The Overall Research Results of Prestressed I-beams Made of Ultra-high Performance Concrete

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Abstract. The design process of short-term and long-term loading of prestressed I-beams made of ultra-high performance concrete (UHPC) and the overall research results are presented in this article. The prestressed I-beams are intended and designed to replace steel HEB beams mainly in the construction of railway bridges with fully concreted height of the beams. These types of structures have the advantage of a low construction height. The prestressed I-beams were made of UHPC with dispersed steel fibres and are reinforced by prestressing cables in the bottom flange. Two specimens of 9 m span, three specimens of 7 m span and two specimens of 12 m span were made for the short-term loading. For the purpose of the long-term loading, two specimens of 12 m span were made and subsequently loaded for 450 days. All specimens were tested in four-point bending tests in the laboratory. The article presents also comparison of results of the experiments with computer simulations.

1. Introduction

UHPC has a number of unique properties, which are superior to conventional concrete. The main outstanding features include the ultra-high strength of the material under pressures exceeding 150 MPa and the high tensile bending strength which is about 15 MPa [1-5]. High levels of strength are provided by the ability to transmit tensions even after cracking using steel fibers. Fibers absorb energy and control cracks growth until pullout failure [6-11]. High water impermeability is provided by a dense cement matrix and a very low level of porosity with unconnected pores. It is caused by a very low water coefficient, close packing of fine grains of solid particles and by reaction of a very fine reactive material admixtures [2]. From high water impermeability are derived high resistance to frost and high durability [3, 12]. The surface of the material has negligible carbonation and so a high capability to protect the reinforcement is obtain [3-5]. The consistency of the concrete along with fine grain aggregates allows casting of complex thin-walled elements [4]. Due to demand for these high-quality properties some elements can be determined as a typical usage of UHPC.

In the case of horizontal structures, an example would be a thin-walled beam of high aspect ratio and a large span with a high preload. The advantage is the low weight that applies during the assembly of the components. In many instances the thin beams of UHPC could be a good substitute for steel beams, since they have the same weight while still maintaining the required bearing capacity, and a considerably longer service life with minimum need of maintenance [13, 14]. It is advisable to design the beams as T-shaped, Π, I or as a box girder [15, 16]. The advantage of this is an automatic camber of the structure during prestressing, while the steel construction needs to be elevated during production.
I-shaped beams are standard representatives of the basic range of classic reinforced concrete beams. As previously mentioned, the superior material properties of UHPC may be conveniently applied for use in prestressed elements. For test purposes, we designed the shape of a classic “I” element with prestressing with bond [17]. This type of beam is designed to be a replacement for steel beams of the type HEB, which is a very popular element in the construction of all types of structures due to its favorable ratio of weight and load bearing capacity. Steel beams of the HEB type are typically used as self-acting elements or composite elements complemented by a concrete slab only above the level of the upper flange. In this way they are usually used in civil engineering construction works and bridge construction for road bridges. They may also be used fully concreted, in which case the monolithic part would include the full structural height of the beam, except for the bottom flange, with the upper flange concreting usually being of up to 200 mm. Such a design is the most common type of construction for railway bridges with a span of up to 15 m.

| Table 1. Dimensions of the elements |
|------------------------------------|
| Beam  | L [m] | A [m] | B [m] |
|-------|-------|-------|-------|
| 7 m   | 7     | 1.3   | 2.85  |
| 9 m   | 9     | 1.3   | 3.85  |
| 12 m  | 12    | 1.6   | 5.2   |

Figure 1.
a) Scheme of the short-term loading tests,
b) cross section of 9 m span beam,
c) cross section of 7 and 12m span beams

2. Material
The proposed prestressed I-beams are made of UHPC of class C110/130 with 120 kg/m3 of dispersed steel fibers. Although adequate strength for the inclusion of this material under the name of UHPC is not achieved, other material characteristics, such as a fine grained structure, resistance to frost and de-icing agents, allows the label to be used.

The material was composed from combinations of the following components:
Crushed stone (PR30, PR33), fibers MasterFiber 482, microsilica 940U, cements CEM II/A-S 42,5 R, CEM II/B-S 32,5 R, CEM II/A-LL 52,5 R, CEM I 52,5 R, slag and fly ash Dětmarovice, ground quartz MT8, MT12 resp. MT300 and additive Glenium ACE 300.

The use of silica fume Elkem MS 971 on comparative cylinder specimens that reduces the w/add to 0.19 leads to an increase in the compressive strength to a value of 175 MPa after 28 days. The mixture has a low water ratio $w = 0.28 \ (water + additive)/cement$, and a very low binder coefficient $b = 0.22 \ (water + additive)/(cement + microsilica + slag)$. The material has a very high resistance to de-icing agents according to ČSN 73 1326 method C peeled parts 25 g/m2 after 250 cycles. The specimens of UHPC produced in August 2010 and exposed to weather conditions, in parallel with those inside the hall, were tested on the depth of carbonation using phenolphthalein after 3 years. The thickness of the carbonated layer was max. 1.5 mm.
3. Detailed course of design and testing

3.1. 9m span beams

In the first instance the beams with a 9 m span were proposed and tested with a cross section of total height of 350 mm. Then after testing some changes, as described below, were carried out, and a 7 m and a final 12 m span beam were tested. The 7 and 12 m span beams had the same cross-section (final shape) with a total height of 400 mm. The upper flange had a width of 300 mm with an average thickness of 100 mm. The lower flange was designed with a width of 300 mm and had an average height of 135 mm. Ten straight cables in the bottom flange were used for the implementation of the stress. Five of them were placed at a distance of 1.3 m from the supports and the protectors were used in order to prevent an excess of stress at the ends of the beam. One straight cable leads in the top flange. All cables had the strength of 1570/1770 MPa and the diameter of 15.7 mm (see Figure 1 and Table 1). They were prestressed by a force of 206.25 kN, i.e. the stress in each cable 1375 MPa.

The stages of loading for 9 meter span beams regarding the operation and distribution of internal forces in the cross-section area and their boundaries were assumed to be as follows:

1. Achieving decompression of the lower strands cross-section, with fully flexible element behavior, the actual deformation corresponding to calculation according to Hook’s law. The load for this limit is set at F = 2 x 52 kN, tension in the lower strands in concrete \( \sigma_x, c = 0 \) MPa, stress in the upper strands in concrete \( \sigma_y, c = -55 \) MPa with an anticipated deflection of 42 mm.

2. The achievement of tension in the lower fibers at the limit of the tensile strength of UHPC. At this stage the formation of cracks is assumed, and the actual deformation will be slightly higher than deflections assuming fully elastic behavior, while there is a partial stress redistribution over the cross section. The load for this limit is set at F = 2 x 75 kN, tension in the lower strands of concrete \( \sigma_x, c = +15 \) MPa, stress in the upper strands of concrete \( \sigma_y, c = -76 \) MPa with an anticipated deflection of 66 mm.

3. Achieving tension near the compressive strength of the material in the upper strands and significantly exceeding the tensile strength of the material in the lower strands, a significant increase of deflections, plasticization under the compression zone and the eventual collapse of the cross section by press violation of the concrete. The load for this limit was set at F = 2 x 98 kN, tension in the upper strands of concrete \( \sigma_y, c = -100 \) MPa with an expected deflection of 120 mm.

4. The test of the produced beams took place in April 2013. The test result was significantly different from the theoretical assumptions. Already in stage No.1 there were significant deflections of beams, leading to the formation of tensile cracks in the concrete, without the creation of any tensile stress. The collapse of the elements was due to a torn upper flange transverse tensile and shear separation of the upper and lower flanges with a crack in the wall.

The tests needed to be carefully analyzed in order to reveal the causes of major discrepancies between the theoretical assumptions and the test results. As possible causes, substantial diversion of behavior was considered:
- Production technology ensuring homogeneous material effect produced the specimens [18]
- Greater than expected losses due to stress from prestressed cables
- Variations in measurements of forces at a test facility in sync presses
- Subtle upper flange with imperfections affecting the production and the yaw

Based on these assumptions, it was decided to implement measures to eliminate or quantify major discrepancies. These would mainly be by change in the technological process of mold-filling, from a process of layering to the method of filling the full depth of the section.

To actually detect the introduced forces on the prestressing cables, the cables were equipped with sensors that made it possible to deduct the appropriate value of the tension in each cable. Only then was it possible to establish the correct value of the prestressed tension in the calculations.
The static scheme was changed for the tests which followed. Instead of using two independent presses synchronized by the introduction of force, only force action moving the press into two locations on the test element at a distance of 1.3 m will ensure spreading strap anchors.

The problem of the subtle top flange is a difficult one to tackle. In practice, the beam is first embedded in concrete in a monolithic plate, the load of the slabs in the construction state is not a significant load. A board ensures the stability of the flange when it is subsequently loaded. To ensure similar conditions for the functioning of the upper flange of the beam during the test itself is difficult.

For the above reasons, it was decided to further test the change of dimensions of the proposed element. The element had its shape and performance to provide compensation for HEB steel beams used in conventional designs.

Figure 2. and Figure 3. Setup of the experiment, deflection, bending and shear failure of 9m span beams

3.2. 7m span beams
The stages of loading for 7 meter span beams regarding the operation and distribution of internal forces in the cross-section area and their boundaries were assumed to be as follows:

1. Achieving decompression of the lower strands cross-section, with fully flexible element behavior, the actual deformation corresponding to calculation according to Hook’s law. The load for this limit is set at \( F = 2 \times 105 \text{ kN} \), tension in the lower strands in concrete \( \sigma_x, c = 0 \text{ MPa} \), stress in the upper strands in concrete \( \sigma_y, c = -41 \text{ MPa} \) with an anticipated deflection of 22 mm.

2. The achievement of tension in the lower fibers at the limit of the tensile strength of UHPC. At this stage the formation of cracks is assumed, and the actual deformation will be slightly higher than deflections assuming fully elastic behavior, while there is a partial stress redistribution over the cross section. The load for this limit is set at \( F = 2 \times 150 \text{ kN} \), tension in the lower strands of concrete \( \sigma_x, c = +14 \text{ MPa} \), stress in the upper strands of concrete \( \sigma_y, c = -58 \text{ MPa} \) with an anticipated deflection of 34 mm.

3. Achieving tension near the compressive strength of the material in the upper strands and significantly exceeding the tensile strength of the material in the lower strands, a significant increase of deflections, plasticization under the compression zone and the eventual collapse of the cross section by press violation of the concrete. The load for this limit was set at \( F = 2 \times 210 \text{ kN} \), tension in the upper strands of concrete \( \sigma_y, c = -90 \text{ MPa} \) with an expected deflection of 85 mm.
The test of 3 produced beams took place in August 2013. The results were already published in 2014 [19]. The course of examination of specimens corresponded to the theoretical assumptions, while lower values were obtained. For all specimens, however, the desired torque carrying capacity in bending wasn’t achieved. The elements collapsed by shear violation - separating the upper and lower flanges by cracking in the wall. In one case the reinforced concrete specimen failed during the experiment in bending, the top flange was simultaneously torn by lateral movement.

The tests were analyzed and the following conclusions were made:
The derogation in behavior of identical specimen sizes and the inserted preload can be caused by inhomogeneous properties of UHPC. Consequently, it is a matter of production technologies. Specimens with an identical load exhibited different deformations, while the prestressing was practically the same, and was verified by mounted sensors.

Technical reasons can be considered as a cause of premature failure of the sample. During the preparation of test specimens for further testing of 7 m span beams, the shear reinforcement would be used, which increases the resistance of the test specimen in shear. This specimens were, however, used as a basis for the testing of 12 meter span beams.

![Figure 4. and Figure 5.](image)

### 3.3. 12m span beams

The stages of loading for 12 meter span beams regarding the operation and distribution of internal forces in the cross-section area and their boundaries were assumed to be as follows:

1. Start of testing - the entire section is fully pressed, with completely elastic behavior of the element, the shape of the beam is determined by flexible camber caused by prestressing and creep of concrete. The beam is free from external load, the tension in the lower strands in the concrete \( \sigma_y, c = -40 \) MPa, stress in the upper strand in the concrete is \( \sigma_y, c = -2 \) MPa.

2. The achievement of decompression in the lower strands of the cross-section, with fully flexible behavior, the actual deformation corresponding to Hook’s law. The load for this limit was set at \( F = 2 \times 55 \) kN, tension in the lower strands of the concrete \( \sigma_y, c = 0 \) MPa, stress in the upper strands in the concrete \( \sigma_y, c = -42 \) MPa with an anticipated deflection of 55 mm.

3. Achieving stress in the lower strands before UHPC tensile strength limits, with elastic behavior of the element, the actual deformation corresponding to the number according to Hook’s law. The load for this limit is set at \( F = 2 \times 80 \) kN, tension in the lower strands of
the concrete $\sigma_y, c = + 14$ MPa, stress in the upper strands in the concrete $\sigma_y, c = - 59$ MPa with an expected deflection of 80 mm.

4. Achieving stress in the lower strands exceeding UHPC tensile strength limits. At this stage, a rise in the number and the moderate development of cracks is expected. The strain will be slightly increased compared with deflections determined assuming fully elastic behavior, while there will be a partial redistribution of stress over the cross section. The load for this limit was set at $F = 2 \times 110$ kN, tension in the lower strands in the concrete $\sigma_y, c = + 30$ MPa, stress in the upper strands in the concrete $\sigma_y, c = - 81$ MPa with an anticipated deflection of 125 mm.

5. Achieving stress near compressive strength limits of the material in the upper strands, and the emphatic exceeding of the tensile strength of the material in the lower strands. Tensile stress is transmitted by prestressing reinforcement, a significant increase of deflections, plasticization in part of compression zone and eventual collapse of the cross section by the compressive violation of the concrete. The load for this limit was set at $F = 2 \times 170$ kN, tension in the upper strands in the concrete $\sigma_y, c = - 130$ MPa with an expected deflection of 320 mm. Establishment of standard oblique shear cracks in the middle of the formation with vertical bending cracks of limited width.

The testing of two beams took place in 2014. The result of the test showed compliance with the assumptions of the calculation.

![Figure 6. and Figure 7. Setup of the experiment, deflection and bending failure of 12 m span beams](image)

4. Computer analysis
A computer model of an UHPC prestressed I-beam was created in a 3D environment using GiD 11 software, whereby the calculation was prepared. The calculation itself was carried out with ATENA Win Statics software [19, 20, 21]. The computer model of the specimen was modelled as a half of a symmetrical structure by means of one macro-element. The prestressing was modelled using line elements with assigned profiles of 15.7 mm according to the actual structure. The surface of the symmetry of the model is prevented from rotating about a horizontal axis (the axis perpendicular to the span) and the horizontal displacement. Steel spreading elements were added for transferring the load to the model [19]. For the modeling of steel fiber reinforced concrete the reduction coefficient of compressive strength was modified due to cracks growth control of fibers [18, 22, 23]. The loading was performed by displacement per 0.1 mm. The displacement and the corresponding force were monitored. In addition to this monitoring, the volume of concrete was monitored for checking the crack width. The model was meshed by hexahedra elements of a size of 0.05 m [19]. For the purpose
of creep simulation, the B3 model [23] was chosen and the results were calculated using ATENA Win Creep software. The simulation was calculated in parallel to the 9 and 7 meter span beams. Adjusted parameters in the calculation were used in the calculation of the 12 m span beam before their testing. The setting of the model was extrapolated for the calculation of another span. In such a way a good congruence of the tests and the predicted calculation were reached.

**Figure 8.** Computer model - Isosurfaces of crack width

(Load bearing capacity to a value of the force 2 x 71 kN, deflection 119 mm)

**Figure 9.** Computer model - Isosurfaces of crack width

(Load bearing capacity to a value of the force 2 x 173 kN, deflection 57 mm)

**Figure 10.** Computer model - Isosurfaces of crack width

(Load bearing capacity to the value of the force 2 x 155 kN, deflection 268 mm)

5. Conclusions

5.1. Short-term loading

The prestressed I-beams of a span of 9 m failed during the experiment in bending and shear at value of the force 2 x 56,6/75,5 kN with a deflection of 81/122 mm in the middle of the span (refer with: Fig. 2 and 3). The numerical analysis showed a very similar load bearing capacity to a value of the force 2 x 71 kN with a 119 mm deflection. Isosurfaces of the cracks width at the maximum force are shown in the following figure (refer with: Fig. 8). Figure 11 shows a comparison of the L-D curves of the experiment and the FEM analysis.

**Figure 11.** L-D for 9 m span beams

The prestressed I-beams of a span of 7 m failed during the experiment in shear at value of the force 2 x 161/212/158 kN with a deflection of 50/60/56 mm in the middle of the span (refer with: Fig. 4 and 5). The numerical analysis showed a very similar load bearing capacity to a value of the force 2 x 173 kN with a 57 mm deflection. Isosurfaces of the cracks width at the maximum force are shown in the following figure (refer to: Fig. 9). Figure 12 shows a comparison of the L-D curves of the experiment and the FEM analysis. The graph shows also comparison with reinforced concrete beam with the same cross section.

**Figure 12.** L-D for 7 m span beams
The final prestressed I-beams of a span of 12 m failed during the experiment in bending at a value of the force $2 \times 170/171$ kN with a deflection of $286/260$ mm in the middle of the span (refer to: Fig. 6 and 7). The numerical analysis showed a very similar load bearing capacity to the value of the force $2 \times 155$ kN with a $268$ mm deflection. Isosurfaces of the cracks width at the maximum force are shown in the following figure (refer to: Fig. 10). Figure 13 shows a comparison of the L-D curves of the experiment and the FEM analysis.

**Figure 13.** L-D for 12 m span beams

**Figure 14.** Creep tests of 12 m span beam

### 5.2. Long-term loading

For the purpose of creep testing, two specimens of a span of 12 m were loaded by a constant load of 22.6 t, which means a force of 111.8 kN for each beam. The prestressed I-beams of a span of 12 m were manufactured with initial deflection (camber) from prestressing of 75 mm in the middle of the span. Instant deflection just after the application of the load were measured as 49 / 45 mm, with a deflection after 450 days of 72 / 75 mm (refer with: Fig. 14). FEM analysis showed an instant deflection of 55 mm and a deflection in 450 days of 73 mm.

The aim of the numerical and experimental research of elements of the UHPC was to design a beam with I-shaped cross section. I-beams are intended to be fully concreted in the bridge slab, in which the monolithic part would include the full structural height of the beam, except for the bottom flange. Such a design is the suitable solution for construction of railway bridges with a span up to 15 m.

Extensive numerical and experimental research was carried out to design a UHPC I-beams for a 12 m span. First, several test specimens were made for a 9 and 7 m span. These specimens served to test beam production and were subjected to static short-term load tests. The resulting set of 12 m beams was subjected to short-term and long-term load tests. From the results of numerical and experimental analyses it can be stated that the beams thus designed can be used for the construction of railway bridges.

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