New UHPFRC bridges in the Czech Republic

J Marek¹, J Kolisko², P Tej³, D Čítek², J Komanec³, M Kalný³ and L Vráblík⁴

¹KŠ PREFA s.r.o., Jinonická 805/57, 150 00 Praha 5-Košíře, Czech Republic
²Klokner institute, Czech Technical University in Prague, Šolínova 7, 160 00 Praha 6-Dejvice, Czech Republic
³Pontex Consulting Engineers, Ltd., Bezová 1658, 147 00 Praha 4-Braník, Czech Republic
⁴NOVÁK & PARTNER, V Olšinách 2300/75, 100 00 Praha-Strašnice, Czech Republic

E-mail: j.marek@ksprefa.cz

Abstract. This paper deals with new UHPFRC (Ultra High Performance Fibre Reinforced Concrete) bridges produced or constructed in 2018 in the Czech Republic. The paper includes a short description of 3 unique pedestrian bridges with load bearing structure made of UHPFRC and 2 steel bridges over the railway track with lost formwork for bridge decks and cornices made of thin UHPFRC slabs. Focus is given on the testing of the material, comparison of test specimens and summary of results from UHPFRC production in real scale. The size effect of control specimen and the results analysis is given in the last chapter. The 3 mentioned unique pedestrian bridges are Footbridge over the Lubina river in city Příbor, Pedestrian and cycle bridge in the vicinity of Black Bridges in city Tábor and Footbridge over Dřetovice stream in Vrapice - a district of Kladno city. Thin panels as permanent lost formwork for two bridges over the railway tracks are in city Přerov. All new UHPFRC structures should be worthy of attention of bridge experts and community of specialists in the field of concrete engineering.

1. About UHPC

UHPC, Ultra High Performance Concrete, usually reinforced with steel (usually high strength) or polyolefin fibres (PP, PA or PVA), is therefore better named as UHPFRC, (Ultra High Performance Fibre Reinforced Concrete). It is a modern material based on principles similar to normal strength concrete (NSC), but applied in the smaller scale, characterized by its material optimization: fine-grained sand, silica fume, fibres, Portland cement with no large aggregate.

High compressive strength, strain hardening, and extremely low porosity leads to the high durability and very long serviceability of UHPFRC structures.

Many lab researchers are currently working with UHPC [7,8], therefore no more detailed information will be written here about UHPC/UHPFRC composition, its preparation, casting and curing in laboratory conditions with small-scale results.

Used mixture was finally developed in 2017 after several years of research and applied tests in cooperation of KŠ PREFA company and Klokner institute of CTU. The exact design of the mixture cannot be published, but it is quite similar to standard UHPC mixtures.

The details of dosing, batching and curing are business secrets of KŠ PREFA Ltd.
2. Standards
There are no valid (or validated by legislative) normative standards in the Czech Republic concerning UHPC, except three methodical manuals published by Klokner institute of CTU in Prague in 2015 [9-11]. The real scale application of UHPC into the structures of bridges or footbridges brings out many questions about the material properties and production quality controlling and testing, e.g.:

- What is the meaning of usually required compressive strength above 150 MPa?
- Which test specimens should be used?
- How to set up quality control schedule?
- How to describe design mechanical parameters?
- Which test specimens are the best for which structural elements?
- Is the test equipment for standard concrete reliable enough for UHPC?
- In the field of concrete structures, an essential characteristic of UHPFRC structure – size effect – should be taken into account.

3. UHPC production in real industrial scale
For application of UHPC in the real size structures, the very important question is the way of dosing and batching the fresh mixture in volume of thousands of litres and necessary technical equipment. Standard industrial concrete batching plants are not ready for so many components in the mixture, required accuracy of dosing and very tricky mixing with fibres.

After successfully managed mixing, the next step is how to cast the fresh mixture into the mould, keeping in mind that moulds have to be used repeatedly, and the element must be cured all the time from casting to demoulding. Moulding technology from common producers is not prepared for hydrostatic pressure and non-Newtonian fluid behaviour of fresh UHPC with microparticles eager to leak through even the smallest gap.

Lifting and transportation of UHPC elements is very different compared to NSC, because UHPC allows to create thin walls and slabs which are not tested by common industry producers of anchors and devices, and their standards, certification and limitations are out of range for UHPC.

One can think of higher strength of UHPFRC as advantage compared to NSC, but other parts of standardized lifting and transport systems (parts not directly connected to concrete) are designed for NSC, which limits the whole system.

As mentioned above, the transformation of technology from laboratory scale UHPC preparation and mixing to real industrial production is not a fast and easy process. It is a part of technology evolution, involving long period of applied research and testing.

3.1. History of real scale use of UHPC in the Czech Republic
Industrial use of UHPC in bridge structures in the Czech Republic started in 2012 in facility Skanska Štětí with first application of ribbed thin slabs as permanent lost formwork for bridge deck 272-008 near city Benátky nad Jizerou, where the volume of the UHPFRC slab was about 50 litres. Another smaller slabs each about 80 litres were produced at the same place as façade tiles for building in Malmö in Sweden.

Some small elements were casted for the family house façade cladding in village Mokrá-Horákov and a few pieces of safety barriers were created for Prague airport.

One of the largest UHPC precast elements till 2018 were segments for footbridge Čelákovice from 2013, where company Metrostav with its fresh concrete producer TBG casted 3.8 m³ in one step for each segment. Similar volume, ca 4.0 m³ was casted in 2014 in Skanska Štětí, one Pi - beam for footbridge over Opatovický channel in village Čeperka. [1-6, 12-16]

3.2. Real scale use of UHPC in the Czech Republic in 2018
Since 2015, company KŠ PREFA Ltd. have become the successor of Skansa company in the facility Štětí and continued with applied research of UHPC. In cooperation with Klokner institute of CTU in Prague and company Pontex Consulting Engineers the research project supported by Epsilon
programme of Technical Agency of Czech Republic called Service life enhancement and construction speed-up of elements of traffic infrastructure using UHPC is being carried out.

The main goal of the project is the application of UHPC into the real structures and projects of traffic infrastructure.

In first year of the project, 2017, were made necessary adjustments of batching plants and preparation of technology, simultaneously with designs of bridges based on the UHPC technology.

Simultaneously were made many laboratory tests of mixture itself, the results were validated by mixing in the batching plants in factory Štětí, and the mixture was optimized for industrial scale.

Year 2018 became the milestone for industrial use of UHPFRC in bridge engineering in the Czech Republic.

UHPFRC load bearing structures of 3 footbridges were designed and built and thin slabs as lost formwork for the bridge deck and cornices of 2 steel bridges were used.

The importance is given by the fact, that all these projects were part of the open competition, and the solution with structures made of UHPFRC was winner of the designing and bidding process.

In this way the UHPFRC came into the standard business world in structural engineering. In total number more than 70 m³, 175 tons of UHPFRC, were commercially produced in the Czech Republic in 2018.

4. Footbridge over the Lubina river in city Příbor
The load bearing structure of the footbridge is a single span prismatic rectangular beam. Span of almost 36 meters and the height of cross section of 800 mm declares boldness of a structural engineer working with concrete and the ratio 1:45 fulfils the requirement of an architect.

The structure itself is made of 5 elements connected by post tensioned monostrand cables, injected in three channels with parabolic shape.

Connections of the elements were sealed by epoxy mortar, for channels were used special waterproof connectors.

The casting of the elements was preceded by tests of 1.0 and 2.0 m³ for checking and testing of heat of hydration, next pre step was 2 test elements together in volume of one typical element casted simultaneously as a test of batching and casting and test of the mould. In that moment it was the largest UHPFRC casting in CR ever. These elements were used for sealing and cable tensioning test, for testing of the handrail anchoring.

Final 5 elements were created in 4 next weeks, in volumes of 2 x 7.8 + 3 x 5.4 m³.

Architectural design of Petr Tej and Marek Blank was statically proofed by Lukáš Vráblik from Novák & Partner, KŠ PREFA cooperated with Klokner institute of CTU on optimization of the mixture, the creation and assembly of the load bearing structural elements were made by KŠ PREFA. Post tensioning was made by Freyssinet, general constructor was Strabag. Finished footbridge is shown in Fig. 1. Quality control tests were performed, and the results are given in Table 1. The analysis of obtained data is given in the last chapter.

| Table 1. Average results of 28 day control material tests - Footbridge Příbor. |
|-------------------------------------------------|
| Test / Set (Element) | 1       | 2       | 3       | 4       | 5       | Avg. | Unit |
| Young’s Modulus - cylinder 150x300mm           | 49.3    | 49.1    | 49.6    | 47.5    | 47.8    | 48.7 GPa      |
| compressive strength - cylinder 150x300mm     | 140.2   | 139.1   | 145.3   | 140.5   | 137.6   | 140.5 MPa     |
| compressive strength - cube 100x100mm        | 157.3   | 150.0   | 149.6   | 140.6   | 144.1   | 148.32 MPa    |
| compressive strength - cube 150x150mm        | 144.5   | 146.8   | 139.2   | 139.1   | 141.9   | 142.3 MPa     |
| compressive strength - beam 40x40x160mm      | 166.0   | 183.0   | 186.0   | 168.0   | 171.0   | 174.8 MPa     |
| flexural strength - beam 100x100x400mm       | 11.1    | 15.5    | 15.2    | 14.6    | 18.5    | 15.0 MPa      |
| flexural strength - beam 40x40x160mm         | 31.7    | 37.7    | 36.2    | 33.5    | 29.2    | 33.7 MPa      |
5. Pedestrian and cycle bridge in the vicinity of Black Bridges in city Tábor

Presented footbridge creates an essential part of complex of pavements and bike paths over the Budějovická street and its access roads in densely built-up part of the city Tábor.

Footbridge is parallel to the steel railway bridge, in the distance of ca 1.1 m.

Load bearing structure is single span Pi - beam, with height of 0.94 m, width 3.0 m and length of 27.0 m; prefabricated as one prestressed element consisting of 12 m³ of UHPFRC. Bridge deck with thickness of 60 mm is reinforced only by ribs in the distance of 1000 mm. Steel rebars are not used in the deck itself.

Structure is designed according to EN 1991-2 and methodical manual for designing of UHPC structures by Klokner institute of CTU [9-11]. Uniform load caused by crowd of people of 5 kN/m², single load of service vehicle of total weight 3.5 t with dynamic coefficient $\delta = 1.10$ and special vehicle of 12 t are considered.

Figure 2. Pedestrian and cycle bridge in city Tábor - cross section.
Casting of UHPFRC in one step in one element with volume of 12 m$^3$ is unique in Europe.

After casting elements for footbridge in Příbor, gained experience allowed to cast whole load bearing beam for footbridge Tábor in one 2-hour long work.

Detailed preparation, comprehensive planning and on-site testing enabled the casting process without any pause, which was essential to avoid cold joints and to achieve optimal scatter of steel fibres, flawless surface and unexceptionable serviceability and durability of the finished UHPFRC element.

One of the largest UHPFRC elements poured in one take in Europe was successfully created, assembled and put in use of public.

Design of load-bearing structure was made by Jan Komanec and it was statically proofed by his team of bridge engineers from company Pontex Engineers Ltd. KŠ PREFA cooperated with Klokner institute of CTU on optimization of the mixture, the creation, prestressing and assembly of the beam were made by KŠ PREFA in factory Štětí. General constructor was Firesta Ltd. Finished footbridge is shown in Fig. 3. Quality control tests during the production were performed, and the results are given in Table 2. The analysis of obtained data is given in the last chapter.

### Table 2. Average results of 28 day control material tests - Pedestrian and cycle bridge Tábor.

| Test                                      | Avg.  | Unit |
|-------------------------------------------|-------|------|
| Young’s Modulus - cylinder 150x300mm      | 45.6  | GPa  |
| compressive strength - cylinder 150x300mm | 138.0 | MPa  |
| compressive strength - cube 100x100mm     | 135.1 | MPa  |
| compressive strength - cube 150x150mm     | 125.9 | MPa  |
| compressive strength - beam 40x40x160mm   | 160.5 | MPa  |
| flexural strength - beam 100x100x400mm    | 17.9  | MPa  |
| flexural strength - beam 40x40x160mm      | 29.0  | MPa  |

![Figure 3. Pedestrian and cycle bridge Tábor.](image)

6. **Footbridge over Dřetovice stream in Vrapice – a district of Kladno city**

Single span footbridge with unique U-shaped cross section leaps over the stream in two arches, both vertically and horizontally. Beam with its length of 10.5 m, thickness of the walls 40 mm, thickness of the deck from 45 to 55 mm, without any steel rebars or prestressing cables, made this experimental structure a unique bridge in the world scale.
Volume of used UHPFRC ca 1.6 m³ was casted in specially designed mould twice. The first attempt was success in casting but unsuccessful in load testing of whole bridge element. The second attempt was casted with thicker walls and upgraded geometry of wall-deck connection. The second bridge beam successfully accomplished load testing and was assembled in place over the stream. Due to its experimental nature, it was given to the city government as a gift from KŠ PREFA and Klokner institute of CTU. Finished footbridge is shown in Fig. 4.

Figure 4. Footbridge over Dřetovice stream in Vrapice – a district of Kladno city.
7. Bridges over the railway tracks in city Přerov

Both steel bridges are over the railway track Přerov – Bohumín and Česká Třebová – Přerov. General constructor, Strabag, was replacing old steel load-bearing structures of both bridges with new ones. Support structures were repaired.

Bridge deck was casted over the steel crossbeams with NSC, but as the lost formwork were used thin UHPFRC panels, both inside between the main steel girders and outside as sidewalk decks. Thickness of the NSC deck varied from 220 to 400 mm. UHPFRC slabs with thickness of 60 mm covered the distance between steel crossbeams with span ca 1.7 m. For the sidewalk part the NSC deck was 190 mm thick and the UHPFRC slab was 50 mm thick. Assembled slabs before placing the reinforcement of the main deck are shown in Figure 5.

Lost formwork panels for bridge cornices were 1900x600 mm and 50 mm thick.

Before casting of the thin panels, the initial testing of the early age properties of the elements had to be performed. The early loading of the panels is the reason for different control testing schedule, as sufficient safety of 7-day old slabs had to be proven. Load bearing parameters together with material parameters were tested in different stages, from 4 days to 14 days, and after that in 28 days.

Table 3. Average results of control material tests - lost formwork panels for Přerov bridges

| Test                              | Avg. | Unit |
|-----------------------------------|------|------|
| compressive strength - cube 100x100mm, 4 days | 92.0 | MPa  |
| compressive strength - cube 100x100mm, 28 days | 156.6| MPa  |
| compressive strength - beam 40x40x160mm, 4 days | 105.0| MPa  |
| compressive strength - beam 40x40x160mm, 28 days | 170.0| MPa  |
| flexural strength - beam 40x40x160mm, 4 days | 19.2 | MPa  |
| flexural strength - beam 40x40x160mm, 28 days | 29.4 | MPa  |
| flexural strength - beam 100x100x400mm, without notch, 28 days | 15.3 | MPa  |
| flexural strength - beam 100x100x400mm, with notch, 28 days | 19.7 | MPa  |

Figure 5. Lost formwork panels for Bridges over the railway tracks in city Přerov.

8. Analysis of control testing results

All the precast elements mentioned above were made of UHPC, class C 110/130 XC4+XD3+XF4, with declared parameters:

- Tensile strength in the time of crack initiation – average minimum 18 MPa, total minimum 15 MPa
- Residual strength class min: \(0.7 < \frac{f_{R2K}}{f_{R1K}}\)

Initial and quality control tests proved all the declared parameters, but more can be said from the results. Used mixture could have been declared as higher strength class concrete, but due to the lack of valid standards, it must have been declared as C110/130, the highest class defined in EN 206.
Size effect can be easily seen in comparison of higher results reached on smaller specimens, and lower results reached on larger ones. (the highest compressive strength in total was 186 MPa on beams 40x40x160 mm).

The effect of the grinding of cylinder (150x300 mm) specimens before tests might be probably responsible for higher results of cylinders, in average comparable to the results of cubes (150 mm). The cubes were not grinded, so it is not confirmed at the moment. Another possibility is that the smooth round surface of the cylinders causes better scatter of the fibres. This hypothesis will be verified in this year by ongoing experimental research.

Another effect was observed. Comparing the compressive test results on new equipment with computer aided testing with older ones with handmade test driving led up to the necessity of proper setting up of the new equipment. The handmade test driving led to higher results, because the operator could continue in stressing of the specimen after the first crack.

With larger specimen (cube 150 mm) it was very common to get higher results after first crack and after activation of steel fibres. This effect cannot be seen with new computer aided test equipment. Also, the smaller specimen (cube 100mm, beam 40 mm) has not shown this difference.

Acknowledgement
The financial support of research connected to this work by the Technology Agency of the Czech Republic, EPSILON programme, Project No. TH02020373, is gratefully acknowledged.

References
[1] Kalný M, Kvasnička V and Komanec J 2016 First practical applications of the UHPC in the Czech Republic HiPerMat 2016 (Kassel, Germany)
[2] Kalný M, Komanec J, Kvasnička V and Fiala C 2017 Experience with UHPFRC applications in the Czech Republic UHPFRC 2017 (Montpellier, France)
[3] Kolísko J, Tichý J, Kalný M, Huňka P, Hájek P and Trefil V 2012 Vývoj ultravysokohodnotného betonu (UHPC) na bázi surovin dostupných v ČR BETON TKS 6/2012, annex Betonové konstrukce 21. století, betony s přidanou hodnotou, pp 51-56
[4] Rydval M, Kolísko J, Huňka P and Tichý J 2013 Závislost únosnosti prvků vyrobených z UHPFRC na distribuči vláken 20. Betonářské dny 27.-28.11.2013 (Hradec Králové, Czech Republic)
[5] Kolísko J, Rydval M and Huňka P. 2013 UHPC – Assessing the Distribution of the Steel Fibre and Homogeneity of the Matrix fib Symposium 2013 (Tel Aviv, Israel)
[6] Vítek J L, Coufal R and Čítek D 2013 UHPC – Development and Testing on Structural Elements Concrete and Concrete Structures 2013 (Žilina, Slovakia: University of Žilina) pp 218-223
[7] Abbas S, Nehdi M L and Saleem M A 2016 Ultra-High Performance Concrete: Mechanical Performance, Durability, Sustainability and Implementation Challenges, International Journal of Concrete Structures and Materials 10(3) pp 271-295
[8] Duque L F M, Varga I and Graybeal B A 2016 Fiber Reinforcement Influence on the Tensile Response of UHPFRC First International Interactive Symposium on UHPC (Des Moines, Iowa, USA)
[9] Metodika 1 – Metodika pro návrh UHPC a materiálové zkoušky Result of project TAČR TA010110269 (Prague, Czech Republic: Klokner institute, 2014)
[10] Metodika 2 – Metodika pro navrhování prvků z UHPC Result of project TAČR TA010110269 (Prague, Czech Republic: Klokner institute, 2014)
[11] Metodika 3 – Metodika pro výrobu prvků z UHPC a pro kontrolu jejich provedení Result of project TAČR TA010110269 (Prague, Czech Republic: Klokner institute, 2014)
[12] Kolisko J, Čítek D and Tej P 2017 Technologie výroby tenkostěnné obloukové dvojitě zakřivené lávky z UHPFRC 14. konference TECHNOLOGIE 2017 (Jihlava, Czech Republic: Česká betonářská společnost ČSSI)

[13] Kolisko J, Čítek D, Tej P and Rydval M 2017 Production of Footbridge with Double Curvature Made of UHPC IOP Conference Series: Materials Science and Engineering 246

[14] Kněž P, Tej P, Čítek D and Kolisko J 2017 Design of Footbridge with Double Curvature Made of UHPC IOP Conference Series: Materials Science and Engineering 246

[15] Kabele P, Sajdlová T, Rydval M and Kolisko J 2015 Modeling of High-Strength FRC Structural Elements with Spatially Non-Uniform Fiber Volume Fraction Journal of Advanced Concrete Technology 13(6) pp 311-324

[16] Blank M., Tej P, Kolisko J and Vráblík L 2016 Design of Experimental Suspended Footbridge with Deck Made of UHPC 3rd International Conference on Mechanics and Mechatronics Research ICMMR 2016 (Chongqing, China)