MUCEM: THE BUILDER'S PERSPECTIVE

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Abstract

The Museum of European and Mediterranean Civilisations, designed by Rudy Ricciotti, is the first building in the world to make such extensive use of UHPFRC. The tree-like façade columns, brackets and bridges decks of the perimeter footbridges, façade and roof lattices, 115 and 69m long pedestrian footbridges and even the protective covers to the prestressing anchorage points all make use of this material. Its suitability for a building located in a port area subject to sea spray is undeniable. However, the use of UHPFRC for the supporting elements of a building open to the public posed a number of problems, particularly with regard to its resistance to fire and seismic activity. Given the systematic use of prefabrication, the assembly techniques are also unusual, not only for the UHPFRC elements but also for the floors.

Résumé

Le Musée des Civilisations de l'Europe et de la Méditerranée, conçu par Rudy Ricciotti, est le premier bâtiment au monde à faire un usage aussi extensif du BFUP. Les poteaux de façade arborescents, les potences et les platelages des passerelles périphériques, les résilles de façades et de toiture, les passerelles piétonnes de 115 et 69m de longueur, jusqu'aux capots de protection des ancrages de la précontrainte, font en effet appel à ce matériau. Sa pertinence est indiscutable pour un bâtiment situé dans une zone portuaire soumise aux embruns. Cependant, l'utilisation du BFUP pour les éléments porteurs d'un bâtiment recevant du public a posé un certain nombre de problèmes, notamment en ce qui concerne sa résistance à l'incendie et au séisme. Les techniques de montage sont également inhabituelles, compte-tenu du recours systématique à la préfabrication, non seulement pour les éléments en BFUP, mais aussi pour les planchers.

1. INTRODUCTION

The construction of the first national museum ever built outside Paris began in the summer of 2010, after ten difficult years of gestation. Designed by the architect Rudy Ricciotti, with the support of the SICA consultancy for the structure, this project is characterised by the extensive use of UHPFRC for its elements (refs. [1] to [3]).

In plan, the building is composed of an 'exhibition' part forming a 50 x 50 m square and 'administration' part at right angles. The administration building and the interior walls of the exhibition building are of fair-faced reinforced concrete. The façades of the exhibition building, carried by tree-like prestressed UHPFRC columns, are encircled by a peripheral access footbridge suspended from UHPFRC brackets. The roof and south and west façades have a lattice that protects the structures and public from the sun. The floors of the large exhibition halls are composed of prefabricated beams prestressed by adherent strands. Only the foundations, structural walls and perimeter beams are cast in situ. The museum is connected by a first 115 m long footbridge to Fort Saint-Jean, then from there to the church of St. Laurent by a second 69 m footbridge.

Photo 1: The building in construction: lattice installation

The construction contract was awarded to the consortium Dumez-Freyssinet, in association with Bonna Sabla for the prefabrication and Lafarge for provision of the Ductal® UHPFRC. Implementation studies were carried out by the consultant engineers SIDF for the overall modelling and also for the cast-in-situ elements, Lamoureux-Ricciotti Ingénierie for the prefabricated components.

2. COLUMNS

2.1 Design

The façade columns are fitted with Freyssinet ball joints at each end. These joints, not allowed for in the original building design (refs. [2] and [3]), were added by project management during the tender stage, following the request of the technical inspection agency not to involve any UHPFRC element in taking up seismic loads. They were the subject of a site ATEX (CSTB technical assessment) and tests to determine experimentally their 'interference' stiffness in rotation (fig. 1).

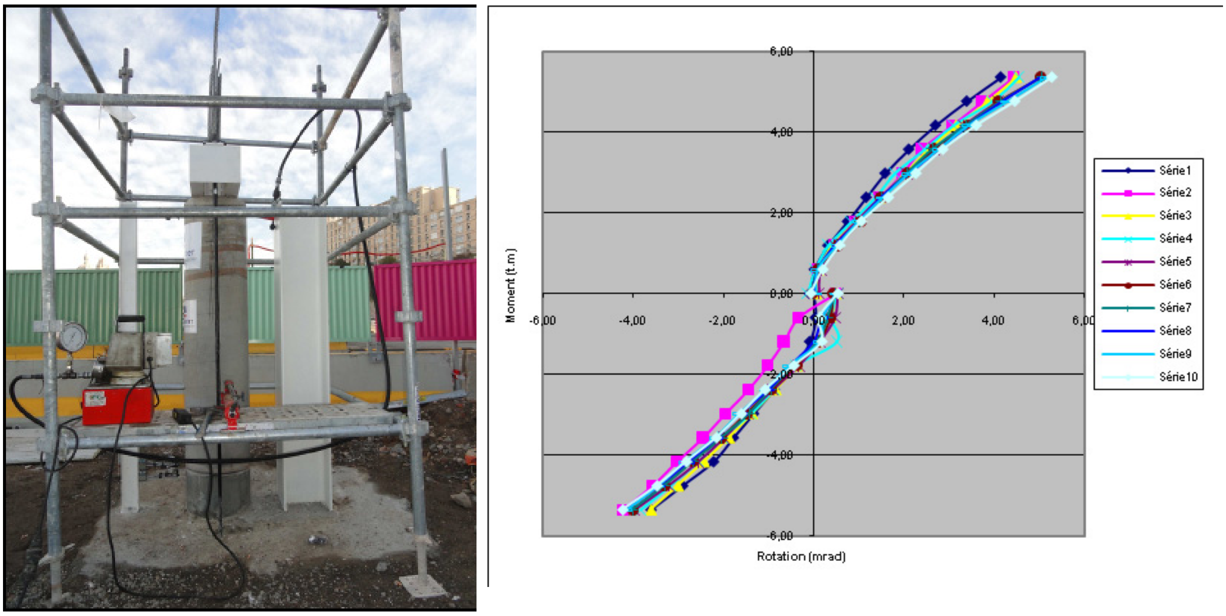

Figure 1: Experimental measurement of the Freyssinet ball joint stiffness

Two requirements of serious consequence emerged from the lessons of the ATEX assessment report: firstly the consideration of a dissymmetrical fire, applying the ISO fire curve to only half of the inner perimeter, the outside of the column remaining unheated; then the need to maintain compressed under load the full reduced section of the ball joints.

The dissymmetrical fire scenario leads by a 'bi-metallic' effect to significant curvatures (up to 20cm deflection for 40 cm diameter columns). The avoidance of tensile stresses on the heated side (the effectiveness of metallic fibres being limited above 450 °C), then leads to an unacceptable number of prestressing strands being called into play. A controlled fire study, taking into account the actual heat load of the premises was carried out by Efectis and enabled reduction of the temperature on the internal face of the columns from 1,000 °C to approximately 600 °C. Crossing the strands specific to each section at right angles to the connections remained, however, impossible to implement. The remedy found was to run the same prestressing strands on all 3 levels of columns, thus eliminating the crossings. This innovative technique required the perfection of a threading process enabling the strands to follow the forks of the column's different 'branches'.

The prestressing was thus intended, essentially, to counter the moments due to dissymmetrical fire, and is of little use in the loaded phase.

The second requirement, keeping the section of the ball-and-socket joints fully compressed under load, leads to a decrease in the diameter of the reduced section, thus aggravating the problem of spreading the localised stress.

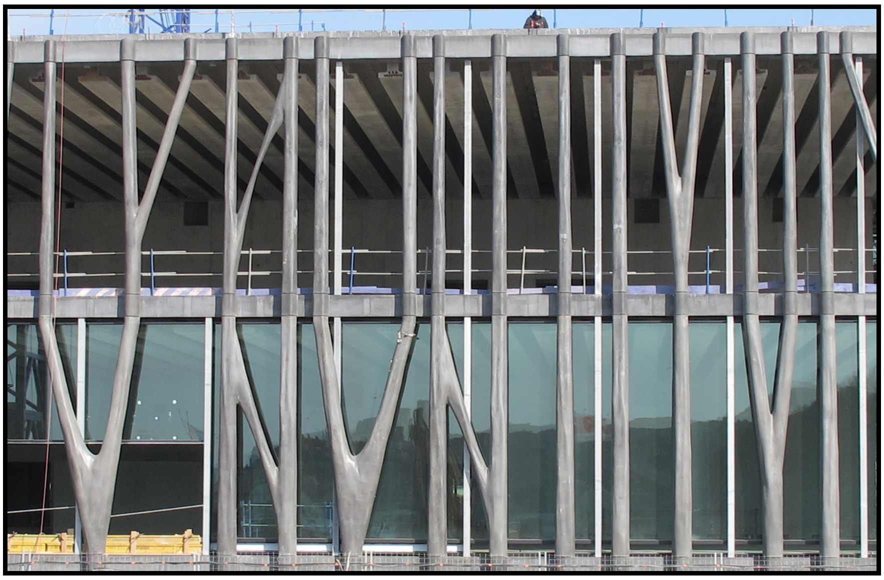

Photo 2: Façade columns (photo G. Detaille)

2.2 Prefabrication

In this project, the manufacture of the columns proved very different from conventional concrete column manufacture. The different models (20 in total): Straight column - Conical column - Y-shaped column - N-shaped column, 2.50, 6.00 and 9.00 metres in height and with the possibility of multiple assembly thus allowing for 80 different types of column. For the entire project, we fabricated 310 columns. Besides the structured aspect of the different models, obtained from a carved wood form and individually checked by the architect, each column had to meet very specific requirements in terms of dimensional tolerances with double ball joints (top and bottom) and integral post-tensioning sheath.

Each 'mixed' polyurethane mould cast on the wood form was reinforced by a metallic corset capable of taking the thrust strains of the UHPFRC during casting and required very high 3D laser-controlled precision. Joint surfaces were particularly carefully treated and reinforced to avoid the slightest leakage during casting. The accuracies obtained on the finished products, both in length and branch spread for the 'Y' and 'N', were in the order of one millimetre.

For the columns, a specific UHPFRC mix containing both polypropylene and metallic fibres was used to avoid concrete spalling. The vapour trapped in the matrix is released through a continuous network of voids created by the melting of the polypropylene fibres.

AFGC/SETRA interim recommendations define a general methodology to assess fibre orientation in such a complex. In fact, this is critical to assess fibre orientation since the characteristic behaviour law is related to the isotropic (2D or 3D) fibre distribution. Prismatic specimens were cut from the column following the main internal stresses and their flexural strength compared to a referenced isotropic flexural behaviour to define the 'K' factor. The MuCEM columns were cast vertically without any casting breaks. Due to spiral rebars near to the anchorage points it was not possible to cut usable specimens of a regular size. In those sections, a fibre-counting technique was selected with 'optical data acquisition' to literally count the fibres. This complementary technique was particularly relevant to check for possible fibre segregation by comparison with specimens cut at the tops and bottoms of the Y columns.

2.3 Implementation phasing

The assemblers of industrial structures are used to the erection of columns and prefabricated floors without major difficulty but this is generally in situations in which the columns, embedded by containment in footings, are stable by themselves and where the beams rest on brackets secured to the columns. The MuCEM situation in which the columns, ball-jointed at each end, have more of a tendency to pass in front of rather than under the beams that they support (a case of 'surface-mounted' connections), is somewhat different. The 'equations' for the problem can be summarised as follows:

1: The keying-in of a given level requires the prior installation and adjustment of the corresponding floor and of the columns immediately below, but also of the columns immediately above.

2: It is much easier to bring the ring beam formwork into operation before the setting the columns in place.

3: The reduced possibilities for adjustment left by the Freyssinet ball joint and corbel system, required not only a millimetre-accurate setting out in level, but also in plan to join up the corbels to connectors or couplers left in the ring beam.

4: The only possible adjustment was not that of the 18 ton floor elements or the single-element ring beam, but of the position of the column itself.

The phasing devised to meet these requirements was as follows:

1: Installation and adjustment of floor level i, set on props.
2: Formwork and pouring the floor ring beam at level i height.
3: Installation of level i+1 floors and ring beams, on props placed in vertical alignment with the previous.
4: Installation and adjustment of the level i and i+1 columns. The presence of the ring beams was used to hold and adjust the tops of the columns.
5: Keying-in columns/ring beam with non-shrink mortar of 60 MPa compressive strength.

Thus, the floors are installed first, then the beams suspended from the floors and the columns keyed in last onto the beam - which constitutes the exactly opposite order to a conventional construction. Moreover, if during the intermediate phase the floor elements are capable of taking the mass of the floor above (their self-weight being of the same order as the design live load), they can not under any circumstances take, even in shear, the mass of two floors. It is thus necessary to retain the props on the three floor levels and wait for the last keying-in before removing them. On the façade side, the building is thus entirely carried by the props until the final load transfer onto the columns. Prestressing of the columns only takes place after load transfer, to avoid the risk of compressing the props more than the columns. This is possible since the prestressing, as previously observed, serves more to take up moments due to dissymmetrical fire than dead loads.

Wind bracing throughout the building is thus provided, as at the end, by the keying of the floor elements onto the central walls.

2.4 Surface-mounted connections

The reduced section of the ball joints, created in UHPFRC, protrudes 15 mm in relation to the ends of the columns. With a minimum tolerance of 5 mm between column ends and connections, this arrangement gives a level adjustment possibility of +/- 5 mm, which demands a placement precision unusual for floors. Reinforcement of the connections is extremely dense (fig. 2) because, in addition to bracing around the ball joint, it must also ensure the transfer of loads from the floor to the column by short inverted-bracket function. After calculation it was found that no rebar manufacturer was able to bend the HA16 hoops required, not to mention a concrete section insufficient to accommodate the reinforcement cover. The hoops were therefore made of 'slices' of oil pipeline, which thus enabled the freeing up of bending and cover, with steels of qualities at least equivalent to that of HA steel. In addition, at equal height, the square section of the frame can accommodate $4/\pi$ times more! The columns are retained at the top by fixings previously attached to the ring beams and adjusted under the supervision of the surveyor. They are placed upright on the UHPFRC connector shells, themselves held horizontally by the same fixings. Level adjustment is ensured by the interposition of shims, while each column is secured to the fixing by straps.

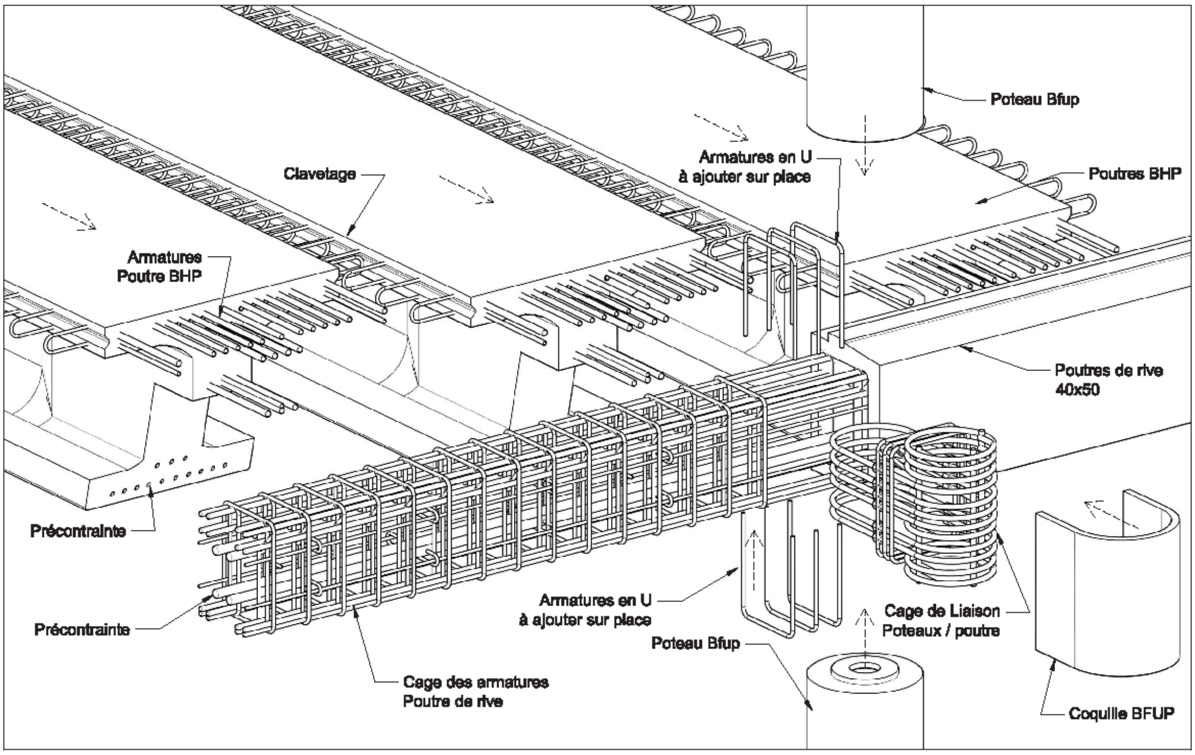

Figure 2: Façade element connection principle (SIDF doc.)

3. LATTICES

3.1 Design

The lattices which spread out over the façade and roof of MuCEM form an over-façade and light filter intended to protect the museum spaces from the effects of the sun. They also enable the creation of shadows that are carried for visitors along the perimeter walkways and onto the roof terrace. In terms of structure, they are 6 m x 3 m panels of self-supporting strands. The façade is simply set on the ground and its component panels are each carried on top of one another. The loads that these lattices support are quite severe, particularly for the façades exposed to the prevailing wind, the Mistral.

With regard to loads perpendicular to their plane, the lattices are positioned on rows of isolated fixings following several static typologies: simply-supported, continuously-supported and cantilever-supported.

The strands thus operate in combined deflected bending. Evaluation of the combined stresses and the resistance of these UHPFRC components was a difficult stage but typical in relation to this material's performance.

The compatibility of deformations between the strands and their supports was integrated into the design of the supports.

Photo 3: Lattices being installed

3.2 Prefabrication

For this project, 2 types of lattice: horizontal for the roof part and vertical for the façade part. Special feature: 'strand' type lattice in panels of 6.00 x 3.00 m with four different designs for the roof, five for the façades and continuity of strands from one panel to another included at corners and roof-façade junctions. In order to guarantee the best visual effect and in particular the perfect finish for the two faces of each panel, we opted for vertical mould fabrication (a specific process well-mastered by Bonna Sabla). With this technology, we have a product that is perfectly formed on all its faces, thus avoiding the risk of corrosion of fibres that could have been improperly covered in a conventional and (on the horizontal), much easier moulding process. Neither is there a risk of injury to the public which has access to the two faces of the panels that clad the museum. These concerns (risk of corrosion of protruding fibres in the 'seaside' context and risk of injury) guided our technological choice in favour of vertical moulding, although this process is trickier and more expensive to carry out. Specific moulds designed by Bonna Sabla were adapted for each of the nine models to be created. A diagonal cut was made in each corner to ensure strand continuity.

As for the other main components erected in UHPFRC, fibre orientation in the branches was carefully checked. This gave excellent results ($K<1$ in the longitudinal direction). The potential risk was therefore concentrated in the nodes where 'fibre flows' could meet. In those zones, fibres from one flow might not penetrate the other flow, thereby leading to a drastic lack of fibres in the section defined by the region where the two flows meet (cold joint). Consequently, in parallel to classical fibre testing, 1:1 scale tests were carried out on a representative number of elements (in this instance three) to check the overall behaviour and redundancy of the network of branches.

3.3 Implementation

The building is draped with a lattice which, for us, represents a bride's veil. This lacework is continuous as all the branches are inter-connected. We started with the installation of the roof lattice so that our teams could become familiar both with the handling of these panels and the implantation and adjustment procedure for the different elements.

As a first step we created a tool for handling the panels. Although adjustable both horizontally and vertically in all directions, our installation team preferred a more direct installation through the use of webbing straps that would not mark the concrete. The roof lattice rests on concrete pads that are located on the building's permanent damp proof membrane. These pads are eight in number per panel and the lattices are mechanically fixed to them. To adjust the overall horizontal position we put neoprene shims onto the concrete pads. The difficulty, that we resolved in advance, was of course the positioning of the lattice panel into its final location - its direction of installation, identification on delivery racks and position in Lambert coordinates. For the installation of the two façades of 72 meters in length, we first thought to install them by tower crane but with the intervention of cradles from the quays that had to be finished for the time of our intervention. Due to delays in this work, not forming part of our contract, a new installation procedure was devised so as to have no interface with the neighbouring construction site. On the previously installed brackets we set up two runner rails for individual cradles to give access to the different lattice fixing points and with the peripheral footbridges that were already in place. Between two vertical panels there are two stainless steel studs positioned on a branch to either side of the panel. Their height adjustment was achieved by means of aluminium wedges. The panels are vertically stabilised by means of hinged stainless steel spinnaker poles on metal uprights that are the stiffeners for the glazing on the façade side; by stainless steel connectors on ball joints, mechanically fixed by stainless steel screws on the lattice side. Once again the set-up procedure is fundamental to achieve perfect alignment and consistent 2 cm joints between panels. It is to be noted that the margin for manoeuvre for a stainless steel connector linking four different panels is 2 millimetres at each fixing hole.

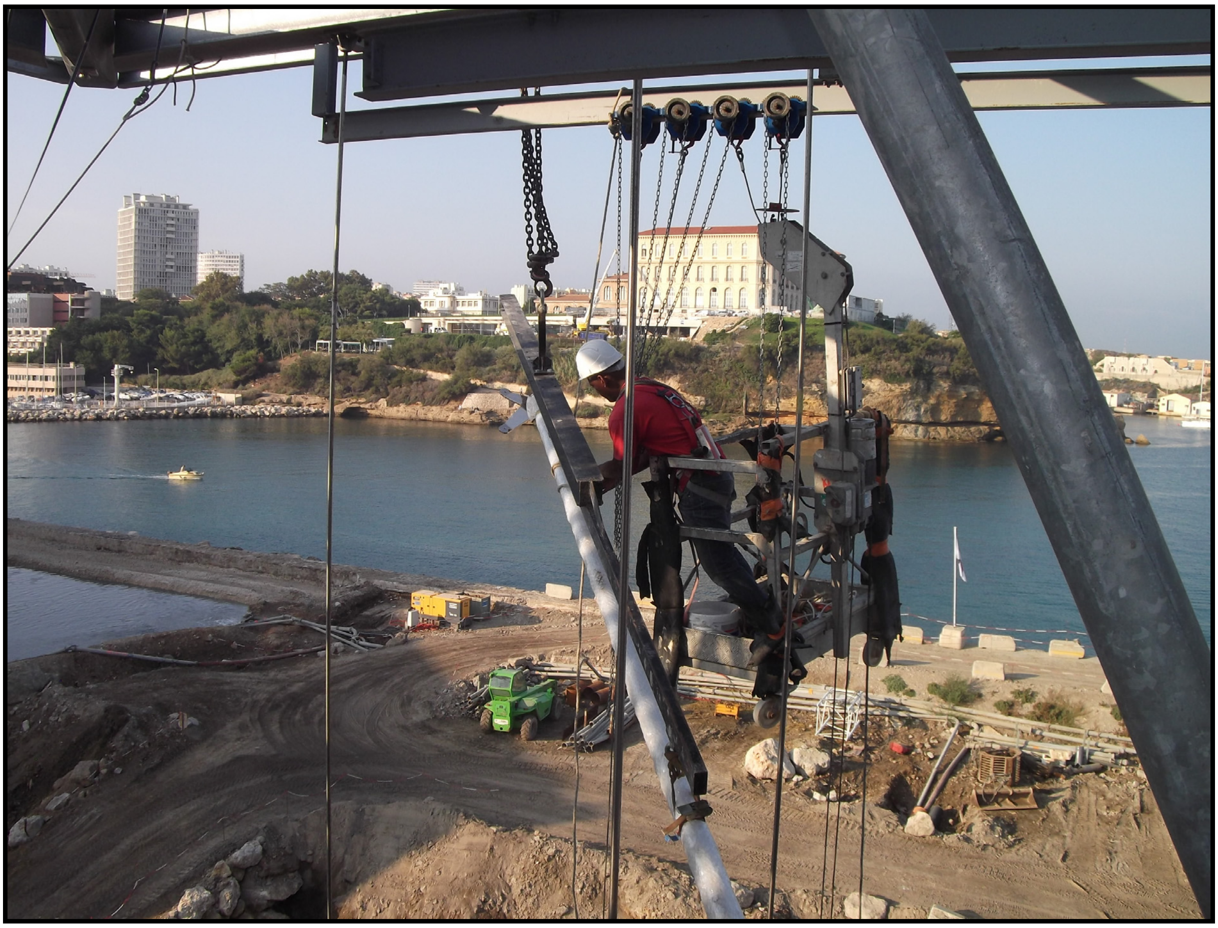

Photo 4: Installation of spinnaker poles before the lattices

4. BRACKETS

4.1 Design

The brackets are essential components of the 'free public access' route formed by the two footbridges and the peripheral access balconies to reach the Church of St. Laurent from the J4 Esplanade. This public promenade, which climbs in ziggurat form around the exhibition galleries, is made up of a (UHPFRC) deck attached to longitudinal and transverse steel beams.

All of this longitudinal structure is suspended at the top level of the building on UHPFRC brackets by pairs of stainless steel suspension cables set out at 3 metre intervals. The considerable loads (approximately 10 tons per cable pair) and the offset in relation to the façade (between 3 and 5 m) demanded consideration regarding both the design of such a cantilever structure and the distribution of stresses onto the rest of the shell and core. The static principle adopted is that of an isostatic frame. The bracket thus derived is articulated on the edge beam and tied at the rear by double stainless steel bars. These rear tie rods are connected to longitudinal spreader beams set out in quincunx to redistribute significant stresses onto different areas of the roof terrace deck. The suspended structure finally forming a footbridge, particular attention was focused on the dynamic behaviour of the entire structure the flexibility of which is, in reality, the result of the accumulation of the flexibilities of all the intermediate structures - of the longitudinal beams, brackets and top level large-span floors.

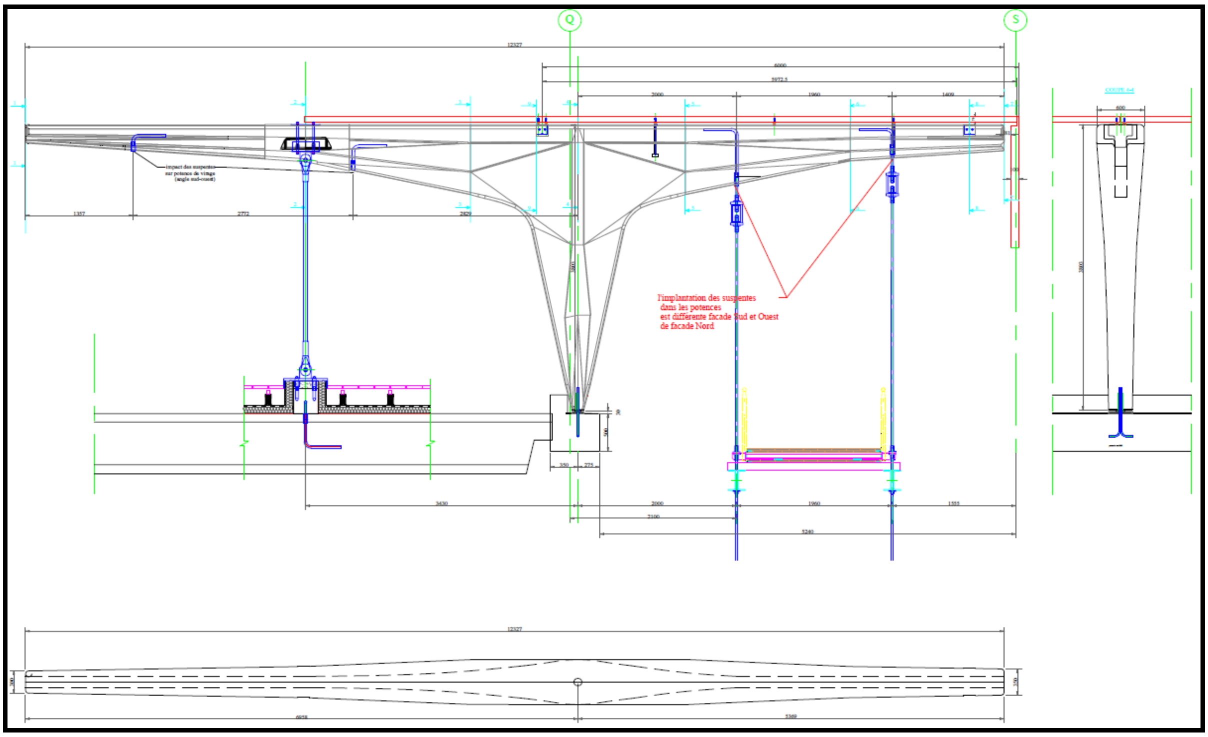

Figure 3: Bracket set-out plan (doc. Lamoureux Ricciotti Ing.)

4.2 Prefabrication

With a span of almost 14.00 m in length and a height of 4.50 m, the brackets have a weight of approximately 9 tons per unit. The ball joint support that proved highly satisfactory for the columns was carried over for the bracket supports.

The brackets were moulded on the vertical, in the direction of installation, in a specific steel mould. Great precision was needed regarding the ball joint supports and anchorage inserts for the different suspension cables for the walkways and tie beams.

4.3 Implementation

The UHPFRC brackets adopted are the result of two developments. The first came from the contractor which, for fire resistance reasons, proposed changing the original metal brackets to UHPFRC; the second from the architect who, due to technical and aesthetic design constraints, developed his design so as to result in this prototype. Given the size of the precast components, they were placed upside down on a trailer for road transfer. On their arrival we had to turn them over in order to present them in their final position. Inserts for handling sockets were of course pre-defined at the design stage so that, at each phase of installation, any improvisation was proscribed. The first bracket unloaded was stored by means of a storage bracket installed on site and the second put directly into its position and maintained by push-pull struts. To take this temporary phase into account, i.e. before the brackets were keyed, braced and permanently loaded, we commissioned a consultancy firm to carry out a site study to calculate the stresses to be taken up by our props until all of the tie beams and suspension cables were operational. Once again the procedure for the installation of these elements was crucial: the sleeve inserts in the brackets to receive the bridge suspension cables had to be perfectly positioned and vertical as no interference stress could be allowed. The set-up and effectiveness of the process so as not to monopolise the site crane for too long and the work of the site surveyor formed part of the success of this operation.

5. FOOTBRIDGES

5.1 Design

The two MuCEM footbridges, that of Fort Saint-Jean (FSJ) and of the church of Saint-Laurent (ESL), used the same mould and have the same general characteristics as the Passerelle des Anges, built in 2008 [4]. The ESL walkway also has the same length of 69 meters in a single isostatic span, making it the clone of the Passerelle des Anges, down to the methods of construction and foundations. On the other hand, the FSJ footbridge is very different in its bridge spans: 3 continuous spans of 17.02, 76.52 and 18.40 m.

This continuity could have called into question the reuse of the existing mould. In fact, the take up of negative moments on supports required the introduction of upper tendons that were impossible to integrate into the mould: no top flange anchorage bosses, and the impossibility of making the tendons 'dive' downwards due to the small core thickness.

The trick used to ensure that the greater part of the moments were taken up by the lower tendons was to phase the assembly:

- First phase, the isostatic centre span alone: tensioning of the main lower tendons (22T15S and 19 T15S in each bottom flange, anchored on lower bosses) and take up of the central span dead loads.
- Second phase: putting the small side spans into continuity by tensioning tendons from one end to the other (19T15S bottom flange and 7T15S top flange) and take up of the side span dead loads and total live loads.

Thus, the majority of the stresses (dead loads of the great central span) are taken up isostatically while the small spans and live loads, of lesser intensity, are taken up in almost-centred compression (due to continuity). This phasing trick was found to correspond well with programming demands which, due to the excavation of the basin under the central bay, required it to be completed at the start of site works. With true MuCEM logic, the central span was thus completed well before the building on which it rests. The MuCEM side pier was thus erected isolated from the rest of the building, which was then constructed around it.

Only the use of UHPFRC could enable the use of such high compression ratios (N/S = 45MPa). In addition, preliminary steam curing of the precast segments, and the reduced creep coefficient that it achieves (0.2), enabled phase overlapping without risking the redistribution by creep that generated so many problems for phased works in the first days of prestressing.

The qualms that we had at the Passerelle des Anges, of putting into operation prestressing ducts with reduced cover (a duct radius), left by the shape of the mould, have since been swept away as the same mould here received 67 strands per beam instead of 49 in the Passerelle des Anges. In fact, the 19 and 7T15S end anchors barely fitted into the mould, but the exceptional strength of UHPFRC enable the applied local compressive stresses to be more than taken up.

As for the Passerelle des Anges, the proper reduced frequencies of the structure (vertical modes at 1.1 and 3.1 Hz in final phase, 0.6 and 2.4 Hz in isostatic preliminary phase) protect it from any risk of resonance due to the effect of foot traffic, but not from the risk of aeroelastic instability. Two sets of tuned dynamic dampers were therefore used. A first pair, set at 0.6 Hz, was installed at the midpoint of the centre span to ensure safety during the first isostatic phase (6 months). It was then replaced by a new pair of dampers set on the higher proper frequency of the structure put into continuity.

Photo 5: FSJ footbridge and columns (photo G.Detaille)

5.2 Prefabrication

As for all the other UHPFRC elements, the footbridges were entirely workshop-prefabricated at the Bonna Sabla factory in Vendargues (34). The footbridges are composed of monolithic precast segments of Ductal® each of 4.60 m, created from a single mould. As works that are highly constrained, the footbridges have minute construction tolerances in the order of 3 to 4/10 of a millimetre for each component.

The precast segments thus had to be fabricated with the utmost precision, in particular as regards the support faces having to receive the enormous post-tensioning stresses.

Contrary to custom in the sector, in which the components are manufactured with 'paired joints', we have chosen a different technology with the introduction of an adjustable high precision mould capable of outputting products with angular and flatness tolerances in the order of 3 to 4/10 mm, which was described as 'flawless' for an assembly capable of taking up post-tensioning stresses.

As the MuCEM footbridge elements were cast with the same mould as the Passerelle des Anges, footbridge and by the same contractors (Bonna Sabla, Freyssinet, Lafarge), it would have been possible to avoid the fibre-orientation checking process. However, for the MuCEM footbridge, the internal stresses are slightly different and the modified prestressed tendon sections did not allow the introduction of an injection pipe at the base of the mould. For the MuCEM footbridge precast elements, the introduction was performed 'by gravity'. On the one hand, an analysis of the K factor in the webs has indicated an increase from K = 1.26 to K = 1.65 in some directions, i.e. 30% using the 'gravity' in comparison to the injection technique. On the other K was, in some parts, less than 1.00 which leads to an increased capacity that compensates, after analysis, for the increased K factor in other directions. A relevant feedback is that injection could, paradoxically, be a good technique to maintain 3D isotropic orientation compared to placement 'by gravity' which strongly orientates the fibres.

5.3 Implementation

The implementation of the FSJ and ESL footbridges was carried using a falsework: each precast segment was placed on a ledger, firmly tightened down onto the preceding section to control geometry, then bonded, the maintenance of a pressure of 0.3 MPa being assured by the prestressing bars.

The realisation of the FSJ falsework posed little problem, thanks to the presence of horizontal ground with little traffic circulation. Conventional scaffolding elements were used. On the other hand, the ESL footbridge falsework is a small construction work in itself. In fact, the structure crosses several roads with very heavy traffic circulation that there was no question of closing: surface roads, underpass exit and tunnel under the old port (Fig. 4). The only possible intermediate supports are located on either side of the underpass in line with the piers, with one of these supports directly above the tunnel located a few meters below the underpass. Numerous checks of the existing structures were therefore necessary. In addition, the tightly enclosed gap that is bridged over forms a 'corridor' where the wind is always stronger than in the surrounding area. The wind factor, user safety nets taken into account, is also important. Precautions taken regarding wind stability were not without their use, since the falsework stood up without damage to the storm of October 28th, 2012, which broke the moorings of the 'Napoleon'.

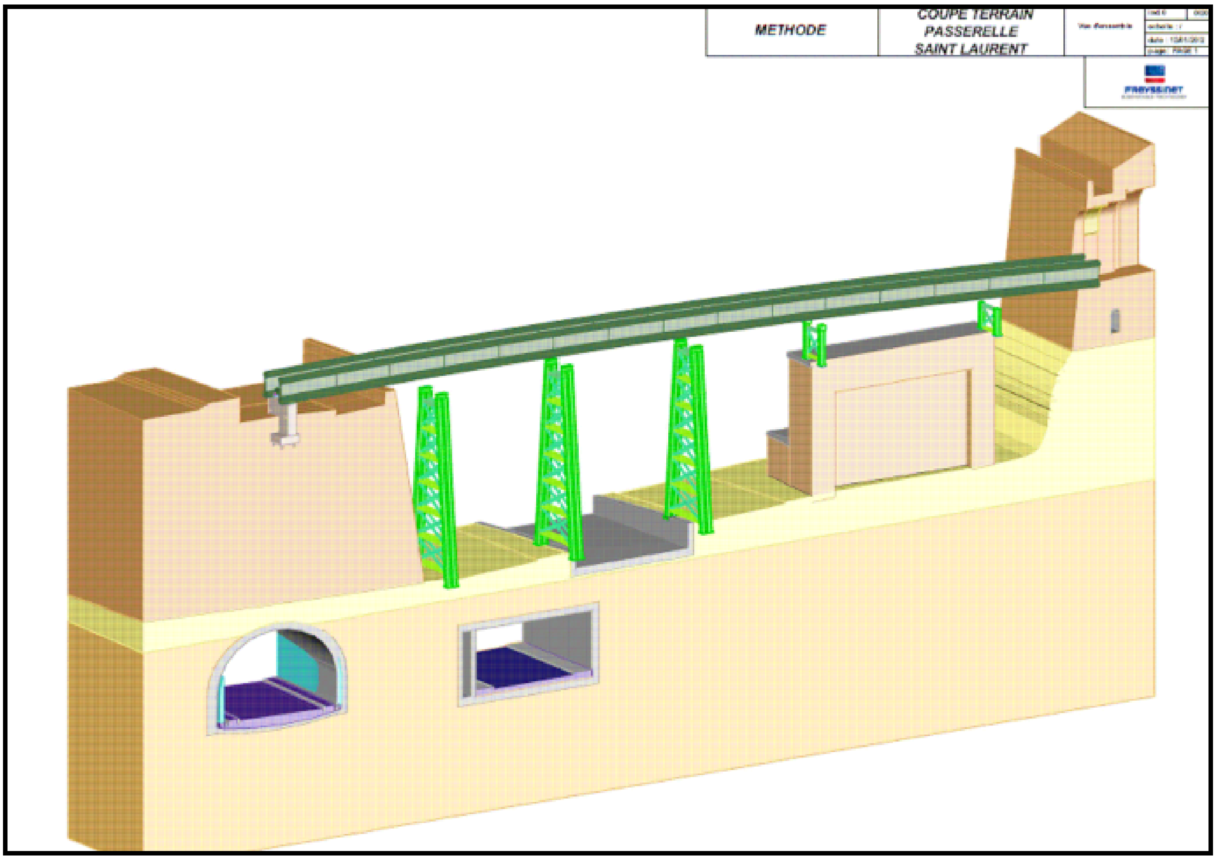

Figure 4: ESL footbridge, location and falsework (Direction Technique, Freyssinet France)

6. CONCLUSIONS

Beyond the challenge of building, within a tight programme, the first museum in the world to use a UHPFRC support structure, and enhanced through the involvement, professionalism and understanding of all stakeholders, some of the difficulties skirted over here must be clarified in the future to allow other creations of this importance to come into being with greater serenity:

- Consideration of dissymmetrical fire scenarios on façade elements should be clarified on a statutory basis.
- UHPFRC, of which it is also known that it performs well under dynamic and repetitive stresses, will see its development hindered for as long as seismic load calculation rules fail to take it into account.

Finally, it seems not inappropriate to mention that a building in UHPRFC is closer, as much in terms of assembly as design, to a metal frame than to a traditional concrete building: 'Meccano' prefabricated assembly rather than successive lifts. Just as in carpentry, the design difficulty lies not in determining the dimensions of a particular component, but in how to make them work together, i.e. designing assemblies, with the additional difficulty that connection zones, often subject to the most stress, are also the zones cast in situ and therefore less resistant. It is important to study these connections carefully and allow them a larger cross section than those of the assembled components.

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