THIN-WALLED U-PROFILE UHPFRC FOOTBRIDGE

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Abstract

This article presents a mix design, preparation and production of thin-walled footbridge made from UHPFRC. Optimization of UHPFRC matrix and parameters of this material leads to the design of very thin structures. In this case an experimental pedestrian bridge was designed and prepared. Single-span bridge with span of 10 m and the clear width of 1.50 m with the total thickness of shell structure 30 - 45 mm was cast as a prefabricated element in one piece. Self-compacting character of UHPFRC with high flowability allows the production of the final structure. Extensive research was done before production of footbridge. Two versions of large scale mock-ups were casted and tested. According to the complexity of whole experiment a casting technology and production of formwork were tested and optimized many times. Experimental reached data were compared with extensive numerical analysis and the final design of structure and UHPFRC matrix were optimized in many details.

Résumé

Cet article présente la formulation du BFUP et la conception et la réalisation d'une passerelle de section profilée amincie constituée de ce matériau. L'optimisation du BFUP et de ses propriétés permet la conception de structures très minces. Dans le cas d'espèce, une passerelle piétonne prototype a été conçue et préparée. Constituant une travée unique de 10 mètres de portée et de largeur utile 1,5 m, avec une épaisseur totale de la coque de 30 à 45 mm, elle a été préfabriquée en un seul élément, ce qui a été permis par la grande fluidité du BFUP et son caractère autoplaçant. Des recherches complètes ont précédé la production de la passerelle. Deux éléments témoins à grande échelle ont été coulés et testés. Compte tenu de la complexité de l'élément la méthode de coulage et le moule ont été testés à plusieurs reprises pour être optimisés. Les données expérimentales ont été comparées à un calcul détaillé et la conception de la structure de même que le matériau BFUP ont été optimisés sur de nombreux points.

1. INTRODUCTION

UHPC is very promising material and its very favourable material properties allow to design very thin structures. Experiences with the real UHPFRC applications and results of many experimental research programs in Czech Republic lead to design modern footbridge using new principles and knowledge [1-7]. This article is focused on experimental research in field of material optimization, testing of material properties and preparation of the preliminary mock-up of the part of the construction, testing of load bearing capacity of thin walls and on final mock-up 1:1 of the whole footbridge. Each part of this extensive experimental research is presented in more detail in this article.

The span of the footbridge is 10 m. The bridge is designed with double curvature – horizontal and vertical. In the vertical and transverse direction it is a circular arc with a camber of 0.4 m. The cross section of the bridge has a width of 1.5 m. The bridge load bearing structure consists of a bottom deck with only 45 mm thickness and 30 mm thick side walls. The side walls serve as handrails. Handrails height is 1.1 m in the middle of the bridge span and 1.5 m at the support area. In place of the support area a bridge deck is a little bit thicker because of anchors zones. These zones are reinforced by ordinary reinforcement for reliable transfer of the shear and anchors forces at the end supports. The rest of the bridge has no conventional reinforcement and it is reinforced only by the steel fibre reinforcement.

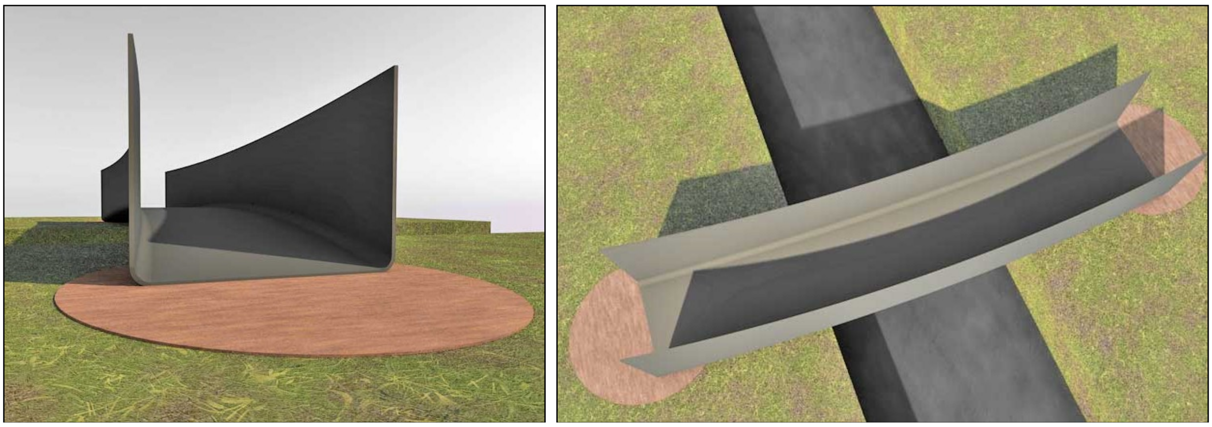

Figure 1: Visualization of the bridge

The main shape of the footbridge ("U" shape) was taken partly from steel construction and partly from shell construction. Optimized UHPFRC mixture should be able to be cast in such a thin and difficult shape. The main outstanding features of this material are the high compressive strength, high tensile (direct and flexural) strength and very high durability also [1-7]. Favourable durability is caused by a very high density of the cement matrix and by very low level of porosity with unconnected pores. This fact is provided by very fine particles (slag, silica fume) and very low water-cement coefficient. High levels especially of flexural strength are provided by using of the steel fibres. These outstanding material properties should be supplemented by high workability [8-11].

Production of "U" shaped UHPFRC footbridge is a very complex problem. Whole construction needs to be cast in one part, one time and design of the structure needs to be optimized with respect to all factors during casting, demoulding, transporting and using.

2. DESIGN - FIRST ITERATTION

Bridge model was created in a computer program ATENA 3D. Which is materially and geometrically nonlinear simulation program mainly for concrete structures. These macro elements have specified material item 3D Nonlinear Cementitious2. We used parameters of UHPC concrete class C110/130 blended with scattered reinforcement in first static approximation. First calculation were performed on a basis of the experimental data gained in the past research in field of UHPC. Material properties are not yet reduced by material coefficients. The resulting structure is considered using one or two class better concrete.

The bottom plate of the bridge was loaded with whole surface load of 4.2 kN /m2, and subsequently up to structural failure, further part with the greatest eccentricity to cause torque to structural failure. Railing was loaded with a force corresponding to 1 kN /m at the top edge and vertical force until failure of the whole structure. The whole bridge was also loaded temperature change of + 40 ° C and -35 ° C.

The bearing capacity of the construction achieves satisfactory values (12.6 kN /m2 – see Figure 2), which is well above the required load capacity (4.2 kN /m2). Gained value of bearing capacity is valid for construction in ideal condition. Which means a footbridge in a state where there are no shrinkage cracks. Due to the shape of the construction, it is a very difficult task and the occurrence of these cracks is expected, which will probably lead to a lower load bearing capacity.

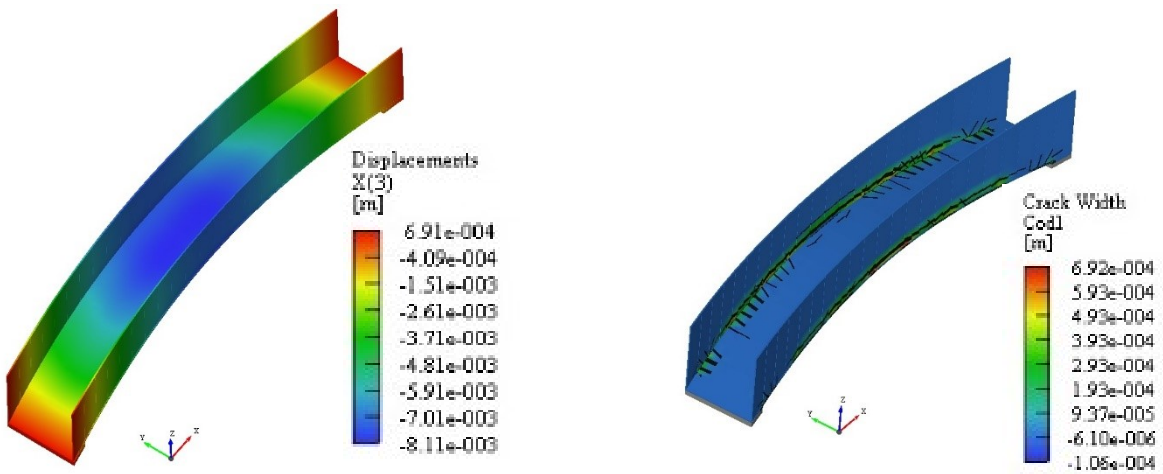

Figure 2: Vertical deflection (left) and cracks (right) of the structure before failure, the applied force of 12.6 kN /m^2, the maximum deflection value -8.11 mm and the maximum crack width 0.692 mm

A static loading test is planned to be performed to verify design assumption. Deflection in the middle of span on both sides of footbridge and crack development on construction will be observed during loading.

3. "U" PROFILE MOCK-UP

Because of very complex design of the footbridge a preliminary mock-up was prepared. The footbridge was casted in the upside-down position because of double curvature and more several reasons that will be describe in more details in this article. The support part of the construction was chosen as a highest part with high of 1.5 m. The wooden formwork of preliminary mock-up was prepared and everything was managed at the same way as for final footbridge was designed. The main reasons of preparing of the mock-up were: verification of the casting process, surface conditions of the element, verification of right consistency of the fresh UHPFRC mixture and ability of the mould to be completely filled. The crucial factor for the element was the time of demoulding, respectively the time of releasing of the formwork. UHPFRC has very high shrinkage that was developed at a very early age. Developing of the shrinkage cracks is than caused by fixed formwork which is relatively stiff and does not allowed any movement of the casted element. All of these factors need to be considered.

3.1 Preparation of the mock-up

The wooden formwork was designed and prepared to withstand pressure of the fresh concrete which is the main load during casting (Figure 3). The technology of the casting was the main issue during whole process of design. Because of double curvature of the bridge and very thin deck and side walls the bridge had to be casted in upside-down position. There was also problem with the surface of the construction which is not in the mould during casting. The formwork was closed from all sides and also the bridge deck (in this position the top deck) was closed. Only three openings were made on the top desk used for pouring of the concrete. Smooth surface of the concrete was achieved in all visible surfaces of the bridge. Only upper side of the casted element in closed formwork has always many pores because of air coming from the UHPC matrix upward from the walls and deck. In this case the position is advantageous because the surface with pores is on the nonvisible bottom part of the bridge in final position. Total volume of used UHPFRC for this element was 0.4 m^3.

Figure 3: Formwork of the preliminary mock-up

Figure 4: Preliminary mock-up after the demoulding

3.2 Optimization of UHPFRC mixture

UHPFRC mixture, used in this construction, need to fulfil very high requirements. Extensive research in the field of material optimization was carried out in Klokner Institute. The key parameter for UHPFRC mixture was high flowability. Because of the upside – down pouring of the footbridge, concrete need to flow inside by the 30 mm thin area and fill both thin walls and upper deck. Usually consistency of the mixture can be adjusted by volume of added water and superplasticizer. In this case (especially for UHPFRC) added water means lower mechanical properties and higher shrinkage. Because of these problems a new UHPFRC mixture were designed and tested. Black pigment was added to the mixture according to requirement of the architect. Many mixtures were tested with a different volume of pigment in dependence to flowability and mechanical properties. The final colour shade was discussed regarding to the material parameters. Final mixture consists of the cement CEM II 52,5 N, fine aggregate with maximum size of 2 mm, slag, silica fume and steel fibres (0.2 mm thick,13 mm long). Volume fraction of the fibres was 1.5 %. The volume of water and superplasticizer depended on the temperature conditions with regard to the workability.

3.3 Material properties of UHPFRC

During casting of the preliminary mock-up the specimens (prisms with dimensions 169 x40x40 mm and cubes with 100 mm edge) were prepared. Because of early demoulding age, many specimens were tested for compressive and flexural strength. Flexural strength was tested by 3-points bending test. First tests were carried out 5 hours after casting. Next set of the specimens was tested after 2 hours and the tests continued until the demoulding of the element. The development of material properties at early age is shown in Figure 5. The crucial value of the compressive strength was set to 30 MPa. At this point the formwork should be released and removed. Preliminary mock-up was demoulded after 11-12 hours after casting. Formwork was completely removed and surfaces of the element were cured by special fluid wax. The surface quality was checked. Element is shown in Figure 4. No shrinkage cracks and no empty areas without UHPFRC were observed. Only the top surface under top wooden desk was covered by the layer with many pores. Development of material properties at first 10 days after casting shows in Figure 6.

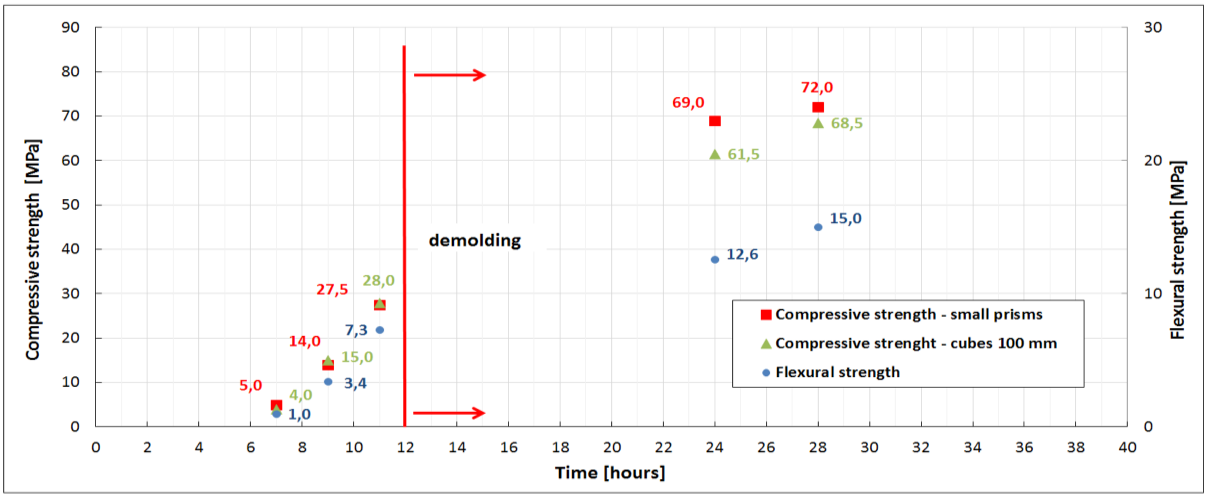

Figure 5: Development of compressive and flexural strength at first 40 hours after casting

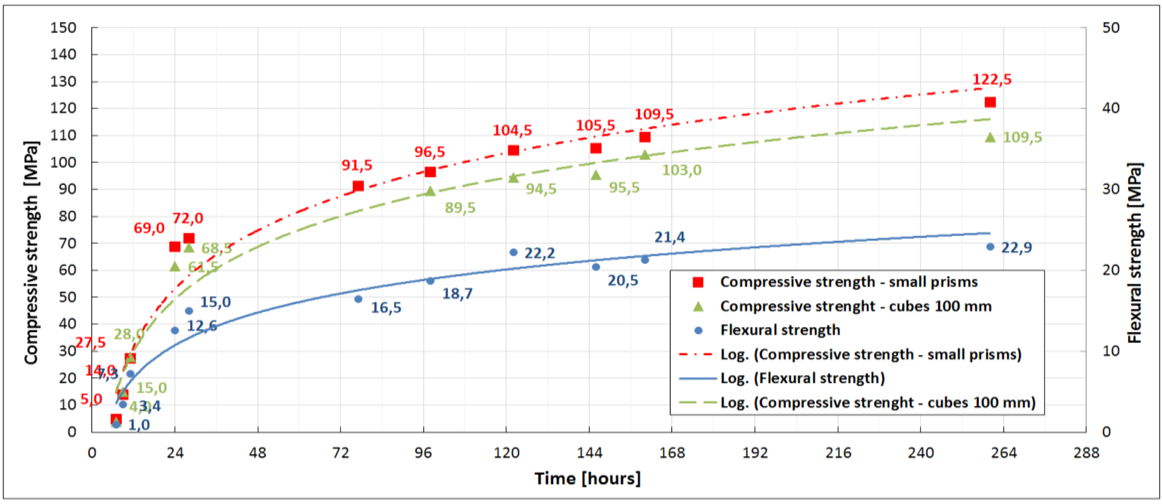

Figure 6: Development of compressive and flexural strength at first 10 days after casting

3.4 Loading tests of the thin walls

The element were turned to the final position and transported on the truck to Klokner Institute 7 days after demoulding. Load bearing capacity of the thin wall was tested by horizontal force at a height 1.3 m. The applied axial force was distributed by steel profile to entire width of the wall. Tests were performed after 35 days after casting. Element was fixed by concrete block to prevent horizontal deflection of whole element. Horizontal deflections were measured by three potentiometric sensors. The first sensor was placed at the height of the applied force, second at the half of the height and third at the bottom deck. This measurement served as control that there was no horizontal deflection of whole element.

At first the load bearing capacity of the right thin wall in inward direction were evaluated (Figure 7). Maximum horizontal force 3.1 kN was reached. It means that force divided by width of the tested wall (1.5 m) was 2.1 kN/m. The second test was performed in opposite direction (a way out direction – Figure 8) and the maximum force was 3.5 kN (2.3 kN/m). It was concluded that load bearing capacity of the walls (handrails) is sufficient.

Figure 7: Test of load bearing capacity of the right thin wall – an inward direction

Figure 8: Test of load bearing capacity of the left thin wall – a way out direction

4. "U" PROFILE FULL SIZE FOOTBRIDGE MOCK-UP

The final formwork was prepared after optimization of many details from preliminary mock-up. Double curvature of the bridge was applied on the top deck and side walls. Two openings for pouring UHPFRC were placed on the edges of the top deck on the ends of the bridge. Development of the material properties and knowledge from casting of the preliminary tests were used for the optimization of formwork and whole construction process.

4.1 Preparation of the final formwork

The formwork was prepared in Klokner Institute. Because of length of the bridge it had to be divided into four parts. Very complex design of the formwork needed to be optimized in case of fast and easy releasing and demoulding. UHPFRC has very high early shrinkage so the fast releasing of the screws and desks is needed to enable some movement of construction and prevent cracks development. Whole final construction of the formwork was prepared at KI premises and transported after control check by designer. Each part of the formwork was transported individually to precast plant Steti, where the bridge was casted (Figure 9). All parts of the formworks were joined together, the release agent was applied to the all surfaces and mould was closed. All formwork beams were reinforced by additional wooden beams (Figure 10) for safety reasons and to withstand the pressure of the fresh concrete.

Preparation of the formwork and casting of the footbridge was in very cold temperatures during winter time. Temperature on the precast plant was between 1-8°C, so the additional heating was necessary after the pouring of the UHPFRC. The crucial effect was to accelerate hydration of cement and increase early age strength of the UHPFRC. Two heaters were placed inside the "tunnel" from the both sides and two and two heaters were placed outside the side walls. Temperature was controlled by extensive measurement. Two temperature sensors were placed into the concrete on the edges (pouring openings) and several sensors were placed on the formwork to control a temperature on the mould surfaces. Sensors placed into a concrete showed development of temperature of the mixture depending on heating and increasing temperature during hydration.

Figure 9: Transport of the ¼ of the formwork

Figure 10: Formwork prepared for the casting

4.2 Casting, demoulding and transport of the footbridge

The prepared mould was poured in January 2017. The final volume of the UHPFRC was 1.4 m^3. Three batches were mixed and transported by crane. The mould was poured from the top of two edges of the bridge, where the final bearing will be installed. No additional vibrations were applied because of the self-compacting character of the mixture.

Because of very low temperatures in the hall an additional heating of the formwork was provided. Maximum temperature outside of the formwork did not reach 40°C but it was still sufficient for increasing early strength of UHPFRC. Casting of the whole element took approximately one hour. Consistency of the fresh concrete was measured in several times after mixing. Cold temperature had a positive effect on consistency so there was not a problem with cold joint between different batches. After the end of casting, whole mould were covered by polystyrene plates and PVC foil to keep the same temperature conditions.

Development of the compressive and flexural strength was tested at the same way as during preliminary mock-up. The time of releasing of the formwork was set to 11-12 hours after casting. Additional heating was provided for the next 5 days. After 4 days a temperature inside concrete was settled to the same temperature as on wooden desk surfaces, so the formwork should be removed with no additional temperature shock. Final footbridge in the upside-down position is shown in Figure 11 and 12. All sides of the thin walls and especially top deck had very smooth surface with good quality.

Construction was removed from the hall to the storage place outside the hall, after 7 days from casting. It had to be stiffened by four inside wooden frames (Figure 12) to prevent damage of the thin shell in torsion during transport. Element was transported by two cranes (Figure 14) and placed on polystyrene desks to allow volumetric changes caused by shrinkage, creep and changes caused by temperature.

The final material properties (measured at the age of 28 days) of the UHPFRC were: compressive strength 149,6 MPa (cubes 100 mm), 152 MPa (small prisms), flexural strength 22,6 MPa (small prisms), modulus of elasticity 51 GPa.

Figure 11: Demoulding of footbridge

Figure 12: Final footbridge after demoulding

Figure 14: Transport of final footbridge in upside-down position

The next step was to turn the footbridge to the final position (Figures 14, 15) and prepare static load test. Turning was provided by two cranes. Footbridge in final position was placed on prepared concrete blocks simulating bearings. Footbridge was anchored on the edges, to transfer load caused by horizontal curvature in opposite sides of load bearings. Static load test is in preparation now in the precast plant. Results will be presented in following publications.

Figure 15: Storing of the footbridge in correct position

5. CONCLUSIONS

Actual paper presents a very complex theoretical and experimental program of the design, casting and testing of the "U" shaped thin walled double curvature arch footbridge made from UHPFRC. A single-span bridge with span of 10 m and the clear width 1.50 m with the total thickness of shell structure 30 - 45 mm was cast as a prefabricated element in one piece. Self-compacting character of UHPFRC with high flowability allowed the production of the final structure. Reinforcement of material of this structure is by randomly distributed steel fibres only without any reinforcement bars. Steel mesh was applied at bearing edges of footbridge, only. An extensive research was carried out in Klokner institute before final foot bridge casting. Based on the requirements of architect and designer a new UHPFRC mixture was developed. Material properties were tested especially at early age of concrete because of releasing of the formwork and demoulding of the mould after 11-12 hours after casting. An extensive numerical analysis was done, too. Preliminary mock-up was produced and technology of casting and many details of formwork and mould were optimized based on experiences gained. Casting of the full scale foot bridge model was performed with very satisfactory result. Complete shape of complicated shell structure was filled with UHPFRC without any cavern or significant entrapped air bubbles. After demoulding the surface of structure was very smooth with very small amount of entrapped air. Hardened footbridge was easily transported to storage place and turned to final position. No static problems occurred during transport and rotation. Now is this unique double arch foot bridge prepared for load bearing test procedure to prove designers assumptions. According to the results of the tests, possible modification of design will be done to prepare final structure which is planned to be installed in a small town nearby Prague.

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