PARKBRIDGE: OPTIMIZATION OF A SLENDER BRIDGE IN UHPFRC

Steffen Grünewald (1-2), Hans Köhne (3), Maurice Nio (4), Matteo Serafini (4), Anja Verdonk (4), Rogier van Nalta (5), Rob Huijben (6), Viktor Mechtcherine (7), Lukasz Dudziak (7), Leo Gielbert (8)

(1) Faculty of Civil Engineering, Delft University of Technology, The Netherlands

(2) Hurks Prefabbeton, Veldhoven, The Netherlands

(3) Cement&BetonCentrum, 's Hertogenbosch, The Netherlands

(4) NIO architecten, Rotterdam, The Netherlands

(5) Pieters Bouwtechniek, Delft, The Netherlands

(6) Hurks Delphi Engineering, Veldhoven, The Netherlands

(7) Technische Universität Dresden, Dresden, Germany

(8) Strukton, Maarssen, The Netherlands

Abstract

Ultra High Performance Fibre Reinforced Concrete (UHPFRC) is a concrete type with superior characteristics concerning strength, ductility and durability compared to conventional concrete. In spite of extensive research efforts the number of applications is still limited. In order to promote UHPFRC in the Netherlands, Cement & Beton Centrum initiated a program that aimed at designing and realizing attractive structures with UHPFRC; the Parkbridge is one of the cases considered. This paper describes the design and the optimization of the 'Parkbridge', a slender bridge with a span of about 20 meters. This pedestrian bridge was designed to replace the existing wooden bridge of a nature park. The bridge consists of a parabolic-shaped load-bearing structure and an ultra-slender balustrade. A tailor-made UHPFRC was applied to produce the largest element of the balustrade. Besides design considerations, production aspects of the slender UHPFRC balustrade-element are discussed.

Résumé

Les bétons fibrés à ultra-hautes performances sont une gamme de béton possédant des caractéristiques exceptionnelles en termes de résistance, ductilité et durabilité par rapport au béton traditionnel. Malgré d'importantes actions de recherche le nombre d'applications reste limité. Afin de développer les BFUP aux Pays-Bas, le centre technique des bétons (C&BC) a

lancé un projet visant à concevoir et réaliser des structures en BFUP susceptibles de faire école. Le pont du parc (Parkbridge) en est un exemple. L'article décrit la conception et l'optimisation du "Parkbridge", ouvrage élancé d'environ 20 m de portée. Cette passerelle piétonne a été conçue pour remplacer le pont en bois existant d'un parc naturel. L'ouvrage consiste en une structure porteuse parabolique associée à un garde-corps ultra-mince. Une formule spécifique de BFUP a été utilisée pour réaliser l'élément le plus important du garde-corps. Outre les considérations de calcul, l'article détaille les questions de fabrication de cet élément mince de garde-corps.

1.   UHPFRC CASE-STUDY

UHPFRC is more than an improvement of traditional vibrated concrete; concerning material performance and production technique it can be considered a new technology. Clients want examples of successful applications and require a perspective on profit on investments. The Parkbridge is one of three case-studies in UHPFRC and an initiative of Cement & Beton Centrum to increase the acceptance of UHPFRC in the Netherlands as an excellent building material. An aim of these studies was to demonstrate the additional value of an integral design approach of cooperating architect, engineer, producer and contractor. The advantages of freedom of shape, a structure without maintenance, ease of use and durability have to outweigh the initial construction costs in order to convince owners.

The design process of the Parkbridge focused on two aspects: harmonious embedment of the bridge in its surroundings (in a nature park close to Voorstonden, The Netherlands) and making full use of the material characteristics of UHPFRC. Figure 1 shows an impression of the bridge in its final version.

Figure 1: Design of an ultra-slender bridge in UHPFRC

The design should result in a very slender structure with an organic appearance. The new pedestrian bridge had to replace a rotten wooden bridge, which would be a step ahead towards reconstruction of this nature park. The Parkbridge was a realistic project with the possibility to construct the bridge in case the design solution would be convincing both in design and project costs. According to the owner of the park, a solution in concrete had a good chance to be selected because of the high durability of the material. By applying UHPFRC a special bridge solution seemed to be achievable.

2.   DESIGN OF THE BRIDGE DECK

NIO architects wanted to design an extremely slender bridge, completely made from UHPFRC. Inspiration for the architect was found in the structure of leave-veins of the countless leaves at the site. The bridge-deck and the balustrade have different functions in the structural design. The balustrade should be as slender as possible and should demonstrate the freedom of shape of concrete. The balustrade does not increase the stiffness or the load-bearing capacity of the slender bridge-deck. The design of the bridge-deck was an exercise in optimal utilisation of the strength and the stiffness of UHPFRC. The bridge-deck (design load: 500 kg/m^2) was designed to be as thin as possible. The optimum structure of the deck is the arc. Figure 2 shows a view of the bridge as well as two cross-sections (in the middle of the span and above the abutments).
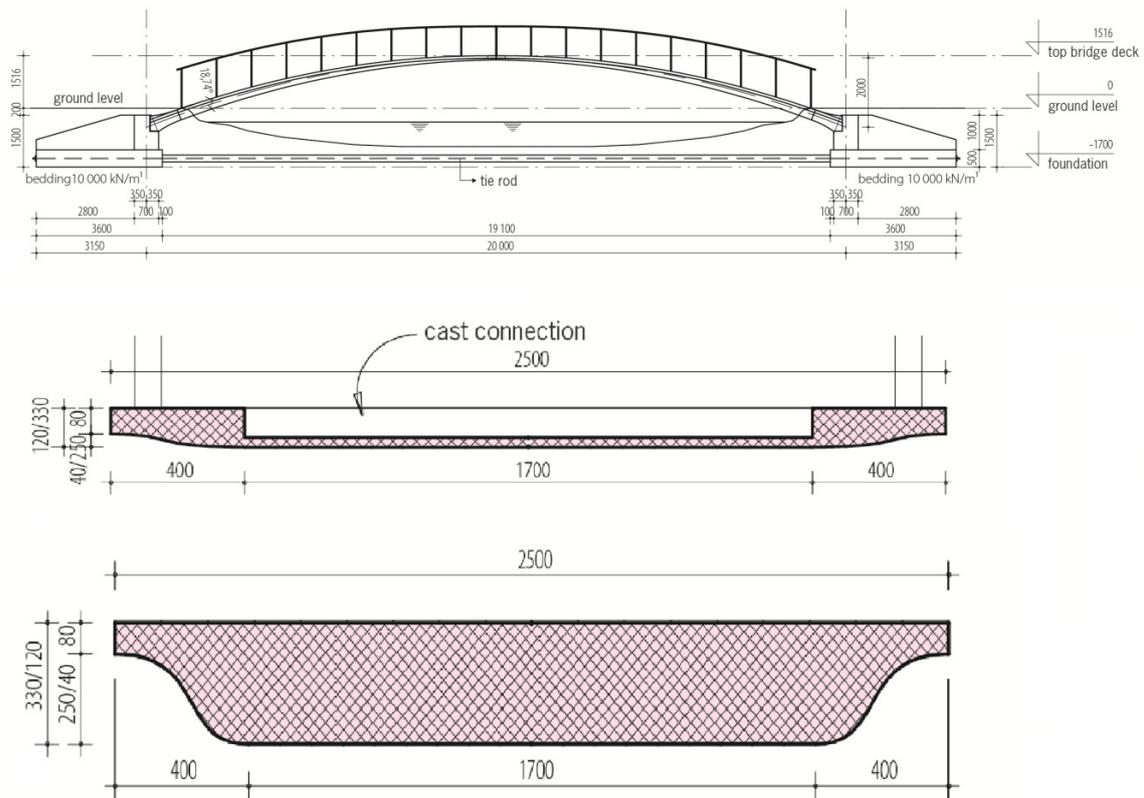

Figure 2: Details of the bridge: a) side-view, b) cross-section of the deck in the middle of the span and

c) cross-section bridge-deck above the abutments

The compressive strength of UHPFRC is much higher compared to conventional concrete; in an arc situation the bridge-deck is loaded mainly in compression, which is why this type of structure produced with UHPFRC is an interesting option. A disadvantage of an arc-structure is the need to transfer a horizontal reaction force. This is solved by coupling the abutments below the water of the shallow stream. In essence, the arc-shape of the bridge-deck is extended in the abutment below the water-level. An important aspect to consider for an arc-bridge is the effect of displacements of the supports; a small displacement already can have a significant effect on the stress distribution in the arc. By restraining the bridge-deck at the abutments (with in-situ cast joints) this effect is minimized and as a side-effect the moment in the middle of the span is decreased. As a result, a robust structure with a very slender bridge-deck was obtained. With the assumed UHPFRC-characteristics listed in Table 1 it was possible to design the bridge-deck with a varying thickness of 330 mm at the supports and 120 mm in the middle of the span. The prefabricated abutments were designed in traditional concrete (strength grade C53/65). In order to make the bridge appear more slender the thickness of both sides of the deck was reduced to 80 mm (Figure 2). The loading of the bridge results in a bending moment at the supports of 410 kN.m and of 98 kN.m in the middle of the span (in comparison: the moment in the middle of the span would be 2060 kN.m for a beam on two supports). The deformations of the bridge are small due to the stiff structure; the vertical deformation is less than 40 mm and the horizontal displacement of the supports is at its maximum 13 mm. In order to minimize the costs for formwork and transport the bridge-deck is prefabricated in two identical parts with a joint at mid-span. Both parts are positioned at the site on temporary supports at mid-span and the joint is connected afterwards with an in-situ connection. The bridge-deck and the abutments are connected with a moment-resistant joint.

Table 1: Material characteristics of two concrete types:
C53/65 (substructure) and UHPFRC (bridge-deck/balustrade)

Characteristic	Prefab concrete C53/65 [MPa]	UHPFRC [MPa]
f'ck	65	150
fb (0,6· f'ck)	39	90
E-modulus	38500	50000
Shear strength, τ	0,86	2,50

3.   BALUSTRADE: DESIGN CONSIDERATIONS

The leaf-impression of the balustrade was studied on different levels. The appearance of the balustrade is aesthetic and organic - the design and the production of such elements turned out to be complex. The target for the design was to produce balustrade elements with leaf-veins as thin as possible and with a minimum of material. The balustrade consists of different elements that are not connected in horizontal direction (in span-direction) and which do not contribute to the load-bearing of the bridge-deck. Still, they have to be connected to the bridge-deck with a moment-resistant connection in order to transmit the design force in horizontal direction (load acting perpendicular to the span-direction: 1 KN/m, acting on the

hand-rail of the balustrade). Several options were discussed to design this connection (i.e. in-situ cast joint and steel anchors with bolts). Material characteristics, economic considerations and production boundary conditions also have to be taken into account to determine the minimum thickness of the leaf-veins. In an iteration process of engineering, material and production optimization a balustrade element was developed and produced. Important considerations were:

- UHPFRC with steel fibres had to be applied in order to meet the high demand on the flexural strength; by applying fibres instead of rebars no concrete cover was required to protect rebars from corrosion.

- Steel anchors connect the balustrade to the bridge-deck (along the straight side of the element).

- The volume of UHPFRC of a balustrade-element is small; costs for formwork, abutments, transport and erection of the structure mainly determine the price of the bridge. Due to repetition related to the use of formwork the total costs of the Parkbridge can be reduced.

- An optimized UHPFRC had to be developed in order to produce the balustrade-element. De maximum aggregate size was 1 mm; a combination of short and long steel fibres (12 & 20 mm) was applied.

In order to study the applicability, different UHPFRC-mixtures were tested containing either steel or plastic fibres; different materials were used for the formwork (wood and different plastic materials i.e. Expanded Polystyrene (EPS)). Figures 3a and 3b show two test elements that were produced in order to study the filling ability and passing ability of UHPFRC, element dimensions and formwork material.

Figure 3 a/b: UHPFRC-test elements a) left: element cast in a wooden mould
b) right: element cast in a wooden mould with dimensions of 12×30×1000 mm

4. UHPFRC AND AUTOGENOUS SHRINKAGE

4.1 UHPFRC-mixture

The vein-structure of a balustrade-element is in contact with a relatively large formwork surface area, which makes it difficult to form off an element. The shrinkage in an early hardening phase of UHPFRC is higher compared to conventional concrete. In order to decrease the risk of cracking during hardening and to facilitate demoulding it was decided to carry out tests on the autogenous deformation in an early phase after casting. Table 2 shows the composition of the applied UHPFRC. A combination of two types of steel fibres was applied (steel fibre length: 12 and 20 mm); the fibre dosage was 300 kg/m^3.

Table 2: Mixture composition of the applied UHPFRC

Component	kg/m^3
CEM I 52,5 R white	450
CEM I 52,5 R grey	500
Metakaolin	100
Limestone powder	90
Water (excl. water in superplasticizer), W/C=0.30	285
Polymers SAP	2.85
Superplasticizer	30.8
Steel fibres 12 mm	180
Steel fibres 20 mm	120
Sand 0-1 mm	651

Water-absorbing polymers were added to provide sufficient water during hardening. The addition of the polymers had a pronounced effect on the workability; in order to obtain a workable concrete the dosage of water and superplasticizer had to be increased compared to the reference UHPFRC, that did not contain water-absorbing polymers. The compressive strength decreased from 150.1 to 122.5 MPa (after 28 days) due to the adjustment of the mixture composition and the addition of the polymers. Table 3 lists test results of compression tests (cubes of 100 mm) and bending tests (prisms of 40/40/160 mm). These tests were carried out load-controlled; each test was executed with three specimens.

Table 3: Test results compressive and flexural strengths

Concrete age	Compressive strength [MPa]	Flexural strength [MPa]
7 days	117.1 (STD: 2.7)	35.3 (STD: 4.6)
28 days	122.5 (STD: 2.1)	36.5 (STD: 2.5)

4.2 Measuring autogenous shrinkage

UHPFRC can significantly shrink in the first period after casting due to self-desiccation and the resulting stresses can exceed the tensile strength in the early hardening phase. Autogenous shrinkage tests were executed by the Technical University of Dresden; the effect of polymers on shrinkage was investigated. The autogenous shrinkage was measured with the

corrugated tube method (Figure 4). This technique was developed by Jensen and Hansen in 1995 [1], one exemplary small-scale set-up which became a ASTM-standard test most recently [2]. It involves a special measuring device called dilatometer (Figure 4) that is equipped with linear displacement transducers of high measuring accuracy and waterproof tube-shaped polyethylene moulds (approximately 420 mm long and 29 mm wide).

Figure 4: Dilatometer for the measurement of autogenous shrinkage

The tubes possess characteristic corrugations and low longitudinal restraint. Other relevant accessories are a reference bar and, for every mould, two Teflon end plugs being 19 mm high and having a geometry fitting in at both ends of the tube. The autogenous deformation captured by this solution is believed to be the linear strain that results from transformation of volumetric change before cementitious material solidification [3]. Prior to casting, the tubes were encapsulated at one end and subsequently placed in a supporting tube. Then the freshly produced mix was poured into the mould under activity of gentle vibration. The casting process was finalized by closing the other end of the tube with a second plug. The measurement started after transporting the moulds to the calibrated dilatometer and was carried out at a quasi-constant temperature of 20±1ºC. Although the method allows continuous monitoring of concrete deformation starting immediately after filling and encapsulating the tubes, deformation before final setting was neglected. In fact, while deformations in the fluid state are incapable of producing stresses, this time-point and time-zero in measurements corresponds well with deviation of chemical and autogenous shrinkage as confirmed by other techniques, cf. [4].

Figure 5 shows the average results of the measurements; two tubes were tested for each mixture. Three different mixtures were tested: 1) a reference mixture, containing no water-absorbing polymers, 2) the reference mixture with a decreased superplasticizer dosage and 3)

a mixture containing polymers (the w/c-ratio was increased by 0,06). Most of the autogenous shrinkage was recorded during the first four days after casting. The autogenous shrinkage of the mixture with polymers after 4 days was 59,2% compared to the mixture without polymers and with less superplasticizer and 62,1% compared with the mixture with 100% superplasticizer and no polymers.
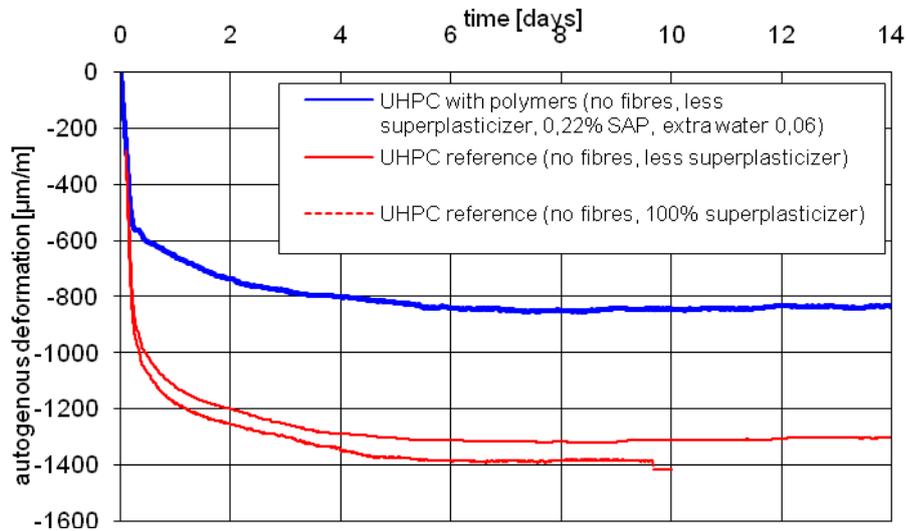

Figure 5: Deformation of UHPFRC after final set within the first 14 days

The final mixture contained steel fibres which can to some extend decrease autogenous shrinkage [5]; the effect probably is more pronounced with preferably oriented fibres. As mentioned, the dosages of water and superplasticizer had to be increased in order to obtain the desired flow behaviour: with less water (autogenous shrinkage testing: w/c=0.33; balustrade element: w/c=0.30) the autogenous shrinkage might be slightly higher than Figure 5 suggests.

5.   PRODUCTION OF A BALUSTRADE-ELEMENT

While designing the bridge, it was not clear whether the bridge would be constructed. After the completion of the design process, it was decided to produce the largest balustrade-element. A characteristic flexural strength of UHPFRC of 27,8 MPa was required for the final design and the ultimate limit state; safety coefficients are considered in this design strength. The balustrade-element consists of veins of three different cross-sections: a thicker girder around the veins, load-carrying veins as well as veins that connect the thicker girder and the load-carrying veins. The thickness of the veins and girder was in the range of 12 to 24 mm. The veins were designed to carry a pedestrian without failure or larger deformation. The balustrade-element was cast in an Expanded Polysterene-mould, which had to be stripped and destroyed in order to demold the element three days after casting. Anchors are difficult to position in the mould for such elements. The EPS-surface was coated in advance in order to decrease the surface roughness. Figure 6a gives an impression of the mould; a complex connection of five veins is shown by Figure 6b.
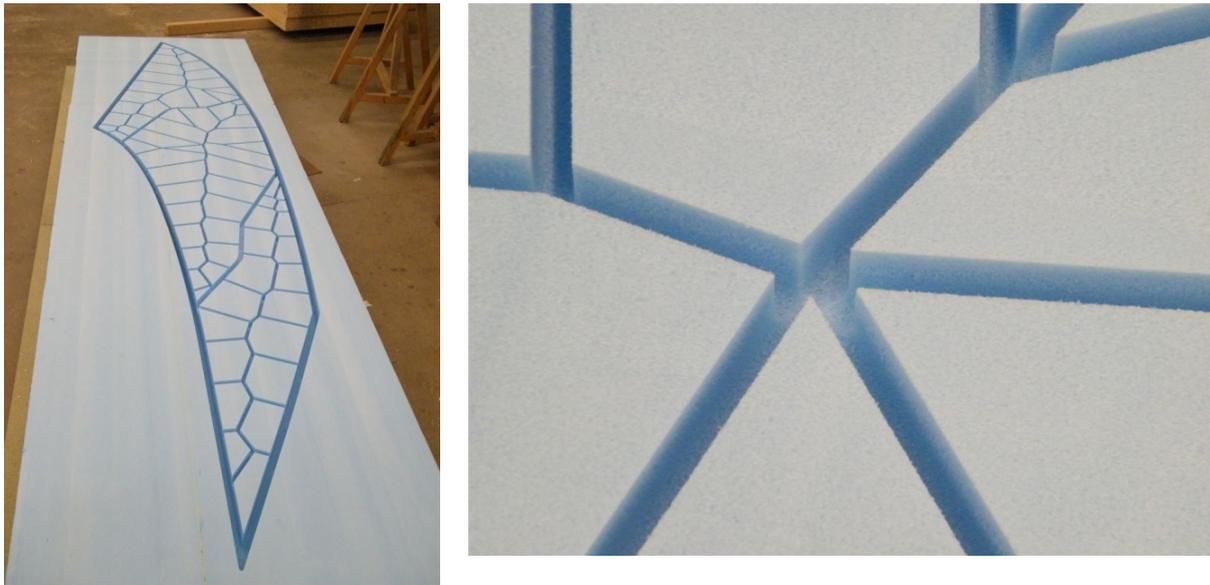
Figure 6 a/b: Impressions of the milled mould produced in EPS

The casting proceeded according to a prescribed path to avoid weak points in the connections of the veins. The balustrade-element (Figure 7) was demolded three days after casting. Due to the length of the fibres, which were in some cases longer than the width of the veins, the fibres oriented in the direction of the flow. A preferred fibre orientation assures that the flexural strength is at least the strength determined by flexural tests.

Figure 7: The largest balustrade-element of the Parkbridge

In spite of the mould surface being covered by a coating, the adherence of UHPFRC to the mould was locally strong; demoulding required special attention in order not to damage the element. No cracks were observed on the surface of the balustrade-element.

6.   CONCLUSIONS

This paper discusses a case-study with UHPFRC that aimed at convincing the owner of a nature park in Voorschoten to construct a slender Parkbridge with UHPFRC. In an integrated design process between architect, engineer and concrete producer an optimized solution was developed. The proposed technical solution represents the state-of-the-art related to material technology, structural design and production technology.

The budget of the bridge was not specified in advance. Finally, the costs of a single bridge turned out to be too high for the owner and an alternative solution was chosen (a wooden bridge); by producing more and preferably identical bridges a significant cost reduction could be achieved making the bridge more competitive. Soft soil (sand is a common ground in the Netherlands) was assumed for the design; for a more stable ground (i.e. rock), the foundation costs of the chosen solution are relatively lower. The costs of the balustrade-elements (unique elements with a repetition of 2) also are relatively high due to the high mould costs; an UHPFRC-bridge with an adopted balustrade design and optimized concrete would be an option.

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