Structural concepts for application of UHPFRC in construction practice: sustainable precast park deck systems

Jörg Jungwirth[2], Nicholas Schramm[1], Oliver Fischer[1], Stefan Maly[3], Filip Orsanic[3], Carsten Geisenhanslüke[4], Manuel Göbel[4]

1: Institute of Structural Engineering, Technical University of Munich, Germany
2: University of Applied Sciences, Munich and SSF Ingenieure AG, Munich, Germany
3: SOFiSTiK AG, Munich, Germany
4: OPTERRA GmbH, Germany

Highly relevant and promising research has been carried out in the domain of Ultra-High Performance Fiber Reinforced Concrete (UHPFRC). However, except for some pilot projects UHPFRC has not yet arrived in German'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. Main focus is on the one hand side to develop structures that uses the high performance of UHPFRC in an appropriate way and on the other hand side to enable simple design and production. In this paper is presented the general approach of the ongoing R&D project as well as first results of the analysis of UHPFRC park deck elements. The slender UHPFRC decks of only 3.5 cm depth show highly efficient structural behaviour. Their flexural failure mode is assessed with experimental investigations and could be well represented in FEM analysis.

Keywords: FEM, slabs, flexural failure, ribbed plate, material development, experiments, park decks

1 Introduction

Despite profound research work and several excellent examples carried out worldwide Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) has not yet arrived in construction practise in Germany. In order to develop efficient UHPFRC structures and to establish the procedure for implementation of UHPFRC projects two R&D projects have been initiated as a cooperation project of scientific institutes (TU Munich and Hochschule München), structural designer (SSF Ingenieure AG) and several industrial partners. By means of two practical applications – park decks and precast bridge girders – are investigated design, detailing and dimensioning issues. In cooperation with the industrial partners are developed appropriate design tools (SOFiSTiK) and an easy to employ and robust concrete mixture (OPTERRA). As a spin-off of the project it is intended to implement prototype projects to prove feasibility.

The research project is in an early phase. As one of the first investigations the application of UHPFRC for precast parking deck systems with separated slab and girder elements is presented in this paper.

2 Conceptual Design

In order to fully take advantage of the high performance of UHPFRC and to achieve economic competitiveness, the material must be employed in an appropriate way using its strong material characteristics [1]. Highly loaded structural members like prefabricated park decks or bridge girders are highly appropriate for the utilisation of UHPFRC. In the case of park decks UHPFRC can take a double role and render superfluous the sealing of the deck surface as the material features high durability and low water permeability.

Park Decks

Car parks are typical structures with a high degree of prefabrication. At present the structural system is generally designed as composite construction combining steel main beams and a normal strength concrete deck with a thickness of approximately 10 cm. Due to the high requirements for park decks, the concrete plates and steel girders have to be coated, which is an expensive procedure and shows generally only limited durability. By using girders and slabs made of ultra high performance concrete, this procedure is not required and in addition the dead load of the slabs can be drastically reduced. By comparing the structural behaviour, manufacturing aspects and the general economic efficiency for different possible alternatives of a slab system, a system of separate girders and slab elements emerged as the best option. To gain more flexural strength and stiffness of the slabs, slender transversal ribs are integrated in the slab panels. Figure 1 shows the structural system:

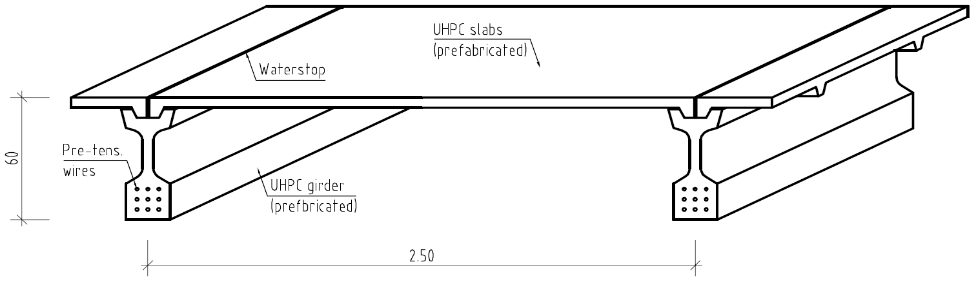

Figure 1: System of separate girder and slab elements for parking decks

For this topology the flexural strength and the resistance to punching of the thin UHPFRC slab is assessed in order to optimize the slab thickness. The load bearing characteristics of the entire system in serviceability and ultimate limit states are investigated in large-scale tests under realistic loading and boundary conditions. Based on the results design approaches will be developed for this new and innovative structural system. In addition, the shear behaviour of the pre-stressed girders with different types of reinforcement (steel fibres, conventional or textile reinforcement) is analysed through experimental and numerical simulations.

The chosen example requires several new design approaches in order to optimise the structure for the use of UHPFRC. The corresponding scientific research as well as engineering detailing is a main focus of the research project. The section of the web, for example, could be reduced to a minimum and the fibres can 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. For this purpose the shear behaviour and stability of these slender pre-stressed girders is assessed. The behaviour will be studied through experimental and numerical simulations.

3 Material Development

In the context of bringing UHPFRC to practice a new easy to use UHPFRC is developed for the project by the industrial partner OPTERRA. Main focus is on economy, easy handling in typical batching plants and robustness with respect to the variable production conditions in construction practice. For this purpose a coarse aggregate UHPC has been chosen that will be delivered as a premix in bags, big bags or in a silo.

The development of the UHPFRC mix design started with the selection of a suitable binder compound. First, several CEM I 52.5 R (C1 to C4) were tested to decide which has high strength as well as good workability. Therefore mortar containing 400 g ordinary Portland Cement (OPC), 80 g microsilica, 1350 g standardised sand according to DIN EN 196-1 [2], 144 g water and 0.3 % PCE related to the binder, was produced. Thus, the water to binder ratio (w/b) was 0.30. The slump test referring to the slump test in DIN EN 196-1 [2], but without shocks, as well as strength tests on mortar prisms (40 x 40 x 160 mm³) at 1, 7 and 28 days were carried out according to DIN EN 196-1. C1 showed good results in slump but lowest strength (figure 2). C2 showed significant lower slump flow at 45 min. C3 showed highest strength but lowest results in slump flow. Thus, C4 was chosen because of good performance for slump flow and strength development.

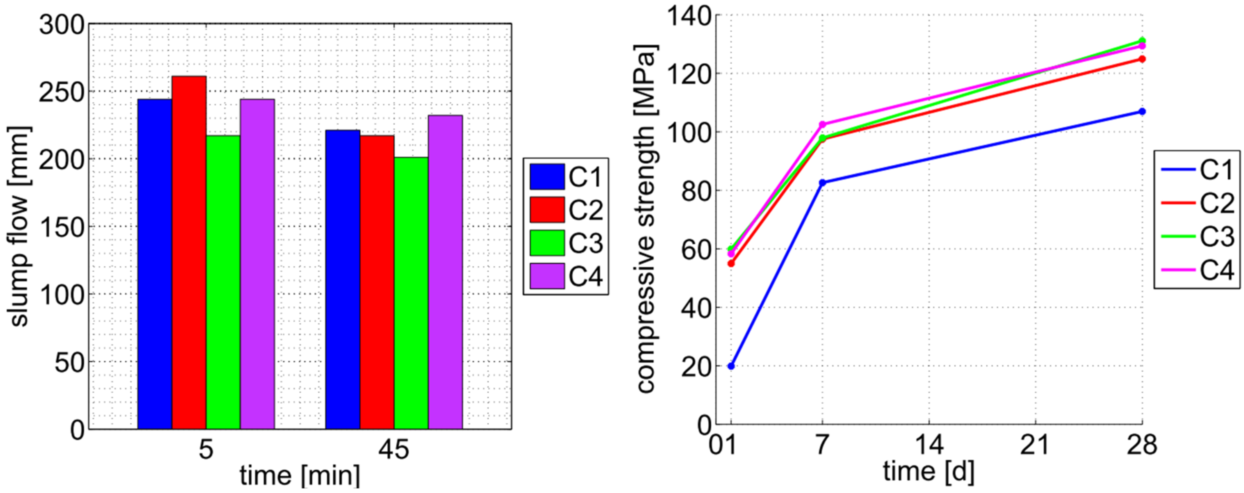

Figure 2: (l.) slump flow and (r.) compressive strengths of mortars containing four different CEM I 52.5 R (C1 to C4)

Due to the low water to binder ratio (w/b) of the UHPFRC mix the use of a suitable superplasticizer is imperative. Three PCE based superplasticizers - P1, P2 and P3 - were tested. As done before, mortar was produced and slump flow as well as strength tests were conducted (figure 3).

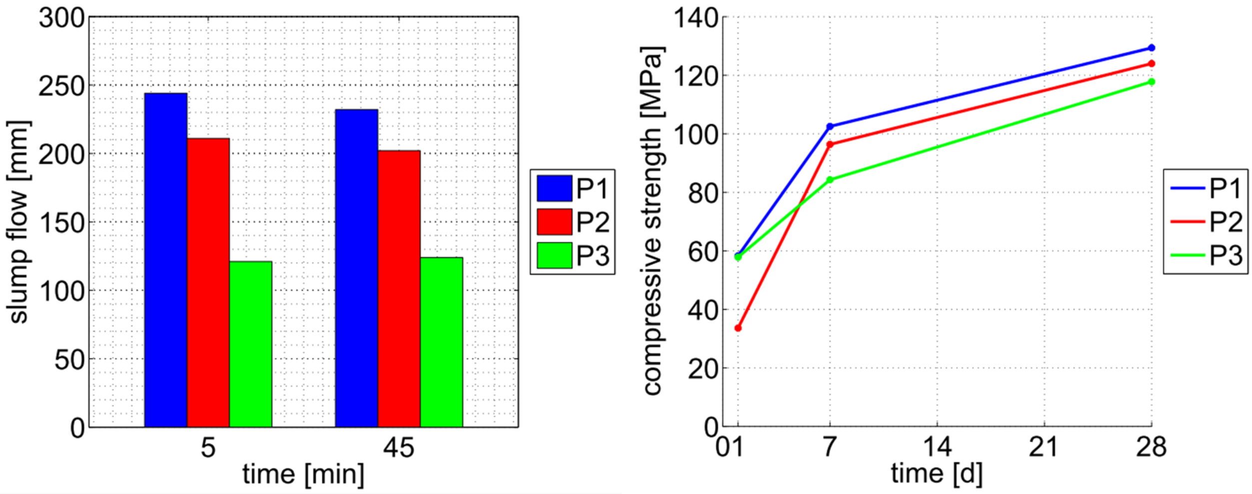

Figure 3: (l.) slump flow and (r.) compressive strengths of mortars containing three different superplasticizers (P1 to P3)

In order to create a robust and sustainable UHPFRC mix design, supplementary cementitious materials (SCM) can be used. Hereby the clinker amount can be reduced and the carbon dioxide footprint of the product decreases. Moreover, SCMs can increase packing density and workability whereas shrinkage and the heat of hydration can be decreased. To obtain bright coloured UHPFRC surfaces the chosen SCMs need to be bright in colour. Thus, in addition to a bright coloured microsilica an also very bright coloured ground granulated blast furnace slag (GGBFS) was added to the compound in different amounts. Again mortar tests were conducted as described before. Now the amount of OPC was partly substituted by GGBFS by volume. Microsilica was reduced to 40 g. Superplasticizer P1 was added with 0.3 % related to the binder. Recipe C4P1H A had the highest and C4P1H C the lowest substitution of OPC by GGBFS with recipe C4P1H B in between. Only slight differences were shown in slump and strength. Still the recipe C4P1H B was chosen as best because of higher slump flow and similar strength compared to recipe C4P1H C.

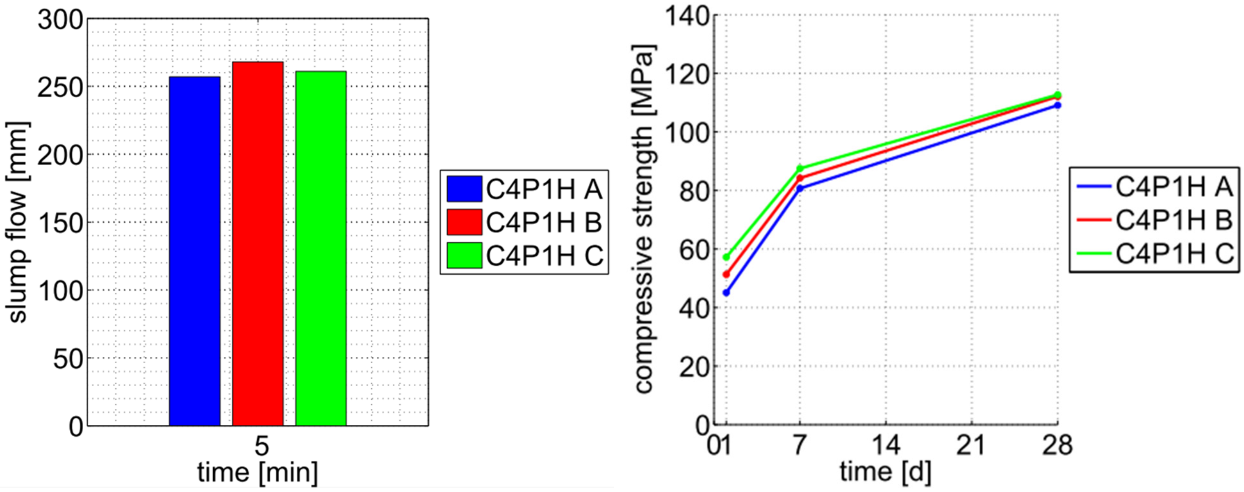

Figure 4: (l.) slump flow and (r.) compressive strengths of three different recipes of mortars containing OPC, microsilica and GGBFS.

In optimized combination of the developed compound with quarzitic and basaltic aggregates high packing density and thus high strength can be achieved. In addition, steel fibres (Ø 0.15 mm x 19 mm) are added to increase ductility and tensile strength. The desired compressive strength (characteristic cube compressive strength) of the UHPFRC at 28 d is more than 150 MPa.

4 Design Software

Numerical simulation using Finite Elements (FE) can be considered the standard tool for designing structures in today's design practice. In order to enable the application of standard design methods for structural analysis of UHPFRC structures, SOFiSTiK Company is involved in the project to develop easy-to-use tools for designers.

The design process for standard reinforced concrete does usually not employ material nonlinear computations. In contrast, analysis of UHPFRC require more advanced considerations to correctly predict deformations and structural behaviour at limit states, especially when the characteristic behaviour is governed by tension in unreinforced sections. Simulation of UHPFRC structures can be carried out by various methods like 3D FE volume models with involved continuum mechanical material models, but standard structural design procedures for such structures are not available in commercial software. Hence a large part of the design consists of calibration and validation of assumptions and chosen numerical models. In addition it is very common to reduce the dimensionality of the analysed problem, most building structures are adequately modelled using beam and shell elements. Numerical models with wider practical application therefore focus on important effects and consider them e.g. as a modification of the tensile part of a 2D stress-strain law.

The SOFiSTiK FE software package allows the input of arbitrary stress-strain curves for the material behaviour of beam and shell elements. The numerical implementation follows the approach of a layered shell element in a classical elasto-plastic constitutive framework, the material response is evaluated and occurs in several material layers over the thickness of the respective element. Already existing applications e.g. for fibre reinforced concrete in Germany followed regulations and worklaws specified by organisations like DBV and DAfStB. For UHPFRC SOFiSTiK worked as project partner with Lafarge to implement a worklaw for Ductal® FM following the SETRA recommendations [3]. In addition to several project applications, the computational results of the approach followed by SOFiSTiK were compared to other software and test results for reinforced UHPC with organic fibres in 2013 [4]. It is important to note that these results and implemented material worklaws were focused on analysing the UHPFRC beams [5] using a beam element modelling approach.

One of the aims of the here presented research is to verify the behaviour of thin UHPFRC plates with integrated ribs by using a relatively easy to handle finite element approach. Therefore, by implementing the layered shell elements the focus is set on determining the corresponding recommendations for material worklaw and FE mesh size in the application area of a modern commercial software.

The load and displacement control analysis of a ribbed plate is performed using the SOFiSTiK FE software package. The effects of the relatively large displacements are caused by implementing the nonlinear analysis according to the third order theory. The material behaviour of the shell elements is described with an input of UHPFRC stress-strain curves obtained from the experiments in the literature [5,6]. A typical material worklaw implemented in the analysis is shown in Figure 5.

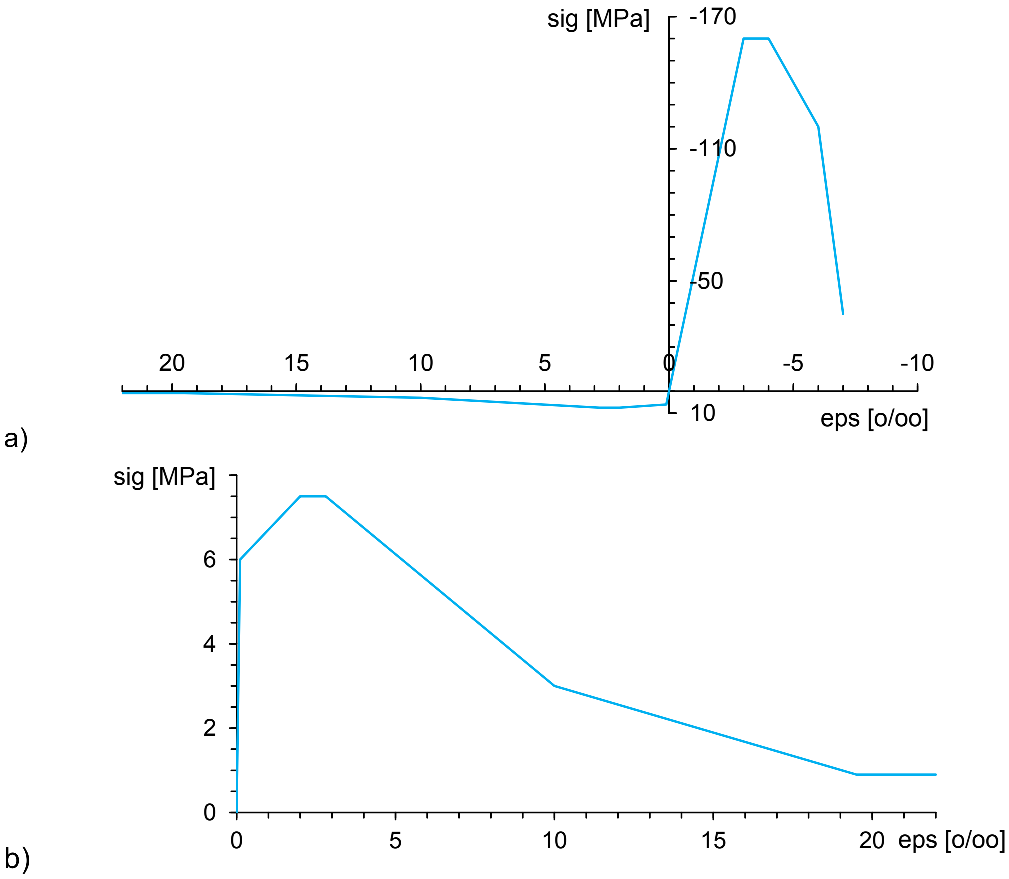

Figure 5: (a) Stress strain curve in tension and compression for UHPFRC; (b) Stress strain curve in tension for UHPFRC

Currently SOFiSTiK has no implemented regularization method, therefore the mesh size has an influence on the obtained results, mainly on the post peak behaviour of the calculated force-displacement curve. As it was shown in the previous research [6], a recommended size of the beam elements was determined, i.e. 2/3 of the beam’s height. It is therefore important to determine an appropriate guideline for an element size in the layered shell modelling approach.

5 Experimental Investigations

In order to investigate structural behaviour, to optimize dimensions and sections as well as to develop design approaches, experimental investigations are carried out. For this initial phase a series of park decks is tested.

According to German design standards proof must be obtained, that no punching shear or bending failure occurs for a wheel load with a design value of 15 kN on a load area of 200 x 200 mm. After certain parametric studies it was concluded, that a slab thickness of only 35 mm is sufficient, but transversal ribs are necessary to reduce the deflection and to improve the vibration behaviour of the system. To determine the influence of the reinforcement and the transversal ribs, three different options (which were investigated numerically in advance, see chapter 6) will be validated by means of large scale-tests.

Table 1 shows an overview of the three different variants of the ribbed plate. The dimensions of the plates were reduced compared to the real geometric dimensions, as described later (see chapter 6).

Table 1: Experimental matrix for investigated slab configurations

Label	Dimensions	Transversal ribs	Reinforcement in transversal ribs
P1-0-tr-0-reinf	2.50 x 2.44 x 0.035	-	-
P2-2-tr-0-reinf	2.50 x 2.44 x 0.035	2 x 0.05 m	-
P3-2-tr-6.28-reinf	2.50 x 2.44 x 0.035	2 x 0.05 m	2 ∅ 20

The end supports of all slabs are designed simply supported and are only on the short sides, thus the slabs are uniaxial spanned. The point load with a load area of 200 x 200 mm will be applied centrally and displacement controlled. To measure the deflection of the plates, linear inductive displacement sensors will be installed. To record the strains in the slab and the discrete reinforcement, strain gauges and fibre optical sensors will be used.

The results of the tests are presented at the presentation only.

6 Numerical Investigations

General

The principal aim of the numerical investigations presented in this paper is dimensioning of the slab for testing. For this purpose is assessed the failure mode of the slabs - punching shear and flexural failure can occur – and the influence of certain parameters such as a discrete reinforcement and transversal ribs. Furthermore, the differences for the above mentioned finite element approaches are analysed.

With the aim to reduce the dimensions of the specimens, the length of the slab was reduced to a quarter of the real length and the stiffness of the continues slab was reproduced by an edge beam. The dimensions of the edge beam are chosen in order to obtain the same structural behaviour for the reduced subsystem (see figure 6). In contrast, the width of the slab is 2.50 m and was not reduced.

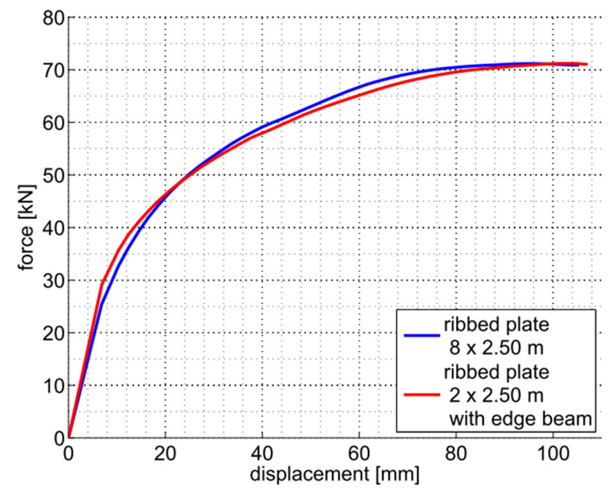

Figure 6 Comparison of load-deflection-curves for a slab with real dimensions (8.0 x 2.50 m) and a dimensionally reduced system (2.50 x 2.00 m) with edge beam

Analysis of the slab with different finite element approaches

The numerically investigation of the structural behaviour of the slabs has been carried out using different finite element approaches and programmes. On the one hand, the system was discretized with 3D continuum finite elements using the program ANSYS with the plastic material model law14 in Multiplas Material Library and on the other hand the previously described layer shell elements in the program SOFiSTiK.

To assess the behaviour of the slabs before testing, the slab configurations shown in table 1 were analysed numerically. For all calculations the similar edge beam (w = 0.22 m, t = 0.085 m, without conventional reinforcement) was used. Table 2 shows the major material parameters of the UHPFRC calculations are based on:

Table 2: Assumed material parameters for all finite element simulations

Compression strength [N/mm²]	Tensile strength [N/mm²]	Young's modulus [N/mm²]	Poisson ratio [-]
160	7.5	50000	0.2

Figure 7 shows the calculated load-deflection-curves for the different slab configurations:

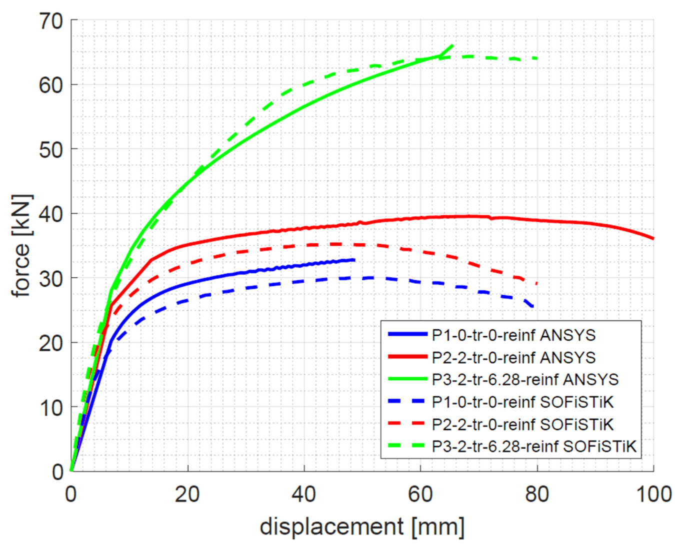

Figure 7: Load-deflection-curves for different slab configurations; dashed line: FEM calculation with layered shell elements (SOFiSTiK), solid line: FEM calculation with 3D-continuum elements (ANSYS)

The numerical analysis shows, that the general structural behaviour can be modelled adequately with both FEM tools. Deviations of the results for the two different finite-element-approaches are relatively small. The slab with integrated transversal ribs shows a higher stiffness and the strength is about 25 % higher. The slab with reinforced transversal ribs (∅ 20 in each rib) shows a significant higher stiffening effect and strength.

The load-deflection-curves for all slabs show the typical branch for a flexural failure. A similar behaviour has also been observed for certain specimens in experimental tests by Harris of fibre reinforced slabs made of ultra high performance concrete without transversal ribs [7].

7 Conclusion

The interim findings of the ongoing R&D project show several promising results. The developed material is ready to use. Further optimisation will be carried out in order to simplify application under real conditions in batching plants. The software tool is able to model the specific characteristics of the UHPFRC. The corresponding software modules will be optimized and implemented in the standard software package to enable use by designers.

The conceptual design of the park deck but also of bridge systems (not content of this paper) are taking advantage of high performance of the UHPFRC and show high efficiency. Their structural behaviour could be represented using standard software (here: SOFiSTiK). Compared to standard concrete solutions could be achieved: easier installation, lighter elements, higher durability, reduced overall life cycle costs.

Main focus of the ongoing R&D project is to continue scientific and experimental work, further develop the structural systems and detailing and finally to realise pilot projects to proof application in construction practice.

References

[1] Jungwirth, J., Zum Tragverhalten von zugbeanspruchten Bauteilen aus Ultra-Hochleistung-Faserbeton, Doktorarbeit EPFL Nr. 3429, p. 158, Lausanne, 2005.

[2] DIN EN 196-1:2005-05, DIN Deutsches Institut für Normung e.V., Berlin, 2005

[3] AFGC SETRA, Ultra High Performance Fibre-Reinforced Concretes, Interim Recommendations, Association Francaise de Genie Civil, January 2002.

[4] Dobrusky, S.; Lussou, P.; Chanvillard, G.; Perez, F.; Corvez, D.: Flexural Behaviour of UHPC beams reinforced with organic fibres and steel bars. RILEM-fib-AFGC Int. Symposium on Ultra-High Performance Fibre-Reinforced Concrete, UHPFRC 2013 – October 1-3, 2013, Marseille, France

[5] Al-Hassani, H.M., Wasan, I. K., and Lubna, S.D. (2015) Proposed Model for Uniaxial Tensile Behavior of Ultra High Performance Concrete. Eng. &Tech.Journal, Vol.33, Part (A) No.1

[6] Al-Azzawi, A.A., Ahmed S.A., and Husam, K.R. (2011) Behavior of ultra high performance concrete structures. ARPN Journal of Engineering and Applied Sciences 6.5: 95-109.

[7] Harris, D.K., Roberts-Wollmann, C.L., Characterization of the Punching Shear Capacity of Thin Ultra High Performance Concrete Slabs, Technical report, Virginia Transportation Research Council, June 2005.