EXPERIMENTAL INVESTIGATIONS ON UHP(FR)C BEAMS WITH HIGH STRENGTH REINFORCEMENT

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Abstract

In the frame of a research project funded by the Austrian Research Foundation (FFG.) several investigations were performed concerning the overall behaviour of ultra high performance concrete members reinforced with different combinations of fibres and high grade steel bars. Small scale beams made out of UHPFRC with a compressive strength of about 180 MPa have been subjected to three- and four-point bending tests and using the results, the post cracking behaviour of the UHPFRC was back-calculated. In parallel large scale beams were subjected to four-point bending tests. These beams were reinforced with high grade steel reinforcement (St900/1100). The ULS and SLS behaviour have been investigated with and without fibres and with different reinforcement ratios. The failure loads and failure modes have been analysed with different analytic approaches in comparison to the test results. During the tests it turned out that the usage of about 2 % steel fibres increased the load bearing capacity of the present beams by about 15 % on average. It turned out that the combination of UHP(FR)C and high grade steel is promising for members subject to bending, provided the SLS criteria are paid special attention in design.

Résumé

Plusieurs études ont été réalisées dans le cadre d'un projet financé par le fonds autrichien de la recherche concernant le comportement globale d'éléments en béton à ultra-hautes performances renforcés par différents types d'armatures et combinaisons de fibres. Des poutrelles en BFUP de résistance 180 MPa ont été testées en flexion 3 et 4 points et on en a déduit le comportement post-fissuration du BFUP. En parallèle de grandes poutres ont été testées en flexion 4 points. Ces poutres étaient armées d'acier de haute résistance (St900/1100). Le comportement à l'ELS et à l'ELU a été étudié avec ou sans fibres et avec différents taux de ferraillage. Les charges et modes de ruine ont été analysés grâce à différents modèles analytiques et comparés aux résultats des essais. Ces derniers ont montré qu'un taux de fibres de 2 % augmentait les capacités portantes des poutres étudiées de 15 % en moyenne. La combinaison BFUP - armatures de haute résistance s'avère prometteuse pour les éléments fléchis, sous réserve d'avoir bien pris en compte en conception les critères liés aux états limites de service.

1. INTRODUCTION AND RESEARCH SIGNIFICANCE

Due to the developments of the last decades several high performance materials appeared in the field of civil engineering. “HiPerComp” is an on-going research project at CUAS with the major aim of bringing these materials into the practice. Since the structural behaviour of high performance materials in terms of durability, sustainability and fractural properties is not investigated sufficiently, and the standards not yet contain recommendations regarding their design, several members made out of UHP(FR)C and high grade steel have been produced and tested to understand better the composite behaviour of these high performance materials, thereby providing necessary knowledge for the realisation of new applications. The use of ultra high strength concretes with their reduced porosity and permeability lead to more sustainable structures in terms of an increased durability while saving materials.

2. TESTING PROGRAM

In order to get a comprehensive understanding of the overall behaviour of UHPFRC, several different types of investigations and a variety of test series were performed in parallel. The main focus was laid on three different subjects. The first subject was to develop UHP(FR)C mixtures optimized in terms of compressive strength (about 160-180 MPa) and workability (details of the mixture proportions are given in [1]). The second target was to carry out a full, in depth material characterization to provide the basis for the following modeling process. The third target was to develop large scale structures where the combination of UHP(FR)C and conventional reinforcing bars are optimized and with which the proposed structural model – developed based on the material characterization results – can be verified.

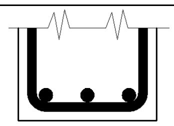
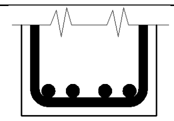
Finally two mix designs with 2% by volume of fibres each, hereafter referred to as “UHPFRC_1” and “UHPFRC_2”, were found to fulfill the strength and workability requirements best. A full material characterization was conducted with both mixtures, however the small scale bending tests for the derivation of the tensile properties were in one case (UHPFRC_1) performed with a notched 3-point setup and in the other case as unnotched 4-point bending tests (with the UHPFRC_1 mixture the target was to get a well-defined crack as this test should also be the basis for the evaluation of the large scale beams). The evaluation was performed using the back analysis method proposed by AFGC [2, 3].

For the large scale tests, beams with and without fibres were produced (with fibres the UHPFRC_1 mixture was used). All beams were reinforced with rebars (St900/1100) and tested in a four-point bending setup. The ULS and SLS behaviour have been investigated with and without fibres and with different reinforcement ratios. Tables 1 and 2 describe the different constellations of the small and large scale tests.

Table 1: Small scale testing program

Test setup	Mixture	Number of specimens	Type of specimen
Three point bending	UHPFRC_1	3	Notched
Four point bending	UHPFRC_2	3	Unnotched

Table 2: Large scale testing program

	Type of mixture	**Type of reinforcement**	**Reinforcement ratio**	**Cross-section**
Beam I. & II.	UHPFRC_1	3 × Φ15	1.41%	
Beam III. & IV.	UHPC	3 × Φ15	1.41%	
Beam V. & VI.	UHPFRC_1	4 × Φ15	1.88%	
Beam VII. & VIII.	UHPC	4 × Φ15	1.88%	

3. MATERIAL CHARACTERIZATION AND MODEL DEVELOPEMENT

For the specimens presented in this paper, the two mentioned mixtures with fibres and one without fibres were used. Table 3 contains main properties for each mixture derived from standard tests (e. g. compression tests carried out on cubes with a side length of 100 mm, splitting tests performed on cylinders with a diameter of 100 mm and a height of 200 mm with the compression load perpendicular to the axis).

Table 3: Material properties determined by standard tests

Mixture	**UHPC**	**UHPFRC_1**	**UHPFRC_2**
28 days compressive strength [MPa]	148	149	182
64 days compressive strength [MPa]	-	164	194
Splitting tensile strength [MPa]	9-11	8-9 *	16-20
Modulus of elasticity [GPa]	49	49	49
Fibre content [% by volume]	0	2	2

* splitting tests for UHPFRC_1 performed without fibres

3.1 Back analysis

In order to derive a full constitutive law also under tensile loading for the fibre reinforced UHPFRC, small scale bending tests were performed. The small scale specimens were produced and tested using the mixtures UHPFRC_1 and UHPFRC_2, three of each. In both mixtures 2% by volume of 15 mm long steel fibres were added (0.20/15).

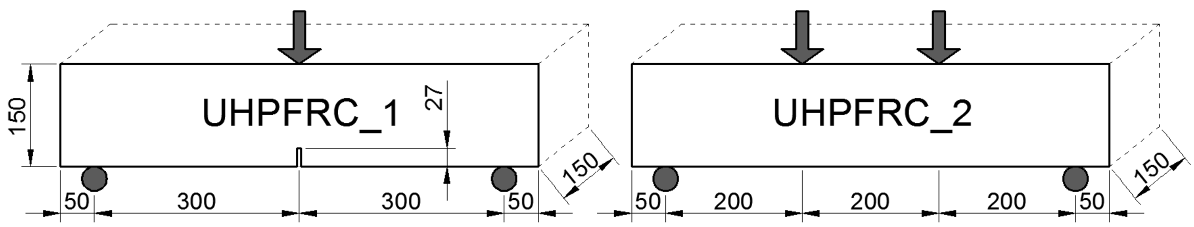


Figure 1: Constellations of the small scale tests

The specimens related to the first mixture were subjected to three-point bending and those which were made from the second mixture were tested under four-point bending according to Figure 1. By providing a notch with the three-point bending test it was expected to get a well-defined crack and thus a better consistency with the large scale tests which also used UHPFRC_1. During the tests the applied load, the deflection at the middle of the span, the crack width and the compressive strain on the top of the beams at the middle of the span were recorded. In addition the length of the decisive vertical crack was measured at certain load levels.

Based on the recorded load vs. crack opening curves, the fibre stress – crack opening law was back calculated using the method proposed by AFGC [2, 3]. Figs. 2 and 3 present the derived mean equivalent fibre stress – crack opening curves determined for both types of specimens. One can see that the magnitude of the equivalent fibre stress is about 30–40% higher in case of the first mixture which is rather surprising when taking into account that the fibre contents and types of the two mixtures were the same and the matrix strength was even lower in case of the first mixture (see data in Table 4). This phenomenon will be discussed later, at the end of the next section.

Table 4 presents main results of the back analysis, which can be the basis of an idealized constitutive law including the post-cracking phase for each of the two used mixtures.

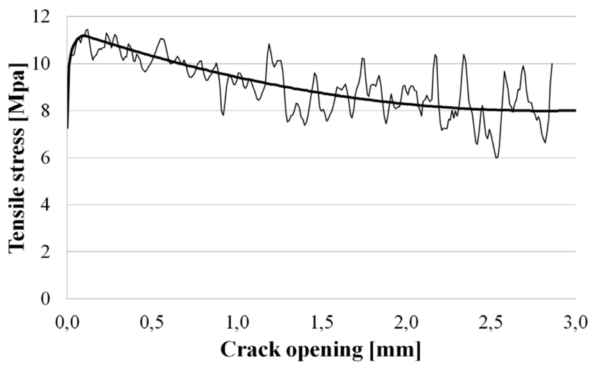


Figure 2: Post cracking behaviour back calculated from the three-point bending tests in relation to the UHPFRC_1 mix

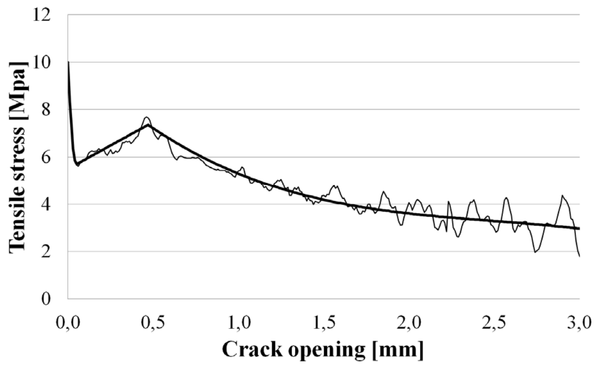


Figure 3: Post cracking behaviour back calculated from the four-point bending tests in relation to the UHPFRC_2 mix

Table 4: Main results of the back analysis

Mixture	**Matrix strength [MPa]**	**Equivalent fibre stress at ultimate load [MPa]**	**Equivalent fibre stress at 0.5 mm crack width**	**Equivalent fibre stress at 3.0 mm crack width**
UHPFRC_1	7.3	9.6	10.3	8.0
UHPFRC_2	9.8	6.7	7.2	3.0

3.2 Proposal for a simplified model

In order to be able to take into consideration the contribution of the fibres to the structural behaviour of the large scale beams, where the UHPFRC is combined with conventional rebars, a simple model has been developed based on the bending test results of the small scale beams. In this model the contribution of the fibres is considered as a smeared constant stress value between the bottom edge of the beams and the neutral axis. The magnitude of this simplified stress block is derived in a way, that based on the depth of the compression zone (derived from strain recordings and measured crack heights just before failure) and the failure load, the average tensile stress in the fibres was back calculated, using the simplified model shown in Fig. 4 and establishing the equilibrium of the inner forces with the applied loading. This method is similar to an approach proposed by Stürwald and Fehling [4] and also to the basic model for FRC design addressed in MC2010 [5].

In case of the three-point bending tests, the equivalent bending stress was calculated according to equation (1) where b is the width, h is the height of the cross-section minus notch depth (if existing), x is the depth of the compression zone just before failure (derived from the measured crack height), L is the span in the test setup and F_{max} is the applied force at failure.

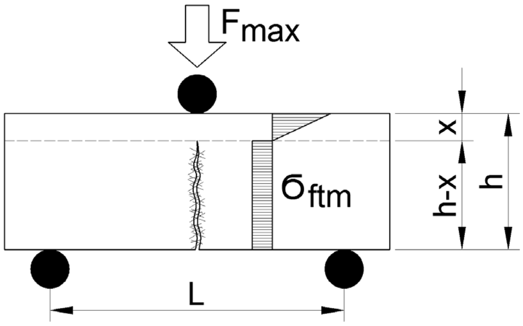


Figure 4: Simplified stress distribution along the cracked section

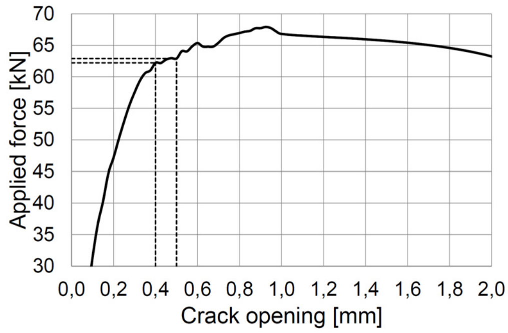


Figure 5: Mean force vs. crack opening curve

$$\sigma_{ftm} = \frac{F_{\max} \cdot L}{4 \cdot b \cdot (h-x) \cdot \left(\frac{h-x}{2} + \frac{2}{3} \cdot x \right)} \quad (1)$$

Using the above described method 10.1 MPa as a mean smeared tensile stress was determined related to the ultimate load of the specimens subjected to three-point bending. Since the tensile force which is provided by the fibres depends on the crack width, this value had to be adjusted when applying the model on the large scale beams where reinforcement bars with a different load-slip behaviour were used in addition. A simple approach to estimate the reduction factor is to derive it based on the crack opening measured just before failure in case of the large beam specimens in comparison to the measured crack width related to the maximum load of the small tests. Fig. 5 presents the mean load versus crack opening curve of the small specimens. In case of the large scale tests the mean crack width just before failure was 0.4-0.5 mm. It can be seen on Fig. 5 that at the same crack opening the reduction of the maximum load should be 10 % or less, therefore a reduction factor χ=0.9 has been chosen.

3.3 Comparison of back analysis and simplified approach

If the simplified model is interpreted to the specimens which were made out of the UHPFRC_2 mixture and subjected to four-point bending without notch, the derived mean smeared tensile stress would be 7.5 MPa.

Thus for both mixtures and test setups the equivalent maximum stresses in the fibres calculated from the back analysis are similar to the stresses calculated by the simplified model when considering the relevant crack opening of about 0.5 mm in Figs. 2 and 3.

The matrix strength values derived from the recorded load-deflection curves of the notched beams when considering the point of the initial crack formation were lower than that of the unnotched beams. This was in line with the observations from splitting tests (Table 3) and can in addition be explained with the stress concentration in the surroundings of the notch.

Concerning the equivalent fibre stresses (the stresses in the tensile zone after cracking) it is striking that the stresses derived from the notched beams were about 35% higher compared to those which were derived using the results of the unnotched specimens. In the present tests the following main reason for this phenomenon was identified: In the case of the four-point bending test, the main crack will propagate in a cross-section which is expected to be the weakest between the two load introductions with respect to the fibre effect, in contrast to the three-point bending tests with the notched specimens where a pre-defined cross-section is weakened in order to make it decisive. In addition it cannot be excluded that the fibre content in the close vicinity of the formwork is somewhat lower, however this effect could not be verified for all the specimens. These two phenomena together can influence the results with the notched specimens in a way that the later on derived equivalent fibre stresses are significantly higher than observed with the unnotched specimens.

4. STRUCTURAL BEAM TESTS

Eight full size beams were cast, four with fibers and four without fibers. In addition, each reinforcement layout was repeated twice (see Table 2). The varied parameters were the reinforcement amount and the concrete mixture (in case of four beams the mixture did not contain fibres). The beams had a rectangular cross section with the dimensions of 250 mm × 150 mm. The length of the beams was 3.5 m. All of them were tested in the same four-point bending test setup (see Fig. 6). The span was 3.0 m, the distances between the load introductions and the supports were 1 m. All tests were carried out displacement controlled by a 0.5 mm/min speed of loading. The testing processes were stopped at different load levels in order to record the crack pattern and to measure the crack widths and the distances between the cracks.

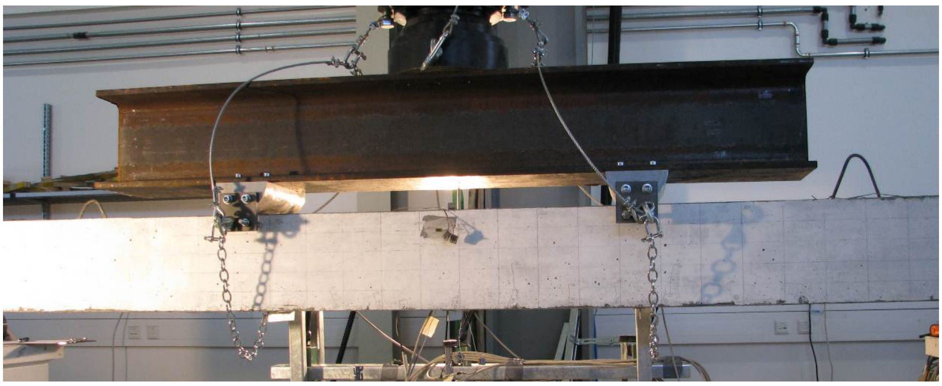


Figure 6: Four-point bending test setup

For all the beams, a high strength steel longitudinal reinforcement (St 900/1100) with a characteristic yield strength $R_{p0.2}$ of 900 N/mm² and a bar diameter of 15 mm was used. The stirrups consisted of BSt 550 with a diameter of 10 mm.

The tests were evaluated in terms of failure load for Ultimate Limit State and mean crack widths and deflections which are related to the Serviceability Criteria. Service load level has been roughly taken into consideration as the failure load divided by 2.1. Figs. 7 and 8 display the load displacement curves of the 4 UHPC and the 4 UHPFRC beams.

The failure modes were different with and without fibres. In case of the UHPC mixtures without fibres, the final failure occurred always due to the crushing of the compressed zone in a brittle way (see Fig. 9), however, yielding of the steel had been reached. By the application of the fibres, not just the compressive strength of the concrete increased significantly, but the failure mode became much more ductile and the final failure occurred due to the rupture of the bottom steel bars after reaching the ultimate strain in the concrete at the top of the beam (see Fig. 10).

Concerning the ultimate load, it can be seen in Table 5, that the usage of about 2% by volume fibres increases the load bearing capacity by about 15% on average.

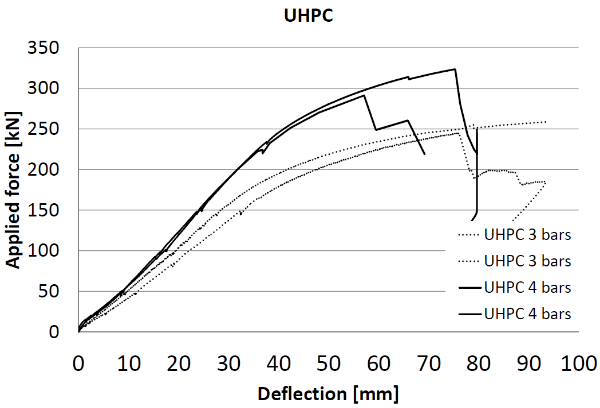


Figure 7: Load-def. of the UHPC beams

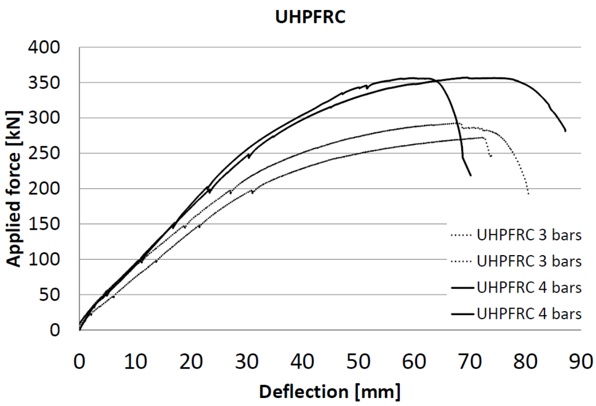


Figure 8: Load-def. of the UHPFRC beams

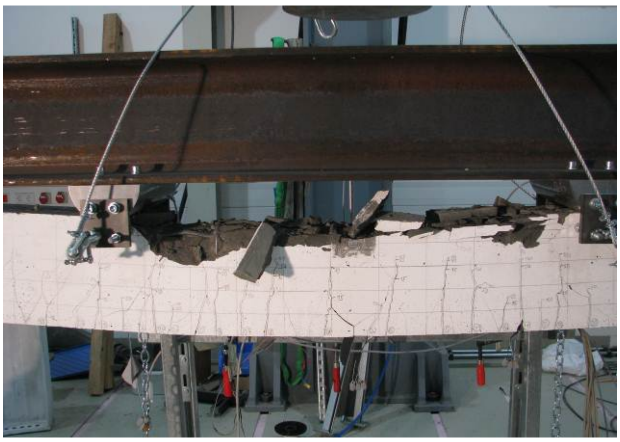


Figure 9: Typical failure mode without fibres

Figure 10: Typical failure mode with fibres

Table 5: Ultimate load and related bending moment

	Mean failure load [kN]	**Related bending moment [kNm]**
Beam I. & II. (UHPFRC)	282.36	141.18
Beam III. & IV. (UHPC)	251.72	125.86
Beam V. & VI. (UHPFRC)	356.72	178.36
Beam VII. & VIII. (UHPC)	307.25	153.63

The most common serviceability criteria which have to be met are the control of the crack widths and the deformations. During the tests the deflections have been recorded and the crack widths have been measured at several load steps. Table 6 contains the mean crack widths and the measured deflections at the middle of the span at the defined service load level. It can be seen, that the crack widths are in all the cases much below the general criterion of 0.3 mm recommended by Eurocode. However, due to the fact that with the application of UHP(FR)C and high grade steel the stiffness (modulus of elasticity) of the elements does not increase proportionally with the load bearing capacity, special attention has to be paid to the criterion of deformations: As can be seen in Table 6, the deflections are about 50% above the criterion of l/250, thereby not yet taking into account long term effects.

Table 6: Deflections and crack widths at SLS level

	SLS bending moment [kNm]	**Deflection at SLS load [mm]**	**Mean crack width at SLS load [mm]**
Beam I.	56.47	15.9	0.11
Beam II.		13.3	0.06
Beam III.	50.34	22.2	0.16
Beam IV.		19.6	0.08
Beam V.	71.34	16.0	0.09
Beam VI.		16.1	0.06
Beam VII.	61.45	20.5	0.14
Beam VIII.		20.0	0.15

5. IMPLEMENTATION OF THE SIMPLIFIED MODEL

In case of UHPC and UHPFRC a linear stress distribution can be assumed in the compressed zone even at ultimate level (Stürwald & Fehling [4]). It can be seen in Table 5 that the load bearing capacity with the UHPFRC mixture is significantly higher due to the effect of the fibres.

As a good estimation, their contribution can be handled by taking into consideration a rectangular stress block in the tensile zone [4, 6]. The magnitude of this stress block has been calibrated by the small scale bending beam tests as it is described above. Figs. 11 and 12 show the applied structural models for cross-sections subject to bending in case of UHPC and UHPFRC mixtures.

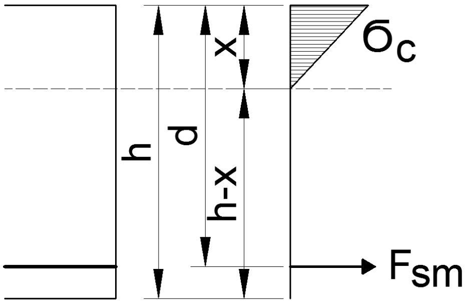


Figure 11: Applied model for UHPC

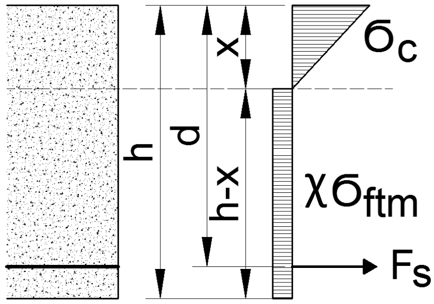


Figure 12: Applied model for UHPFRC

It is important to mention in this context that the size of the cross section of the large scale beams (250 × 150 mm) did not differ so much from the small scale beams (150×150 mm), however small size effects may affect the result.

In case of the beams made out of UHPFRC_1 the expected ultimate bending moments have been calculated using the values determined by the three-point bending tests. As can be seen in Table 7, the calculated results agree quite well with the observations from the tests, but are in each case about 4 to 10 % higher than the actual result. Taking into account the observations summarized in section 3.3, it can be concluded that in this case the equivalent fibre stress derived from the notched 3-point bending tests leads to an overestimation of the overall fibre contribution of about 35 % (which in total leads in the calculation to an exceeding of the load bearing capacity of the large scale beams of about 5% on average). In case of UHPC, the proposed model follows relatively well the test results as it is seen in Table 8.

Table 7: Comparison of the applied model to the test results in case of UHPFRC

	Reached ultimate moment [kNm]	**Calculated ultimate moment using σ_{ftm}=10.1 MPa [kNm]**	**Difference [%]**
Beam I.	136	152	+10.4
Beam II.	146	152	+3.8
Beam V.	178	188	+5.2
Beam VI.	179	188	+4.5

Table 8: Comparison of the applied model to the test results in case of UHPC

	Reached ultimate moment [kNm]	**Calculated ultimate moment [kNm]**	**Difference [%]**
Beam III.	122	119	-2.8
Beam IV.	129	121	-6.9
Beam VII.	162	157	-3.0
Beam VIII.	146	157	+7.3

6. CONCLUSIONS

The combination of UHP(FR)C and high strength reinforcement allows for making use of the high concrete strength in bending without an over-proportional amount of steel. The incorporation of 2 % by volume of steel fibres increases the load bearing capacity by about 15 % on average.

The applied simplified structural model estimates the ultimate cross-sectional resistance with sufficient accuracy. When deriving the smeared fibre stress on the basis of the simplified model from the small scale beams, thereby taking into account the observed crack height measurements, the result was well in accordance with the equivalent fibre stress derived from the more sophisticated method of the back analysis.

Even though, the failure of the beams without fibres is relatively ductile, the final crushing of the concrete compression zone itself is very brittle without fibres. Special attention has to be paid for SLS criteria (limitation of deformations), due on one hand to the increased slenderness of the structure and on the other hand to the fact that the stiffness of the components does not increase proportionally to the load bearing capacity.

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