SLENDER UHPFRC PRE-STRESSED GIRDERS FOR MID-SPAN BRIDGES AND PARK DECKS: CONCEPTUAL DESIGN AND MODELLING OF THE STRUCTURAL BEHAVIOUR

Jörg Jungwirth (1), Jakob Engel (2), Amine Koubaa (2), Nicholas Schramm (3), Oliver Fischer (3)

(1) University of Applied Sciences, Munich and SSF Ingenieure AG, Munich, Germany

(2) University of Applied Sciences, Munich, Germany

(3) Chair of Concrete and Masonry Structures, Technical University of Munich, Germany

Abstract

Highly relevant and promising research has been carried out in the domain of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) during the last two decades. However, except for some pilot projects e.g. Gärtnerplatz Bridge, UHPFRC has not yet arrived in Germany's construction practice. In order to push forward this efficient technology and bring it to practice, two R&D projects have been launched in cooperation with several industrial partners. The main focus is to develop structures that use the high performance of UHPFRC efficiently while also enabling simple design and production.

In this paper the general approach of the ongoing R&D projects is explained. The conceptual design of the structures, the detailing concept of the shear joint is discussed. Moreover, the bending behaviour of the precast girders as well as an economic evaluation of the developed UHPFRC structures is presented.

Résumé

Plusieurs recherches pertinentes et très prometteuses sont menées dans le domaine du Béton fibrés à ultra-hautes performances (BFUP) depuis plus de deux décennies. Cependant, mis à part quelques projets pilotes comme le pont du Gärtnerplatz, le BFUP n'a pas encore trouvé sa place dans la pratique allemande de la construction. Afin de pousser cette technologie efficace et de développer des applications pratiques, deux projets de R&D ont été lancés en coopération avec plusieurs partenaires industriels. L'objectif principal est le développement de structures tirant bénéfice des hautes performances du BFUP tout en permettant une conception et une production simples.

Dans cet article sont présentés l'approche générale des projets R&D en cours, la conception des structures, le détail du joint de cisaillement, le comportement à la flexion des poutres préfabriquées, ainsi qu'une évaluation économique des structures BFUP développées.

1 INTRODUCTION

In order to bring UHPFRC to Germany's construction practice two collaborative R&D projects are currently being carried out [1]. The design, detailing and dimensioning issues are investigated by means of two practical applications: park decks and precast bridge girders. In this paper the following three central aspects of the research project are presented: detailing and calculation of the shear connection, bending analysis of the girders and the economic assessment.

Research partners are the Technical University of Munich, the University of Applied Science Munich and the structural designer SSF Ingenieure AG. In order to enable direct application and to assure good manufacturability, several industrial partners like LUPP (precast company), Goldbeck (contractor), SOFiSTiK (analysis software) and Lafarge-Holcim (building materials) are involved in the project. Financial support is provided by Bauindustrieverband Bayern (sponsor bridge girders) and Forschungsinitiative Zukunft Bau (sponsor park decks).

2 RESEARCH APPROACH

The main objectives of the research project are the conceptual design and detailing aspects of slender UHPFRC pre-stressed girders for bridges and park deck systems. In order to enable appropriate design, the main aspect of the scientific research work is the investigation of the structural behaviour of the prefabricated and pre-stressed main girders. The practical applicability is checked by means of an economic study.

Due to UHPFRC's high strength, the section of the web can be reduced to a minimum and the fibres can partly replace traditional reinforcement. This reduces dead load of the girders and, in combination with pre-stressing, the structural efficiency as well as the construction process of the girder is optimized. Structural behaviour in bending and shear is different to traditional reinforced concrete (RC) structures. Appropriate analytical design models which consider the crack bridging effects of the fibres, are applied to correctly model the structural behaviour and to enable design of the girders. In order to enable practical and easy to handle design in the future, the structural behaviour is modelled with standard design FEM software using layered shell and beam elements. The performance of these approaches is validated by recalculating experiments from literature and tests completed by the authors.

In order to optimize structural and cost efficiency, only the highly loaded girders are in UHPFRC, whereas the other elements like the bridge deck remain normal strength concrete (NSC). Thus, the joint at the interface UHPFRC – NSC, which is the connection between the girder and the slab is the main focus of the detailing design work. The park deck girders and slabs are both in UHPFRC, in order to reduce the dead load of the slabs and to avoid coating against abrasion and chloride penetration of the park deck slabs. Other positive aspects of UHPFRC slaps are the reduced material consumption and the lower transportation costs due to the lower weight. The shear joint between girder and slab has to assure a rigid bound to provide composite action. Corresponding detailing concepts and design approaches are assessed.

3 STRUCTURAL CONCEPTS OF BOTH PROJECTS

In order to fully take advantage of the high performance of UHPFRC and to achieve economic competitiveness, the structural design must be optimized by using its strong material characteristics optimally [2]. Highly loaded structural members, such as prefabricated park decks or bridge girders, are highly appropriate for the utilization of UHPFRC. To enhance the efficiency of the system further aspects add additional advantages. In the case of park decks UHPFRC can take a double role and render the sealing of the deck surface superfluous, as the material features high durability and low water permeability.

3.1 Park Decks

Car parks are typically structures with a high degree of prefabrication. At present the structural system is generally designed as composite construction combining steel main girders and a NSC deck with a thickness of approximately 10 cm. Using UHPFRC thickness and thus dead load of the slabs can be reduced significantly. Due to the high exposure requirements for park decks (e.g. chlorides from de-icing agents), the concrete plates and steel girders have to be coated, which is an expensive procedure and provides generally only limited durability. By using UHPFRC girders and slabs, this procedure is not required as the material provides high penetration resistance. By comparing the structural behaviour, manufacturing aspects and the general economic efficiency, a system of separate girders and slab elements emerged as the best option. Slender transversal ribs are integrated in the slab panels to gain more flexural strength and stiffness. In the context of park decks fire resistance is also an issue. By adding PP fibres excellent firer resistance could be achieved. As solutions are available this topic is not addressed in the paper.

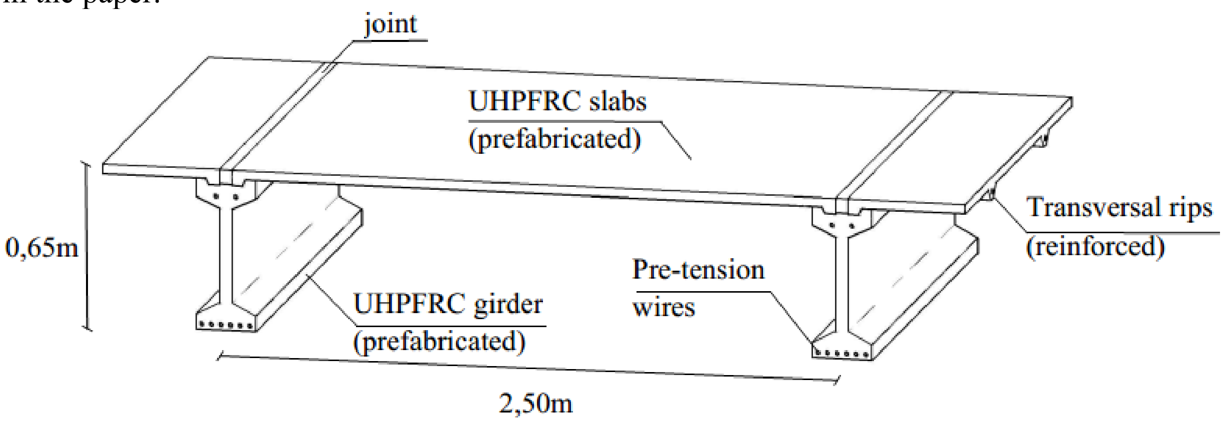

Figure 1: Parking deck system using separate girder and slab elements

3.2 Bridge Girders

For bridge structures standard crossings over 2 x 2 lane highways are considered. For security and maintenance reasons, authorities often demand that these bridges span approximately 36 m without any middle pier. The bridge deck is supported by four to eight longitudinal UHPFRC girders, depending on the width of the bridge. For the girder, two different pre-stressing concepts are proposed. One design approach is a pre-tensioned UHPFRC girder, similar to the ones of the park deck, and the other a post-tensioned girder. Both act in composite action with the NSC bridge deck. The connection will be assured by an in-situ cast joint or with shear keys as shown in figure 2.

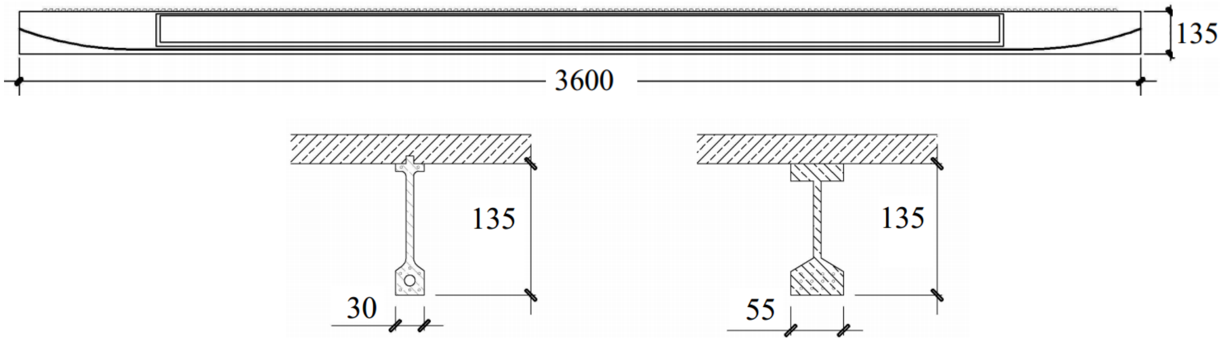

Figure 2: UHPFRC girder (top), section post-tensioned (left), section pre-stressed (right)

4 SHEAR JOINT

To achieve highly efficient structural behaviour of the construction, the precast deck elements have to act together in composite action and transmission of the shear forces has to be assured. To achieve maximum efficiency of the structural system the shear connection should be designed as rigid connection without any slip. In addition to the structural properties, the joint has to be impermeable for water to ensure the serviceability of the parking deck and provide simple assembling.

4.1 Conceptual design

Two different approaches are used for the design of the shear joint. The first option is an in-situ cast joint with 12 mm diameter reinforcement rods. The second option is a dry joint with shear keys, compressed by six threaded rods. Both designs are based on the consideration, to achieve not only an efficient structural behaviour, but an economic and easy to assemble solution.

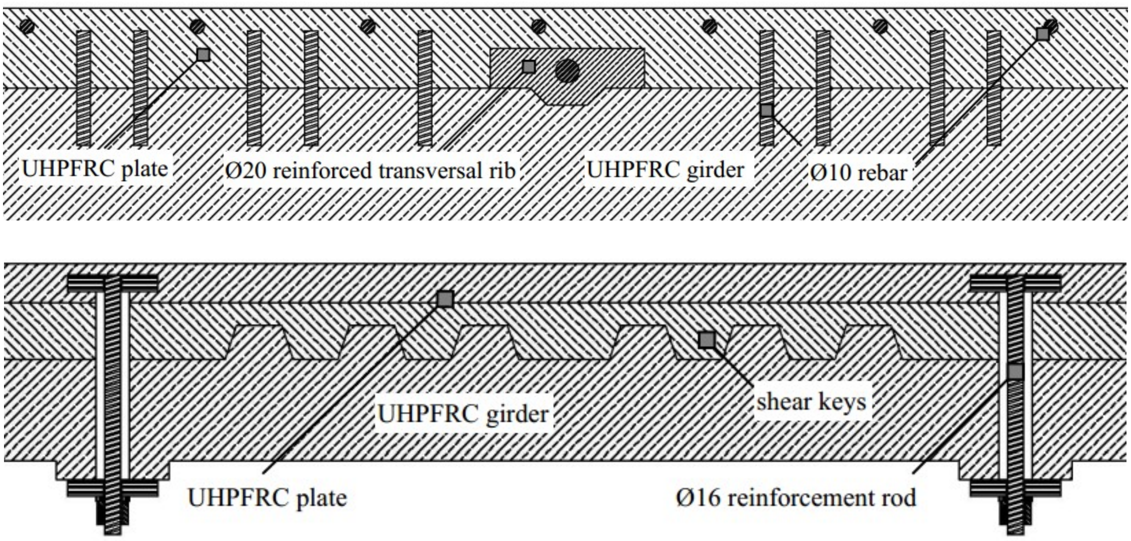

Figure 3: Longitudinal section of shear key design (top) and in-situ cast joint (bottom)

4.2 Structural Analysis

The load-bearing system consists of 16m pre-stressed UHPFRC single span girders with 2.5 m spacing. Slender UHPFRC slabs (3.5cm) with reinforced transversal ribs are placed on top of the girders. The dead load and the service loads for parking areas for light vehicles cause a bending moment of 536 kN at mid-span of the girder and shear stresses of 2.8 MN/m^2 at the highest loaded section in proximity to the support. Alternatively, an equivalent single force of 1.1 MN on both sides of the girder over half the length is considered. According to DIN EN 1992 [4], a distributed shear force for the in-situ cast joint is equated as follows:

$$v_{Rdi} = c \cdot f_{ctd} + \mu \cdot \sigma_n + \rho \cdot f_{yd} \cdot (\mu \cdot \sin \alpha + \cos \alpha) \leq 0.5 \cdot \nu \cdot f_{cd} \quad (1)$$

Thus, in the present case with f_{ctm} taken from [1] and absent of normal stresses:

$$v_{Rdi} = 0.5 \cdot 3.53\text{MN/m}^2 + 0.0126 \cdot 435\text{MN/m}^2 \cdot (0.9 \cdot \sin 90) \leq 0.5 \cdot 0.49 \cdot 200\text{MN/m}^2/1.5 \quad (2)$$

$$v_{Edi} = 2.8\text{MN/m}^2 \leq v_{Rdi} = 6.7\text{MN/m}^2 \leq 32.7\text{MN/m}^2 \quad (3)$$

For the alternative design procedure, according to Empelmann and Oettel [3], the shear resistance can be determined as given in Equation 4:

$$V_F = \mu \cdot \sigma_n \cdot A_{joint} + f \cdot f_{ck} \cdot A_{shear\ key} \quad (4)$$

Thus, in the present case with quasi absent of normal stress in the joint (minimum compression of 0,05 · f_{cd} is assured by the rods):

$$V_F = 0.05 \cdot 113\text{MN/m}^2 \cdot 0{,}075\text{m}^2 + 0{,}19 \cdot 113\text{MN/m}^2 \cdot 0{,}045\text{m}^2 = 1{,}2\text{MN} \geq 1.1\text{MN} \quad (5)$$

The threaded rods allow the slab to stay in place despite the lifting forces caused by the shear keys. They do not participate in the shear resistance.

4.3 Experimental approaches

To verify the theoretical approach, experimental investigations are carried out. For the cast in-situ joint, the behaviour of the reinforcement bars is investigated considering especially the case of a small concrete cover of 2cm. Both are tested to investigate the failure mode. The joints are tested by means of push-out tests where the central part is displaced against the side parts.

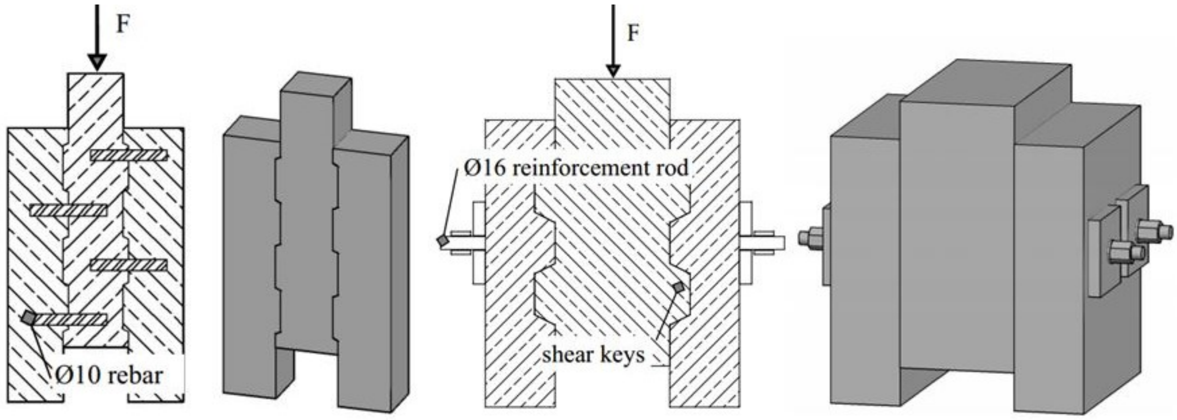

Figure 4: Section and 3D view of test setup: cast in-situ joint (left) and shear key joint (right)

The expected fracture load is 250 kN (100 kN design resistance) for the cast in-situ joint test specimen and 3 MN (1,2 MN design resistance) for the shear key test specimen.

5 BENDING IN GIRDERS

5.1 Design approach

To assure appropriate and efficient design of UHPFRC in bending, the participation of the crack bridging fibres has to be taken into account. At serviceability limit state (SLS), fibres provide excellent crack control with very small crack spacing and little crack width, due to the strain hardening behaviour of UHPFRC.

For choosing the pre-stressing steel quantity the generally applied criteria of 'decompression' according to table 7.1N of DIN EN 1992-1-1 has to be reconsidered. The high strength of the UHPFRC matrix together with excellent crack control of the embedded fibres assures resistance against penetration of aggressive liquids. Thus, at least the matrix resistance f_{ctm} of about 4 to 10 MPa should be considered admissible for the external fibre of the cross section. It would even be possible to consider the resistance of the crack bridging fibres f_{cf0k} (so called ultimate fibre effectiveness), as durability is assured also in cracked state. The ultimate fibre effectiveness f_{cf0k} is defined as the strength of the section provided by the fibres crossing a crack (see [5]). For calculation of the cracked state a non-linear stress distribution has to be considered. For the limit of f_{ctm} only a simple linear elastic calculation is applied.

In order to take full advantage of the material and enable efficient load bearing at ultimate limit state (ULS) fibre participation has to be taken into account for the bending strength of the section (see figure 6).

5.2 Structural analysis

According to DIN EN 1991-1-1, a service load of $q_k = 2{,}64$ kN/m^2 is required for the park decks. For the surface of $A = 2{,}5$ m $\cdot$ 16 m = 40 m^2 the service load for a girder is $q_k = 7{,}26$ kN/m. The dead load resulting from the girders and the slabs own weight is $g_k = 4{,}23$ kN/m. At ULS, these loads cause a bending moment at mid-span of the girder of $M_{Ed} = 531$ kNm. Considering the rare combination of actions, in SLS a bending moment of $M_{Ed,raare} = 367{,}86$ kNm results.

The required pre-stressing steel cross-section has to be determined, according to table 7.1N of DIN EN 1992-1-1, by applying the decompression criterion. This criteria requires that for the external fibre of the cross section no tension is admissible. The criterion was established for conventional reinforced concrete and does not take into account the special characteristics of UHPFRC. If we apply this criterion, a pre-stressing steel section of $A_p = 6{,}84$ cm^2 is required. If a tensile strength f_{ctm} as low as 10 MPa would be considered admissible, the resulting pre-stressing steel is reduced to $A_p = 4{,}5$ cm^2.

In order to equilibrate the resulting moment in the transportation state, 2 pre-stressing steel tendons are placed in the upper cord of the cross section. 6 pre-stressing steel tendons are placed in the lower cord of the cross section. The resulting pre-stressing section in the lower cord is $A_p = 5{,}58$ cm^2.

The bending behaviour of UHPFRC pre-stressed girders is different to the behaviour of traditional reinforced concrete (RC) or pre-stressed girders. For UHPFRC, after initial cracking, tensile stresses continue to be carried by the steel fibres that are crossing the crack.

The stress carried by the steel fibres depends on the crack width. In the phase of fibre activation, this stress can be calculated according to Jungwirth [2] with the formula:

$$\sigma_{cf}(w) = \sigma_{cf0} \cdot \left(2\sqrt{\frac{w}{w_0}} - \frac{w}{w0}\right) \tag{6}$$

σ_{cf0} is according to Lautbecher [5]

$$\sigma_{cf0} = \eta \cdot g \cdot \rho_f \cdot \frac{\tau_f \cdot l_f}{d_f} \tag{7}$$

with
g : fibre effectiveness coefficient (g = 1)
η : fibre orientation coefficient (η = 0,5)

In the present case σ_{cf0} = 15,12 MN/m².

The calculated crack width when reaching the resistance of the crack bridging fibres at peak load is calculated according to Lautbecher [5]:

$$w_{0,cal} = \frac{1{,}7 \cdot f_{ctm} \cdot l_f^2}{E_f \cdot \phi_f} = \frac{1.7 \cdot 10{,}26 \cdot 17^2}{210000 \cdot 0{,}15} = 0{,}16mm \tag{8}$$

For a crack width of 0,16 mm

$$\sigma_{cf,d}(w = 0{,}16\ mm) = \sigma_{cf0,d} = 9{,}88\ {}^{MN}/_{m^2} \tag{9}$$

The equilibrium at the cracked section considering the force on the steel fibres is illustrated in Figure 6.

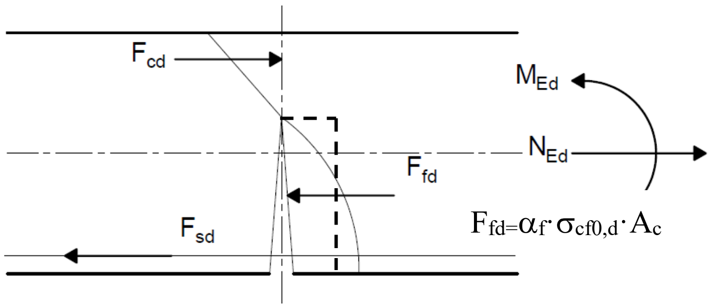

Figure 5 : Equilibrium at cracked section.

According to Beton Kalender 2013 [6] this equilibrium is fulfilled by the equation:

$$F_{sd} = \frac{M_{Eds}}{z} + N_{Ed} - \alpha_f \cdot \sigma_{cf,d}(w) \cdot A_c = \frac{0{,}531}{0{,}578} - 0{,}5 \cdot 9{,}88 \cdot 0{,}077 = 0{,}537\ MN \tag{10}$$

For a small compression zone α_f= 0,5.

Thus required steel force for a crack width of w = 0,16mm is F_{sd} = 0,66 MN. This force is less than the force that can be carried by the pre-stressing steel section. An additional reinforcing steel section is not required.

The deflection of the girder in mid-span calculated in un-cracked state is f = 2,8 cm < 1/500 = 3,2 cm.

In order to verify the calculation, the research partner SOFiSTiK has implemented the material law of UHPFRC in his FEM analysis software. The results of both, the analytical calculation presented herein and the SOFiSTiK FEM modelling, will be compared with experimental investigations.

5.3 Results

The bending behaviour of a UHPFRC pre-stressed girder allows significant design changes compared to conventional reinforced concrete. First the needed pre-stressing steel section can be reduced when tensile stresses are considered admissible at the external fibre of the cross section, secondly the effect of the steel fibres reduces the required reinforcing steel substantially. In addition to that, the higher Young modulus of the UHPFRC reduces the deflection of the girder.

6 ECONOMIC ASSESSMENT

New materials and design approaches will only be successful when they are economic. To assess the economic reliability a cost analysis is carried out, considering the construction costs as well as the operation period. The higher material costs of UHPFRC compared to NSC are compensated by its higher strength, better durability (lower life cycle costs) and by its light construction (lower transport cost and erecting costs). In the cost assessment, only the divergent cost items are considered. Thus, the total is only a value to compare the costs, it does not show the real total costs. All costs that are identic in both constructions (UHPFRC and NSC), like installation costs, are not mentioned.

Information about prices for UHPFRC vary between low costs for research purpose where only material costs are considered and the higher costs of commercialised products where development costs, material, transport and technical support is included. For the economic assessment UHPFRC costs are calculated with an intermediate value of 1600 €/m^3. This allows a realistic estimation without having to make assumptions about future price development and price politics on the market.

6.1 Costs park decks: traditional NSC structure and optimized UHPFRC structure

Traditional park decks are built as composite structures using steel girders and NSC decks. The UHPFRC structure consists of pre-stressed girders and slender prefabricated slabs. All costs are calculated for one unit of 2,50 m x 16,00 m. As shown in Figure 6, the NSC park deck is slightly more economic under the given boundary conditions. The system in NSC is already highly optimized. The optimized UHPFRC version is an economic system, the costs are similar to the NSC system.

NSC Park Deck

Position	Comment	Costs	Unit	Qty.	Unit	Costs [€]
Base cost						
NSC Material	cast in-situ joint	150	€/m^3	0,15	m^3	22
Coating	includes renovation	75	€/m	18,50	m	1388
NSC Slab	complete	60	€/m^2	40,00	m^2	2400
Steel Girder	complete	2000	€/t	0,80	t	1600
Transportation Costs per unit (16m x 2,5m)						
NSC Slab		1200	€/trip	0,50	trips	600
Steel Girder		1200	€/trip	0,10	trips	120
Installation Costs similar, hence not indicated						
					Total	6130

UHPFRC Park Deck

Position	Comment	Costs	Unit	Qty.	Unit	Costs [€]
Base cost						
UHPFRC Material	cast in-situ joint	1600	€/m^3	0,15	m^3	237
UHPFRC Slab	material only	1600	€/m^3	0,80	m^3	1280
UHPFRC Slab	without material	35	€/m^2	40,00	m^2	1380
UHPFRC Girder	without material	477	€/t	2,41	t	1148
UHPFRC Girder	material only	640	€/t	2,41	t	1539
Transportation Costs per unit (16m x 2,5m)						
UHPFRC Slab		1200	€/trip	0,20	trips	240
UHPFRC Girder		1200	€/trip	0,17	trips	200
Installation Costs similar, hence not indicated						
					Total	6024

Figure 6: Cost assessment for park decks: NSC structure (l.), UHPFRC structure (r.)

6.2 Costs bridge girders: traditional NSC structure and optimized UHPFRC structure

For the bridge of 36 m span four different systems are investigated. A two span bridge with pre-stressed NSC girders (Figure 7), a single span bridge with pre-stressed UHPFRC girders (Figure 7), a single span bridge with pre-stressed NSC girders (Figure 8) and a single span bridge with UHPFRC girders and post-tensioning (Figure 8). To be able to compare the costs, the girder costs for the two span bridge (2 x 18m) are doubled. For each option the girder cross section including bridge deck and a view of the structural system are shown on top and the cost calculation below.

NSC Bridge Girder

Position	Comment	Costs	Unit	Qty.	Unit	Costs [€]
Base cost						
NSC Girder	without material	10110	€	1	-	10110
Reinforcement	normal	1000	€/t	2,07	t	2071
Reinforcement	pre-stressed	3000	€/t	0,79	t	2357
NSC Girder	material	150	€/m³	13	m³	1890
Transportation Costs						
NSC Girder		2000	€/trip	1	-	2000
Installation Costs, similar, hence not indicatd						
Additional Girder	half span girders	18429	€	1	-	18429
					Total	36857

UHPFRC Bridge Girder

Position	Comment	Costs	Unit	Qty.	Unit	Costs [€]
Base cost						
UHPFRC Girder	without material	10110	€	1	-	10110
Reinforcement	normal	1000	€/t	1,51	t	1509
Reinforcement	pre-stressed	3000	€/t	1,06	t	3179
UHPFRC Girder	material	1600	€/m³	15,76	m³	25215
Transportation Costs						
UHPFRC Girder		2000	€/trip	1	-	2000
Supplement	higher load	2000	€/trip	1	-	2000
Installation Costs, similar, hence not indicatd						
Supplement	higher lifting load	2000	€	1	-	2000
Deduction	no pillar required	-11059	€	1	-	-11059
					Total	34955

Figure 7: Cost assessment for bridge girders: NSC structure (l.), UHPFRC structure (r.)

NSC Bridge Girder

Position	Comment	Costs	Unit	Qty.	Unit	Costs [€]
Base cost						
NSC Girder	without material	10110	€	1	-	10110
Reinforcement	normal	1000	€/t	4,19	t	4190
Reinforcement	pre-stressed	3000	€/t	1,40	t	4205
NSC Girder	material	150	€/m³	20	m³	2993
Transportation Costs						
NSC Girder		2000	€/trip	1	-	2000
Supplement	higher load	3000	€/trip	1	-	3000
Installation Costs						
Supplement	higher lifting load	2000	€	1	-	2000
					Total	28497

UHPFRC Bridge Girder

Position	Comment	Costs	Unit	Qty.	Unit	Costs [€]
Base cost						
UHPFRC Girder	without material	10110	€	1	-	10110
Reinforcement	normal	1000	€/t	0,71	t	710
Reinforcement	pre-stressed	3000	€/t	0,93	t	2798
UHPFRC Girder	material	1600	€/m³	7,85	m³	12561
Transportation Costs						
UHPFRC Girder		2000	€/trip	1	-	2000
Installation Costs						
Supplement	pre-stressing	500	€	1	-	500
					Total	28679

Figure 8: Cost assessment for bridge girders: NSC structure (l.), UHPFRC structure (r.)

6.3 Comparison

The comparison of the costs for the NSC and the UHPFRC structures shows almost similar prices for both types of structures. By changing the structural system from a two span bridge in NSC to a single span bridge in UHPFRC, the UHPFRC system is more economic. In the studied cases an economic solution is obtained for all of the structures at a UHPFRC price of 1600 €/m^3. Only the second bridge girder (Figure 7 right) is slightly more expensive. Below the assumed price of 1600 €/m^3, UHPFRC structures are highly cost efficient.

The difference for the park decks –about 100€/deck seems to be small, but a standard park deck consists of approximately 250 units. Thus, the total additional costs are quite high. The amount of bridge girder per bridge is significantly lower, but the cost difference is higher.

Thus, for optimized systems UHPFRC is already competitive today, but when UHPFRC is frequently used in construction practice material prices will decrease and enable economic application of UHPFRC in a wide range of structural systems. In addition there will be monetary advantages due to higher durability and reduced maintenance costs of UHPFRC structures.

7 CONCLUSIONS

Park decks and pre-stressed bridge girders are both highly suitable for the use of UHPFRC. The research has shown the high potential of UHFPRC. Slender and simple designs are possible. In this article main research aspects of the two research project are presented. Further research work and experimental investigations are ongoing.

The shear connection between girder and deck can be designed with shear keys or with an in-situ cast joint. Both theoretical approaches have shown promising results and will be verified by experimental investigations. The proposed shear connections assure a high structural efficiency.

The investigation on bending behaviour of the park deck showed that it is possible to have a girder with only pre-stressing steel and without traditional reinforcement. This is due to the effect of the steel fibres, which participate in load bearing and provide excellent crack control. The higher Young modulus of the UHPFRC leads to a stiff structural behaviour and reduces the deflection of the girder. The shear behaviour was not presented in this paper, however this topic is an important and integral part of the research project. Results of the investigations on this topic will be presented in future publications.

The cost assessment has shown the potential of UHPFRC for economic constructions. The lower weight of the girders and slabs allows cost reduction for transport and installation. As soon as UHPFRC is part of the daily construction practice, the costs for material will decrease and make the UHPFRC design even more economical.

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