Chapter 10

Gärtnerplatz – Bridge over River Fulda in Kassel: Multispan Hybrid UHPC-Steel Bridge

A 132 m-long hybrid ultra high performance concrete (UHPC)-steel bridge with six spans has been built across the river Fulda in Kassel, Germany. UHPC offers supreme durability characteristics and, hence, has been selected for the replacement of an existing, damaged timber structure. The novel structural concept consists of a hybrid steel-UHPC truss structure and precast UHPC plates for the bridge deck. The deck plates are glued to the upper chords of the truss structure. For the transfer of shear forces from the truss diagonals (steel tubes) to the UHPC chords, prestressed bolted friction connections are used. This chapter describes the conceptual design, the final design, accompanying tests and the erection of the bridge structure. A monitoring system has been installed in order to gather practical experience with the new materials and the novel structural concept.

10.1. Introduction

UHPC not only offers very high strength but also superior durability characteristics due to its low permeability to liquids and gases. Both the very high strength as well as the significantly improved durability in comparison to normal and high-strength concrete are a consequence of the extreme packing density of the cement matrix.

At the University of Kassel, the mix design and optimization as well as the investigation of the characteristics of the hardened UHPC with values of

Chapter written by Ekkehard FEHLING, Kai BUNJE and Michael SCHMIDT.
compression strength between 150 and 400 MPa have been in the focus of research since 1998. Furthermore, the behavior of UHPC elements in bending and shear has been studied intensively [FEH 05]. Meanwhile, a series of bicycle and pedestrian bridges made from one single precast element and spanning from 7 m to 18 m have been built. The Gärtnerplatz-Bridge in Kassel is the first multi-span UHPC bridge in Germany. It is a hybrid UHPC-steel structure and was finished in 2007.

10.2. Advantages of UHPC for bridge construction

With respect to the conceptual design and verifications for structures made of UHPC, the following principal conclusions could be drawn from the research work (compare also [AFG 02, SAC 08]):

– For elements subject to bending or bending and normal force, the tensile strength of UHPC with fibers can be used, since the fibers’ ductile behavior in tension can be ensured. Reduction factors accounting for the inhomogeneity of the spatial distribution of the fibers and their orientation should be introduced. For thin elements, the dominating fiber orientation can be observed to be parallel to the formwork.

– For rectangular cross-sections, failure due to shear forces could only be observed for very low or no fiber contents. For UHPC without fibers, the shear force resistance can be calculated well by the model proposed by Zink [ZIN 99], mainly based on the bearing capacity of the compression zone.

– Bar reinforcement and fibers as reinforcement can be combined effectively.

– UHPC can develop very high bond stresses (of about 50 MPa) leading to short anchorage lengths or splice lengths. However, in order to avoid or control longitudinal cracks due to bond stresses, a minimum fiber content should be provided.

– The fatigue strength of UHPC with fibers under cyclic compression amounts to about 40% of the static compressive strength, i.e. UHPC behaves in a similar way to normal strength concrete in this respect.

– The use of fine aggregates with maximum particle sizes up to 1 to 2 mm improves the homogeneity of the matrix. However, UHPC members with larger dimensions can be economically produced using aggregates with larger diameters, e.g. up to 8 mm.

– Precasting may be recommended in order to obtain structural elements with high quality. The relatively high, mainly autogenous shrinkage can be eliminated for the final product if heat treatment (70–90°C) is applied. The residual shrinkage is
then very low and the creep coefficient is decreased drastically, from $\varphi = 0.8 \ldots 1.2$ to $\varphi = 0.2 \ldots 0.3$.

– Prestressing and post-tensioning can effectively be used in order to exploit the high strength of UHPC. Also, serviceability characteristics can be influenced in a positive way (e.g. minimization or avoidance of cracking due to shrinkage and reduction of deflections due to creep and shrinkage).

– The fire resistance of UHPC can be improved substantially if quartzitic aggregates are replaced, for example by basalt. Polypropylene fibers can help to provide expansion space for water vapor, as is known from high-strength concrete.

– Due to the relatively high tensile strength (around 10 MPa) and the dense structure, the surface of UHPC is very well suited for gluing. This holds true, for example, for the application of glued carbon fiber laminates as well as for gluing UHPC elements to each other.

10.3. First UHPC bridge projects in Germany

Following these observations, the first UHPC bridges in Germany have been built in Niestetal near Kassel [SCH 06]. These bridges (see Figures 10.1 and 10.2) consist of precast, post-tensioned or prestressed UHPC elements with spans of 7, 9, and 12 m. The 12 m bridge, which was the first one to be mounted, has an inverted U-shape. The two webs have been post-tensioned, each by a tendon with 1.2 MN prestressing force.

![Figure 10.1. Mounting of the 12 m UHPC footbridge in Niestetal](image)

No bar reinforcement has been used, except for the anchoring regions of the tendons and for the integrated transverse girder at the supports.
The other bridges have been prestressed in the factory. The geometry of the cross-section is a \( \pi \)-shape. The curved geometry of the lower side of the webs leads to the center of gravity of the cross-section being variable. As a consequence, the variation of the prestressing moment along the bridge becomes curvilinear, although the prestressing strands are straight. Thus, it suits the distribution of moments due to external loads quite well.

![Figure 10.2. The 9 m bridge with \( \pi \)-shaped cross-section](image)

### 10.4. Conceptual design of the Gärtnerplatzbrücke

The timber bridge existing until 2005 had been built for the 1981 federal garden show (Bundesgartenschau) in Kassel to enable pedestrians and bicycles to cross the river Fulda. It had been severely damaged due to fungus attack. Thus, the city of Kassel as the owner of the bridge was searching for a durable, lightweight structure to replace the old bridge. UHPC, as an innovative material being investigated at the University of Kassel, promised superior durability in comparison to timber, steel or conventional concrete. Since the bridge is part of a regional bicycle trail, the state of Hesse would financially support the new bridge. However, the budget for a bridge using an innovative material had to be oriented to the costs of a conventional solution. For the design of the new bridge, the city of Kassel commissioned IBB Fehling+Jungmann consulting engineers in Kassel.

For the conceptual design, the following conditions had to be observed:

- The existing pillar foundations had to be used also for the new bridge. The old foundations would otherwise have to be demolished, since they should not obstruct the ship traffic on the river. Although larger spans could have been conceived, this requirement would have increased the cost of the whole project substantially.

- Since the old foundation had to be re-used, the new superstructure could not be much heavier than the old timber structure. A conventional prestressed concrete
solution would have had disadvantages in that respect, but a filigree UHPC structure could easily overcome this problem.

– The new bridge should have a deck width of 5 m. The loads to be carried are those for pedestrian and bicycle traffic and, in addition, a 6-tonne rescue or service vehicle.

– For the ship traffic, a usable height of 5.50 m and a width of 30 m were required. With respect to disabled persons, the maximum slope of the deck could not exceed 5%.

– Loads from ice and ship impact on the pillars had to be considered.

Different design concepts were evaluated. Mainly, systems with two or three UHPC girders, including truss systems, have been discussed. In addition, cable-stayed bridge solutions have been conceived. The required supervision and maintenance of the cables, however, has been regarded as a disadvantage. In order to avoid vibration problems, a continuous girder system was preferable to a system of independent single-span girders. The lower chords might be curved in order to avoid a somehow “industrial” appearance of the bridge. Since the geometry of the bridge is skew in plan, a superstructure with two or three parallel truss girders might appear rather unclear. Depending on the viewing angle, a lot of diagonals might obstruct the transparency. Hence, a three-chord truss system with triangular cross-section was preferred. Figure 10.3 gives an impression of such a proposal.

Figure 10.3. Proposal for a three-chord system with UHPC chords and diagonals made from steel tubes
Figure 10.4. Superstructure in longitudinal direction
Although the lower chord is curved, it might be produced as a straight precast prestressed beam. The high strength and corresponding large strains theoretically enable us to bend a slender prestressed UHPC beam without cracking. Since no practical experience was available at that time, it was decided to apply this principle for the upper chord only, which also has to be curved across the main span 36 m-long above the river, but with a larger radius of curvature (see Figure 10.4). The lower chord was to be built in steel. The cross-section at midspan is depicted in Figure 10.5.

Figure 10.5. Cross-section of the hybrid three-chord truss at midspan

10.5. Final design and execution

The continuity of the multispan system was provided by the bolted connections of the steel plates that were attached at the ends of the UHPC chords and the lower (steel) chord. The precise deck plates (dimensions 2.00 m x 5.00 m) were glued to the upper chords and to each other. Gluing was selected since mechanical (steel) connectors would be difficult to put into the filigree UHPC elements.

The precast deck plates were prestressed with strands in transverse direction in order to ensure the required bending resistance. The selected UHPC mix used 0.9% by volume of high-strength steel fibers (diameter 0.15 mm and length 17 mm). For drainage of the bridge, a 2% gradient in transverse direction down towards the middle was provided. The longitudinal direction made use of the gradient towards
the abutments, avoiding the requirement for additional joints for drainage on the deck. For the gradient in transverse direction the thickness of the deck plates were varied from 8 cm in the middle to 12 cm at the edges. Originally, it was assumed that the deck plates would be poured upside down. Then the final upper side would have to have been defined by the mould geometry. Since the UHPC used was almost self-compacting, the upper surface would be horizontal and plane after pouring. However, the precaster (ELO, Eichenzell near the city of Fulda) finally decided to use vertical formwork. In this case, the thickness was theoretically kept constant. It should be noted that in this case it was necessary to deviate the prestressing strands in order to ensure sufficient concrete cover at the edges.

The UHPC chords were also prestressed with strands in the factory. However, the strands were bondless in order to enable a wedge anchoring the end plates made from steel. For the production phase as well as for transport and mounting, the chords were sufficiently prestressed. For the final state, continuous post-tensioning was applied in order to provide enough compression for the serviceability limit state in the bridge deck, especially in the joints between the deck plates. For this reason, a duct 125 mm in diameter was provided, where a 2 MN tendon was placed. The selected tendon type was one that would normally be used for external prestressing (SUSPA Type EX 6-12). The tendons were anchored in the transverse girders (made from in situ concrete) at the abutments.

![Figure 10.6. Gärtnerplatzbruecke at the end of October 2006](image)

Until October 2006, the truss system was completely mounted and the deck plates were placed (see Figure 10.6). The total dead load of the deck plates, hence, was already in effect. For gluing, the plates had to be lifted one at a time and glued
to the upper chord and to the previous plate. This procedure was necessary in order to reduce the additional tensile stresses in the plates due to the construction process as well as additional shear stresses at the interface to the chords. Finally, the continuous post-tensioning in the chords provided sufficient compression stresses in the deck. The continuously glued connection of the plates to the chords enabled the engineers to activate both the chords and the deck plates for the live loads or traffic load cases.

The erection procedure was taken into account in the structural model (3D finite-element model, using the Sofistik software). In this model, all effects due to creep and shrinkage were accounted for. For gluing of the epoxy-based material, the temperature remained above 8°C during placing of the glue and hardening. Since this was not guaranteed during wintertime, the contractors (Beck-Bau, Eschwege, responsible for all in situ concrete works, and ELO-Beton, Eichenzell) waited until spring of 2007 for elevated temperatures. The bridge then was finished in July 2007. Figure 10.7 shows the completed bridge.

**Figure 10.7. The completed bridge**

### 10.6. Additional investigations

#### 10.6.1. Single case approval

Since no commonly accepted regulations for UHPC currently exist, single case approval by the authorities has been necessary in addition to the verification of the design by an independent checking engineer.
For single case approval, an expert report on the design concept and the required additional experimental investigations was prepared by Professor Tue at the University of Leipzig. The following investigations were included:

– characteristics and quality control of the UHPC;
– experimental validation of the bearing capacity of the deck plates in bending and shear and for the anchoring of the posts for the railing;
– friction coefficient for the bolted connection between a steel plate and the UHPC girder;
– tensile and shear strength of the glued connections as well as durability for thermal/hygral loading action.

All tests have shown the UHPC elements to have sufficient resistance (see Figure 10.8). For the epoxy glue (SIKA), it was shown that the tensile and shear strength are practically identical with the tensile strength of the UHPC itself. The measured friction coefficient between UHPC and steel (sand blasted) amounted to $\mu > 0.80$.

For the durability of the glued connection, additional tests were carried out with combined mechanical and thermal/hygral loading. As a result, it was stated that sandblasted UHPC-surfaces provide a good connection and a durable strength.

10.6.2. Monitoring

Since several new technologies have been applied in the Gärtnerplatz bridge, a continuous survey of the behavior of the structure and its elements was desirable. For this reason, a monitoring program has been developed. The instrumentation
comprises the continuous measurement of local strains, partly by fiberoptic sensors, relative displacements between upper chord and deck plates, and accelerations. Furthermore, temperature and humidity are recorded at selected locations.

In order to identify changes in load-bearing behavior, the dynamic characteristics of the system are monitored continuously. In addition, episodic measurements of the periods of vibration (eigenfrequencies) and the corresponding mode shapes are made in order to identify possible changes in the overall dynamic behavior as well as the local mechanisms responsible for these changes. With this in mind, a dynamic finite element model of the structure has been generated and compared with the results from the experimental modal analysis of the structure just after the end of the construction process. The model has been fine-tuned by parameter updating in order to deliver the best possible fit with the experimentally-obtained eigenfrequencies and mode shapes.

If changes in the dynamic characteristics of the structure are detected over time, the model will be updated again, showing which model parameters at which locations have changed. The authors are optimistic that this will enable them to identify possible sources and mechanisms of damage, if there are such effects. The University of Kassel, Laboratory of Lightweight Structures (UKL, Professor Link), the German Federal Institute of Materials testing (BAM, Berlin) as well as TUEV Rheinland are working together on the monitoring program. The State of Hesse and some of the contracting firms (Beck-Bau, Eschwege and ELO-Beton, Eichenzell) are also supporting the monitoring program. Recent results have been reported by [FRO 09]. According to the measurements, no evidence for any damage has been recorded and the bridge is in good structural health.

10.7. Discussion, conclusions and acknowledgments

As a pilot application for UHPC in bridge construction, the Gärtnerplatz bridge across the river Fulda in Kassel is the first large bridge project using such material in Germany. It is also the first time a hybrid UHPC-steel structure bridge has been erected. In addition to the application of UHPC, further innovations include the use of structural gluing for the connection between the truss chords and the deck plate and the use of prestressed bolted friction connections between the UHPC and steel.

The Gärtnerplatzbrücke project applies some of the research results obtained at the University of Kassel and at other places in practice and follows some smaller bridge projects in Niestetal, which is situated nearby. Special case approval was obtained since the project comprised several innovative aspects outside the commonly-accepted technical rules. Experimental investigations were performed in order to validate the proposed design and the design checks.
A monitoring program is enabling possible changes in the structural behavior of the superstructure to be identified. Thus, experience on the service life behavior of UHPC, as well as about glued connections, will be gathered.

The authors would like to thank the people at the city of Kassel and at the State of Hesse authorities who made it possible to apply UHPC for this innovative bridge project.

10.8. Bibliography


