UHPC-2008: The Second International Symposium on Ultra High Performance Concrete
March 05 - 07, 2008, Kassel, Germany

Cornelius Oesterlee
Dipl. Ing., Civil Engineer
Ecole Polytechnique Fédérale de Lausanne
Lausanne, Switzerland

Hamid Sadouki
Senior Scientist, Dr., Material Science
Ecole Polytechnique Fédérale de Lausanne
Lausanne, Switzerland

Eugen Brühwiler
Prof., Dr., Civil Engineer
Ecole Polytechnique Fédérale de Lausanne
Lausanne, Switzerland

Structural analysis of a composite bridge girder combining UHPFRC and reinforced concrete

Summary

Reinforced concrete being the most applied construction material today performs very well in most applications but still lacks durability under severe environmental conditions. Especially existing structures built decades ago show degradation. Using Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) to improve durability is a promising option seen the extraordinary performance of this material when applied in a composite section. Restrained shrinkage of the overlay plays an important role in this type of application.
A conceptual bridge cross section combining UHPFRC and reinforced concrete has been numerically analysed. Two main parameters, tensile strength and strain hardening capacity, were varied. The analysis indicates the importance of strain hardening of UHPFRC and the influence of its tensile strength on the structural response under restrained shrinkage (deformation controlled loading) and traffic loads (force controlled loading). The results validate the concept of using a UHPFRC layer to improve the structural durability of concrete constructions.

Keywords: *UHPFRC, composite structure, variability, strain hardening, FE-Analysis*

1 Introduction

Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) defines a class of strain hardening – softening cementitious composites with outstanding performance in terms of mechanical properties and durability. High fiber dosage and high quantities of reactive powders make these materials rather expensive compared to normal reinforced concrete, and therefore besides other reasons not appropriate for mass applications in massive structural elements. Applications turn out to be efficient only if several of the outstanding properties of UHPFRC are exploited to a maximum, especially its high compressive and tensile strength, its capacity for strain hardening and softening and its very low permeability towards water and aggressive substances. This requires new ways of design and construction leading to structural elements combining different types of concrete. At the same time it has the potential to solve the major problem of reinforced concrete structures: durability. Applying UHPFRC locally to “harden” the most severely exposed zones of a structure helps to improve durability and load bearing capacity. This scheme replies effectively to the above pointed out issues.

The present paper shows findings of a FE-analysis of a conceptual bridge girder design combining a thin UHPFRC overlay with a reinforced concrete substructure (Figure 1) [1]. Besides its load carrying contribution, the UHPFRC overlay replaces conventional waterproofing membrane and therefore has to remain in an impermeable state under service conditions and during the whole service life in order to protect the below conventional reinforced concrete structure effectively. The present structural analysis focuses thus on the serviceability limit state of the structure.

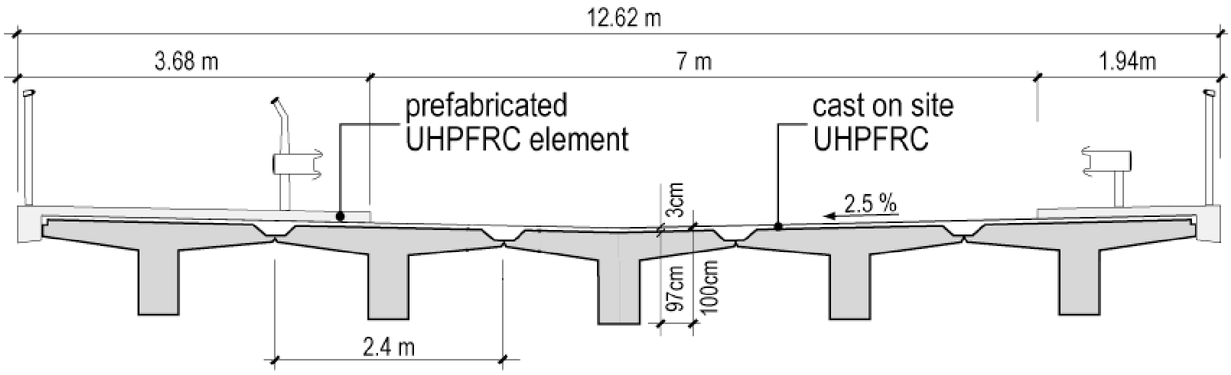


Figure 1: Cross section of the composite bridge girder [1]

2 Constitutive material modelling of UHPFRC

2.1 Requirements

The UHPFRC designed for this application responds to the following general requirements:

- high compressive and tensile strengths
- strain hardening and softening in tension
- very low permeability
- self-compacting fresh mix with the ability to be cast with a slope of 3%
- low variability of mechanical properties

Details about UHPFRC mixes fulfilling these requirements can be found in [2, 3, 5].

2.2 Tensile behaviour

High tensile strength as well as strain hardening and softening are characterising properties of UHPFRC. The uniaxial tensile behaviour was determined using dogbone specimens. The results of several experiments were averaged (Figure 2a) and transformed into the constitutive material law for tension (Figure 2b) as input for the FE-program.

2.3 Viscoelastic behaviour

UHPFRC develops important shrinkage (mostly autogenous shrinkage) which leads to Eigenstresses in the composite element due to the restrained deformation conditions. Free shrinkage under drying conditions reaches up to 590 µm/m after 1 year with an evolution of 2/3 of the value after 35 days [2]. Induced stresses are partly balanced as a function of time by an important creep and relaxation capacity. The high dosage of fibers prevents micoracking of the matrix and provides a high deformation capacity. Both effects are crucial for the proper working of the UHPFRC-layer regarding mechanical and physical requirements. Input data for the FE-analysis was deduced from comprehensive laboratory tests on the evolution of mechanical and physical properties depending on maturity [2, 3, 5].

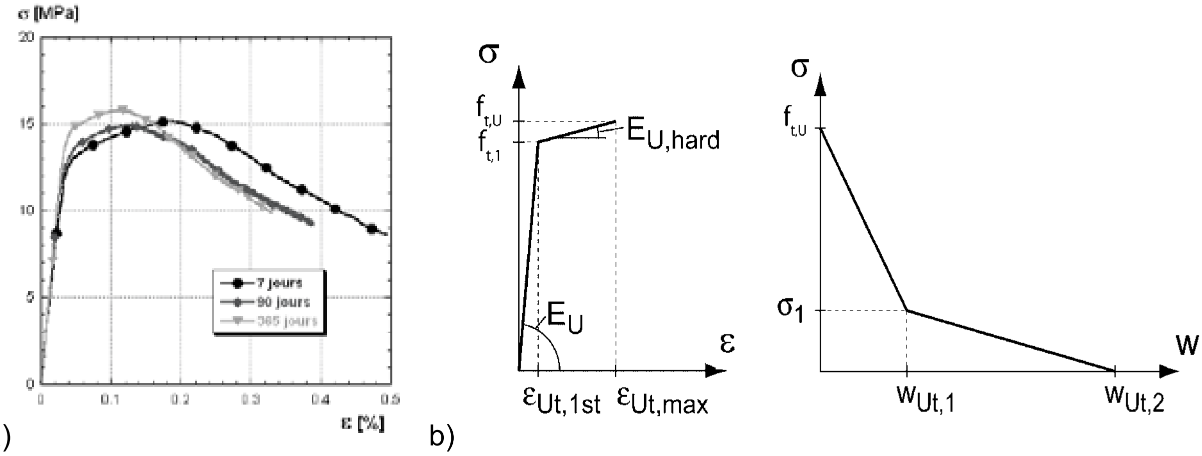


Figure 2: a) Stress-strain diagram from experiments [3] and b) corresponding constitutive tensile law for FE-analysis input

2.4 Variability of mechanical properties

An inherent property of fiber reinforced composites is the non-uniform fiber orientation and distribution depending on the mixing process, casting method and formwork boundaries [3]. This was taken into account in the FE-analysis by varying the values of tensile strength and deformation capacity (Figure 3).

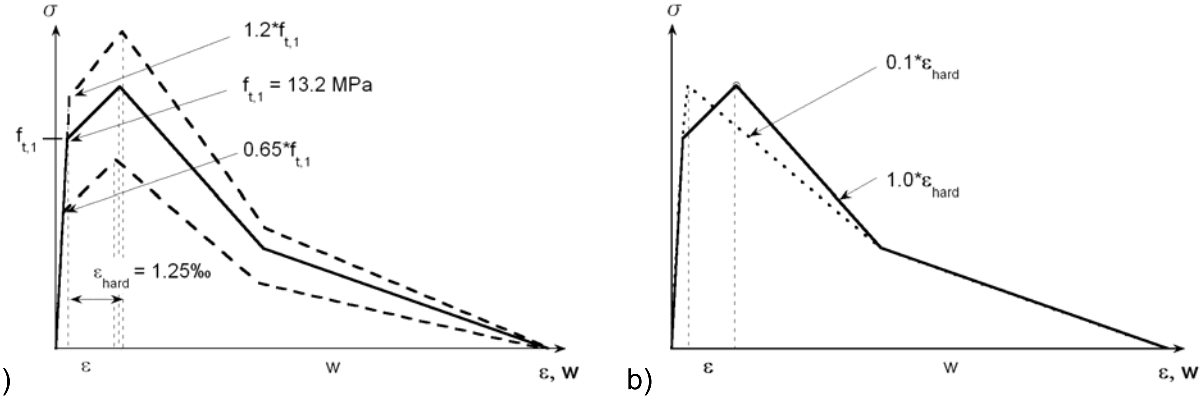


Figure 3: Variation of a) tensile strength f_t and b) deformation capacity ε_{hard}

The tensile strength, defined as elastic limit of the material, was modified to 65% and 120% of the reference value $f_{t,1}$=13.2MPa (Figure 3a), while the strain hardening, defined as the deformation between $f_{t,1}$ and the ultimate tensile strength $f_{t,U}$, was modified between 10% and 100%

of the reference value $\varepsilon_{hard} = \varepsilon_{Ut,max}-\varepsilon_{Ut,1st}$=1.25‰, (Figure 3b). The ultimate tensile strength $f_{t,U}$ is considered to evolve with a constant factor of 1.25*$f_{t,1}$ in relation to the elastic limit.

3 FE-Analysis

3.1 Description of the numerical tool

The FE-analysis was done with FEMASSE MLS [4]. This numerical tool allows to conduct comprehensive analyses including the coupling of age dependent thermal, hygral, chemical and mechanical properties.

In the given 2-D model the deformation in z direction (longitudinal sense of the bridge girder) was not restrained. The UHPFRC layer was applied to inert concrete, cured for 7 days and afterwards exposed to environmental conditions described by constant values at a temperature of 20°C. The numerical analysis starts at the instant of the UHPFRC overlay casting (time 0).

The structural analysis can be considered as representative regarding the observations made concerning the age-dependent variation of stresses and mechanical properties in the present structural element.

3.2 Cross sectional model

The model represents an exemplary transversal cross section of the bridge girder near the support, showing 5 (prefabricated) T-beams in conventional prestressed concrete with the UHPFRC overlay (Figure 5). The bottoms of the beams are vertically and horizontally fixed limiting the flexional deformability of the bridge deck to a minimum and increasing the degree of restraint to a maximum.

The loads are transferred laterally by the UHPFRC that also connects the longitudinal beams. The thickness of the layer is increased at the longitudinal joints to 15 cm instead of 3 cm on top of the T-beams.

In general, viscoelastic behaviour of the T-beams is beneficial for the stress evolution in the UHPFRC since it indirectly reduces the degree of restraint but this effect was not considered in the analysis.

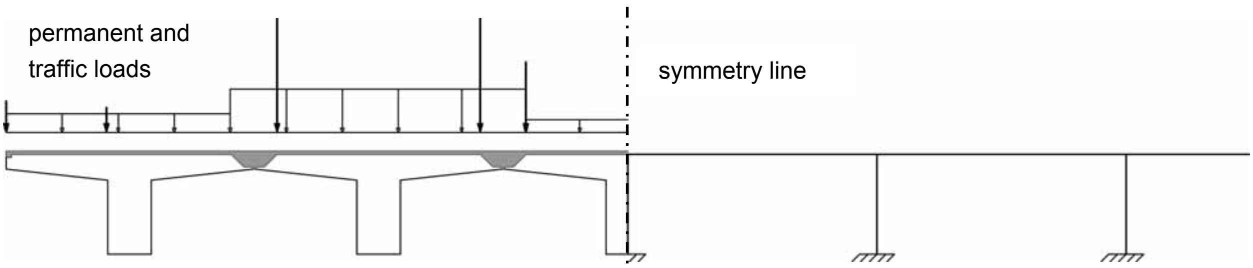


Figure 5: Transversal bridge section with UHPFRC layer, exemplary loading scheme and static system

3.3 Load cases

The following load cases were considered in the modelling:

- Permanent loads due to self weight of the structure and the UHPFRC layer
- Permanent loads due to self weight of non-load bearing elements such as the curbs, crash barriers, railings and the asphalt layer, applied at 28 days
- Traffic loads at serviceability limit state including two traffic lanes according to EC 1 [6], applied at the most unfavourable position regarding stresses in the UHPFRC layer in the transversal sense

All external loads are superimposed to the continuous evolution of the mechanical and physical properties of UHPFRC such as Young's modulus, compressive and tensile strength, shrinkage and viscoelasticity.

4 Results

The results of the numerical simulation are presented exemplary for a typical reference point showing highest stresses:

4.1 Restrained shrinkage

Restrained shrinkage is the load case the UHPFRC overlay is subjected to from the very beginning (after casting) and also the one that consumes an important part of the resistance capacity of the material. It is a deformation controlled loading process, and consequently, it is the deformation capacity of the material that predominantly replies to this load case (Figure 6). The absolute value of the tensile strength is not of great importance here. Depending on the level of the evolving tensile strength, shrinkage causes Eigenstresses that almost reach the elastic tensile strength $f_{t,1}$ before the external loads are applied. If the UHPFRC overlay is stressed beyond its elastic limit due to restrained shrinkage it enters into the hardening domain where it possesses an important deformation capacity, i.e. the stress increase at this stage will be very small. In this way, the strain hardening behaviour represents a significant stress release potential which is essential for the structural response of the overlay in terms of avoidance of macrocrack localisation and maintaining the low permeability of the UHPFRC layer.

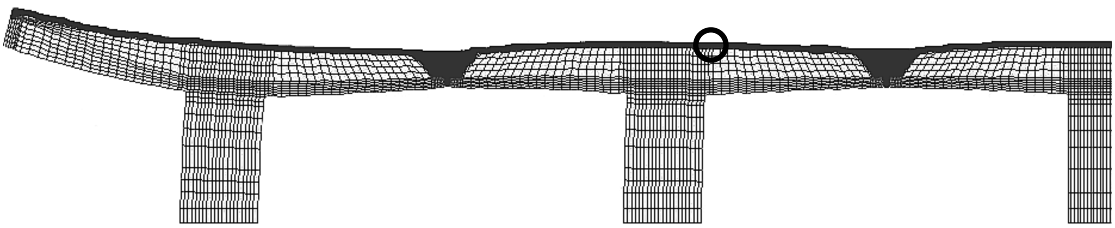


Figure 6: Deformed shape (not in scale) due to shrinkage of UHPFRC (without external loads) and location of the reference point

4.2 Permanent and traffic loads

Permanent and traffic loads are applied 28 days (672 h) after the application of UHPFRC. They represent a force controlled load case. The UHPFRC layer is subjected to an immediate stress increase which is superimposed to the stresses induced by restrained shrinkage.

Figure 7 shows the stress and strength evolution on the time axis until 42 days (1000 h) for three cases. The lower dotted lines represent the elastic strength evolution $f_{t,1}$ whereas the upper dotted lines show the evolution of the ultimate strength $f_{t,U}$. The solid lines describe the stress evolution at the reference point. The step in the solid lines marks the point in time of external load application.

- In case of $f_{t,1}$=0.65*$f_{t,1,ref}$ (Figure 7a) the stresses due to restrained shrinkage reach the elastic limit before the external loads are applied. The application of these creates an inelastic response in the hardening domain. The important deformability of the strain hardening domain keeps the stress level in the UHPFRC layer very close to its elastic limit. The ongoing shrinkage does not significantly raise the stresses. The stress evolution closely follows the elastic strength evolution.
- In case of $f_{t,1,ref}$ (Figure 7b) the stress increase due to the external loads at 28 days is balanced partly by an elastic response and partly by the strain hardening of UHPFRC. The global behaviour is again similar. Once the stress level exceeds the elastic limit further stress increase is very small.
- In case of $f_{t,1}$=1.2*$f_{t,1,\ ref}$ (Figure 7c) external loads lead to a purely elastic response of the overlay. The loads induce a principal tensile stress of approximately 3 MPa at the reference point. Further stress increase is then induced by the continuing shrinkage until the stress level reaches the elastic limit and subsequently follows it.

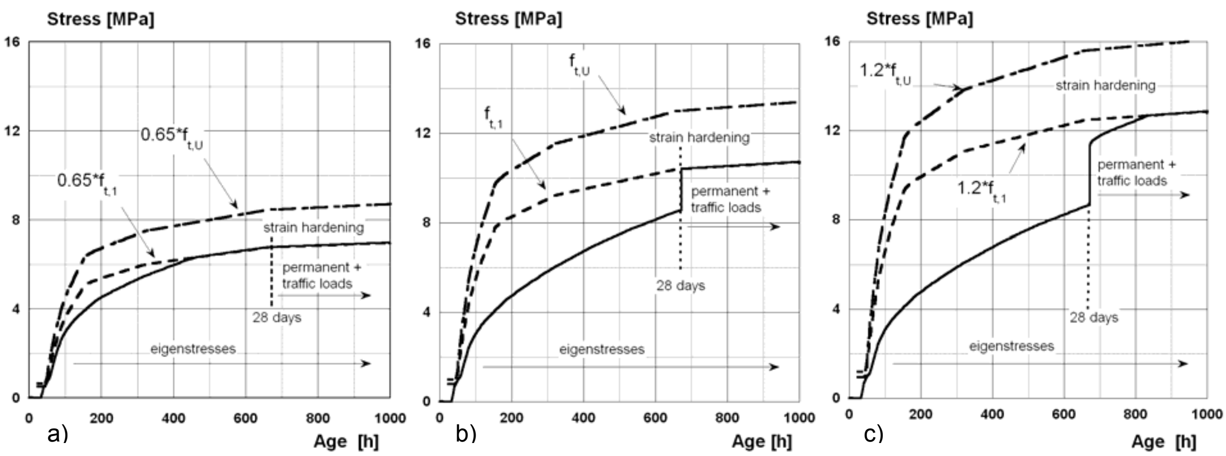
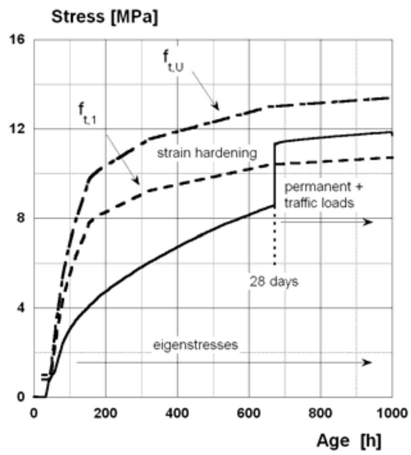


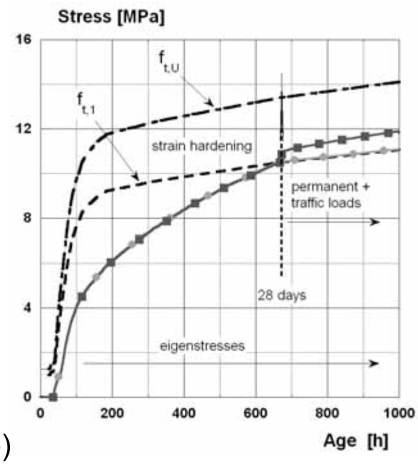
Figure 7: Evolution of stress and strength for a) 0.65*$f_{t,1}$; b) 1*$f_{t,1}$ and c) 1.2*$f_{t,1}$

In all the cases, it can be seen that once the material exceeds its elastic limit strength external loads and continuing shrinkage do not cause a significant further stress increase. The redistribution of loads and increased deformability due to the pronounced strain hardening behaviour and loss of stiffness prevent further stress increase in the UHPFRC layer. Therefore, it is unlikely that the tensile strength $f_{t,U}$ of the UHPFRC is reached. The UHPFRC layer thus remains at the initial stage of multiple microcracking without developing localised macrocracks. The material enters merely very little into the hardening domain, thus keeping its low permeability. It is not subjected to softening within the considered period of 1000 h.

An exemplary simulation with traffic loads increased by a hypothetical factor of 3 shows that in fact the stress step continues significantly into the hardening domain if the level of loading is sufficiently high (Figure 8a). Then the stresses evolve parallel to the elastic tensile strength but at a higher level. UHPFRC seems to possess enormous reserves in a setup as described above to resist localised cracking even if its elastic tensile strength is exceeded.
In case the strain hardening capacity is reduced significantly the UHPFRC overlay obviously enters far into the hardening domain, (Figure 8b). The two lines with markers show the stress evolution at a reference point for two materials with $0.1*\varepsilon_{hard,ref}$ (upper line with square markers) and full strain hardening capacity (lower line with round markers).



a)



b)

Figure 8: a) Evolution of stress and strength for $1.0*f_{t,1}$ and three times the external loads; b) influence of ε_{hard} on the stress level for $\varepsilon_{hard}=0.1*\ \varepsilon_{hard,ref}$

4.3 Serviceability and waterproofing

Charron et al. [7] have shown for a UHPFRC respecting the requirements given in 2.1 that the water permeability of UHPFRC remains low ($K_{w\ equiv.} < 2 \times 10-8$ cm/s) until a tensile deformation of 1.3‰. This threshold deformation corresponds to a cumulated crack opening equal to 0.13 mm as compared to 0.05 mm for normal concrete. Since the numerical results show that at all levels of tensile strength the principal stresses in the UHPFRC overlay do not significantly enter into the strain hardening domain, the proposed concept of an “impermeable” and waterproof UHPFRC layer is validated.

5 Conclusions

A structural analysis of a composite bridge girder combining reinforced concrete and UHPFRC at the serviceability limit state was performed. The structural response under combined loading due to restrained shrinkage and traffic loads was investigated. The obtained results show:

- Restrained shrinkage and external loads may generate stresses close to the elastic tensile strength in the UHPFRC overlay of the composite element with a high degree of restraint. The stresses then follow the age-dependent elastic strength evolution of UHPFRC.

- The evolution of applied stresses in the strain hardening domain is independent of the level of the elastic tensile strength. The loss of stiffness of the UHPFRC layer as it enters into the hardening domain causes a stress release and redistribution.
- The risk of transverse cracking of the UHPFRC layer in the presented structural configuration is unlikely due to the increased deformation capacity and significantly lower stiffness at strain hardening.
- Strain hardening is an essential property for the described type of application since it allows maintaining the low permeability of UHPFRC in its function as waterproofing layer.

6 References

[1] Brühwiler, E., Fehling, E., Bunje, K., Pelke, E. 2007., Design of an innovative composite road bridge combining reinforced concrete with Ultra-High Performance Fibre Reinforced Concrete. Proceedings, IABSE Symposium “Improving Infrastructure Worldwide”, Weimar, September 2007.

[2] Kamen A. (2007) Comportement au jeune âge et différé d’un BFUP écrouissant sous les effets thermomécaniques. Doctoral thesis n° 3827, Swiss Federal Institute of Technology Lausanne (EPFL), Switzerland.

[3] Wuest J. (2007) Comportement structural des bétons de fibres ultra performant en traction dans des éléments composés. Doctoral thesis in press, Swiss Federal Institute of Technology Lausanne (EPFL), Switzerland.

[4] Roelfstra P. E., Salet A. M., Kuiks J. E. (1994) Defining and application of stress-analysis-based temperature difference limits to prevent early-age cracking in concrete structures. Proceedings n□25 of the International RILEM Symposium: Thermal cracking in concrete at early age, pp. 273-280. Munich, Germany.

[5] Habel, K. (2004) Structural behaviour of elements combining ultra-high performance fibre reinforced concretes (UHPFRC) and reinforced concrete. Doctoral thesis n° 3036, Swiss Federal Institute of Technology Lausanne (EPFL), Switzerland.

[6] Eurocode 1: Einwirkungen auf Tragwerke - Teil 2: Verkehrslasten auf Brücken; Deutsche Fassung EN 1991-2:2003

[7] Charron, J.-P., Denarié, E., Brühwiler, E. (2007) Permeability of Ultra High Performance Fiber Reinforced Concretes (UHPFRC) under high stresses. Materials and Structures, 40, n°3, pp 269-277.