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STRUCTURAL BEHAVIOUR OF REINFORCED CONCRETE ELEMENTS IMPROVED BY LAYERS OF ULTRA HIGH PERFORMANCE REINFORCED CONCRETE

John Wuest[1]

Abstract

The investigated composite elements combine a reinforced concrete central core with two UHPFRC layers with the objective to increase the load carrying capacity and to improve durability. The experimental investigation was comprised of six UHPFRC-concrete composite elements. The goal of this study was to investigate the UHPFRC layer restrained shrinkage under a high degree of restraint and to test the elements in bending up to failure. The main conclusions are that the UHPFRC layers provide an increased stiffness under service conditions and the composite elements structural behaviour was not influenced by varying the change in interface roughness.

Keywords

UHPFRC, composite elements, restrained shrinkage, experimental structural response.

1 Introduction

An increasing number of civil structures are in need of rehabilitation to address durability problems and to increase the load carrying capacity. Ultra-High Performance Fibre Reinforced Concretes (UHPFRC) are being used to rehabilitate existing structures because of their ease of on-site casting (Denarié 2005) combined with their excellent strength and durability properties (AFGC 2002) and (Rossi 2000). The UHPFRC layers are used to “harden the skin” of the existing elements by creating a protective layer. To evaluate the rehabilitation potential of UHPFRC, the structural behaviour of six post-rehabilitated composite elements was investigated. The goal of this study was to investigate (1) the composite UHPFRC-concrete wall element early age deformational behaviour under a high degree of restraint and (2) the composite elements structural response up to the ultimate force. The test parameters include the UHPFRC-concrete core interface roughness, the UHPFRC layer thickness and the UHPFRC composition.

2 Conceptual approach

The conceptual approach developed by MCS at EPFL is to use the UHPFRC locally to “harden” the existing concrete element where it is subjected to high mechanical and severe environmental actions (Figure 1).

[1] Ecole Polytechnique Fédérale de Lausanne (EPFL), john.wuest@epfl.ch

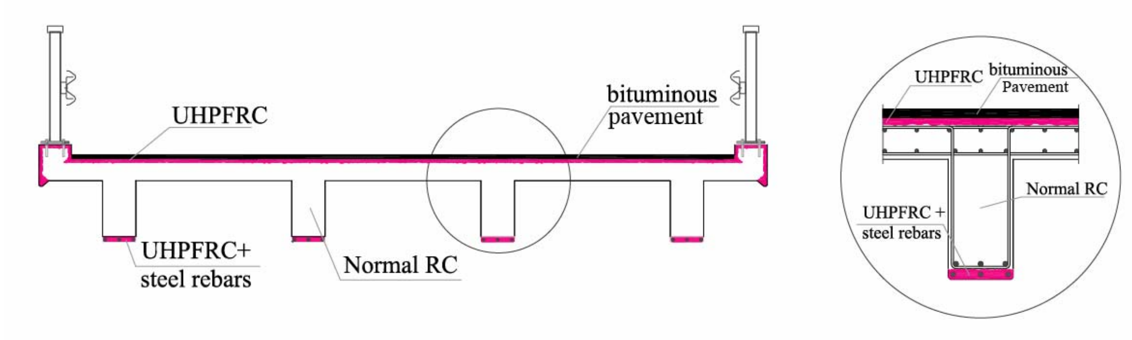

Figure 1 UHPFRC application on a bridge.

The goal is thus to combine an existing (or also a newly constructed) reinforced concrete structure with UHPFRC layers located at high-stress zones rather than constructing a complete structure with only UHPFRC.

Figure 1 shows a double UHPFRC layer application. The principle is to use a UHPFRC layer on the reinforced concrete upper side to prevent the ingress of aggressive agents and to place a UHPFRC layer on the bottom (tensile) side to increase the element's strength.

3 Material properties

Two UHPFRC compositions were tested (Table 1). The first material, CM0, contains straight steel fibres with an aspect ratio (l_f/d_f=10/0.2, where l_f denotes the fibre length and d_f the fibre diameter) of 50 and in the second material, CM11, the fibres have an aspect ratio of 33.3. The CM11 has a higher fibre volume (10%) in comparison to CM0 (6 %).

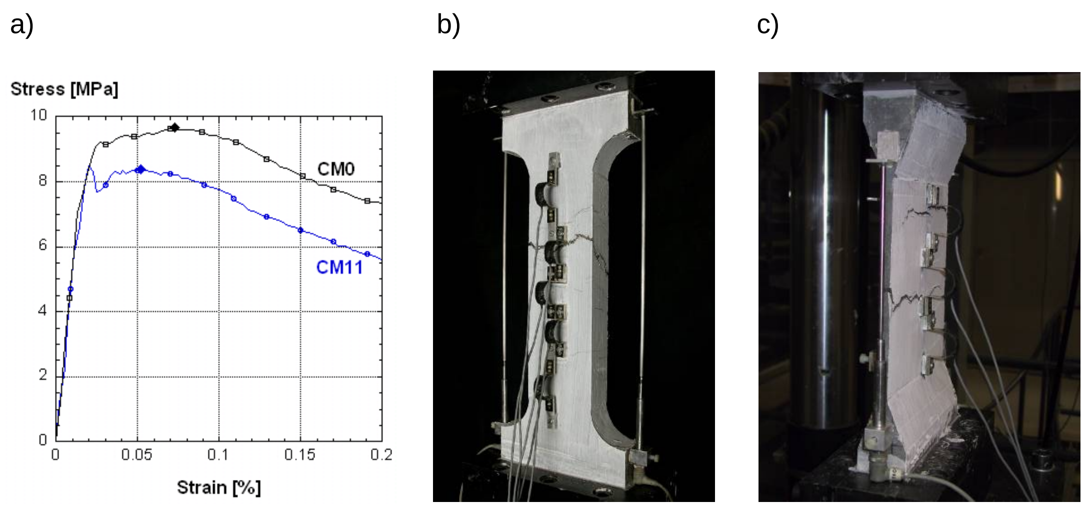

Figure 2 a) UHPFRC uniaxial tensile responses (Value at the peak: CM11, ε=0.052 %, σ=8.4 MPa and CM0, ε=0.073 %, σ=9.7 MPa) b) Dog-bone shaped CM0 specimen (thickness 5cm), c) Dog-bone shaped CM11 specimen (thickness 1cm).

Both compositions have a high amount of cement and a low water/cement ratio. A high dosage of superplastifizer of 36 kg/m^3 was used in both mixes to obtain a self compacting UHPFRC. Vertical casting of UHPFRC over a height of 1 m could be realized even for a thin layer thickness of 2.25 cm.

The uniaxial tensile tests on dog-bone shaped specimens (Denarié 2006) show that CM0 has a pronounced strain hardening behaviour while CM11 exhibits an elastic-plastic yielding behaviour. Moreover, the CM0 attains a higher stress value than the CM11. These test results were obtained from different specimen configurations: The CM0 specimen had a 30 cm long, a 10 cm wide and 5 cm thick tapered section. The CM11 specimen had a 20 cm long, a 20 cm wide and 1 cm thick tapered section.

Table 1 UHPFRC mix compositions CM0 and CM11.

	CM0	CM11
Steel fibres	6% volume, l_f/d_f = 10/0.2=50	10% volume, l_f/d_f = 5/0.15=33.3
Water / Concrete	0.18 [-]	0.17 [-]
Water / Binder	0.143 [-]	0.135 [-]
Cement Quantity	1050 [kg/m^3]	1125 [kg/m^3]
Sand	732,5 [kg/m^3]	504,5 [kg/m^3]

4 Test configurations and composite element parameters

4.1 Composite element configuration and test set-up

The 3 m long composite walls consisted of a reinforced concrete core and two UHPFRC layers (one applied to each side). The concrete core was composed of C40/50 and had a 100*24 cm section with a 2 cm concrete cover (Figure 3a).

a) b)

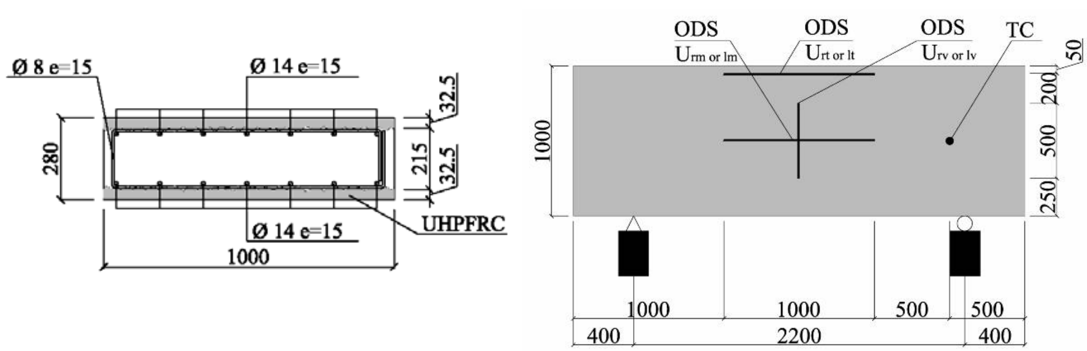

Figure 3 a) Wall dimensions (SAMW1 and SAMW3) in mm b) Early age measurements testing configuration and sensor position.

The interface between the core and the UHPFRC was prepared by hydrojetting and 0.25 to 1.25 cm of the concrete cover was removed depending on the desired roughness. The UHPFRC layers were then cast in the vertical direction as if the prefabricated elements were wall elements. The early-age measurement system, i.e. optical deformation sensors ODS, were embedded in the UHPFRC layers according to Fig. 3b before the UHPFRC casting.

4.2 Composite element parameters

The composite element parameters presented in Table 2 included the UHPFRC thickness (h_U) (2.25 or 3.25 cm), the materials composition (CM0 or CM11) and the interface roughness (rough or smooth).

The degree of restraint presented in Table 2 is calculated according to (Bernard 2000).

The difference between each composite element, within each group, is in the instrumentation. In SAMW1, two rows of ODS were placed parallel to the element's height on each hydrojetted side of the concrete core surface to measure the deformational gradient along the element's height. The first sensor and the second sensor were offset 50 cm and 5 cm from the top of the element respectively. In SAMW3 and SAMW4, in addition to the ODS placed horizontally along the element mid-height, an ODS was placed vertically to measure the vertical deformation. In SAMW5 and SAMW6 a new type of ODS, a SOFO SMARTAPE

(Glisic 2000), was used in combination with a sensor running horizontally in the reinforced concrete core.

Table 2 Composite element elements test parameters and measurement devices

Name	h_U [cm]	Thickness [cm]	UHPFRC mix	Horizontal sensors	Vertical sensors	Roughness	Degree of restraint
SAMW1	3.25	28	CM0	2 Centre, 2 Top	-	Rough	0.72
SAMW2	3.25	30	CM0	2 Centre	-	Smooth	0.74
SAMW3	3.25	28	CM0	2 Centre	2 Centre	Rough	0.7
SAMW4	3.25	30	CM0	2 Centre	2 Centre	Smooth	0.74
SAMW5	2..25	29	CM11	2 Centre (SMARTAPE)	-	Smooth	0.75
SAMW6	2.25	29	CM11	2 Centre (SMARTAPE)	-	Smooth	0.77

4.3 Early age measurements

The elements were stored at the laboratory ambient temperature. The fabricated walls were simply-supported with a 220 cm central span and 40 cm cantilevers (Figure 3b). The measurements were recorded using only the ODS sensors. The duration of the early age measurements varied between 70 and 90 days. The element configuration induced a high degree of restraint (more than 70%) in each UHPFRC layer (Table 2) due to the two UHPFRC layers on opposite sides which limited the out of plane element deflection.

4.4 Fracture testing

The elements were tested as a beam under bending rather than a wall under predominant normal force. A four point simply-supported bending system was employed (Figure 4a) inducing a constant negative bending moment in the composite element mid-span. The test was controlled by jack displacement and the imposed jack displacement speed was 0.02 mm/s.

Nine LVDTs were used to record the central span deflection and one LVDT was located under each jack to record the cantilever deflection (Figure 4b). An additional LVDT was placed at each support to measure the element support compression. The hydraulic jack forces were recorded with a force cell.

a) b)

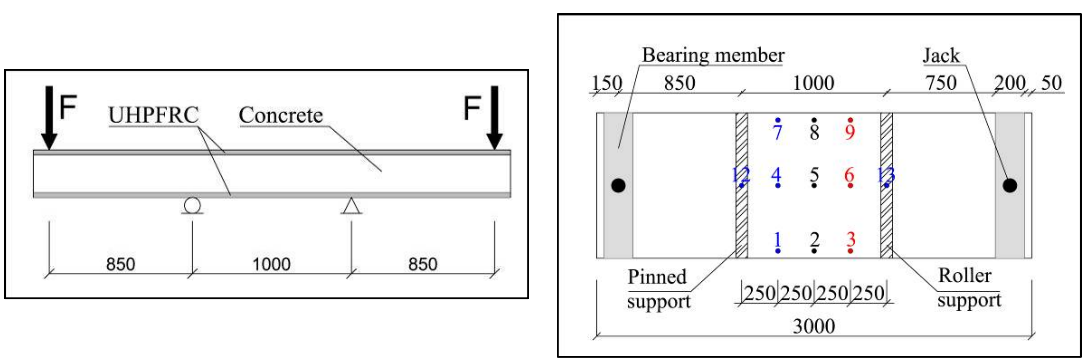

Figure 4 a) Fracture test configuration, b) Location of LVDT.

5 Results and discussion

5.1 Early age measurements

5.1.1 Response of optical deformation sensors

The early age UHPFRC deformation was mostly attributed to autogenous shrinkage. The measured values in the elements SAMW1 to SAMW4 varied between -635 [μm/m] (SAMW1 at day 73) and -400 [μm/m] (SAMW4 at day 68 (Fig. 5)). These deformation values are in the same order of magnitude with results from unrestrained UHPFRC (Kamen 2006). From this follows, that the UHPFRC layers degree of restraint seems to have no observable influence on the early age deformational behaviour.

The measured vertical deformation on walls W3 and W4 was about 50 % smaller than the measured horizontal deformation. This result may be due to a number of parameters: the UHPFRC autogenous shrinkage may not have been the same in all directions due to non-isotropic restraint and fibre orientation; also, it was not possible to embed the two ODS at the same depth in the UHPFRC layer.

a) b)

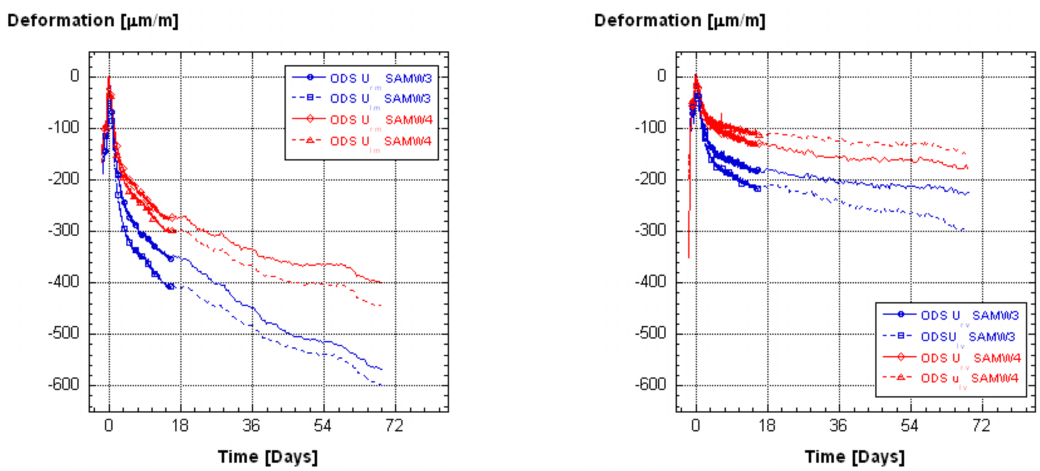

Figure 5 Deformation measured in SAMW3 and SAMW4 a) Horizontally b) Vertically.

5.1.2 Influence of interface roughness

Figure 5 shows a comparison between walls SAMW3 (rough interface) and SAMW4 (smooth interface) which have the same UHPFRC layer thickness. The results indicate that using a rough interface seems to produce a deformation increase. The explanation may be that a smaller UHPFRC quantity is required to fill shallower crevices in a smooth interface element, resulting in smaller early-age deformations. Additionally, rough interface elements have a greater UHPFRC quantity and a reduced concrete core combining to produce higher early-age deformations.

5.1.3 Cracking pattern

Some fine microcracks, smaller than 0.1 mm were observed in the UHPFRC layers during the first 28 days. Thereafter, only a small number of microcracks formed. This was also confirmed by the results in Figure 5 which showed a high deformation rate during the first weeks after casting. After 28 days, the deformation rate became relatively small.

The microcracks tended to form on the wall top or in the middle of the section, at the casting joint, with only a few occurring in the wall bottom.

5.2 Fracture testing

5.2.1 Overview of results

The same general structural behaviour was observed for all tested composite element elements (Figure 6). The element structural responses can be described by a linear response followed by non-linear behaviour and finally by the yielding of the reinforcing bars (Table 3).

Table 3 Characteristic force and deflection values for the different response parts.

Composite element	Interface	Mix	Linear response		Nonlinear response	
			Deflection [mm]	Force [kN]	Deflection [mm]	Force [kN]
SAMW1	Rough	CM0	0.17	98.00	1.9	207
SAMW2	Smooth	CM0	0.15	120.00	1.7	262
SAMW3	Rough	CM0	0.19	100.00	2.5	205
SAMW4	Smooth	CM0	0.08	70.00	1.6	154
SAMW5	Smooth	CM11	0.13	102.00	1.4	173
SAMW6	Smooth	CM11	0.14	95.00	1.4	175

Subsequently, the maximum force was reached and then the force decreases with increasing deflection until the steel reinforcement bars picked up additional force. The tests had to be stopped before complete failure (and the complete post-peak response could not be recorded) because the jack hinge's rotational capacity was reached.
Moreover, the jack displacement was paused during the testing for 5-15 minutes to permit crack width measurement and documentation of the crack pattern. During this period, the force slightly dropped due to relaxation (Figure 6). In all the tested elements, no delamination was observed at the interface until the force drop.

a) b)

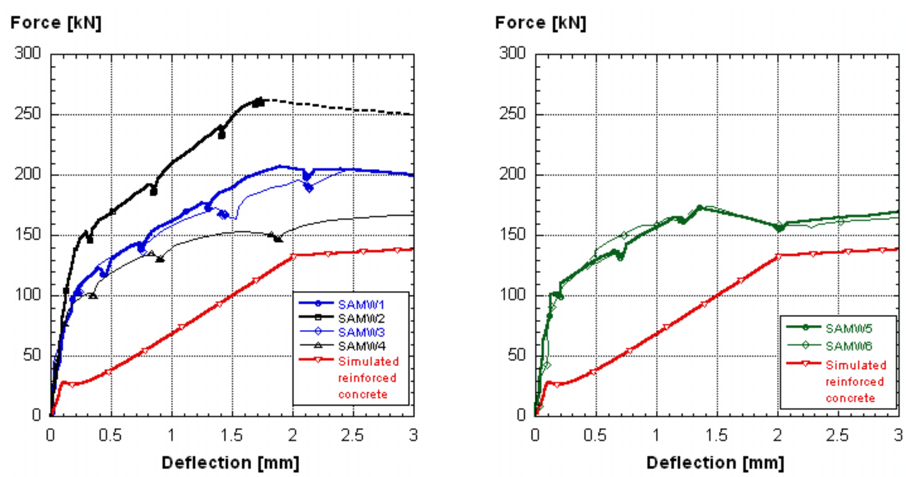

Figure 6 Detailed presentation of the Composite element linear and non linear structural response a) SAMW1 to SAMW4 and b) SAMW5 and SAMW6.

5.2.2 Comparison with the normal reinforced concrete

For the sake of comparison, the structural response of the plain reinforced concrete element was calculated using conventional analytical models for structural concrete. The results show that by adding the UHPFRC layers the resistance in the linear and non-linear pre-peak domain and the linear domain stiffness is significantly improved (Figure 6).

5.2.3 Reference composite elements

SAMW1 and SAMW3 are considered to be reference composite elements because the interface roughness employed is commonly used in rehabilitation. Their structural response is in close agreement (Figure 6a)). The first part of the curve, the linear behaviour, ends at a mid-span deflection of approximately 0.2 mm for the two elements. In the linear response, element SAMW1 is slightly stiffer than SAMW3. After the linear domain is exceeded, the slope of the force-deflection curve changes and remains linear until a deflection of approximately 2 mm, after which the force-deflection curve decreased indicating that the element's maximum resistance had been exceeded. At ultimate force, the cracks (width 0.1-0.8 mm) in the UHPFRC were spaced, on average, every 5 cm.

5.2.4 Influence of the interface roughness

While the results for the reference elements were in close agreement, the results for the smooth-interface elements (SAMW2 and SAMW4) exhibited a divergent behaviour. SAMW2 exhibited higher linear and ultimate force compared to the reference elements. This performance change is due to the increased thickness and thus moment arm of the element. For SAMW2, the crack development was similar to elements SAMW1 and SAMW3.

SAMW4 linear and nonlinear response is significantly less than for the other elements. This change in the structural response is a direct result of a vertically embedded ODS locally compromising the tensile UHPFRC layer. The cracking pattern was thus limited because a localized crack quickly developed in the reduced section.

SAMW3 also contained an embedded vertical ODS in the tensile UHPFRC layer, but the high interface roughness facilitated a more complete ODS embedment and intact UHPFRC layer. Therefore when the elements transitioned from the linear domain to the non-linear domain, the SAMW3 tensile UHPFRC layer was able to carry additional force until the peak while element SAMW4 reverted more and more force to the steel rebar.

No significant difference between the smooth and the rough interface has thus been found.

5.2.5 Influence of the material and layer thickness

The structural response of SAMW5 and SAMW6 (Figure 6b)) was similar. It exhibited a higher stiffness in the linear domain and transitioned from the linear to nonlinear behaviour at the same force as compared to the reference elements. The nonlinear deflection and force are respectively reduced by material properties, smallest deformation at the peak for CM11 compared to the CM0 (section 3), and the UHPFRC layer thickness.

The use of UHPFRC with short fibres offers an improved structural behaviour when compared to conventional reinforced concrete, but results shows some force drop with increasing deflection after the force peak. This force drop may be due to a sudden stiffness reduction, caused by the pull-out of short fibres.

At ultimate force, the UHPFRC layer cracks had widths ranging from 0.15 to 0.95 mm and were spaced at an average of 15 cm.

The response for elements SAMW5 and SAMW6 was similar to the element SAMW4 response. This may confirm that the short 5 mm fibre UHPFRC underperformed in the nonlinear zone as compared to the long 10 mm fibre UHPFRC.

6 Conclusions

The six post-rehabilitated composite UHPFRC-concrete composite elements structural behaviour experimental investigations provide the following conclusions:

1. UHPFRC layer early age deformation occurs mostly during the first 28 days. Despite the high degree of restraint provided by the UHPFRC layer composite wall configuration, the measured deformations are similar to unrestrained UHPFRC. The measurements showed non-isotropic behaviour associated with the vertical UHPFRC layer casting.
2. The use of UHPFRC in composite elements provides an increased stiffness under service condition and the high tensile strength of UHPFRC produces a significant increase in ultimate force of the tested composite elements as compared to conventional concrete elements.
3. The structural response of the composite elements up to ultimate force was not influenced by the change in interface roughness.
4. The use of UHPFRC with short steel fibres (5mm) improves the element stiffness and the ultimate force as compared to conventional reinforced concrete elements, but is out-performed by UHPFRC with the long fibres (10mm) in the non-linear zone.

7 Acknowledgments

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