FDN MODULAR UHPFRC BRIDGES

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Abstract

The need for durable traffic bridges in the Netherlands has induced development of a modular building system for bridges so that bridges up to 30m length and 5m width can be built economically with two standard elements: (1) the Railing element and (2) the plate element. All elements are made from UHPFRC and are post-tensioned together to form a bridge. The requirement for the development was to design a bridge with no maintenance for 100 years and to have an economical bridge which does not cost more than the standard existing bridges. FDN Engineering + Construction designed and built the first bridge in Rotterdam with a length of 18.9m and 3.4m width. The deck has a thickness of 60mm and the railing beam has a maximum thickness of 125mm. We achieved a very slender deck by adding traditional reinforcement. The railing was produced with only the fibre reinforcement.

The test loading of the bridge was a uniformly distributed loading of 5 kN/m² and a twelve ton vehicle. The bridge passed the test with excellent results and the calculated deformations were nearly the same as the measured deformations.

Résumé

La volonté de disposer d'ouvrages routiers durables et économiques aux Pays-Bas a conduit au développement d'un système de construction modulaire pour les ponts allant jusqu'à 30m de portée et 5m de largeur sur la base de deux éléments standards: (1) un élément de garde-corps et (2) un élément de dalle. Tous les éléments sont réalisés en BFUP et sont précontraints. L'exigence pour le développement de ce concept était de concevoir un ouvrage sans entretien pendant 100 ans et de coût comparable à des ouvrages classiques. Le concept FDN fut appliqué pour la première fois à Rotterdam sur un pont de 18,9 m de longueur et de 3,4 m de largeur. La dalle a une épaisseur de 60mm et le garde-corps a une épaisseur maximale de 125 mm, produisant un ouvrage très élancé en ajoutant un renforcement traditionnel. Le garde-corps a été réalisé sans renforcement additionnel.

La charge d'essai du pont était une charge uniformément répartie de 5 kN/m² et un véhicule de 12 t. Le pont a passé le test avec succès avec un bon accord entre déformations mesurées et calculées.

Figure 1: realised Bridge in Rotterdam

1. INTRODUCTION

Market research had concluded that Dutch Councils have a growing interest for maintenance-free bridges with low lifecycle costs. In order to respond to this demand, FDN Engineering + Construction has developed a concept for sustainable modular bridges in UHPFRC concrete. The first bridge was built recently, tested and placed in collaboration with the Council of Rotterdam (Fig. 1). As the aforementioned market research had shown, the various management and maintenance authorities were very satisfied with the existing concrete culvert structures. Hence the question arose, whether it is possible to apply such a maintenance-free structure to the design of a bridge. Further research showed that hundreds of bridges, spanning up to 30 m, needed replacement in the Netherlands. For this reason, the idea immerged to develop a modular bridge, which could be constructed with different lengths and widths. In collaboration with Delft University of Technology and Professor Walraven, the first concepts were made (Figs. 2-3).

2. DESIGN

The design of the bridge had to satisfy the following requirements:

- All parts maintenance-free for at least 100 years;
- Economic structure (cost lower than current traditional steel, concrete and composite bridges), Low lifecycle costs;
- Different lengths and widths made of standard elements;
- Low inconvenience and rapid construction at site;
- Attractive architectural design;
- Low CO_2 footprint

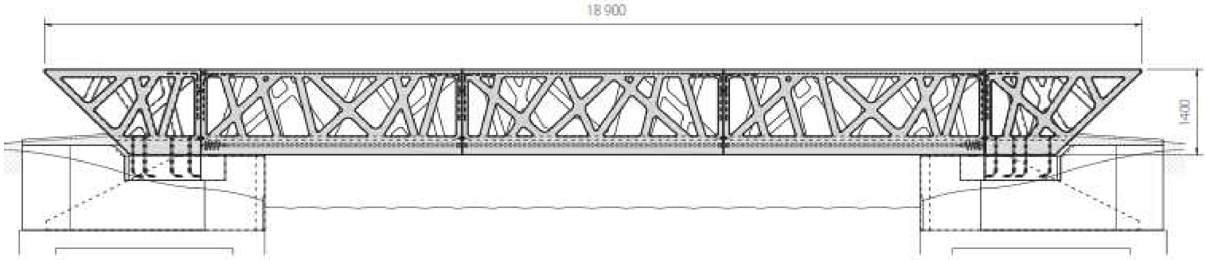

Figure 2: Side view of the bridge

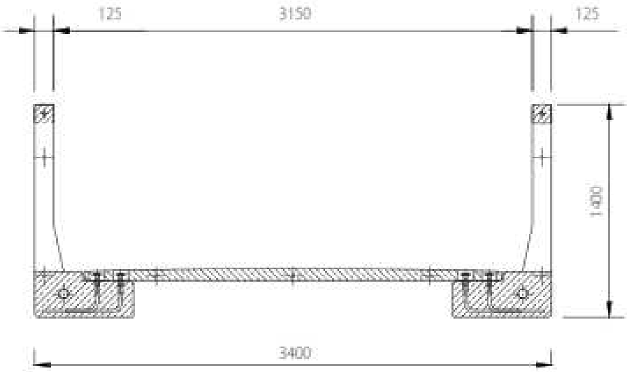

Figure 3: Cross-section of the bridge

Figure 4: The 4.3m long handrail element (left), and post-tensioned elements (right)

In the search for a material with the highest possible durability, ultra-high performance concrete (UHPFRC) showed the best results. In order to construct the bridge with low costs, standardisation was necessary. The modular standardisation allows building the bridge with various length, width and design of the handrails with two small moulds for a railing and a plate element. The handrails of the first bridge were cast in a wooden mould with special polystyrene blocks, which would fill out the openings. The wooden mould for the deck plate was standard. The handrail elements, each with a length of 4.3 m (Fig. 4), were positioned and post-tensioned to each other. The plates, also with a length of 4.3 m, were put on the side beam of the railing elements (Fig. 4). The deck is fastened with a special patented bolt connection, which was experimentally proven.

3. MATERIALS

The prior research conducted resulted in specific changes in the mixed design with respect to consistency, presence of fibres and maximum grain diameter. For the bridge of 18.9 m length and 3.4 m width, less than 9 m^3 of concrete was used. The structural material was a steel-fibre reinforced concrete UHPFRC with strength class C170/200. This strength is achieved through the dense microstructure of the binder.

The developed mixture is composed of:

- Calcinated bauxite in fractions of 0-6 mm;
- Portland cement 52.5;
- Micro-silica, additives and admixtures;
- 200 kg steel fibres per m^3 (0.4 mm in diameter and 12.5 mm long);
- Water-cement ratio (w/c) 0.16 to 0.17.

4. STRUCTURE

The advantage of the applied concrete is the extremely high compressive strength. The design value of the compressive strength is 130 N/mm^2. The design value of the tensile strength is 4.3 N/mm^2 and the flexural tensile strength 7.1 N/mm^2. This is based on [6]. During the pouring of the elements, normative concrete cubes were poured aside for later testing. The minimal measured compressive strength was 190 N/mm^2, the flexural tensile strength fluctuated around 18 N/mm2.

The bridge has been designed for a variable load of 5 kN/m^2 effective over the whole bridge deck and a 120 kN maintenance vehicle. Next to the steel fibres, reinforcement Ø10-200 mm was applied in the deck plate. In terms of deck dimensions, large slenderness was achieved. The applied deck thickness is 60 mm. However, theoretically just 40-45 mm is sufficient (1/60 L), if so-called CRC principle (Compact Reinforced Composite) is assumed. This principle was developed by Hans Henrik Bache (Aalborg Portland, Denmark) in 1986. The deck is bulged in transversal direction for drainage. The drainage of rain water is assured by a gap between the side elements and the deck plate. The underside of the deck is straight.

The handrails are without traditional reinforcement with a maximum thickness of 125 mm. The thickness may be limited to <90 mm, if traditional reinforcement is applied.

In this case the cover of the reinforcing steel is 15 mm. According to our concrete technologist, the cover can be reduced up to 10 mm only, but due to execution tolerances, 15 mm was finally applied. The handrails without traditional reinforcement seemed to be more convenient for the production speed. However, together with larger cross-section, pouring and vibrating can get more complicated. Looking retrospectively, thinner handrails would have been a better option.

5. PRACTICAL EXPERIENCE

In order to achieve the highest possible compressive strength, the water-cement ratio must be relatively low. Although the higher strengths are also achievable by adjusting the mixture and by temperature treatment, however no greater savings of material is assured. The overall cost would not be reduced anyway, due to the additional labour.

The low w/c ratio affects the workability (consistency and initial hydration). The concrete with low w/c ratio behaves like a dense thixotropic material (Fig. 5), especially at temperatures above 27°C. However, by the application of high-frequency vibrators (flex-shaft vibrators in this case), thixotropy changes into more fluid behaviour, which is more suitable for compacting.

Figure 5: Low w/c ratio makes the concrete thixotropic

The strength development of UHPFRC is temperature dependent. However, during the first period after pouring, time is also an important factor along with the temperature influence for strength development. The initial idea was to remove the mould the next day after pouring the concrete. This was theoretically possible with temperatures above 20 ° C, but in practice the removal of the mould was not possible without any damage to the elements. In addition, night temperature below 20°C caused slower strength development of the concrete. Hence, the de-casting was carried out only after two days for safety reasons.

At a temperature above 20°C, the strength after the first seven days reaches 60% of the 28-day strength of concrete. If the material is exposed to high temperatures and low humidity, the top layer of the freshly poured concrete tends to crack. The cracking is the result of rapid plastic shrinkage, which develops after 30 minutes. This problem mainly arises with thicker concrete components (> 100 mm). A solution could be to design a mixture with slightly higher w/c ratio (> 0.16) and an appropriate working environment such as an air-conditioned hall.

The UHPFRC was dosed in a compulsive mixer. After dry mixing of aggregates, the mixing water was added. Steel fibres were added later and mixed for a few more minutes. The total production time of one m^3 of UHPFRC was approximately ten minutes. The fresh concrete was poured through a steel channel to the concrete-mix container and transported to the place for the casting. The concrete was poured into the mould by opening the bung of the container, which was hung approximately one meter above the mould. The higher position of the container assures better compaction of the concrete. Concrete can also more easily get between the reinforcing bars of the deck elements. The orientation of steel fibres is random and depends partly on the flow of concrete in the mixer. The influence of the fibre orientation is negligible and random distribution gives more homogenous properties of the concrete.

6. POST-TENSIONING

The bridge is post-tensioned along the whole length at once by two pairs of straight tendons, which go through the handrail elements. Whilst the top pair of tendons is applied just for stabilization, the primary bottom tendons have structural function to carry the bridge. Before the handrails are post-tensioned and compressed against each other, the sides should be roughened by a special chipping machine. The hammering ensures flat and rough contact surface for post-tensioning. A two-component epoxy adhesive is applied between the handrails, just before tensioning. The curing time of the adhesive is two hours. At first, the bottom cable is post-tensioned at 10 % of its final post-tensioning force in order to let the glue (epoxy) harden.

The straight movement of the handrails was assured by tightened guiding profiles installed at every glued connection. In order to facilitate the guiding, TEFLON plates were installed under the elements. After full tensioning of the bottom tendon, the upper tendon in the handrail was directly post-tensioned up to 100 %. After full post-tensioning, the ducts were grouted. Subsequently, the deck-plate elements were placed on the handrail elements. The gains with bolt connection between handrail and plates were filled with concrete C170/200. The whole bridge can be assembled in one day. After one week the grout in the post-tensioning ducts and connection channels is generally hard enough to be transported to the site (Fig. 6).

Figure 6: Transport of the bridge to the definite location

7. TESTING OF THE BRIDGE

Besides the check of the design calculation, the local authorities required additional testing of the whole bridge. The assumed loading for testing was 1.2 times of the variable load 5 kN/m^2 acting over the entire deck of the bridge (normative load), and a horizontal load, 1.2 times of 3 kN/m^{-1}, acting against the railings. The results of the test-load should correspond to the calculated values (Fig. 7), which was a requirement for issuing the final building permit (Table 1). The variable load was applied by means of water containers covering the whole deck (Fig. 8). These were filled with 60 cm of water (Fig. 9). The horizontal load on handrails was represented by a tirfor (grip-hoist device), which was connected to digital extensimeter (connected with strops and wires). This set-up was positioned at every meter along the whole bridge. Measurements of the deflection of the bridge in the unloaded and loaded conditions were performed by Professor Walraven from Delft University of Technology. The bridge was also checked for cracking, but no cracks were found.

Table1: Vertical deflection under variable load 5 kN/m^2

	Calculations 2D-model	Calculations 3D-model	Testing	Permitted values
u_Z railings - middle	2.5 mm	2 mm	3 mm	21 mm
u_Z deck - middle	2.3 mm	1.7 mm	2 mm	4.5 mm
u_Z total	4.8 mm	3.7 mm	5 mm	25.5 mm

The measured values corresponded with the calculated deflections. This implies that the calculation method is valid. No visible cracking occurred during the testing.

The results show that the 60 mm thick deck, using traditional reinforcement is reasonably optimized in terms of deflections. The handrail can be optimized by the application of reinforcement into the smaller cross-section, 90 mm instead of 125 mm (28 % reduction in thickness).

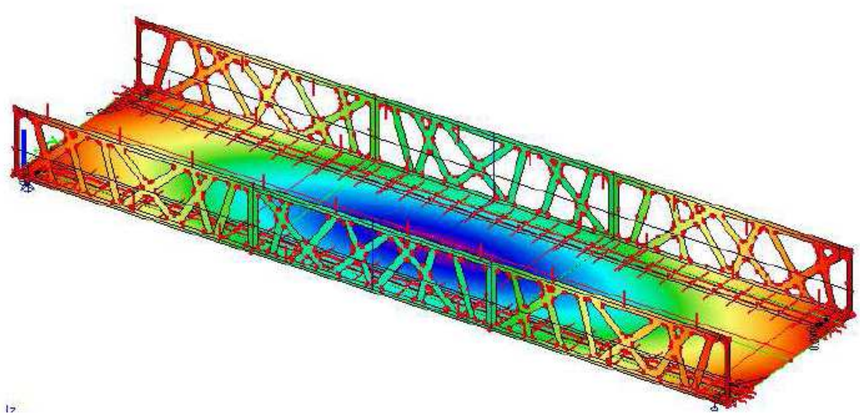

Figure 7: 3D model – vertical deflections [2]

Figure 8: Testing of the bridge

Figure 9: For the testing of the bridge, water containers were filled with water

8. POSSIBILITIES OF THE BRIDGE SYSTEM

The system of modular bridges enables a countless number of handrail designs (Fig. 10). Architects have the freedom to choose the handrail pattern to suit any type of environment. The presented bridge is a flat bridge, but an arched bridge is also possible with standard elements. The potential arch effect can also contribute to even smaller dimensions of the concrete elements. The polystyrene blocks, which are used to create the openings in the rails, can be manufactured in any shape. This gives more freedom to be creative, which is very often limited in Civil Engineering projects. The 3D PS blocks are made by an automatic trimming system. The blocks can be reused several times.

The current mould system enables to build a bridge with a maximum length of 30 m and width of 5m. The bridges can also have different colours with added pigment. Possibilities for temporary bridges also arise by applying a post-tensioning system without grouting, which enables dismantling of the bridge. Hereby also bridges needed for a period of 30 years or shorter can be built with this system as re-use of elements elsewhere is possible.

The disposition of the bridge elements enables to install distribution cables and ducts underneath the deck, without any visual disturbance.

An additional advantage of this modular system is that the elements for a 30 m long bridge can fit into a 20-foot container with an open top. There are usually restrictions for volume and weight of transported material. Hence, the transport of this type of bridge is inexpensive and enables easy export from The Netherlands.

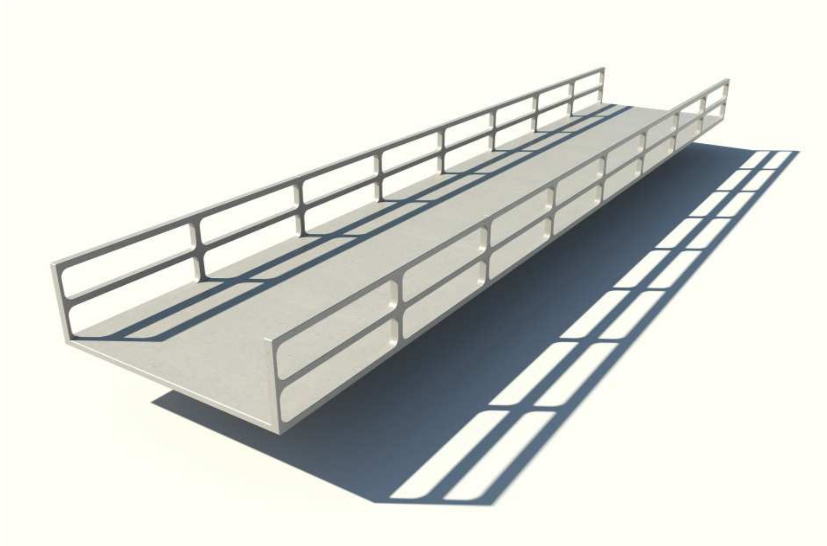

Figure 10: alternative design Modular UHPFRC Bridge

9. CONCLUSIONS

Several statements can be concluded from this project:

- It is feasible from an economical point of view to build a bridge, which is up to 30 m long and 5 m wide, and it is still assembled from two small moulds (handrail and plate);
- Slenderness 1/60 L is achievable;
- The calculations, which were performed by FDN Engineering, including derived material properties, are correct;
- The combination of traditional reinforcement and post-tensioning leads to the optimal structures;
- A lifetime of 100 years is guaranteed if coverage is a minimum of 10mm; however practically, 15mm is recommended;
- The applied concrete has showed self-compacting properties, however, more research is needed in the area of shrinkage behaviour and influence of fibre orientation;
- The casting of concrete is relatively easy to execute with flex-shaft vibrators, but a high frequency vibration table is recommended;
- There are no problems occurring during post-tensioning. No damage was observed due to the applied tensional force. The problems in connections between the adjacent parts are not expected, if the contact surfaces are properly treated and a high-quality adhesive is applied.

The first UHPFRC bridge in the Netherlands was successfully built and installed in Rotterdam. A unique appearance of the handrails evokes interest and brings something novel to the neighbourhood.

INFORMATIONS

For more information about the maintenance-free modular UHPFRC bridges, contact us at: info@fdn-engineering.nl or go to www.ultrabridges.com

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