INNOVATIVE SOLUTION FOR STRENGTHENING ORTHOTROPIC DECKS USING UHPFRC: THE ILLZACH BRIDGE

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Abstract

The technical solution (Orthodalle process) for repair of the bridge on the local RD201 road over the Huningue canal in Illzach, near Mulhouse, eastern France, was derived from the Orthoplus research programme initiated in November 2006 by the French National Research Agency. The main objective of the Orthoplus research project coordinated by Sétra (French Highways Technical Agency) was to develop theoretical and methodological resources for taking account of the thickness and type of road overlay when calculating the fatigue strength of a steel bridge with an orthotropic deck. These resources were then used to develop an innovative thin wearing course made with ultra-high performance fibre-reinforced concrete (UHPFRC). The Orthodalle process uses the strength and durability properties of UHPFRC to extend the service lifetime of existing orthotropic slabs or, more generally, any other steel-framed structures. This article presents the main steps of the project: the design of the UHPFRC element for strengthening the orthotropic deck, the suitability tests performed on full-scale elements before the works, the precasting of slabs, the reinforcement works, and the validation of the trial comparing measurement campaigns carried out before and after the works.

Résumé

La solution technique pour le projet de réparation du pont de la RD201 sur le canal de Huningue à Illzach est issue du programme de recherche Orthoplus retenu en novembre 2006 par l'Agence Nationale de la Recherche. L'objectif principal du projet de recherche Orthoplus piloté par le Sétra était de mettre au point les outils théoriques et méthodologiques de prise en compte de l'épaisseur et de la nature du revêtement dans le calcul en fatigue d'un tablier métallique à dalle orthotrope. Ces outils ont ainsi été appliqués dans un second temps pour optimiser les revêtements bitumineux épais existants et pour développer une solution innovante de revêtement mince en béton fibré à ultra-hautes performances (BFUP). Le

procédé Orthodalle utilise la résistance et la durabilité du BFUP pour augmenter la durée de vie des platelages orthotropes. Cet article présente les étapes principales du projet : la conception des éléments en BFUP pour le renforcement des platelages orthotropes, les essais en vraie grandeur, la préfabrication des dalles, les travaux sur place et la validation du procédé par comparaison entre les résultats des épreuves de chargement réalisées avant et après l'intervention.

Photo 1: The Illzach bridge

1. DESCRIPTION OF THE BRIDGE AND OF DISORDERS OBSERVED

The bridge (Photo 1), which came into service in 1970, is a through-bridge with a single statically determinate span. The 106-m-long Warren girders support an orthotropic deck. The bridge is 12.60 m wide and carries an 8-m-wide 2-lane single carriageway (effective deck width of 11.00 metres).

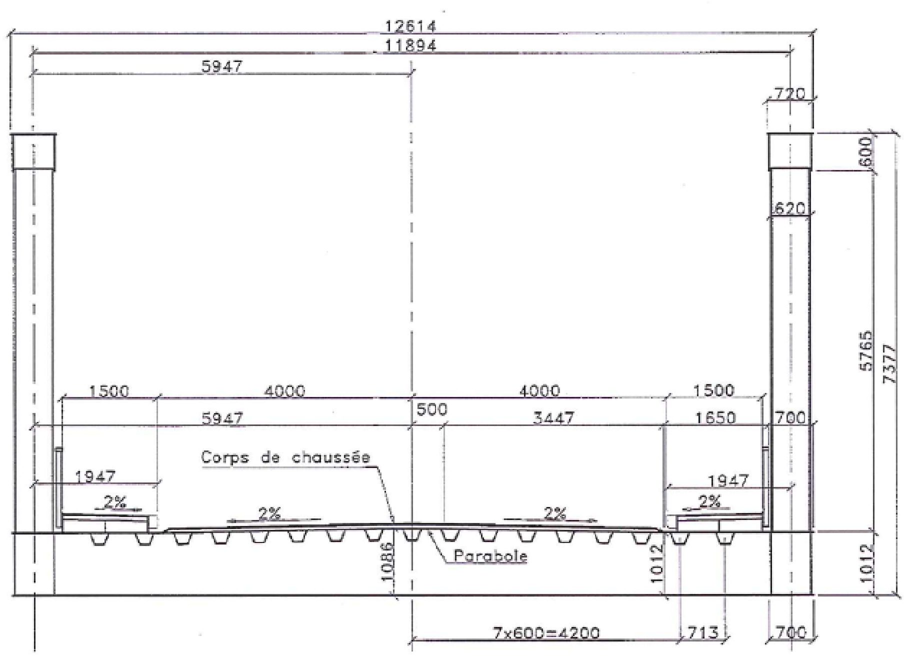

Figure 1: Cross-section

The orthotropic deck (Photo 2) consists of 12-mm-thick steel plate stiffened transversally by 34 crossbeams forming 33 'bays', and stiffened longitudinally by 17 ribs or 'troughs' (Figure 1). The crossbeams are spaced about 3.20 m apart, and the discontinuous troughs span between pairs of crossbeams.

The 80-mm-thick bridge surfacing laid at the time of construction consisted of a two-course asphalt layer with a coarse bituminous-concrete wearing course. Before it was repaired, the deck had large numbers of cracks along the welds between the troughs and the crossbeams (183 cracks were identified in 2001, with a further 60 being added to the inventory during detailed inspection in the summer of 2009). These cracks were generally located at the bottom of the weld beads, most commonly in the crossbeam web, though some cracks were also in the deck plate. There was no crack propagation, strictly speaking, although four cracks were observed to have extended longitudinally between the trough and the deck plate (Photo 3).

Photo 2: Deck plate soffit

Photo 3: Desorders observed

Since water was observed in the troughs, it was feared that there might be fatigue cracks in the deck plate that were not detectable because of the surfacing. A lot of corrosion was also observed on the diagonals of the Warren girders and on the soffit of the deck plate.

To ensure the bridge could be kept in operation, work was carried out in February 2010 to make it safe with respect to the risk of the troughs coming loose. At the same time, the regional General Council (CG68) and the Ministry of Public Works' local agency (CETE de l'Est) set about finding a solution for reinforcing and repairing the bridge.

2. THE REPAIR SOLUTION PROPOSED BY EIFFAGE TRAVAUX PUBLICS

The damages observed were chiefly located in the deck, where the trough ribs and crossbeams join, whereas the Warren girders were in a good state of repair. Consequently, the most appropriate repair solution involved local stiffening of the upper deck plate by rigidly connecting it to a thin slab of UHPFRC. Since this appreciably increases the moment of inertia, longitudinal bending forces are filtered by the topping and stresses in the trough-rib–crossbeam welds are considerably reduced. This technical solution was applied with a combination of precasting and in situ keying of the precast parts.

The UHPFRC topping consists chiefly of sixty-six 5-cm-thick precast slabs measuring 3.45 m x 2.70 m. They were placed in two rows lengthways. In addition to these precast units, cast-in-place UHPFRC was placed as three longitudinal keying strips (one 30-cm-wide strip in the centre and two 20-cm-wide strips at the sides) and as 60-cm-wide transverse strips centred on the crossbeams. Mechanical continuity of the UHPFRC across the keying joints was achieved by an ST 65C welded fabric placed at the level of the neutral plane of the slab. The UHPFRC slab is connected to the deck plate by means of 'miniature' Nelson shear studs St37-3K (Ø = 13 mm ; h = 25 mm) in the keying strips and in 380 mm x 380 mm boxouts in the precast units (Figure 2).

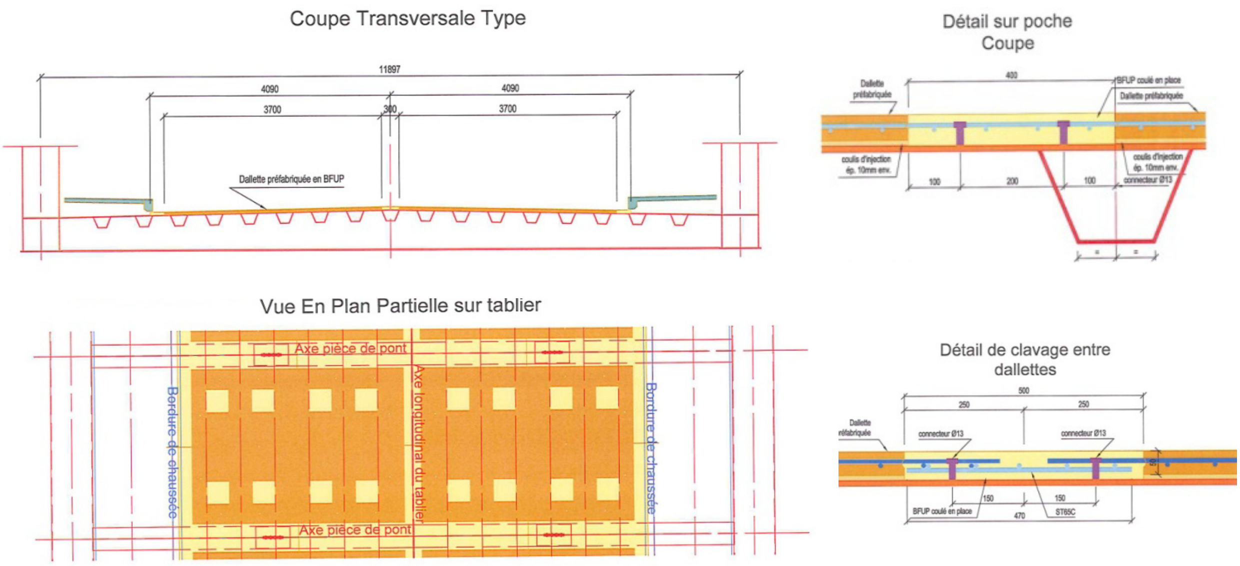

Figure 2: Reinforcement principle

Precast slabs reduced disturbance and traffic restrictions to the strict minimum, minimized the volume of UHPFRC to be cast in place and, consequently, the amount of concreting equipment required.

Application of this solution with precast slabs was also facilitated by the geometry of the deck (straight), which made it possible to cover the entire area with a single type of unit.

3. EXPERIMENTAL MONITORING PROGRAMME

Since the experimental study of the behaviour of the orthotropic–UHPFRC slab could not be based on a conventional test procedure, as it is an innovative composite of two structures for which there was no previous experience in France, it was deemed to be appropriate to carry out a first campaign of tests based on the five-point bending test used by roading contractors for fatigue testing of road pavements (test addressed by French standard NF P 98-286).

The tests were carried out as part of the Orthoplus research project. They studied three types of connection on small specimens (580 x 220 mm) with a constant UHPFRC thickness of 35 mm. These small-scale tests demonstrated excellent static and fatigue behaviour of the steel/concrete composite for all kinds of connection: shear studs, welded fabric, and welded fabric with crenellated connection plates welded to the deck plate.

Since the five-point bending test cannot simulate the behaviour of the orthotropic deck and its trough ribs, it was possible to determine neither the longitudinal flexural behaviour nor the total longitudinal and transverse stress of the system.

It was therefore necessary to carry out a campaign of static and fatigue tests on larger specimens at the central laboratory of IFSTTAR. This involved orthotropic deck units measuring 2.40 x 4.00 m manufactured especially for the purpose in the Eiffage Construction Métallique plant in Lauterbourg, and coated with either bituminous concrete or UHPFRC.

In addition, a campaign of tests was carried out on life-size structures under the Orthoplus programme. The tests involved studying the behaviour of the orthotropic deck of a modular steel emergency bridge (*Viaduc Métallique Démontable* (VMD)) provided by the national emergency bridge agency (Centre National des Ponts de Secours). The 12.80-m-long, 3.50-m wide VMD deck was transported to the Monthyon site near Meaux, where Eiffage Travaux Publics has a coating plant and other permanent facilities, for testing. The main purpose of the VMD deck was to quantify the structural contribution of the UHPFRC topping relative to configurations with just the bare steel or with a non-structural bituminous coating.

The campaign tested several solutions which could be adopted, depending on the type of project to be carried out under a contract for either construction of a new deck or for repair of a distressed deck. To validate the technical solution adopted for the RD201 bridge in Illzach, a precast UHPFRC slab was connected to the orthotropic steel deck of the VMD bridge (Photos 4 and 5).

Photo 4: VMD bridge deck – Precast slab

Photo 5: VMD bridge deck – concreting of keying areas

The precast concrete slab had boxouts enabling connectors to be concentrated in groups and the slab to be keyed to the steel by means of cast-in-place UHPFRC. This arrangement is similar to that used for composite ladder-deck bridges with precast reinforced-concrete slab decks. The VMD deck was instrumented and loading tests were carried out to quantify the improvements in local and general bending.

4. CONSTRUCTION DESIGN STUDIES

The works were verified for two configurations, 'initial state' and 'strengthened state', under the civil and military traffic loadings for which the bridge had originally been designed.

The structure was analyzed by means of 3D finite-element modelling using shell elements reproducing the orthotropic steel deck and its UHPFRC surfacing at a fine scale (Figure 3). The analysis first considered linear elastic behaviour of the materials with a constitutional law for the steel–concrete interface derived from the results of push-out tests performed under the Orthoplus project. The eventuality of cracking of the UHPFRC in areas above supports, i.e. at crossbeams, was also analyzed in order to assess the effects of load redistribution in the composite steel-UHPFRC deck. Comparison of results of analysis of the bridge before and after strengthening (Table 1) showed a significant increase in stiffness and an appreciable reduction in the stresses in the steel deck plate.

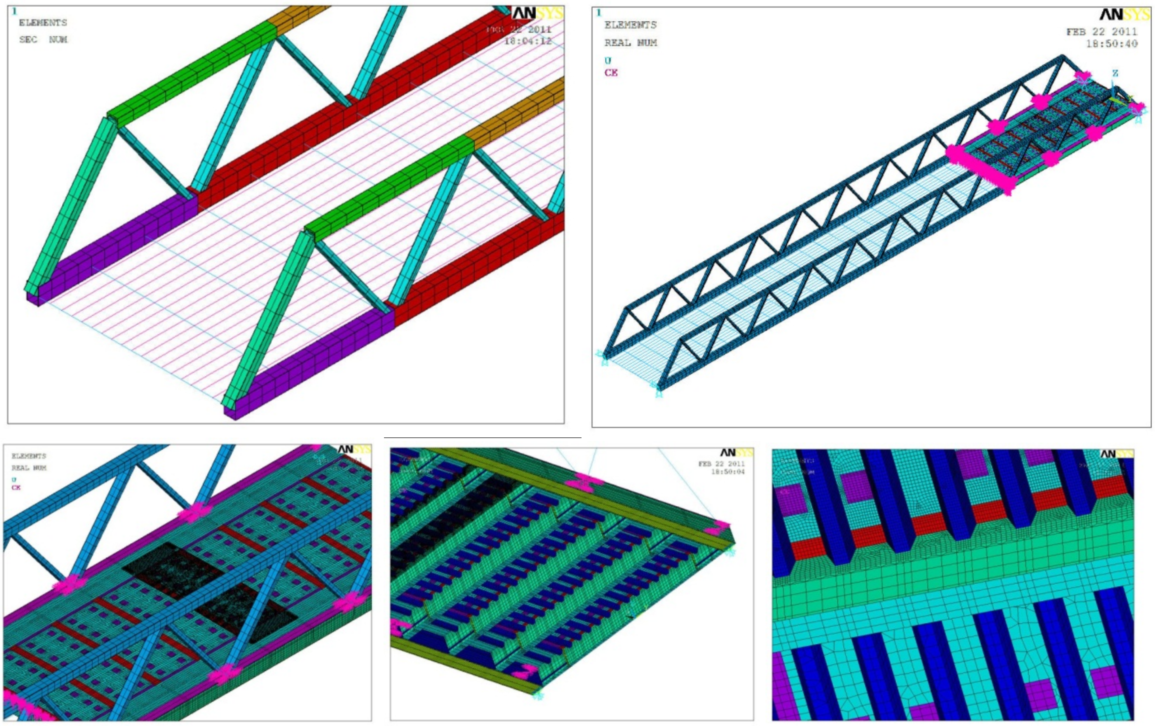

Figure 3: 3D model

Table 1: ULS stresses - Initial state / Strengthened state comparison

	Stress in MPa	Initial bridge	Strengthened bridge	Difference
Steel deck plate	σx (longitudinal)	263	163	**-38%**
	σy (transversal)	390	154	**-61%**
Troughs	σx soffit	398	298	**-25%**
	σx web	252	107	**-58%**
	σxz web	122	59	**-52%**
Crossbeams	σy	243	210	**-14%**
	σxz	120	104	**-13%**

Fatigue analysis was carried out with the 'cumulated damage' method. By examining the history of loading and predictions of future traffic, damage at the initial state and strengthened state was assessed, and the effect of the UHPFRC slab on the bridge's expected lifetime after strengthening was calculated. The two critical details of the bridge are the fillet welding of discontinuous troughs to crossbeams (Detail 36 as per EN 1993-1-9) and of troughs to the steel deck (Detail 71 as per EN 1993-1-9 or 125 as per the work of Kolstein and the Orthoplus project). For the first detail, existence of the UHPFRC slab helped to reduce stress at the bottom fibre of the troughs, where they are welded to crossbeams, by close to 50%, which extends the lifetime of uncracked details by close to 20 years. For the second detail, the reduction in stress results in a lifetime of more than 80 years.

As regards verifications specific to the BSI® topping, they are based on the 2002 AFGC-SETRA interim recommendations for UHPFRC, taking class IV corresponding to a sectional area reinforced by fibres and passive reinforcement. For the construction joints, the strength of the section is that of a reinforced-concrete section without any contribution by fibres.

5. REPAIR WORK

The challenge was to carry out the work to strengthen the orthotropic deck during a total bridge closure period of only two months (July and August) in the summer of 2011. Precasting of the UHPFRC slabs (66 in all) began early in April 2011; the plant produced an average of 4 slabs per day.

On-site, the preparatory work consisted of:

- stripping of the surfacing on the bridge (macadam and waterproofing),
- surface preparation of the orthotropic steel deck plate (after stripping of surfacing) by means of high-pressure water blasting to remove any loose material.

The strengthening work, which was programmed to take place over nine weeks, involved the following:

- drawn-arc welding of shear studs (Photo 6). In all, close to 12,000 studs were welded to the bridge,
- placement and adjustment of precast UHPFRC slabs (Photo 7) using a telehandler, starting mid-span and working to the abutments,
- placement of reinforcement (welded fabric) in transversal and longitudinal keying zones,

Photo 6: Welding of miniature studs

Photo 7: Placement of precast slabs

Photo 8: Placement of precast slabs

Photo 9: Laying of wearing course

- in-situ concreting of transverse keying strips and boxouts in the UHPFRC slabs (Photo 8). The BSI® concrete manufactured on-site (same formula as that used for precast slabs) was made with in 250-litre batches using a conventional vertical-shaft mixer,
- grouting of the slab/steel plate interface with a non-shrink mortar. Grouting and venting holes were provided in the precast slabs to ensure proper filling of the interface,
- waterproofing and laying of the surfacing. After preparation of the deck by abrasive blasting, bridging of concrete construction joints, and application of an epoxy-resin primer, a wearing course of gravel and resin was laid to a total thickness of about 10 mm (Photo 9).

The preparatory work began on June 14, 2011. The slabs were placed in July and August. The strengthened bridge was put back in service on September 1, 2011, in time for school buses to use it after the summer break.

6. INSPECTION OF WORKS AND VALIDATION OF TRIAL

The scientific and technical network (SETRA & CETE de l'Est) of the Ministry of Ecology, Sustainable Development, and Energy was in charge of inspecting and validating the construction design, the choice of materials, and implementation. The purpose of validation was to analyze the actual mechanical working of the bridge, in comparison to its theoretical working determined at the construction-design stage with finite-element models. It also involved studying the mechanical behaviour of the bridge before and after strengthening in order to assess the residual lifetime of the repaired structure and to study its mechanical behaviour subsequent to damage such as failure of a stiffening trough.

With respect to general bending, this involved examining the effect the added slab has on the behaviour of the initial steel structure (general bending of the bridge as a whole and local bending of crossbeams), focusing in particular on the reactions of connections to traffic loading, thermal effects (temperature differential between the concrete slab and the steel beams), and shrinkage. For local bending, it involved assessing variations in fatigue stress with the new configuration, compared to the original bridge, particularly at trough ribs.

A monitoring campaign was carried out to determine fatigue actions:
- traffic monitoring for two months to characterize the actual traffic using the bridge;
- simultaneous monitoring of stress variations in the main girders and in the troughs studied in order to determine the global and local dynamic effect of traffic.

The instrumentation installed for this comprised:

- instrumentation of an end zone and of a mid-span zone on a set of three troughs below the wheel tracks of heavy goods vehicles;
- instrumentation of the mid-span section of the main girders with extensometers (top and bottom chords) and with temperature sensors,
- instrumentation of the mid-span section of the mid-span crossbeam with extensometers (top and bottom chords) and with temperature sensors,
- instrumentation of the end zone of the bridge to detect any slippage between the concrete slab and the steel deck plate,
- monitoring of the global deformation of the bridge (mid-span) and local deformation of the mid-span section (bending) of the mid-span crossbeam.

Photo 10: Instrumentation of steel deck plate

A total of 72 strain gauges were bonded to the bridge soffit and to the main girders (Photo 10). The mid-span section was also surveyed topographically. Reflectors were placed on the top and bottom chords of the main girders. Another was placed on the underside of the bottom flange of crossbeam No. 17, on the bridge centreline. This monitoring served to examine the overall behaviour of the strengthened bridge. Loading tests were carried out before and after strengthening in order to assess the behaviour of the strengthened bridge. Mid-span, the bridge was loaded with 6 trucks, but two were sufficient for the end zones.

The main conclusions drawn from the loading tests before and after repair are as follows:

- the general behaviour of the bridge (under static load) is not changed; deflection has been reduced by about 2% and stresses in the main girders are much the same;
- longitudinal bending of crossbeams is reduced: the effectiveness of the connection of the UHPFRC slabs is thus validated for the stud connection;
- it is particularly difficult assess the local behaviour of the trough ribs: differentials between wheel positions in theory and in practice, and between two loading tests, induce differences in the local behaviour of the structure that it is impossible to explain.

Consequently only general trends can be deduced from the readings:

- the UHPFRC slabs appear to provide better distribution of forces into adjacent troughs,

- the neutral axis is located in the UHPFRC layer, proving good connection between the concrete and the steel deck plate,
- stresses transferred through the trough ribs appear to be reduced by 30%,
- stresses transferred through the deck plate seem to be reduced by 50%.

7. PROGRAMME FOR MONITORING THE DURABILITY OF THE REPAIR

This aspect of the project involves ensuring the repair continues to perform adequately over a period of ten years Monitoring of the bridge returned to service will include regular detailed inspections whose frequency will be adjusted in accordance with observations made, and an annual inspection by an expert engineer from CETE de l'Est. For the moment, detailed inspections are scheduled one year, five years, and ten years after the repair.

When the inspections are carried out, the evolution of stresses and deflection under static loading will also be monitored by means of tests similar to the loading tests carried out at the end of the works. The primary objective of this instrumentation will be to check the lasting nature of good connection between the UHPFRC slabs and the steel deck. This campaign of instrumentation may be simplified by the specially appointed technical monitoring committee in light of the first results.

After one year of service, the detailed inspections of the repaired bridge showed no changes in the cracking of the steel deck, and no issue related to the UHPFRC layer or the resin wearing course connection to the slabs. Also note that one year after the repair, the loading tests carried out on October 2012, showed similar results to those of 2011.

8. CONCLUSION

The Orthodalle process applied to repair of the bridge on the RD201 highway shows all the interest of this innovative technique:

- it increases the loadbearing capacity of the orthotropic deck by reducing stresses in the steel deck,
- the lifetime of the bridge is increased by at least 20 years for a highly advantageous cost relative to replacement,
- it uses UHPFRC, the most durable composite material known to date. The expected lifetime of the UHPFRC topping considerably enhances the environmental whole-life cost of the bridge.

The Orthodalle process successfully implemented for the Illzach bridge was awarded the IVOR Label (*Innovation Validée sur Ouvrage de Référence* – Innovation Validated on a Reference Bridge) by the Steering Committee of the *Réseau Génie Civil & Urbain* (a joint agency of the French Ministry of Public Works and the national research agency (ANR)) at its meeting of June 4, 2012.