

## PRECAST THIN UHPFRC CURVED SHELLS IN A WASTE WATER TREATMENT PLANT

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### Abstract

Following the new European standards and in order to upgrade the existing waste water treatment plant of Achères near Paris, a design and build contract was attributed by the owner SIAAP to a consortium included the firm Eiffage TP and the architect Luc Weizmann. The extension plant project is partly based on a particular process of water biologic treatment called Biostyr®, a large tank in which water is filtered by micro-balls made of polystyrene. Due to its mechanical and durability properties, the BSI®, the UHPFRC developed by Eiffage TP, was chosen for the designing of thin architectural structures in such an aggressive area. Not less than 180 precast and pre-stressed thin shells were necessary to cover the whole 3500m<sup>2</sup> of the Biostyr® tank, according to the drawings of high waves imagined by the architect. This article presents the main steps of the project: the designing of the different structures, the suitability tests performed in a full scale mock-up to validate the casting method and to verify the K coefficients dealing with the real fibres orientation, the concreting and pre-stressing of the elements in the precast factory, and finally the implementation methods of the structure on the construction site.

### Résumé

Le projet de mise aux normes de la station d'épuration Seine Aval DERU, réalisé dans le cadre d'un marché de conception-réalisation, et confié par le SIAAP au groupement (Eiffage TP, OTV, Lwa et BG ingénieurs conseil), s'appuie principalement sur la technologie de biofiltration BIOSTYR® et sur le procédé de traitement BIOSEP®. La couverture des bassins, d'une surface totale de 3500m<sup>2</sup>, est réalisée par la mise en place de 180 coques préfabriquées précontraintes par post-tension en BSI®, le béton fibré à ultra hautes performances (BFUP) développé par EIFFAGE TP. Le choix du matériau ultra performant a été retenu par l'architecte pour sa plastique minérale et son extrême résistance, qualités permettant de dégager une structure d'une grande finesse et à forte valeur esthétique, tout en offrant une très bonne résistance en milieu agressif, qualité notable puisque le ciel gazeux des BIOSTYR® est chargé en H<sub>2</sub>S. Le présent article décrit la conception détaillée de cette structure aérienne en BFUP constituée de 160 coques courbes en forme de vague, 20 coques plates, 80 cadres supports ainsi que des résilles habillant les façades.

## 1. INTRODUCTION

The Seine Aval sewage treatment plant operated by SIAAP is located on the banks of the Seine River downstream of Paris. To have it upgraded to the standards of the European Commission's UWW Directive, SIAAP awarded a design-and-build contract to a consortium made up of Eiffage TP, OTV, Luc Weizmann Architecte/LWA, and BG Ingénieurs Conseils. The upgrade is based chiefly on use of the Biostyr<sup>®</sup> biological aerated filter and Biosep<sup>®</sup> separation technologies for biofiltration and treatment respectively. It will increase the plant's treatment capacity to 1,700,000 m<sup>3</sup> per day. The roofing over the new tanks, totalling 3500 m<sup>2</sup> (1<sup>st</sup> phase of works) was designed to be built using ultra-high-performance fibre-reinforced concrete (UHPFRC). The post-tensioned precast shells were made with BSI<sup>®</sup>, an UHPFRC developed by Eiffage TP. Architect Luc Weizmann chose UHPFRC because it meets three important criteria: high strength, allowing structural slenderness, superior durability, a particularly important criterion given the aggressive environment (the vapour above the Biostyr<sup>®</sup> units has high H<sub>2</sub>S concentrations); and aesthetics, achieving a hard, mineral appearance. A second phase of works due to start at the end of 2013 comprises construction of a further two, similar biofiltration tanks representing an additional tank area of about 7000 m<sup>2</sup>.

## 2. THE ARCHITECTURAL DESIGN

- Fibre reinforced concrete for water architecture

The aim in terms of landscape and architectural integration of the new wastewater-treatment plant was to present an entirely new image of the contemporary structures serving the environment. With this in mind, a creative approach was adopted for the design of the biofilter units and was pursued jointly by architects and engineers right from the earliest design stage. This made it possible to draw every advantage from UHPFRC in a technically and architecturally innovative application.



Photos 1: General view of the tank roofing project

- Tank roofing : thin shells reflecting the dynamics of air and water

The roofing over the tanks took full account of the specifications imposed by conditions related to the treatment process:

- roofing to shade the tanks in order to prevent algal growth at the surface of the water,
- high throughput of natural ventilation above the water surface,
- need for as broad as possible a view of each tank to facilitate operator inspection.

Several roofing methods were studied. After analysis from all the angles of technical, economic, and architectural criteria, this approach led to selection of a solution using UHPFRC, a material that is extremely well suited to this type of structure and the particular conditions in which it is used. The tank roofing project (see Photos 1) involved creating a series of identical curved shells, each covering a separate tank: the thin shells rest simply on concrete walls separating the tanks; they are flush with the top of the walls on the southern side and sweep upwards towards the north to allow air from the process to circulate naturally while preventing any penetration of direct sunlight; they are arranged to an optimum module width of 1.80 m and are stiffened by longitudinal ribs. Their curvature allows rainwater to run off naturally into the tanks, passing through weepholes. Operators can walk on the bottom part which, in addition, has been given a non-slip texture by the mould.

The succession of identical units gives the roof a sculptural effect and at the same time, when viewed from the side, the dynamic effect they create evokes the slow and permanent movement of water through the tanks.

- Facades : diaphanous side screens

The facade elements consist of UHPFRC screens forming a diaphanous enclosure standing on the plain-concrete perimeter walls of the tanks. By closing the area at the sides of the waveform roof shells, they prevent falls from the access ways and, like oriental mashrabiya screens, they filter out direct sunlight that would otherwise strike the water surface.

The alternation of shadow beneath the shells and the brightness above, together with the play of shade and sparkling reflections off the water, produces a startling effect of movement which suggests the inner workings of the filtration plant.

### 3. DESCRIPTION OF THE PRECAST UNITS

The tank roofing consists of a total of 260 precast units: 160 curved waveform shells, 20 flat shells, and 80 structural frames supporting the curved shells. The plan-view dimensions of the curved shells are 11.83m x 1.8m, and their longitudinal profile is a wave form with an amplitude of 2.81 m. Structurally, their static design is that of statically determinate beams with a span of 10.63 m. In their typical cross-section (see Fig. 1) each shell consists of a thin (50mm-thick) flange and a central rib with a downstand of 200 mm, which represents a structural slenderness of 1:42 and an equivalent depth of 81 mm.

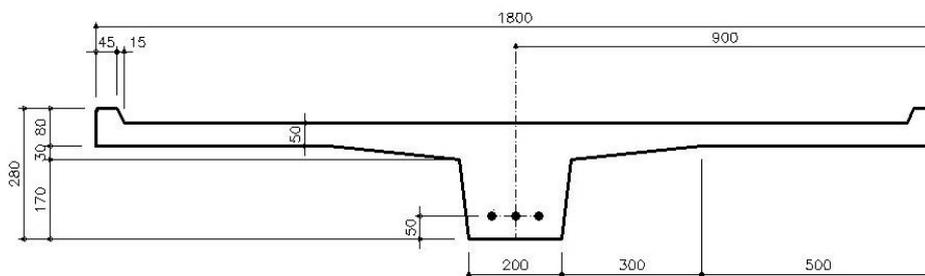


Figure 1: Cross-section of curved shell

The inherent strength of UHPFRC, and particularly its ductility under tensile force due to the steel fibres it contains, means that no passive reinforcement is used. Moreover, each unit

is prestressed longitudinally with a DSI 3T15S system comprising 3 greased and sheathed monostrand tendons which follows the curve of the shell. The both ends of the shells, where the prestress is introduced and distributed, called for very careful study. The design of this area is particularly complex since that is also the location of the end cantilever transmitting the load of the shells to their bearings (see Fig. 2), and therefore subject to support reactions.

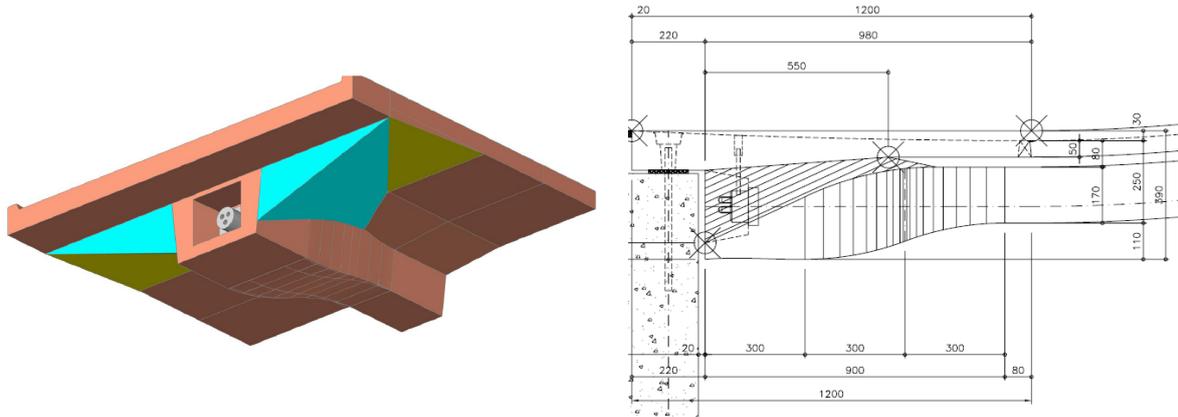


Figure 2: End block of curved shells

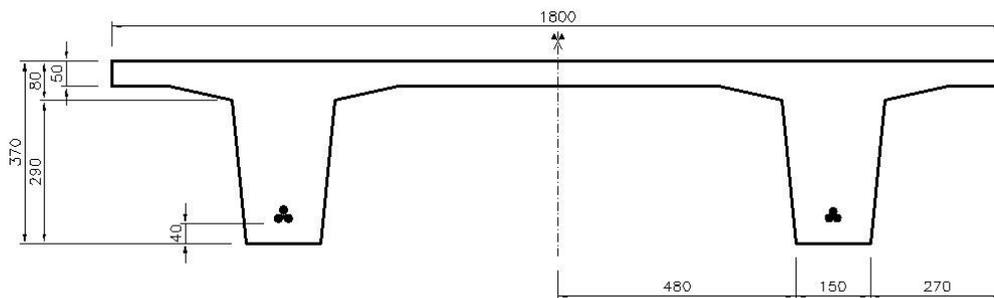


Figure 3 : Cross-section of flat shell

The ‘top’ end of each curved shell is supported by a UHPFRC portal frame. These 80 precast units contain no reinforcement, neither passive nor prestressed. The vertical members of the frames are 2.8m high, with a cross-section measuring 120x180 mm.

The 20 flat shells (slabs) are to the same plan dimensions as the curved shells and share the same static design. However, they must withstand higher service loads than the curved shells for they are trafficked by maintenance staff and machines. Their cross-section is that of a double-ribbed slab with a total depth of 370 mm and a 50 mm-thick flange (see Fig. 3), which represents an equivalent depth of 119 mm. Each rib is prestressed with the same DSI 3T15S system of greased and sheathed monostrands.

In addition to the elements already described, 70 white BSI<sup>®</sup> sidescreen elements were manufactured to wall in the Biostyr<sup>®</sup> building (see Photo 2). They consist of two beams with vertical members between. Three elements are joined together to make a screen having the length of the shell elements (10.63 m). The upper beams, which carry the horizontal forces exerted on the vertical screen members, are connected by steel assemblies designed to transmit the flexural moments induced by horizontal actions, and the assembly of three units

is secured at each end by the frames supporting the top ends of the curved shells. The lower beam rests directly on the perimeter wall of the tanks. To simplify precasting and transport the sidescreens were divided into three panels. All three types were cast from a single mould.



Photo 2: Layout of screen units

#### 4. BSI<sup>®</sup> CONCRETE

BSI<sup>®</sup> is an UHPFRC developed and patented by the Eiffage TP group. Previous projects built with BSI<sup>®</sup> include the two pioneering Bourg-lès-Valence bridges [4], the canopy over the Millau Viaduct toll gates [5], and the Pinel and Sarcelles road bridges [6]. The main characteristics of the BSI<sup>®</sup> mix used for this application are as follows:

##### Ingredients of BSI<sup>®</sup> (for 1m<sup>3</sup>)

Premix (*):	2296 kg
Superplasticizer	39.6 kg
Water	185 kg
Steel fibres L <sub>f</sub> = 20mm Ø <sub>f</sub> = 0.3mm	195 kg
The steel fibres are straight and made from very high tensile strength steel	
	

\* The premix is a combination of all the dry ingredients (cement, silica fume, sand, coarse aggregate).

##### Characteristics of the BSI<sup>®</sup> mix

Density	ρ	2.75 t/m <sup>3</sup>
Characteristic 28-day compressive strength	f <sub>c28</sub>	165 MPa
Characteristic 28-day tensile strength of concrete cimentitious matrix	f <sub>t28</sub>	8.8 MPa
Characteristic 28-day tensile strength of fibre-reinforced concrete	σ <sub>bt-28</sub>	8.04 MPa
Mean Young's modulus at 28 days	E <sub>i28</sub>	57 GPa
Autogenous shrinkage strain at infinite time	ε <sub>re-∞</sub>	550 μm/m
Drying shrinkage strain at infinite time	ε <sub>rd-∞</sub>	150 μm/m
Basic creep and drying creep (loading time t=48h)	K <sub>fl</sub>	1.00

The diagram in Figure 4 shows the design constitutive law for the UHPFRC, and how it takes account of tensile strength. It can be seen that post-cracking behaviour (after the tensile elastic phase) is expressed not as strain but as widening of the crack.

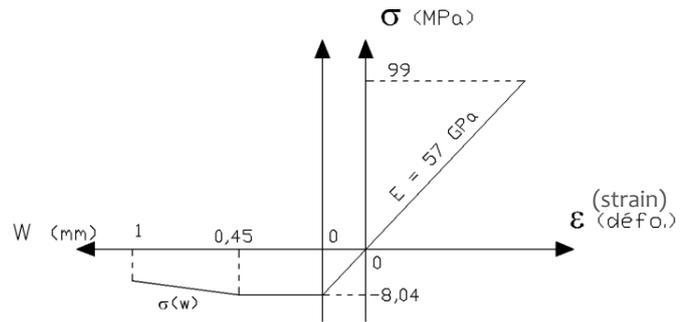


Figure 4: Constitutive law of BSI<sup>®</sup>

## 5. CONSTRUCTION-DESIGN STUDIES

All the verifications of the units are based on the 2002 interim French recommendations for UHPFRC published by an AFGC-SETRA work group [1]. In the case of the shells, since the structure is prestressed only longitudinally, different verification principles apply, depending on whether transverse or longitudinal behaviour is addressed.

The verifications for longitudinal behaviour are based on the French “BPEL” code [2] (limit state design of prestressed concrete structures), considering class II for limit stresses of the materials. Normal tensile stresses at SLS are thus limited to the tensile strength of the matrix (see Table 1).

Table 1: Prestressed elements – SLS normal stresses limited

<b>Interim phases</b>	• Compressive stress	$\sigma_{\max}$ [Mpa] =	32.17	< 81	
	• Tensile stress	$\sigma_{\min}$ [Mpa] =	-4.98	> -7	Top face
<b>Rare SLS</b>	• Compressive stress	$\sigma_{\max}$ [Mpa] =	25.61	< 99	
	• Tensile stress	$\sigma_{\min}$ [Mpa] =	-6.19	> -8.8	Bottom face

The ultimate resistance bending moment (see Fig. 5) is calculated using the characteristic constitutive law of the cracked concrete, with a partial safety factor  $\gamma_{bf} = 1.3$  for tensile stress.

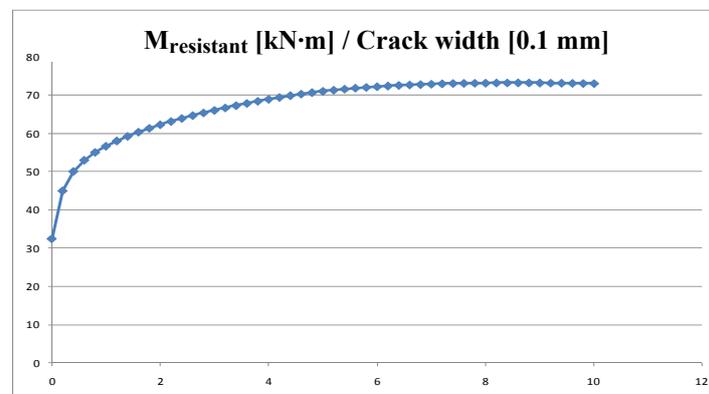


Figure 5: Resistant moment of the typical section of a shell versus crack width

Transversally, since forces are taken solely by the fibre-reinforced concrete, the verifications refer to Class IV of French UHPFRC recommendations [1], which means the tensile behaviour of the concrete can be taken into account even if there is no active or passive reinforcing steel.

A feature of the curved shells is that they do not bear on their ribs. At each end they have an unstressed cantilevered bearing section where the flange is simply thickened. This design, which is unusual in that there is no reinforcement at all in such a critical zone, was necessary because of the very limited freeboard of the tank walls and the difficulty in shaping them to house the ribs. It was the strength contribution of the steel fibres which made this cantilevered bearing design possible. Verification of the cantilever included finite-element modelling of the end block. Moreover, the design was validated by laboratory tests on specimens sampled from a prototype shell as part of the suitability testing procedure.

The absence of any reinforcement in the area of introduction of prestress was validated by testing: laboratory tests on a BSI<sup>®</sup> anchor block demonstrated a safety factor of 3 for failure of the block.

## 6. SUITABILITY TESTING

Application of French AFGC-SETRA recommendations [1] [3], means a number of preliminary tests must be carried out to check that the materials and equipment used under actual site conditions are consistent with the design assumptions. Consequently a representative sample of the actual structural element was built (see Photo 3) to validate concreting methods and equipment and to measure K factors representing the distribution and orientation of fibres in the structure.



Photo 3: Trial element after test prism sampling

Prisms sawn from the trial specimen served to verify the performance of the concrete in two characteristic zones (see Photo 3 and Fig.6). The principles for prism sampling are presented below.

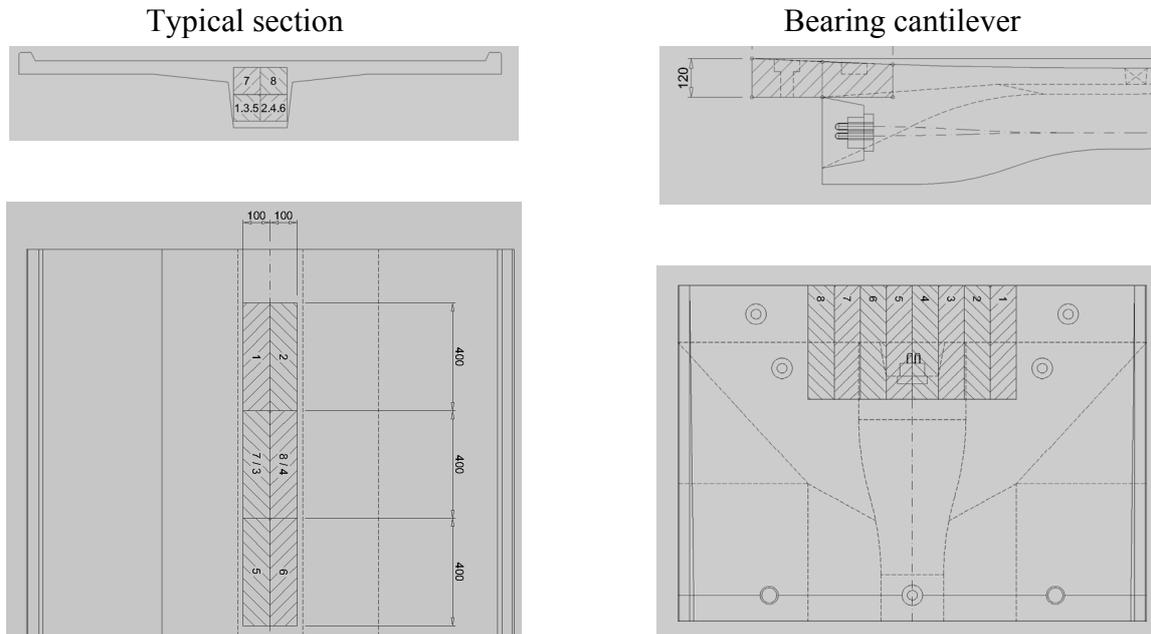


Figure 6: Representative model - sampling positions

Table 2: K factor values

	Typical section	Bearing cantilever	Default values AFGC
Global effects	K = 1.20	K = 1.35	1.25
Local effects	K = 1.65	K = 1.55	1.75

The K factor values determined by flexural strength testing on notched prisms (6 tests for each zone) are given in table 2. In comparison, the default values in the AFGC-SETRA recommendations are K = 1.25 for global effects and K = 1.75 for local effects.

## 7. PRECASTING OF BSI<sup>®</sup> UNITS

The architect's desire to have a high-quality finish to both the top and bottom surfaces of the flange, the curvature of the elements, and the fact that BSI<sup>®</sup> is a self-compacting concrete meant horizontal casting was not an option for the curved shells. The units were therefore cast vertically, on edge. Given the large number of times the mould was to be used, plus the geometrical accuracy required, a steel mould was built.

The concrete was placed without vibration and was not heat treated. The mould was removed as soon as the cylinder compressive strength reached 35 MPa, i.e. after about twenty hours in cold weather. With temperatures of 20°C or more, the strength reached 60 MPa after 20 hours, so a daily casting cycle was possible.



Photo 4: Handling after form removal



Photo 5: Storage before prestressing

The strength of the BSI<sup>®</sup> at the time of mould removing was sufficient for shells to be handled and moved to the storage yard (see Photo 4). The shells were prestressed in the casting yard, in the vertical position in the case of curved units (see Photo 5). The compressive strength required for prestressing was 130 MPa.



Photo 6: Flat shell with textured top face



Photo 7: Removing a screen unit from the mould

The flat shells (see Photo 6) were cast horizontally, but upside-down since the top surface is to be trafficked and is therefore textured. Using a turning lifting beam, they were turned over and removed from the mould once the concrete compressive strength had reached 50 MPa. The screen panels of the Biostyr<sup>®</sup> building walls were cast in two identical polyurethane moulds (see Photo 7) cast from the same reverse mould. The panels were produced by placing stop-ends at predetermined points in the polyurethane moulds (see Photo 7). The moulds could be removed as soon as the compressive strength reached 75 MPa.

## 8. ERECTION OF PRECAST UNITS

The curved shells were carried to the construction site by truck. There a cradle turned them into the horizontal position and a crane with a special lifting beam (see Photo 8) lifted them into place on the building.



Photo 8: Erection by crane



Photo 9: BSI® shells over Biostyr™ tanks

The flat shells were transported face-up. The supporting frames and screen units were also transported in the horizontal position and turned to the vertical by means of a lifting sling placed around their top beams.

## 9. CONCLUSION

The roofing-over of Biostyr® tanks with precast BSI® units is another pioneering development demonstrating that UHPFRC provides new solutions combining lightness, durability, and quality aspect.

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