# SLENDER SUNSHADES BEAMS MADE OF UHPFRC BETWEEN TWO TUNNELS IN MARSEILLE

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**Abstract**

The project was to implement beam elements above an area between two tunnels in Marseille, with two objectives: to protect drivers from the sunlight at tunnel exit and to protect residents from noise due to the traffic. Very slender UHPFRC prestressed beams, 14.50m long, with an omega-shaped inclined cross section and a 5cm thick web, were built. To meet the fire resistance requirement, a specific BSI® formula was used, mixing two types of fibres: steel fibres for the concrete mechanical properties and polypropylene fibres to ensure stability in case of fire. Laboratory tests coupled with numerical simulations were performed to confirm the design. To achieve the noise reduction performance required, an insulating material has been placed into the omega cross section. The adopted solution efficiency has been validated by measurements on site. Before starting the production of the 90 elements, a prototype was made. It allowed to validate all steps for beams precasting, and to justify the K coefficients of fibres orientation, according to French AFGC recommendations.

**Résumé**

Le projet consistait à mettre en œuvre des poutres au-dessus d'une trémie située entre deux tunnels à Marseille, avec deux objectifs: protéger les conducteurs des rayons du soleil en sortie de tunnel et protéger les riverains du bruit généré par la circulation. Des poutres précontraintes très élancées en BFUP, de 14.50m de portée, avec une section inclinée en forme d'oméga et une âme de 5cm d'épaisseur, ont été fabriquées. Pour respecter l'exigence de tenue au feu, une formule spéciale de BSI® a été utilisée, combinant deux types de fibres: en metal pour les propriétés mécaniques du béton et en polypropylène pour assurer la stabilité au feu. Des essais en laboratoire couplés à des simulations numériques ont été réalisés pour confirmer le dimensionnement de la structure. Pour atteindre les performances d'isolation acoustique demandées, un matériau isolant a été placé au centre de la section en oméga. L'efficacité de la solution adoptée a été démontrée par des mesures sur le site. Avant le démarrage de la production des 90 éléments, un prototype a été réalisé. Il a permis de valider toutes les étapes de la préfabrication des poutres, et de justifier les coefficients K d'orientation des fibres, conformément aux recommandations françaises de l'AFGC.

# 1. THE PROJECT

## 1.1 Context and objectives

In a global context of the upgrade works for the Boulevard du Littoral and compliance works for the tunnel of the Vieux Port, the CUMPM (Communauté Urbaine Marseille Provence Métropole) initiated this project of sunshade beams.

During the previous compliance works in the tunnel of the Vieux Port, the existing sunshade beams located between the tunnels of Joliette and of Vieux Port were disassembled (Fig. 1). Those sunshades, made of aluminum truss beams, turned out to be too damaged to be simply reconditioned and put back, as it was initially foreseen. As a consequence, the project owner intended to replace those sunshade beams with new ones, with the three following targets:

- prevent users from being affected by the sun rays when driving between the two tunnels, while still allowing for the airflow needed by the tunnels' ventilation system,
- ensure an acoustic insulation of the tunnels, in order to significantly lower the noise nuisance for the nearby inhabitants,
- ensure a fire resistance (one hour with a ISO-834 fire [1], as required by the Brigade des Marins Pompiers of Marseille), even though the sunshade beams are not strictly in the tunnel portion.

Figure 1: General view of the area between the two tunnels before the works

Those specifications, along with the necessity of building a large number of sunshade beams, led the project's owner to choose a solution with ultra-high performance fiber-reinforced concrete (UHPFRC).

The engineering society Setec TPI and the architect André Mascarelli were appointed for the project management.

### 1.2 Preliminary studies

The works consist in building 90 prestressed UHPFRC beams to cover the existing hopper (Fig. 1). The preliminary studies led to pre-tensionned Ω-shaped beams, with a 45° angle.

The thickness, number and spacing of the Ω-beams were determined so as to prevent any contamination between the ventilation systems of the adjacent tunnels. During the preliminary phase, this condition was studied and validated through aerolic simulations, and the lighting criterion was validated.

Moreover, the project manager assigned CIA Acoustique for the the acoustic study of the project, which consists in assessing, justifying and measuring the acoustic efficiency of the beams. Noise exposure measurements, carried out before and after the works, allowed to confirm the calculations: UHPFRC beams garnished with sound-absorbing material (rock wool) allowed to significantly lower the noise nuisance in the surroundings of the tunnels (from -4 dB(A) to -7 dB(A)).

A relevant formula of UHPFRC, *i.e.* justified through testing, has been required to reach the fire resistance of the Ω-beams and to ensure that there is no risk of bursting.

Based on French AFGC recommendations [2], the preliminary studies justified that the Ω-beams, garnished with rock wool panels which protect one side of the beam's web, could be compliant with the specifications regarding the fire resistance. In addition to this first function, those panels also ensure the acoustic insulation of the tunnels.

## 2. BSI® FIRE SPECIFIC MIX

In order to comply with the peculiar specifications of this project regarding fire resistance, a specific formula BSI® "Fire" was used. This formula mixes 2 types of fibers: steel fibers ensure the tensile strength of the material, and polypropylene fibers prevent its bursting under high temperature. The Table 1 provides the details of the material's composition:

Table 1: BSI® Fire specific mix

| | |
|---|---|
| Premix (cement + silica fume + aggregates) | 2296 kg/m$^3$ |
| Superplasticizer | 56 kg/m$^3$ |
| Added water | 208 kg/m$^3$ |
| Straight Steel fibers ($L_f$=20mm / Φ=0.3mm) | 195 kg/m$^3$ |
| Polypropylene fibers ($L_f$=12mm / Φ=0.18μm) | 3 kg/m$^3$ |

The temperature dependency of the properties of this UHPFRC has been measured in the fire laboratory of the CSTB (Centre Scientifique et Technique du Bâtiment). The Figure 2 illustrates the results of the tests run for the assessment of the compressive strength (based on the maximal values of the curves) and the Young's modulus (based on the slope of the curves). Typically, one can see that the compressive strength of the BSI® at 600°C is as high as the one of a UHPC at 20°C (more than 60 MPa).

To confirm the UHPFRC stability and the lack of any bursting under extreme fire conditions, numerous tests were performed, many of them up to 1300°C, the maximum temperature of the HCM tunnel fire curve [3].

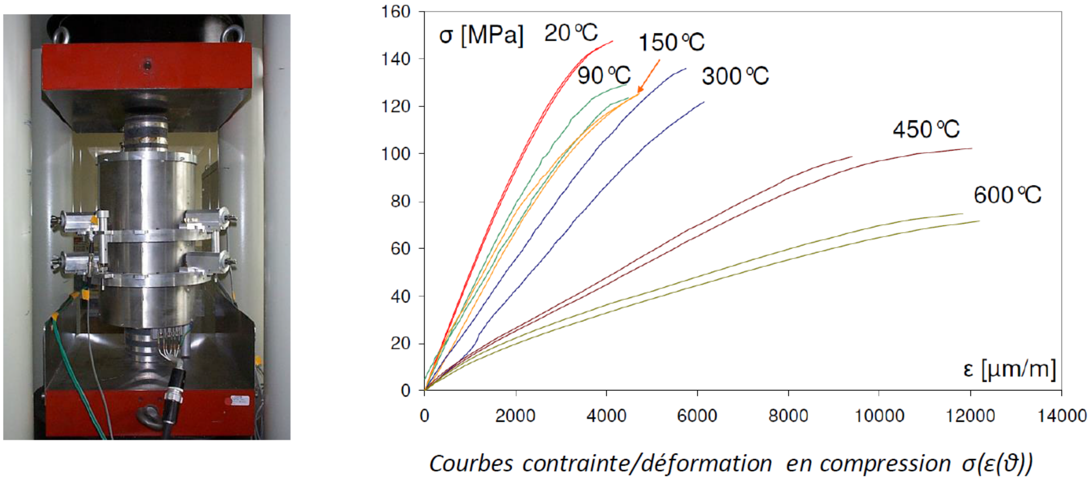


Figure 2: Compressive strength and Young's Modulus versus temperature

The material's heat transfer properties have also been determined, in order to enable the simulation of the temperature fields within the Ω-beams at each time step of the fire scenario considered. To do so, three separate properties are needed, all being dependent on the temperature: thermal conductivity (λ), specific heat (C) and density (ρ). Tests were run on UHPFRC flat samples, using the hot-wire method, coupled with weight loss testing made on cylindrical samples. The results were then refined using an inverse method: fitting of measured and numerically simulated temperature fields at each time step of a fire curve (Fig. 3).

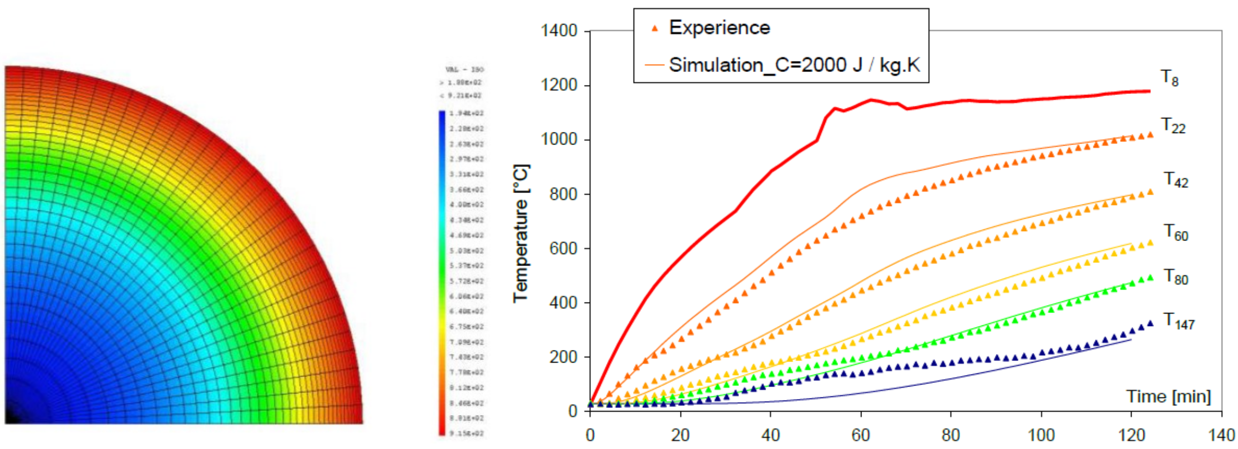


Figure 3: Heat transfer properties calibration by inverse method

## 3. EXECUTION PHASE ENGINEERING

Execution phase engineering studies have been performed by the Direction des Moyens d'Ingénierie (DMI) of Eiffage Infrastructures company. They have been checked and certified by Setec TPI at Vitrolles. They were done according to AFGC recommendations on UHPFRC, published in 2013 [2]. Table 2 presents the mechanical properties of the selected UHPFRC, taken into account for the design calculations.

Table 2: Mechanical properties of the BSI® Fire

| | | |
|---|---|---|
| Density | $\rho$ | 2.7 t/m$^3$ |
| Compressive strength | $f_{ck}$ | 150 MPa |
| Tensile strengh of the matrix | $f_{ctk}$ | 7.5 MPa |
| Post-crack tensile strength | $\sigma_{bt}$ | 6.1 MPa |
| Young's modulus | $E_{cm}$ | 55 GPa |

The current cross section of the beams has an oméga shape, with a 5 cm thick web (Fig. 4). The 45 degrees inclination of it, offers a protection for the drivers who are affected by the sun rays at the Vieux Port tunnel entry.

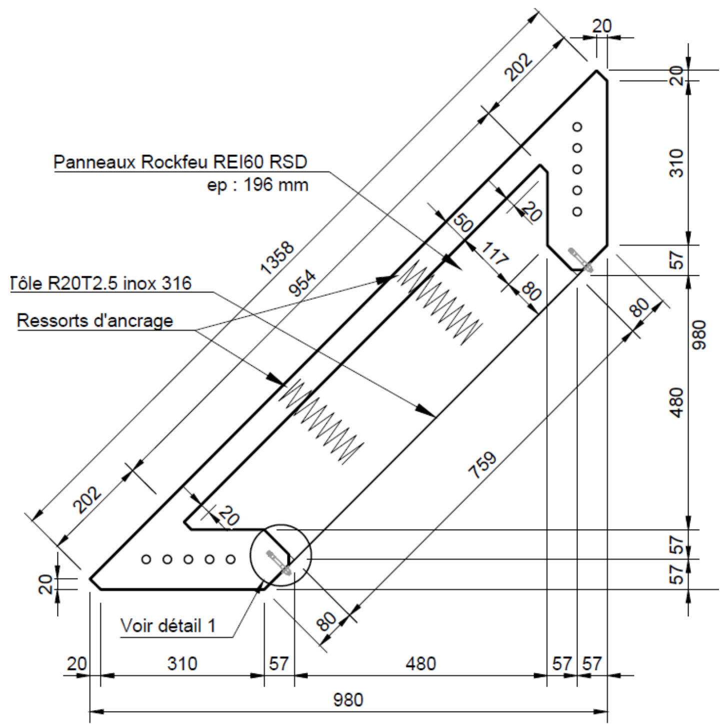


Figure 4: Current cross section of the beams

Due to the large and variable width of the area between the two tunnels, a solution with prestressed by bonded wires beams was selected. To keep the same cross section for all the 90 beams, with a varying span between 2.00 m and 14.50 m, an optimization of the prestressing has been performed. Five ranges of spans were selected (Fig. 5), allowing a variation from 2x1 up to 2x5 T15s wires per beam.

As usual with bending structures made of UHPFRC, tensile capacities of the material are very well used for the design of cross sections, but not at all the compressive strength. Here, the maximum tensile stress at characteristic SLS is 6.6 MPa, compared to a tensile strength of 7.5 MPa. In the same time the maximum compressive stress is 34 MPa, compared to a 150 MPa strength.

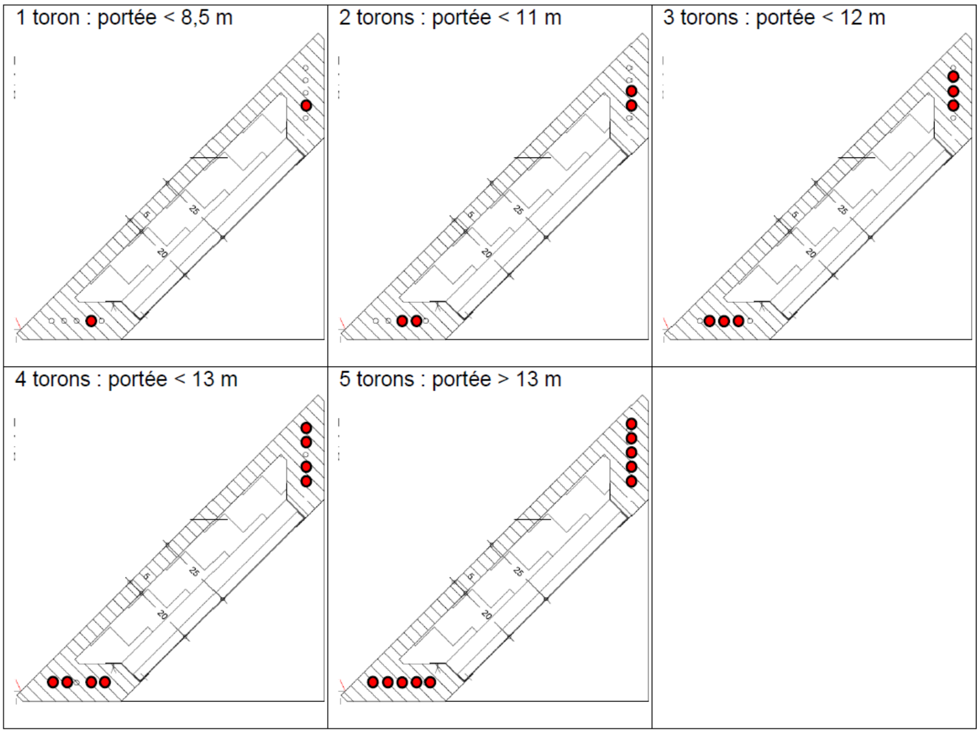


Figure 5: Optimization of the prestressing with the span of the beams

For stability under fire calculations, Eurocode 500°C isotherm curve method [4] was applied. A heating simulation of the structure, during one hour with ISO-834 fire curve, has been done, allowing to draw the isotherm curve in each cross section (Fig. 6). Considering this curve, residual capacities of the cross sections are calculated, by taking into account the UHPFRC affected properties and the temperature into the wires.

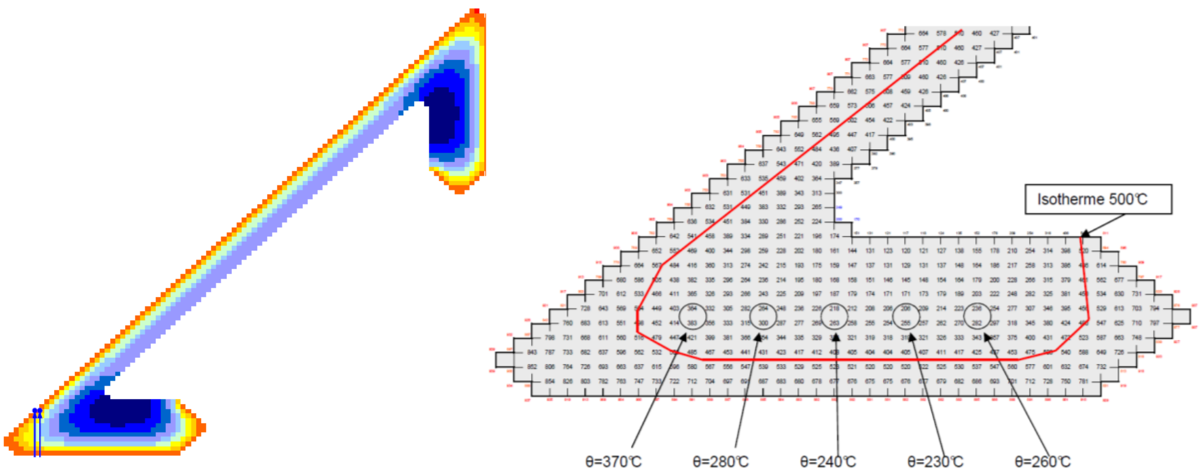


Figure 6: Current cross section - Heating simulation during 1 hour with ISO-834 fire curve

## 4. SUITABILITY TESTS

As recommended for UHPFRC by the AFGC, a prototype of the Ω-beam was built prior to starting the production. This prototype was used to check the K coefficients considered in the design for characterizing the orientation and distribution of the steel fibers in the structure. Several 150 x 50 x 600mm$^3$ samples were extracted by sawing into the prototype (Fig. 7). Since those are slender samples (5cm-thick), they were tested using a 4-points bending (without making a notch).

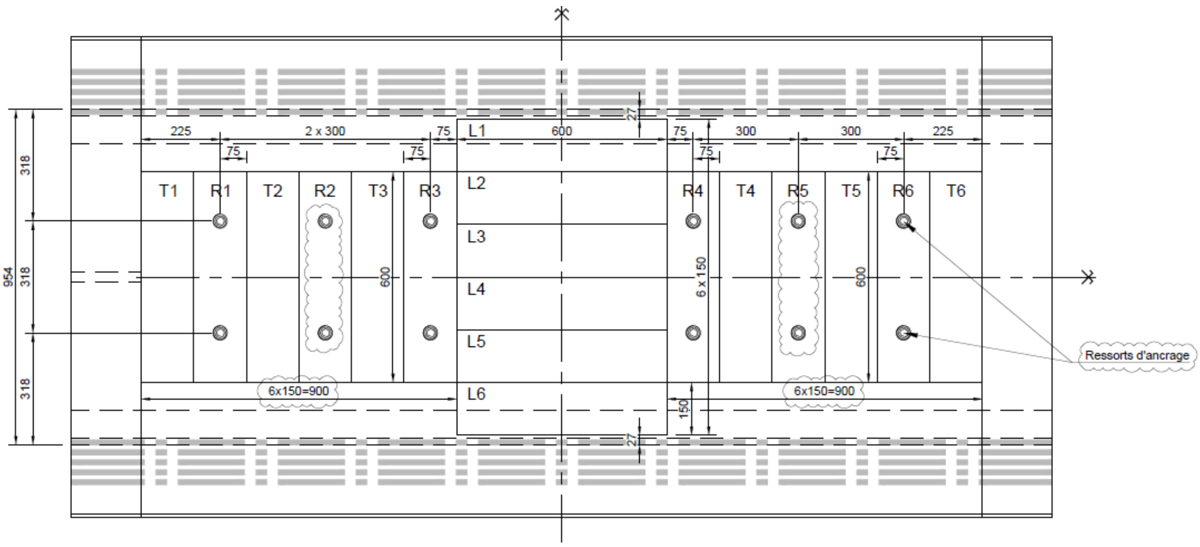


Figure 7: Location of the samples extracted from the prototype

Making the prototype (Fig. 8) also allowed developing the formwork and validate the casting procedure, including the triangle-shaped edges. A fair amount of this original design's technical particularities were validated during this suitability test phase: control of the restrained shrinkage, holding device for the rock wool acoustic panels (Archimedes' force), shape and resistance of the perforated 316 stainless steel sheet, fastening of the acoustic panels to the UHPFRC using prefixed springs…

The K coefficients have been determined by comparing the measurements made on the samples extracted from the prototype, with the measurements made on reference samples, cast on the same day as the prototype. The hypothesis considered for execution phase studies, *i.e.* $K_{global}$=1.35 and $K_{local}$=1.75, have been confirmed by the suitability tests (Table 3).

Table 3: Suitability tests – Check of K coefficients

| | $K_{global}$ | $K_{local}$ |
|---|---|---|
| Test series L | 1.30 | 1.47 |
| Test series T | 1.00 | 1.14 |
| Test series R | 1.00 | 1.62 |
| Design values | 1.35 | 1.75 |

The prototype was prestressed using 2x3 strands T15s, as soon as the concrete resistance reached 100 MPa. A 48 h-construction cycle was then validated for the manufacturing of the 90 elements.

The material's bursting resistance had to be validated either by fire tests on reference samples, or based on tests already run on similar samples (similar shapes, with similar load and temperature levels) completed with a technical approval provided by a certified laboratory which confirms that the tests are consistent with the project considered.

The BSI® has been thoroughly studied and tested with extreme temperature conditions, with samples using the same formula as the one used for the sunshade beams. Based on those tests, the CSTB validated the bursting resistance of the structure.

Figure 8: Casting the prototype in the prefabrication factory

## 5. PRECASTING

The 90 UHPFRC Ω-beams were prefabricated by Hürks Beton in its factory in Veldhoven, Netherland (Fig. 9). The manufacturing cycle was organized in order to produce one element per day: 2 formworks were used, with a rate of 2 days per formwork. Amongst other parameters, this 2-days laps allowed reaching the 100 MPa compressive strength needed for the prestressing of the elements.

Given the variability of the Ω-beams length (from 2.00 m to 14.50 m) and variable ends angles, nine geometrical families were defined. On one side of the formwork, a fixed edge formwork with a given angle; on the other side, a mobile edge formwork (to allow for length variation) with another angle (the edge of the hopper being neither straight nor parallel).

In order to have a unique cross section for all the Ω-beams albeit the length variability, five prestressing families were defined, from 2x1T15s to 2x5T15s. For the families 2x4T15s and 2x5T15s, a partial ducting of the strands was made at the edges (*i.e.* strands were debonded), in order to spread the prestressing force application and limit the stresses within the material.

Figure 9: Formwork in the prefabrication factory


Figure 10: Transportation of the Ω-beams

All the Ω-beams have been conveyed by trucks (Fig. 10) from the prefabrication factory to a storage area located in Fos-Sur-Mer, close to the construction site located in Marseille. Storing the sunshades in the city itself was not an option.

## 6. CONSTRUCTION SITE

While the sunshades were being prefabricated, preliminary works were achieved on the construction site in Marseille: positioning and casting of the bearing support atop the existing cornices (with a cadency of 10 supports per night).

As the manufacturing went on, the sunshades were gradually sent to the storage area in Fos-Sur-Mer. There, the surface finishing was achieved (a light sanding and application of anti-graffiti paint as stated by the architect) and the perforated stainless steel sheets were fixed on the rock wool.

Eventually the sunshades were placed using a 70T mobile crane (Fig. 11), located on the upper roadway closed during the night. Ten elements were placed each night, including the installation of the neoprene supports (1 support on East side and 2 supports on West side) and fastening of the stainless anti-tracking stop, sealed in the cornices. The final result is illustrated Fig. 12.

## REFERENCES

[1] NF EN 1991-1-2 "Eurocode 1 – Actions sur les structures – Partie 1-2: Actions générales – Actions sur les structures exposées au feu", 2003.
[2] AFGC (Association Française de Génie-Civil) "Ultra High Performance Fiber-Reinforced Concrete – Recommendations", 2013.
[3] CETU (Centre d'Etudes des Tunnels) "Comportement au feu des tunnels routiers", 2005.
[4] NF EN 1992-1-2 "Eurocode 2 – Calculs des structures en béton – Partie 1-2: Règles générales – Calcul du comportement au feu", 2005.


Figure 11: Nightly installation of the sunshades, using a 70T mobile crane

Figure 12: Global view after completion