Load-Carrying Behaviour of Connectors under Shear, Tension and Compression in Ultra High Performance Concrete

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ABSTRACT:

The present paper summarizes the results of an experimental research program including the testing of continuous shear connectors (puzzle strip and saw tooth) under shear, tension and compression in ultra-high performance concrete (UHPC). The initial stiffness, the load carrying capacity and the ductility of the connectors were determined and compared for various parameters. In the shear tests, the thickness and the geometry of the connectors were varied. According to EC 4 (EC 4, 2004), the POST (Push-Out Standard Test) has to be applied to simulate the shear transfer in the composite joint. In this paper, the much smaller SPOT (Single Push-Out Test) has been used. The results are compared to those tested with the POST. In the tests under compression and tension the influence of the concrete cover on the load carrying behaviour of a single shear connector was determined. The various effects are described and evaluated.

1 INTRODUCTION

Composite structures combine the favourable features of structural steel and concrete. Taking into account the mechanical properties the steel carries the tensile forces and the concrete is arranged in the compression zone. Due to the composite action a significant increase in load carrying capacity and stiffness of the beam is achieved, resulting in savings in dead load, construction depth and construction time. So far, composite structures made of high strength steel and high performance concrete have been investigated (Hegger et. al. 2001, Hechler et. al. 2006). Within a collaborative research project (SPP 1182) ultra high performance concrete (UHPC) with micro steel fibres is applied for hybrid and composite structures. Due to its high compressive strength of up to 200 MPa without thermal treatment even more slender and attractive structures are feasible. In addition, ultra high performance concrete features a high tensile strength under considerable tensile strains which is primarily caused by the steel fibres. Fibres are added to the concrete not only for the strength but also for ductility reasons.

In composite beams, shear connectors are necessary to transfer the shear forces between the steel beam and the concrete slab. So far, headed studs have been used as a shear connector. However, as reported in (Hegger et. al. 2006), in high strength concrete they are not as appropriate as continuous shear connectors like the puzzle strip, which has been applied e. g. at the railway bridge in Pöcking (Schmitt et. al. 2005).

A possible new application for UHPC is presented in Figure 1. Here, two examples of a composite foot bridge are shown. Regarding this construction, the questions which have to be solved are the connection details between the truss elements and the concrete deck. Common possibilities for this detail are bar dowels and binders. For this paper, the geometry of the puzzle has been tested in Push- and Pull-Out Tests to investigate the load and deforming capacity in hybrid constructions.

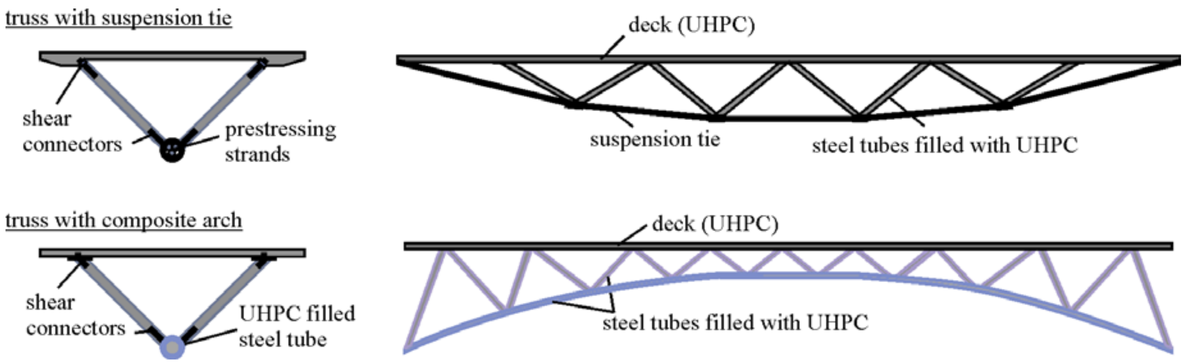


Figure 1. Hybrid Truss Beams

2 ULTRA HIGH PERFORMANCE CONCRETE

The composition of ultra high performance concrete (UHPC) differs fundamentally from conventional concrete such as normal strength concrete (NSC) or high strength concrete (HSC). The main characteristics of UHPC are a high compressive and tensile strength as well as a high durability compared to NSC and HSC. The UHPC features a compressive strength of up to 200 MPa without thermal treatment. The high performance of UHPC is based on the following vital factors: a low water-cementitious materials ratio (w/cm) of 0.19 and a high density which is achieved by a high content of cement, fine sands (mainly quartz) and silica fume. This is essential to fill the cavities between the solid particles. The silica fume functions as a superplasticizer. Table 1 shows the components of UHPC which has been employed for the tests.

	Unit	-
Cement CEMI 52.5 R	kg/m³	650
Silica Fume	kg/m³	177
Quartz Powder	kg/m³	456
Coarse Aggregates	kg/m³	951
Steel Fibres	% per volume	0.9
w/cm - ratio	-	0.19

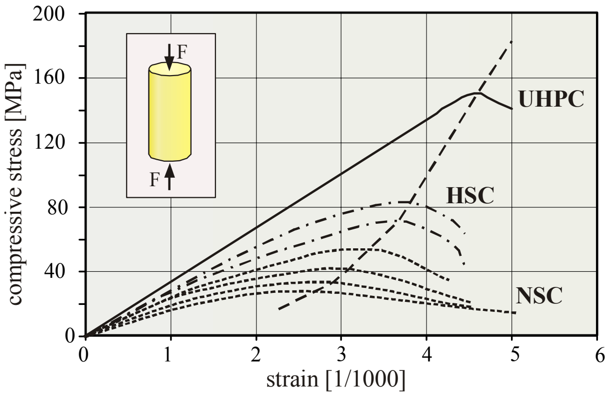


Figure 2. Characteristics of UHPC and stress-strain diagram

To ensure a sufficient ductility thin micro steel fibres are added. Due to the steel fibres, UHPC not only features a high compressive strength but also a linear-elastic behaviour until about 90 % of its compressive strength which is achieved at a strain rate of about 4.5 ‰ (Figure 2). Conventional concrete (NSC and HSC) shows a distinctive nonlinear behaviour due to the micro-cracks which develop at a stress level of about 40 % of the compressive strength.
Besides the ductility the tensile strength of the UHPC is also increased because of the steel fibres.

3 ANCHORAGE AND SHEAR FAILURE

Eligehausen (Eligehausen et. al. 2000) conducted pull-out tests with headed studs, undercut anchors and expansion plugs. He defined anchorage failure within four types (Figure 3, left): pull through, concrete breakout, splitting and steel failure. The tests within this paper were designed to achieve concrete failure in order to determine the influencing factors concerning the concrete. In this case, the anchor as well as the puzzle teeth create a coned breakout, where the tensile strength of the concrete is governing (Figure 3, right).

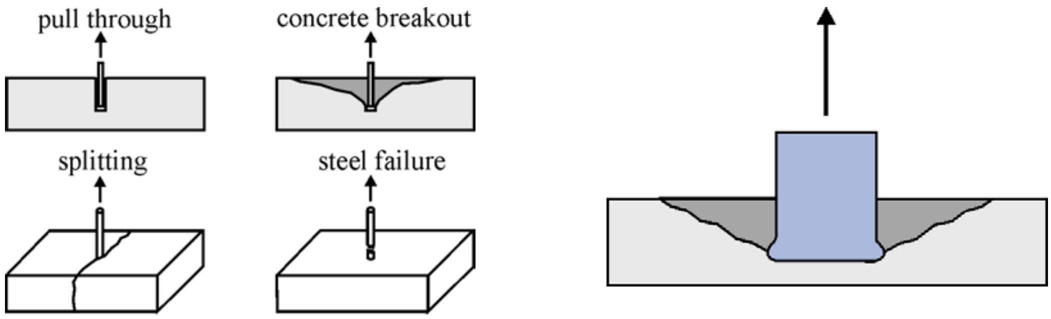


Figure 3. Types of failure (left) and concrete breakout of a puzzle tooth (right)

The load bearing behaviour of continuous shear connectors has been investigated by several researchers (Hegger et al. 2001, 2006, Wurzer 1997). Four failure modes have to be considered under pure shear load (Figure 4): local concrete failure in front of the shear connector, concrete pry-out failure, shear failure of the concrete and steel failure due to the moment stress of the puzzle profile which is described in (Hegger et al. 2006).

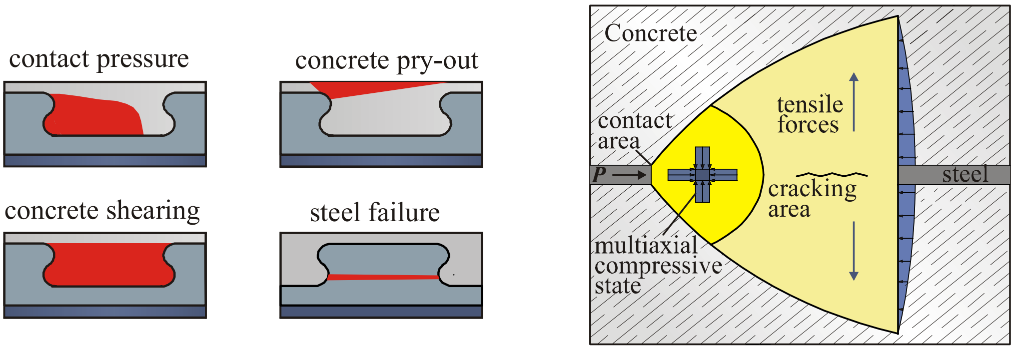


Figure 4. Failure modes (left) and stresses in the concrete (right) of continuous shear connectors

According to the model of (Wurzer 1997) there are lateral tensile forces between the steel teeth resulting from the concentrated load introduction of the steel profile (Figure 4b)

4 TEST PROGRAM

The geometry of the puzzle was tested under pure shear loading as well as under centrical tension and compression loading. The test parameters investigated within five test series are summarized in Table 1.

Table 1. Test program

Series	Number of Tests	Test Set-Up	Description	
A1	2	Shear (SPOT)	Saw Tooth	Direction 1
A2	2	Shear (SPOT)	Saw Tooth	Reverse direction 2
B1	2	Shear (SPOT)	Puzzle	t_w= 20 mm
B2	2	Shear (SPOT)	Puzzle	t_w= 15 mm
B3	2	Shear (SPOT)	Puzzle	t_w= 10 mm
C1	2	Shear (POST)	Puzzle	t_w= 20 mm, Comparison to SPOT
D1	2	Pull-Out	Puzzle	c_o= 6 cm
D2	2	Pull-Out	Puzzle	c_o= 5 cm
E1	2	Push-Out	Puzzle	c_u= 3 cm
E2	2	Push-Out	Puzzle	c_u= 2 cm

The Single Push-Out Test (SPOT, Figure 5, left) consists of a steel frame embracing the UHPC block. Due to its compactness it is an appropriate possibility to test the steel puzzle and the saw tooth under nearly pure shear load. It has been designed at the Institute of Structural Concrete at

RWTH Aachen University and has been used for several tests with headed studs in high strength concrete (Hegger et. al. 2005).
In Series A, another geometry, the saw tooth profile, was tested in two directions under nearly pure shear force. Furthermore, in Series B the thickness of the shear connector (puzzle strip) was varied. Both series were tested in the SPOT.
Since the SPOT is not the proper testing set-up according to EC 4 (EC 4, 2004), comparative tests with the Push-Out Standard Test (POST) have been carried out in Series C. The set-up of the POST (Figure 5, right) according to (EC 4, 2004) is described exactly in (Hegger et. al. 2008).

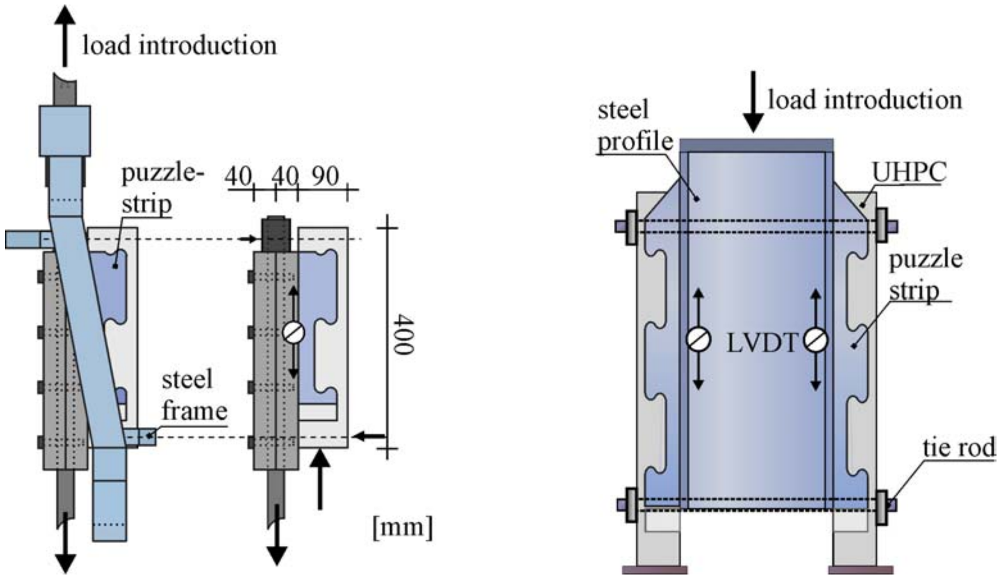


Figure 5. Single Push-Out Test (SPOT, left) and Push-Out Standard Test (POST, right).

For the tests with one puzzle under pure compression and tension loading, a new test stand has been developed, the Pull- and Push-Out Tests (Figure 6). All specimens for these tests consist of one steel puzzle with the thickness of 20 mm in a 500x500x100mm UHPC-plate. The measuring program of the Push- and Pull-Out Tests contained the global deformation of the UHPC-plate, the deformation of the steel puzzle relative to the concrete and the strain distribution in the middle of the concrete-plate (Figure 6).
The Pull-Out Tests (Series D) were designed for concrete breakout. For the Push-Out Tests (Series E), the distance of the bearing construction (a=200 mm, Figure 6 left) was designed for punching failure. In all tests a bending failure was prevented by short spans. The effect of different concrete covers were investigated in the Series D and E.

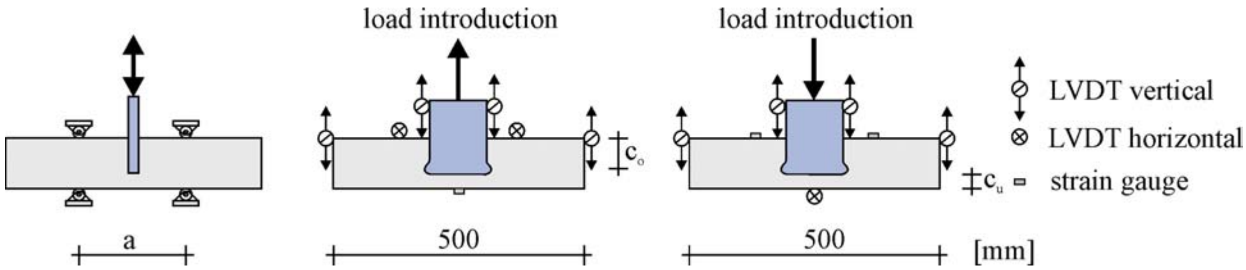


Figure 6. Bearing situation (left), Pull-Out Test (middle) and Push-Out Test (right).

5 SHEAR TESTS

The shear tests in Series A to C were evaluated according to the procedure of EC 4 (EC 4, 2004). The characteristic slip δ_{uk} specifies the deformation measured in the tests during the plastic period when the characteristic load P_{Rk} was maintained.

The concrete compressive strength for a 100-mm-cube $f_{c,cube100}$, the yield strength of the shear connectors, the mean maximum loads $P_{max,mean}$, the characteristic loads P_{Rk} for one recess and the corresponding slip δ_{uk} are presented in Table 2.

Table 2. Compressive strength and test results – Series A to C

Series	$f_{c,cube100}$ [N/mm²]	f_y [N/mm²]	$P_{max,mean}$ [kN]	P_{Rk} [kN]	δ_{uk} [mm]
A1	176.1	499	457.5	396.8	6.5
A2	182.6	499	418.4	354.5	1.2
B1	179.5	499	412.6	330.5	5.2
B2	178.0	521	375.2	327.0	11.8
B3	182.6	441	326.2	282.1	15.1
C1	194.4	499	432.9	369.5	4.6

With the saw tooth it was intended to increase the confined area in front of the connector and thus to improve the load carrying behaviour. Since the saw tooth has no symmetrical shape it was tested in Series A in two directions (Figure 7).

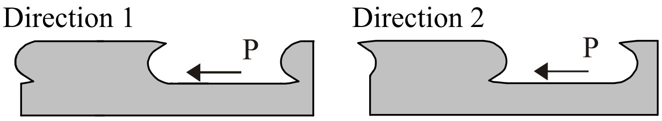
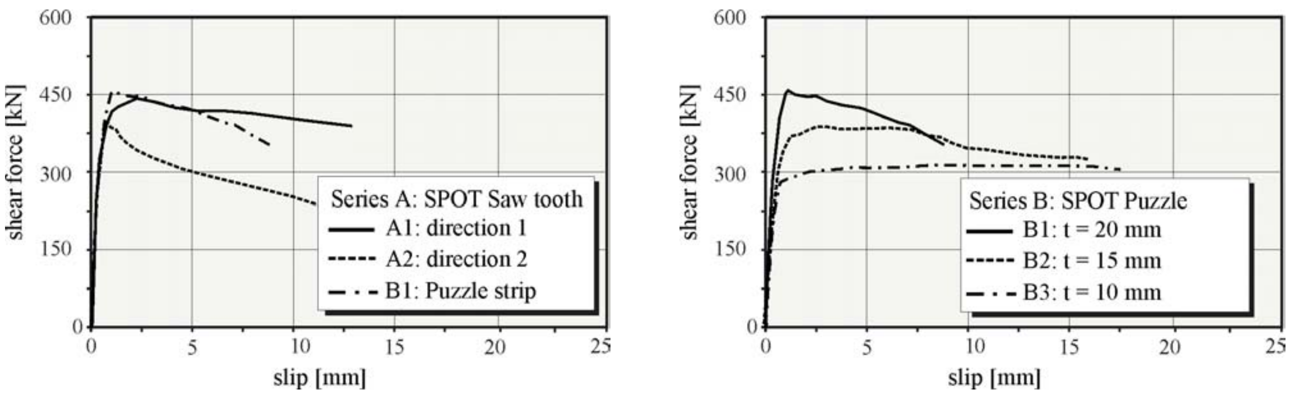


Figure 7. Load directions for the saw tooth.

In Figure 8 a the results of the SPOT with both saw tooth-directions are compared to the results with the puzzle geometry. The initial stiffness was equally high independent of the load direction and geometry. The saw tooth direction 1 and the puzzle show no noticeable differences in ultimate load. However, when the saw tooth was stressed in reverse direction 2, both, the load carrying capacity and the ductility were significantly reduced.
Since in most structures and especially bridges the direction of shear forces between steel profile and concrete slab changes depending on the load state, the symmetrical puzzle is preferred.



a) Effect of load direction b) Effect of shear connector’s thickness

Figure 8. Load-slip diagrams – Series A and B.

The influence of the connector’s thickness was investigated in Series B. There is a slight difference in initial stiffness. With increased thickness of the connector higher ultimate loads were achieved (Figure 8 b). The specimens of Series B3 with a thickness of 10 mm failed due to the yielding of the puzzle. After the test the puzzles were deformed noticeably and a horizontal crack was observed. In Series B2 with a connector thickness of 15 mm a combined steel and concrete pry-out failure was observed. Due to the larger thickness pure concrete pry-out failure occurred in Series B1 with no deformation in the steel. With increasing thickness and predominating concrete failure the ductility was significantly reduced compared to pure steel failure. However, even for concrete failure the behaviour is not brittle due to the steel fibres.

In Figure 9 the 10 mm and the 20 mm puzzle are presented after testing. The concrete directly in front of the puzzle was compressed and in both specimens there are cracks visible in the concrete.

Whereas the thick 20 mm puzzle shows no deformation at all, there is a significant offset and plastic deformation in the thin 10 mm puzzle.

a) 10 mm puzzle b) 20 mm puzzle

Figure 9. Puzzle strip after testing

In the following, the results of the Single Push-Out Test (SPOT) are compared to the Push-Out Standard Test (POST) according to EC 4 (EC 4, 2004).

Figure 10 shows the comparison of the POST and the SPOT specimens. The ultimate load of each Push-Out Standard Tests was divided by four to equal the load carrying capacity of one puzzle strip in the SPOT. It is noticeable that almost the same ultimate loads could be achieved. Thus, it can be concluded, that the much smaller and economic SPOT can be used as a test set-up to investigate the load carrying behaviour of shear connectors properly.

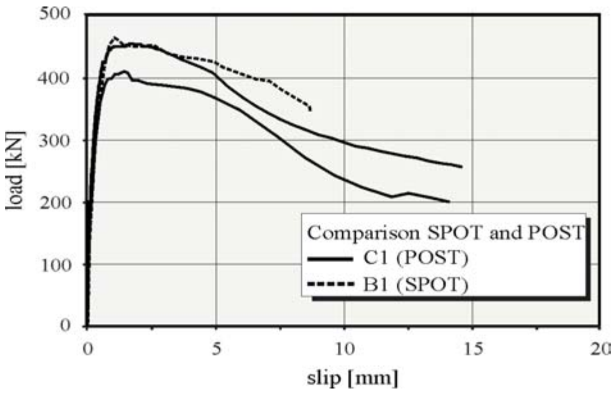


Figure 10. Comparison of POST and SPOT specimen (Series C).

6 PUSH- AND PULL-OUT TESTS

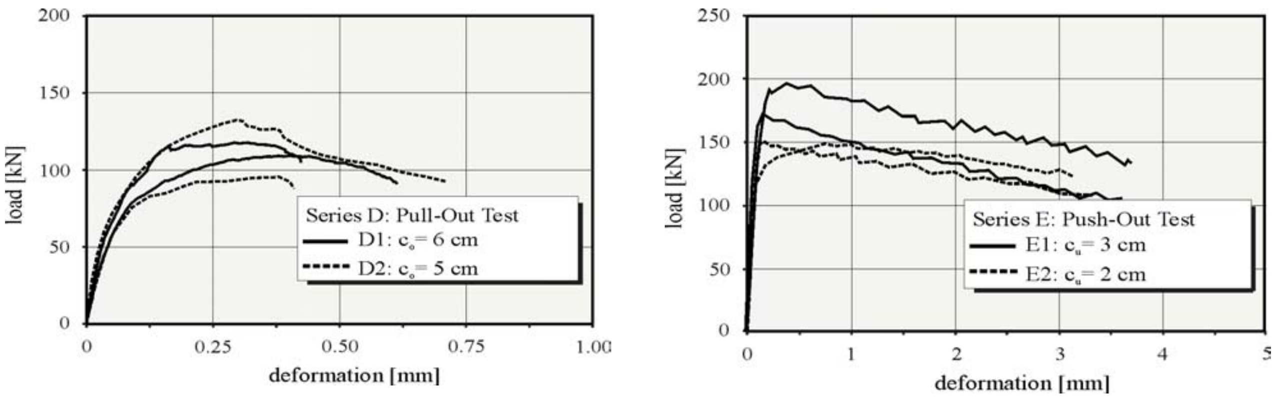
The results of the Push- and Pull-Out Tests are evaluated in the following. The corresponding deformation δ_{cor} describes the travel measured in the tests when the maximum load P_{max} was achieved. The concrete compressive strength for a 100-mm-cube $f_{c,cube100}$, the mean maximum loads $P_{max,mean}$ and the corresponding deformation δ_{cor} are presented in Table 3.

Table 3. Compressive strength and test results – Series D and E

Series	$f_{c,cube100}$ [N/mm²]	$P_{max,mean}$ [kN]	δ_{cor} [mm]
D1	176.0	113.6	0.38
D2	176.0	114.1	0.33
E1	175.6	183.4	0.27
E2	174.8	148.8	0.55

The increase of the concrete cover from 5 cm to 6 cm didn't show an explicit trend concerning the maximum force. Reasons for this are the low increase of the concrete cover and the straggling of the concrete's tensile strength. The ultimate load in the Pull-Out Tests of the two specimens with an upper concrete cover of c_o= 5 cm varied about 27 % and with c_o= 6 cm about 7 % (Figure 11 a). Thus, further tests with more extreme dimensions will be performed. After reaching the maximum load, every specimen had a ductile behaviour.

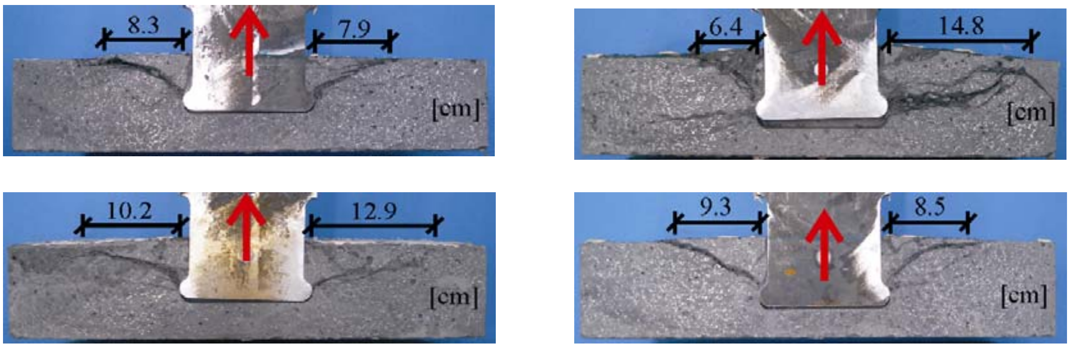
Due to the larger concrete cover of the Push-Out Tests the mean maximum load could be increased by 19 % with equal initial stiffness (Figure 11 b). The failure of every specimen also was ductile because of the steel fibres.



a) Pull-Out Tests (Series D) b) Push-Out Tests (Series E)

Figure 11. Load-deformation diagram – Series D and E.

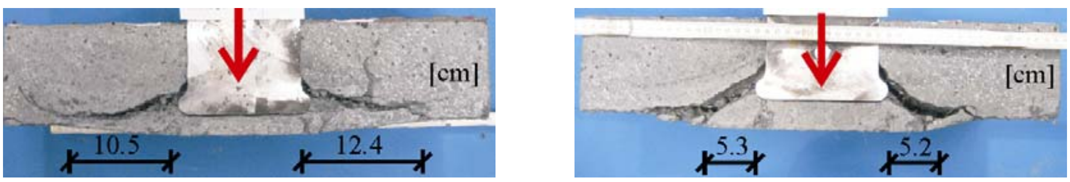
After the tests all specimens were opened to investigate the failure mode. By means of the cracking pictures a coned breakout was formed due to the tensile forces generated by the puzzle (Figure 12). The inclination of this breakout cones also varied strongly with the same concrete cover (Figure 12 a). Reasons for this are differences in the adjustment of the steel fibres and local inhomogenities of the concrete. This also explains the different levels of the maximum loads during the Series D2 with an upper concrete cover of 5 cm.



a) c_o= 5 cm b) c_o= 6 cm

Figure 12. Breakout cones – Series D.

Figure 13 shows a typical punching failure for the specimen with a concrete cover of 3 cm (Figure 13 b). Furthermore, a larger concrete cover developed a sharper angle of the punching cone. With a concrete cover of 2 cm, the angle of the punching cone was much flatter (Figure 13 a). A bending failure can be declined. This also explains the slight more ductile load-deformation curve in Series E2 (Figure 11 a).



a) c_u= 2 cm b) c_u= 3 cm

Figure 13. Punching cones – Series E.

7 CONCLUSIONS

Tests with connectors have been carried out in UHPC under shear, tension and compression. Under shear load, the thickness of the puzzle was varied and another geometry, the saw tooth, was tested. The results of the SPOT were compared to those carried out in the POST, according to EC 4 (EC 4, 2004). The parameter for the tests under tension and compression was the concrete cover.

The results from the test series can be summarized as follows:

- Generally, the puzzle strip shear connector is capable of carrying high shear loads with an appropriate ductility.
- The saw tooth loaded in optimal direction showed a high carrying and ductile behaviour under a pure shear load. However, in the reverse direction, the load carrying capacity and the ductility were significantly reduced.
- The comparison of the test results of the SPOT and the POST showed that with the much smaller - and thus easier to handle – SPOT, shear connectors can be tested effectively.
- Under a pure shear load, different failure modes were observed depending on the thickness of the shear connector. For thin puzzles (10 mm) steel failure occurred with a very ductile behaviour showed. Concrete failure (pry-out failure as well as local concrete compression failure) was achieved at a thickness of 20 mm. A combined steel and pry-out failure occurred at a thickness of 15 mm.
- With a higher concrete cover in the compression tests an increase in the load capacity of 19 % could be achieved.

Further tests to describe the load and deformation capacity of one puzzle teeth in UHPC will be investigated in the future. In these tests, the effect of a reinforcement will be determined and further tests concerning the concrete cover will be carried out.

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