

## **ROOFING OF THE STADE JEAN BOUIN IN UHPFRC**

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### **Abstract**

Erection of the new Stade Jean Bouin in Paris is based on a 21000 m<sup>2</sup> Ductal<sup>®</sup> Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) envelope. The UHPFRC is used for the lattice facade and roof, which is waterproof, with a double curved surface geometry. The entire design is based on UHPFRC, used efficiently in terms of durability and structural performances. A key geometrical simplification has been applied through the use of lightweight, triangular panels. The envelope thickness and complexity is reduced, with a UHPFRC skin composed of precast elements, erected in one stage, with glass inserts embedded during the casting process.

### **Résumé**

La reconstruction du Stade Jean Bouin à Paris comprend une enveloppe en béton fibré à ultra-hautes performances (BFUP) Ductal<sup>®</sup> de 21000 m<sup>2</sup>. La résille forme l'enveloppe en façade et en couverture de manière étanche et en décrivant une surface gauche. L'ensemble de la conception est fondée sur l'emploi efficace des principales caractéristiques du BFUP. Face à la complexité géométrique du projet, les performances du BFUP permettent d'envisager une simplification de tous les procédés constructifs. L'épaisseur et de la complexité de l'enveloppe est réduite à une peau BFUP présente en une seule couche. Le tout est préfabriqué en usine puis posé en une seule fois et présente un procédé nouveau d'inclusion de verre réalisé lors du coulage.

## 1. INTRODUCTION

Having increased the capacity from 5,000 to 20,000 spectators, the new Stade Jean Bouin has been designed by Rudy Ricciotti to be light and airy. Opened in August 2013, 21,000 m<sup>2</sup> of undulating latticework surrounds rugby fans in a concrete cocoon (the world's first structure of its kind – see Fig.1) that addresses a wide range of technical challenges.

As part of the reconstruction of the new Stade Jean Bouin, architect Rudy Ricciotti conceived a highly innovative cladding system for the stadium in Ultra-High Performance Fibre-Reinforced Concrete (UHPFRC) with:

- a 10,000 m<sup>2</sup> roof system that is structural, waterproof (with glass inserts) and aesthetically pleasing and;
- an 11,000 m<sup>2</sup> façade in the form of a multi-strand lattice system.



Figure 1: Stade Jean Bouin, general view at completion of the envelope erection (Dec 2012)

## 2. MATERIAL EMPLOYED

The material employed is “Ductal® G2” with metallic fibres. Titanium dioxide was added to achieve a lighter colour.

### 2.1 Tensile properties

To assess tensile properties, a specific analysis was developed on the premix used. The results were compared with the necessary design load calculations during the schematic and detailed design phases. The post cracking design stress, after thermal treatment, is constant at 7.5 MPa up to a crack opening of 0.3 mm. A reverse analysis on 70 mm x 70 mm x 280 mm notched specimens under three-point bending was performed.

The method developed by Gilles Chanvillard, Pierre Rossi and Pascal Casanova is detailed in [6, 7]. The “moment-crack opening” curve is then analysed to achieve the post cracking tensile behaviour with an “isotropic” fibre content of 2%.

The results of this material study on 6 specimens confirm the value given during the design phase. (See Fig.2)

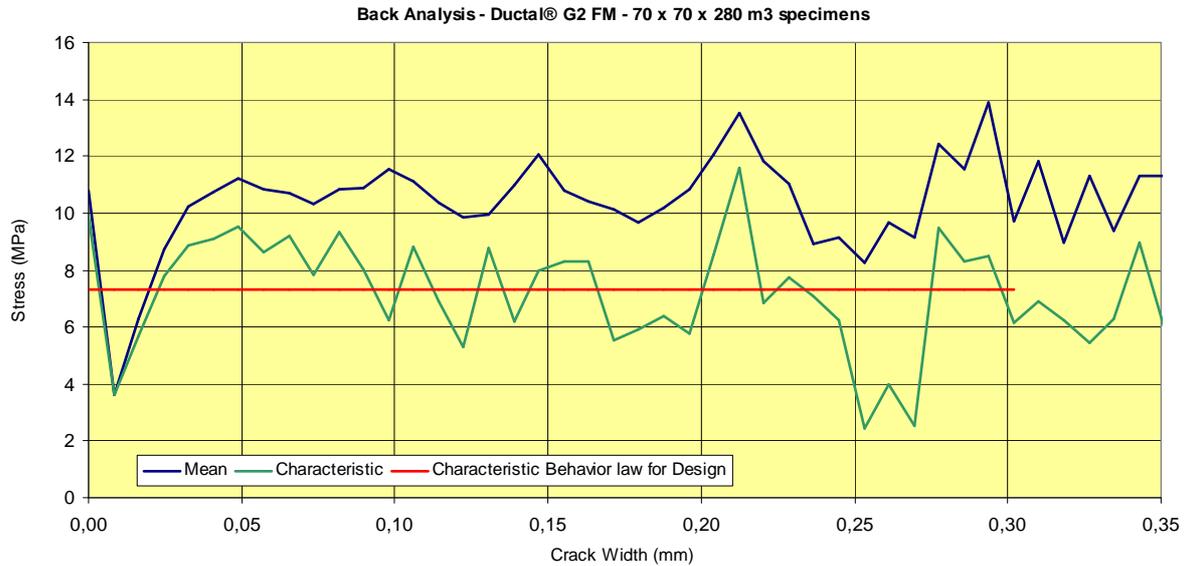


Figure 2: Reverse analysis – prism according to AFGC-SETRA

For practical reasons, routine checks are performed on-site through four-point bending tests on unnotched specimens and compared with a “reference mean value”, obtained through four-point bending tests on 6 specimens, conducted during the material study.

## 2.2 Tensile properties in the plates

The same material has to be characterized differently for plate elements to take into account the improved properties for those types of structures. The fibre orientation is no more 3D isotropic but rather 2D isotropic. This leads to better mean performances. A UHPFRC plate is defined as an element of thickness less than  $3 L_f$  with  $L_f$  being the fibre length. In this instance, it means less than 40 mm which is the case with the 35 mm thickness of the triangles. Plate elements are treated specifically with a dedicated plate analysis developed by Gilles Chanvillard [8].

The cracking concept is not introduced explicitly. The crack distribution is considered constant over the constant moment in a four point bending test. This allows the development of a mechanical model based on the assumption of a constant curvature between the two loading points. Strain can then be used in replacement of crack width. The third kinematic relation in the classical reverse analysis is simplified in the two Newton equations (N and M equilibrium). This was done on typical equivalent bending stress vs. deflection (Fig. 3). The results for a Stade Jean Bouin typical “roof” plate element thickness are presented in Fig. 4. The characteristic constitutive law for the design of roof plates has been chosen as an elastoplastic curve with a “plateau” of 10 MPa, up to a strain of 0.4 %.

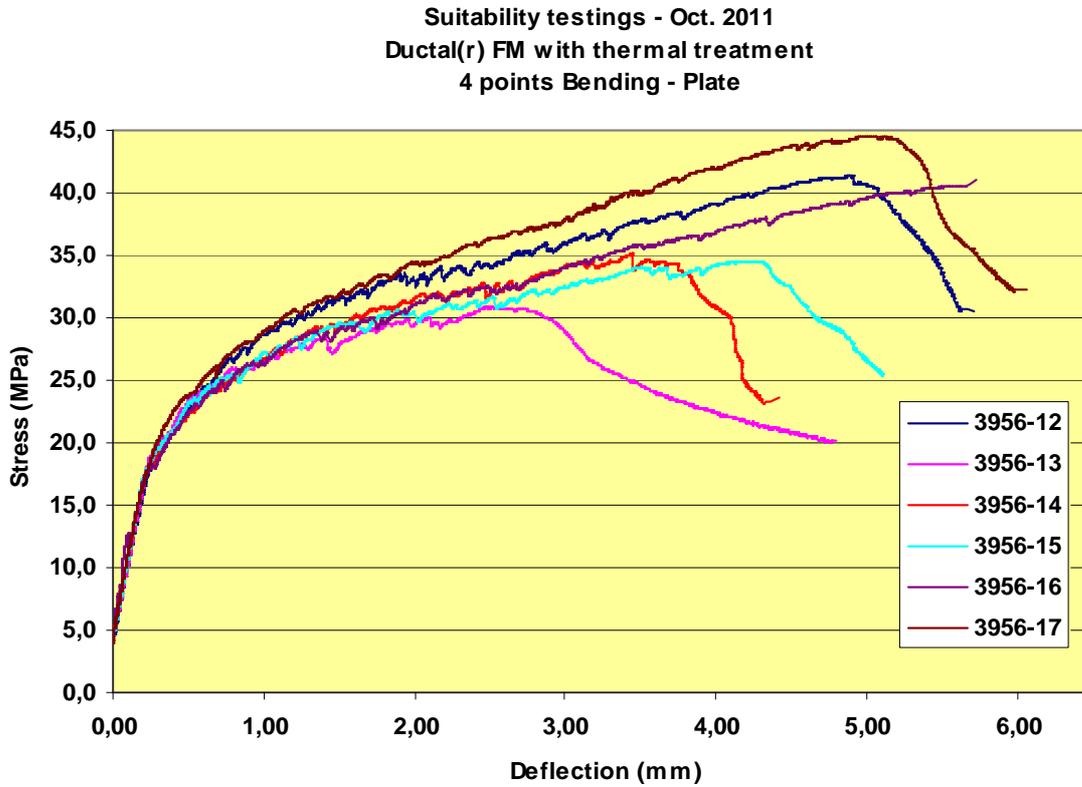


Figure 3: Flexural behaviour of plates

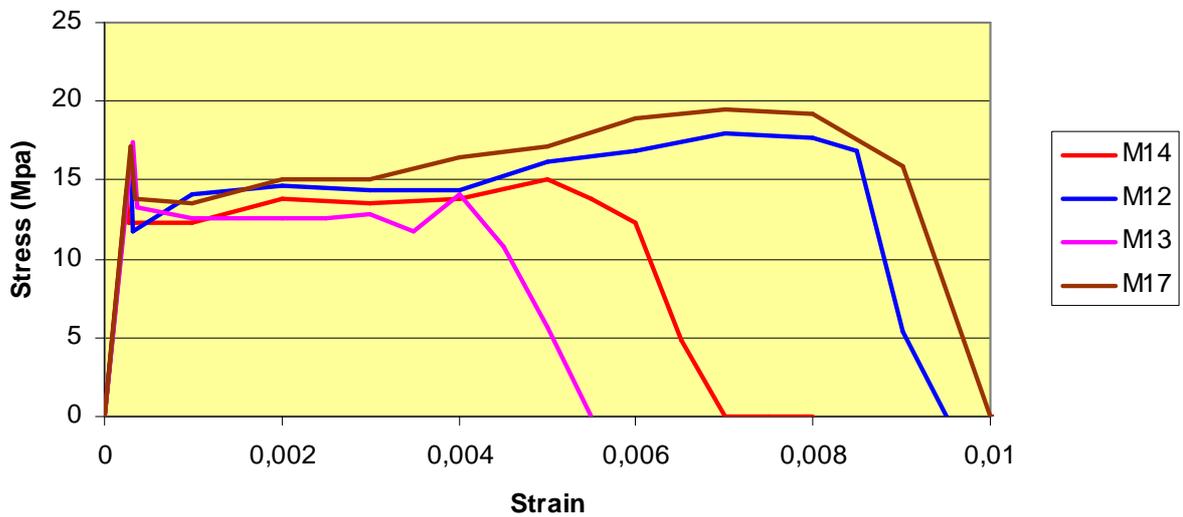


Figure 4: Direct Stress Strain Tensile curve from a reverse analysis

### 3 A WATERPROOF UHPFRC ROOF SYSTEM

#### 3.1 Design

The functions of this roof system are multiple; it:

- is an architectural envelope (the overall form of the roof exploits the maximum height allowed by the local development plan) with reduced visual impact through the incorporation of glass inserts;
- protects spectators from the rain, and;
- supports climatic and maintenance loads.

To respond to the requirements stated above, it was decided to prefabricate the roofing panels in Ductal<sup>®</sup> (with metallic fibres) from Lafarge. This material can provide a suitable answer with regard to all the characteristics required for this project (aesthetics, waterproof properties and resistance). The roof is made up of ribbed, triangular panels which are flat and self-supporting. These panels were then placed on the primary metal structure of beams. During assembly, a mechanical connection was ensured between the Ductal<sup>®</sup> panels and the metal beams. The beams are fitted with gutters for rainwater drainage.

The Ductal<sup>®</sup> and glass roof panels were assembled by interlocking, thereby ensuring waterproofness and water drainage to the gutters incorporated in the beams. The specificity of these roof panels is to constitute a waterproof "skin", which forms a shelter from the rain for spectators. For the roof elements, the Ductal<sup>®</sup> material used is a UHPFRC with non-connected micro pores; therefore waterproof under normal mechanical stresses.

#### 3.2 Prefabrication

The panels were prefabricated at the Bonna Sabla plant in Conflans, Sainte Honorine, France (78), a precaster specializing in the manufacture of UHPFRC elements. The glass pieces, surrounded by a specially designed joint (developed by Bonna Sabla and LRING), was originally produced with ethylene propylene diene monomer (EPDM) but, silicon was chosen in the end. The joint was incorporated into the roofing panels during the moulding phase, within the thickness of the Ductal<sup>®</sup> material.

Between the panels, an ingenious male/female connection with 25 mm spacing acts as a gutter (respecting French building code standards) to allow water to flow along the waterproof surface. Male and female ribs on each panel have a different geometry but the same inertia to provide similar deflections when loaded.

Nevertheless, all panels are geometrically different. A specific customization of molds has been provided with strict adherence to tolerances and dimensions. Four angles have been imposed (8° 10° 12° and 16°) with a triangular base length less than 2.40 m for transport reasons.

#### 3.3 Suitability testing

The thin, ribbed roof panels for this project provide an interesting case study which involved two strategies. For the planar regions, without any reinforcement, 9 samples are cut out of a sacrificial panel, corresponding to 9 critical zones (blue segments in Fig. 5) to analyse fibre orientation in terms of internal forces. The results in flexure (four point bending on the unnotched specimens) are then compared to the specific flexural capacity of a plate with the constitutive law defined for plates to assess the K factor.

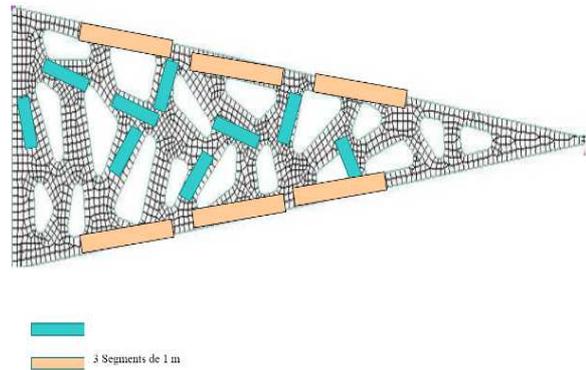
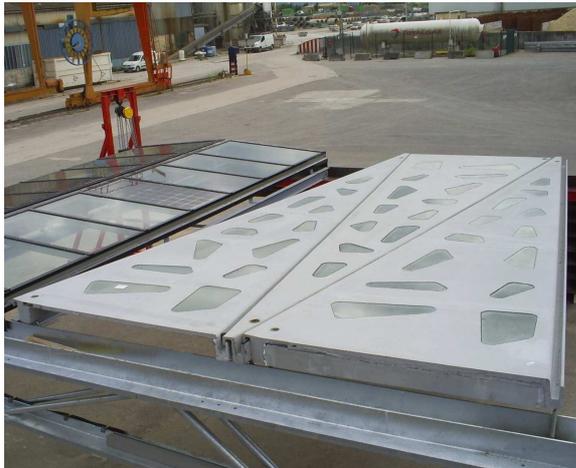


Figure 5: Cutting pattern of Stade Jean Bouin roof elements.

Different processes, including the injection process, have been tested in a closed mould, from the top of the ribs and an “opened casting process” in an “open mould” that is closed after placing of the material around the glass elements. With an “open mould”, it is possible to correct concrete flows which is not the case in a “closed mould”. During trials, with “closed mould”, the K factor could increase up to 1.70 since “cold joints” from opposite flows meeting around the glass insert obstruction have been observed. It was recommended not to use this process. Lateral casting in an open mould that is closed afterward was selected.

Shear strength of the reinforced ribs is assessed with short beams testing. Six samples of beams were cut and tested in “shear” (orange segments in Fig. 5). Fibre contribution, in interaction with “real” rebar placement (see Fig. 6.), can then be analysed indirectly. Safety factors are assessed directly in comparison to design solicitations. This testing has demonstrated that the design in shear (with the process used) will not lead to failure in shear but in flexure.

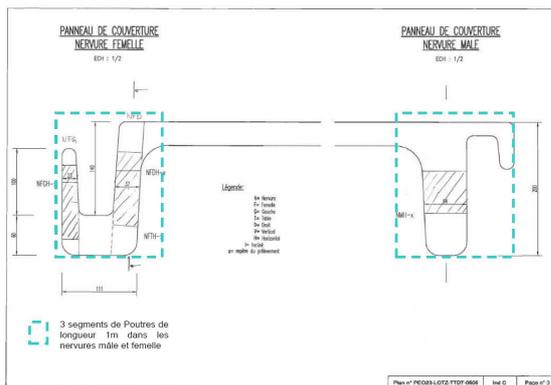


Figure 6: Stade Jean Bouin ribbed elements and cross section pattern

A global test performed by the CSTB (French Research Centre for Building) has confirmed a global safety factor of 5 for the ribs. This testing has shown a high ductile

behaviour (see deflection in Fig. 7) that can be used for future projects to calibrate reliability indices.



Figure 7: Global testing at CSTB

## 4. UHPFRC LATTICE FAÇADE

### 4.1 Design

This unique architectural envelope design exploits the full, maximum dimensions allowed by the local development plan, yet it also reduces the overall visual impact to the surrounding community with the use of a multi-strand lattice system. Furthermore, it:

- provides a protective guardrail, directly above the circulation passageways;
- supports climatic and maintenance loads, and;
- assures natural light throughout the circulation passageways

To respond to the requirements stated above, it was decided to prefabricate the facade panels with Ductal® from Lafarge; a material that could meet all of the performance characteristics required for this project, including aesthetics and resistance.

### 4.2 Façade Prefabrication

The façade is also made of flat, self-supporting triangular panels; prefabricated at the same Bonna Sabla plant, specializing in the development of UHPFRC. The panels were placed on a primary metal beam structure and, during assembly, a mechanical connection was ensured between the Ductal® panels and the metal trussed beams.

All panels have a different pattern and a specific tolerance follow-up procedure was satisfied before every casting, which was more complex than the molding for the roof panels.

### 4.3 Suitability Testing

With respect to other main components made with UHPFRC; fibre orientation in the “branches” was carefully checked, with excellent results ( $K < 1$  in the longitudinal direction). The potential risk was therefore concentrated in the nodes, where 'fibre flows' could meet and create cold joints. In those zones, fibres from one concrete flow might not “bridge” into a second concrete flow, thereby leading to a drastic lack of fibres in the section defined by the region where the two flows met. A limited number of K factors in nodes, superior to 2, have been observed.

Consequently, in parallel to classical fibre testing, 1:1 scale tests were carried out on a representative number of elements (in this case, three) to check the overall behaviour and redundancy of the network of branches.

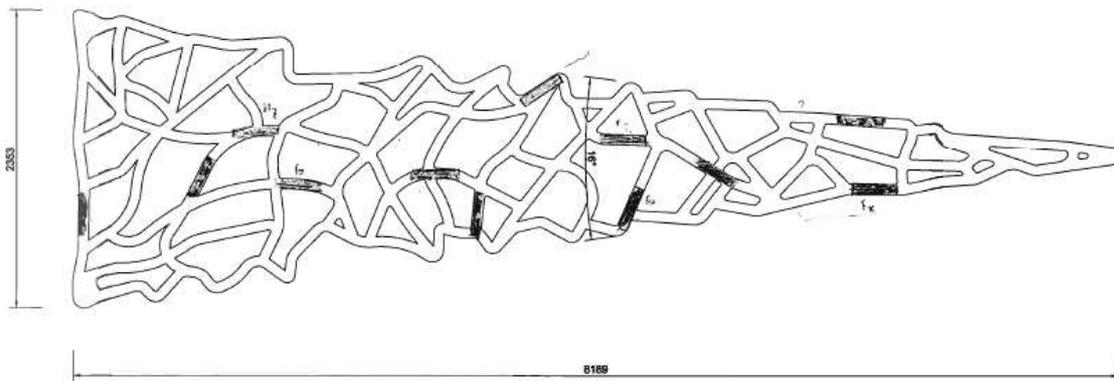


Figure 8: Stade Jean Bouin  
perforated panels



## 5. CONCLUSION

This project demonstrates the technical possibilities offered today by UHPFRC at an industrial stage: durability, waterproofness and high strength.

The geometrical complexity led to a rather simple, modular approach based on lightweight isostatic triangular panels with a limited number of angles. This allowed for easier erection and, consequently; a shorter site mobilization. Optimization of the unique thickness (35 mm) of the envelope skin had a major impact on the project feasibility and cost.

Finally, the innovative use of glass, inserted directly into the panels during casting, demonstrates that a thin solution made of a cementitious material (UHPFRC) can meet today's most rigid envelope design and performance requirements, even in terms of weight and transparency!

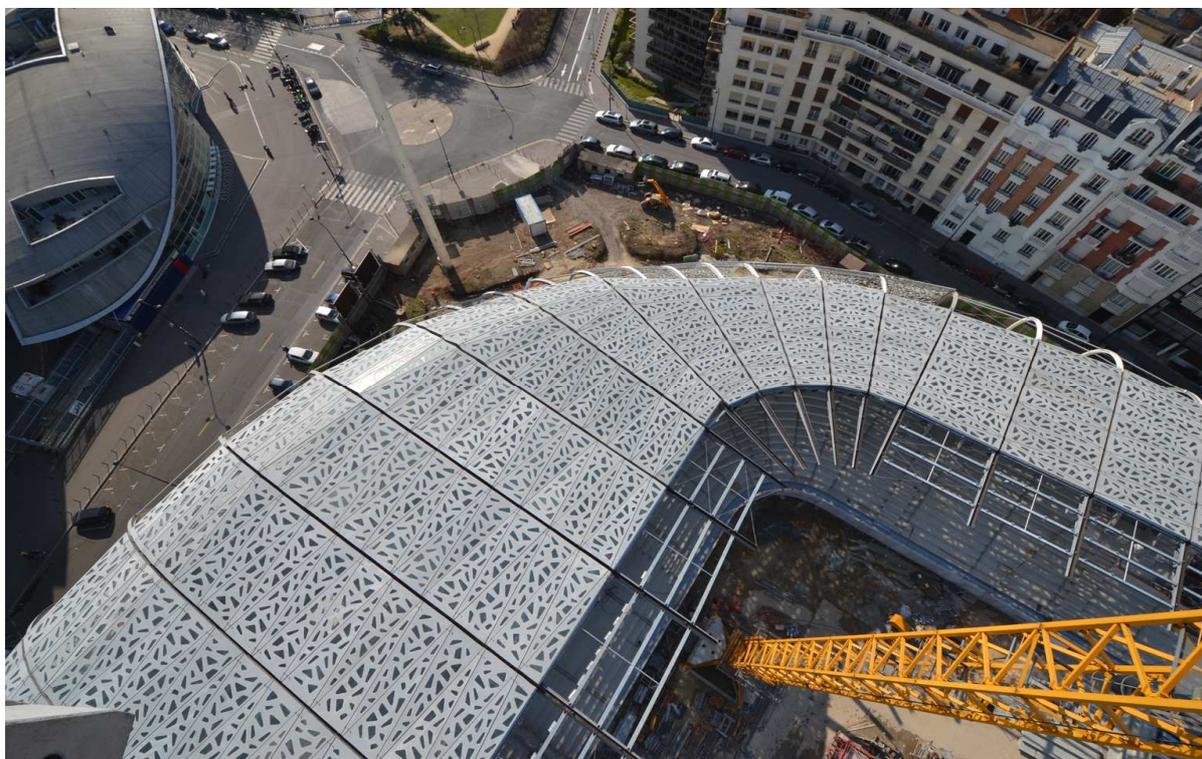


Figure 9: View from the roof

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