Experimental Verification of Concrete Elements Strengthened with UHPFRC

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Abstract:

UHPFRC may be used for new structures, but it is also an excellent material for strengthening of existing structures. Such strengthening is very efficient mainly because of the excellent bond between UHPFRC and existing concrete and for its high strength. Low amount of added material may result in significant mechanical effect which makes such method economical.
The experimental research is focused on investigation of bond between existing concrete and UHPFRC and on testing of large-scale elements at different loading situations. The precast elements about 10 years old were used first for investigation of bond. Their surface was prepared by different ways (high pressure water spraying, sand blasting, etc. in some cases in combination with adhesive layer between existing concrete and UHFRC added layer). A bond between existing concrete and a new UHPFRC layer was tested by direct tensile test on drilled cores and by pull-off tests.The first series of large-scale tests is focused on short term and long term bending tests. The results will be reported in the paper.

Keywords:

Ultra-high performance fibre-reinforced concrete, UHPFRC, concrete structures, strengthening, experiment, bending test, bond

1. Introduction

Concrete structures are designed for a limited lifetime, depending on their function. At present this means that many structures are approaching the end of their design lifetime and at the same time it is necessary to modify the purpose of existing structures for future use in many cases. With regard to technical and especially economic demands on older structures it is necessary to consider procedures for renovations and strengthening of the existing structures. The number of existing structures, which are approaching their end of service life, is very high. It would be rather inconvenient to demolish them and to replace by new structures. Their renovation and/or strengthening seems to be an efficient way for economic improvement of their technical parameters and for extending their service life for next 50 years.
First, the strengthening of the structure is focused on increase of its load bearing capacity. Second, the strengthening must ensure sufficient durability of the structure and therefore also an extension of the lifetime. Sufficient durability of the structure is conditioned by durability of the actual repair. Current methods and materials used for the strengthening of concrete structures are able to reliably increase the load bearing capacity of the structure, but in many cases, they do not feature any special durability. UHPFRC (ultra-high performance fibre-reinforced concrete) with its excellent mechanical properties (cylinder strength exceeding 150 MPa and flexural strength above 15 MPa) and its durability is very suitable for use at the strengthening of concrete structures. The amount of the added material is rather small which results in a small additional loading of the structure, which makes such intervention very efficient. Another key characteristic of UHPFRC, as far as strengthening is concerned, is its ability to create excellent bond with the surface of the original concrete to be strengthened. With a suitable mix design and suitably selected treatment of the original concrete surface it is therefore possible to ensure a perfect interaction of layers during the load up to the element failure without occurrence of delamination of layers.

The paper describes experiments concerning the strengthening of concrete elements with UHPFRC. Some of the experiments were focused on suitability and influences of selected surface treatments on the resulting bond of original surface layer and UHPFRC. Within the framework of the second part of the experiments, bending tests were made on the existing prefabricated concrete elements, which were strengthened with a layer of UHPFRC after the selected surface treatment.

2. Properties and use of UHPFRC for the strengthening of structures

A considerable increase of applications using UHPFRC were observed recently. UHPFRC is a relatively young composite material with high fibre contents. Excellent mechanical properties of UHPFRC and its durability make it possible to design low thicknesses of strengthening layers. While applying a thin UHPFRC layer onto a concrete element to be strengthened, it is therefore possible to ensure increase in the load bearing capacity and durability at a lower increase in the permanent load than it would be in the case of ordinary concrete materials. In real practice this means lower material consumption, leading to reduction of environmental impacts associated with consumption of primary raw materials, recycling and waste disposal. By using fibres in UHPFRC it is possible to achieve also improvement of ductility. [2] [3] [4]

These properties make UHPFRC a suitable material for the strengthening of structures, and depending on the selected thickness and method of the load of the strengthening layer it can perform either protective or static functions. In our case the research is focused on structural strengthening of concrete panels loaded by bending. In the first stage, the strengthening of the element under bending at the upper surface (in the compressive area) was selected. The experiments simulate for example the strengthening of floor panels. The execution of the described strengthening in a sufficient thickness leads to an increase of effective depth of cross section and at the same time to a decrease of the depth of the compressive zone, since the UHPFRC layer has higher strength than ordinary concrete.

Material properties of the applied mixture after 28 days were, as follows: the density was at the level of 2400 kg/m^3, cylinder strength around 150 MPa, flexural strength 15 - 20 MPa and tensile strength approximately 7 MPa [5].

3. Experimental methods

Experimental program was divided into two phases described in the following sections. The experimental program was carried out at the Klokner Institute, Czech Technical University in Prague, while the specimens were prepared in co-operation of Metrostav a.s. and TBG Metrostav, s.r.o.

3.1. Surface treatments and bond tests

A basic presumption for perfect interaction of the strengthening UHPFRC layer and the original concrete surface is a sufficient bond between these layers. Although UHPFRC provides excellent conditions of bond, the resulting bond is influenced by a large number of factors. Main factors include surface roughness, in other words the influence of the surface treatment of the original concrete. Within the framework of the experiment, three basic types of surface treatments were selected together with a reference surface without any treatment. We used such treatments that are commonly used in practice – sand blasting, manual high-pressure water spraying (hand-operated water spraying under the pressure of about 2500 bar) and mechanical high-pressure water spraying (machine-operated water spraying under the pressure of about 3200 bar). These four types of surfaces were prepared on two identical prefabricated panels rotated to opposite sides, i.e. to the side from the formwork with a smooth surface and the upper side after concrete casting with a rough surface. Moreover, each of these surfaces was provided, before the casting of the strengthening UHPFRC layer, on one half of the area with the Sikagard 110 Armatec bonding agent. This way 12 areas with different surfaces were created (the surfaces on both the panel sides treated by manual as well as mechanical spraying were considered as treated identically).

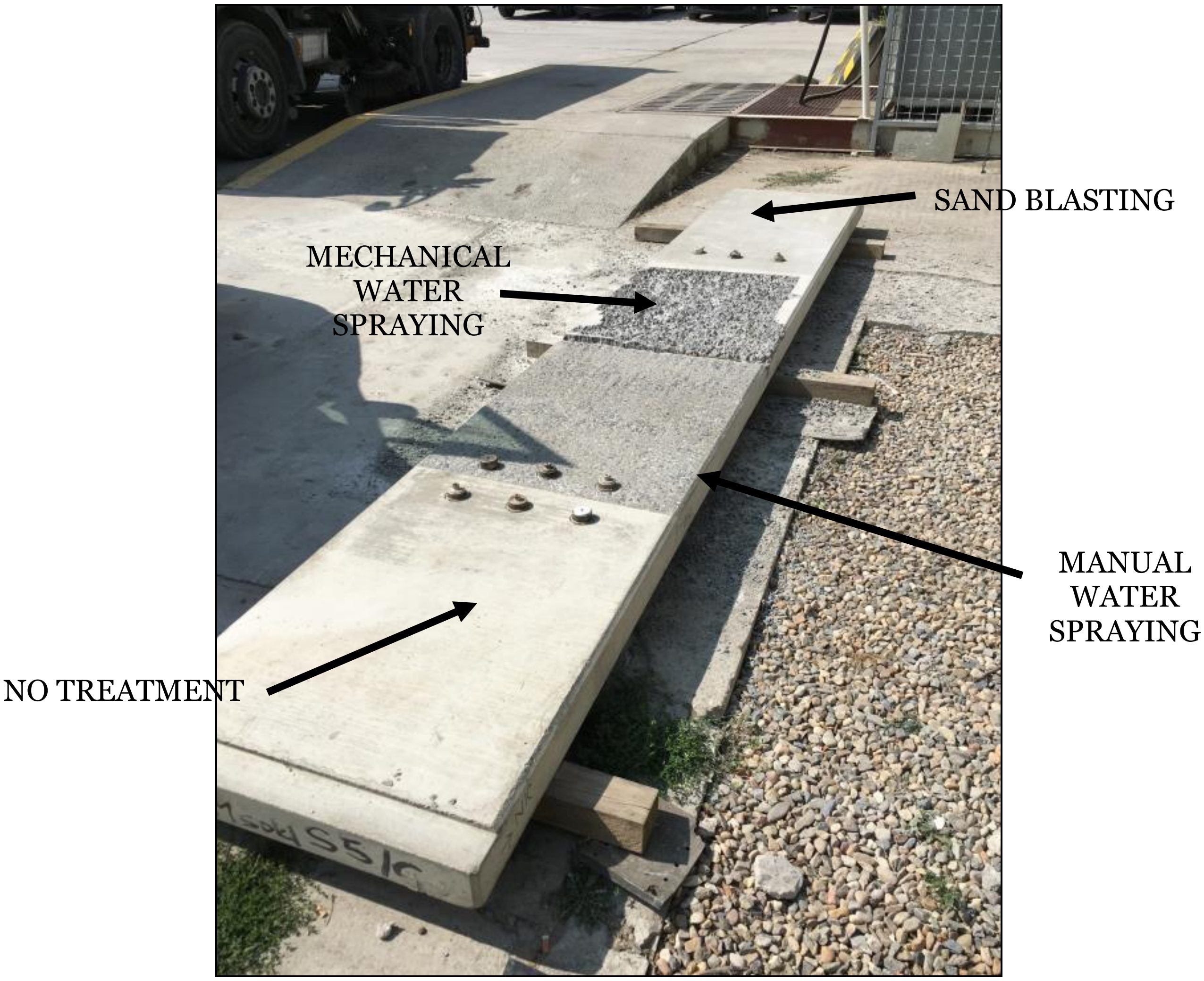

Figure 1. View of the panel with different surface treatments

The material removed from the surface during the treatments was measured and expressed as a mean value of a removed thickness. The resulting values were as follows: manual high-pressure water spraying 3.2 mm, mechanical high-pressure water spraying 27.6 mm and sand blasting 1.0 mm.

Casting of the strengthening UHPFRC layer was made on the samples prepared this way at TBG Metrostav. After 28 days, the bond tests were commenced on the samples in two ways, together with direct tensile test on drilled cores and pull-off test on the panels. Three cores were taken from each area and three pull-off tests were performed there. In case of untreated smooth surfaces from the formwork with a bonding agent as well as without a bonding agent the delamination of layers occurred already during the drilling process, and therefore it was not possible to carry out any bond tests.

3.1.1. Tensile tests on drilled cores

The drilled cores taken, with a diameter of 100 mm, were photographed and measured in the laboratory after drilling. By using the Sikadur 31 CF Rapid adhesive, circular steel discs for tensile tests were glued onto their cleaned and roughened surfaces. The maximum tensile force and failure mode of the test sample were recorded during the actual test.

3.1.2. Pull-off tests

In order to ensure stress on the contact of layers, it was necessary to pre-drill (with the use of a drilling bit through the UHPFRC layer) circular cuts approximately 5 mm into the original concrete on the test location. Then the surfaces were cleaned and circular pull-off discs with a diameter of 50 mm were glued onto them by using the Sikadur 31 CF Rapid adhesive. During the actual test, maximum tensile force and failure mode were recorded.

3.2. Bending tests of strengthened elements

Bending tests were carried out for verification of behaviour of strengthened elements subjected to bending. The aim was to verify the hypothesis whether the layers in the composite section perfectly interact during the increasing load, and whether this happens only at suitable surface treatment of the strengthened concrete surface and without the use of any mechanical connections. In other words, whether there will not be any delamination of layers. The tests were carried out on 3 types of cross sections with different thicknesses of the top strengthening UHPFRC layer.

The tests were carried out with the use of reinforced-concrete prefabricated elements which were strengthened in the compressive area with the UHPFRC layer. The reinforced-concrete panels with a thickness of 120 mm and ground plan dimensions of approximately 2, 750 mm x 490 mm. With regard to missing background documentation concerning these panels, basic diagnostics was carried out for identification of concrete strength and reinforcement. The concrete used in the elements was classified as C 30/37 strength class with average cylinder strength under pressure 32.3 MPa. With regard to the low reinforcement ratio all panels were strengthened by the additional reinforcement glued at the lower surface.

Three types of cross sections were selected – reference non-strengthened panel, panel strengthened with a layer of 30 mm UHPFRC in the compressive area and a panel strengthened with a layer of 50 mm UHPFRC in the compressive area with additional reinforcing mesh (Ø 8) with spacing of individual bars 100 mm. Three panels were tested for each type, altogether nine panels. Before concrete casting for the strengthening layers, which was carried out by TBG Metrostav, all surfaces were treated the same way by manual high-pressure water spraying on the basis of the results [1]. Then the surfaces were cleaned and shortly before concrete casting they were moistened.

After 28 days the panels were transported to the Klokner Institute of the Czech Technical University in Prague where tests were carried out in the four-point bending with the spacing of supports 2,500 mm and spacing of loads 800 mm. The bending deflection on the panel edge in the span centre was measured during the tests. The load was controlled by the shifting up to the element failure and during this process the force introduced by the cylinder into the panel was measured. Besides, the development of cracks was monitored.

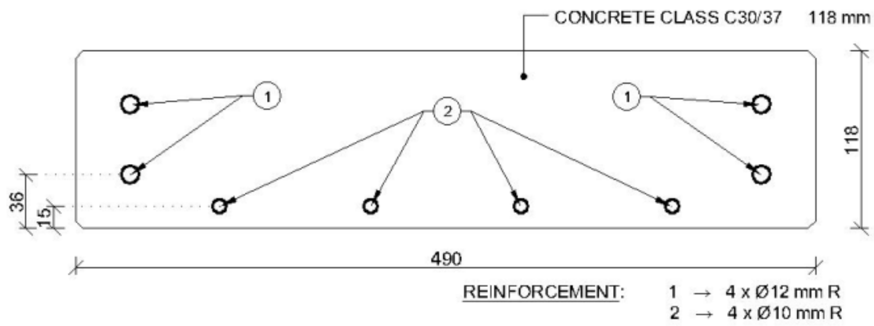

Figure 2. Typical cross section through the reference panel

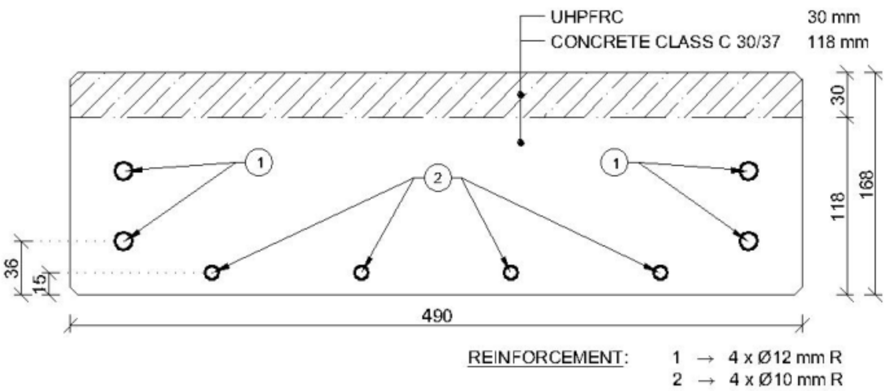

Figure 3. Typical cross section through the panel strengthened with a 30 mm UHPFRC layer

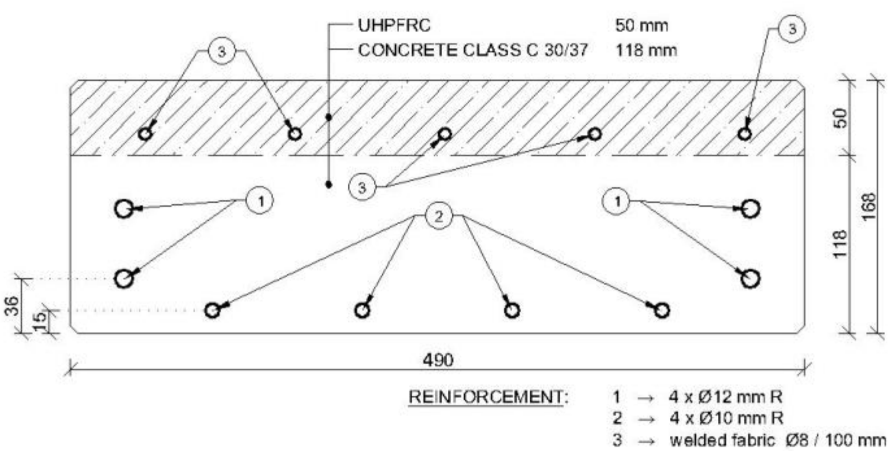

Figure 4. Typical cross section through the panel strengthened with a 50 mm UHPFRC layer and a Ø 8/100 mm additional reinforcing mesh

4. Results

4.1. Bond test results

The basic learning acquired is the fact that the selected bonding agent did not have any positive influence on the bond of layers. The obtained tensile stress values at which the connection is delaminated are lower at surfaces with the use of the bonding agent than at surfaces without its application. For all tested samples (with bonding agent) the layers were delaminated directly in the bonding agent.

			PULL-OFF TEST		TENSILE TEST	
			σ [MPa]	Failure	σ [MPa]	Failure
FORMWORK SURFACE	WITH BONDING AGENT	No treatment	-	BA	0,18	BA
		Manual water spraying	2,75	BA	1,69	BA
		Mechanical water spraying	1,63	BA	1,99	BA
		Sandblasting	1,73	BA	0,80	BA
	WITHOUT BONDING AGENT	No treatment	-	-	-	-
		Manual water spraying	3,38	C	2,81	C
		Mechanical water spraying	2,84	C	2,84	C
		Sandblasting	3,46	C	3,19	C
UPPER ROUGH SURFACE	WITH BONDING AGENT	No treatment	2,75	BA	1,24	BA
		Manual water spraying	2,75	BA	1,69	BA
		Mechanical water spraying	1,63	BA	1,99	BA
		Sandblasting	1,63	BA	1,40	BA
	WITHOUT BONDING AGENT	No treatment	3,07	C	2,59	C
		Manual water spraying	3,38	C	2,81	C
		Mechanical water spraying	2,84	C	2,84	C
		Sandblasting	4,09	C	2,28	C

BA = Bonding Agent, C = Concrete

Table 1. Overview of the values obtained from the bond test

For other surface treatments a damage in the original surface layer was registered. It is therefore possible to suppose that during the use of any of these surface treatments it will be possible to achieve sufficient bond of the layers and there should not occur any delamination. Although all the obtained values are in fact tensile strengths of the surface layers of concrete, they slightly differ. From the resulting values it is therefore possible to observe how the surface treatment used damaged the surface mechanically. The highest mean values in tension were achieved for surfaces treated by sand blasting and manual high-pressure water spraying. The surface was just slightly mechanically damaged during these treatments, and therefore there did not occur any micro-cracks in surface layers. The high pressure water spraying (here called mechanical water spraying) resulted in rather severe damage of the concrete surface. This treatment caused exposure or release of aggregate grains, and strength of concrete surface layers was reduced, which subsequently affected the resulting bond of the connection. In case of surfaces where no treatment was carried out, the greatest difference was registered between results on the surface from the formwork and on the rough surface. While on the surface from formwork, it was possible to observe delamination of layers already during the sampling of t drilled cores and drilling of cuts for pull-off tests, the resulting mean values on the rough surface are comparable with values during treatment by mechanical high-pressure water spraying.

4.2. Bending test results

The charts of dependence of the effective load on the bending deflection in the centre of the span of the test elements were evaluated on the basis of the data recorded from the bending tests. The following charts in the figure 5 show typical courses of individual types of the cross sections tested (REF, 30, 50). The surfaces of the original panels were treated by manual water spraying under the pressure of about 2500 bar. It is possible to observe a significant influence of the strengthening layer and its thickness on the increase in load bearing capacity and ductility of elements.

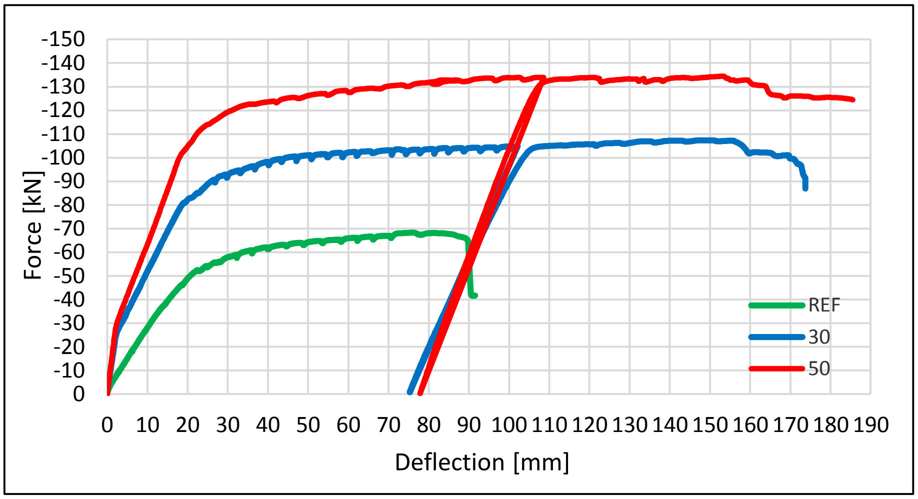

Figure 5. Comparison of typical courses of dependence of the load on bending deflection

	Deflection [mm]	Max. Force [kN]
REF - 1	75,8	68,3
REF - 2	79,6	66,3
REF - 3	84,2	69,3
Mean value		**67,9**
30-1	147,9	107,4
30-2	161,5	108,0
30-3	242,8	106,5
Mean value		**107,3**
50-1	126,7	129,8
50-2	110,2	136,7
50-3	153,4	134,4
Mean value		**133,6**

Table 2. Bending test results

Figure 6. View of the testing frame for bend test

Relieving branches on the charts are a consequence of relieving on achievement of the range of the hydraulic cylinder which was used for the loading. While loading the panels strengthened with a 30 mm UHPFRC layer, the maximum load higher by 58 % was achieved during the bending tests in comparison to non-strengthened elements. The panels strengthened with a 50 mm UHPFRC layer achieved a 97 % growth of the load bearing capacity.

5. Conclusion

The first part of experiment was focused on the testing of the bond of surface layers of the original concrete of the panels and of the new strengthening layer of UHPFRC developed by TBG Metrostav. Various types of treatments of the strengthened panel surface were compared. The best results were achieved for surfaces treated by sand blasting and manual high-pressure water spraying. On the other hand, the most unfavourable results were achieved during the use of a bonding agent, on all the types of treated surfaces, in all cases the layers were delaminated directly in the bonding agent. The second part of the experiment is focused on the execution of tests of strengthened panels in four-point bending. Delamination of individual layers of the tested panels was not observed during the tests in any case. While loading the panels strengthened with a 30 mm UHPFRC layer, the load bearing capacity higher by 58 % was achieved during the bending tests in comparison to non-strengthened elements. The panels strengthened with a 50 mm UHPFRC layer achieved a 97 % growth of the load bearing capacity.

An important part of the research was verification of the presumption of interaction of the concrete surface layer of the existing element and the UHPFRC strengthening layer without using any anchorage element, which was proved by the experiments. It is only sufficient to select suitable surface treatment of the existing surface of the concrete element to be strengthened. The experiments verified application of a thin UHPFRC layer on the concrete element to be strengthened for assurance of a higher load bearing capacity than in the case of use of ordinary concrete mixtures, at a small growth of the permanent load.

6. References

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7. Acknowledgements

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