# ANCHORAGE BEHAVIOR OF STRANDS IN ULTRA-HIGH PERFORMANCE CONCRETE

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## ABSTRACT

*Ultra-High Performance Concrete (UHPC) is an appropriate construction material for pretensioned girders. To ensure an economic and safe design, a detailed knowledge of the behavior of pretensioned strands in the anchorage zone is essential. The dimension of the bond anchorage zone favors the cost-effective design of pretensioned girders, especially when the shear resistance is decisive. However, a minimum concrete cover is required to avoid splitting cracks in the transmission zone, since they lead to an uncontrolled increase in transfer length and may cause a premature anchorage failure.*

*Within a priority program*[1] *supported by the German Research Foundation (Deutsche Forschungsgemeinschaft DFG) experimental and theoretical investigations on the bond behavior of strands in UHPC are carried out at the Institute of Structural Concrete at RWTH Aachen University. The influence of the Hoyer-effect*[2-6] *and the concrete cover were systematically investigated by pull-out-tests, where the bond strength was app. 30 MPa after full release, 20 MPa after 50 % and 12 to 14 MPa without release. Especially with full release, the bond strength is influenced by the concrete cover. A variation of the fiber content had no significant effect on the bond strength inside the tested range of the fiber amount. Additionally, small scale beam tests were carried out to determine the transfer length and the end slip. Furthermore, the experimental as well as the theoretical results were verified on full scale beams. The detailed test results were published in journal and conference papers*[7-8]*. The transfer length ranged between 22 and 28 cm, primarily affected by the concrete cover and the strand density. Therefor a minimum specific concrete cover $c/d_p = 2.5$ as well as a minimum clearance $s/d_p = 2.5$ was required to keep the concrete uncracked. With 2.5 % p.v. (% per volume) fibers the concrete cover seems to be reducible to $c/d_p = 2.0$. A bond model was derived based on the test results and will be presented at the conference.*

**Keywords:** Research, Ultra-High Performance Concrete, Steel Fibers, Anchorage, Pretensioning

## INTRODUCTION

Generally, the number of strands in pretensioned girders results from the bending design. In addition, the prestressing force above the support is essential to calculate the shear resistance. A decisive part of the shear carrying capacity arises from arch action as presented in Figure 1. When the anchorage length is shorter than the support overhang, the full prestressing force is available to intensify arch action. The vertical support reaction corresponds with the prestressing force and the arch action.

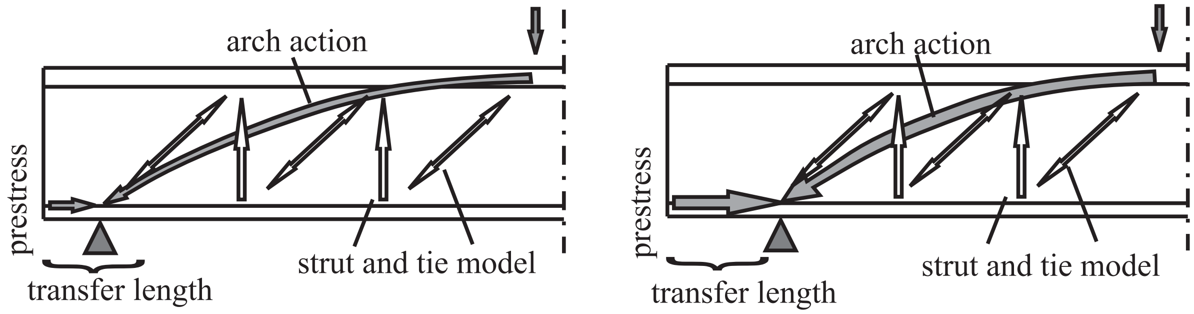


Figure 1: Principle of arch action with corresponding prestressing force

The higher the bond stresses are between strands and concrete the shorter is the transfer length. On the other hand, higher bond stresses lead to increased tensile stresses in the concrete cover around the strands. Therefore, the minimum concrete cover for strands in UHPC has to be determined. The compressive strength of UHPC is about five times higher than normal strength concrete. The bond strength and the compressive strength, however, show no linear coherence. Nevertheless, the concrete compressive strength is normally used in design methods. To ensure a safe design, constitutive design rules to calculate the anchorage and transfer length of strands in UHPC are required. The gradient of the bond forces is influenced by the slip, the Hoyer-effect, the material properties and the concrete cover. With an adequate theoretical method derived from test results, the transfer length can be determined merely knowing the end slip, the compressive strength and the concrete cover.

## BOND BEHAVIOR OF STRANDS

While ribbed rebars rely on a direct load transfer between the ribs and the supporting concrete under each rib, strands depend on friction to a greater extent. Hence, the stress-slip relation of strands has a plastic branch after exceeding the ultimate bond strength. So far, several investigations have been performed on the bond behavior of strands[2-6]. Generally, the bond stresses can be described with three parts (Figure 2):

- a constant part caused by the basic friction, also called the rigid-plastic bond behavior;
- a stress dependent part which is based on the Hoyer-effect and which increases with the transfer of pretensioning;
- and a slip dependent part which is also independent of the prestressing. This effect can be explained by the "lack of fit" which results from the geometry of the strands which is not completely uniform.

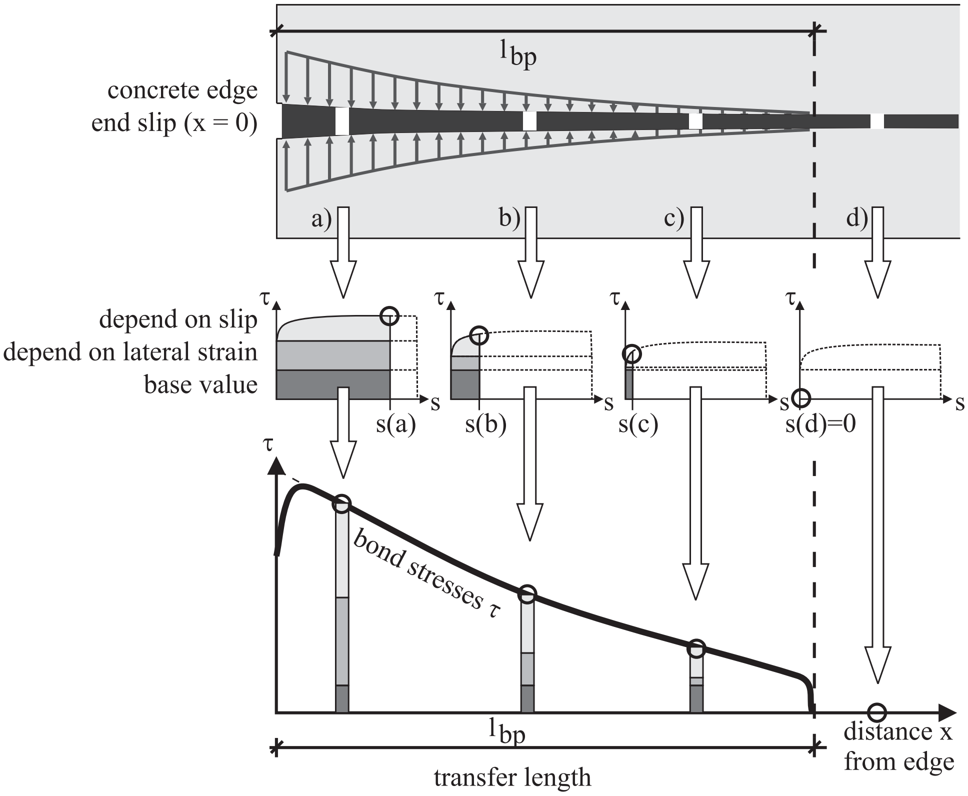


Figure 2: Schematical stress distribution along the transfer length of strands

Due to the dependency on slip and lateral strain, the bond stresses are not constant along the transfer length (Figure 2). The slip as well as the lateral stresses rise from the difference between steel and concrete strain while the pretensioning is released. At the end of the member, the slip has the highest value and the longitudinal steel stress is zero. All three bond parts are fully activated ((a) in Figure 2). In the middle of the transfer zone, the slip as well as the lateral stresses are decreased. Hence, the bond stresses are on a lower level (b). At the end of the transfer length, most stresses already have been transferred from steel to concrete. Here the lateral stresses and the slip are very low and the bond is mainly established by the base value of the bond (c). Outside the transfer length, there are neither bond nor lateral stresses nor slip due to pretensioning (d).

To determine the bond stresses along the transfer length and to investigate the bond behavior, pull-out tests with different steel stresses, which means different lateral strain, were performed. In the next step, small scale beam tests were carried out to measure the transfer length and to investigate the influence of the concrete cover. Finally, the results are used for dimensioning the pretensioned I-beams[7,8]. The end slip and the transfer lengths of the I-beams were measured to verify the results.

## EXPERIMENTAL INVESTIGATIONS

### CONCRETE MIXTURE, FIBERS AND STRANDS

All specimens were fabricated with the concrete mix presented in Table 1. Merely the fiber ratio was varied. All fibers were straight – without hooks – and of high strength steel ($f_y^f$ > 2,200 MPa (320,000 psi)). The diameter of 0.15 mm (0.06 in) is specified by the manufacturer and the margin is ±0.02 mm. In several spot measurements the diameter was about 0.17 mm in average. The steel fibers had a length between 9 mm (M0 with 2.5 %) and 17.5

mm (M1 with 0.9 %). In the M7 mix a fiber cocktail with 6 and 13 mm long fibers was added and the reference composition MR contained no fibers. The 7 wire strands with a cross section $A_p = 93$ mm² (diameter 0.5'') respectively $A_p = 140$ mm² (0.6'') had an E-Modulus of 200,000 MPa and $f_{py} = 1500$ MPa (218,000 psi).

Table 1: Concrete mix

| Mix/fiber ratio | | M0 | M1 | M7 | MR |
|---|---|---|---|---|---|
| Material | | 2.5% p.v. | 0.9% p.v. | 1.04% p.v. | w/out |
| Cement CEM I | [kg/m³] | 650 | 660 | 660 | 666 |
| Silica fume | [kg/m³] | 177 | 180 | 180 | 181 |
| Quartz powder | [kg/m³] | 456 | 463 | 463 | 467 |
| Sand 0.125-0.5mm | [kg/m³] | 354 | 360 | 359 | 363 |
| Basalt 2-8mm | [kg/m³] | 598 | 606 | 606 | 612 |
| Steel fibers 9.0/0.15 | [kg/m³] | 194 | - | - | - |
| Steel fibers 17.5/0.15 | [kg/m³] | - | 70 | - | - |
| Steel fibers 13.0/0.16 | [kg/m³] | - | - | 39 | - |
| Steel fibers 6.0/0.15 | [kg/m³] | - | - | 42 | - |
| Water | [kg/m³] | 158 | 161 | 160 | 162 |
| Superplasticizer | [kg/m³] | 31 | 32 | 32 | 32 |

## PULL-OUT-TESTS

A total of 72 tests were performed (Table 2). The main test parameters were the fiber ratio, the specific concrete cover and the concrete strength (age). Because of the high bond stresses, short embedment lengths between 25 and 50 mm (0.98-1.97 in) were chosen. Each test batch consisting of a total of 9 tests included three times three tests with different lateral strain stages (0 %, 50 %, 100 %), where 100 % means a change of prestressing stress $\Delta f_p = 1200$ MPa (174,000 psi), 50 % means $\Delta f_p = 600$ MPa (87,000 psi) and 0 % without a change. In the test batches PO10-PO15, one test was carried out for each concrete cover and change of prestressing. Figure 3 shows the sequences of the pull-out tests. Three strands have been prestressed inside a rig before casting with the maximum allowed initial prestressing stress $0.9 \cdot 1500 = 1350$ MPa ($P_0 = 1350 \cdot A_p$) according to the German design code[9]. After three days, the first three tests were carried out. Afterwards, the prestressing force was decreased about 50 % (600 MPa) and the next three tests were performed. Finally, the last tests were carried out with full release (100 %, 1200 MPa), which means nearly full lateral strain of the strand. The remaining $f_p = 150$ MPa were needed to avoid total relaxing of the strands on one side while increasing the bond forces ($P_b/2$ on each side in Fig. 3, phase IV).

Table 2: Parameters of the pull-out tests (72 tests)

| test batch | concrete mix / age | concrete cover $c/d_p$ [-] | strands $d_p$ [in] | bond length $l_b$ [mm (in)] | number 0 %/ 50 %/100 % | $f_{c.cube100}$ [MPa] |
|---|---|---|---|---|---|---|
| PO1-3 | M1 / 3d | 4.4 | 0.6 | 30 (1.18) | 3 / 3 / 3 | 116 |
| PO4-6 | M0 / 3d | 4.4 | 0.6 | 30 (1.18) | 3 / 3 / 3 | 118 |
| PO7-9 | M7 / 3d | 4.4 | 0.6 | 30 (1.18) | 3 / 3 / 3 | 111 |
| PO10-12 | M1 / 3d | 1.5/2.0/2.5 | 0.6 | 30 (1.18) | 1 / 1 / 1 | 113 |
| PO13-15 | M1 / 3d | 1.5/2.0/2.5 | 0.6 | 50 (1.97) | 1 / 1 / 1 | 112 |
| PO16-18 | M1 / 3d | 5.5 | 0.5 | 25 (0.98) | 3 / 3 / 3 | 107 |
| PO19-21 | M1 / 14d | 4.4 | 0.6 | 30 (1.18) | 3 / 3 / 3 | 154 |
| PO22-24 | MR / 3d | 4.4 | 0.6 | 30 (1.18) | 3 / 3 / 3 | 105 |

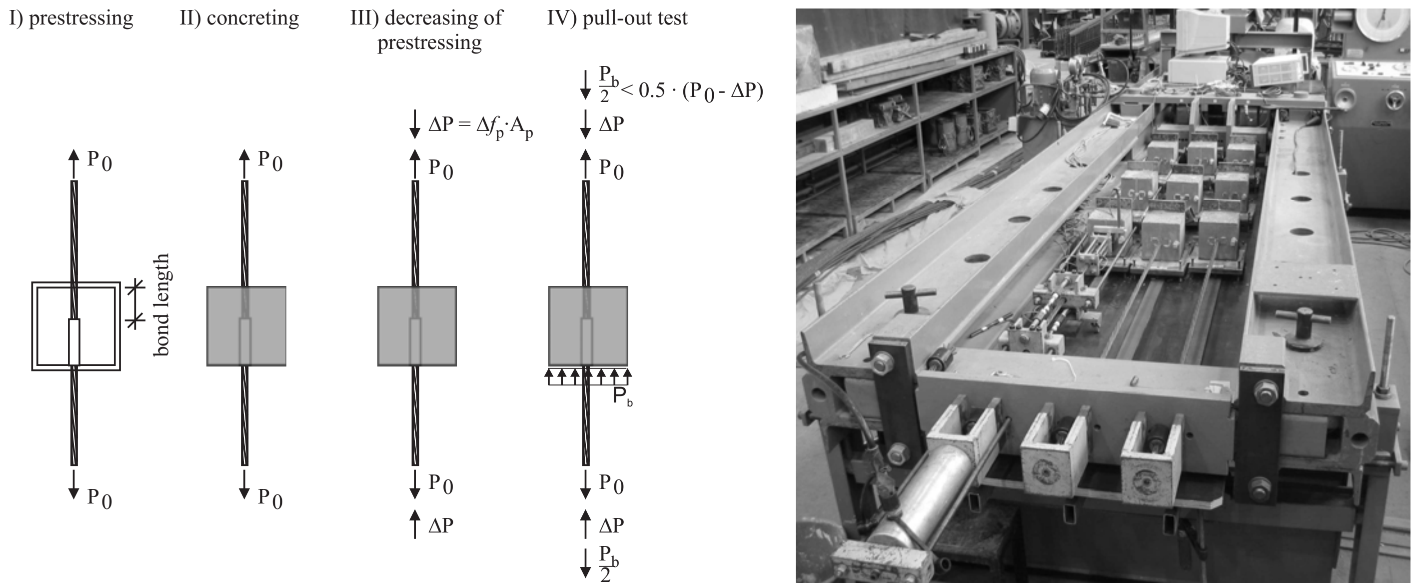


Figure 3: Fabrication and test sequences of the pull-out tests and test rig

The diagrams in Figure 4 indicate, that the fiber ratio had no significant influence within the tested range. With a concrete compressive strength of app. 100-115 MPa (≈ 15,000 psi) at an age of three days a bond strength of 30 MPa (≈ 4,350 psi) was achieved with full lateral strain (100 % release of prestressing), 20 MPa (≈ 2,900 psi) with 50 % release and about 12 to 14 MPa (≈ 1,900 psi) without a change of the prestressing force. The bond stresses $f_{pb}$ were calculated with the nominal diameter $d_p$.

$$f_{pb} = P_b/(l_b \cdot \pi \cdot d_p)$$

with
$f_{pb}$: bond stress
$P_b$: bond force
$l_b$: bond length

The variation of the concrete cover showed no effect on the bond strength when the prestressing remains unchanged as presented in Figure 5 (left diagram). A release of 50 % (middle diagram in Fig. 5), however, led to a reduction of the bond stresses of about 10 to 15 %. When the full lateral strain was preset, visible splitting cracks appeared below a specific concrete cover of $c/d_p = 2.5$. Hence, the transferred bond stresses were reduced for 10 to 30 % according to the existing concrete cover (right diagram in Fig. 5).

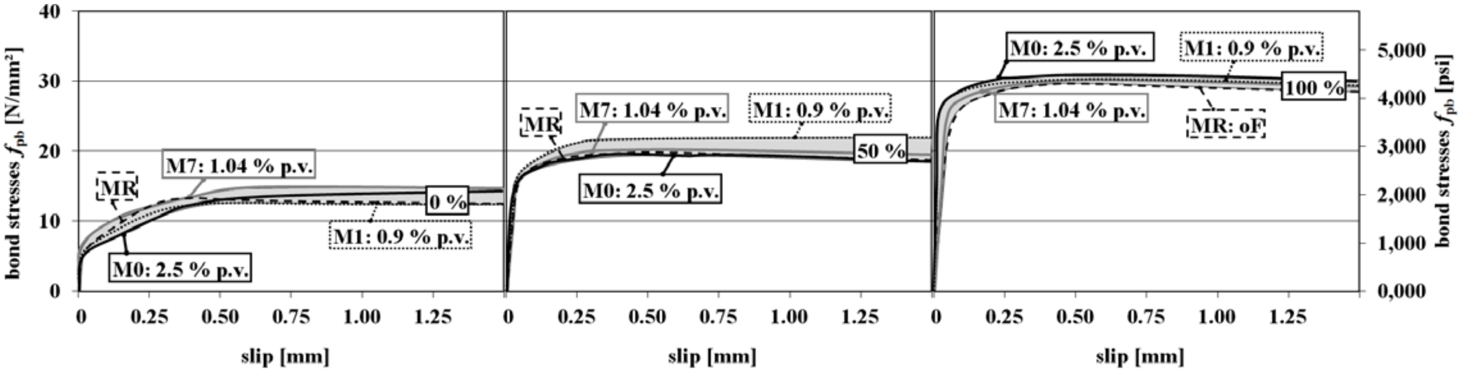


Figure 4: Influence of the fiber ratio and the prestressing (0 %, 50 %, 100 %) on the bond slip behavior of the test batches PO1 to PO9, PO22 to PO24

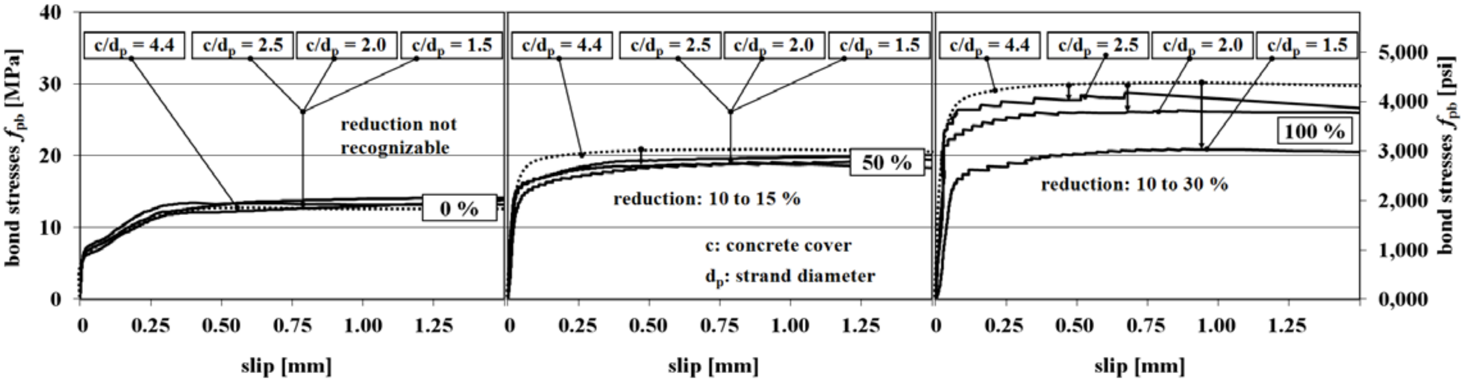


Figure 5: Influence of the concrete cover on the bond slip behavior of the test batches PO10 to PO12

In further tests, the concrete age, the bond length and the strand diameter were varied. The strand diameter had no effect on the bond stresses. The tests with a bond length $l_b$ = 50 mm (PO13-PO15) confirm the tests with 30 mm (PO10-PO12), when the change of prestress was 0 or 600 MPa (0 %, 50 %). After full release (100 %), the bond forces were too high with $l_b$ = 50 mm and splitting cracks were intensified. More detailed test data is given in further papers[8,10].

## SMALL SCALE BEAM TESTS

The main targets of these 14 tests were to determine the minimum dimensions of the concrete cross section to avoid splitting cracks and the transfer length of the specimens which remained uncracked. Furthermore, the corresponding end slip is important. Specimens with two strands were chosen to investigate the minimum concrete cover (Figure 6). Four strands were required to test the minimum spacing between the strands. The test parameters and the main results are listed in Table 3. The concrete cross section $b \cdot h$ results from the specific concrete cover $c/d_p$ and the spacing $s/d_p$ horizontal as well as vertical.

Similar to the pull-out tests, the specimens were fabricated in a rig. The 0.5'' strands were already prestressed at the time of concreting. After three days the prestressing was gradually released in five steps of 20 %. At each load stage the concrete strains were measured along the longitudinal axis of the specimen. This way, the transfer of prestressing could be derived from the strain differences. In addition, the slip at the end of the specimen was measured continuously with displacement transducers.

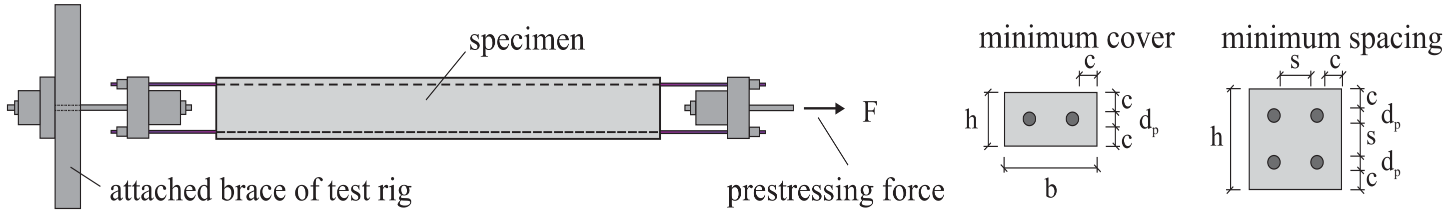


Figure 6: Test setup of the small scale beam tests

Table 3: Parameters and main results of the small beam tests

| | mix/ stirrups | $b$ | $h$ | $c/d_p$ | $s/d_p$ [-] | | 0.5'' number | | cracked | | $f_{c.cube100}$ | $f_{ct.fl}$ | end slip [mm] | transfer length [mm] | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| test | | mm | mm | [-] | hor. | vert. | 2 | 4 | left | right | MPa | MPa | min – max | left | right |
| SE1 | M1 | 101.6 | 50.8 | 1.5 | 3.0 | | x | | x | x | 106 | 19.3 | 0.70 – 0.89 | * | * |
| SE2 | M1 | 114.3 | 63.5 | 2.0 | 3.0 | | x | | x | x | 106 | 19.3 | 0.53 – 0.67 | * | * |
| SE3 | M1 | 120.7 | 120.7 | 2.5 | 2.5 | 2.5 | | x | - | - | 99 | 21.3 | 0.39 – 0.56 | 206 | 210 |
| SE4 | M1 | 127.0 | 127.0 | 2.5 | 3.0 | 3.0 | | x | - | - | 99 | 21.3 | 0.42 – 0.56 | 205 | 206 |
| SE5# | M1 | 127.0 | 76.2 | 2.5 | 3.0 | | x | | - | - | 115 | 23.6 | 0.48 – 0.63 | 193** | 195** |
| SE6# | M1+Ø6 | 127.0 | 76.2 | 2.5 | 3.0 | | x | | x | - | 115 | 23.6 | 0.63 – 0.71 | * | 239** |
| SE7 | M1 | 108.0 | 108.0 | 2.0 | 2.5 | 2.5 | | x | x | o | 100 | 20.9 | 0.54 – 0.87 | * | * |
| SE8 | M1 | 108.0 | 101.6 | 2.0 | 2.5 | 2.0 | | x | x | x | 100 | 20.9 | 0.59 – 0.75 | * | * |
| SE9 | M1 | 120.7 | 120.7 | 2.0 | 3.5 | 3.5 | | x | - | x | 108 | 20.5 | 0.44 – 0.63 | 204 | * |
| SE10 | M1 | 114.3 | 114.3 | 2.0 | 3.0 | 3.0 | | x | x | x | 108 | 20.5 | 0.44 – 0.88 | * | * |
| SE11 | M1 | 225.0 | 150.0 | 5.4 | 4.9 | | x | | - | - | 106 | 23.7 | 0.44 – 0.60 | 228 | 243 |
| SE12 | M1 | 158.8 | 101.6 | 3.5 | 3.5 | | x | | - | - | 110 | 20.6 | 0.43 – 0.53 | 213 | 219 |
| SE13 | M0 | 114.3 | 63.5 | 2.0 | 3.0 | | x | | - | - | 112 | 26.3 | 0.46 – 0.48 | 205 | 183 |
| SE14 | M0 | 127.0 | 76.2 | 2.5 | 3.0 | | x | | - | - | 107 | 23.4 | 0.44 – 0.56 | 225 | 205 |

| | |
|---|---|
| * | Transfer zone cracked / transfer length not evaluable |
| ** | Concrete strain measured with strain gauges (no manual measuring with gauge points) |
| o | Crack not observable visually, but concrete strain indicates cracks |
| # | Test carried out after 5 days |

The specimen SE1 with a specific concrete cover $c/d_p = 1.5$ started cracking when 70 % of the prestressing was induced. Due to the splitting crack the stress depending part (Hoyer-effect) diminished leading to a higher slip. SE2 with $c/d_p = 2.0$ cracked at 95 %. The transfer lengths were evaluated by a German method[11]. It becomes shorter compared to tests with high strength concrete (HSC) or even normal strength concrete (NSC)[3] when cracks were avoided. In these cases the measured transfer length in UHPC was about 20 to 24 cm (7.9 to 9.4 in). Further data is given in the journal paper[8].

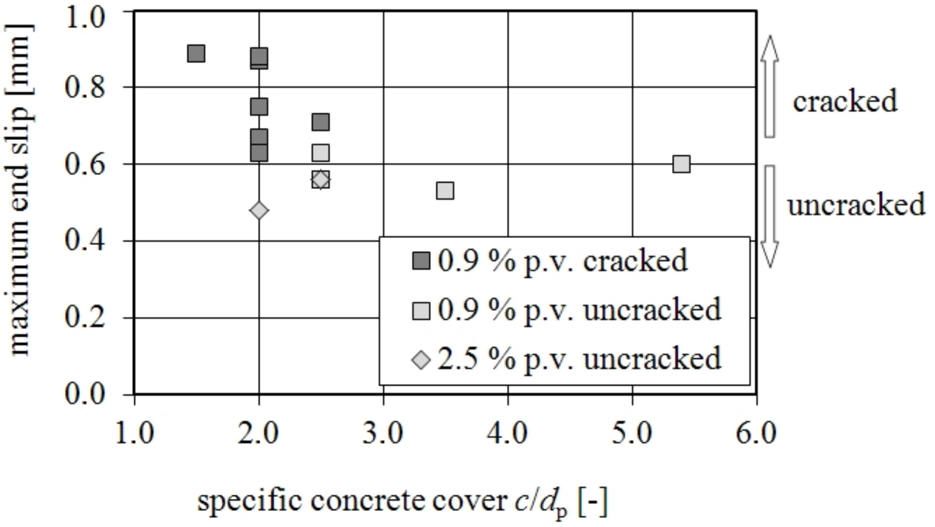
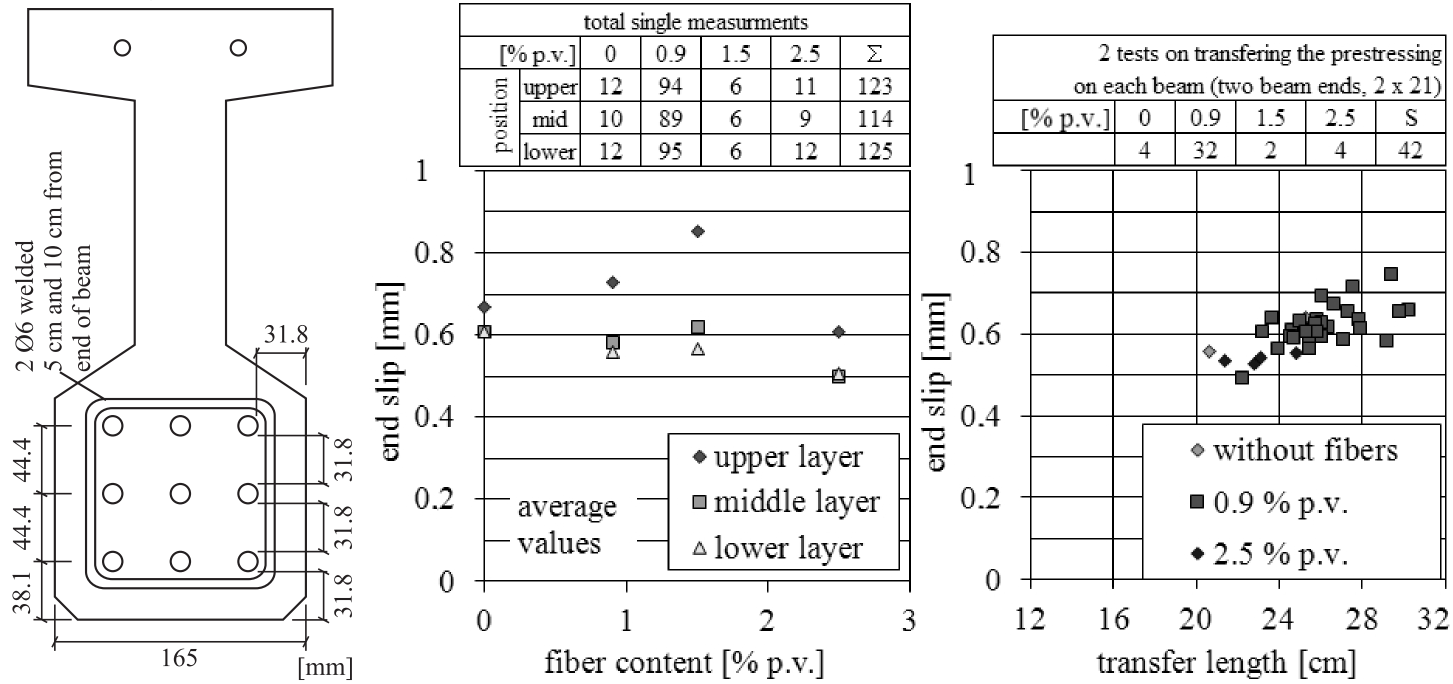


Figure 7: Influence of specific concrete cover and fiber content on end slip and cracking

The influence of the concrete cover and the fiber content on end slip and cracking is illustrated in Figure 7. An end slip of app. 0.5 to 0.6 mm (0.20 to 0.24 in) indicates a transfer without cracks. Compared to HSC a reduction of the minimum concrete cover $c/d_p = 2.5$ could not be accomplished. Most likely, the splitting stresses arose simultaneously due to the higher bond stresses. Only when the specific concrete cover was at least $c/d_p = 2.5$ the full prestressing was feasible without visible cracks. With higher fiber content, a reduction to $c/d_p = 2.0$ seems possible.

## TRANSFER LENGTH AND END SLIP OF THE FULL SCALE BEAMS

According to the small scale beam tests the specific concrete cover of the girders was always $c/d_p = 2.5$ (Fig. 8) and the prestressing was released after three days in the same way. The right diagram shows the transfer lengths of 21 beams. The transfer length was slightly increased to 22 to 28 cm (8.7 to 11 in). There seems to be a slight coherence to the end slip, but splitting cracks were not observed. The middle diagram in Figure 8 shows the average values of 362 measurements on the end slip. The end slip values of the middle and the lower strands did not indicate any cracks as well. They are comparable to the small scale beam tests without cracks. But it is remarkable, that the values of the upper strands are increased. There seems to be a decreased bond strength due to the covering lateral form work.



| total single measurments | | | | | | |
|---|---|---|---|---|---|---|
| | [% p.v.] | 0 | 0.9 | 1.5 | 2.5 | Σ |
| position | upper | 12 | 94 | 6 | 11 | 123 |
| | mid | 10 | 89 | 6 | 9 | 114 |
| | lower | 12 | 95 | 6 | 12 | 125 |

| 2 tests on transfering the prestressing on each beam (two beam ends, 2 x 21) | | | | | |
|---|---|---|---|---|---|
| [% p.v.] | 0 | 0.9 | 1.5 | 2.5 | S |
| | 4 | 32 | 2 | 4 | 42 |

Figure 8: Cross section of the beams and evaluation of the influence of the fiber content and strand position on end slip and transfer length

## CONCLUSIONS AND OUTLOOK

The bond strength of strands in UHPC amounts app. 30 MPa (≈ 4,350 psi) with full release, 20 MPa (≈ 2,900 psi) with 50 % and 12 to 14 MPa (≈ 1,900 psi) without release. The transfer length ranged between 22 and 28 cm (8.7 to 11 in), primarily affected by the concrete cover and the strand density. Therefor a minimum specific concrete cover $c/d_p = 2.5$ as well as a minimum clearance $s/d_p = 2.5$ is required. With 2.5 % p.v fibers the concrete cover seems to be reducible to $c/d_p = 2.0$.

Further details of the model are not described in this paper. The bond model as well as the calculation method are published in a German journal[8] and will be presented at the conference. An English Version will follow soon.

## ACKNOWLEDGEMENTS

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