Construction of an Ultra-High-Performance Fibre-Reinforced Concrete thin-shell structure over the Millau Viaduct toll gates

Ziad HAJAR
Civil Engineer Ph.D
Eiffage TP
Neuilly S/Marne, France

Alain SIMON
Civil Engineer
Eiffage TP
Neuilly S/Marne, France

Thierry THIBAUX
Technical Manager
Eiffage TP
Neuilly S/Marne, France

Pierre WYNIECKI
Director/Associate Professor
Geonumeric/INPG – Laboratoire 3S
Grenoble, France

Summary

The aim of this paper is to present the design and construction of the thin shell structure covering the Millau viaduct toll gates.

The BSI-CERACEM concrete used for this innovative structure is an Ultra High Performance Fibre reinforced concrete (UHPFRC), with a compressive strength of 165 MPa, in which steel fibre ensure ductile behaviour under tension and allow the elimination of passive reinforcement.

The concept used for the design of the structure is a precast segment based on thin shell box assembled by prestressing.

Special experimental methods for characterizing FRC properties, are used to get pertinent data. This application also required several test campaigns to validate the assumptions used for design and to verify the behaviour of the concrete at the scale of the actual structure.

Keywords : Ultra-high-performance fibre-reinforced concrete ; BSI®-CERACEM ; precast segment ; prestressing ; thin shell ;

1. Introduction

The Millau Viaduct project, built, entirely financed, and to be operated by the Eiffage group under a 75-year concession, also comprises a toll plaza. The toll gates are located about 6 kilometres north of the viaduct and will convey to drivers the message that they are approaching an exceptional natural site, the Tarn River Gorge and, at its base, the town of Millau.

When working on its design proposal, the Contractor-Concessionaire carried out a special architectural study aimed at combining two objectives: it wanted to give travellers a strong visible signal through a striking toll-plaza roof, and to highlight the architectural potential of ultra-high-performance fibre-reinforced concrete (UHPFRC).

The architect appointed, Michel Herbert, found inspiration in the elevated situation of the site, designing a “floating leaf” which, together with its multiple supporting columns, evokes the parapente wings seen soaring in the region.

This innovative structure (hollow-core thin shell) also provided an opportunity for the Eiffage design department to test new CAD-CAM tools hitherto little used for concrete structures.

2. General presentation

The structure is a thin shell of BSI®-CERACEM supported by 48 clustered steel columns laid out in 4 rows to provide free spans of up to 28 metres for siting the toll booths and traffic lanes.

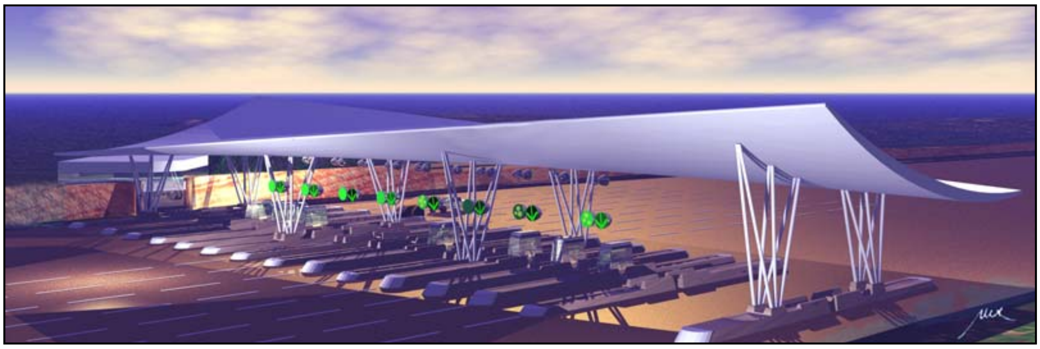


Fig. 1 Architect's impression of the project

The roof structure is 98 m long and 28 m wide. Geometrically, its cross-section is defined by two circular arcs of different radius, and the entire 98 m length is rotated 23° to produce a helically warped structure.

Since the size and shape of the structure called for match-casting of the segments, special design provisions had to be made to enable all segments to be cast in a single mould. It was decided to use a mould warped for vertical match-casting.

Each segment is cast on top of the previous segment used as the control face, the control-face segment being rotated into the appropriate position. The structure is made up of a total of 53 segments.

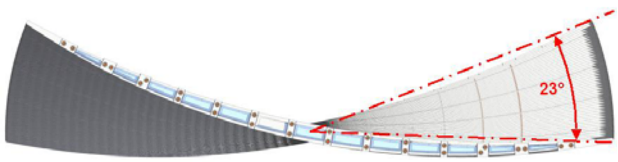


Fig. 2 Cross-section - rotation

After casting, each segment is placed on falsework and stitched to the previous segment with prestressing bars. Once all 53 segments have been installed, twenty-eight 12T15S prestressing cables are installed from one end of the structure to the other, then tensioned, and the falsework is removed.

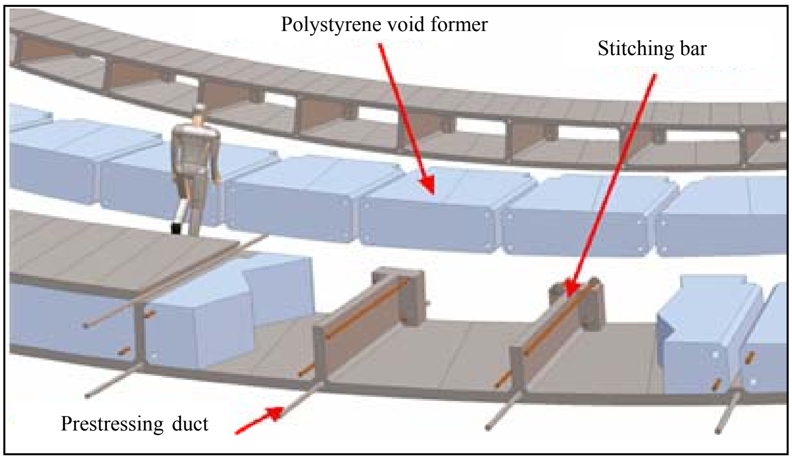


Fig. 3 Cutaway of typical segment

3. BSI®-CERACEM concrete

The BSI®-CERACEM concrete used for the toll gates roof is the result of special development based on mix designs used previously for different projects. Previous projects include beams for the Cattenom (Fig. 4) and Civaux nuclear power plants (1998-1999) and the two innovative Bourg-lès-Valence bridges built in 2000-2001 (Fig. 5). The Bourg-lès-Valence project served to help validate use of this kind of material for road bridges and to help draft the first recommendations on the use of UHPFRC in civil engineering.

Fig. 4 Cattenom: validation of beams

Fig. 5 Bourg-lès-Valence: erection of beams

The concrete mix design used for the Millau Viaduct toll plaza roof is as follows:

Ingredients per m^3		Mechanical characteristics (**)	
Premix (*)	2355 kg	Density	2.8 t/m^3
SIKA superplasticizer	45 kg	28-day compressive strength fc28	165 MPa
Mix water	195 kg	28-day tensile strength ft28 (matrix)	8.8 MPa
Steel fibres (Lf=20mm ∅=0.3mm)	195 kg	28-day tensile strength σbt28 (fibres)	8.8 MPa
The fibres are straight, and are made from very-high-elastic-limit steel.		Modulus of deformation Ei28	65 GPa
		Total autogenous shrinkage	550 µm/m
		Total drying shrinkage	150 µm/m
		Total creep	Kfl = 1

(*) Premix is a mixture of all the dry ingredients: cement, silica fume, & aggregate.
(**) Strength values are characteristic results.

Fibres were used in the quantity of 2.5% by volume. The reduction in this proportion relative to previous projects (3%) is chiefly due to changes made to the concrete matrix to improve its stability and uniformity in combination with fibres.

The BSI®-CERACEM mix for the Millau project is self-compacting nonetheless and, what is more, has a practical working life of 2 hours. This working life may prove to be necessary when working on complex and large-volume components.

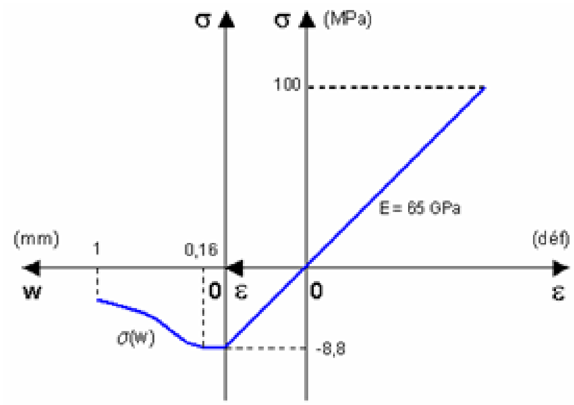


Fig. 6 Constitutive law

4. Construction design

4.1 Calculation of action effects

Because of the complex geometry of the shell, analysis of the structure's behaviour under the various design actions (permanent loads, wind, snow, temperature effects, etc.) required several finite-element models to be run; some of them used special modelling techniques.

4.1.1 General action effects

General action effects were determined from discretization of the structure into "shell" elements by the ROBOT structural analysis program. These calculations provided the force vector fields (membrane and flexural stress) at all points of the shell for each of the load cases studied. The figure below illustrates the membrane stresses in the top member of the shell under the effect of permanent loads.

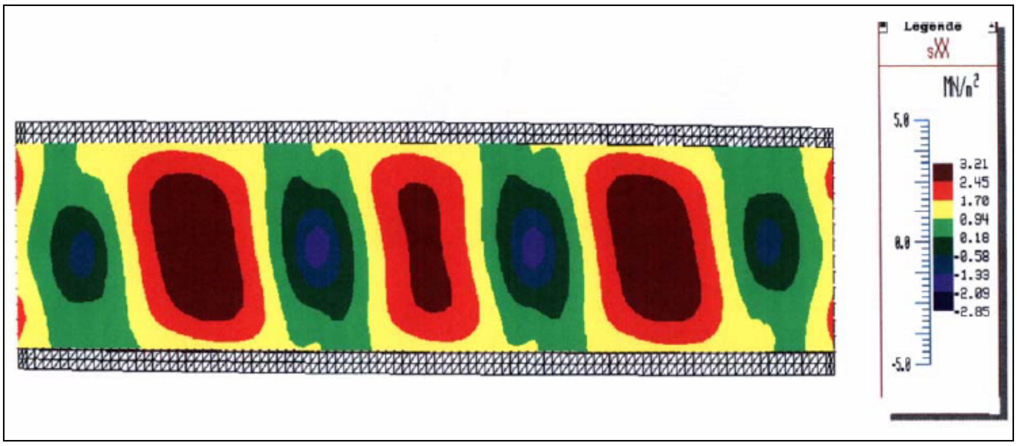


Fig. 7 Top member – transverse stress pattern

The effect of wind on the structure was assessed by the CSTB building research centre in Nantes. Numerical studies were carried out to characterize the reference wind at the site and to determine the wind pressure coefficients affecting the shell. Numerical analysis of air flows (Fig. 8) and pressure fields was performed with the FLUENT fluid mechanics program.

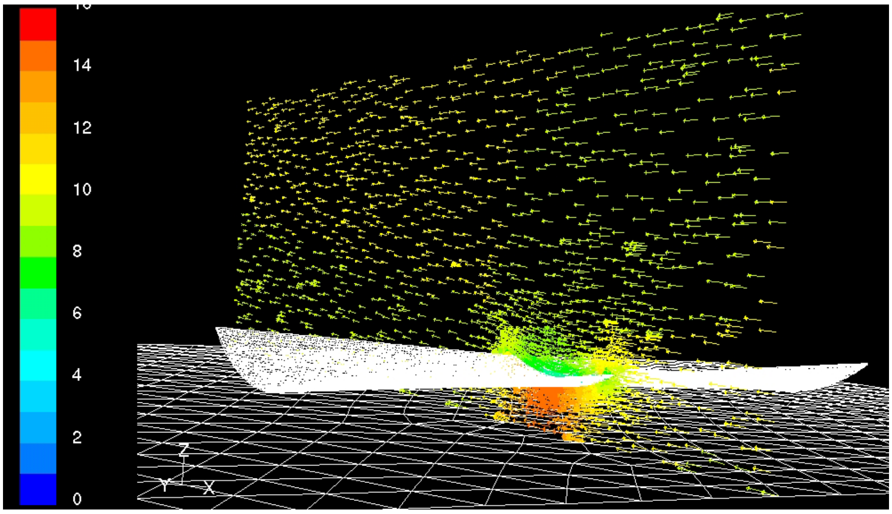


Fig. 8 Wind – Air flow

Overall, the prevailing wind (perpendicular to the roof) tends to push the shell down against the ground, with generalized torsional effects because of the upturned parts.

4.1.2 Local action effects

Local action effects at supports and end blocks (where the permanent prestressing cables are anchored) were determined with finite volume elements using the ANSYS program. Transmission of forces from the shell to the columns was analyzed with a finely meshed volume model of a 4-m-wide strip centred on the columns and connected to the general model of shell elements.

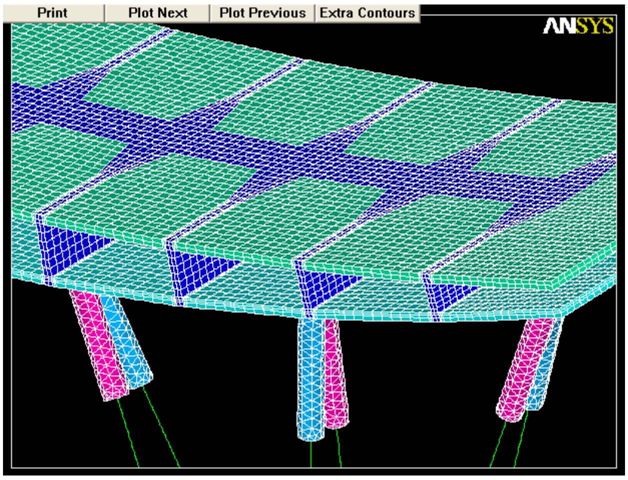


Fig. 9 Modelling of support area

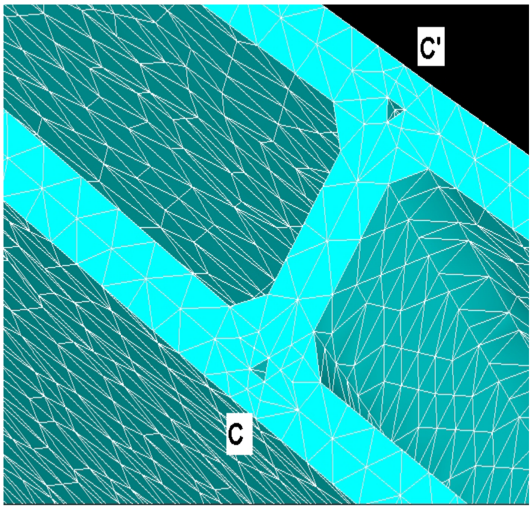


Fig. 10 Modelling of end blocks

Modelling of the end blocks required a special methodology which involved acquiring the CAD design of the end-block segments from the INVENTOR program (STL or VRML files) and generating tetrahedral volume elements from the skin mesh, using a technique for polyhedral enhancement and decimation (SIMPOLY program). This consisted in enriching the initial meshes by subdividing each triangular facet and then decimating the block, retaining triangular shapes suitable for finite elements and using element sizes consistent with the mechanical behaviour of the structure.

What makes this method special is that irrespective of the quality of the initial CAD model, it is capable of achieving a representative mesh and of smoothing details that do not correspond to the level of discretization required for the finite-element model.

4.2 Shell verifications

Verifications of the BSI®-CERACEM elements are based on the AFGC recommendations on ultra-high-performance fibre-reinforced concretes [1], though some additional assumptions are also made for verifying the parts of the structure where membrane-type action effects are determining.

Since the structure is prestressed solely longitudinally, the principles of verification differ depending on whether the transverse or longitudinal behaviour of the structure is to be studied.

For the longitudinal examination, verifications were carried out to class I of the French BPEL limit state prestressed concrete design code [2], the class usually applicable for verification of structures made from precast segments, and in which no tension is allowed under serviceability limit state conditions.

For the transverse examination, since forces are taken solely by the fibre-reinforced concrete, class IV of the UHPFRC recommendations was used: this is the special verification class for UHPFRC without reinforcement and prestressing steel.
Additionally, in the case of pure tension (where membrane effects are determining), the allowable stress is calculated assuming an uncracked section and is limited to 0.8 x f_{t28} in service.

Ultimate resistance effects are calculated using the characteristic law for behaviour of the cracked material, with a partial safety factor $\gamma_{bf} = 1.3$.

The distribution of concentrated prestress forces in the end blocks is verified on the basis of the principal tensile stresses and their directions as determined by the finite-element model described above, and verifying that they remain less than the strength contribution of the fibres, σ_p / γ_{bf}, with

$$\sigma_p = \frac{1}{K} \cdot \frac{1}{\omega_{lim}} \cdot \int_0^{\omega_{lim}} \sigma(\omega) \cdot d\omega$$

where: $\sigma(w)$: characteristic direct tensile strength
K : coefficient taking account of the anisotropy in orientation of fibres due to concrete placement
K = 1.75 for spalling and bursting effects ("local" value of K)
K = 1.25 for general distribution effects ("global" value of K), and
w_{lim}: 0.3mm (crack width).

5. Preliminary testing

A certain number of preliminary tests had to be carried out to validate some of the proposed design features before production could actually start. In particular, this concerned the distribution of prestress for the two different techniques (post-tensioning with end-to-end cables, and short bars stitching two consecutive segments together). No hooping was used in either case.

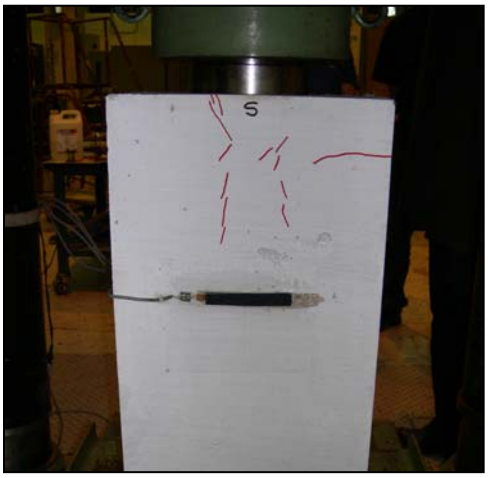


Fig. 11 Testing end block with 12T15S anchorage (CEBTP)

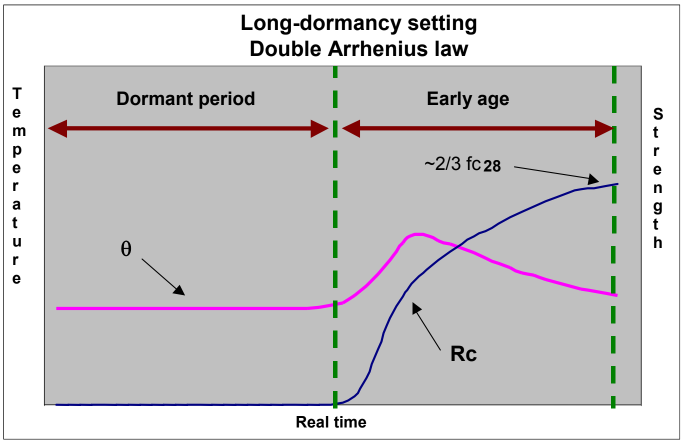
Fig. 12 Bar stitching test by QRD laboratory (Eiffage TP)

The tests revealed ultimate strength safety margins of more than 2. The detailing was thus adopted.

Full-scale prototypes (segment sections) were also built on the site to adjust all the production parameters: BSI®-CERACEM production cycle with the batching plant proposed for precasting, segment concreting procedure and effect of fibre distribution within the structure, precise calibration of curing in order to make provision for the effects of partially restrained shrinkage in the mould, by co-ordinating the form striking sequence.

This is because the concrete setting mechanism has a long dormant period of around 14 hours at 20°C. A double Arrhenius law is necessary to describe the entire setting process from the moment the concrete is batched.

The calibration derived from testing campaigns was based on work carried out by France's national CALIBE project on measurement of concrete curing.



Lastly, 10x10x40 prismatic samples were sawn from the prototypes and run through third-point and centre-point bending tests to validate the mechanical performance of the BSI®-CERACEM concrete actually produced at the site (tensile strength of the cement matrix and tensile strength contribution of the fibres respectively).

6. Casting yard

The segment casting yard is located very close to the toll plaza site. It consists of a concrete batching plant specially equipped for BSI®-CERACEM, a PERI mould, a tower crane, a shed for storing bulk bags of premix and fibres, and a storage yard with rail-mounted trolleys for moving the segments.

Fig. 13 Mould and crane

Fig. 14 Segment lowering

The preliminary test campaign and the last-minute adjustments made when the first segments were produced enabled a regular casting cycle of 2 days per segment to be established. The workforce was therefore organized around a succession of four-day and six-day working weeks to achieve mean output of 2.5 segments per week.

The breakdown of this cycle is perfectly conventional: segment "n-1" is lowered from the form and positioned as the match-cast control face, prestressing ducts and polystyrene void formers are installed in the form, the form is closed, segment "n" is concreted, sets, and is attached to the tower crane, the form is struck, segment "n-1" is removed from beneath, and segment "n" is lowered to serve as the next control face.

Fig. 15 & 16 Segments in storage yard awaiting installation on erection falsework

By the end of 2003, the first 16 segments had been manufactured.

7. Conclusion

After use in several striking projects, UHPFRC is little by little conquering new territory where it enables architects to imagine new kinds of structures and engineers to explore new construction procedures.

The development of UHPFRC in France has been facilitated by the recent publication of guidelines which are encouraging all those involved in construction to make greater use of this new material and tailor it to their specific requirements.

References

[1] AFGC-SETRA "Bétons fibrés à ultra-hautes performances – Recommandations provisoires / Ultra High Performance Fibre-Reinforced Concretes – Interim Recommendations", January 2002.

[2] BPEL 91, 1999 revision "Règles techniques de conception et de calcul des ouvrages et constructions en béton précontraint suivant la méthode des états limites", Fascicule 62, titre I, section II du CCTG, April 1999.