MEMORIAL OF NOTRE-DAME-DE-LORETTE

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Abstract

Dedicated to the 579,606 militaries (all countries and all grades) fallen during the First World War in the North of France, the Memorial of Notre-Dame-de-Lorette is a large elliptic ring in UHPFRC (BSI-Ceracem®). The perimeter of the ellipse (328 m) is composed with 122 precast elements and prestressed for 49 of them. The horizontal ring is for the two third buried in the slope of the topography and for one third in cantilever (prestressed hollow-cored beam). From the beginning, the memorial was designed with the UHPFRC. The choice of this material is due to durability required and to performances necessary for bridging the curved span of 60 meters. All details were adapted to maximize the capacities of the material, both in terms of structure and expressivity. This paper first presents the requirements of the project and the architectural proposal of Philippe Prost. Then the paper describes the technical details and explains why the UHPFRC is particularly adapted for this project. In conclusion, a reflection is made on the feedbacks of this emblematic project.

Résumé

Dédié aux 579 606 militaires (toutes nationalités et tous grades) tombés durant la Première Guerre Mondiale dans le Nord de la France, le mémorial de Notre-Dame-de-Lorette est un grand anneau elliptique en BFUP (BSI-Ceracem®). Le périmètre de l'ellipse (328 m) est composé de 122 voussoirs préfabriqués et précontraints pour 49 d'entre eux. L'anneau horizontal est enterré pour les deux tiers dans la pente du terrain, et en porte-à-faux pour un tiers (poutre précontrainte en caisson). Depuis le début, le mémorial a été conçu en BFUP. Le choix de ce matériau est dû autant aux exigences de durabilité qu'aux performances requises pour franchir une portée de 60 mètres en courbe. Tous les détails ont été adaptés pour maximiser les capacités du matériau, tant en termes de structure que d'expressivité. Cet article commence par présenter les exigences du concours and la proposition architecturale formulée par Philippe Prost. Ensuite l'article décrit les détails techniques et explique pourquoi le BFUP est particulièrement adapté à ce projet. En conclusion, une réflexion est menée sur le retour d'expérience de ce projet.

1 PROJECT DESCRIPTION

1.1 Context

In 2011, the Nord-Pas-de-Calais Region launched an architectural competition for the construction of an international memorial to celebrate the centenary of the First World War. The project had to be built in a very short time with a tight budget, on the Notre-Dame-de-Lorette hill, a natural and heritage protected site, alongside the French national necropolis of the twentieth century. The aim was to engrave the names of the 579,606 combatants who fell on the battlefields of the Nord-Pas-de-Calais, arranged in alphabetical order without any distinction of nationality, rank or creed, united now and forever in their common humanity. The architect Philippe Prost (AAPP) was invited to submit an entry, together with a pluri-disciplinary team: the engineering company C&E, the landscape architect David Besson and the graphic designer Pierre di Sciullo … [1]

1.2 Requirements of the competition

Responding to the ambition to make a strong political statement, we conceived a project that seeks to overcome the horror of the First World War in order to commemorate its combatants, to constantly remind us of the importance of peace and to offer to Europe a peaceful vision of the future, with three major ideas:

To give a shape to brotherhood

To reunite those who once were enemies and gather together their names, we chose the figure of the ring, thinking of the circle that is formed when people hold hands (Fig. 1). The ring is synonymous with both unity and eternity: unity because the names now constitute a sort of human chain; eternity because the letters continue without end, alphabetical order prevailing over all distinctions of nationality, rank or creed. Implanted in its setting the ring takes the form of an ellipse, turned on one side towards the entrance of the necropolis and on the other towards the plain of Artois.

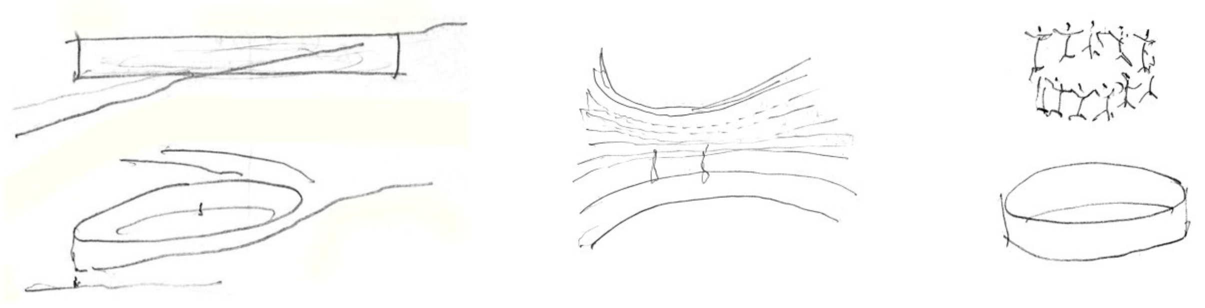

Figure 1: First conceptual sketches by Philippe Prost during the competition design.

To give expression to peace

The choice of horizontality for the memorial appeared self-evident. Firstly, in order to respond to the verticality of the lantern tower and furthermore because the horizontal is a sign of balance and a token of timelessness. Rooted in the ground for two-thirds of its diameter, the ring detaches itself from the earth where the slope of the hill becomes steeper: this 56 meters-span cantilevering is here to remind us that peace will always remain fragile. In setting out to storm the horizon the memorial creates a weightless space between the sky and the earth.

To unite art and nature in the service of memory

On the same site where horrific battles were played out nature has now reclaimed her rights; the memorial will inscribe the memory of the fallen in space and, moreover, will celebrate rediscovered peace.

At first, the ring was just a concept quickly sketched by the architects; but as we worked on it and became convinced by its significance and simple beauty, it also became a major technical challenge for the team engineers. The use of a new material – a ultra-high performance fibre-reinforced concrete – has made its construction possible and will allow it to defy the passing of time.

1.3 The choice of the UHPFRC

Since the competition, the material of the elliptical ring is the UHPFRC. This material is the only one that solves the requirements of static, durability and appearance. The material did not change during the project development because none of the other materials considered (HPC, steel + cladding, etc.) fulfils all the criteria as well.

Durability was an important criterion for this emblematic project. During the competition, three of the five architectural proposals had chosen to use UHPFRC. The low porosity and high rate of anhydrous cement contribute to maintain a high pH (basic) inside the material and to reduce the carbonation and the corrosion [2].

The cantilevered curved beam requires both to have good mechanical performances and to be lightweight. In order to bear the bending and torsional moment, the cross-sections are thickened. But that way, the moments are increased. There are only two structural options left: a steel structure or prestressed UHPFRC.

The structural ring is visually present, especially from the bottom of the slope. The finishing of the ring has to be simultaneously raw, smooth and sustainable, which precludes the use of cladding (not strong enough and requiring regular maintenance). The precast concrete, and especially the UHPFRC, has the right performances and the right finishing. A transparent anti-graffiti coating is applied on the external surface to protect it against vandalism. Recently in 2008, Muslim tombs of the adjacent necropolis had been degraded.

The proportions (ratio of dimensions) are very important to keep the impressive effect of the spanning. With the UHPFRC, the thickness of the cantilevered slabs and the canopies can be reduced to few centimetres, enhancing the visual slenderness.

2. DESIGN WITH UHPFRC SINCE THE COMPETITION

2.1 General design

The choice was made to half-buried the memorial into the site (Fig. 2). Anchored in the land to the North, it can hardly be seen from the existing national necropolis. On the contrary, from the South, thanks to the slope of the land, the ring is suspended "*between heaven and earth*". The work covers a 328 metres perimeter. The ring is made up of 122 L-shaped segments. 49 of which are reinforced and they form a curved footbridge 125 metres long on four supports including a 56 metres-span opposite the battlefield where the terrain falls away under the memorial… Access is from the North-West side, through a U-shaped trench. All of the segments have ultra-high performance fibre-reinforced concrete cantilevered slabs and are topped with a canopy overhanging from the vertical face of the footbridge.

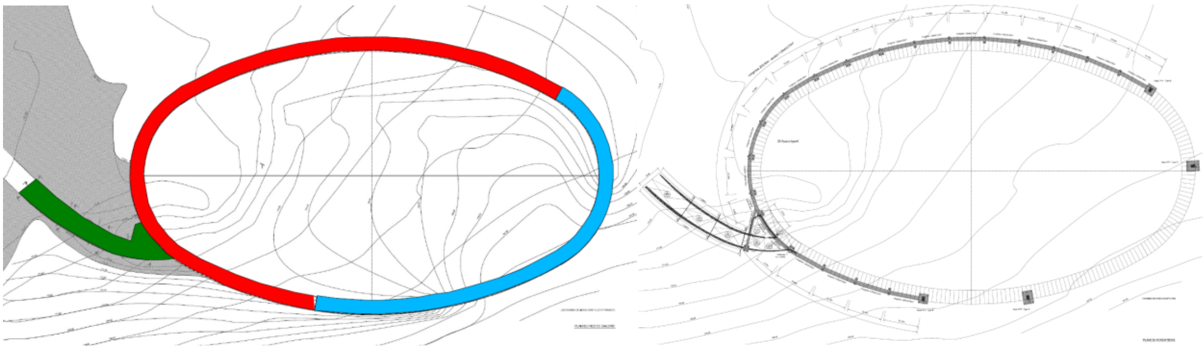

Figure 2: Memorial structural parts (left): U-shaped trench (green), 73 Normal grounded segments (red) and 49 reinforced segments (blue).
Topography and ground foundations (right) (Drawing by C&E Ingenierie)

In order to obtain visually a continuous ring from singular elements, it is necessary to design carefully the joints and the continuities. The geometric continuity of a curve may be of different kinds: position, tangent, curvature radius, variation of curvature radius… To do not give the impression of a "*broken*" curve at each junction, the "*tangent continuity*" must be at least satisfied. In the case of a perfect elliptic ring, each segment must be different to obtain the "*tangent continuity*", because the curvature radius changes along the curve. In order to limit the number of moulds, we chose a "*pseudo-elliptic*" ring called "*en tiers point*" (in third point). This ancient geometrical construction (Fig. 3) makes it possible to have only four moulds for all the ring:

- "*Normal segment*" with great radius 1
- "*Normal segment*" with small radius 2
- "*Reinforced segment*" with great radius 1
- "*Reinforced segment*" with small radius 2

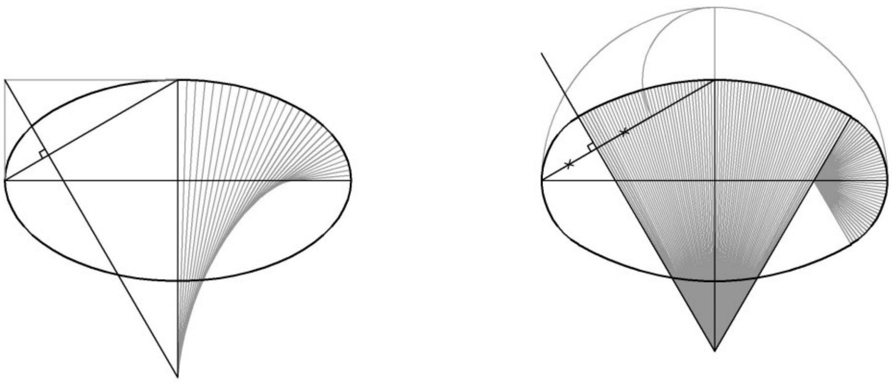

Figure 3: Perfect elliptical ring with a different curvature radius for each segment (left) and Pseudo-elliptical ring "en tiers point" (in third point) with only two different curvature radii

Figure 4: The light reflection and the skyline are good ways to check le geometric continuity (Pictures by R. Fabbri)

Figure 5: "*Normal Segments*" during and after the implementation (Pictures by R. Fabbri)

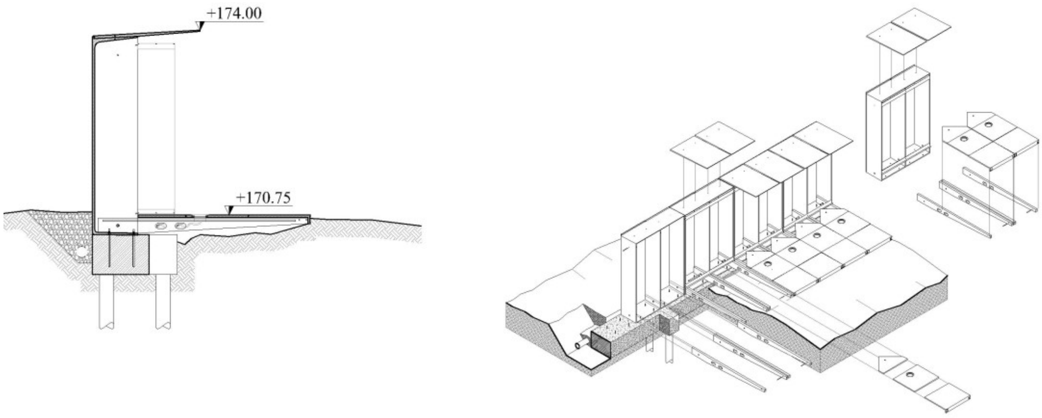

Figure 6: "*Normal Segments*" as designed before the construction stage
(redrawn after by C&E Ingéniérie and R. Fabbri)

Although they are externally identical, the "*normal segments*" and the "*reinforced segments*" are designed differently, as they do not support the same kind of forces. The "*normal segments*" bear only the earth pressure and the stainless-steel plates with the names engraved. They are designed as a large monolithic empty box of 3.50 m high by 0.80 m deep and 2.60 m wide (Fig. 4-6). The changes made by Eiffage TP concern the "*canopies*" and "*cantilevered slabs*" (Fig. 7-8). Those one were at the beginning designed in UHPFRC, they are finally made with reinforced concrete. Eiffage TP has made a real improvement in the design of the "canopies", with a vertical plinth and a non-apparent fixing.

The cross-section of "*reinforced segments*" is a hollow-core rectangle, measuring 3,50 m high by 0,80 m deep and 2.60 m wide. The minimum thickness in the vertical walls is 100 mm. The "*cantilevered slabs*" are mechanically attached to "*reinforced segments*", and they support the walkway. The changes made by the Eiffage TP concern the "*canopies*" (as for the "*normal segments*") and the minimum cover. In order to spare weight (see chapter §1.3), the minimum cover had been reduced to values below the diameter of the prestressing ducts. The UHPFRC Recommendations of 2013 [3] allow this choice provided it is validated by suitability tests. In that case, the following criteria have been checked:

- the minimum thickness required for durability;
- the resistance to the thrust of the prestressing cables;
- the fibres distribution.

For taking no risk, Eiffage TP has chosen to increase the cover thickness to the diameter of the ducts. This hypothesis, positive for durability, has changed the applied load on the "*reinforced segments*".

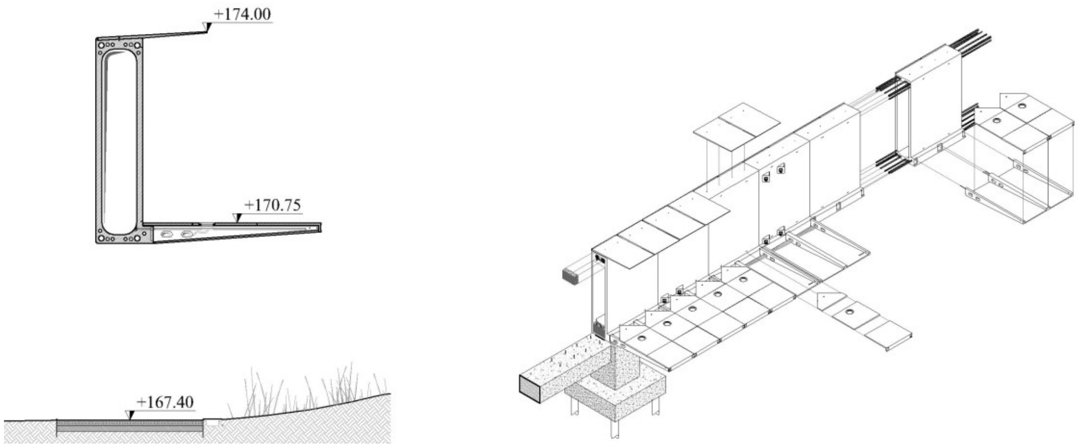

Figure 7: "*Reinforced Segments*" as designed before the construction stage (redrawn after by C&E Ingéniérie and R. Fabbri)

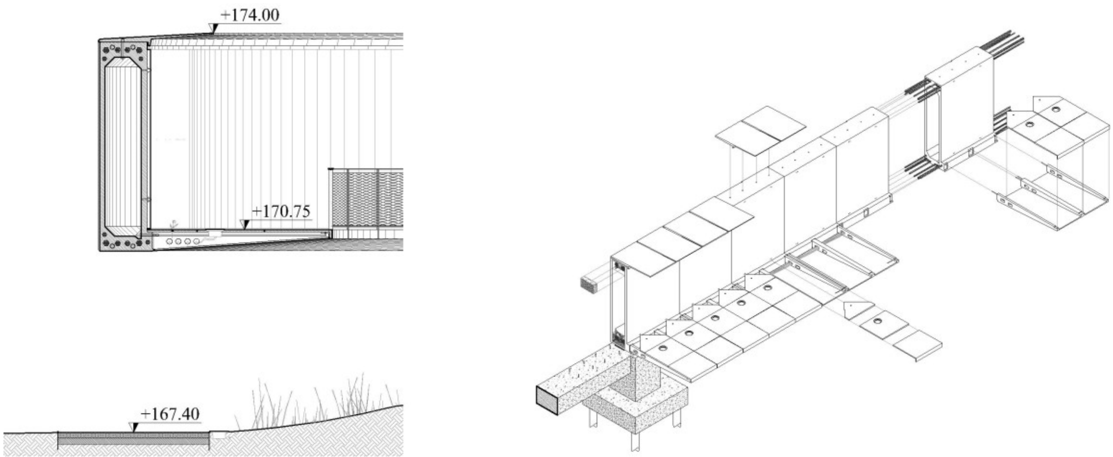

Figure 8: "*Reinforced Segments*" as built (redrawn after by AAPP and R. Fabbri)

2.2 Details design

In the precast structures, the assemblies may be of four different kinds: by contact; by mechanical assemblies (bolts, screwed bars, axes …); by sealing or joint fills; by prestressing.

In order to ease the implementation, or even to allow the replacement (as for the "*canopies*"), the assemblies are mainly designed with simple contact or with bolts (Fig. 9). The slabs of the walkway are simply laid on the "*cantilevered slabs*". Those one are assembled with bolts and couplers. The "*normal segments*" are also mechanically fixed on the foundations.

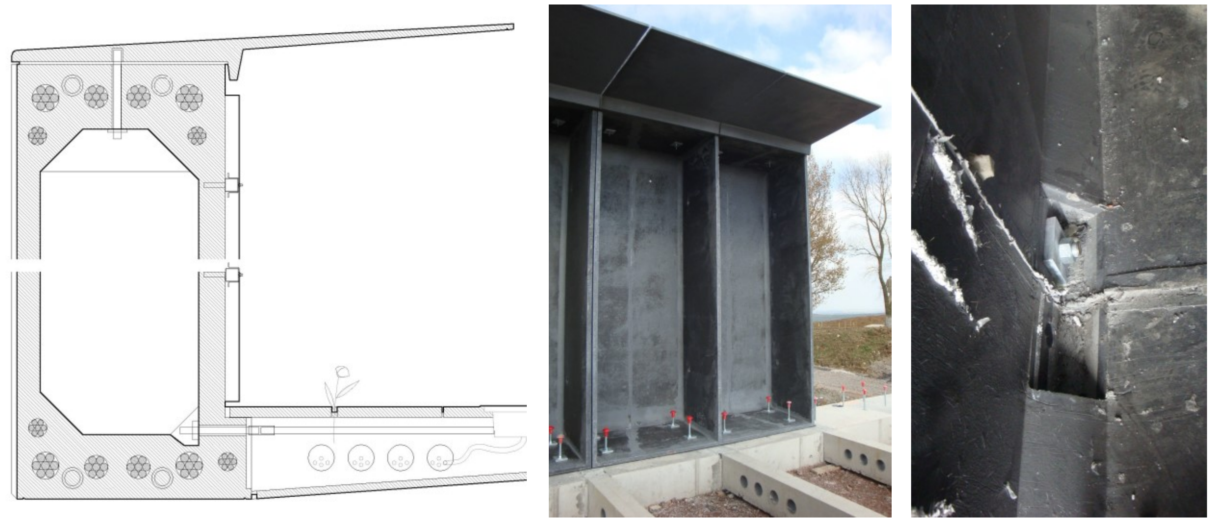

Figure 9: Details of the connection between the canopy, the cantilever slabs and the reinforced segments (left), view of the connection of the normal segments (middle), the view from the inside of the connection of the cantilever slabs (redrawn after by AAPP and R. Fabbri, pictures by R. Fabbri)

The issue of the joint is fundamental in the architecture of precast elements. The size first: "*too big*", the joint breaks the visual continuity; "*too small*", the joint reveals all the imperfections between the elements. In this project, there are four kind of joints:
- the joints between "*normal segments*", filled with PVC profiles;
- the seals between "*reinforced segments*", done with Epoxy glue;
- the construction joints at the junction between the "*normal segments*" and the "*reinforced segments*", also filled with PVC profiles;
- the "*false joints*" in the middle of each segment.

The goal is that a non-specialist does not distinguish between joints, and see only a single kind of joint (Fig. 10). The width of the joint is given by the size of the construction joints (the biggest of all), the depth of the joint is in such a way to do not see traces of Epoxy glue. The "*false joints*" are added to give a rhythm that reminded the inner stainless-steel plates.

The contact with the ground is an important part of the project. The "*reinforced segments*" only lay on four supports. In order not to distinguish the "*reinforced segments*" and the "*normal segments*", embankments have been added over the concrete supports. This earthmoving (Fig. 11) increases the "*visual tension*" between the ring and the ground. The concrete piles are completely buried into the ground.

Figure 10: View of the limit between the reinforced segments and the normal one, four kinds of joints with only one aspect (left) PVC profile in the joint (right) (Pictures R. Fabbri)

Figure 11: External view before (left) and after the earthmoving (right) (Pictures R. Fabbri)

2.3 Static design

The "*reinforced segments*" form a continuous beam, supported by four points. The ending supports are fixed (in order to avoid the displacements close to the "*normal segments*"), and the intermediate supports are fixed only vertically, so as to allow the thermal expansion. The spans between the supports measure 28.3 m - 56.1 m - 37.9 m.

The curved beam has to support, in addition to bending moment, an important torsional moment (Fig. 12). The prestressing is composed of 4 main cables (19T15S), passing through the entire beam (125 m) and 12 short cables (7T15S), added to compensate peaks of forces (Fig. 13). The composition of the prestressing does not change between the design and the construction.

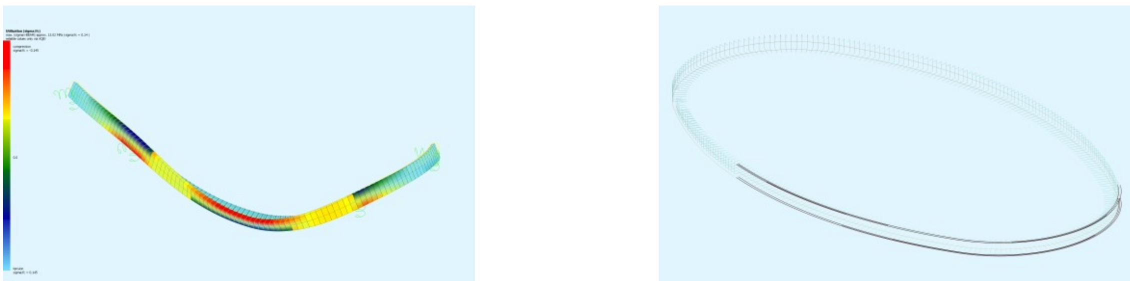

Figure 12: Design model with SOFISTIK (Pictures C&E Ingéniérie)

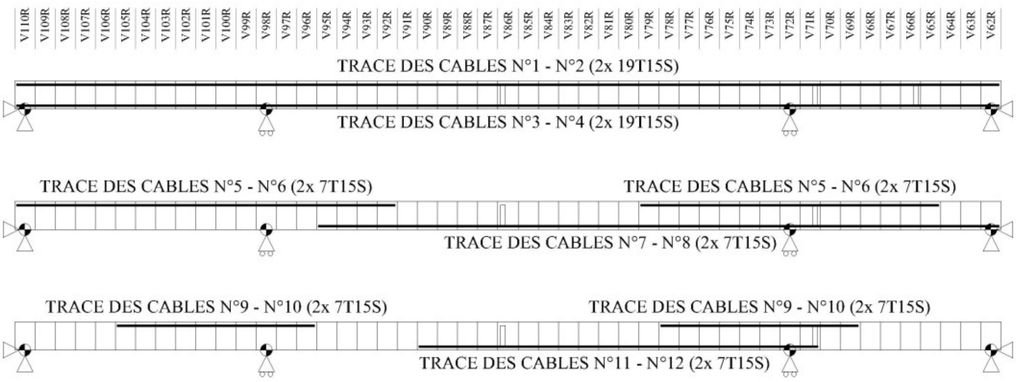

Figure 13: Prestressing cables position (top right and bottom)

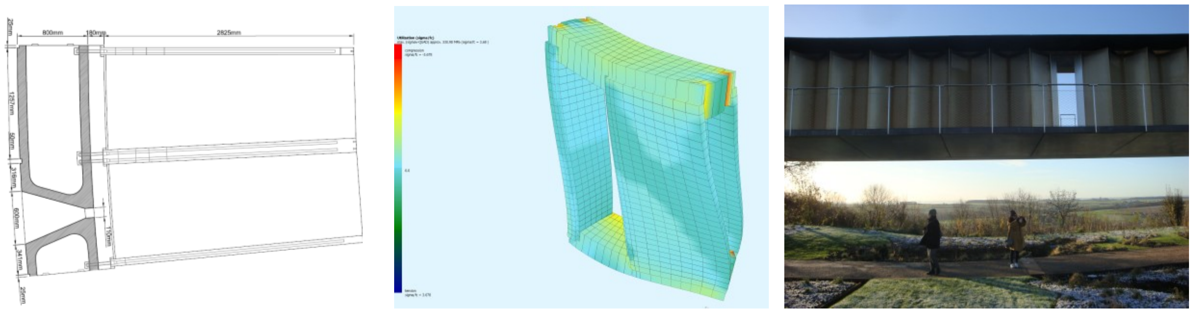

Figure 14: First design of the window (left), Design model (middle) and view of the window (right) (Pictures C&E Ingéniérie)

The ring has two windows that frame, on one side the landscape on the plains of Artois and the ruin of the church of Abalin-Saint-Nazaire, and on the other side the mining basin and the Vimy Memorial. First designed as vertical slots, the windows were expanded at the request of the client (Fig. 14). In the hollow-core cross-sections, the torsional moment is essentially transmitted by a torsion of Saint-Venant (shear flow). At the level of the windows, the capacity of the torsion of Saint-Venant is insufficient and the torsion of Vlassov (bi-flexion) becomes preponderant. In order to analyse the stresses due to the Torsion of Vlassov, a shell model of the "*window segment*" was carried out. The "*window segment*" also supports the thrust due to the deviation of the prestressing in the top and bottom parts of the section. The fibres of the UHPFRC are taking part of the resulting tension and are reducing the sections of reinforcement added.

2.4 Dynamic analysis

The dynamic tests done on site have shown that [4]:

- The first calculated eigenvalue (0,87 Hz – horizontal) doesn't appear on the measured acceleration spectra. We can explain it, by the fact the intermediate supports don't perfectly slip horizontally and generate a fixing point.
- The second calculated eigenvalue (1,89 Hz – torsional) does appear at a frequency of 1,85 Hz and with damping of 1,2 % (above the damping of 0,4 % measured on UHPFRC footbridges with similar spanning), and an suitable acceleration below 0,5 m/s² (according the AFGC Guide [5])

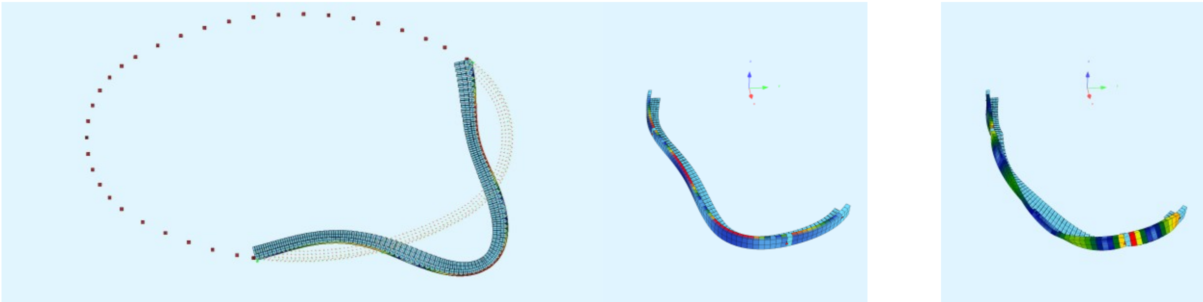

Figure 15: First calculated eigenvalue F=0,87Hz horizontal (right), Second calculated eigenvalue F=1,89Hz Torsional (Left) (Pictures C&E Ingéniérie)

3. CONCLUSIONS

The Memorial of Notre-Dame de Lorette is a project particularly adapted for UHPFRC. From general design to details, the project was designed with the properties and characteristics of this material in mind. It was realized in a very short time (Construction begins in January 2014 – delivery occurs in September 2014). Now what is blocking the development of the UHPFRC is that, except few architects and engineers, designers do not think about it when it is relevant, and few of them use this material with good design rules.

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