INTERFACE SHEAR TRANSFER BETWEEN PRECAST UHPFRC ELEMENTS AND NORMAL CONCRETE OVERLAY

Norbert Randl (1), Martin Steiner (1) and Tamás Mészöly (1)

(1) Carinthia University of Applied Sciences, Austria

Abstract

Several series of different small scale tests were performed in order to determine the adhesive bond strength between precast UHPFRC elements provided with different surface profiles and subsequently applied NSC. Slant shear tests with variable interface inclination as well as push-out tests consisting of an UHPFRC plate in the middle and two outer NSC plates provided the basis for judging the effect of adhesive bond on the overall interface shear strength. Waffle-like profiles with square-shaped comb indentations proved to be most effective when taking into account both interface shear strength as well as easiness of potential production in a pre-casting plant with the profiled surface on the top side. In order to judge the friction effect after loss of adhesion, some single pull-off friction tests with de-bonded interface were made. In addition to the small scale tests also some larger T-shaped composite beams have been produced and tested in four point bending setups. The T-beams were made of fibre reinforced UHPC with a NSC layer as subsequent supplement on the upper flange.

Résumé

Plusieurs séries d'essais à petite échelle ont été réalisés pour déterminer la capacité d'adhérence entre des éléments préfabriqués en BFUP pourvus de différents profils surfaciques et un béton ordinaire rapporté. Des essais de cisaillement biais avec différents angles d'interface ainsi que des essais d'enfoncement d'une plaque de BFUP entre deux plaques extérieures en béton ordinaire ont constitué la base de l'évaluation de la capacité d'adhérence comme partie intégrante de la résistance de l'interface. Les profils gaufrés avec indentations crénelées se sont avérés les plus efficaces, en tenant compte à la fois de la résistance au cisaillement de l'interface et de la facilité de produire en usine la surface supérieure profilée. Pour évaluer le frottement après perte d'adhérence, quelques essais d'arrachement avec surface décollée ont été réalisés. En plus des essais à petite échelle, quelques poutres mixtes en Té ont été fabriquées et testées en flexion quatre points. Ces poutres en Té étaient constituées de BFUP avec une couche de béton ordinaire rapportée sur le hourdis.

1. INTRODUCTION

Precast elements frequently require completion on the site by adding normal strength concrete (NSC) layers. As Ultra High Performance Concrete (UHPC) becomes increasingly attractive for the production of precast elements, the question of adhesive bond and interface shear transfer between UHPC and subsequently applied NSC is raised. Examples are in situ cast bridge decks on UHPC girders where for economic reasons NSC may be preferred as top layer providing the required stiffness in transverse direction [1] or small UHPC elements embedded in ordinary NSC where load transfer along the interface between the two concretes is a decisive feature (see e.g. [2, 3]). The main focus in research is so far rather laid on bond between existing NSC members and HSC or UHPC concrete overlays (see e.g. [4]). Only few researchers have investigated interface shear transfer between precast (U)HPC panels and subsequently cast NSC layers [5-7]. These tests show that the surface of the high strength precast elements has to be provided with a pronounced profile in order to achieve a satisfying interface shear transfer to the cast in place concrete layer.

Therefore a number of different small scale and larger scale tests were performed in order to determine the adhesive bond strength between UHPFRC and subsequently applied NSC. The precast fibre reinforced UHPC elements were provided with different surface profiles like indentations (similar to Eurocode 2 design recommendations for very rough interfaces), waffled with square-shaped combs or dimpled structures. In addition some single UHPFRC specimens with originally very smooth formed surface were subsequently roughened by high-pressure water jetting (HPW) which led to an excavation of shallow fibres. The T-shaped composite beams have been made of fibre reinforced UHPC with a NSC layer as subsequent supplement on the upper flange, thus verifying the results of small scale tests under realistic structural conditions.

2. MATERIAL PROPERTIES

All test specimens consisted of a precast part made of fibre reinforced ultra-high performance concrete (UHPFRC) and a supplementing layer of cast-in-place normal strength concrete (NSC). The UHPC was a fine grain mixture with a maximum aggregate size of 0.8 mm. It basically was a composition of the following 6 ingredients: Portland cement type CEM I 42.5 R HS, silica fume, quartz powder, quartz sand, superplasticizer and water. The water-to-binder ratio, taking into account a 70 % water content in the superplasticizer, was 0.22. 2 Vol.-% of steel fibres with an aspect ratio ($l_f/ø_f$) close to 75 were added.

The average value of the compressive strength of the UHPFRC measured on cubes with a side length of 100 mm was around 170 MPa on the day of testing. The mean concrete strength of the NSC (with a maximum grain size of 16 mm) measured on 150 mm cubes on the day of testing was about 45 MPa.

3. TESTING PROGRAM FOR SMALL SCALE TESTS

3.1 Surface characteristics

Several different types of surface profiles were produced and tested in different setups (see below) with respect to interface bond properties and practical production requirements. The surface textures were prepared by using dimpled sheets, wooden waffle-shaped or indented profiles or rubber mats as part of the formwork for the UHPFRC segments. The wooden indented profile was in line with the Eurocode 2 [8] requirements for an indented construction joint. Figure 1 shows the different used surface profiles. With the dimples sheets, interfaces with both indentations in the UHPFRC (i.e. knobs protruding from the NSC, referred to as "dimpled 9 mm NSC" and "dimpled 18 mm NSC") as well as knobs protruding from the UHPFRC ("dimpled 9 mm UHPFRC") were tested. The NSC was applied on the dry surface of the UHPFRC without pre-wetting.

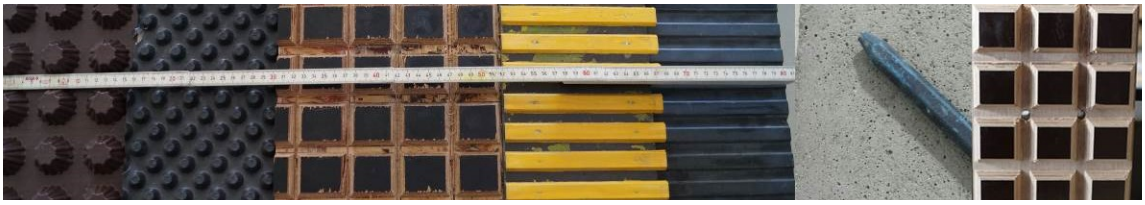

Figure 1: Different investigated surface profiles for the UHPFRC

3.2 Push-out tests (type I)

There exist a variety of possible setups for small scale tests with respect to adhesive bond strength along an interface [9, 10]. The herein used specimens for the push-out tests in shear are shown in Figure 2. Such types of test specimens are useful for analysing the pure shear transfer capacity via an interface. The inner part represents the subsequently cast UHPFRC layer, while the two external NSC (overlay) parts were produced in advance. The height of the prisms was 300 mm and the surface of the two interfaces 300 x 150 mm each. Each concrete segment had a thickness of 100 mm. The load was introduced vertically into the mid-segment, very close to the interface in order to avoid significant eccentricities and in consequence load deviations.

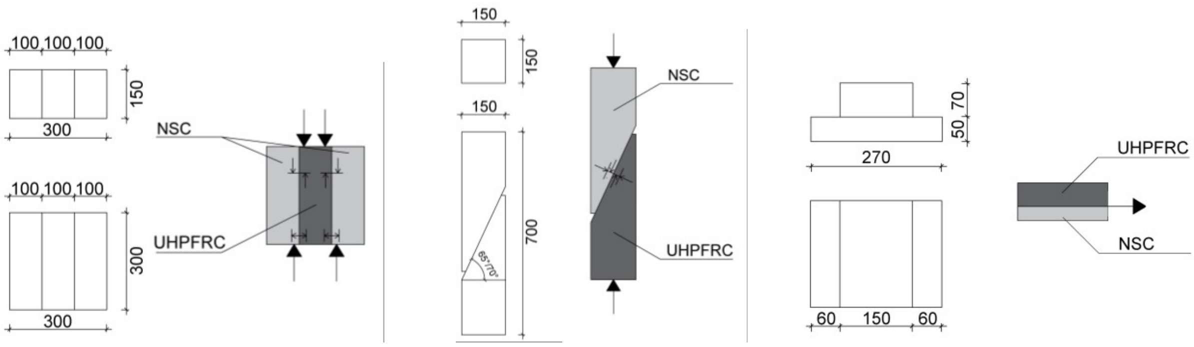

Figure 2: Push-out (type I), slant shear (type II) and pull-off tests (type III) (units: [mm])

3.3 Slant shear tests (type II)

Slant shear tests (specimen geometry see Figure 2) represent a typical setup for the determination of the interface shear transfer based on adhesive bond strength in combination with normal forces perpendicular to the interface. The ratio between shear force and normal force depends on the inclination of the interface. To prevent the introduction of lateral forces, plain steel plates with lubricant in between were placed on top between specimens and actuator and a spherical bearing was used at the bottom.

3.4 Pull-off friction tests (type III)

In order to judge the friction effect after loss of adhesion, pull-off friction tests with de-bonded interface were performed (Figure 2). The shear force was introduced to the upper UHPFRC layer as close as possible to the interface, and the resulting small eccentricity balanced by a steel lever arm (configuration according to the test setup presented in [10]). Depending on the roughness profile, the friction resistance was superimposed by interlocking effects so that it was not always possible to identify the real coefficient of friction.

3.5 Measuring equipment for interface shear tests

To measure the crack opening and the parallel displacement along each interface, a set of four inductive displacement transducers (LVDT) were installed at the sides of the push-out specimens. Similarly, the slant shear test specimens were provided with 2 LVDTs at the height of the centre of the interface. The LVDTs were arranged parallel to the interface in order to record the parallel shifting as well as perpendicularly in order to measure the joint opening. In the case of the type III tests, the 2 LVDTs recording parallel shifting and opening of the joint were fixed at the back side of each specimen.

4. SETUP OF T-BEAM TESTS

Based on the results from the small scale tests, 4 larger scale beams with T-shaped cross-section were designed and produced. Decisive design criteria for the beam specimens were the smallest possible thickness of the UHPFRC web and creating a high interface shear stress between precast UHPFRC beam and NSC overlay at failure.

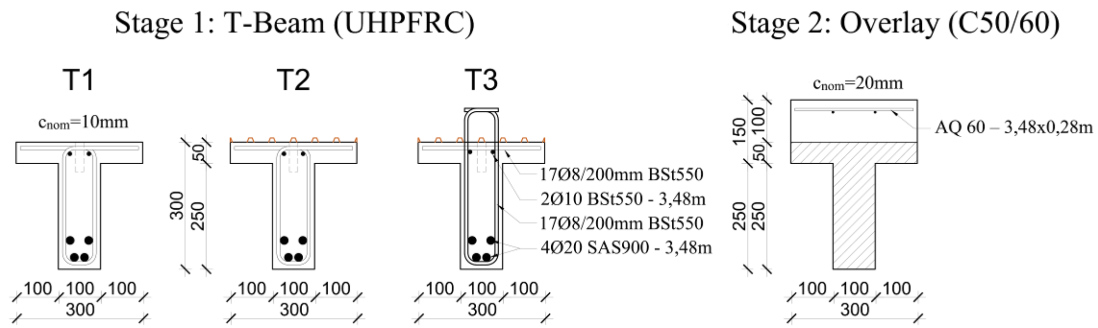

Figure 3: Interface constellations and production stages

With the four beams, three different types of interface structures were tested: a smooth one without any treatment (beam T1), two beams with the final waffle profile (beams T2.1 and T2.2), and one with the final waffle profile together with stirrups crossing the interface surface up to the compression zone (beam T3). The beams were produced in two steps: In the first stage the lower, T-shaped UHPFRC beam part was produced in a pre-casting plant. At an age of 12 days the NSC overlay was cast on top of the UHPFRC T-beams. Figure 3 shows the three different interface types and the two stages of the production.

The beams were tested in a four-point bending test setup (see Figure 4). The mixture of the UHPFRC was the same as used in the small scale tests. The overlay was a class C50/60 concrete with a 28-days mean compression strength (measured on cubes with a side length of 150 mm) of about 70 MPa. The shear span-to-depth ratio (λ=a/d) of the test setup was 2.9.

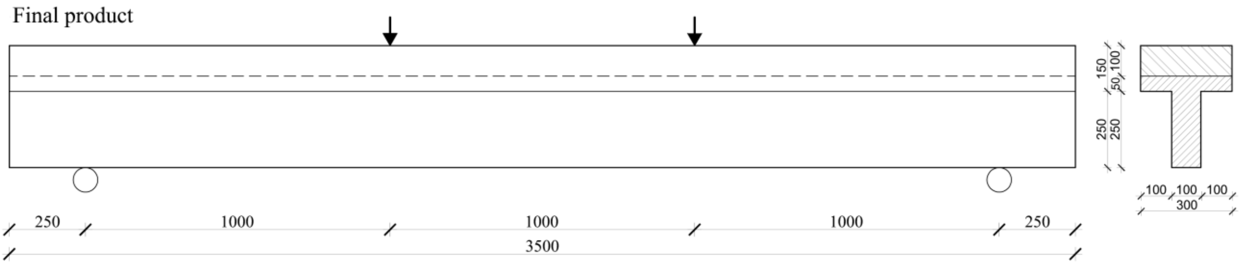

Figure 4: Setup of T-beams (four-point bending test)

The areas between the waffle segments were prepared in such a way that the surface percentage of the NSC toothing was much larger than the proportion of the UHPFRC ridges, so that the lower NSC strength was more or less compensated (see Figure 5).

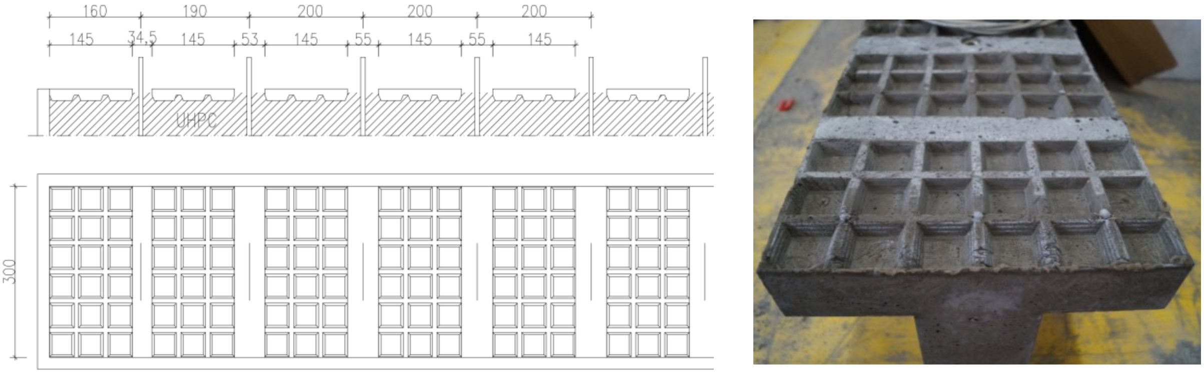

Figure 5: Interface with final waffle profile allowing for stirrup crossings (units : [mm])

5. RESULTS OF SMALL SCALE TESTS

All push-out tests ended up with a clear rupture along one or sometimes both interfaces, i.e. adhesive bond failure along the interface. The shear load was superimposed by a very small moment due to the unavoidable eccentricities between interface axis and load introductions resp. bearings. Therefore the bond failure initiated always from the bottom end, in a very abrupt way at only small displacements. The test results are summarized in Figure 6.

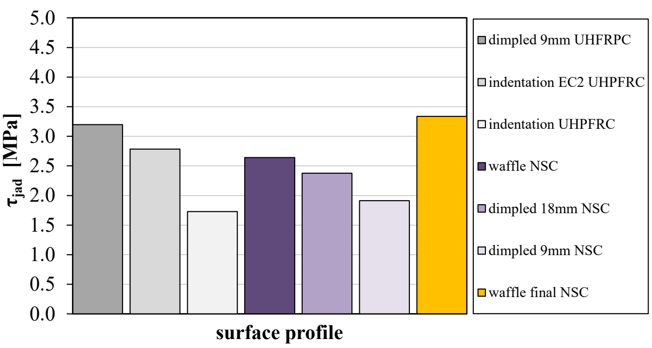

Figure 6: Interface shear strength from push-out tests

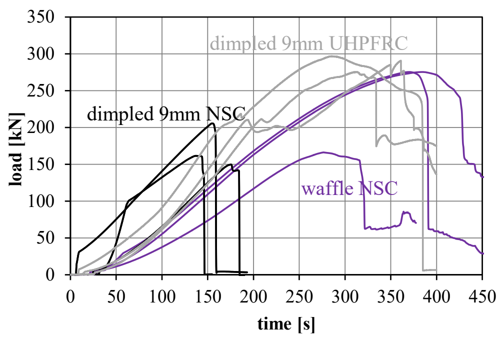

Figure 7: Comparison of push-out tests with dimpled surface and waffle

The “dimpled 9 mm UHPFRC” profile (knobs protruding from UHPFRC) showed the highest adhesive bond values together with the final waffle profile (however, in the latter case the NSC concrete strength of about 60 MPa was somewhat higher). As the production of the “dimpled 9 mm UHPFRC” profile in a precasting plant turned out to be very difficult mainly because of unavoidable entrapped air pockets, finally the waffle profile was chosen. The waffle profile provides reliable data for the interface shear resistance in both directions. The comparisons of the load deflection curve between “dimpled 9 mm NSC” profile and waffle profile and “dimpled 9 mm UHPFRC” and NSC are shown in Figure 7. The failure of the waffle and the dimpled 9mm UHPFRC was not so abrupt due to some interlocking effect. In Figure 8 the broken push-out test specimens are shown. The surface texture of the waffle profile was even on the NSC side not entirely destroyed after the test. In contrast, the knobs of the dimpled 9 mm and 18 mm NSC profile were sheared off completely.

Figure 8: Interface profiles after push-out (left) and slant shear tests (right)

Beside the push-out tests several series of slant shear tests were performed with different surface profiles and a joint angle varied between 65° and 70°. A picture of the broken specimens is shown in Figure 8 (right). From the maximum loads reached in the slant shear tests, the corresponding stresses σ_j perpendicular and τ_j parallel to the interface were derived on the basis of the measured actual cross-sectional and geometric data for each specimen. In the next step, the adhesive bond $\tau_{j,ad}$ without superimposed normal stresses was back-calculated using Mohr-Coulomb's failure hypothesis and reasonable values for the friction coefficients (Figure 9 depicts the derived adhesive bond values).

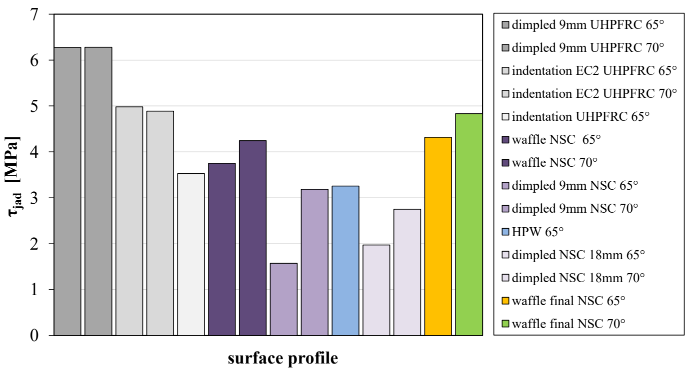

Figure 9: Interface shear strength from slant shear tests (back-calculated adhesive bond)

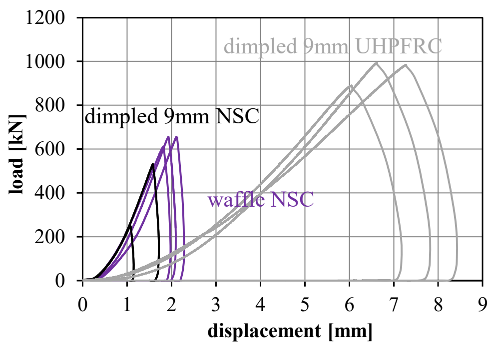

Figure 10: Load displacement curves from slant shear tests

As expected the maximum interface shear strength was reached with brittle failure of the adhesive bond, occurring always along the interface. The lowest shear strength resulted from dimpled profiles with small knobs protruding from the NSC into the UHPFRC and also from the water jetted UHPFRC surface (due to the fine grain the surface remained rather smooth except for the protruding fibres). In Figure 10 the load-displacement curves of different tested constellations are shown. Similar to the push-out tests, also in the slant shear tests the "dimpled 9 mm UHPFRC" profile led to the highest interface shear resistance. In comparison, the "dimpled 9 mm NSC" profile with indentations in the UHPFRC led to premature and complete shearing-off of the NSC knobs. In the specimens with the waffle profile, after the tests the roughness structure was still nearly intact. Only a small number of waffle segments had broken out as shown in Figure 8, meaning that the proportion between UHPFRC ridges and NSC combs was chosen correctly.

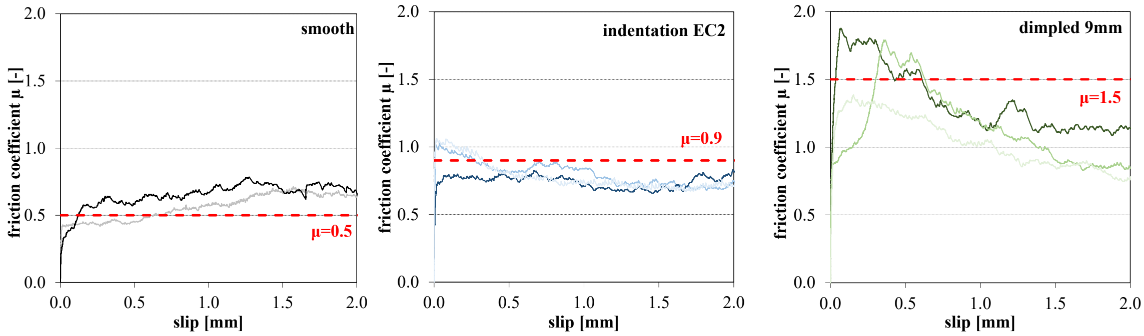

Figure 11: Evaluation of the friction coefficients

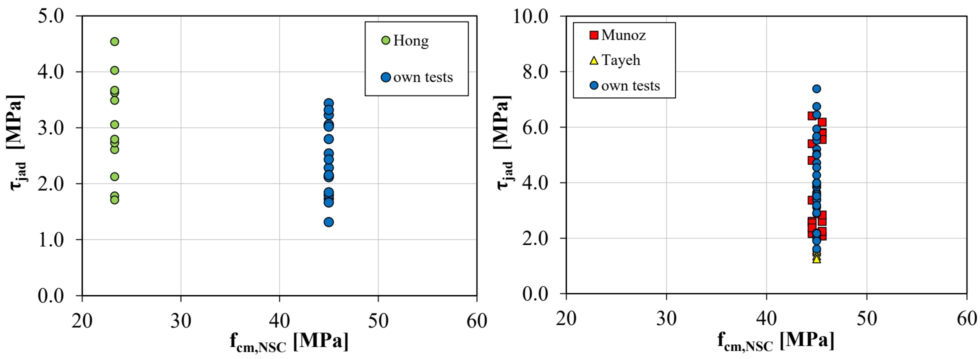

Figure 12: Comparison of push-out test (left) and slant shear test (right)

To investigate the global friction coefficient for the variation of the different profiles, pull-off friction tests were performed (type III). Figure 11 shows the evaluation of the friction coefficient for each surface structure. From the tests with smooth interface, on average a global friction coefficient of 0.5 was reached. This value for a smooth surface is also given in Eurocode 2 [8]. The profile with the trapezoidal indentations reached a friction coefficient 0.9. The dimpled 9mm profile produced the highest friction coefficient with a value of 1.5. The friction coefficients in the range of 0-1 mm displacement are most relevant. Dimpled 18mm and waffle profiles led to strong interlocking so that no global friction coefficient could be detected.

The above described test results (type I and type II setups) have also been compared to results from literature (Figure 12). The compression strength of the UHPC used by Hong [5] was about 155 MPa. Comparable slant shear tests have been performed by Muñoz [6] (compressive strength of HPC about 105 MPa) and Tayeh [7] (UHPC with strength of 180 MPa). As can be seen in Figure 12, all tests result in comparable strength levels.

6. RESULTS OF BEAM TESTS

Table 1 shows the mean compressive strength values measured on cubes on the testing day of each beam (side length of the cubes 150 mm for NSC and 100 mm for UHPFRC mixtures). The splitting tensile strength of the NSC mixture (measured on cylinders with a diameter of 100 mm and a height of 200 mm) was 5.3 MPa and the according strength data were between 19.2 MPa and 20.9 MPa for the UHPFRC mixtures. The mean value for Young's modulus of elasticity was 33.7 GPa for the NSC and 51.0 GPa for the UHPFRC mixture.

Table 1: Mean compression strength of the concrete on the testing day in MPa

	NSC	**UHPFRC**
T1	70.5	170.8
T2.1	77.7	175.6
T2.2	77.0	175.6
T3	72.0	172.3

Beams T1, T2.2 and T3 exhibited primary failure in shear. Beam T1 with the untreated (smooth) interface reached an ultimate load of 717.2 kN. The bond between the UHPFRC part and the NSC overlay was deficient in this case, and already at a load level of 301 kN on one side and at 329 kN on the other side the adhesive bond of the interface failed. At these load levels the back-calculated interface shear stress was only 1.6 MPa and 1.8 MPa, respectively. T2.1 reached an ultimate load of 928.3 kN and T2.2 a value of 804.9 kN, both with the waffle profile along the interface. In the case of beam T2.1 which yielded the highest ultimate load, after formation of pronounced shear cracks finally bursting of the compression zone due to the high bending moment was observed. Beam T3 with the waffle profile and the stirrups reached a load of 880.9 kN and failed in shear without any sign of failure along the interface. However, there was no clear advantage detectable, neither on interface bond behaviour nor on the ultimate load, when using the stirrups as interface shear reinforcement. Figure 13 shows the measured load vs. deflection curves.

To compare the test results with current design models, the bending and shear capacity of each beam was calculated using the regulations of Eurocode 2 [8], Model Code 2010 [11], ACI-318-14 [12] and the AFGC Guideline [13], and results are presented in Table 3. Since the interface bond failed at a low load level in case of the T1 beam, in the calculation the concrete overlay is not taken into account. The calculations for beams T2.1, T2.2 and T3 are based on the assumption of perfect bond between the UHPFRC part and the NSC overlay. Calculations based on the first three standards didn't take into account the effect of the fibres, and provided a significantly lower capacity. The approach according to the AFGC Guideline, taking into account the effect of the fibres, delivered a good prediction of the test results (see in Table 2); thereby confirming the significant contribution of the fibres to the overall shear resistance of the beams.

Table 2: Beam test results

	T1	**T2***	**T3**
Ultimate load (UL) [kN]	717	866	880
Calculation acc. to EC2	360	476	473
Calculation acc. to MC2010	355	436	433
Calculation acc. to ACI	297	402	401
Calculation acc. to AFGC	738	888	886
Interface shear stress at UL [MPa]	–	4.6	4.7
Residual tensile strength [MPa]	4.4	4.7	4.9

* Results in column "T2" are mean values from the tests T2.1 and T2.2

For the design of the beams and the prediction of the failure load according to AFGC, a value of 5.0 N/mm^2 had first been introduced as rough approximation of the residual tensile strength from accompanying flexural tests on small scale prisms. After the tests, based on the measured failure loads, this parameter was back-calculated and checked for each beam: the resulting values were between 4.0 N/mm^2 and 5.5 N/mm^2, and the mean values are shown in Table 2. The values show that already a small change in the residual concrete tensile strength affects the shear capacity of a structural element, and this scatter can come from different fibre orientations and fibre distribution.

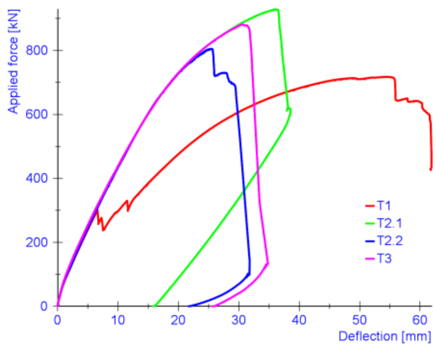

Figure 13: Load-deflection curves of the T-beams

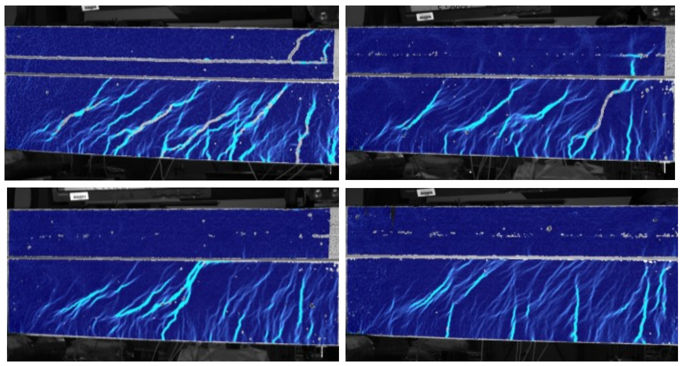

Figure 14: Crack patterns of T1, T2.1 (top), T2.2 and T3 bottom) at load level of 600 kN

In addition to the traditional measurement systems (LVDTs and strain gauges measuring the reinforcement tensile strains and concrete compression strains) a digital image correlation (DIC) system was used for measuring the surface deformations. The DIC system provides good information about the actual crack pattern at any load level. This is very useful to analyse the fibre reinforced UHPC structures, because of the fine multi-cracking behaviour. Figure 14 shows the measured crack pattern for each beam at 600 kN (Note: pictures show only one side between the load introduction and the support).

At T1 the interface bond was not large enough to prevent delamination of the two structural parts, but at the other three beams cracking of the interface surface happened only locally before the ultimate load was reached. Table 2 shows the calculated shear stress values at ultimate load, and it can be concluded, that the shear stress with the waffle-profiled surface reached about 4.6 - 4.7 MPa.

7. CONCLUSIONS

Several series of different small scale tests have been performed in order to determine the adhesive bond strength between precast UHPFRC elements and cast in place NSC. In order to achieve satisfying interface shear strength, an adequate surface profile of the UHPFRC is required. With respect to production constraints, a waffle-like profile was found to be most suitable. In addition four T-shaped composite beams made of UHPFRC with a subsequently cast NSC top layer have been tested in four-point bending setups. The tests show that

- without surface preparation (smooth, glossy interface surface) not enough bond was provided so that the two separated structural parts worked separately,
- the used waffle profile provided an adhesive shear strength of more than 4.5 MPa, which was enough for the composite structure to behave like a monolithic element,
- stirrups crossing the interface did not affect the overall load bearing behaviour,
- the beam's shear resistance can be satisfactorily predicted based on [13].

ACKNOWLEDGEMENTS

The presented study is part of a research program carried out in cooperation with Graz University of Technology and the industrial partners Voestalpine Special Wire GmbH and Kirchdorfer Industries GmbH. The funding of the project by the Austrian Research Promotion Agency (FFG) and the above mentioned industrial partners is greatly acknowledged, likewise the fruitful cooperation with all involved parties.

REFERENCES

[1] Voo, Y.L., Foster, S.J., Voo, C.C., 'Ultrahigh-Performance Concrete Segmental Bridge Technology: Toward Sustainable Bridge Construction', *Journal Bridge Eng.* **20** (8) (2015).
[2] Randl, N., Ricker, M., Häusler, F., Steinberger, S., 'Erhöhung des Durchstanzwiderstandes von Flachdecken durch Verbundeinbauteile aus UHPC', *Beton- und Stahlbetonbau* **110** (12) (2015).
[3] Ricker, M., Häusler, F., Randl, N., 'Punching strength of flat plates reinforced with UHPC and double-headed studs', *Engineering Structures* **136** (2017), 345-354.
[4] Bruehwiler, E. and Denarie, E., 'Rehabilitation and Strengthening of Concrete Structures Using Ultra-High Performance Fibre Reinforced Concrete', *SEI-Journal* **23** (4) (2013).
[5] Hong S., Kang, S., 'Effect of Surface Preparation and Curing Method on Bond Strength between UHPC and Normal Strength Concrete', IABSE Conference 2015 (Geneva, 2015) 1537-1543.
[6] Muñoz M., 'Compatibility of ultra high performance concrete as repair material: bond characterization with concrete under different loading scenarios', Dissertation, MTU (2012).
[7] Tayeh B., Bakar B., Johari M., Voo Y., 'Evaluation of Bond Strength between Normal Concrete Substrate and Ultra High Performance Fiber Concrete as a Repair Material', *Procedia Engineering* **54** (2013) 554-563.
[8] Eurocode 2, 'Design of concrete structures - part 1-1: General rules and rules for buildings' (2011)
[9] Zilch, K., Müller, A., 'DIBt-Forschungsbericht April 2007, Grundlagen und Anwendungsregeln der Bemessung von Fugen nach 1992-1-1', (in German) (Berlin, 2007).
[10] Randl, N., 'Design recommendations for interface shear transfer in fib Model Code 2010', *Structural Concrete* **14** (3) (2013) 230-241.
[11] fib, 'fib Model Code for Concrete Structures 2010'. Wilhelm Ernst & Sohn, (Lausanne, 2012).
[12] ACI, 'ACI 318-14: Building Code Requirements for Structural Concrete and Commentary' (2014)
[13] AFGC, 'Ultra High Performance Fibre-Reinforced Concretes – Recommendation', Revised ed., Association Française de Génie Civil (AFGC) (2013).