FULL UHPFRC C200 PEDESTRIAN BRIDGE IN EINDHOVEN, THE NETHERLANDS

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Abstract

A new single-span pedestrian bridge from Ultra-High Performance Fibre-Reinforced Concrete (UHPFRC) has been built in Eindhoven, The Netherlands. The architectural and structural bridge design is unique and innovative. UHPFRC has excellent properties, which enables to design a light, durable and maintenance-free structure. Demand for a light-weight bridge was the key requirement in this case. The footbridge, crossing a water channel, has a span of 21.4 m and it is 3.8 m wide. The bowed bridge deck is built up from five curved pre-cast elements, which are post-tensioned together by internal tendons. The deck has a cross section of a hollow box girder. The total height of the girder is only 0.4 m, which results in a large slenderness of 1/54. The side walls of the girder are inclined in such a way that the bridge appears even more slender from the side-view. The thickness of the top deck is only 80 mm. The railing elements are cast separately and fixed later on to the deck. The railing has a bionic shape with 50 mm thick struts. The minimal concrete class of the deck is C170/200. In order to fully exploit advantages of UHPFRC, both steel fibres and traditional reinforcing bars are applied.

Keywords: Bridge Engineering, Design, Dynamics, Girder box, Steel fibres, UHPFRC

1 Introduction

During last few years the Ultra-High Performance Fibre-Reinforced Concrete (UHPFRC) has become more recognized and respected as a building material in The Netherlands. Several architectural and engineering companies have become aware of a great potential for this material, which would bring new possibilities into the current design practice and fill in the gap in the civil engineering market. Increasing demand for new durable, sustainable and architectural pedestrian bridges is one of the key opportunities for UHPFRC. FDN spotted this opportunity already eight years ago, when the first pedestrian bridge was developed and later successfully built in Rotterdam. In May 2015 FDN completed a new pedestrian bridge for city of Eindhoven, The Netherlands. This project is a perfect example in the sense that UHPFRC is fully competitive with other building materials such as steel, timber or composite. The proposed variant of the bridge with UHPFRC won the public tender thanks to its exceptional properties and attractive design.

This paper describes the innovative pedestrian bridge made from UHPFRC, which has been designed and built by FDN. This paper aims to provide an insight into use of UHPFRC in an existing project – from theoretical calculation up to practical issues such as production and testing.

2 Bridge description

2.1 General concept

The new footbridge, also called bridge “Zwaaikom” has been built in a future residential area, where the architectural and structural design must respects the surroundings and create no aesthetical disturbances. Significant durability, no maintenance costs and low weight of the bridge deck are other prior demands. The UHPFRC fully satisfies these architectural and structural requirements. The bridge is relatively light (55 tons whole deck), which enables easy removal by a mobile crane. The grace of lightness is enhanced with a slender-looking shape and creamy-beige colour of concrete.

Fig. 1 Pedestrian bridge Zwaaikom, built in Eindhoven, The Netherlands – 3D visualisation

2.2 Deck

The footbridge, crossing a water channel, has a total length of 22.1 m, span 21.4 m and it is 3.8 m wide. The bridge deck is built from five pre-cast elements; each with length of 4.4 m. These elements are later positioned against each other and post-tensioned by five bonded strands. The deck is in the shape of a circular bow with a constant radius and cross-section is a hollow box girder. The total height of the girder is only 0.4 m. This small height results into slenderness around 1/55. The corresponding bridges from standard concrete have slenderness around 1/40. The side walls of the girder are inclined towards each other under the angle of 25°. The thickness of the girder side walls is 100 mm. The thickness of the top deck is only 80 mm and it is supposed to carry load from 12-t vehicle.

The whole deck is reinforced both by steel fibres and classical reinforcing bars. Only this combination of bars and fibres utilize UHPFRC the most in terms of ductility, because brittle behaviour would lead both to micro-cracking and large-scale cracking. The reinforcement ratio in the deck is relatively large. One can see the deck as a cage made from steel bars, which is covered by concrete.

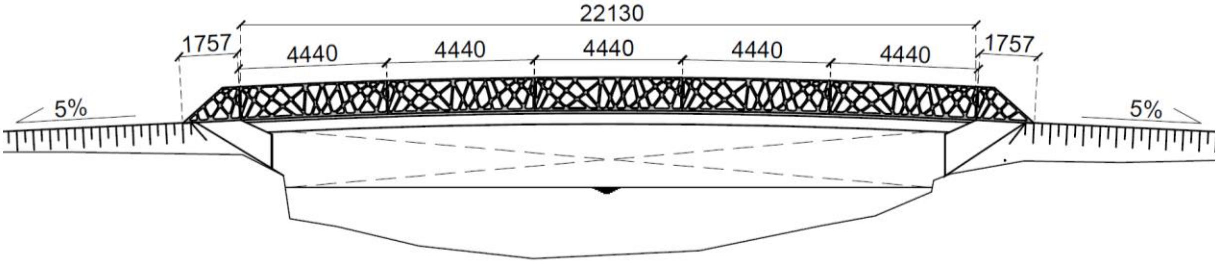

Fig. 2 Side view of the bridge

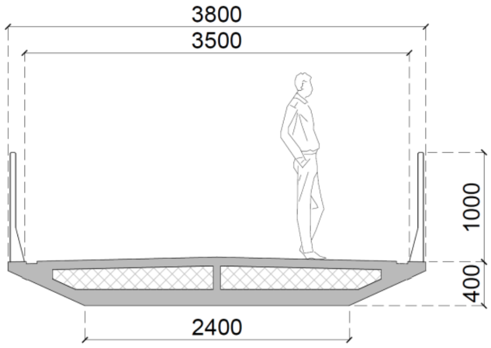

Fig. 3 Cross-section of the bridge deck. The rib in the middle of the cross-section does not have a structural function. It is just for better control of concrete pouring in the bottom slab.

2.3 Post-tensioning

The bridge deck is post-tensioned by five bonded strands. Each strand has 13 wires. Relatively large pre-stressing force has been applied. The cross-section is under compression of 17 MPa. The anchor systems are same at the both ends of the deck. Active pre-stressing is carried out only at one end of the bridge. Due to the large slenderness of the bridge, special attention must be paid in design of splitting reinforcement. The size of the duct determines thickness of the bottom slab. Additional reinforcement is applied in the bottom slab against pull out of the ducts from concrete since cover of duct sheet is only 30mm. Relatively large autogenous and drying shrinkage ($\varepsilon_a = 550$ µm/m; $\varepsilon_a = 150$ µm/m; $t = \infty$) has been considered for pre-stressing loses.

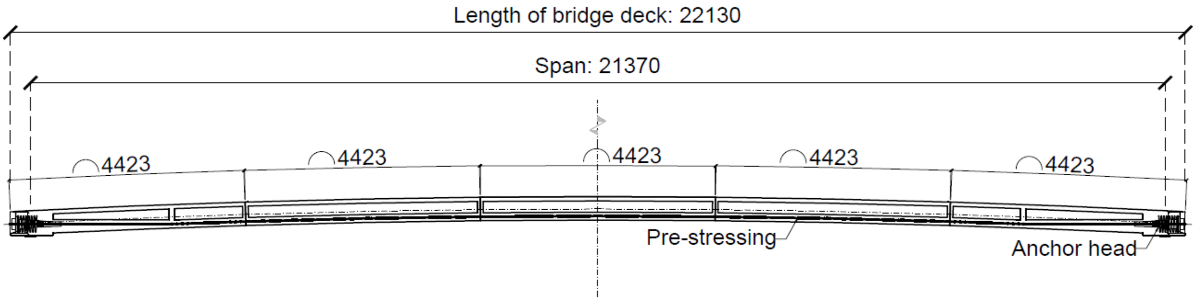

Fig. 4 Layout of pre-stressing ducts in the bridge deck

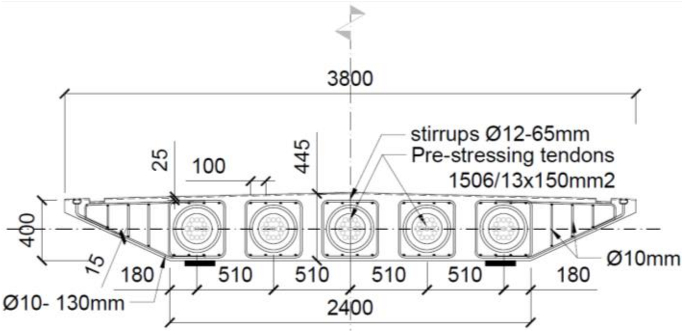

Fig. 5 Cross-section of the end beam with anchorage for pre-stressing system.

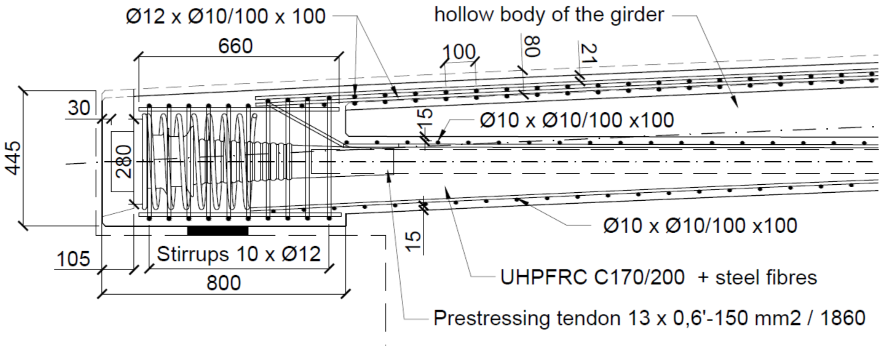

Fig. 6 Longitudinal cross-section of the anchor head. Standard reinforcement together with steel fibres have been used in the whole deck.

2.4 Railing

The railing elements are also made from UHPFRC C170/200. Elements are cast separately and fixed later on already post-tensioned deck. The railing does not contribute to overall carrying capacity of the bridge, but must withstand certain vandalism. The railing has a bionic shape and struts are randomly distributed. Thanks to the high strength of the concrete, the struts are only 50 mm thick. Each strut is reinforced with a steel bar. The railing is attached to the deck by a special rail anchor system. The rails are pre-cast into the deck. In addition a special lighting system is attached and installed onto to the railing.

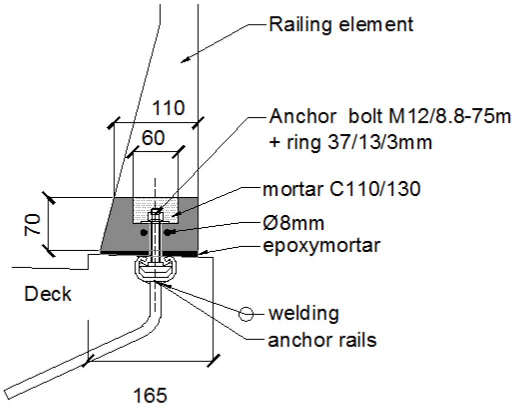

Fig. 7 Detail of connection between railing and deck.

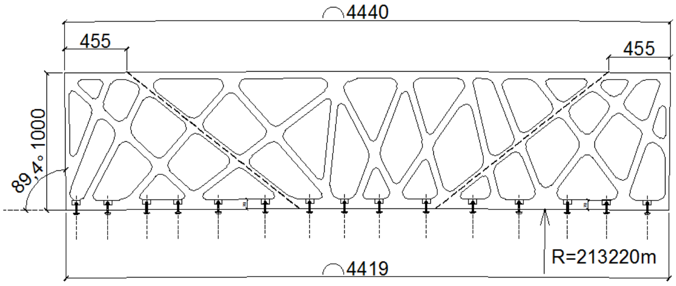

Fig. 8 Standard railing element – side view.

2.5 Material

The minimal concrete class used for deck is C170/200. It means that minimal compressive cubic strength is 200 N/mm2.The concrete mixture reflects the strength requirements. The high-quality calcinated bauxite has been used as the aggregate. The grain size of the aggregate is in the range 0-6 mm. White Portland cement 52.5 with rapid hardening process has been chosen for the bridge as a binder. The water-cement ratio is very low, around 0.17. The proper hydration and thixotropic behaviour in fresh state is assured by other admixtures and additives such as super-plasticizer and un-hydrated micro-silica. The required colour of the bridge is creamy beige. For this reason a pigment compound must be applied into the admixture. The pigment should not decrease the final strength of the concrete significantly. The amount of the pigment should thus not be larger than 5 % of cement content. Satisfactory ductility and tensile strength properties of the concrete are provided by presence of fibres. For this case of the bridge in Eindhoven, straight steel fibres have been used. The length of the fibres is 12 mm and the diameter is 0.4 mm. Convenient alternative to steel is application of basalt fibres. Basalt fibres are stronger in tension than steel but their density is very low and price is high. Some issues can be encountered with insufficient bonding stresses between the basalt and concrete. Hence the high-quality fibres are recommended. The basalt fibres should not disperse during mixing and pouring process. The volumetric amount of basalt fibres is usually within the range of 3-5 %.

Fig. 9 UHPFRC in fresh state with thixotropic properties (left) and sampling during lab testing (right)

UHPFRC is a building material, which requires special care during its fresh state. Large autogenous shrinkage can cause cracking in the case, when too large segments are cast in time-delayed steps. For this reason, the bridge in Eindhoven has been divided into five smaller elements. The risk of a failure is hence diminished by a better control of casting and mixing. As mentioned before, the material is thixotropic and starts to be workable only under a substantial vibration. It must be hence assured that a vibration table underneath of the mould is installed and several flex-shaft hand vibrators are available during casting.

3 Specifics of design

3.1 Slenderness

The whole bridge is very slender and all slabs and walls of the deck are thin. In contrary, the internal post-tensioning force must be relatively large (13.5 MN in the whole cross-section), because eccentricity of tendons is very small and hence less effective. Large compressive force in combination of slender cross-section can cause some stability issues during initial pre-stressing of the elements. Large precision during production process must be assured. In addition, design of the anchor system and ducts must respect limited space in the structure. Large splitting, bursting and buckling forces must be carefully verified.

3.2 Dynamics

The natural frequency of the bridge is only 2.29 Hz. This value belongs to the critical range for pedestrian and joggers, who can step on the bridge with the same frequency and cause unintended vertical vibration. Hence more detailed calculation is necessary to be carried out. Realistic boundary load conditions (pedestrian density, number of joggers, comfort level or maximal accelerations) have to be set up and agreed with client at first. This step is essential since many codes and recommendations are too general or too conservative and do not reflect the reality. More detailed calculation required cooperation with TU Delft students. The ongoing study has focused on several methods of calculations and gave more accurate insight into the problem. The most common methods such as SDOF and Response spectra method seems to be still conservative since they are based on non-realistic loading conditions and simplified structural properties. The dynamic calculation has been hence completed with additional differential equations, which describe boundary conditions more precisely. The whole calculation was also supported by a probability study, which investigates chance of load occurrence and its consequent structural response.

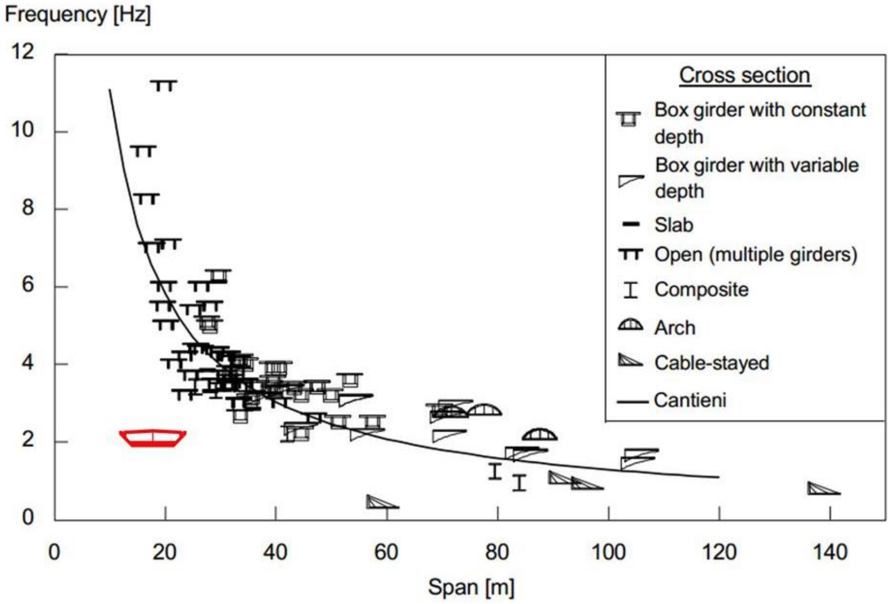

Fig. 10 Comparison of natural frequencies between the’’Zwaaikom’’ bridge from UHPFRC and existing bridges with various cross-sections. It can be derived that the bridges from UHPFRC have lower natural frequency and shift the averaging curve downwards. [5]

Mathematical description of the case when pedestrians and joggers go over the bridge has been generally expressed by the following equation:

$$m_n\ddot{q}_n(t)+c_n\dot{q}_n(t)+k_nq_n(t)=\left(P\sin(\Omega t)\sin\left(\frac{n\pi}{L}vt\right)\right)[H(t)-H(t-L/v)]$$

The left side of the equation describes the structural conditions such as modal mass (m_n) or modal damping (c_n) per its eigen mode. The right side express the loading on the bridge where loads from pedestrians/joggers are described by a harmonic function in combination with Heaviside function (*H(t)*).

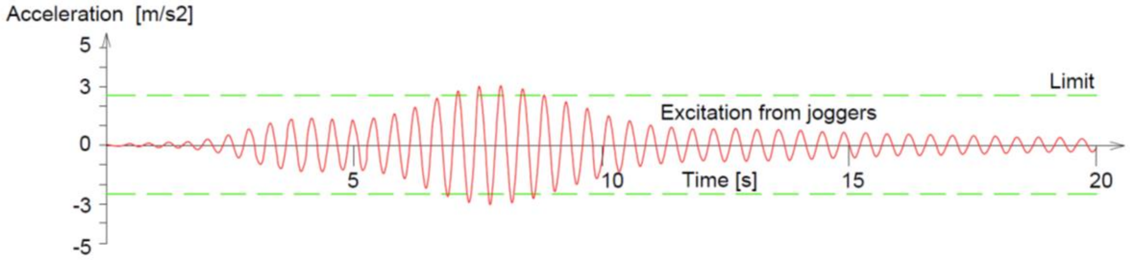

Fig. 11 An example of dynamic response of the structure to 37 joggers running over the bridge

3.3 Lack of guidelines

Design of this bridge has been partly affected by the fact that there is still a deficiency of understandable and reliable codes and recommendations for UHPFRC. For this reason, design of the bridge tends to be rather conservative in some aspects. For example cracking in UHPFRC has not been fully described and accepted into practical guidelines. This is also the issue in the design of “Zwaaikom” bridge. It is considered that the whole cross-section of the deck is in compression in any time during any loading case. This assumption makes the bridge very durable, but on the other hand design becomes more conservative. Tensional transversal stresses in the top deck have been solved similarly as in the case of standard concrete. The maximal stresses in tensional bars in relation to maximal crack width have been limited in the same manner as it is stated in EN 1992-1-1. As for the calculation of bending capacity of a cross-section in ULS, the contribution of steel fibres in tensional zone of concrete was disregarded and distribution of stresses in compressive zone has been assumed linear, without any plastic redistribution. Due to relative brittle properties of UHPFRC, the maximal strain has been considered around 0.2 %. The negative impact of random fibre orientation can effect tensile strength of concrete. This has been considered by so-called factor K, which distinguishes global and local effects of stresses. For the case of the bridge in Eindhoven, global factor K=1.75 has been considered for the whole calculation.

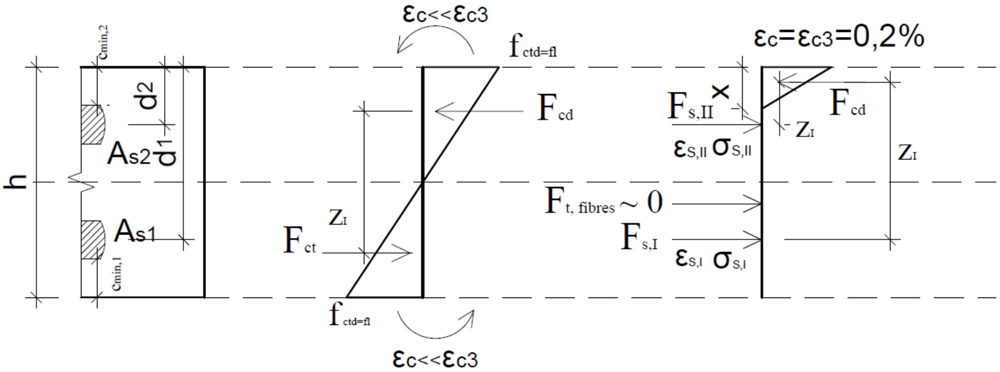

Fig. 12 Calculation of moment resistance of top slab and related assumptions is made for UHPFRC. The redistribution of stresses in the left figure corresponds with un-cracked cross-section. The figure on right is cracked cross-section.

3.4 Computer modelling

Several computer models have been carried for simulation both global behaviour of the bridge and local affects such as splitting stresses around anchor head or stress distribution around the wheel of maintenance vehicle. The whole bridge deck has been simulated by two models. One consists of 1D elements and the second one from 2D elements. Material properties had to be additionally setup since programs do not calculate with UHPFRC.

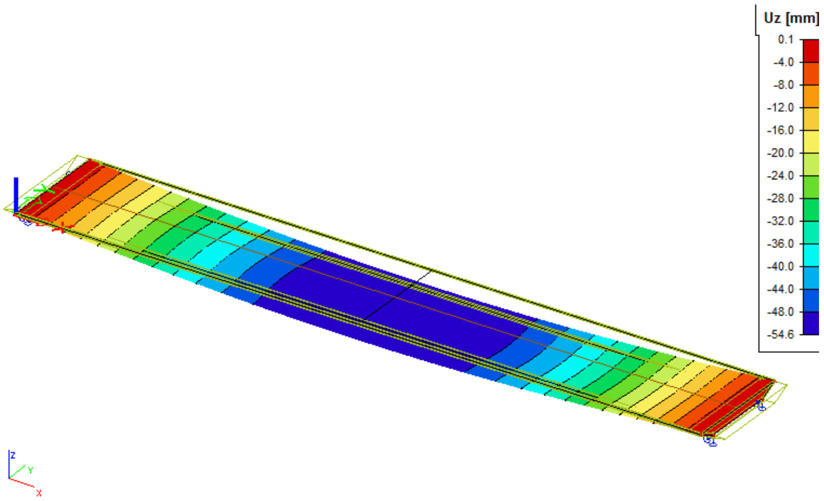

Fig. 13 Vertical deformation of the bridge deck under uniformly distributed load according to EN-1991-2.

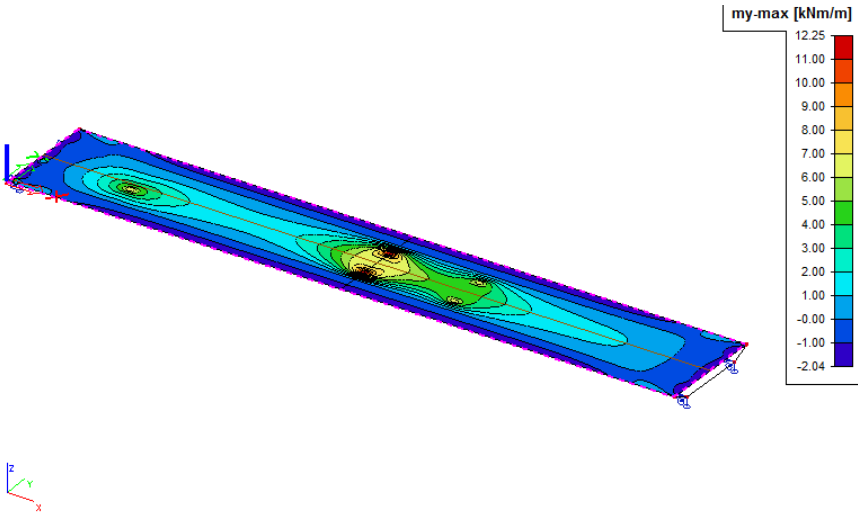

Fig. 14 Moment distribution in the top deck under the load combination envelope with the maintenance vehicle.

4 Production

4.1 Production of the deck

The bridge deck consists of five closed prefabricated elements, which are later positioned against each other and post-tensioned by bonded pre-stressing system. There are three identical intermediate elements and two end-elements with a solid end-beam for the anchor heads. Because the bridge is in the shape of a circular bow and curvature is constant over the whole length of the deck. Hence only one wooden mould is necessary.

A large vibration table is installed underneath the mould. Vibration of this table assures proper workability of the fresh concrete. Each element has been cast horizontally at once in order to avoid “cold connection” in concrete, which could lead to development of unwanted stresses. The whole element is cast up-side down. One of the reasons is better control of the concrete flow between the pre-stressing ducts. The second reason is that profiled rubber pads can be placed on the bottom of the mould. The pads will make an anti-slippery pattern on the top surface of the bridge deck.

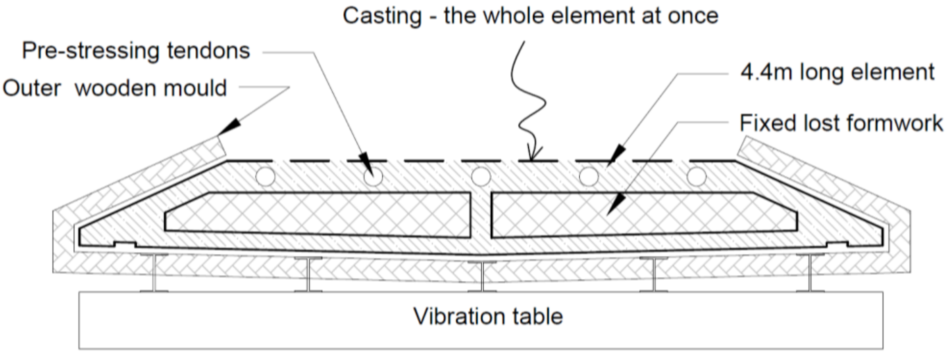

Fig. 15 Setup for casting of one deck element. The rib in the middle of cross-section does not have any structural function. It only allows better control of casting of the bottom slab.

Hardening process is very fast. Time between the mixing and pouring into a mould should not take longer than 20-30 min. The choice of production place is hence essential. Furthermore temperature at production place should not exceed 30°C otherwise more precautions must be made in order to avoid excessive cracking at surface. Volume of one batch is usually also limited. It depends on local conditions and production facilities. The concrete is usually poured from a container from the height around one meter. The larger height of container gives better compaction of concrete. The orientation of fibres is random and no special attention has been made to assure homogenous distribution. The bridge in Eindhoven has been produced without any thermal treatment. Only top surface of concrete should be sprayed by convenient compound and covered by a plastic sheet right after casting.

4.2 Production of the railing

The railing elements are made also from UHPFRC C170/200, and will be cast simultaneously with the deck elements. The complexity of the shape and slender struts demands large amount of work. The master railing mould is made from wood. The holes between the struts are filled with polystyrene blocks, which are nailed to the wooden mould. Because of the complex shape of the holes, an automatic computer-added trimming system must be adopted for the production of PS blocks. Several vibration engines are assumed to be attached to the mould. The proper vibration is necessary after every casting. No hand vibration is allowed.

5 Testing

Due to lack of relevant codes and recommendations regarding design with UHPFRC, additional testing has been necessary for this project. Both testing of material in a laboratory and full-scale tests of the whole bridge have been demanded by client. The material testing has been carried out both by concrete producer and independent research institute. The scope of testing was partly limited, because the similar concrete mixture has been already verified by FDN’s supplier and experienced in previous project. The main attention has been paid on final colour of concrete because the aim was to reach creamy beige shades.

The full-scale tests are supposed to check deflection of the bridge deck due to uniformly distributed load UDL 5.0 kN/m2. It is common practice, that this load is multiplied by safety factor 1.2. The UDL is usually simulated by water containers resting on the top of the deck. The dynamic response can be measured precisely by relevant devices or simply by a crowd of people with unfavourable step frequency. Cracking of the bridge components is not allowed during any type of testing.

6 Conclusion

This project has shown that UHPFRC is a fully feasible material for small up to medium size pedestrian bridges both from structural, environmental and economic point of view. The initial costs were comparable to the options with other building materials. Exceptional durability properties and low maintenance of UHPFRC makes this material even more profitable. It seems that prefabrication is the most effective way of building from UHPFRC in terms of costs. Smaller elements diminish the risk of production failure and the repetition suppresses the costs down.

UHPFRC enables to design pedestrian bridges with larger slenderness, which can be between 1/50-1/60L. The combination of traditional reinforcement and basalt or steel fibres leads to an optimal design. Density of fresh UHPFRC is large, but under proper vibration it performs self-compacting properties. Hence the casting of elements with a complex shape is not the essential problem. The heat treatment of fresh concrete is not always necessary. Although moderate temperature conditions during casting should be present.

This type of bridge is still unique in Netherlands. Lack of official and understandable codes and recommendation discourage engineers to consider UHPFRC in their designs. This bridge in Eindhoven pushes this distrust backwards and brings UHPFRC steadily on the stage.

Information

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

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