THE INTERNATIONAL MEMORIAL OF NOTRE DAME DE LORETTE: DETAILED DESIGN AND REALIZATION

Amélie Bouhours (1), Jérémie Burlot (2), Richard Petit (2)

(1) BSI® Department, Eiffage, Vélizy, France

(2) Eiffage Infrastructures, Vélizy, France

Abstract

Upon request of the Region Nord-Pas-de-Calais, the architect Philippe PROST designed an International Memorial to pay tribute to the 580.000 soldiers, regardless of nationality, who perished during World War I. The architect chose Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) to build the Memorial; the entire structure is made of precast voussoirs, and part of it is prestressed by post-tension. Eiffage TP was awarded the contract and built this extraordinary civil engineering work with BSI®, Eiffage's own UHFRPC. This material's extreme durability will allow it to remain through the upcoming century a part of the necropolis on the hill of Notre Dame de Lorette. The International Memorial is one of the first works in UHFRPC designed according to AFGC UHPFRC 2013 Recommendations. Material shear strength properties were fully used to prove the resistance of precast UHPFRC segments in the curved prestressed structure. The main difficulty for structural studies was to justify the beam under the effect of the torsion generated by its very large curvature. Unlike habits, preload has been designed to maximize the shear strength of the structure. This architectural prowess was a challenge for both detailed design and on-site construction.

Résumé

Sous Maîtrise d'Ouvrage de la Région Nord-Pas de Calais, l'Architecte Philippe Prost a conçu un Mémorial International en hommage aux 580 000 soldats, de toutes nationalités, tombés au cours de la Première Guerre Mondiale. Le matériau choisi par l'Architecte pour la réalisation de la structure est un Béton Fibré à Ultra-hautes Performances (BFUP) ; une partie des éléments préfabriqués qui constituent le Mémorial sont assemblés par précontrainte. Les équipes d'Eiffage TP ont réalisé cet ouvrage, avec le BFUP d'Eiffage : le BSI®. La très grande durabilité de ce matériau lui permettra d'être présent pour le prochain siècle dans ce lieu de mémoire de la colline de Notre Dame de Lorette. Le mémorial Notre Dame de Lorette est l'un des premiers ouvrages en BFUP à avoir été justifié selon les recommandations AFGC BFUP 2013. Cette structure courbe précontrainte réalisée à partir de voussoirs préfabriqués en BFUP, a été justifiée en utilisant parfaitement les caractéristiques du matériau sous sollicitations tangentes. Ce défi architectural se retrouve également tant au niveau des études d'exécution qu'au niveau de la réalisation sur chantier.

Figure 1: The Memorial of Notre Dame de Lorette – Photo: Karine Warny

Figure 2: Aerial view of the necropolis Notre Dame de Lorette – Photo: Karine Warny

1. INTRODUCTION

The International Memorial of World War I, baptized “L’anneau de la mémoire” (the Remembrance Ring), houses the biggest national necropolis north of Arras, on the Notre Dame de Lorette plateau in Ablain-Saint-Nazaire (62), France (Fig. 1-2). It is one of the most sizable memorials in the world, as it lists 579 606 names of soldiers who perished on French departments Nord and Pas-de-Calais soil. The names are listed in alphabetical order, regardless of nationality, thus intertwining the names of friends and foes of yore (Fig. 3).

The Region Nord-Pas-de-Calais has mandated the architect Philippe PROST with the conception of this International Memorial. He designed a pseudo-elliptical structure composed of a 328 m-perimeter ring, cantilevered on almost 60 m. Following a call for tenders in 2013, the first package for main civil works was awarded to Eiffage TP and Eiffage Energie.

The International Memorial was inaugurated by President François Hollande, president of French Republic, on November 11th, 2014 (Fig. 4).

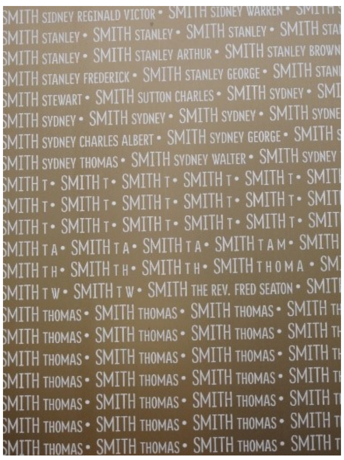

Figure 3: « Lorette » typography detail, designed by Pierre di Scullio. © P. Vuillemin

Figure 4: November 11th, 2014, the French President reveals the commemorative plaque located at the center of the ring. In the background, a part of the prestressed area. © Présidence de la République.

Figure 5: Presentation of the structure

The elliptical ring occupies a 129 m x 75 m area (Fig. 5) and is divided into two sub-structures: one structure merely rests on the ground, and the other is made of prestressed by post-tension segments in UHPFRC, the Eiffage Ultra-High Performance Concrete (BSI®). The latter forms a 125 m-long curved beam divided in 3 spans (27.5 m for 28 m, 56 m), with a 27 m-bending radius. Its prestressed part is made of precast match-cast segments called "voussoirs"; its peculiar geometry, led to bending-twisting stresses that were not intuitive. Most importantly, the constructor achieved the architect's elegant style by using a UHPFRC.

In the reinforced area of the ring, the cross-section shown Fig. 6 identifies all components of the Memorial.

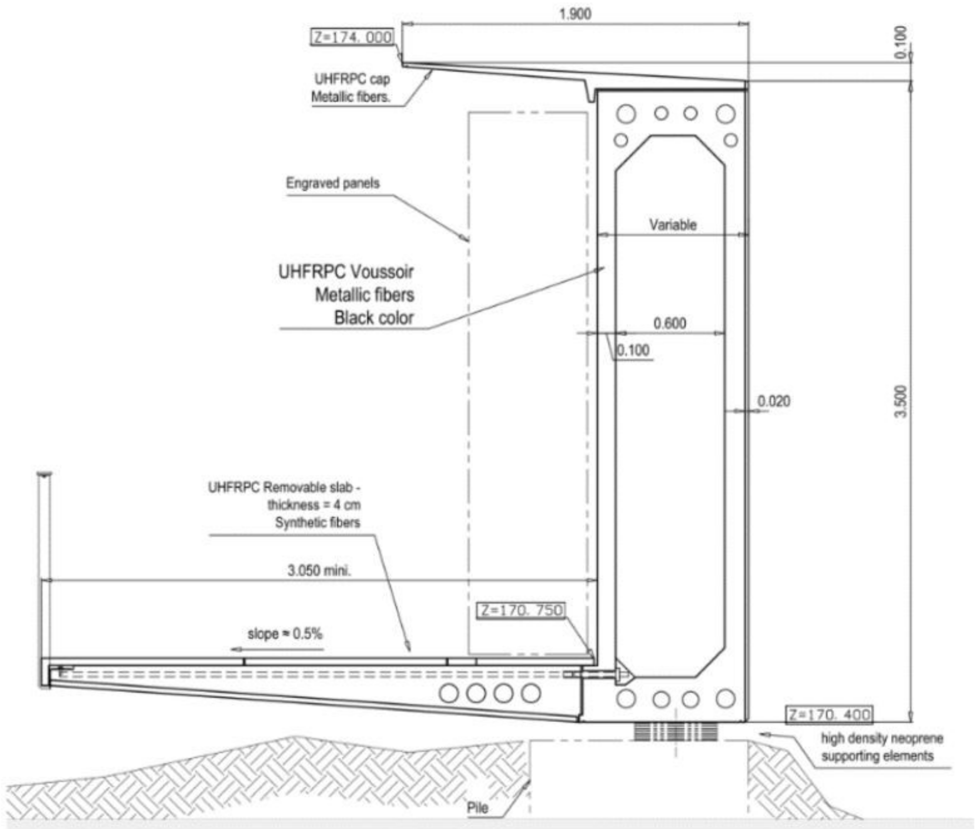

Figure 6: Cross-section of prestressed reinforced "voussoirs"

2. A TIME-RESISTING MATERIAL: BSI®

The precast voussoirs of the Memorial were made of of BSI®, an Eiffage-patented UHPFRC since 1998. Its mix-composition relies on a prepared mix called "Premix", water, superplasticizer, and either steel or synthetic fibers depending on use. Eiffage TP controls the entire UHPFRC line production.

2.1 BSI® ID

BSI® is a UHPFRC mix with a specific ID (Table 1), listing the properties to be used in structural design and supervised by control tests. Properties were established as per the SETRA-AFGC UHPFRC Recommendations dated June 2013.

Table 1 : BSI® ID

Fresh Concrete Properties		
Workability		Up to 90min
Flow table test (DIN)	e (cm)	$58 \leq e \leq 68$
Entrained air content		≤ 3.5%
Hardened Concrete Properties		
Density	ρ	2.75 t/m^3
Compressive strength at 28 days	f_{ck}	165 MPa
Matrix tensile strength at 28 days	f_{tk}	- 8.0 MPa
Fiber tensile strength at 28 days	$\sigma_{ct\text{-}28}$	- 6.3 MPa
Modulus of elasticity at 28 days	Ei_{28}	58 GPa
Poisson's ratio	ν	0.2
Shear strength	Gi_{28}	25 GPa
Coefficient of thermal expansion	α	13 µm/m/°C
Autogenous shrinkage (final value)	$\varepsilon_{ca\text{-}\infty}$	600 µm/m
Drying shrinkage (final value)	$\varepsilon_{cd\text{-}\infty}$	240 µm/m
Drying creep and proper creep (t_1 = 7 day-load)	K_{fl}	1
Durability Indicators		
Water porosity	< 5%	
Oxygen permeability	< 10^{-20} m²	
Chloride ingress by diffusion ratio	0.23%	
Capillary absorption	0.22 g/cm²	
Formulation Example		
Premix	2 296 kg	± 2%
Superplasticizer	35 kg/m^3	± 5%
Mixing water	195 kg/m^3	± 2%
Steel fibers	195 kg/m^3	± 2%

Adding either steel or polypropylene fibers depending on BSI® use increases its tensile strength, thus avoiding structural steel reinforcement. Hence, material thickness can be reduced: International Memorial's ground slabs are only 2 cm thick, and simple voussoirs 4 cm thick.

2.2 Premix Production

Premix is the major component of UHPFRC. It is a mix of dry granular materials, such as cement, silica fume, and aggregates, with a 1-2 % tolerance for each component guaranteeing that the obtained concrete is in accordance with expectations. This criterion is specified in SETRA-AFGC documentation. Using premix guarantees an almost constant composition, especially controlling aggregates' water content.

2.3 Molding Programme

BSI® is produced in traditional concrete mixing plants. It is an automated process. BSI® component mixing lasts 15 to 20 minutes. BSI® gains in strength very fast without thermal treatment. Average compressive strength is between 60 and 80 MPa at 18 hours reaching a 60-70°C temperature, meaning all types of elements, even the thinnest ones, can be demoulded no later than the day following concrete pour. Each voussoir required on average 2.8m^3 of BSI®. Depending on pre-stressed boss, they weighed between 7 and 10 tons (Fig. 7).

Mold geometry varied from one element to the next, all highly technical; molds were made of steel, polyurethane or wood. Mold-making was given to proficient specialists, who produced molds in about 6 to 8 weeks from final formwork drawings. For the International Memorial, daily production included: 2 simple voussoirs big and little, radius 27.54 m; 2 reinforced voussoirs big and little, 3 caps, 9 ground slabs; and 1 reinforced gallery support. The simpler and more numerous elements were made in about 4 months. Reinforced voussoirs were made in 7 weeks.

Figure 7: Reinforced voussoir - © H. Abbadie

Figure 8: Strikable core with polystyrene and steel butts - © H. Abbadie

Figure 9: Window voussoir with rebars and specific core - © Eiffage TP

The "window voussoirs" were a specific architectural demand. They are hollow voussoirs for visitors to admire the Artois plain from the ring; they are located on the prestressed part of the structure. An inner formwork was added to the mold, along with strong structural steel reinforcement (Figs. 8-9) to resist to stresses the BSI® alone could not take in. 250 kg/m^3 of passive rebars were placed. Pouring BSI® in the mold between rebars and prestressing sleeves was a tricky task, all the more when perfect inner and outer concrete faces were expected.

3. DETAILED DESIGN

3.1 Positioning on Design Codes and Regulations

As the project's tender documents were prior to June 2013, they referred to ancient norms like AFGC BFUP 2002 Temporary Regulations and BAEL/BPEL 91 revised 99. However UHPFRC regulations and UHPC structural design were revised by AFGC in June 2013. The Client, the Project Management and the Detailed Design Office agreed to set a coherent normative frame based on Eurocodes (Fig. 10), for this extraordinary work.

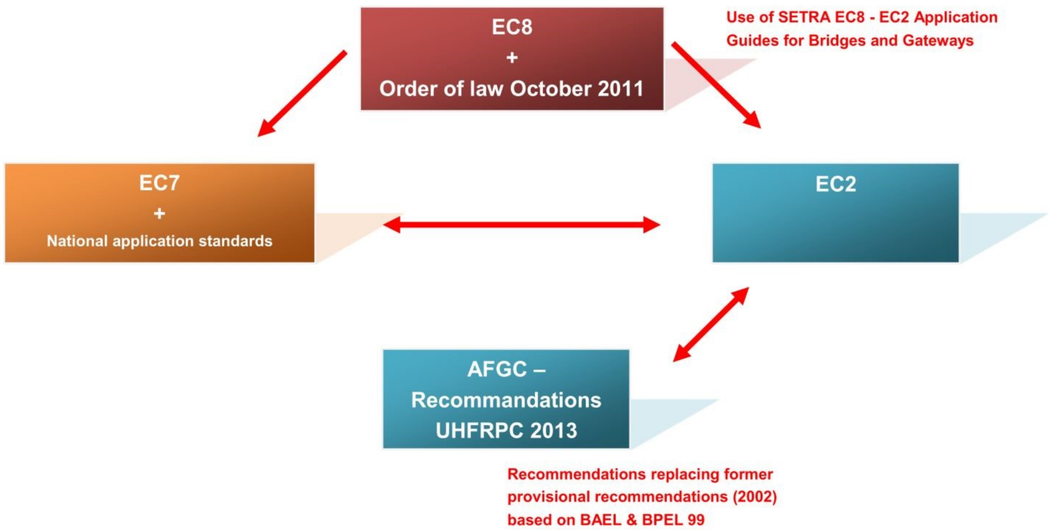

Figure 10: Normative frame based on the Eurocodes

3.2 Finite Element Analysis – Software Selection

In order to approach the footbridge's structural behavior, the Design Office relied on different computing programs:

- **ST1 Software** for the structure's general behavior using a wireframe model. Given the high complexity of calculations, Eiffage TP entrusted CEREMA with a counter calculation using PCP Software, worth external control. As project management used Sofistik Software, the project's design benefitted from three different models whose results converged.
- **ROBOT 3D Structural Analysis** for finite element analysis of local behavior: compression and tensile stress diffusion at window openings, concentrated efforts on voussoirs at supports.

3.3 Support B: Horizontal Release

Preliminary calculations proved necessary to release support B (Fig. 5) in order to ease stresses due to thermal and wind loads. Support reactions were considerably decreased in all supports and deep foundations, as well as lateral bending stress. The structure indeed benefitted from its natural curve stiffness on that particular support; a horizontal support in that area would have generated a point of inflection in horizontal deformations. However, changing support types also moved the structure's natural horizontal frequencies to a range requiring a comfort study under pedestrian loads.

3.4 Torsion and Shear Stress Phenomena

Axial stress analysis complied with allowable stresses as per EUROCODE 2 (Fig. 5):

- Allowable compressive stress worth 0.6 x f_{ck} = 99 MPa for characteristic SLS;
- Allowable tensile stress worth:
    - In UHPFRC areas, f_{tk} = -4.25 MPa;
    - In joint areas, 0 MPa.

Nevertheless, tangential stress analysis (shear force and torsional moment) led to major disorders within the structure. Torsion induced only by vertical load on the curved beam overstressed the section; and the main loads causing this torsion are the highly dominant permanent loads on the structure.

In compliance with EUROCODE 2, the structural analysis under tangential effects was assessed via 3 parameters: concrete shear strength, increased for compressed concrete; steel fiber strength; and passive reinforcement strength: general cross sections are not reinforced, thus annulling this value.

To solve the shear overstress problem, the prestressing layout was changed to maximize compression where torsion was greatest, and readjust the 2 peaks of positive and negative torsion (Fig. 11). Short tendons balance torsion peaks and guarantee maximum compression in torsion peak areas.

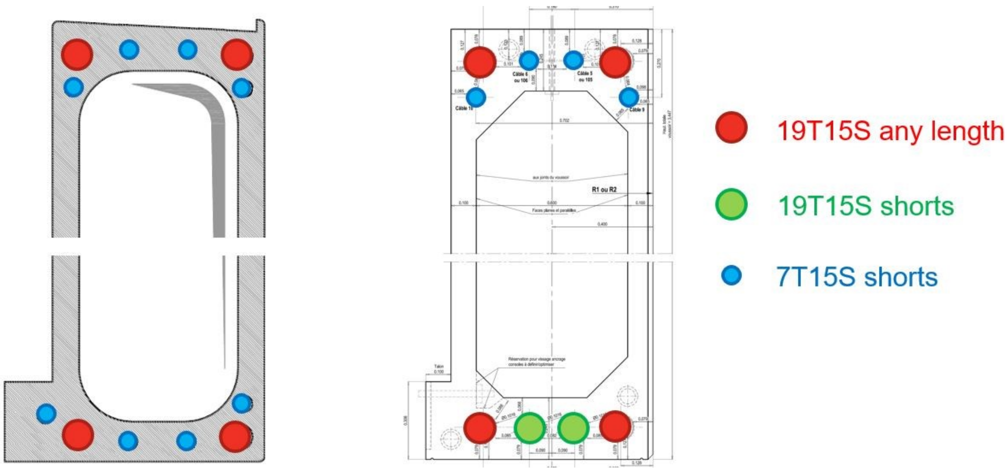

Figure 11: Prestressing tendon arrangement in preliminary (left) and detailed design (right)

3.5 Reduced Span and Tendon Anchorage

However, improving the prestressing tendon arrangement in detailed design was not enough to respect allowable criteria. The beam spans were then slightly readjusted and approved by the

Architect. Initially 66.2 m long, the central span was reduced to 56.1 m (Fig. 12), thus guaranteeing a better balance between the 3 spans (28.3 m – 56.1 m – 37.9 m) and cutting down the natural torsion in the curved beam by 50 %.

Figure 12: Central span of the beam – Photo: Karine Warny

3.6 Final Modelling

The final prestressing layout in the structure was as follows (Fig. 13):

- Important continuous prestressing tendons made of 4 x 19T15S – Cables 1 to 4;
- Long tendons 2 x 19T15S in the lower section of the central span – Cables 7&8;
- Short tendons of smaller diameter 7T15S in upper section – Cables 5&6 and 105&106;
- Long tendons of smaller diameter 7T15S in upper section – Cables 9&10

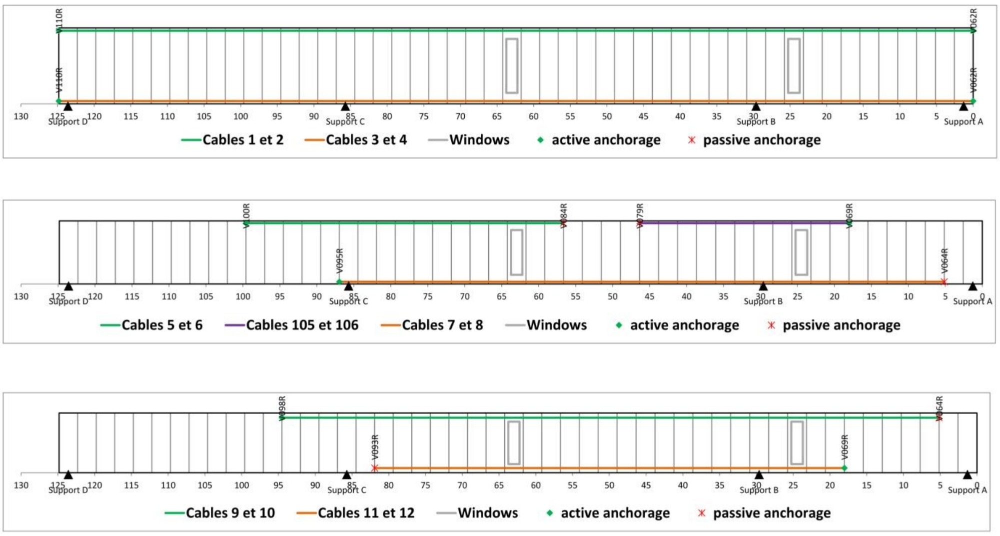

Figure 13: Final prestressing layout (elevation)

The final axial stresses and the final shear stresses in the beam are displayed in Figs 14-15, respectively. Both minimum and maximum axial strengths in UHPFRC provide a good safety margin. Readjusted supports and optimized prestressing provide the necessary shear strength in the beam to resist to both bending and torsional shear stress.

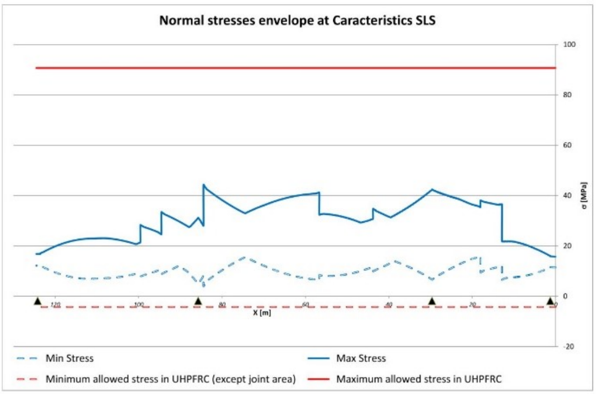

Figure 14: Minimum and maximum axial stresses at final stage

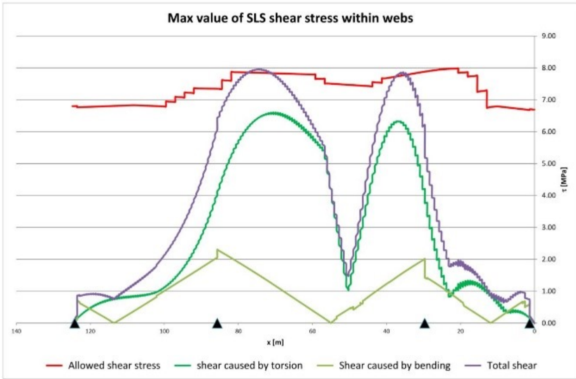

Figure 15: Maximum shear stress compared to allowable shear at characteristic SLS

3.7 Dynamic design

The dynamic study of the structure allowed the verification of dynamic comfort criteria under pedestrian loading. The curved beam was modelled with ROBOT Structural Analysis, using a wireframe model with eccentric weights for the footbridge and the caps. This model was used to determine the beam's mode shapes, both for the seismic design and the pedestrian comfort design. Complex vibration modes were assessed, mixing vertical and horizontal displacements along with torsional displacements. The top 11 modes amounted to 80% of the horizontal modal mass, and 95% for the top 20.

As previously mentioned, releasing the horizontal degree in support B relieved the structure stress-wise, but also reduced its natural frequencies, entering a range where the structure would potentially resound under crowd loading.

The following assumptions were considered:

- Building class III, for a normally-used footbridge; may be used by important groups but is never fully loaded at once;
- Basic dynamic pressure = 0.6 kPa per pedestrian;
- Ground flexibility neglected;
- Critical damping ratio $\xi = 0.6\%$, issued from experience on prestressed UHPC footbridges. This value is more severe than that recommended by CEREMA Recommendations ($\xi = 1.0\%$) for prestressed concrete works.

Considering these criteria, dynamic horizontal loads create accelerations of about 0.08 m/s². This value is lower than the lock-in threshold (0.10 m/s²), from which pedestrian pace is forced to meet structure vibration frequency, thus developing a self-amplifying phenomenon. Vertically, the third mode shape also creates accelerations of about 0.08 m/s², placing the structure in an average comfort zone.

CEREMA's counter-calculation resulted in lower accelerations, confirming that dynamic dampers were not required in this case, contrary to most footbridges. CEREMA's model took ground flexibility into account, which led to lower acceleration values.

3.8 3D Design at the Heart of Detailed Design

In civil engineering, drawings are the keystone information transferred from the design office to the construction site. Years of practice and 2D CAD software standardized the drawing-making process. The complex geometry of this memorial gave us the opportunity to enter a third dimension: 3D geometry models were drafted with AUTODESK's INVENTOR v.2014. Having frequently used this 3D CAD software helped deal with irregularities on the project.

As previously mentioned, established design with CEREMA proved necessary to arrange the prestressing tendons inside the voussoirs. The 24 prestressing anchorages (Fig. 16) were represented in 3D along with the tension jacks to validate this option. The space left around the 19T15S jacks was no greater than 2cm: the 3D model was used in the precast factory, and confirmed by a simplified model of the jack in the voussoirs.

Moreover, these 3D models were appreciated by formwork manufacturers, allowing them to design specific butt formwork using a particular folded steel sheet device. Anchor positioning butts were directly made with a CNC machine based on voussoir 3D models. File extension to swap models was ".step". 3D CAD was also very useful to place inserts required at the interface with work package #2 (Fig. 17)] (metallic elements such as steel sheets and side parapets provided by CITYNOX) and for temporary works (voussoir lashing after face pasting).

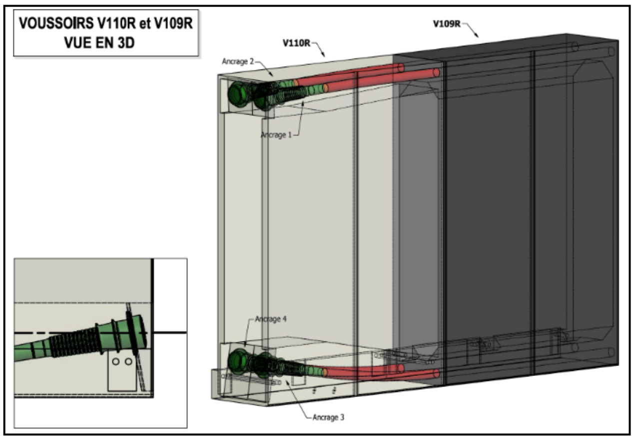

Figure 16: Prestressing anchorage 3D modelling

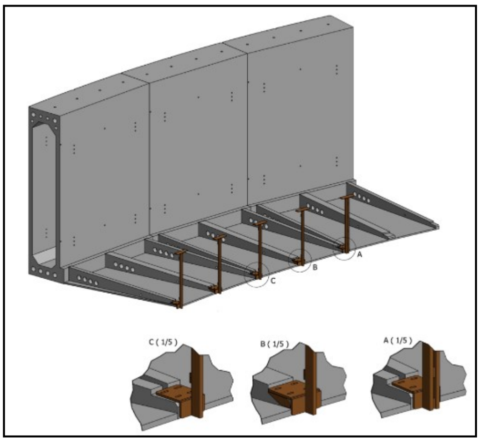

Figure 17: 3D model

4. CONCLUSION

With UHPFRC material, very thin precast elements with high compressive and shear strengths were achieved to resist unusual stresses in this extraordinary civil engineering work. The extreme durability of the material will allow it to remain through the upcoming century in this place of memory on the hill of Notre Dame de Lorette.

Through constant and constructive exchanges with all project members, the design and construction were completed in due time, despite a short overall project period. Furthermore, this project's detailed design forced the design office to master evolving numerical tools for complex works.