ROOFING OF MONTPELLIER - SOUTH OF FRANCE TGV STATION

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Abstract

The roof covering the new Montpellier - South of France TGV station is made of a perforated mineral latticework comprising 115 modular and self-supporting elements in precast white UHPFRC known as "palmes" – allowing the strong southern light to be filtered. These perforated double-cambered elements, in line with the long tradition of glazed vaults in reinforced concrete, have a width of 5 cm and span 20 m. This UHPC layer homogenously ensures durability, protection from sun and rain, and provides natural ventilation of the concourse thanks to the joints between the palmes: a watertight cover-structure. The palmes required the development of a UHPFRC new mix, the White Ductal B3 FI 1.75 % and were subject to a procedure of Technical Experimental Evaluation validated by the CSTB. All roofing elements (10,000 m² in total) were prefabricated within 5 months and installed with tight geometrical requirements in only 2 weeks.

Résumé

La couverture de la nouvelle gare TGV de Montpellier - Sud de France est une dentelle minérale perforée constituée de 115 éléments modulaires et autoporteurs en BFUP blanc précontraint - appelés « palmes » - permettant de filtrer la lumière du Sud. Ces éléments perforés à double courbure, qui s'inscrivent dans la grande tradition des voûtes vitrées en béton armé, ont une épaisseur de 5 cm et une portée de 20 m. Cette peau en BFUP assure de manière unitaire la tenue, la protection au soleil et à la pluie, et la ventilation naturelle du hall de gare grâce aux joints entre les palmes : une structure-couverture étanche. Les palmes ont nécessité la mise à point avec l'équipe Lafarge d'une nouvelle formulation de BFUP, le Ductal B3 FI 1.75%, et ont fait l'objet d'une procédure d'Appréciation Technique d'Expérimentation (ATEx) validée par le CSTB. L'ensemble des éléments de couverture (10 000 m² au total) ont été préfabriqués en 5 mois et installés avec une grande précision géométrique en seulement deux semaines.

1. OVERVIEW

Montpellier – South of France TGV station will host French high-speed trains coming from Paris, Lyon, and Marseille and heading for the destination of Barcelona Sants. It is part of the Montpellier and Nimes railway bypass plans. The station is located south of Montpellier in the Odysseum neighbourhood. Marc MIMRAM Architecture in partnership with Marc MIMRAM Ingénierie, ICADE, and FONDEVILLE general contractors will finalise the station at the end of 2017. The cost of the construction is 150 million euros, in addition to an extra ten million euros for the tramway access extension.

Described as a Mediterranean Station, the building has been designed to filter direct southern light through the roof, which is made of 115 precast, modular "palmes" made of Ductal UHPC. These double-cambered perforated units, inspired by the great tradition of thin concrete and glass grid-shells, are 4 centimetres thick and span 20 meters. The sunlight filter is provided by a random perforation of the thin Ductal shell, corresponding to the changing position of the sun (Fig. 1). Bioclimatic and structural inertia rules have determined the overall curvature of the elements. The station will be the focal point of the future Oz Montpellier Nature Urbaine neighbourhood, which is expected to accommodate 400 residents in the years to come. The edifice will be included in this context of vast landscapes between city and nature, more specifically focusing on its southern garden parvis. The train platforms will also receive landscape treatment in order to maintain continuity with the overall design.

Figure 1 - Interior view (competition)

2. DESIGN OF THE ROOF COVERING

Marc Mimram designed the new TGV of Montpellier – South of France as a "Mediterranean station", attentive to the variations of light and climate. The idea here was not to limit the space by a glass layer, but to create shade to guide strong light through an opaque filter. The folds in the covering enable the large span to be created, to construct a canopy that on the west side becomes the tramway station and the entranceway parvis. It extends to the east, bringing the split levels of the station into direct contact with the railway lines. The broad open span enables a versatile occupation of the commercial space to be envisaged, while providing far-reaching views over the Nègue-Cats park. In this way, the main covering structure was designed to maximise the pleasure of filtered light, for the purposes of climatic treatment, while opening onto the landscape, in keeping with the wind characteristics of the site.

The UHPFRC fulfills structural and waterproof functions, and permits to make a roof by the use of one material, allowing a large plastic drawing possibilities. After casting, palmes are ready to be installed. A very fast installation (2 weeks) allowed an extreme reduction of the construction time, which was one of the main issues of the project (Fig. 2). These properties oriented the choice of the UHPFRC as the material of the roof.

Figure 2 - Interior view (construction)

3. GEOMETRY

The roof of the transport building consists of 5 identical spans measuring 54 x 19.435 m, arranged along an east-west axis on a radius of 875 m, and with canopies from edge to eaves on all four sides (Fig. 3).

Each span is made up of 23 modular elements in UHPC, called “palmes”, which are self-supporting, across 17.5 m (Fig. 4). Five types of palmes can be defined (Fig. 5):

- The 4 palmes at the extremities of each span (types 1 to 4), with variable geometry
- The 15 central palmes (type 5), identical.

The palmes alone measure 20 m in length, 2.4 m in width, and 3 m in height. These dimensions comply with maximum road transport dimensions, notably in terms of maximum width and height.

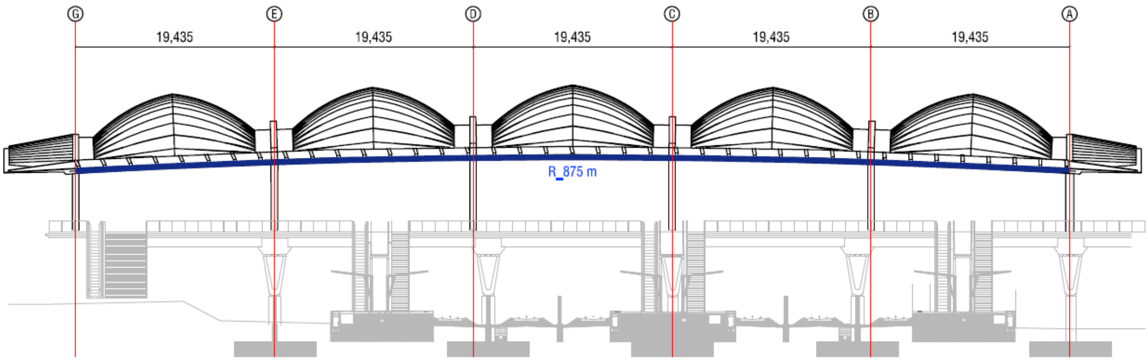

Figure 3 - Cross section

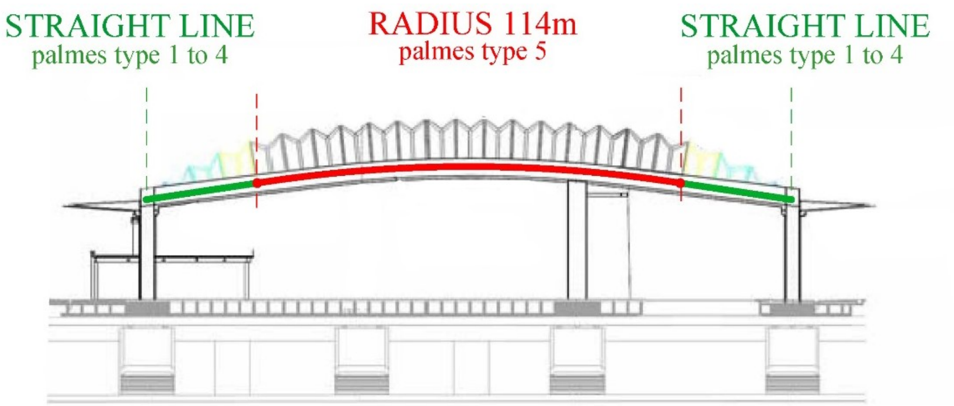

Figure 4 - Longitudinal section

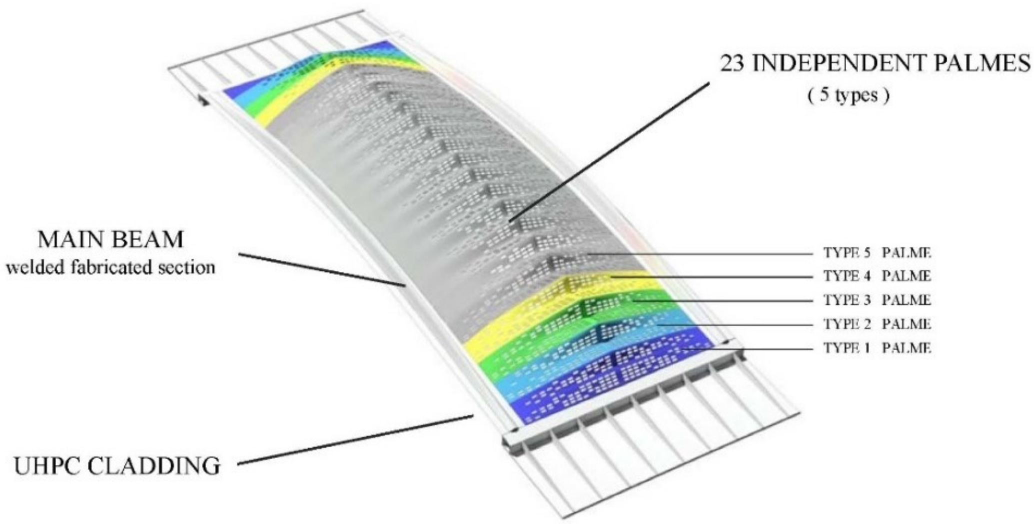

Figure 5 - View of a span

The palmes (Fig. 6) are made up of:

- A central longitudinal rib with variable geometry (40 x 20cm at the bearing points, 20 x 60 cm at the ridgeboard);
- A warped, perforated shell, 4cm thick. The reservations, with dimensions of 40 x 16cm, are arranged according to 22 longitudinal rows of 6 elements each;
- A transversal, V-shaped diaphragm, at the ridgeboard of the palm, 3cm thick;
- Peripheral connecting walls with dimensions of 3 x 15cm;
- Two bearing joists, turned up at the extremities to enable the installation of the bearing supports.

The 3D model of the palm integrates the coves required for localised form removal, humps, and reinforcements, in order to install leverage casings and surface joints guaranteeing rainwater run-off and prevention of zones of stagnation.

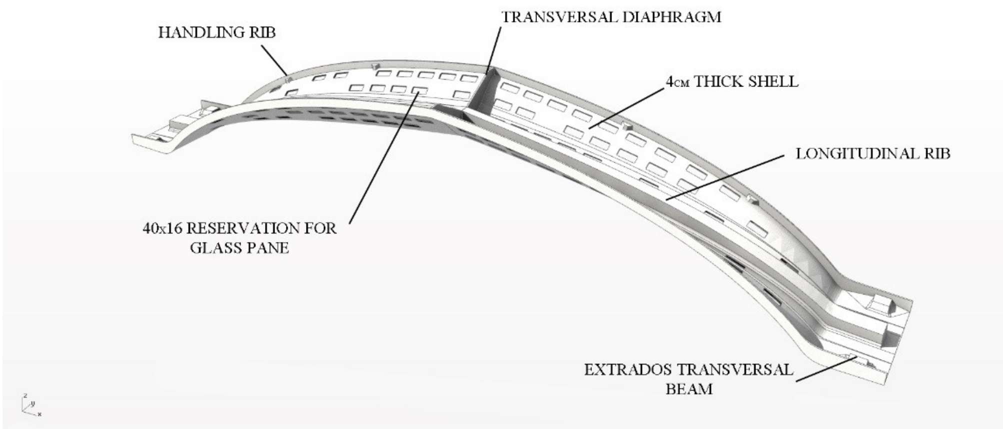

Figure 6 - View of a palme

4. FEATURES OF THE ROOFING SYSTEM

4.1. Structure / Cover / Watertightness

This double-cambered layer is made out of a mineral latticework that gives it both its structural status and filters light, while protecting the concourse from poor weather conditions. Thanks to its low porosity, its resistance to cracking and its highly compact density, UHPFRC is a waterproof material throughout. The protection from water perpendicular to the 10,500 reservations is ensured by a process of glass treatment that was the subject of an ATEx and numerous water resistance tests. The joints between palmes are treated with traditional procedures (elevations according to localised angles, installation of a hood fitted to the shape of the palm), the ventilation of the hall is kept perpendicular to the elevations.

4.2. Light

The palmes are progressively perforated over the full length of each fold. At the roof level, an exterior and an interior space can be distinguished (Fig. 7).

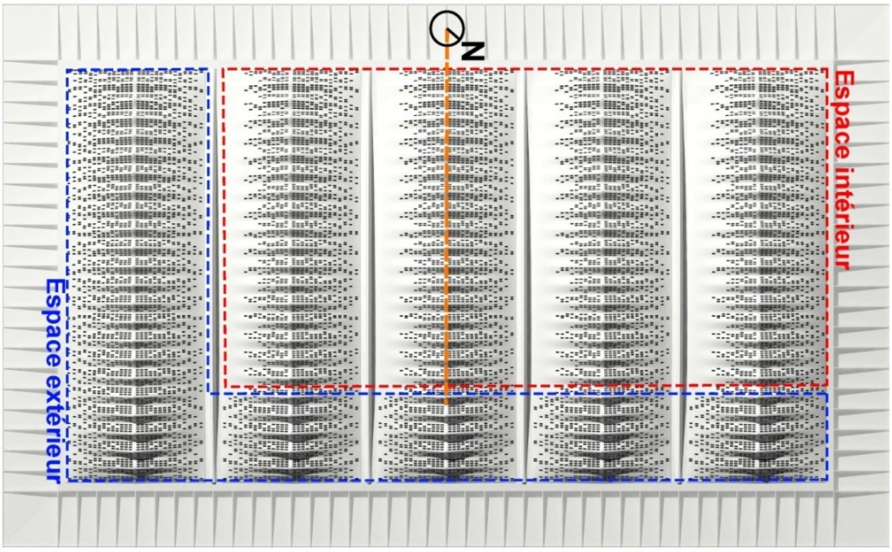

Figure 7 - Map view of the roof

On the part of the roof covering the interior space of the station, the perforation level on the vaults is progressive from south to north, in order to master the amount of light and warmth entering the volume of the hall. On the part of the roof over the exterior space, the amount of light let in is greater and homogenous, enabling a gentle transition towards the entrance/exit of the railway station. For each palme, the percentage of perforation depends on the orientation of the four generative surfaces, as illustrated Fig. 8.

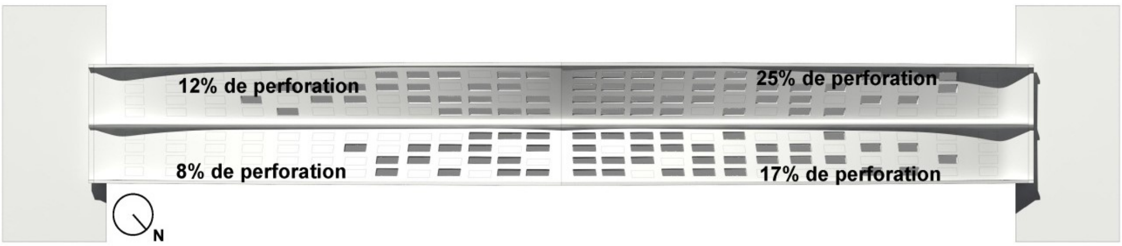

Figure 8 - Map view of a palme

The perforation level of the palmes varies in the north-south direction, following the same principles as for the roof as a whole. A progression is also present in the east-west direction, designed to encourage the amount of light in the morning and limit it late in the day, when the thermal levels on hot days are more critical.

4.3. Thermal features

This mineral filter is also a tool for climate regulation owing to its form, meaningful both in terms of the conditions of its harmonisation within urban space and in the way in which it handles prevailing winds. The covering of the concourse is a “porous” roof; the palmes are separated between them by 7-cm inline jointing. The study of the natural ventilation (carried out through fluid dynamics computational analysis) enabled the dimensions of the natural vents to be validated, with the aim of ensuring sufficient fresh air flow for the thermal comfort experienced by passers-by and the evacuation of the humidity associated with humidifying.

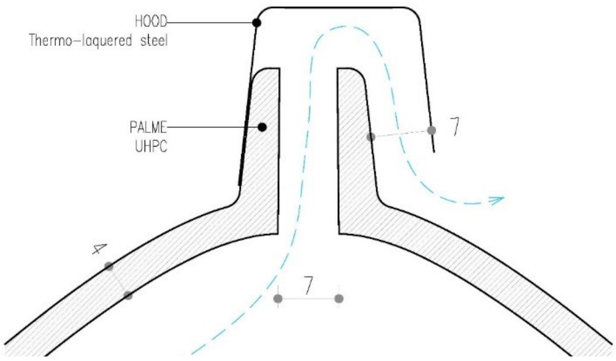

Figure 9 - Detail of the hood

4.4. Acoustics

Owing to its cambered form, the roofing system enables a natural attenuation of the reverberation phenomenon. The acoustic study integrated the complex geometry of the roof in order to take into account and minimise the absorbent acoustic surface, allowing the project's acoustic objectives to be attained.

5. STRUCTURE

5.1. Structure of the railway station

The new Montpellier railway station is organised into four large structural strata.

- The first is the foundation framework established by SNCF-R. This 18m framework longitudinally and 19.45 m across is defined by the distribution of the railway lines and serves as a structural framework for the whole station.
- The second structural layer is comprised by all of the concrete structures with the floor coverings at the +28.50 m level, which constitutes the main hall of the station. The paving structure follows the structural framework described above.
- The third structural stratum consists of the main skeleton framework of the main roof covering over the whole concourse, in metalwork. This structure comprises a post/beam system made of welded fabricated sections, materialising frames in both directions (5 spans of 19.45 m in the north-south direction, 2 spans of 18m and 36m in the east-west direction).
- The final structural layer is the envelope of this main roof covering. It comprises a series of prefabricated perforated palmes made of Ultra-High Performance Concrete (UHPC) which bears the load between the main beams of the structure of the roof covering, forming a structural mineral latticework. These elements have a static schema of the isostatic beam type, and do not contribute to the overall stability of the structure of the station.

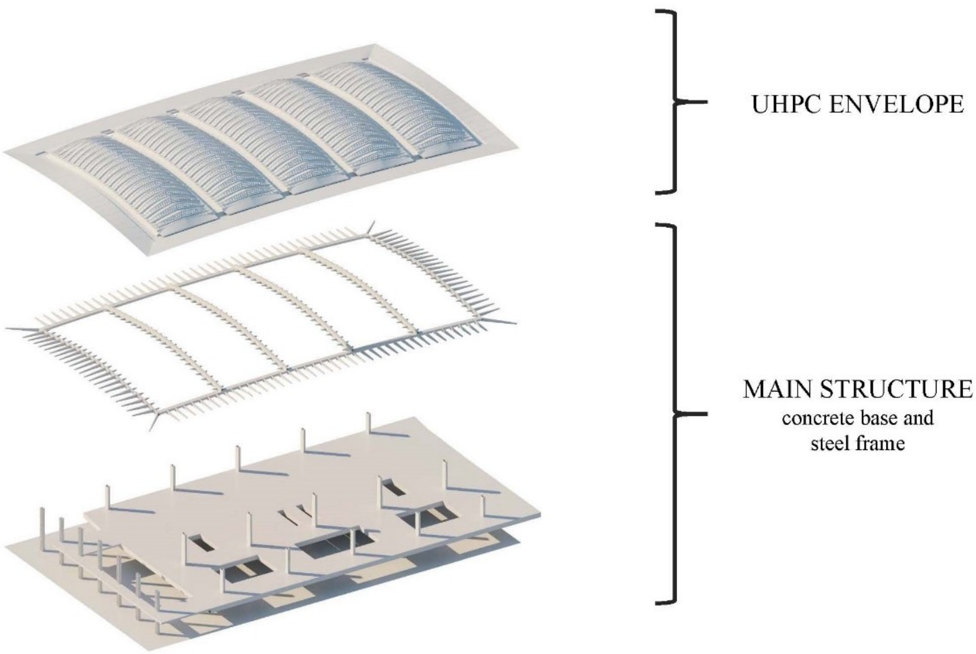

Figure 10 - Railway station structural strata

5.2. Structural analysis of the palme

The palmes are self-supporting structures over 17.5 m, made of precast UHPC post-tensioned by 4 T15S tendons. They are made up of a central rib of variable geometry and a thin, perforated, double-cambered shell (4 cm).

The bearing points are positioned at the four extremities of the palme, perpendicular to upper convex sections on bearing joists.

The palmes restore a static isostatic schema, with one side fixed and another side sliding longitudinally, and do not contribute to the overall stability (diaphragm, bracing, etc.). They therefore only bear their own weight, withstanding maintenance live loads, climatic effects (snow, wind, temperature), and earthquakes.

The extreme thinness of the product as well as localised forces that are sometimes considerable, called for the development – in association with the Lafarge team – of a UHPFRC new mix designated White Ductal B3 FI 1.75%, with a stainless steel fibre content greater than in the basic mix-proportion. Mechanical properties of the mix measured at 28 days are the following: characteristic compressive strength: 130 MPa; characteristic limit of linearity in tension: 7.5 MPa; characteristic maximum post-cracking stress (corresponding to 0.3 mm crack opening): 6.4 MPa; average maximum post-cracking stress: 7.5 MPa; average Young's modulus: 52 GPa; Poisson's ratio: 0.2. The design constitutive law adopted for SLS verifications is displayed on Fig. 11, and on Fig. 12 for ULS verifications. In the preliminary design assumed default values were 1.35 for K_{global} and 1.80 for K_{local}. Referring to Fig. 12, l_c = 2/3 of the members thickness [1] and γ_c=1.30 in relation to the premix and UHPFRC mix quality control [2].

A study of the completed elements, undertaken using Sofistik calculation software, enabled the complex geometry of the structure and the non-linear behaviour of the Ductal to be taken into account (Figs. 13-14).

The palme acts overall as a beam: the bending forces are taken over by the perforated shell, which behaves as a Vierendeel truss beam. Due to more intense stresses at the extremities (diffusion of the post-tensioning force at the ends of the central rib), the perforations in these areas are less dense.

The non-linear stresses (compression – red -, and traction – blue -) in the central rib under selfweight and prestressing are illustrated Fig. 15. In the extremities the main rib works as an isostatic beam, with a classic stress distribution: compression acting over the upper part and traction over the lower part (Fig. 16). In the midspan, the entire V section of the palme works as a beam: the central rib works as a tie with mostly tensile stresses. The central diaphragm provides rigidity to the ridge board and opposes the closure of the V-shaped section, which would have caused significant traction on the intrados side.

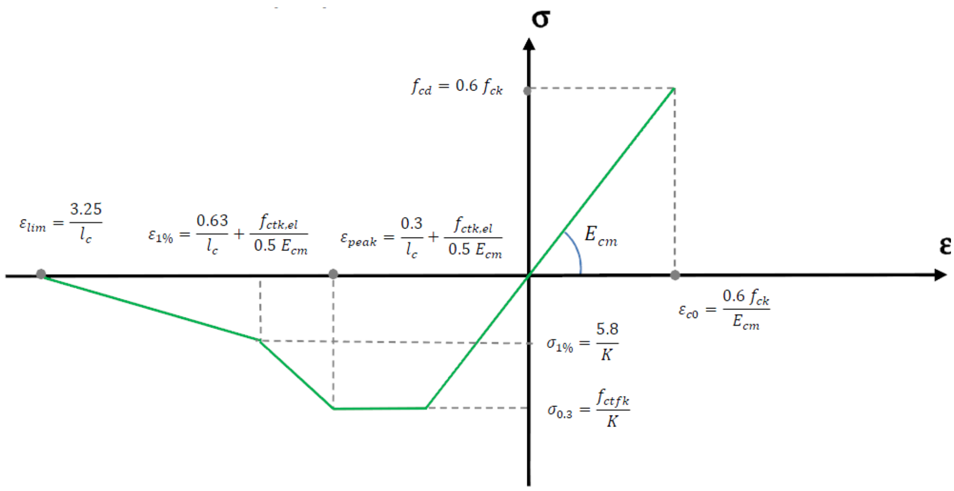

Figure 11 – SLS constitutive law of the UHPFRC

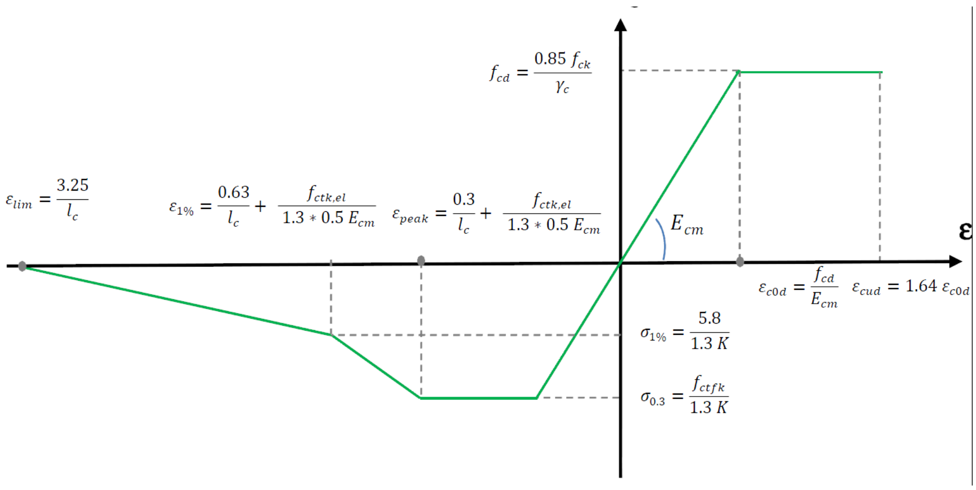

Figure 12 - ULS constitutive law of the UHPFRC

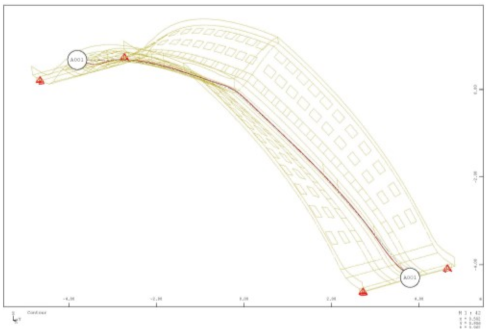

Figure 13 - Prestressing cable in the structural model

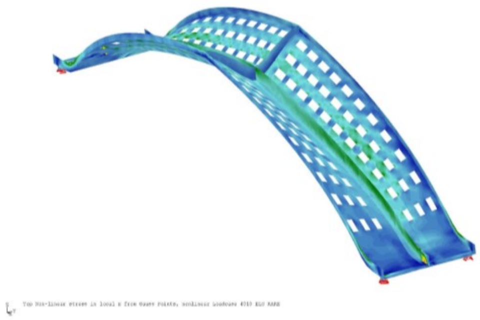

Figure 14 - Non-linear stresses – X

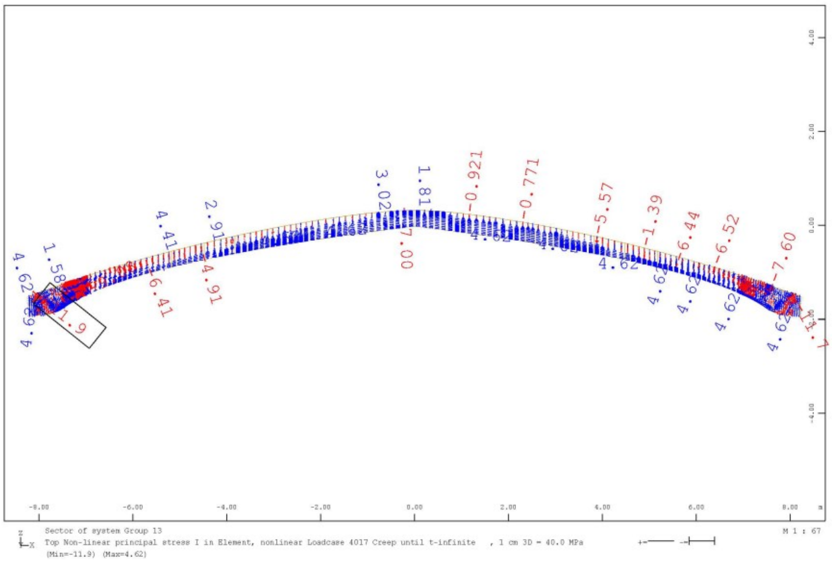

Figure 15 - Non-linear stresses in central rib

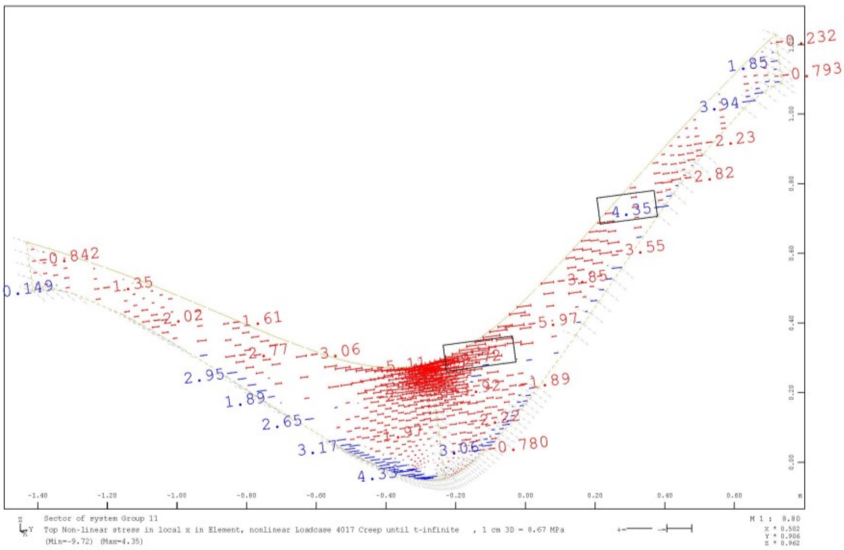

Figure 16 - Non-linear stresses in V-shaped section at midspan

The palmes have a significant rigidity due to their shape. The maximum displacement at mid-span under their own weight is 6.79 mm at the ridgeboard, including creep, which represents 1/1200 of the span. As illustrated from non-linear computation Fig. 17, the maximum SLS stresses under selfweight and prestressing are 4,62 MPa in tension and 60.4 MPa in compression. Meanwhile, the maximum admissible SLS tensile stress is $f_{ctf,k}/K = 6.4/1.35 = 4.74$ MPa, and the maximum SLS compressive stress is $0.6{*}f_{ck} = 0.6 * 130 = 78$ MPa. The Sofistik software enabled the non-linear behaviour of the material to be integrated, and the maximum crack openings to be verified (Fig. 18), which corresponds to 0.1 mm, in compliance with AFGC Recommendations [1].

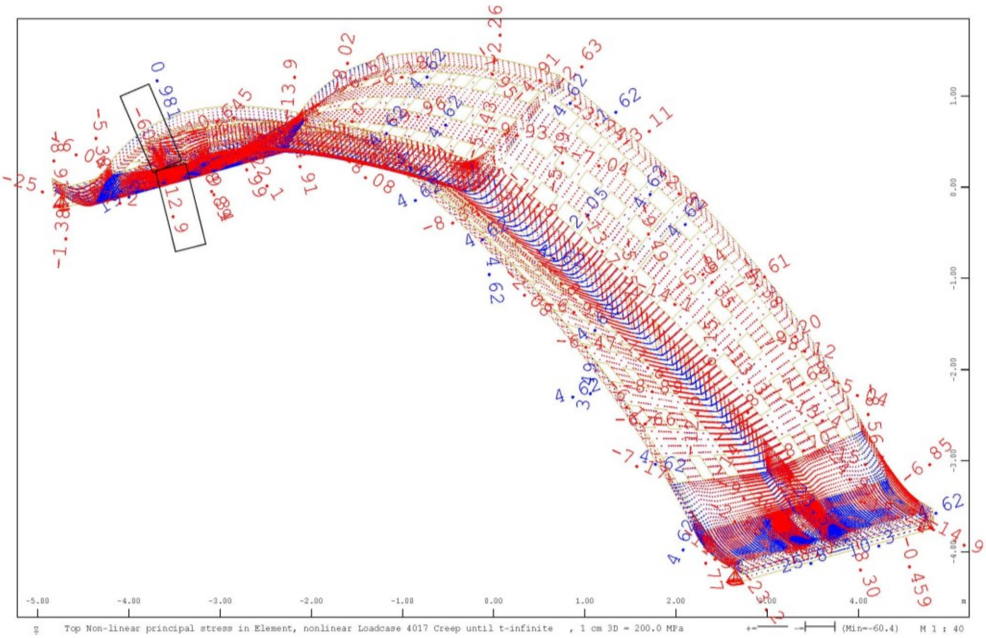

Figure 17 - Non-linear stresses in palme - SLS

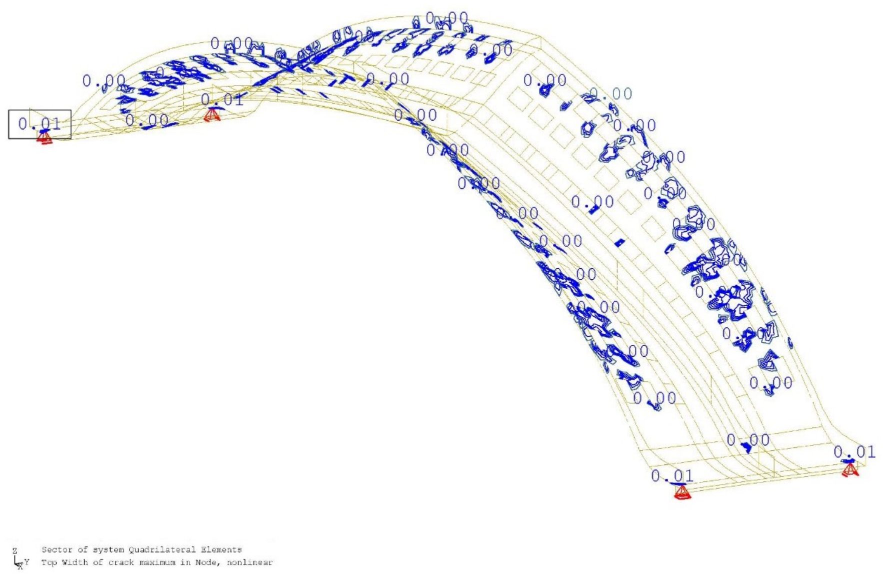

Figure 18 - Crack width– SLS

The transverse seismic displacements are +/- 28 mm and led to the dimensioning of the width of the joint between the palmes of 70 mm. These values were calculated in an overall model enabling the participation of the metal frame supporting the roof to be taken into account.

5.3. Wind conditions analysis

In order to better understand the wind-structure interactions on the complex geometry of the roof, it was necessary to perform wind tests on a physical model, equipped with 390 outer and 100 inner pressure sensors. The aerodynamic analysis was undertaken from 11 to 16 June 2015 in the atmospheric boundary layer simulation at the CSTB in Nantes (Figs. 19-20) on a physical model at a scale of 1 / 150. Samplings of pressure were performed for 24 wind directions, by 15° intervals, with a sampling frequency at 512 Hz (approx. 3 Hz at the real scale).

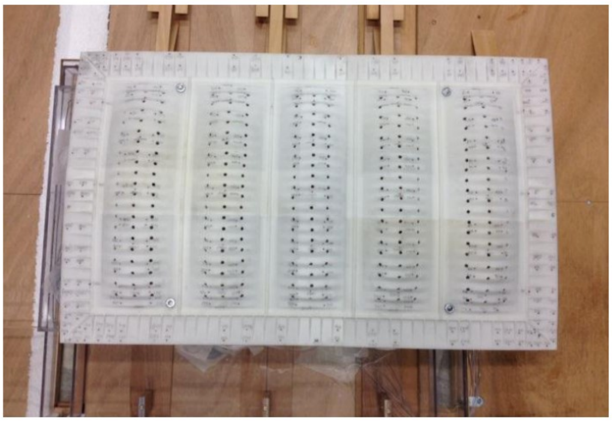

Figure 19 - Model for wind conditions analysis

Figure 20 - Model for wind conditions analysis

The analysis mainly focused on the characterisation of aerodynamic loads exerted on the roof of the railway station, namely: the differentials in pressure on the various sections of the roof and on the façades; the total and semi-total quasi-static efforts on the various parts of the roof (palmes, spans, ridges, and angles); the case of loads associated with the maximum and minimum concomitant forces (total and semi-total); the dynamic behaviour to be added to the quasi-static effects.

5.4. ATEx

The palmes were subject to a "Technical Experimental Evaluation" (ATEx) delivered by an expert panel led by the French Authority for building (CSTB). This procedure required the implementation of tests on a scale 1 palme, based on several load-bearing configurations, with data recorded corresponding to deformations and deflections of the structure, enabling the static and dynamic behaviour of the palme to be confirmed (Fig. 21).

The natural frequency of the palme was measured by a group of sensors checking the vibration speed variations in several points. Resulting values were: F1: 5,7 Hz (natural frequency for the first mode of torsion) and F2: 9,6 Hz (natural frequency for the first mode of vertical flexion). We compared these measured natural frequencies to the calculated natural frequencies in two bearing conditions. The calculated natural frequencies with translational and rotational bearings were: F1: 2.87 Hz (torsion) and F2: 3.45 Hz (vertical flexion). The calculated natural frequencies with rotational bearings (translations are not allowed) were: F1: 7.1 Hz (torsion) and F2: 10.3 Hz (vertical flexion). Due to the friction between their upper and lower parts, the real behavior of the bearings lays in-between a full translational and a fixed condition.

Figure 21 - One palme during the test

6. CASTING

The technical problems to be solved for the prefabrication of the palmes mainly concerned the general requirement of geometric control, with major items such as:

- General tolerance +/- 5mm
- Planarity of the 4 bearing points +/- 2mm
- Positioning of post-tension cables/ducts in the central beam during the precasting phase.
- Integration of reentrants for the glass elements (120 per palme) in the "wings" of the palmes

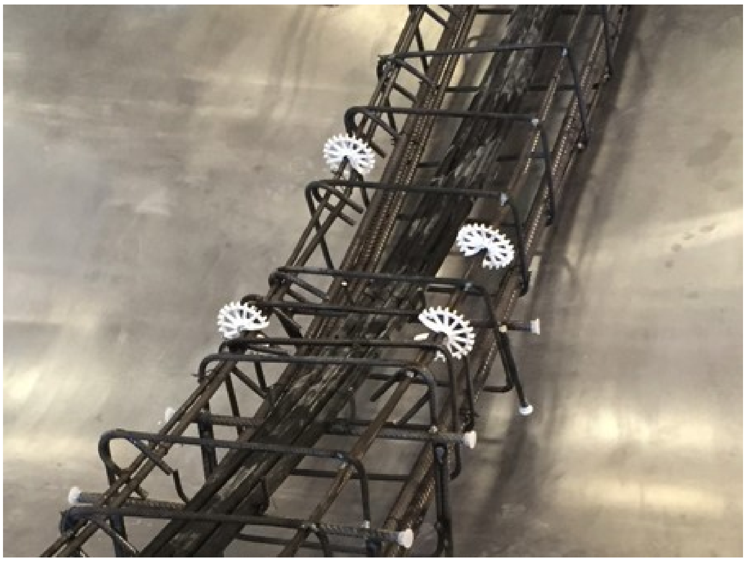

Figure 22 – Positioning of the post-tension cable

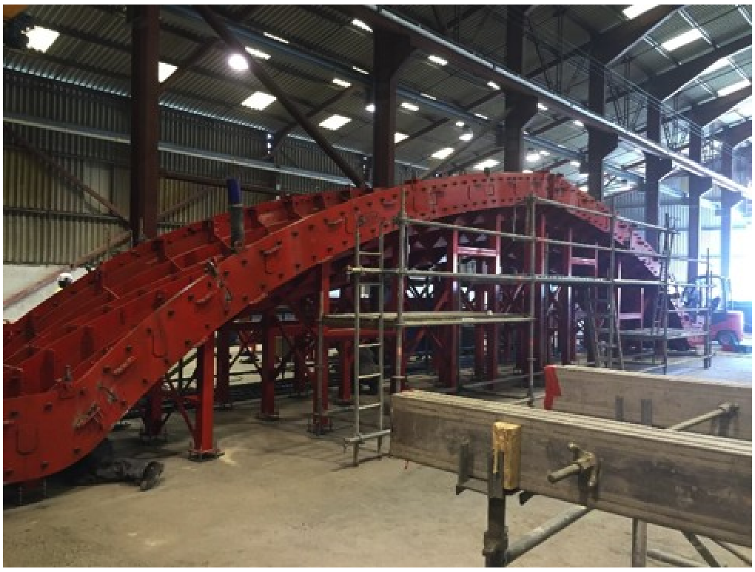

Figure 23 – Metal mould

To address these requirements in relation to the casting phase, the following measures had to be taken:

- Control of the reinforcing frame and post-tensioning cables position before UHPFRC placement (Fig. 22);
- Adaptation of the UHPFRC mix-proportion in collaboration with the premix producer teams to raise the workability time; Monolithic casting in a stiff and precise metal mould (Fig. 23);
- Control of the coefficient of orientation of fibres and limitation of autogenous shrinkage;
- Specific tools for form removal and transportation (Fig. 24). Namely, form removal was done with the aid of a 10-tons crane with 2 spreaders with cables, specifically designed and built for this operation; since post-tensioning was applied only on-site, the palmes had to be supported during transport phases to limit stresses as well as shock and vibrations effects.

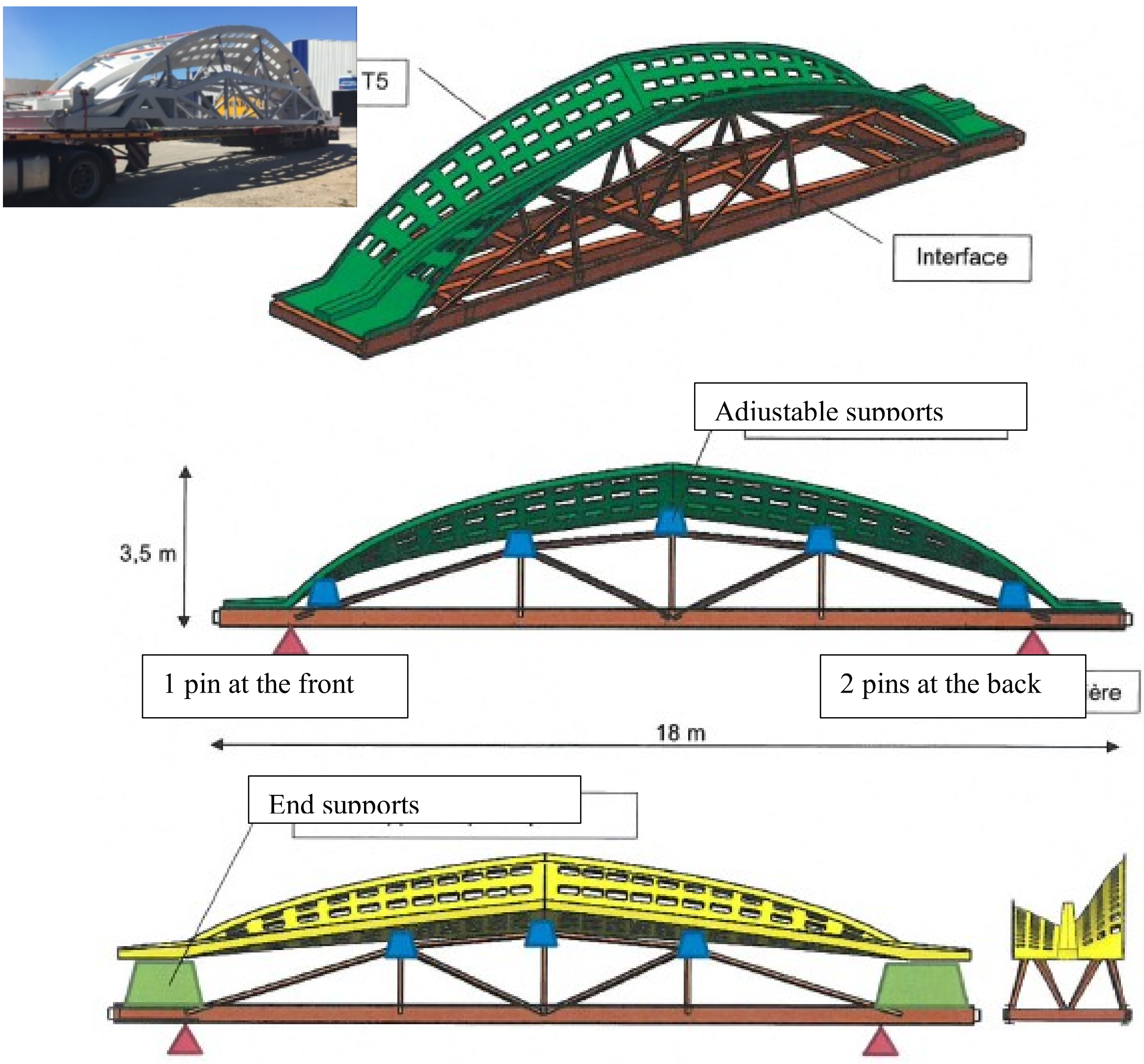

Figure 24 – Form removal deck

Figure 25 – Temporary stabilization device

7. ON SITE OPERATIONS

7.1. Unloading and handling

Upon its arrival on-site, each palme is unloaded via the same type of slinging as the one used for form removal or loading at the factory. At this stage, the post-tensioning tendons positioned in each palm are still not under tension. Therefore, in order to store the palms, it is compulsory to provide temporary lateral strutting (Fig. 25).

7.2. Post-tensioning

Once the UHPC strength has been attained, approximately 3 weeks after casting, the cables are tensioned (Fig. 26). These are sheathed greased strands.

Figure 26 – Post-tensioning

Once post-tensioned, it is no longer necessary to support the palmes laterally, and these are then stored on their definitive bearing points, via skids, the levels of which have been particularly carefully obtained so as not to cause a warping effect on the palmes. In this way, and throughout the full production period, the construction site received, unloaded and stored each week 5 to 8 palmes. The post-tensioning of the cables is done through a progression of 5 campaigns, each of around twenty palmes.

7.3. Bearings

The palms bearings on the metal framework represented one of the main technical issues of this project. These bearings have two functions: (i) Enable the static schema of the palmes (critical for their design) to be respected; and (ii) Guarantee that each palm rests on a set of bearing points that constitutes a plan. The static schema relies on 4 bearing types: The first one enables a considerable longitudinal displacement; one enables transversal displacement; one enables displacement in both directions; and the final one enables fine-tuned transverse displacement. These bearings do not exist commercially and had to be specially designed.

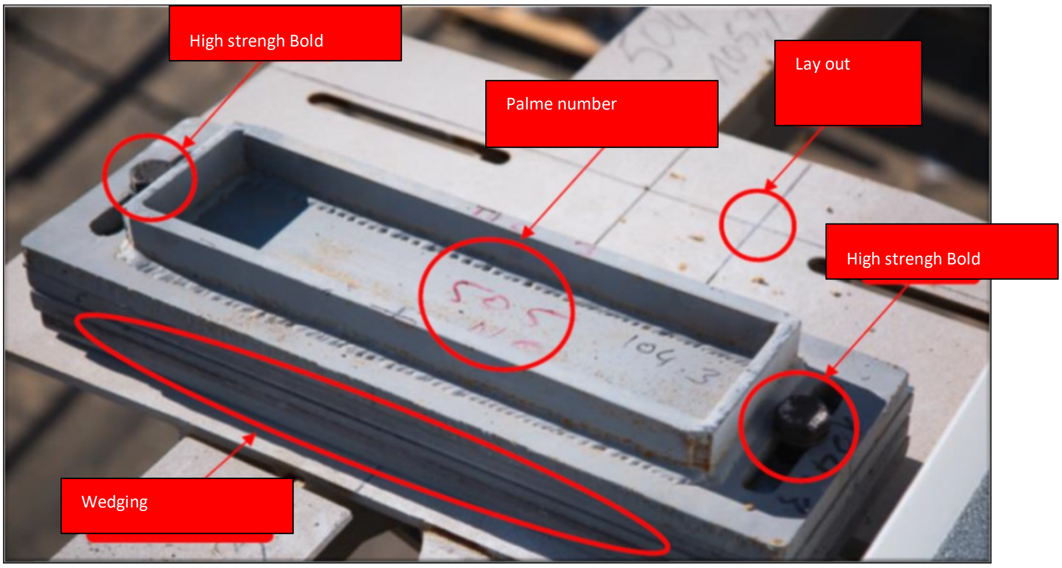

Figure 27 – Bearings

These bearings (Fig. 27) were put in place on the brackets of the metal framework and are assembled by high-strengh bolts with tightening torque. Their position is based on the theoretical plan, in order to do away with the implantation discrepancies of the framework due to installation tolerance. Their altimetric position, attained through bracing as required, was determined in such a way that each palme was based on a plan never permitted to present an imperfection or warp of more than 1 cm. The determining of the bracing of each bearing was established through a simple geometric calculation based on a 3D topographical measurement of the metal brackets. Prior to the laying of the palmes, a mock installation was performed with the aid of a frame especially designed for this purpose, materializing a perfect plan, in order to ultimately guarantee the implantation requirements within the space for each of the bearings.

7.4. Installation of the palmes

Figure 28 – Installation of the palmes

Figure 29 – Installation of the palmes

The 105 palmes were installed on the framework in a single laying phase. This was made possible by all the work done in advance as described above, which enabled the perfect alignment between the measuring and installation of the bearings and the given palme to be guaranteed in advance. The laying was performed with the aid of a motorized crane of a capacity of 1 200 tonnes, whose boom height of nearly 150 m obliged to operate by night so as not to interfere with the launch cone of the Montpellier airport (Fig. 28-29).

The palmes were then equipped with 10,540 glass panels in order to ensure the airtightness of the roofing. As for the 7 cm space between the palmes, necessary for seismic purposes but also for ventilation control, its airtightness was ensured by the installation of aluminum sheets that were reconstituted, soldered, and then thermo-coated.

7.5. Installation of the shells under the main steel beams

Besides the palmes that clearly have a roofing function, three types of decorative UHPFRC elements ensure casing of the metal structure: the windshields present across the full periphery of the railway station, hung from metal brackets; the casing element shells of the main beams supporting the palmes; and the ridge shells encasing the peripheral beam of the structure. Installation proved complex, owing to the relative fragility of the pieces, which required the design of lifting and slinging tools, and mostly due to the presence of the palmes at the time of installation of these casing elements. In addition, similarly to the requisite coplanarity of the bearing points of the palmes, tight geometrical control was required for the prefabricated casing elements. It was therefore necessary, for each type of casing, to design attachments that would allow the precast elements to be suspended on the metal framework, with settings enabling the points of contact to be positioned within a plan (Fig. 30-31).

Figure 30 – Installation of shells with the aid of a cradle

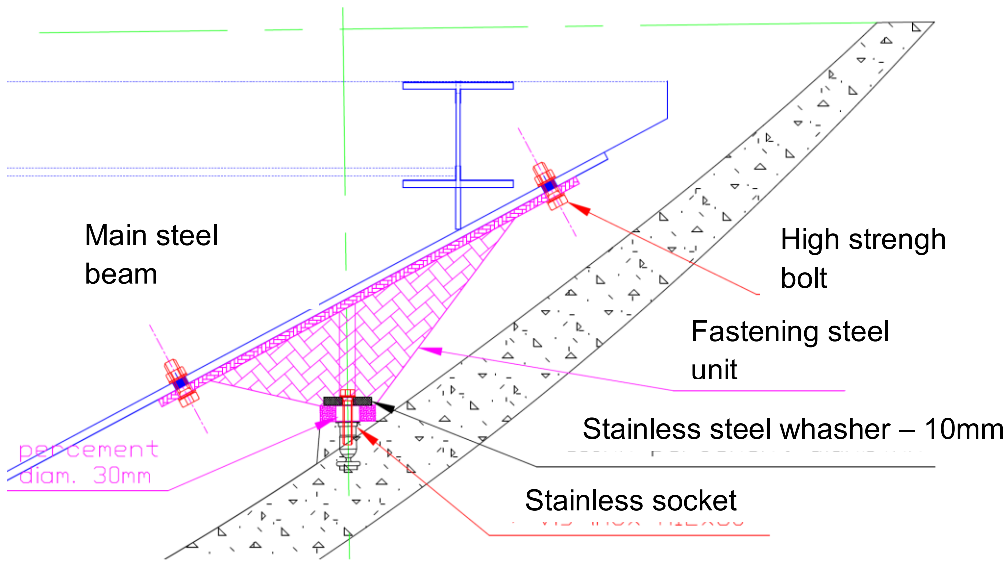

Figure 31 – Attachments between shells and framework

8. CONCLUSION

The construction of the Montpellier-South of France TGV station was the opportunity to explore all the UHPFRC performances in multiple fields: structure, durability, waterproof.

Due to the geometrical complexity of the roof, a roof made by a single elements permits a huge simplification of the construction processes. The high UHPFRC durability permits a reduction of the maintenance operations. For all that, the overall cost is reduced and controlled.

Modular elements and a very fast installation (2 weeks) allowed an important reduction of the construction time.

ACKNOWLEDGEMENTS

The following entities, not mentioned in this paper focused on the UHPFRC palmes, took part to the design and realization of the project:

- Client (owner): Réseau Ferré de France
- Jointly funding entities: the French government (Agence de Financement des Infrastructures de Transport en France), Languedoc-Roussillon Region and Montpellier Agglomeration
- KCAP and Guéric Péré from Ilex Paysagistes (Urban planning).
- LafargeHolcim (development of the special UHPFRC mix-design)
- Elioth Engineering (ventilation study).
- AVLS Engineering (acoustics)
- LRing (detailed design of UHPFRC palmes)

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