Improvement of existing structures using Ultra-High Performance Fiber Reinforced cement-based Composites (UHPFRC)

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Improving structures using Ultra-High Performance Fiber Reinforced Concrete (UHPFRC)

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1 Introduction

- Rehabilitation of deteriorated concrete structures is a heavy burden from the socioeconomic viewpoint since it leads to significant user costs.
- Sustainable concrete structures of the future will be those requiring just minimum interventions of only preventive maintenance with no or only little service disruptions.
- Novel concepts are needed. We need to improve the structure ... not just repair it!
- Ultra-High Performance Fibre Reinforced Concretes (UHPFRC) have improved resistance against severe environmental influences and high mechanical loading.

2 Conceptual idea

- protective watertight UHPFRC overlay to improve durability
- increase structural capacity (stiffness, ultimate resistance)
2 Conceptual idea

**UHPFRC** for waterproofing

\[ t_u = 20 \text{ to } 30 \text{ mm} \]

Reinforced Concrete

**R-UHPFRC** for strengthening

\[ t_u = 40 \text{ to } 70 \text{ mm} \] + rebars

Reinforced Concrete

\[
\text{composite (R-)UHPFRC} - \text{RC elements}
\]

**UHPFRC** = Ultra-High Performance Fiber Reinforced cement-based Composites

Concrete
**UHPFRC = Ultra-High Performance Fiber Reinforced cement-based Composites**

Cement-based matrix: cement, reactive powders, quartz grains (<1mm)
Steel fibers (10-15mm): > 3% vol. (or: synthetic fibers)

Fresh UHPFRC: self-compacting, workability, slope stability (up to 13%)
Hardened UHPFRC: high strength (compression: 150-200MPa) and deformability, waterproof
Combination with rebars and posttensioning: R-UHPFRC, P-UHPFRC

### 3 Mix design and fresh UHPFRC properties

**Matrix:** composed of powders

- cement: CEM I 52.5, CEM II 32.5: 700 to 1100 kg/m³
- silica fume - SF/C = 0.20 to 0 (mass) / limestone filler
- super-plasticizer – SP/C = 1% (mass, dry extract)
- water / binder = 0.13 to 0.17
3 Mix design and fresh UHPFRC properties

Fibrous reinforcement: steel fibers, (synthetic fibers)

- total content 234 ... 468 kg/m³ (3 to 6 % Vol.)

Fabrication: ➔ prefabrication / on-site casting
- UHPFRC production in conventional ready mix plants
- fresh UHPFRC transported by truck to the site
- construction works at ambient temperatures: 7 to 35 °C
- UHPFRC is self-compacting
3 Tensile behaviour of plain UHPFRC (strain hardening)

deforination capacity very favourable for SH-UHPFRC
(viscous + strain hardening) def. capacity > restrained shrinkage def.
3 Tensile behaviour of plain UHPFRC

Constitutive material law:
- Hardening
- Softening

Anisotropy effects due to casting procedure and geometry!!
Adding reinforcing bars to the UHPFRC reduces anisotropy effects.

3 Tensile behaviour of plain UHPFRC (strain hardening)

4 point bending test and inverse analysis:
3 UHPFRC permeability under high tensile strain

UHPFRC is “practically” waterproof up to 1.3%o and “uncracked” up to 2.5%o

3 Tensile behaviour of R-UHPFRC

reinforcing bars with different steel grades and surface characteristics (ribbed and smooth bars)
3 Tensile behaviour of R-UHPFRC

- 4 types of steel ($\rho=1.5\%, \varnothing 8$ mm):
  - B500, gerippt
  - $f_y=360$ MPa, Walzhaut
  - $f_y=560$ MPa, blank
  - $f_y=700$ MPa, blank

- Section: $200 \times 50$ mm$^2$

Rupture

[Oesterlee; thèse EPFL, 2010]
**UHPFRC: tensile behaviour**

- **UHPFRC**
  - Stress $\sigma_{Ut}$
  - Deformation $\varepsilon_{Ut}$
  - Elastic
  - Hardening
  - Softening

- **R-UHPFRC**
  - Force
  - Displacement
  - Steel rebar

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### 3 Structural response of R-UHPFRC – RC composite beams

<table>
<thead>
<tr>
<th>Load Level</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F=0 \text{ kN}$</td>
<td>0%</td>
</tr>
<tr>
<td>$F=29 \text{ kN}$</td>
<td>73%</td>
</tr>
<tr>
<td>$F=37 \text{ kN}$</td>
<td>93%</td>
</tr>
<tr>
<td>$F=38 \text{ kN}$</td>
<td>95%</td>
</tr>
</tbody>
</table>
3 Structural response of R-UHPFRC – RC composite beams

Behaviour due to bending:
→ conventional model for RC with an extension to account for the R-UHPFRC layer:

R-UHPFRC layer principally acts as an added flexural reinforcement for the RC element.
Both steel rebars and UHPFRC contribute to the resistance.

Design of bending strengthening

- moment – curvature diagram:

limit state:
- $\varepsilon_{UL} = \varepsilon_{UL,\text{max}}$
- $\varepsilon_{c,\text{app}} = -3.5\%$
- $\sigma_{s,U} = f_{y,U}$
- $\sigma_{s,c} = f_{y,c}$
3 Structural response of R-UHPFRC – RC composite beams

- Shear resistance:

Favorable effects of R-UHPFRC layer:
- "confinement" of the zone under high stresses and trend towards ductile bending failure (rather than brittle shear failure)
- increase to the ultimate resistance: contribution tensile membrane in R-UHPFRC and forming of a ICD (Crack Induced Debonding zone)

Failure mode in:
- predominant flexure
- predominant shear
3 Structural response of R-UHPFRC – RC composite beams

Behaviour due to combined bending and shear: Design for shear strengthening

\[ V_{BU,RC} = V_c + V_s + V_U \]

Intermediate-Crack-induced debonding

\[ V_s = A_s f_{k,s} \]

\[ l_c = c_{RS} \sin(\theta) \]

\[ \alpha + \theta = 90^\circ \]

Fatigue behaviour:

existence of a fatigue limit (at 10 million cycles) at a solicitation level of about 50% of the ultimate static strength of the R-UHPFRC – RC beam.

[T. Noshiravani; Thesis EPFL, 2012]
UHPFRC – RC composite elements: Fatigue behaviour

Fatigue resistance of UHPFRC – RC elements

Fatigue resistance of UHPFRC

Fatigue fracture surface

EPFL Thesis Makita, 2013

Fatigue behaviour of R-UHPFRC

Stress redistribution from UHPFRC to steel rebars:

- ∆σ_s: stress range in steel rebars
- ∆σ_U: stress range in UHPFRC

Regression line for the largest stress range data at the first cycle (r = -0.89)
Regression line for stress range data at the first cycle (r = -0.89)
Regression line for the largest stress range (r = -0.83)
Fatigue fracture surface of R-UHPFRC

Structural response of R-UHPFRC – RC composite beams:

- Bending:
  - Cross section
  - Internal efforts
  - Strains
  - Stresses
  - Internal forces

- Combined bending and shear:

- Fatigue limit (10 million cycles) at 50% of static ultimate resistance
4 Applications – Waterproofing of bridge deck slabs

First application!  

Rehabilitation and widening of a 10m short road bridge deck slab

UHPFRC casting: October 2004
05/2004 (avant intervention)

06/2009

03/2014

… 10 years after …

23 October 2014
2011/12: 10 small deck slabs of a road pass **Col des Mosses**

- 30 m³ of UHPFRC / max. slope: 10.6%
- Duration of intervention: 10 days per site

**thixotropic «green Swiss» UHPFRC**
- Cement = limestone filler = 636 kg/m³
- Water/fines = 0.175 (fines = C + F)
4 Applications – Protection of vertical surfaces
Tensile stresses in the UHPFRC due to restrained shrinkage

Crash barrier wall

\[ \sigma_{t,1} \text{ [MPa]} \]

no cracking!

Sept. 2006
UHPFRC shell (40mm)

May 2007

Cast in place UHPFRC surface protection layer (35mm) on a bridge pier near Zurich – May 2013

Monitoring of durability
UHPFRC surface protection and strengthening of a lighthouse – June 2013
4 Applications – Strengthening of slabs

a)  

b) A-A  

c) B-B 

[mms]
Strengthening of a slab of an industrial building:

Motivation: increase in live load
Strengthening of a slab of an industrial building
Strengthening of a slab of an industrial building

September 2008
Road surface after 15 months
Improving bridges using UHPFRC

Val Tschiel Bridge (1925), Robert Maillart
Rehabilitation September 2013

UHPFRC for strengthening and waterproofing of deck slab, drivable surface
detailed design by: Conzett, Bronzini & Gartmann
Improving bridges

Montbovon Bridge: RC road bridge, 1916

External post-tensioning

R-UHPFRC for deck slab strengthening and waterproofing

detailed design by: sd ingénierie fribourg

Sept/Oct 2013
Reinforced concrete structure, 1916
Improving bridges using UHPFRC

Highway overpass Jupiterstrasse, Berne: strengthening and waterproofing
detailed design by: Hartenbach & Wenger

Gerber joint closure:

April – July 2014

Improving bridges using UHPFRC

Chillon Viaducts
near Montreux, 1969
Monod & Piquet ing.

2'100m long

Concrete showing alcali-aggregate reaction (AAR)
⇒ anticipation of concrete strength reduction

M-V tests on slab strips
Improving bridges using R-UHPFRC

**Functions of R-UHPFRC:**
- Strengthening of deck slab in the transverse direction: bending, shear and fatigue resistance
- Increase in stiffness and strength in the longitudinal direction
- Waterproofing of slab
- No increase in dead load
- Short duration of intervention

**R-UHPFRC:**
- Thickness: 40 / 50 mm

**Numerical simulations to determine the required type of UHPFRC**

**R-UHPFRC:**
- Design values of tensile properties
Resistance Models: bending (UHPFRC in tension)

Ultimate Resistance:
- deformations
- stresses
- sectional forces

Fatigue:
- stresses

Resistance Model:
- shear:
  \[ V_R = V_{Rc} + V_{Rs} + V_{RU} \]

Improving bridges using R-UHPFRC

July and August 2014:
- Casting of 1'200m³ UHPFRC on the first 2'100 m long viaduct
- Intervention cost:
  200 Euro / m² deck surface
Photo: August 23, 2014

UHPFRC ready mix plant
Maximum slope: 7%
cold joints
4 Applications – Economic aspects

Four level consideration :

1: UHPFRC fabrication cost : 2 Euro / dm³ (➔ producer, ready mix plant)

2: Construction cost : 400 Euro / m². 40mm R-UHPFRC (incl. hydro-jetting) (➔ contractor) [Chillon: 180 Euro /m² ]

3: Intervention cost = construction cost + indirect (user) costs (➔ owner)

4: Life cycle cost : reduction of maintenance (➔ owner, society)

Favourable to the balance :

- several requirements are fulfilled with one UHPFRC casting/layer.
- no or little increase in dead load
- reduction of duration of construction intervention
- reduction of environmental impact
First application of the UHPFRC-technology in Japan:  
120m long road bridge near Sapporo: waterproofing and strengthening of the deck slab with 30mm layer  
Casting: 3 – 19 October 2014
5 Conclusions – Existing structures

- Concept of «targeted local hardening / strengthening » of concrete structures, in severely exposed zones, by using UHPFRC.

- Combines effectively the protection and resistance properties of UHPFRC to improve durability and extend service life

- Simplification of the construction process, reduction of intervention duration (user costs), cost effective

- Approach successfully validated by several on-site applications:
  All recent applications were strongly motivated by significant money and time savings for owners!