

Overlay Ductal®: a durable solution for bridges retrofiting

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Abstract:

The Chillon Viaduct, built by prestressed box girder segmental construction, was constructed in the late 1960s. Recent examination of structural performance showed that punching of wheel loads through the deck slab is prevailing, though structural safety requirements currently can be fulfilled. Furthermore, the box girder concrete is prone to alkali silica reaction (ASR). The chosen strengthening measure is adding a layer of ultra-high performance fiber reinforced concrete (UHPFRC) additionally reinforced with steel rebars on the top surface of the deck slab, also serving as waterproofing layer. A new 45 mm (1.7 in.) Ductal® bridge deck delivers an effective response to these challenges.

Keywords: composite structure, Ductal®, overlay, retrofit, strain-hardening, thixotropic

1. Introduction

The Chillon Viaduct located on the Swiss National Highway on the East end of the Lake of Geneva, was constructed in the late 1960s. The variable height box girder structure, spanning between 92 m (302 ft.) and 104 m (341 ft.) over a total length of 2 210 m (7 250 ft.), was built by prestressed segmental construction with epoxy-glued joints which was a world novelty at the time.

Recent structural assessment showed that the governing failure mode at Ultimate Limit State (ULS) is punching of wheel loads through the 18 cm (7 in.) thin deck slab, though structural safety requirements currently can be fulfilled. Further investigations revealed that the concrete is prone to alkali aggregate reaction (AAR). The latter is expected to lead to significant concrete strength reduction in the future, with an associated reduction in punching shear resistance.

As the replacement of the waterproofing on the deck slabs was planned for 2014-2015, its combination with a strengthening intervention was investigated. It has been decided to consolidate the viaduct by adding, on the previously hydro-jetted top surfaces of deck slabs, a 40 to 50 mm (1.6 to 2 in.) thin layer of Ultra High Performance Fibre Reinforced Concrete (UHPFRC) which is additionally reinforced by steel rebars, on the top surface of the deck slab.

The choice of UHPFRC as a strengthening material, was motivated by its outstanding mechanical properties, namely high tensile and compressive strengths and its important deformation capacity due to the high amount of incorporated steel fibres in the cement-based matrix of the material, as well as by its very low porosity implying minimized moisture exchange and ingress of aggressive chemical substances such as chloride ions from the surrounding

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atmosphere. Consequently, the latter property (low porosity) will have beneficial effects on a further evolution of the AAR (because of lack of water supplies) and on corrosion of reinforcement of steel rebars.



Figure 1. View of the Chillon viaduct



Figure 2. Construction of the viaduct with prestressed box girder segments

2. Background

The concept of application of strain-hardening UHPFRC for the rehabilitation of structural members is schematically illustrated on Figure 3. A dense layer of UHPFRC with 25 to 60 mm (1 to 2 in.) thickness is applied on the superstructure in zones of severe environmental and mechanical loads (exposure classes XD2, XD3) and only where the UHPFRC fits the requirements. The construction process becomes simpler, quicker, and more robust, with an optimal use of composite construction. The waterproofing capabilities of UHPFRC exempt from applying a waterproofing membrane. Thus, the asphalt pavement can be applied after only 7 days of moist curing of the UHPFRC composite layer, in a wide range of climatic conditions. This constitutes a very significant time saving with respect to the drying period of up to 3 weeks necessary prior to the application of a waterproofing membrane for a usual mortar or concrete and to their limited durability.

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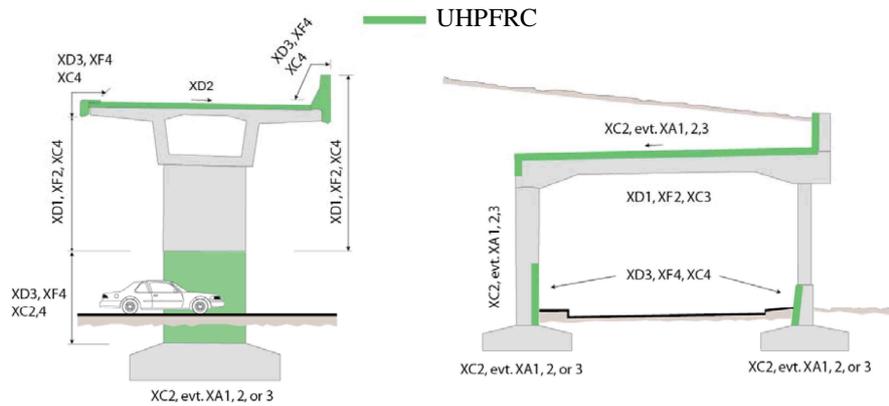


Figure 3. Concepts of application of the local strengthening of structures with UHPFRC

Cast-on site applications require strain-hardening UHPFRC able to withstand the development of eigenstresses due to restrained shrinkage, without cracking. Their rheology can be adjusted from self-compacting to thixotropic for application on inclined substrates. Their tensile response must be validated on specimens representative of the application (fiber orientation and rheology). When it is required, the combination of the protective properties and deformation capability of UHPFRC with the mechanical performance of reinforcement bars (normal or high grade) provides a simple and efficient way of increasing the stiffness and load-carrying capacity. Reinforcement bars also help mitigate the variability of the tensile response of UHPFRC over large surfaces. These concepts have been validated by means of extensive research aimed at characterizing UHPFRC materials and the structural behavior of composite reinforced UHPFRC structural members, as well as numerous successful applications in Switzerland and abroad, since 2004.



Figure 4. Bending and shear tests on composite slabs reinforced with strain-hardening UHPFRC



Figure 5. Examples of applications with strain-hardening UHPFRC

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3. Testing Methods

The UHPFRC designed for the overlay application responds to the following general requirements: high compressive and tensile strengths, strain hardening in tension, very low permeability, self-compacting fresh mix with the ability to be cast with a slope of 7%.

3.1. Rheology

The lever used to modify the self-compacting behavior to a rheo-thinning behavior is the admixture. The simple slope test (Figure 6) allowed us to identify the best solution and to evaluate the robustness with temperature (5 to 35 °C so 41 to 95 °F).

Due to the mechanical casting method developed by the company Walo Bertschinger AG, scale-up tests have also been performed to check the compatibility between the Ductal® mix and the process and its influence on the fibres orientation.



Figure 6. Slope test and scale-up test with the casting machine

3.2. Tensile behavior

High tensile strength as well as strain hardening and softening are characterising properties of UHPFRC. The uniaxial tensile behavior was determined using 4 points bending tests on thin plates measuring 500x100x30 mm (19.7x3.9x1.1 in.) and a back analysis method afterwards. Complementary direct tensile tests have also been carried out on dogbone specimens.

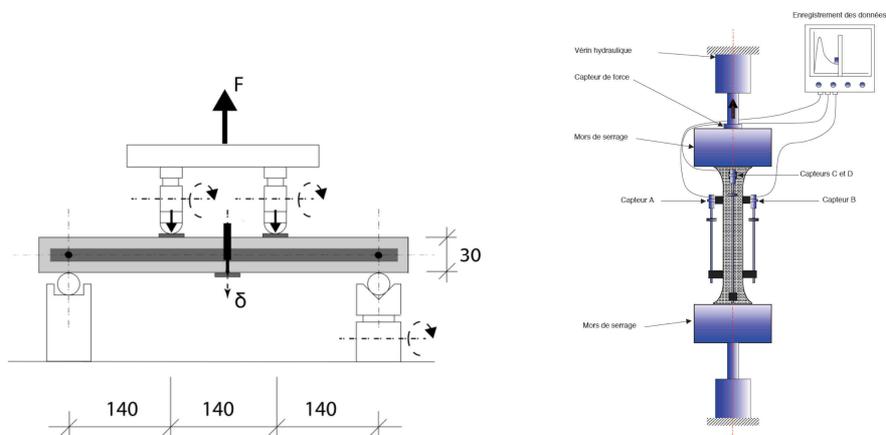


Figure 7. Bending and direct tensile tests on strain-hardening Ductal® specimens

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4. Results

During the 2 phases of the Chillon project, a huge amount of tests have been carried out by different laboratories:

- fresh state: density, air content, slump and slope maintain
- hardened state: compressive and bending tests, bonding tests (adhesion between Ductal® and the existing concrete on the deck), Young's modulus, water absorption and air permeability

Tables 1 summarizes the main characteristic of the thixotropic Ductal® evaluated under samples produced at the R&D Center and also on the job site (casted plates and plates cut on the deck). The performances of this new Ductal® product comply with the project specifications (class UA), coming from the Swiss technical recommendations.

Table 1. Results of the characterization for the Ductal® mix

Characteristics	Unit	Thixotropic Ductal®
Slope control	(%)	up to 10
Total shrinkage at 90 days	$\mu\text{m}/\text{m}$ (10^{-6})	500
Compressive strength at 28d	MPa (ksi)	125 (18)
Limit of elasticity under tension at 28d	MPa (ksi)	8.0 (1.2)
Post-cracking resistance at 28d	MPa (ksi)	9.0 (1.3)
Young's modulus at 28d	GPa (ksi)	45 (6530)
Water porosity at 90d	(%)	6 (very high durability)
Diffusion coefficient of chloride ions at 90 days	$10^{-12} \text{ m}^2 \cdot \text{s}^{-1}$ ($\text{sq ft} \cdot \text{s}^{-1}$)	0.1 (1.1) (very high durability)
Apparent gas permeability at 90 days	10^{-18} m^2 (sq ft)	0.5 (5.3) (very high durability)



Figure 8. Fresh Ductal® poured on a 7% sloped rough plate (dimensional control)

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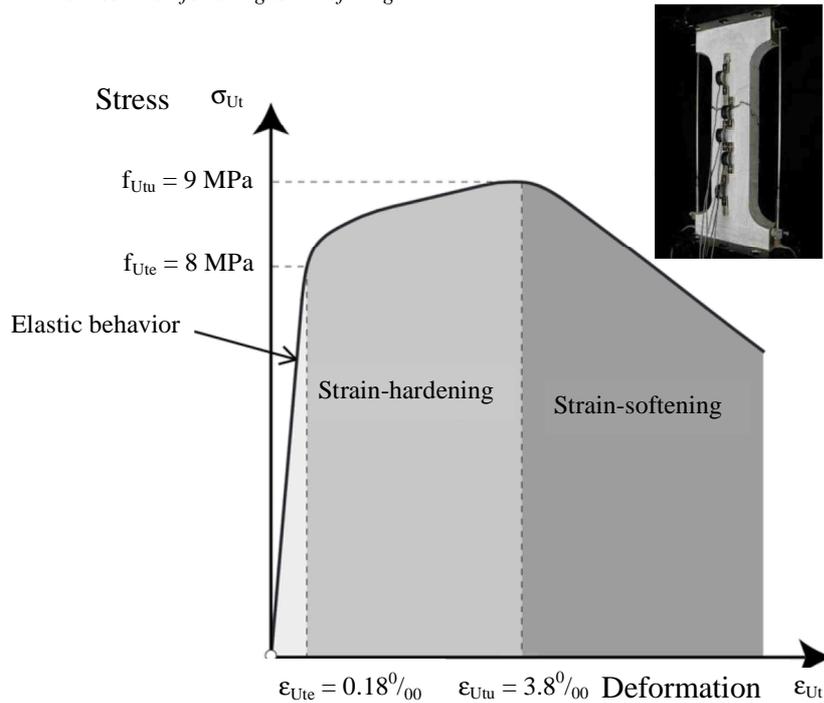


Figure 9. Direct tensile behavior of strain-hardening Ductal®

5. Discussion

The constitutive law in tension obtained with the 2 methods, direct tensile tests and back analysis from bending tests, gave similar results for the strain-hardening phase. It confirms the good reliability of the back analysis approach, based on the relationship between the curvature and the deflection but only valid in the elastic domain (Figure 10).

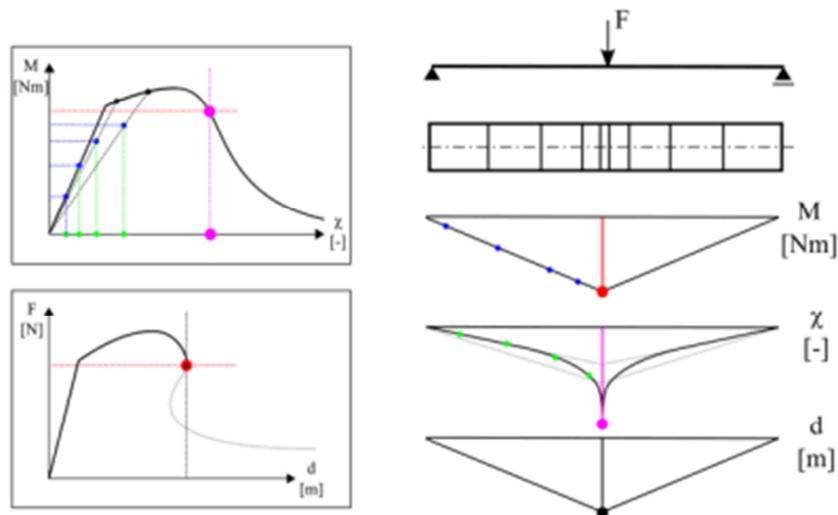


Figure 10. Principles of the curvature-based formulation

About the rheology, the robustness has been validated during the design phase, and 3 different mixes implemented in the automatic mixing plant, to take into account of the ambient temperature. A simple adjustment of the superplasticizer guaranteed the appropriate workability and adequacy with the casting process.

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6. Conclusions

The concept of application of strain-hardening UHPFRC for the improvement of existing structures has been applied successfully on Chillon viaduct. This project is the biggest overlay project in the world right now, with industrial quantities of Ductal® cast per day (up to 80 m³), over several weeks (6 in 2014 and 5 in 2015) to reinforce a twin 2.1 km long highway viaduct. Exceptional execution methods developed for this project have demonstrated the effectiveness of the reinforced UHPFRC strengthening solution. The robustness of the established formula has reduced the hazards during the construction, particularly the workability of UHPFRC with the temperature.

Combination of UHPFRC with rebars offers an efficient way to produce highly durable reinforced UHPFRC tensile membranes to reinforce existing structures.



Figure 11. Implementation of thixotropic Ductal® on Chillon viaduct's deck

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