# EXPERIENCE WITH UHPFRC APPLICATIONS IN THE CZECH REPUBLIC

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**Abstract**

The authors have been involved in research and development of ultra-high performance concrete (UHPC) and its applications for precast members in the Czech Republic since 2010. Other partners in the research team are Klokner Institute of the Czech Technical University in Prague, contractors (Skanska CZ and Metrostav) and a supplier (BASF). Local materials are preferably used, the main concern is given to durability, sustainability aspects and competitiveness of structures in life-cycle assessment. The experience from this research has been utilized for the design and implementation of several bridges in the Czech Republic. The cable-stayed footbridge over the Labe in Celakovice, as the most significant achievement, is described in detail. This research and development led to the draft proposal of the recommendations for the material specifications, design, testing and execution of precast structures made of UHPC in the Czech Republic.

**Résumé**

Les auteurs ont été impliqués dans la recherche et le développement du béton fibré à ultra-hautes performances (BFUP) et ses applications dans des éléments préfabriqués en République Tchèque depuis 2010. Les autres partenaires de la recherche sont l’Institut Klokner de l’université technique Tchèque à Prague, des entreprises (Skanska CZ et Metrostav) et un fournisseur (BASF). La préférence est donnée à l’utilisation de matériaux locaux, et la priorité aux questions de durabilité, d’empreinte environnementale et de compétitivité des ouvrages évaluée sur l’ensemble de leur cycle de vie. Les acquis de cette recherche ont été appliqués à la conception et à la réalisation de plusieurs ponts en République Tchèque. La passerelle haubanée sur la rivière Labe à Celakovice, réalisation la plus importante, est décrite en détail. Cette recherche a conduit à un projet de recommandations pour la spécification du matériau, le calcul, les essais et l’exécution des structures préfabriquées en BFUP en République Tchèque.

# 1. INTRODUCTION

In the Czech Republic the research and development of UHPC was commenced concurrently by two contracting companies Skanska CZ, a.s. and Metrostav, a.s. in collaboration with the Klokner Institute and Pontex Ltd. UHPC with an optimum particle packing, low water-cement ratio and randomly distributed short steel fibre reinforcement shows a large potential for demanding light-weight slender structures. Beside a high compressive strength this material has many other advantages. The steel fibres assure small crack distances and a large ductility. The very dense and compact material leads to a low penetration of aggressive environmental agents and that's why high durability is achieved. Due to low maintenance and reasonable life cycle costs this concept improves the sustainability compared to traditional steel or prestressed concrete beams.

# 2. DEVELOPMENT OF PRE-TENSIONED UHPC BEAMS

## 2.1 Pre-tensioned beams for road and railway bridges

Precast pre-tensioned beams are among the most promising UHPC members. Several trial tests of the manufactured UHPC bridge beams took place in the premises of Skanska a.s. between 2010 and 2014 (Fig. 1). Pre-tensioned prestressed UHPC beams have excellent properties in comparison with steel or standard prestressed beams. They resist an aggressive environment, no additional protection is required and they have adequate fire resistance. Although the price of pre-tensioned UHPC beams compared to the conventional reinforced/prestressed concrete beams is higher, they are still clearly beneficial, because the total weight is about half that of RC beams, which saves costs on beam handling and substructure including foundations as they are less robust. Prestressed concrete, UHPC and steel beams for the span of 12 m were compared by structural survey and load test. All 3 types of beam were designed for the same limit load in four point bending by 2 jacks of 170 kN each. The total camber of the UHPC beam (a depth of 400 mm) before the test was about 120 mm, the total deflection was 310 mm and when loads were removed, a remaining deflection of just 15 mm was measured.

Figure 1: Deflection of the pretensioned UHPC beam during testing, an unloaded UHPC beam with upwards camber due to prestressing is nearby

## 2.2 Pre-tensioned beams for footbridges

The Czech Railway Infrastructure Administration is gradually upgrading the rail network for current transport needs, i.e. increased safety, higher speed and better comfort. A new footbridge over the Opatovice creek at the access to the railway station in Ceperka was required in the section Hradec Kralove - Pardubice. The client decided to test and monitor the UHPC beam at this opportunity mainly for long-time behaviour and durability. For the footbridge span of 15.3 m a pre-tensioned thin-webbed "TT" beam was designed instead of the previously considered post-tensioned "T" beam (Fig. 2). The concrete quantity was reduced with the more efficient material from 14 m$^3$ to 4.5 m$^3$ only. Transport and assembling of the light UHPC beam (weight of 13 t) was very easy (Fig. 3), therefore already the investment cost remained the same while future maintenance is expected to be limited and the durability should be better. The design concrete class was C110/130 XF4 however the real concrete strength was C130/150. After this successful implementation several UHPC footbridges are now in the design stage.

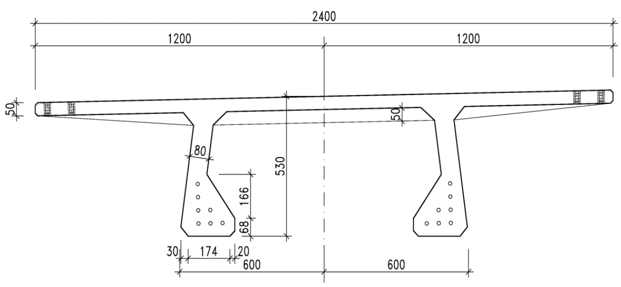



Fig. 2: Cross-section of the UHPC beam

Fig. 3: Installation of the UHPC beam

## 3. UHPC PERMANENT FORMWORK FOR THE BRIDGE COMPOSITE DECK

Bridge slabs of permanent UPHC formwork were manufactured by Skanska CZ a.s. and samples were tested at the Klokner Institute for the project "Reconstruction of the Bridge in Benatky upon the Jizera" in the beginning of the year 2012 (Fig. 4). The bridge slabs were manufactured of UHPC class C110/130 reinforced with dispersed steel fibres. For safety reasons all slabs of the permanent formwork delivered to the site were subjected to the static load test in the manufacturer´s facility. Following the results of the tests it was decided whether a slab can be used on the site. The two following conditions, based on


Fig. 4: Installation of UHPC permanent formwork

fulfilling the requirement regarding the elastic behaviour of the slab under the existing load, had to be met:

(i) Total deflection of the slab after 3 minutes does not exceed the value of 5 mm;

(ii) Irreversible deflection of the slab after unloading does not exceed the value of 1 mm.

Apart from the financial benefit, the project also has a positive environmental impact - due to the use of the formwork slabs it was not necessary to erect any scaffolding or auxiliary supporting structure under the bridge deck. Among another applications tested by Skanska were UHPC columns for anti-noise barriers and UHPC skin for crash barriers.

## 4. CABLE-STAYED FOOTBRIDGE OVER THE LABE IN CELAKOVICE

### 4.1 Structural system of the Celakovice footbridge

The footbridge in Celakovice is connecting the town on the left bank of the Labe River with a popular recreational area on the right bank. It enables comfortable river crossing for pedestrians, cyclists and emergency vehicles. In the tender documents, a cable-stayed footbridge with a composite superstructure consisting of two longitudinal side beams of welded steel profiles, steel cross beams and a concrete slab was designed. The composite slab was designed from precast concrete elements of C110/130 with steel fibre reinforcement, the elements were supported on the bottom flange of the side beams and cross beams. After assembling, all gaps between the slabs and steel beams should be filled with in-situ cast concrete. The contractor proposed an alternative solution of a segmental bridge deck made entirely of concrete C130/150 (for intentionally conservative analysis C110/130 was considered) with steel fibre reinforcement and the arrangement of spans 43 + 156 + 43 m (Fig. 5).

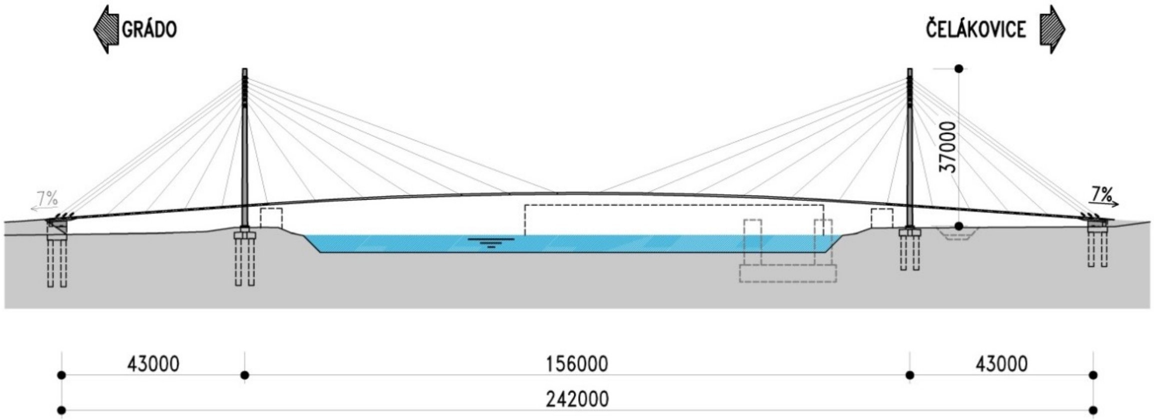



Figure 5: Longitudinal section

Steel pylons with a total height of 37 m are shaped like the letter A and they are fixed on the foundation blocks on in-situ cast piles. Stays are arranged in two planes, the lower adjustable anchorages are located on the side of the deck. The deck is supported by fully locked cable-stays with galvanisation corrosion protection. Abutments on both river banks are massive reinforced concrete blocks on piles that form a counterweight to uplift reactions of the superstructure. The walkable surface of the deck is covered by sprayed waterproofing of a 5mm thickness. The steel railings 1.3 m high have integrated lighting.

In the original tender design, the stays' layout was optimised for the steel longitudinal superstructure with a distances of 11.3 m between the stays and the designer could not increase the number of stays due to tender conditions. Therefore, segments were cast in two steps, the joint between them being reinforced. The segmental joints with a length of 11.3 m were glued with epoxy resin. The stresses in these construction joints proved to be critical for the design, especially during the construction stage, where decompression had to be avoided with a reserve of 1 MPa compression required. A special launching gantry was used for the assembly of the superstructure. A detailed analysis model was prepared including the launching gantry movements, stressing and removal of temporary cables, adjustment of forces in final tendons etc., resulting in approx. 120 stages. The analysis included the effects of nonlinear behaviour of the structure caused by varying stiffness of stays due to their sag.

## 4.2 Development of UHPC

The UHPC was developed by the team of Metrostav and TBG Metrostav from 2010 on both for precast as well as for in situ cast structures. Local materials are used, the size of aggregate is limited to 5 mm and short high strength steel fibres are applied. The experiments started in the laboratory and later they continued in a large mixing plant as the mixing and the type of the mixer has a substantial influence on the properties of the UHPC in the fresh as well as in hardened state. The tests executed on laboratory specimens proved that the compression strength measured on cylinders exceeded 150 MPa, which was the objective of the development. The design required a tensile strength higher than 15 MPa, therefore 160 kg of steel fibres per $m^3$ were used. The developed concrete mix kept its workability for about 90 minutes which allowed to use it for the application of ready-mixed concrete. Tests were also carried out for verification of pouring concrete into the moulds and curing, self-compacting were required. Besides mechanical parameters, like compression and flexural strengths, elastic modulus, etc., the development of heat of hydration, autogenous shrinkage, drying shrinkage and creep were measured on laboratory specimens. The construction of the footbridge over the Labe River was a good opportunity for the first application of UHPC. The experiments were then focused on this project.

Figure 6: Test of the anchorage zone

The footbridge is prestressed and the anchors of the prestressing bars are coupled in the match cast joints. The small space for the anchors required verification of the concrete area under the anchors, which is loaded by concentrated load and transversal tensile stresses. Tests following the recommendations of ETAG 013 were carried out with two alternative solutions (Fig. 6). Specimens of Type 1 were produced without any reinforcement (with exception of fibres), specimens of Type 2 contained moderate reinforcement of stirrups and longitudinal bars. The tests showed that no cracks appeared in the specimens without reinforcement up to the level of 1.4–1.5 of the characteristic prestressing force $F_{pk}$, and up to the level of 1.6–1.7 $F_{pk}$ for specimens with stirrups. Then the load was increased up to the level of about 1.7 to 1.9 $F_{pk}$ without any failure. Such values are far above the realistic load during prestressing works.

The tests were performed on concrete at an age of 5 days. During construction the real segments were much older.

In the longitudinal direction, the footbridge side beams are prestressed and reinforced. In the transversal direction only the ribs of the slab are reinforced by two bars 22 mm in diameter. A small model (Fig. 7) was tested in order to check the load carrying capacity of the slab in transversal direction. The point load was increased up to 110 kN, while the assumed axial load of a light vehicle will only be about 25 kN. The slab failed in bending of the transversal ribs (Fig. 8). The slab remained without any damage (with exception of small cracks) although the point load was located in the middle between the ribs.

Figure 7: Small model of the bridge deck

Figure 8: Bending failure of the ribs

### 4.3 Production of segments

For the production of segments a steel mould was designed and produced. The mould has a fixed bottom part, longitudinal tiltable sideboards and a top cover (Fig. 9). The mould has only one front face, since a match casting is assumed, and the second face is created by the segment which was cast earlier. The segments were cast by halves with a reinforced working joint; the complete standard segment 11.3 m long was then transported to the site. Only one match glued joint could be designed between the two stays.

The mould was equipped with reinforcement, ducts for prestressing bars and tendons and with steel elements for the anchorage of stays. The mould with top cover was filled with fresh UHPC from two truck mixers that flowed into the two openings in the middle of the longitudinal edge beams. The concrete filled the complete mould space. The air was pushed out through the openings in the top cover, which were subsequently closed, the openings also served for the inspection of the casting process. The concrete was transported from the mixing plant of TBG Metrostav, which is about 25 km from the precasting plant that is situated at the river harbour in order to facilitate shipping of segments to the site. The hardening of concrete had to be slowed down. In order to accelerate the production, the segments were heated up to the temperature of 60°C which allowed for demoulding after 7 to 8 hours. Time of the mould releasing was very important due to avoiding early shrinkage cracks. The standard segments could be produced in 2 to 3-day intervals, depending on the weather conditions.

Figure 9: Open steel mould

Figure 10: Punching of the slab

The slab, which is only 60 mm thick and has no reinforcement, seemed to be the weakest element of the footbridge. The slab was loaded by a point load acting on the circular area 200 mm in diameter. The load was increased up to the level of 22 kN and 5 cycles up to the maximum load were completed. Then, the load was increased until failure. The test was repeated 4 times. The first cracks appeared at the level of about 150 to 200 kN, and the failure loads were in the range of 320 to 370 kN. The smaller values were observed at the end of the slab, due to the edge effect and lower stiffness at the end span of the slab. The failure due to punching is illustrated in Fig. 10. The test proved that the load carrying capacity of the slab is much higher than the requirements of the design.

### 4.4 Assembly of the footbridge

After construction of the pile foundations and abutments the steel pylons were erected. The side spans were assembled on the light fixed scaffolding delivered by PERI. The first segment was assembled under the pylon and the others were laid on the scaffolding and then connected to the first segment and post-tensioned by prestressing bars (Fig. 11). The remaining part at the abutment was cast in situ using ordinary concrete.

Fig. 11: Side span on the light scaffolding

Fig. 12: Segment lifting by launching gantry

The main span was assembled with the cantilever method. The segments were transported on pontoons and lifted to the appropriate level by a launching gantry moving on the top of the already completed footbridge. The launching gantry has two main longitudinal beams which are anchored on the footbridge and it forms a cantilever of approximately 12 m long. On the cantilever, a movable frame was installed, which allows longitudinal movement of the lifted segment as well as transversal adjustment. Then the prestressing VSL bars diameter 32 or 36 mm are connected and the segment is moved longitudinally ~ 0.5 m to the last segment. The joint is filled with the epoxy glue and it is closed by moving the frame and by prestressing of the bars.

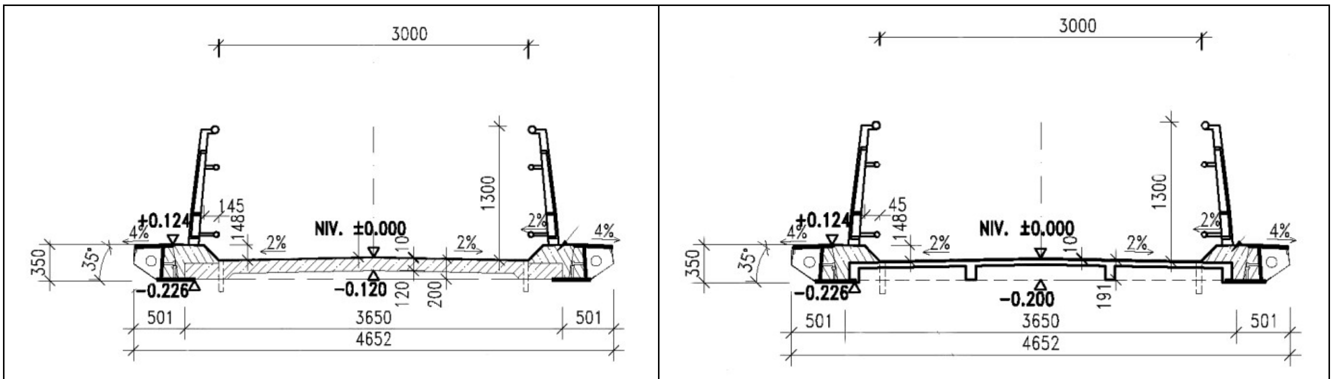
The cantilever of the launching gantry has an auxiliary stay from the pylon, which carries a substantial weight of the lifted segment (Fig. 12). The reaction forces on the pylon were transferred to the abutment by auxiliary back stays. After the bars' prestressing and installation of the final stays, the auxiliary stay was disconnected and the launching gantry moved to the next position.

After the assembly of 7 segments on each side of the river, the middle short segment was lifted and two closing joints were cast in situ. For this operation only one launching gantry was used. It provided a stiff connection between the two cantilevers and allowed for welding the reinforcement. When the closing joints were casted, the longitudinal tendons (2 x 15 strands of 15.7 mm diameter) were prestressed and grouted.

During assembly, the positions of the segments and the forces in stays had to be carefully observed and adjusted when necessary. The measurement of forces in stays caused some problems, since the forces during installation are rather small. The results were evaluated and the actual forces were determined and compared with the assumption of the structural analysis. After completion of the longitudinal prestressing, the dampers of horizontal displacements were assembled at the abutments, which completed the construction works. The bridge was completed in spring 2014 after the winter break.

### 4.5 Environmental assessment of Footbridge Čelákovice

During the tendering stage, 3 conceptual variants of cross-section were thoroughly analysed and later evaluated from the point of initial and life cycle costs and also sustainability aspects (Figs. 14-15). It is clear that the realized footbridge superstructure of UHPC has slightly higher initial costs but with respect to the whole life cycle assessment it is definitely advantageous (Tables 1-2).




Variant V1: Steel + precast panels C45/55 | Variant V2: Steel + UHPC panels

Figure 14: Variants V1 and V2 of the footbridge deck

Input data for the assessment of variants are as follows:

- production of construction steel elements – 14 km to construction site
- production of monolithic concrete and prefab elements – 8 km to site
- life cycle of footbridge – 100 years
- utilization phase – twice repair of surface of ordinary concrete (10 % of surface)
- recycling center 30 km from the construction site

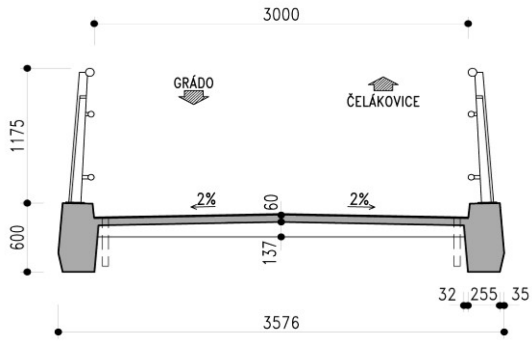



Figure 15: Typical cross-section : Variant 3 - implemented UHPC segments

Table 1: Aggregated data of assessment variants – total life cycle

| CONCRETE_LCA Tool 3.0 CZ | | CONSTRUCTION + UTILIZATION + END OF LIFE = TOTAL | | |
|---|---|---|---|---|
| | | V1 | V2 | V3 |
| Aggregated data of assessment variants | unit | STEEL + C45/55 | STEEL + UHPC | segment UHPC deck |
| consumption of primary raw materials | kg | 1,267,190 | 961,842 | 1,080,912 |
| water consumption | $m^3$ | 1,191 | 1,076 | 1,089 |
| primary energy consumption[1)] | MJ | 9,339,292 | 8,673,962 | 8,244,572 |
| global warming potential \| GWP | kg | 875,845 | 808,263 | 780,107 |
| acidification potential \| AP | g | 5,131,720 | 4,772,345 | 4,474,846 |
| photochemical ozone creation potential \| POCP | g | 205,281 | 190,923 | 178,349 |

Note:
[1)] non-renewable primary energy

Table 2: Final assessment of variants – total life cycle

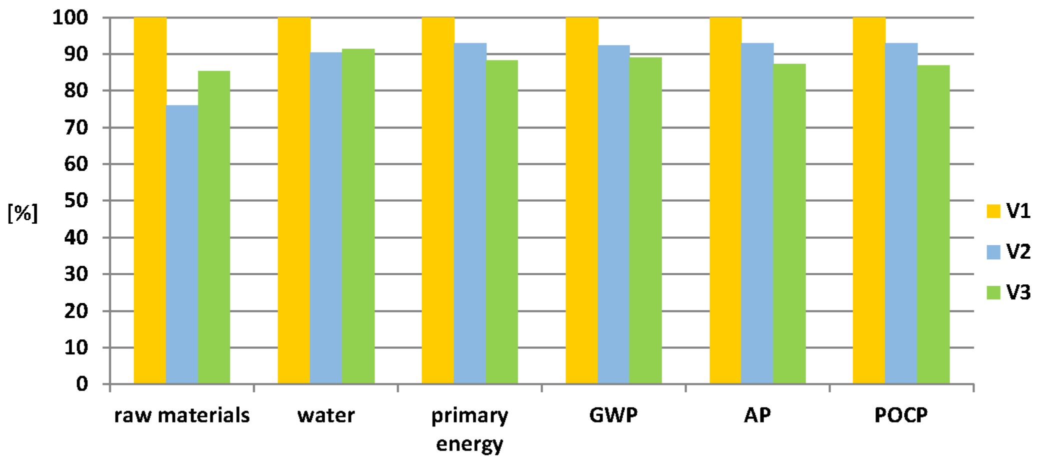


Figure 16: Completed footbridge

| Table 3: Consumption of superstructure materials | TOTAL | PER 1 m2 |
|---|---|---|
| UHPC C130/150 | 126.5 m3 | 0.171 m3 |
| CONCRETE C40/50 | 19.4 m3 | 0.026 m3 |
| REINFORCING STEEL | 12.7 t | 17.1 kg |
| PRESTRESSING STEEL | 17.5 t | 23.6 kg |
| STAYS – REDAELLI LOCKED COIL CABLES | 48 t | 64.7 kg |

## 5. CONCLUSIONS

The footbridge over the Labe River in Čelakovice is the first structure in the Czech Republic with an entire superstructure made of UHPC (Fig. 16, Table 3). The design and the execution of the footbridge were based on experimental experience with the new material. The design of some parts is conservative due to the limited knowledge on the performance of the UHPC. The application of UHPC for the deck resulted in a smaller weight of the footbridge. The stays and pylons are then also rather light. The use of UHPC should guarantee long term durability of the footbridge, with low maintenance required.

The Celakovice footbridge received several national awards and also the 1st place in the ACI Excellence Awards 2015 in the category of infrastructure and 2nd place in the ECSN European Concrete Award 2016 in the category of civil engineering.

Following good practical experience Czech recommendations for the production technology, testing and design of precast structures made of UHPC in the Czech Republic were drafted and later approved by the Ministry of Transport in 2015.

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