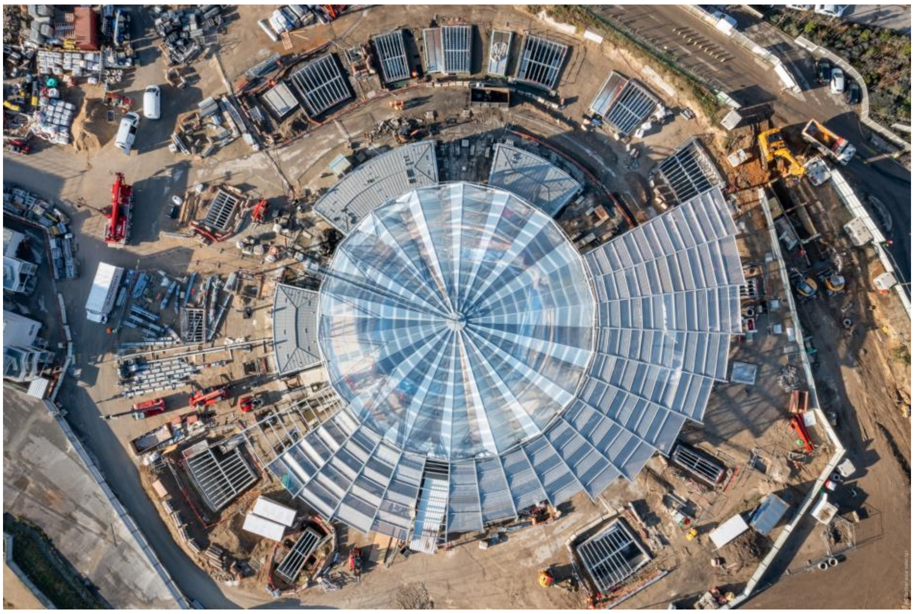

Figure 14: Drone flight over construction site [credit: Anne-Claude Barbier]