Road Bridge WILD - UHPFRC for a segmental arch structure

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Summary
With the pilot project “Road Bridge - Wild” the UHPFRC segmental construction method combined with the swivel in method for arch erection comes to application. So the eminent properties and possibilities of UHPFRC are utilized in two regards: quick erecting and durable structures. The 157m long bridge consists of two foreland bridges and an UHPFRC segmental arch which spans 70m. The halves of the arches are built up vertically, tied together by external tendons and easily swivelled in. Afterwards the columns and deck slab are conventionally completed. Because current codes and guidelines do not cover the application of UHPFRC, full scale tests, many other tests for local response and various numerical investigations have been necessary for a save realisation. This contribution describes design, construction, scientific investigations and the learning effect which gives us conclusions for both, further applications and continuative research.

Keywords: arch structure ; construction principles ; design ; detailing ; full scale tests ; precast ; road bridge ; segmental construction method ; segmental joints ; UHPFRC (ultra high performance fibre reinforced concrete).

1. Introduction

UHPFRC with its inherent benefits of high compression strength and extraordinary durability opens new possibilities in structural engineering. For such new construction materials the need of new types of structures is essential for meaningful and economical applications. The fact that the ratio of the modulus of elasticity between UHPFRC and structural steel is nearly a fourth, studies have shown that very light and thin-walled cross sections with sufficient stiffness are required. Thus we can classify the construction principles for UHPFRC structures between conventional steel and concrete structures. If such light cross sections in conjunction with prefabricated segmental construction, external prestressing and dry joints come to application, new or adapted and very fast erection methods in bridge construction are imaginable. These should compensate the higher material costs. By the high durability compared to conventional concrete bridges, the life-span shall be increased to 200% while the costs of maintenance shall be halved. Since these aims can be met, the life cycle costs will decrease to 50%, which causes low afford for maintenance and a long lifetime. Last but not least these advantages unburden our political economy.

Due to its geometrical stiffness arch structures provide excellent possibilities for maximum utilization of the high compression strength of UHPFRC due to transfer of the loads mainly by compression. Such utilization can never be reached in beam structures for traffic bridges because of the strict limits regarding the deformation and vibration for road and in particular rail bridges to achieve sufficient traffic safety. Some studies and other pilot projects have been shown that compression strengths of more than 150 MPa are not necessary for beam structures [1]. If the thrust line of the arch is optimal adapted to the acting loads, tensile stresses and shear forces in the structure are very low. So an arch bridge is very predestined for a first UHPFRC pilot project in such dimensions.
The Road Bridge - WILD is one component of a new service road for the hi-tech company “WILD” in Völkermarkt (Carinthia, Austria) which provides fast and direct access to the federal road B70. The road design requires the crossing of a deep gorge. It is obvious that the best solution can be found in an arch structure which does not require any kind of falsework. The client community consists of 3 partners. One partner is the hi-tech company “WILD” who prefers a hi-tech bridge structure for purposes of representation in the context of the company’s philosophy and this UHPFRC bridge met this demand. It is important to mention that during the bidding procedure alternative proposals of the bidders have been permitted at request of the other 2 clients who represents the local government. Hence, UHPFRC combined with the swivel-in method for the arch has been the cheapest solution in consideration of financial aid which covers the required accompanying scientific investigations. A visualization of the concept design is showed in figure 1.

Fig. 1 Visualization of pilot project Road Bridge WILD

2. The pilot project Road Bridge - WILD

The pilot project road bridge - WILD in Carinthia, Austria for an UHPFRC-segmental-arch-bridge, is an example of the swivel-in-method that is used in realization. The polygonal-arranged UHPFRC segmental arches, as shown in figure 2, consist of individual 6 cm thin-walled (and for this reason very light) precast UHPFRC-segmental-box-girders made of C 165/185. They are assembled by the use of external tendons running inside the arches. Since the actual shear force in the arches is very low, the thin-walled webs made of UHPFRC do not need any shear reinforcement for carrying the loads.

Fig. 2 General view, standard cross section and details of the Road Bridge - WILD

Assuming that the dead load of the arches is low compared to the further loadings from columns, deck construction and traffic, the thrust line of the arch is polygonal. The additional prestress, applied by the use of external tendons, reduces the eccentricity of the loads and causes an important
increase of the bending stiffness of the arch. These tendons are unbonded monostrands which are easy to assemble and exchange. At the bends of the arches so called “knee-elements” are arranged. They work as deviator and anchor block for the external tendons. The columns have a rigid connection to the knee-element as well as to the deck. The overall length of the bridge including foreland bridges is 157m. The columns between the arch and the deck are made of high strength concrete, the columns of the foreland bridges are made of normal reinforced concrete. During the bidding procedures the columns between arch and deck were designed as precast spun concrete pipes, but at the request of the contractor cast-in-situ columns will finally be realized. The cast-in-situ deck slab with a depth of 60cm has only passive reinforcement with standard span lengths of 15m. In table 1 the required material properties for the pilot project WILD are given.

Table 1 Required material strengths and properties of UHPFRC

<table>
<thead>
<tr>
<th>Property</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>characteristic compressive strength cylinder $f_{ck}$</td>
<td>≥ 165 MPa</td>
</tr>
<tr>
<td>($\phi/h = 150/300 \text{ mm}$)</td>
<td></td>
</tr>
<tr>
<td>modulus of elasticity $E_{cm}$</td>
<td>≥ 50,000 MPa</td>
</tr>
<tr>
<td>characteristic flexural tensile strength $f_{ck,\text{flex},0.5 \text{ mm}}$</td>
<td>≥ 18 MPa</td>
</tr>
<tr>
<td>(four point bending test 150 x 150 x 600 cm; DBV)</td>
<td></td>
</tr>
<tr>
<td>characteristic direct tensile strength at loss of linearity behaviour $f_{ck}^\prime$</td>
<td>≥ 7 MPa</td>
</tr>
<tr>
<td>characteristic direct tensile strength (fibre bridging) $f_{ck}$</td>
<td>≥ 7 MPa</td>
</tr>
<tr>
<td>characteristic friction coefficient at joint surface $\mu_k$</td>
<td>≥ 0.20</td>
</tr>
<tr>
<td>evenness at surface of segmental joint</td>
<td>± 0.1 mm</td>
</tr>
</tbody>
</table>

3. Assembling and erection of the arch

After completion of the foreland bridges, the several arch-segments are assembled in a vertical position using external tendons. The effort for equipment is minimal: a mobil crane for the manipulation and temporary ties for fixing the arch’s position. The very light arch halves can easily be swivelled in and are jointed at the crown (figure 3). The hinge for swivelling is a simple steel bolt with a diameter of merely 80 mm. The maximum force in the swivelling cable is about 2x450 kN, which can be borne by 2x4 monostrands. After joining the arch halves further tendons overlapping at the arch’s crown, are installed. Due to pouring the hinge between the arch and the springing foundation, the arch gets a rigid restraint.

Too large production tolerances of the precast arch segments will have far-reaching consequences on the erection work and on the final arch shape. For this reason project-oriented considerations have already been made during the bidding procedure. The permitted deviations of the single segments as well as for the final arch shape have been specified. At present these demands can only be met, when the joint surfaces are milled by a CNC-machine.

The construction supervisor claims extensive industrial safety rules during vertical assembling and swiveling. Amongst others, it was not permitted for working staff to stay in the inside of the arches during the vertical assembly. Therefore the problem arise how to perform the successive installation
of the external tendons in the arch. The combination of afore installed ropes, the use of complex coupling systems and guiding devices leads to a threading procedure, which allows pulling the tendons from the top of the arch to the springing without any working staff in the inside of the hollow box girders.

The concentrated loads due to lifting devices or other anchorage elements during assembling can hardly be introduced and distributed in the thin walled elements. Even the space necessary for conventional lifting devices is not available in most cases. Only at the more massive knee-elements it is possible to fix temporary lifting devices as shown in figure 4. Also special considerations regarding storage, transportation and handling during assembly must be made during design in order to avoid damage or harmful cracking of the filigree thin walled elements. Specially developed lifting devices and a mobile crane with two independent winches provide simple and fast adjustment in all directions. Doing it that way, the required assembling accuracy can be ensured. Further the fixing of the rotation axis of the swivelling hinge at the springing will be carried out not before the real geometry of all segments will have been measured and therefore the correct position of the arch’s crown is known. Little deviations at the arch’s crown will be corrected with a special centring device. The restraints resulting from this correction are taken into account in the further design calculations.

![Fig. 4 Lifting and swivelling devices](image)

### 4. Design and detailing

In order to analyse and design the arch, the material laws and the associated partial safety factors for UHPFRC are gathered from [2]. For the global structural design calculations of the arch in longitudinal direction under ULS conditions the gapping of the segmental joints is limited by one third of the height of the section [3]. Considering a characteristic friction coefficient of 0.20, the shear forces can be very easily transferred in the remaining compression zone of the segmental joints. For the assessment of the shear carrying capacity in the standard cross section the given design rules from [4] are used. In order to focus on the aims of the construction method proposed, a high durability of the arch should be reached. Therefore, decompression in the arch under the characteristic combination of loads is specified as a design criterion. The analytical model considering each construction stage is given in figure 3.

Investigations of the buckling behavior of the segmental arch during the construction as well as in the final state, require the consideration of the change of stiffness due to the gapping of the segmental joints. Therefore a numerical three-dimensional model, where beam elements represent the arch and cable elements represent the external tendons, is adapted as following. In the region of the joints a stress-strain law without tensile strength is assigned to short beam elements with a characteristic length according to the discontinuity area, where the assumption that the sections remain plain is no more valid. Outside of that area a stress-strain law considering the tensile properties of the UHPFRC was assigned to the beam elements of the arch. The applied numerical model is calibrated with the conducted full scale tests and with tests performed in [5]. Further short beam elements connect the cable elements with the beam elements of the arch in the region of the knee elements. Applying third-order theory the change of the axial force in the cables as a result of
deformation of the arch can be correctly included. As expected the numerical investigations show, that the construction state during concreting the outermost section of deck over the arch is more critical than the final state. Hence the concreting of the deck slab must be performed simultaneously from both ends of the foreland bridges to the arch’s crown.

![Image of a arch structure with tensile stress](image)

**Fig. 5 Ultimate load FE-Analysis and conclusions for design of the “knee-elements”**

The only steel fibre reinforced knee-elements with their complex shape at the bends of the segmental arch are sensitive discontinuity regions. Several actions such as anchoring and deviation of the prestressing tendons, bending moments induced by the columns as well as the shear and axial force in the compression zone of the segmental joint stress these elements. Investigations by means of a nonlinear and linear 3D-FE analyses (figure 5) deliver information about the stress distribution in the knee-element. As illustrated in figure 5, mainly the change of the cross section from the thin-walled segmental-box-girder to the thicker wall of the knee-element in the compression zone of the joint causes tensile stresses in longitudinal and also in transverse direction at the inside of the upper chord. Considering the large scatter of properties like the distribution and orientation of the fibres in such a complex geometrical construction element, it has been decided to use additional wrapping with carbon fibre reinforced polymer (CFRP) sheets as shown in figure 5 in order to avoid a brittle failure in this region.

5. **Full scale test**

Present design codes and guidelines do not completely cover the use of UHPFRC in relation to the structure presented. Experimental tests will answer open questions in designing and construction. In addition to many other experiments, full-scale laboratory tests within the scope of the pilot project are carried out. More detailed information about the full-scale tests can be found in [6]. The focus of the full-scale test is the load carrying behaviour in the region of the springing. The test setup is shown in figure 6. The elements involved are fixed to the testing wall by the use of external tendons having the same type and position as in the real arch bridge. The necessary loads are performed in two complementary ways: firstly by means of Dywidag Steel Threadbars (axial force and bending moment) and secondly by a servo-hydraulic testing jack (bending moment and shear force). Hence, the total load path (red line in figure 7) is performed according to the design calculations and beyond until the point of failure. In the axial force – bending moment – diagram the green dots represent the internal forces at the springing and the purple dots the internal forces at the first bend of the arch from permanent loads, characteristic loads, ultimate loads up to ultimate loads multiplied with the partial safety factor for the material. The purple line shows the decompression limit for the cross section, the black line the design resistance of the cross section, the blue line the resistance of the cross section determined with mean values. The failure predicted by nonlinear FEM-analyses is represented by the blue dots for different axial forces.
The full scale test shows the same load carrying behaviour and failure as found in the preliminary nonlinear FEM-analysis for the preparation and also the recalculation of the full scale test. Also the numerical investigations of the knee elements showed the same behaviour as observed in the tests. In order to get these proper results the material model for this nonlinear FEM-analysis was verified by recalculation of previous uniaxial tensile tests, bending tests, compression tests and shear panel tests [7]. At the loading levels which represent the serviceability limit state with characteristic loads and the ultimate limit state there was absolutely no indication of a failure. Even with 1.5 times magnified ultimate loads and at the maximum force of the servo-hydraulic testing jack the point of failure could not be reached. In order to reach the point of failure the prestress in the Dywidag Steel Threadbars was released to reduce the axial force. At the lower level of the axial force an over-proportional increase of the gapping of the segmental joint between the knee element and the box girder could be observed and a redistribution of the compression zone in the stronger corners of the knee elements occurs. Finally a typical compression failure by shear takes place all over the compression zone.

Fig. 6 Test setup for the full scale tests
The test elements for the first full scale test have been fabricated by the laboratory of structural engineering of the TU Graz without the possibility for a mechanical treatment of the joint’s surface by CNC grinding and milling. The accuracy of the joint’s evenness is in the range of 2 mm so that there is no uniformly distributed contact in the joint. This punctual compression in the joint leads to single stress peaks which cause tensile stress in transverse direction with longitudinal crack formation in the thin-walled box girder. These longitudinal cracks have no influence on the global failure load but substantiate the necessity of a maximum deviation of 0,1 mm of the joint’s evenness to transfer the high compressive stresses. At further tests with accurate joint surfaces no longitudinal cracks in the box girder are observed.

**6. Final comments for further applications and continuable research**

The tensile behavior of UHPFRC depends significantly on the fiber orientation and distribution in the real structure. Therefore it is not sufficient to define in the bidding procedures the required mechanical properties which should be determined on the basis of test specimens. Additional information about one or more required suitability tests should be given. The specimens for these suitability tests should be produced with a representative geometry and the way of placing the concrete as in the real structure in an early state before the production process of the segments will have started. If required it should be enough time to change and optimize the way of placing the concrete or maybe optimize the applied fiber geometry or cocktail. According [8], different specimens for bending tests can be cut out from the test element. The results from the bending test give information about the real tensile strength at the real structure in different directions. This test assures the assumptions made in the design calculations. The contractor should be provided in the bidding procedures with all sufficient information to work out a realistic time schedule for all preliminary tests which should be coordinated with the planner. The subject-matter fiber orientation and distribution has emphasized as a main task in this pilot project. Therefore further research is required to find appropriate non-destructive test methods which give proper information about the tensile strength at all positions in the real structure.
7. Conclusions

New construction principles that lead to segmental construction methods can be deduced thanks to a detailed and continuous involvement of the material properties of UHPFRC, the possibilities provided by the precasting industries and the inclusion of erection methods in bridge construction. With proper and wise use of UHPFRC the typical design rules and construction principles of structural concrete and structural steel will be merged. As far as the lightness is concerned, UHPFRC segmental bridges bring economical advantages in comparison to common concrete bridges, because they will be built faster, will be easier to maintain and will have a longer service lifetime. The presented pilot project points clearly out the high performance of UHPFRC. During carrying out the design and detailing for the prototype many necessities and special features appear. These are due to the specific material properties and the filigree construction method. Moreover it has been shown that further research is required to implement UHPFRC as a building material in practice e.g. to find proper analytical models for continuity regions and to find methods for non-destructive test methods for fiber orientation and distribution. The UHPFRC segmental arch represents a further step for showing the excellent properties of this material in an application and gives us a lot of new knowledge, even if sadly the bridge deck is made of conventionally concrete – but one can convince the client and the authorities only step by step. Nevertheless, we must appreciate the courage of the authorities in Austria to make this step forward and realize the pilot project road bridge WILD.

8. References