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Quality specifications for roadway bridges, standardization at a European level

Report for
a Short Term Scientific Mission:

Extraction of Performance Indicators for UHPFRC strengthened bridge structures

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1 INTRODUCTION

Over the past years, developed societies have been faced with the problem of aging of existing infrastructure, often leading to costly rehabilitation works with associated downtimes and societal toll. In view of this, the notions of sustainability and resilience have become paramount in the way developed societies plan ahead and manage own resources.

A relevant example may be drawn on existing bridge infrastructure. Many roadway and railway bridges, built more than 50 years ago, have not been designed to undertake current loads. A characteristic example in the case of steel bridges pertains to hot rolled steel or cast iron structures, connected with rivets. For steel bridges in particular, strengthening may be achieved via addition of a load-bearing deck above the main girders without replacing these. The conversion of a metallic section into a composite cross-section modifies the neutral axis, favoring capacity for additional loads. In addition, the concrete deck may stiffen the upper steel flange, thus eliminating stability issues for the cross-sectional part under compression.

Within the context of rehabilitation of steel bridges, the development of new composite materials allows for sustainable strengthening methods, alleviating damage and enhancing resistance of existing structures. Particularly interesting is the recent use of Ultra High Performance Fiber Reinforced Cement-based Composites (UHPFRC) in rehabilitation projects. This material is described by a set of special traits, such as durability, outstanding material properties, and ease of application, which render UHPFRC an ideal candidate for strengthening solutions. Laboratory tests indicate a compressive strength, which ranges from 150 to 200 MPa, while tensile strength lies in the range of 7-15 MPa [2]. The fibres play an important role in defining the range of these properties depending on the content (3-6%), orientation, length and composition. As a consequence, UHPFRC delivers a workable material whose mechanical properties may be properly adjusted according to the desired application scheme. As indicated via laboratory testing and in-situ experience, the durability of the structure may be extended not only due to the properties of UHPFRC but also due to the additional impermeability protection it offers, as shown in [7].

This STSM deals with an actual case study, involving the rehabilitation of the former Buna Bridge, in Croatia, on the Zagreb-Sisak railway. This bridge is about 9 meters long and 0.9 m in height. The cross-section consists of two main girders made of hot rolled steel plates joined with rivets, and represents a beam structure that is typical of its construction period. The main girders are connected via horizontal and vertical grids for stiffening. Due to its handling weight of only 8.0 tons, this non-ballasted bridge offers a unique opportunity for transportation and subsequent experimentation in the laboratory. Structural Health Monitoring techniques are used in this project to obtain parameters that allow an identification of the actual condition of the structure in a first stage, and to compare the behavior of the bridge after the rehabilitation is performed. The latter includes a UHPFRC slab on top of the existing girders, connected via steel studs as in common composite section. An amelioration on fatigue and increase on strength is expected, which is intended to be proved though experiments and simulation.

2 DETAILED PLAN OF ACTIVITIES

2.1 Objectives

The scope of this project is twofold; on one hand, we will look into ways of extending the lifetime of existing structures through novel intervention methods and materials as UHPFRC. On the other hand, important knowledge regarding structural condition can be retrieved via collection of appropriate sensory information and appropriate monitoring techniques. Collection of static and dynamic response information, coupled with adequate data processing tools, offers a realistic verification of structural performance. A deeper understanding of the system's condition under operation offers a tool for extending the nominal lifetime of existing building stock. This in turn contributes to the significant reduction of building materials, energy consumption and CO_2 emissions, which are detrimental in currently employed standard approaches, which often require full replacement of structures once they fulfill their design expectancy, regardless of their actual condition.

2.2 Previous Works

In order to determine a baseline reference case, a first testing campaign has been implemented, divided in two stages. The first one is described in [5] and consisted on a static test, where deflection and strain were measured. The second was carried out by the applicant and dealt with the dynamic analysis of the bridge. This task was performed in November 2016 with the collaboration of the department of Civil Engineering from Zagreb University, at the facilities of VIADUK company where the bridge was stored. Both a shaker and a hammer were used to induce the vibrations, measuring each response with a different set of accelerometers. The post process of the results showed a good agreement between both methods, hence allowed to calibrate the FE model that was created based on information contained solely in drawings.

2.3 Activities during the STSM Period

The original planned activities at the first proposal included the testing of the bridge after rehabilitation. However, due to some complications at ZAG laboratory, the casting had to be postponed and therefore the testing could not take place. As the arrangements for the visit were already done (traveling and lodging were booked), it was decided from both the host institution and the applicant to continue with the STSM and focus the works on improvement of the strengthening solution. A summary of the final tasks is depicted in Table 1 .

			WEEK			
Task num	INITIAL TASK	FINAL TASK	Week 0	Week 1	Week 2	Week 3
0	Vibration monitoring campaign	Vibration monitoring campaign				
1	Gatehring information	Gatehring information				
2	Sensor installation for loading test	Studs preparation for future casting				
3	Loading test	Study on UHPFRC properties				
4	Model develoment and improvement	Testing on UHPFRC new Mixes				
5	Sensor installation for vibration test	Rearreangement of sensor implementation based on on site information				
6	Vibration test	Fatigue study				
9	Data processing	Model develoment and improvement (extended)				

Table 1. Description of final tasks performed by the applicant.

A detailed explanation for the most relevant activities is given herein, as well as the process for extracting performance indicators.

3 METHODOLOGY

3.1 Description of the structure

As aforementioned, the structure to be rehabilitated is a steel riveted bridge, originally from 1893. A new solution was implemented on 2010 at this location, rendering the old bridge unused. Therefore, it was decided to use this opportunity to study the real condition of the structure and plan a strengthening program, with a novel material as UHPFRC.

The bridge is about 9 m long and is conformed by two main girders, 0.9 m depth with an I shape. Both girders are distant 1.8 m one from the other and jointed at four sections by means of L profiles creating a truss, as well as a zig zag diagonal on the top. The lower zone of the structure remains unrestrained. It is particularly noticeable that wooden sleepers were applied directly on the girders, without any other structural element joining both elements.

Figure 1 Original location of Buna Bridge

3.2 Testing campaigns

3.2.1 Static Test

The first testing campaign was performed at IGH laboratory, in Croatia, aiming to determine maximum defections and stress under a train load (Load model 71) based on the Eurocode EN 1991-2. The testing set up can be observed in Figure 3, and the results can be found in [5].

Figure 2. Buna Bridge testing at IGH facilities.

3.2.2 Dynamic test

Two different dynamic test were performed on November 2016, carried out by the applicant and the department of Civil Engineering from Zagreb University. In the first one, the excitation was obtained by means of a shaker mounted both in vertical and transverse direction, as appreciated in Figure 4; whereas in the second one, ambient excitation was simulated by means of two hammers hitting randomly the structure. In both cases, the original bearings sustained the structure, although the rails and sleepers were not present. This decision was made due to the lack of fixation between the superstructure and the steel, which could have induced false modes on the analysis.

Figure 3. Shaker mounted in lateral direction for dynamic testing.

3.3 Performance indicators

Performance indicators for railway bridges differ from those used for road bridges in two main aspects: the type of load and the material. The former concerns not only the higher load traffic but also the dynamic effects trains involve. The latter refers to the common use of steel instead of concrete, consequently changing not only the material checks but also the construction details, such as weldings and bolted connections.

The most relevant performance indicators used in this project are classified in Table 2. They have been used to assess the condition of the bridge prior the rehabilitation, allowing tracing down the main problematic areas and therefore designing the strengthening accordingly.

Performance indicators derived from…			
Visual inspection	**Static testing**	**Dynamic Testing**	**FEM analysis**
Loosen bolts	Deflections	Modal frequencies	Deflections
Dented/ flatten surfaces	Strain	Damping	Stress
Steel corrosion	Weight distribution		Fatigue

Table 2. Performance indicators used to assess the condition of Buna Bridge.

The observations related to each one of the concepts are described herein:

3.3.1 Visual inspection

Since the bridge is no longer on its original location but in the laboratory facilities, visual inspection of every detail is more accessible. However, as the structure has been painted, corrosion on the steel is not possible to assess directly. A thorough examination of the pictures available from the moments prior the repainting was done, concluding that the bridge does not present a problem in regards this concept.

Furthermore, there is no buckling of the girders or the diagonals, all the surfaces presenting a flatten profile.

However, there is some concern in respect to the rivets, as in certain areas it seems that the plates are not completely connected. This hypothesis will be confirmed by the experiment results.

3.3.2 Testing and FEM analysis

The main objective for the experiments is to render parameters that can be contrasted with the desired values stated in the codes, in this case the Eurocode. Some criterions can be directly compared, such as deflections or maximum strains. However, in some cases a numerical model is necessary to stablish the thresholds and define the safety factors of the structure.

For the case of overall deflections and maximum stresses, it was shown that the structure did not suffer any damage. Nevertheless, a careful study was performed in terms of fatigue for the different details and connections.

3.4 Modal Update

Two Finite Element models were used in order to match the properties retrieved from the experiments. First, the program SAP200 was used in a simple model, where a sensitivity analysis was carried aiming to find the more influencing parameters for the model update. Eventually, a detailed model using shell elements was developed using SOFISTIK, where the final tuning was achieved.

Based on the results from the modal frequencies and visual inspection, several hypothesis were considered:

- Load transfer between both girders in lateral direction was not completely effective. This statement was based on the fact that each girder exhibited a different frequency for lateral modes.
- The riveted plates may not be acting as a single plate and therefore present a diminished stiffness.

This hypothesis was confirmed whit the FE model, as the ideal structure was stiffer than what the results showed. It was therefore necessary to introduce a reduced elastic modulus for several sections, in order to retrieve the actual condition of the bridge.

Table 3 presents a summary of the modes from both the experiment and the model, as well as a description of each of them. Furthermore, Figure 4 shows a visual comparison for mode number 1.

Mode number	Mode description	Remarks	Frequency (Hz)	
			Experiment	FEM
1	1st lateral mode	--	18.84	18.79
2	1st bending mode + 2nd lateral mode	One girder exhibits a more pronounced deflection than the other	24.21	27.00
3	1st lateral mode + 1st bending mode	One girder exhibits a more pronounced deflection than the other	27.09	27.12
4	1st bending mode		35.6	36.66
5	3rd lateral mode	--	61.95	60.89
6	Lateral local mode of all plates	--	97.01	97.43

Table 3. Modal results from dznamic test and FEM updated frequencies.

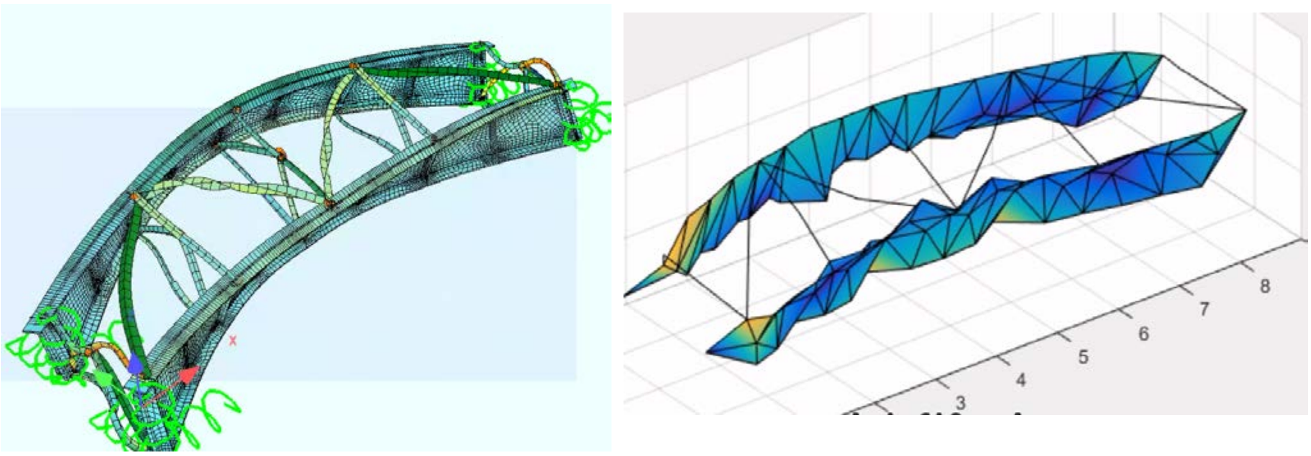

Figure 4. Mode number one, in SOFISTIK (left) and from the dynamic experiment (right).

3.5 Fatigue assessment

Fatigue response of steel bridges under variable amplitude and long life loading is well detailed in the literature [8], [3], and most codes include simplified estimations for this type of calculation. In this case the Eurocode procedure has been followed, although this norm does not include yet the specifications for existing structures, where certain coefficients and loads may be treated in a different manner. Since the application of these conditions is of particular importance in the case of rehabilitated structure and performance indicators, the Swiss normative (SIA 269) requirements are integrated, especially taking into consideration that the future Eurocode will be based on this regulation.

Particular attention is required at the riveted connections and the zones with higher stresses, consequently the values from the updated FE model are evaluated on those sections and the procedure is followed. For the particular case of the bolted connections in the middle of the bridge, the safety factor either does not comply with the norm or present a value close to the unit, as stated in Table 4, hence the strengthening solution will be focused on ameliorate this problem.

Section	Position	Description	Security factor
A-1	Bottom	Central plate (10mm), left girder	0.99
A-2	Bottom	Flange, left girder	1.07
B-1	Top	Central plate (10mm), right girder	1.02
B-2	Top	Flange, left girder	1.04

Table 4. Fatigue analysis and security factors

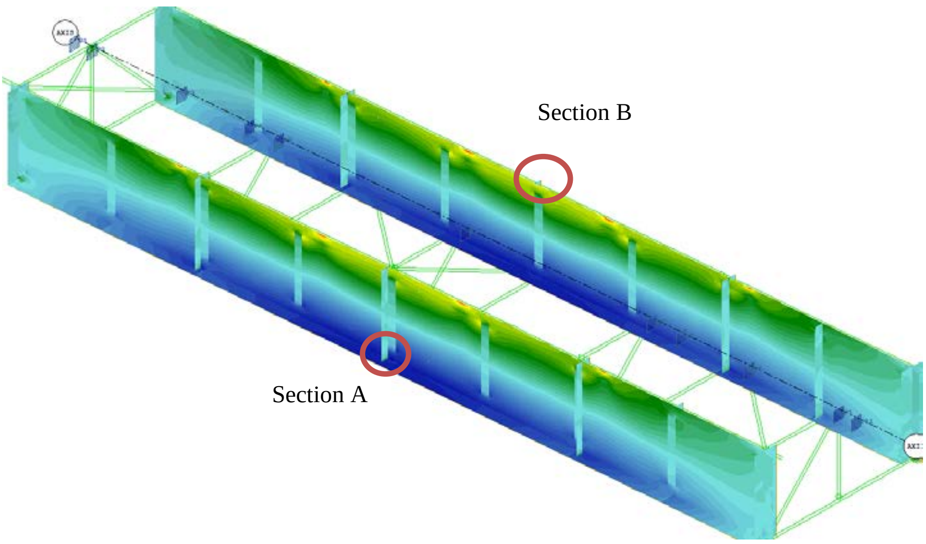

Figure 5. Most problematic sections for fatigue analysis.

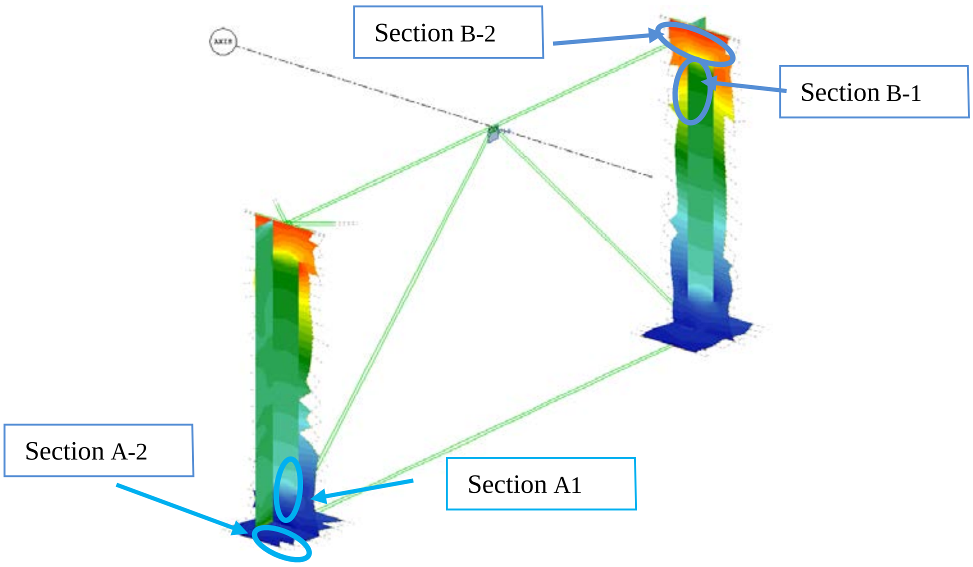

Figure 6. Sections for fatigue study

3.6 UHPRC mixes

One of the main goals of the project was to achieve a UHPFRC homemade product with comparable characteristics to a commercial one, aiming for a compressive strength of 150 MPa in compression. The most challenging aspect of this task is to reach the desirable strength without losing the workability of the material. In order to obtain the requested results, several aggregates, hyperplastifiers and fiber contents were tested, leading to the results described in Table 5.

Aggregate	Hyperplastifier	Sample Number	Density of fresh concrete (Kg/m3)	Compressive strength	Remarks
Hotič 0/4	Hiper 486	B 17245	2635	119.7	
Kmetov Špruh 0/4	Hiper 486	B 17256	2697	148.1	
"	Hiper 206	B 17277	2613	155.6	Low workability
"	Hiper 266	B 17278	2621	151.7	
"	Hiper 172 + 210	B 17279	2659	143.8	
"	Hiper 463	B 17283	2653	149.8	10 % less fibres
"	Hiper 172 + 210	B 17284	2656	150.2	10 % less fibres
"	Hiper 463	B 17296	2600	148.9	No steel wool

Table 5. UHPFRC Mixes and characteristic values.

3.7 Strengthening solution

3.7.1 Proposed design

The rehabilitation of the Buna bridge intends to ameliorate several problems that were observed during the previous testing and inspection, listed herein:

- fatigue on mid span and exceeding stresses at localized areas,
- uneven distribution of lateral loads between both girders, and
- lack of waterproof layer between the rails and the superstructure, allowing contaminated substances to directly fall on the river bed.

The proposed solution consist on a UHPFRC slab on top of the existing steel girders, connected by means of steel studs as in a conventional composite section concrete-steel. The depth of the section was reduced from the initial value of 120 mm proposed in [5] to 70 mm, thanks to the accurate model and the improved material properties. A detailed section can be observed in Figure 8.

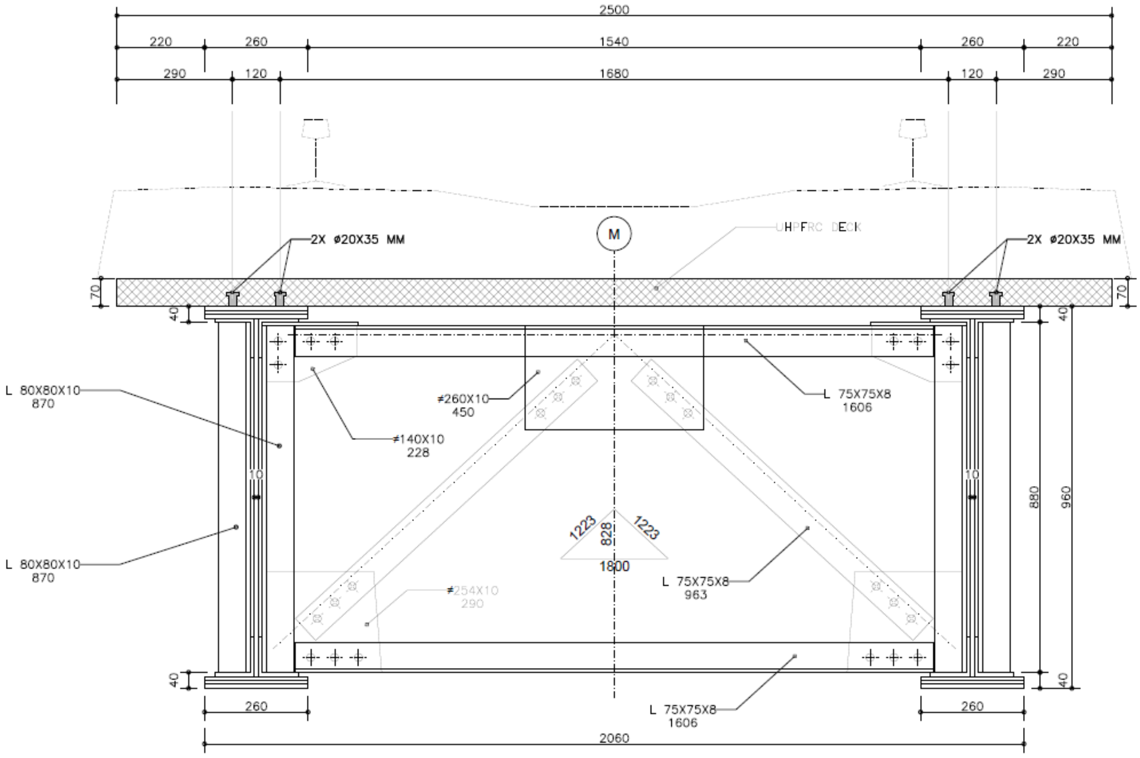

Figure 7. Typical section of the bridge after rehabilitation.

4 RESULTS

The proposed solution shows an improvement in all the desired areas, as detailed herein.

4.1 Fatigue

In order to study the feasibility of the suggested strengthening, a UHPFRC slab was added to the calibrated FE model. As expected, the slab receives the compression due to the bending moment and reduces considerably the compression on the top steel girder members. Furthermore, the neutral axis of the section moves to an upper position, and the tensile stresses are reduced. Thanks to these effects, the fatigue problem described in chapter 3.4 is solved, leading to the results depicted in Table 6.

Section		**Description**	**security factor**	**Improvement (%)**
A-1	Bottom	Central plate (10mm), left girder	1.08	7.67
A-2	Bottom	Flange, left girder	1.25	14.50
B-1	Top	Central plate (10mm), right girder	2.44	58.30
B-2	Top	Flange, left girder	2.82	63.30

Table 6. Fatigue assessment on rehabilitated bridge.

4.2 Stability

The slab permits the transfer of lateral loads and creates a stable structure. Both girders deform with the similar amplitude in transverse direction and deflections are significantly reduced, as demonstrated in Table 7. The results from the Finite Element analysis will be validated once the rehabilitation takes place and the bridge is tested.

Vertical deflection (mm)				**Transverse deflection (mm)**			
Initial structure		**Rehabilitated structure**		**Initial structure**		**Rehabilitated structure**	
Left girder	Right Girder	Left girder	Right Girder	Left girder	Right Girder	Left girder	Right Girder
8.87	8.23	6.1	5.34	14.8	13.7	6.5	5.9

Table 7. Displacements obtained from FE model, from the initial and strengthened structure.

4.3 Spillage prevention

UFPFRC has proven to act as a suitable waterproof layer in many projects, as shown in the literature [4], [6]. Its high density, low porosity and the micro-cracking render the material a reliable solution when sealing is needed. In this case, the benefit is twofold: On one hand, spillage of liquids or substances that may fall on the river is controlled. On the other hand, the steel structure is protected from corrosive agents that could deteriorate the bridge and lead to damage.

5 FUTURE MONITORING CAMPAIGN

In view of the results obtained from the testing and modelling, a testing campaign is designed, aiming to prove the numerical estimations. This campaign includes state of the art sensors, such as embedded Fiber Optic sensors inside the UHPFRC slab and Digital Image Correlation (DIC), as well as conventional strain gauges, LVDTs and accelerometers. The envisaged sensors, presented in Table 8, will be provided by the three institutions involved in the project (ETH Zurich, University of Zagreb and YAG Laboratory in Ljubljana).

Sensor type	Number	Provided by	Installation moment
Accelerometers +impedance head	15 +1	ETH/Zagreb	Dynamic test
Shaker	1	Zagreb	Dynamic test
Fiber optics	8	ETH	Casting
Strain gauges on Steel	18	ZAG	Static test
LVDTs on UHPFRC	30	ZAG	Static test
LVDTs for deflection	6	ZAG	Casting
Temperature	3	ZAG	Casting
Humidity	3	ZAG	Casting
SOFO	4	ZAG	Casting (after 2 days)
DIC	-	ZAG	Static test

Table 8. Envisioned sensors for the next project phase

6 DISSEMINATION AND FURTHER RESEARCH

Once the retrofitting is completed, particular attention should be placed on the UHPFRC-steel connection, as debonding failure may occur in this zone. The latter poses a challenge in terms of adequate simulation. For this reason, an experiment has been designed solely to study the shear behavior at the contact zone, as described in Figure 9. The main objective is to reach the capacity level indicated by the Eurocode, and to record possible deviations potentially towards or away from the side of safety, along with associated requirements in terms of service limit states. Signatures of a clear improvement on the capacity of the composite section is expected, which would comply with the extensive research performed currently on UHPFRC. The results of these works are expected to be published in a journal.

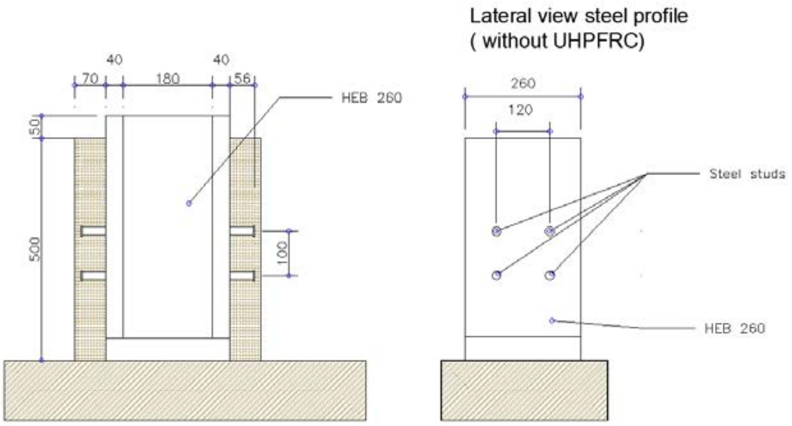

Figure 8. Example of specimen for a shear test, UHPFRC slab welded to a profile with the same dimensions as the bridge girder flange.

Furthermore, in regards to fatigue, a study with probabilistic counting damage estimation methods, following the approach described by Berglind [1], is in process, in order to compare results from both prior and after strengthening. The final results will be submitted to IALSCEE 2018, in the paper "Towards the use of UHPFRC in railway bridges: the rehabilitation of Buna bridge".

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