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Structural behavior of UHPC under biaxial loading

Summary

Within a research program, reinforced ultra high performance concrete (UHPC) panels have been investigated experimentally under biaxial compression-tension loading. The effects of transverse tensile stress and the cracking as a result of the compressive strength have been studied. Based on the experimental results and those of an earlier research program on normal strength concrete (NSC) panels, a proposal for the reduction of the compressive strength of cracked reinforced non-fibered and steel fiber concrete against the applied tensile strain, could be developed.

Keywords: *UHPC, bar reinforcement, steel fibers, panel, compression, tension, biaxial test, reduction factor, material model*

1 Introduction

Over the past 40 years tests on the bearing capacity of cracked concrete panels have been carried out, e.g. by Vecchio/Collins [1], Belarbi/Hsu [2], Eibl/Neuroth [3], Mehlhorn/Kollegger [4] and Schlaich/Schäfer [5].

The results of particular tests vary significantly and lead to contradictory conclusions because of the partly different objectives and due to the highly differing execution of tests (test setup, order of load application etc.), the dimensions of test specimens and the reinforcement configurations. This was the motivation to start a research program on normal strength concrete (NSC) panels at first [7] and subsequently for the current research program on UHPC-panels [8].

This paper describes the investigations on UHPC-panels. The experimental results are used to develop a proposal for the reduction of the compressive strength in dependence of the applied tensile strain. Furthermore, the results of the UHPC-panels and of the NSC-panels are compared.

2 Test Program

In the test program a total number of 47 plain, fiber and/or bar reinforced UHPC-panels were tested. A general overview of the test program on UHPC-panels is given in table 1.

Table 1: Overview of the test series

reinforcement:	plain	steel fibers	steel bars	bars and fibers
series 1	3 (3c)	3 (3c)	3	3
series 2	-	-	6	6
series 3	1 (1c)	-	9 (2c)	-
series 4	-	1 (1c)	-	1 (1c)

(c) specimens that were tested with compression load only

Except for the panels loaded only by compression, the specimens were loaded sequentially, i. e. at first the tensile loading and afterwards the compressive loading was applied.
The influence of the magnitude of applied average tensile strain (between approx. 0.5 ‰ and 8 ‰), of the addition of steel fibers and of the interfering effect of the reinforcement on the reduction of the compressive strength at simultaneously acting lateral tension have been studied.

3 Test Specimens

The dimensions of the UHPC-panels were 350 mm in compressive direction, 500 mm and 1000 mm respectively in tensile direction. The thickness was 70 mm. The panels were reinforced orthogonally in two layers in tensile and compressive direction with high-strength reinforcing steel bars d_s = 8 mm, St 1420/1570. The high-strength steel was selected to enable high elastic strains (> 6 ‰). For the panels with a length of 500 mm the dimensions and the configuration of reinforcement are shown in figure 1.

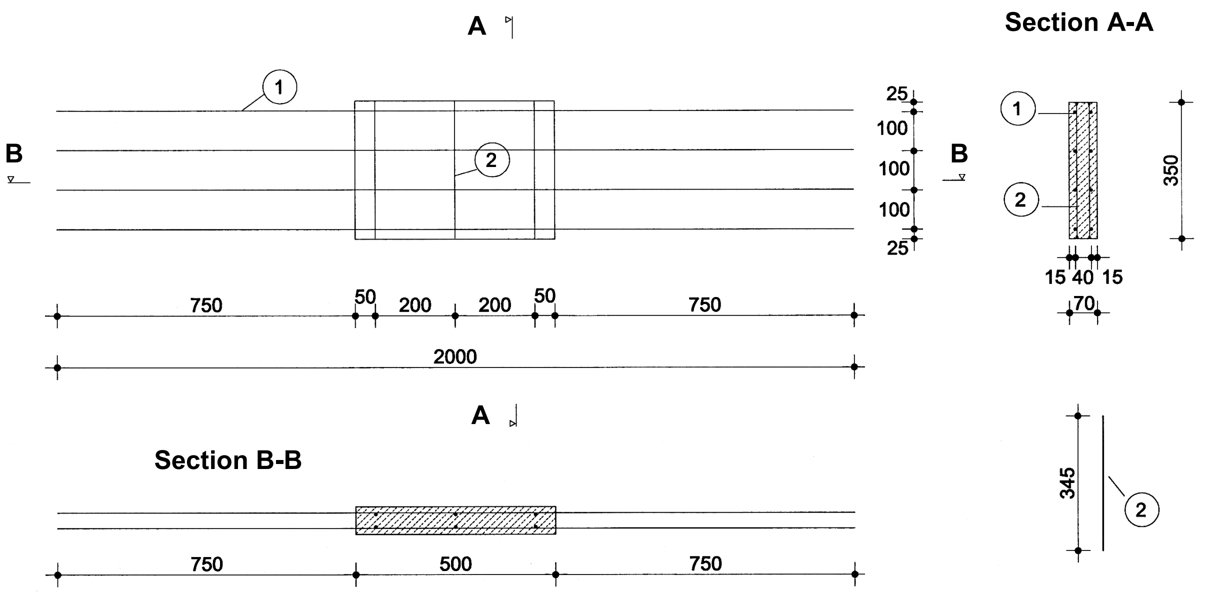
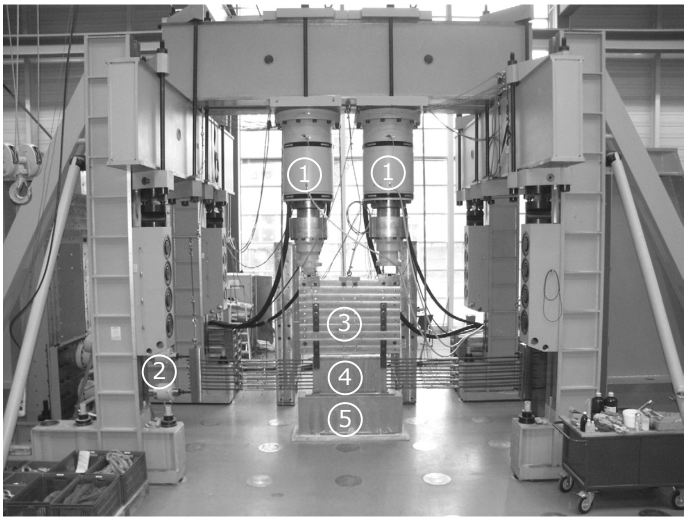


Figure 1: Reinforcement dimensions of the concrete panels

The spacing of the reinforcing bars was 100 mm in tensile direction (reinforcement ratio ρ_s = 1.64 %) and 200 mm in compression direction (reinforcement ratio ρ_s = 0.86 %).
The concrete mixture of the fine-aggregate UHPC was M1Q with a fiber content of 1.0 vol.- %. The high strength steel fibers had a length of 17 mm and a diameter of 0.15 mm. Further details of the concrete mixture are given in the research report "Entwicklung, Dauerhaftigkeit und Berechnung Ultra-Hochfester Betone (UHPC)" [6].
Standard concrete cylinders with a diameter of 150 mm and a height of 300 mm were fabricated accompanyingly with the panels. They were cured under the same conditions and were tested on the same day as the panel. The compressive strengths of the cylinders served as reference values.

4 Execution of the tests

The compression tension tests were carried out at the Strong Floor of the Central Laboratory of the Institute of Structural Engineering of Kassel University. The test setup is shown in figure 2.



(1) 2.5 MN-hydraulic jacks for compressive forces
(2) 2 x 400 kN-hydraulic jacks for tensile forces
(3) load distribution
(4) specimen
(5) UHPC-bearing block

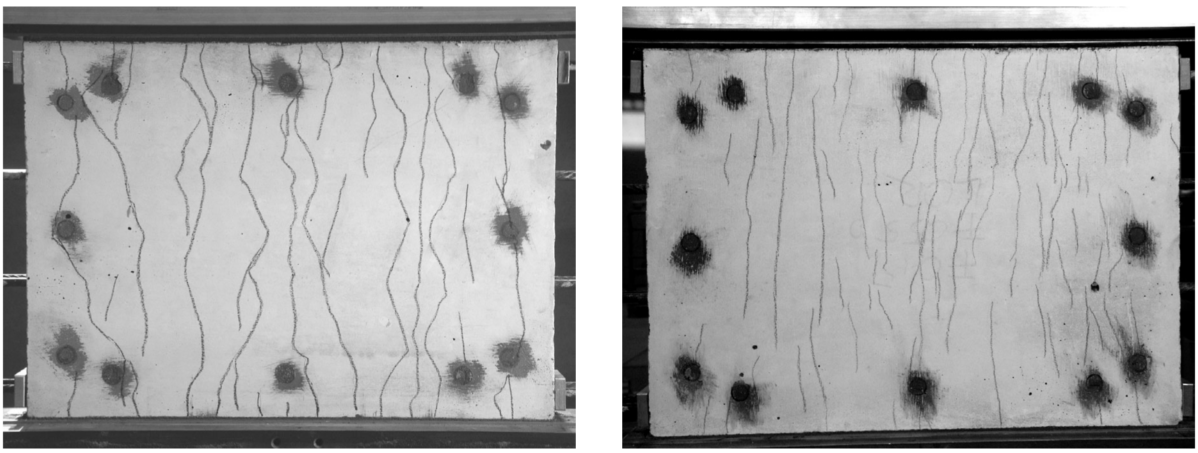
Figure 2: Testing frame for the compression-tension tests

The horizontal tension force was applied by two hydraulic jacks, each with a nominal capacity of 400 kN. This force was routed by a crosshead as well as by interposed threaded bars and sleeves to the rebars of the reinforced concrete panel. The vertical compression forces were applied by two hydraulic jacks, each with a nominal loading capacity of 2.5 MN, and were routed by two roller bearings in two load distributing steel panels and into the specimen. The steel panels were protected against a deviation from the loading plane by horizontal guidance struts. A block of reinforced UHPC acted as the bearing for the specimens.
The vertical compression forces were measured by load cells at the two hydraulic jacks. The measurement of the horizontal tension forces was performed by load cells at the hydraulic jacks and by further load cells on the abutment side, to check the balance of the forces. The tension forces in the continuous reinforcing bars were measured additionally by load cells to check the constancy of the load application distribution across the panel height.

Three inductive displacement transducers were fixed in vertical and horizontal direction respectively on the front and on the back of the panel to measure the displacements. For the panels the gauge lengths were 270 mm in vertical and 420 mm in horizontal direction.
The recording of the forces and displacements was carried out continuously (one measured value per second) with a multi-channel-measuring-system. The measured values were routed to a PC, registered there with a software package for monitoring the measurement reading and were stored on the hard disk.
The loading of the specimens was performed under displacement control using a process monitoring unit and a control software. For this purpose, displacements were measured at the panel and were read by the monitoring unit with a clock rate of 1000 Hz. The software-based processing and the output of the control commands to regulate the hydraulic jacks followed subsequently.
A drop of the displacement transducers fixed at the panel directly could not be avoided, because of the cracking. Therefore the displacement values used for the control were collected with separate measuring mechanisms in vertical (compression) and horizontal (tension) direction respectively outside the specimens.
The specimens were placed in the testing device in such a way that the compression loading could be carried out centrically after applying the respective tensile strain. The loading of the panels was carried out sequentially. At first the tensile loading was applied in horizontal direction and then the vertical compression loading was carried out until the specimen failed.

5 Experimental results

There is a significant difference between the behavior of the UHPC-panels with fiber reinforcement and the panels without fibers.
The different crack patterns are shown in figure 3. After tensile loading up to a tensile strain of 4.5 ‰, the fiber reinforced panels showed smaller crack spacings and smaller crack widths than the panels reinforced only with rebars.



a) specimen with rebars only   b) specimen with rebar and fibers

Figure 3: Crack pattern of the UHPC-specimens at an applied tensile strain of 4.5 ‰ in horizontal direction.

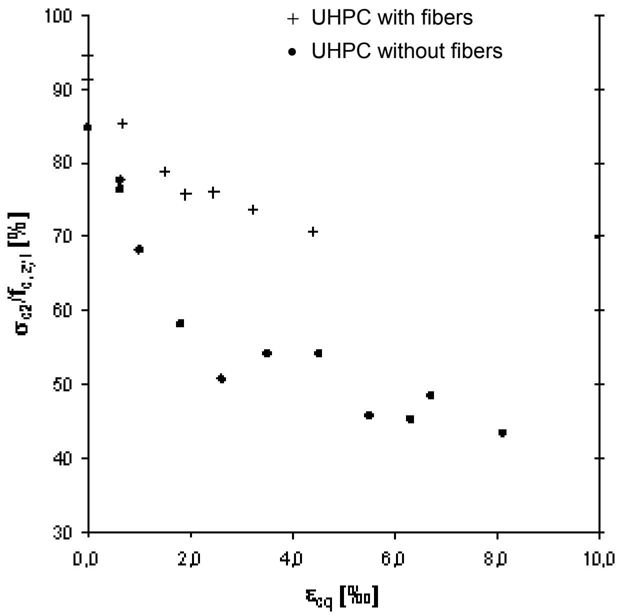
At the end of the compressive loading a different failure pattern of the panels could be observed. As shown in figure 4, the failure pattern of the non-fibered UHPC-panels was very brittle in contrast to the panels reinforced with a small fiber content of 1.0 vol.-%. The panels with fiber reinforcement also reached higher compressive strengths.

a) specimen with rebars only
(applied tensile strain is 1.5 ‰)

b) specimen with rebars and fibers
(applied tensile strain is 3.5 ‰)

Figure 4: Failure pattern of the UHPC specimens.

Selected results of the tests on UHPC-panels are shown in figure 5. Further details are summarized in a research report by Fehling et. al. [8].



The ordinate represents the normalized compressive strength $\sigma_{c2}/ f_{c,zyl}$. At this, σ_{c2} is the compressive stress referring to the concrete gross cross-section and $f_{c,zyl}$ is the compressive strength of the standard concrete cylinders.
The absissa shows the transverse tensile strain ε_{cq}.

Figure 5: Test results of the UHPC-panels

6 Proposal for the reduction of the compressive strength due to applied transverse tensile strain

The development of the compressive strength of the panels in dependence on the applied tensile strain clarifies some characteristics. The compressive strength of the UHPC-panels decreases significantly and almost linearly already at small tensile strains. The normalized compressive strength stabilizes for average tensile strains of more than approx. 2.5 ‰. For higher tensile strains, an influence of the applied tensile strain is hardly noticeable.

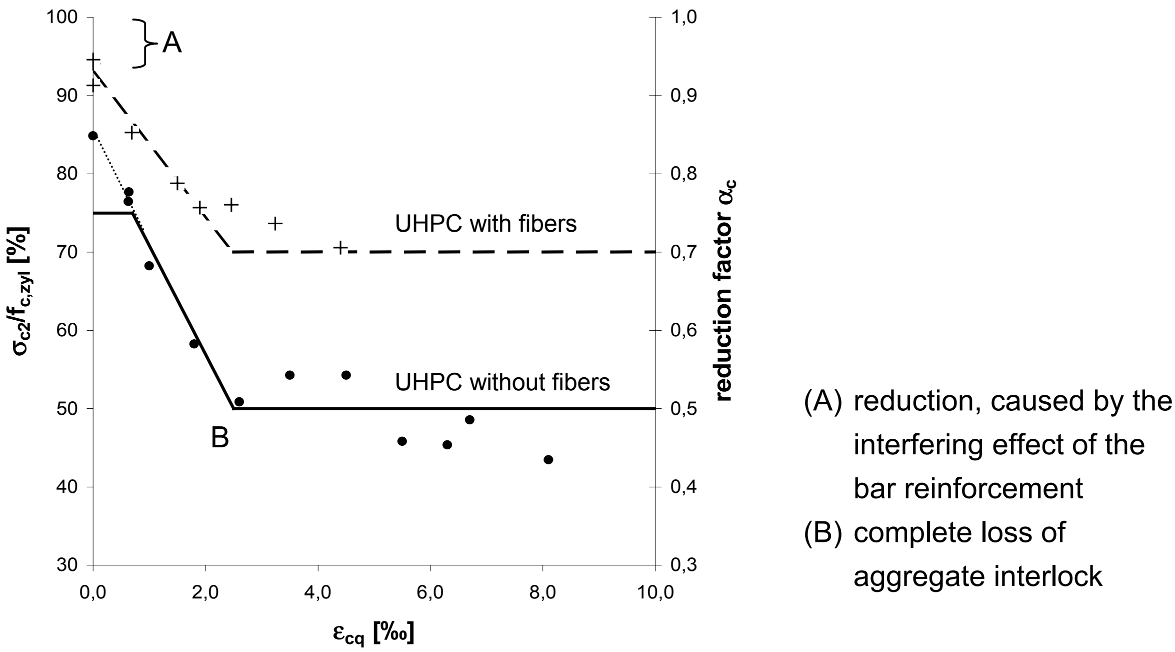


Figure 6: Proposal for the reduction of the compressive strength of reinforced UHPC against the applied tensile strain

Figure 6 shows the proposal for the reduction of the compressive strength of cracked reinforced fibered and non-fibered UHPC.

Because of the interfering effect of the bar reinforcement (A in figure 6), the compressive strength decreases even for the non-tensioned specimens. This effect is more distinctive for the non-fibered panels, due to the ability of the fibers to transfer tensile forces effectively already in the state of micro cracking. The initial reduction caused by the bar reinforcement depends on the geometry of the concrete member and on the reinforcement ratio.

The biaxial tension compressive strength of reinforced UHPC is significantly affected by the crack width and the crack spacings. To consider the reduction of the concrete compressive strength due to transverse tensile strain $\varepsilon_{c,q}$, a simple bilinear approach is suggested.

The linear descending for small tensile strains considers the decrease of the aggregate interlock effect due to the increasing crack width. Conservatively, for non-fibered UHPC a reduction factor of 0.75 according to the valid German code 1045-1 [9] can be introduced.

After complete loss of aggregate interlock (B in figure 6), the load has to be beared by small compressive struts. Because of the crack formation up to high elastic strains (small crack spacings and crack widths) this effect is less distinctive for fiber reinforced UHPC. For the non-fibered specimens a minimum reduction factor of 0.5 has been obtained. With 1.0 vol.-% of steel fibers a limit value of 0.7 could be achieved.

7 Comparison of UHPC and NSC under biaxial loading

UHPC and NSC show a similar behavior under biaxial loading (figure 7).
Due to the smaller aggregate size (aggregate interlock!), the decrease of the compressive strength is steeper for UHPC. Furthermore, the maximum reduction of the compressive strength of the non-fibered concrete is higher for UHPC, because of the lower ductility and the smaller resisting compressive struts.

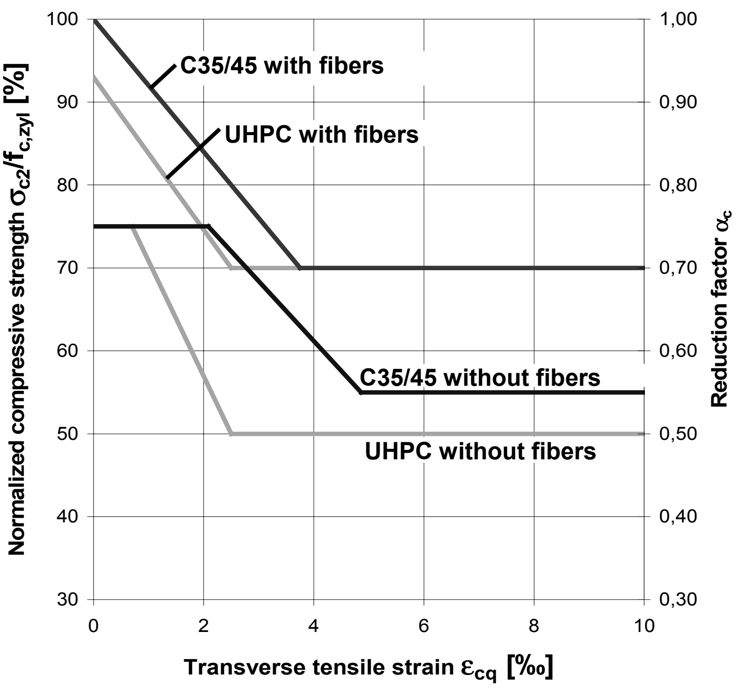


Figure 7: Proposal for the reduction of the compressive strength of NSC (C 35/45) and UHPC against the applied tensile strain

8 Conclusion

On the basis of experimental results, a proposal for the reduction of the compressive strength of cracked reinforced UHPC-panels with and without steel fibers has been presented. The experimental investigations show, that the aggregate size, the crack spacing and the crack width have an important influence on the decrease of the compressive strength. In contrast, the yield point of the reinforcement shows obviously no effects. Over all, reinforced UHPC and NSC behave similar under biaxial compression-tension loading.

Acknowledgement

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