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The strongest UHPC bridge in the Netherlands

Durable pedestrian bridges have become one of the most important applications of ultra-high performance concrete (UHPC) in the Netherlands. In 2015 FDN engineering designed and built an UHPC pedestrian bridge called 'Zwaaikom', over a water channel in the city of Eindhoven, The Netherlands. This project has shown that UHPC can be competitive with other materials such as timber or composite for this specific application. The proposed bridge won an open tender thanks to its exceptional durability and attractive architecture, which fits into the surrounding.

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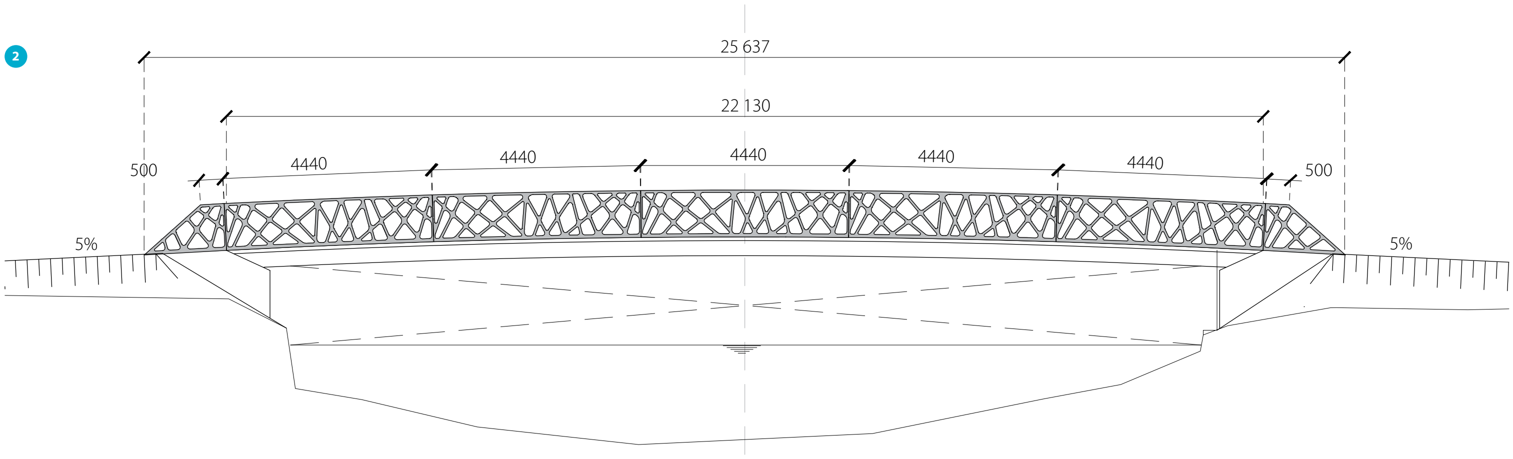
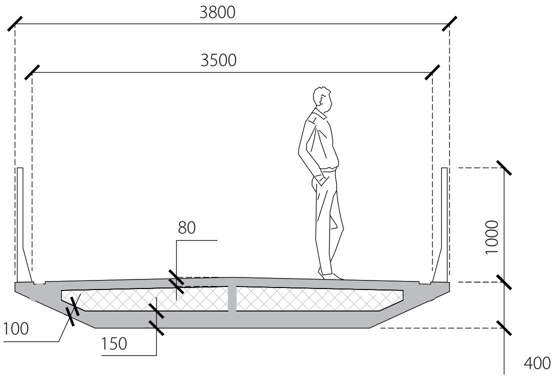


1 UHPC pedestrian bridge 'Zwaaikom' in Eindhoven
2 Side view of the bridge
3 Cross section of the bridge deck
4 Longitudinal cross section of the anchor head

Design

The bridge, fully made of ultra-high performance concrete (UHPC) C175/190 class, has a total length of 25.60 m, a clear span of 21.40 m and a total width of 3.80 m. The bridge deck is only 400 mm high. This corresponds with the slenderness of 1/55.
The cross-section of the bridge with a hollow girder box can be seen in figure 2. The hollow part is filled with polystyrene, which was used as a lost formwork during the production process. The average thickness of the cross-sectional walls is around 100 mm. 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.

Apart from having compressive strength higher than 175 MPa, UHPC contained steel fibres which made it very ductile. In order to fully utilize advantages of its high compressive strength, beside traditional reinforcement, pre-stressing is applied.
The bridge deck was post-tensioned with five tendons (photo 12), each with 13 strands. The cross-section is hence subjected to the relative large compressive force (around 13 500 kN) resulting in large stresses (around 17 MPa). In order to accommodate the anchor system and withstand large splitting forces, a solid end beam was designed at both ends.
Additional reinforcement was applied in the bottom slab to avoid pull out of the ducts from concrete since the cover of the duct was only 30 mm.



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The railing elements were also made from UHPC, with a cubic compressive strength of 150 MPa. The railing has a bionic form with randomly distributed struts. (fig. 6). The railing does not contribute to the general load bearing capacity of the bridge, but it must still withstand several loads. Thanks to the high strength of the concrete, the railing struts are only 50 mm thick. The anchor bolt rails have a zinc protection against the corrosion.

Material

The concrete mixture contains large amount of binder (white Portland cement 52.5 with a rapid hardening process) and a high-quality calcinated aggregate (bauxite), with a grain size 0-6 mm. The water-cement ratio was 0.17. The proper hydration and thixotropic behaviour in the fresh state was assured by additives such as super-plasticizer and un-hydrated micro-silica.

The biggest challenge was to reach the required creamy-beige colour of the concrete, because the natural colour of the UHPC is dark grey. This was This was achieved by using a combination of white Portland cement, microsilica and a corresponding mixture of the pigments. Therefore, an additional experiment-

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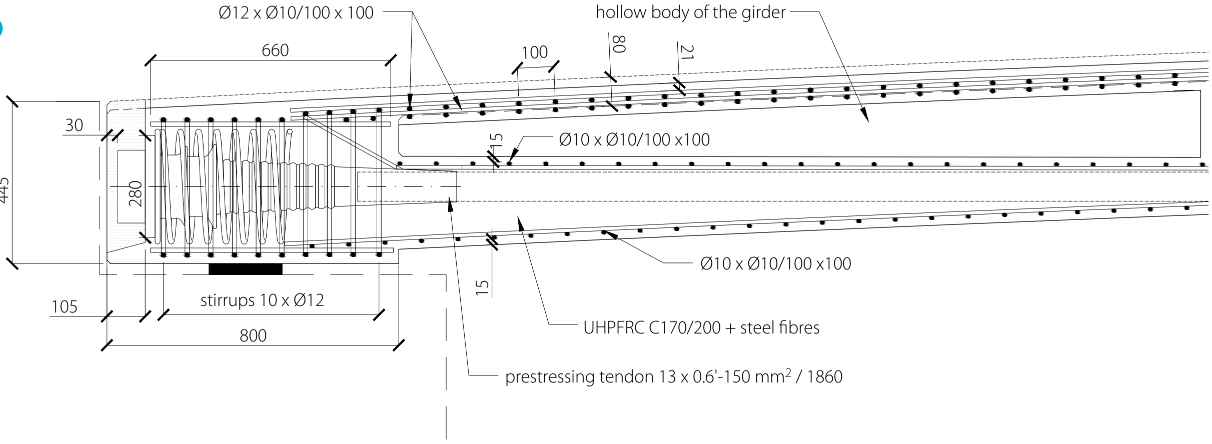
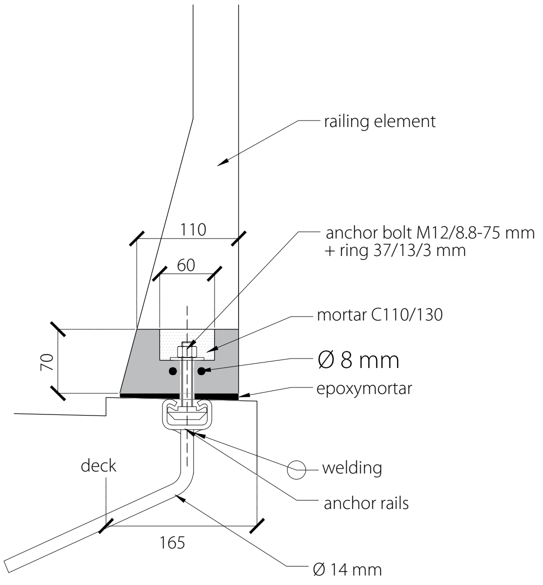


5 Detail of connection between railing and deck
6 Standard railing element – side view
7 An example of a dynamic response of the structure, based on calculation, to 37 joggers running over the bridge [4]
8 Calculation model for determining of the bending capacity in ULS. The distribution of stresses in the figure corresponds with an un-cracked and cracked cross-section (from left to right) [1]



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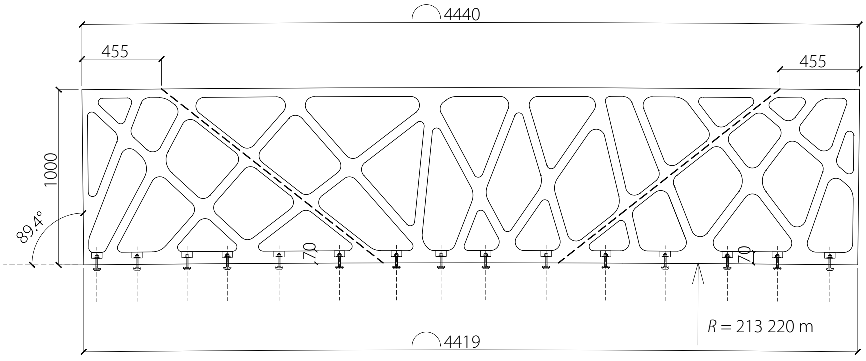

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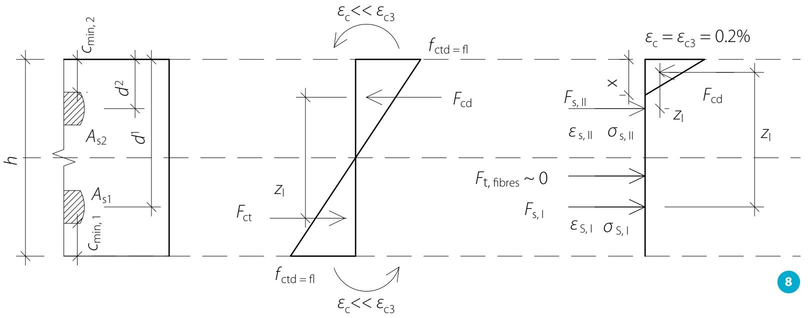
ing with these materials was necessary. The pigment tends to reduce the final strength of the concrete. Hence the designed amount of the pigment was lower than 5 % of the cement content.

In order to reach a satisfactory ductility and tensile strength of concrete, 200 kg/m³ of straight steel fibres with tensile strength of 2000 MPa have been used. The length of the fibres is 12 mm and the diameter is 0.4 mm.



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Dynamics

The natural frequency of the bridge is only 2.29 Hz. This value lies in the critical range for pedestrian and joggers, who can move on the bridge with the same frequency and cause unintended vertical vibration (fig. 7). Hence a detailed calculation had to be carried out. The most common methods such as SDOF and Response spectra method seemed to be still conservative since they are based on non-realistic loading conditions and simplified structural properties. The dynamic calculation was hence completed with additional differential equations, which described boundary conditions more precisely. The whole calculation was also supported by a probability study, which investigated a chance of a load occurrence and its consequent structural response.

Guidelines and calculation methods

Design of this bridge has been partly affected by deficiency of understandable and reliable codes and recommendations for UHPC. The applied calculation has been primarily based on combination of French recommendations AFGC-SETRA [3] and experience, which FDN gained from the previous project. Furthermore several small and full-scale tests had to be carried out in order to give a guarantee to the client.

Due to lack of guidelines, the design of the bridge has been rather conservative in some aspects. For example it was assumed that the whole cross-section of the deck must be in compression anytime during any load case both for SLS and ULS. Tensional stresses in transversal direction in the top deck have been dealt with in a similar way as in standard concrete.

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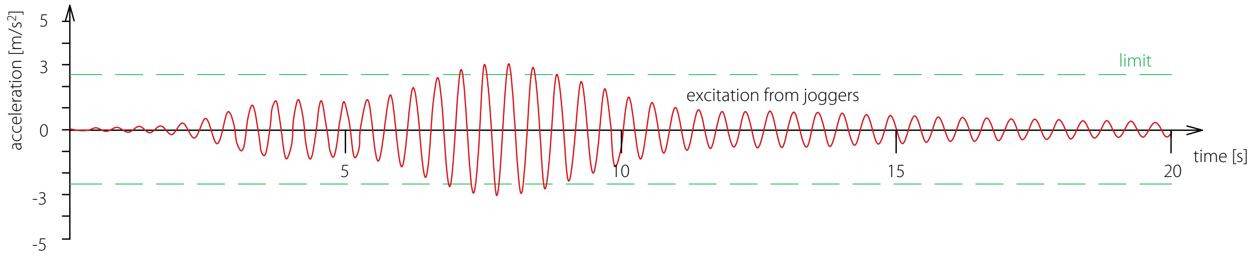

9 Output from a computer model: Vertical deformation in SLS of the bridge deck under uniformly distributed load according to EN-1991-2 [2]

10 Output from a computer model: Moment distribution in ULS in the top deck under the load combination envelope with a maintenance vehicle [2]

11 Setup for casting of one deck element. The rib in the middle ensures better control of casting of the bottom slab

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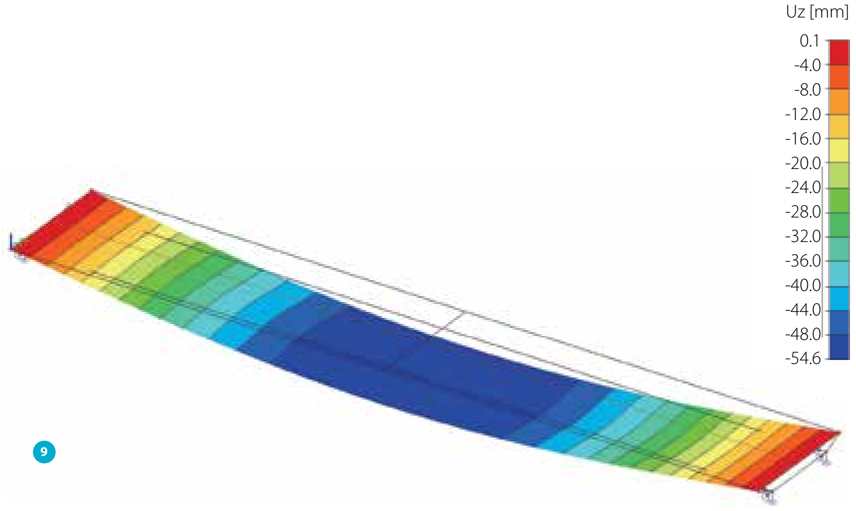

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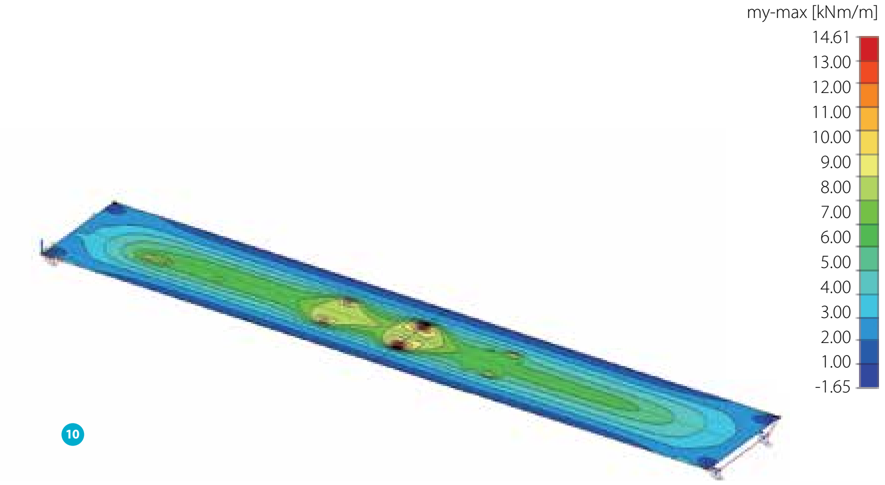

The maximal allowed tensile stresses in reinforcement in the relation to a maximal crack width has been assessed according to EN 1992-1-1. As for the calculation of bending capacity of a cross-section in ULS, the contribution of steel fibres in tensional zone of concrete was disregarded and distribution of stresses in compressive zone has been assumed linearly, without any plastic redistribution. Due to relative brittle properties of UHPC, the maximal compressive strain, ε_c, has been limited to 0.2% (fig. 8). The random fibre orientation can negatively affect 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 adopted for the whole calculation.

Production

The bowed bridge deck consists of five prefabricated elements. Each deck elements was cast separately up-side down in order to control the concrete flow and to get a profiled surface of the bridge deck against the slippage (fig. 11). A proper workability of the fresh concrete was assured by a large vibration table, which was installed underneath the mould.

Due to a large autogenous shrinkage and fast hardening of the concrete, the casting process and curing was carefully considered. Maximum air temperature during production was limited to 25°C. The concrete was delivered in containers in several batches for each element. The pouring was performed from a height of minimal one meter in order to get a better compaction of concrete. The orientation of fibres is random and no special attention was paid to assure a homogenous distribution. After approximately two days, the sides of the mould were dismantled and the element was taken out. The elements did not undergo any thermal treatment. Only the top surface of concrete was sprayed by a convenient curing compound and covered by a plastic sheet for few days after casting.

After four weeks of hardening time, the deck elements were positioned against each other and fully post-tensioned (photo 12 and 13). No shear lock was used between the elements. The interfaces of the elements were only roughened with a special hammer and a layer of high-strength mortar was applied on both sides of every adjacent element, just before the post-tensioning. The mortar prevented stress concentration at the interfaces.

The UHPC railing elements were produced separately. A horizontal wooden mould was used. The problem to cast the complex shape of openings between the railing struts was solved by polystyrene blocks, which were made by a computer-added trimmer. Proper vibration was necessary after each casting. After post-tensioning of the deck, the elements were fixed by a special anchor system, which was cast into the deck elements (fig. 5).

The whole bridge was transported in one piece to its final location.

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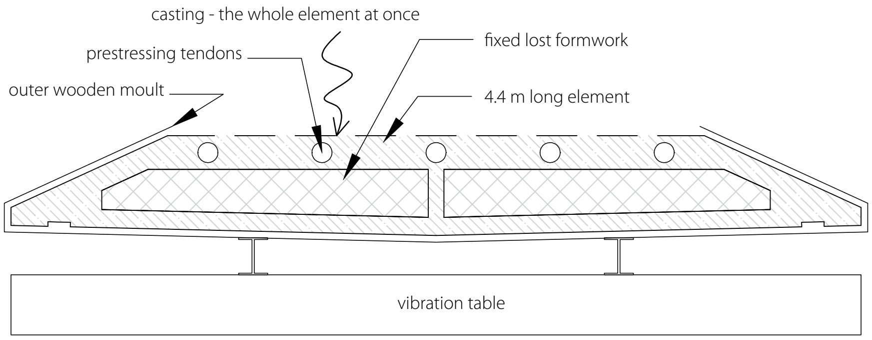

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12 Post-tensioning of the bridge-deck elements

13 Detail of a connection between two adjacent elements

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Testing

Due to lack of relevant guidelines for UHPC, additional testing was necessary. Both testing of material in a laboratory and full-scale tests of the whole bridge were demanded by the client. The full-scale test was performed at the production yard in order to check vertical deflection of the whole bridge. The uniformly distributed load of 4.3 kN/m^2 was simulated by water containers and concrete blocks, which were placed on the bridge deck. The measured deflection proved the theoretical calculation and showed that the bridge is safe. ☒

Conclusion

This project has shown that UHPC is a convenient material for small and medium-sized prefabricated pedestrian bridges and can compete in public tenders. Thanks to its high strength and durable properties, the bridge has an attractive design. Slender and light elements enable easy manipulation during the production process. Large durability of UHPC gives an indubitable advantage in terms of maintenance and life span. For these reasons UHPC can be considered as a serious competitor with other traditional materials such as timber or steel.

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4 Beers, F., Buur, M. (2014). Dynamische berekening Zwaaikom – Dynamics of Zwaaikom bridge, Amsterdam, The Netherlands.