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# Experimental evaluation of the developed reinforcement system in FASSTBridge project

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ABSTRACT: One of the aims of Infravation FASSTbridge (Fast and effective Solution for the Strengthening of existing steel bridges) project is to develop a specific reinforcement system dedicated to the preventive fatigue reinforcement of steel bridges. The proposed system relies on the use of an adhesively bonded composite plate. The adhesive has been specifically formulated within the project to respect the required fulfillments of the studied application.
The communication will first give insight of the required properties of the adhesive, the composite plate, and the overall system. Based on these requirements and existing literature and standards on the topic, the chosen experimental plan will be described. It will concern investigations on the adhesive before curing, the adhesive after curing, the composite plate and the whole reinforcing system. Both short term and durability investigations are being considered. This experimental plan is currently carried out by the different partners implied within the projects and first results will be presented, especially regarding the properties of the adhesive and the composite plate and first results obtained on assembly.

## 1 INTRODUCTION

Steel bridges serve as vital components in the transportation infrastructure. Bridges are a frequent cause of the major negative impact in densely populated areas with regard to both users' convenience (such as service disturbances, disruptions, accessibility problems, delays, traffic jams) and welfare (such as obstacles to safety and security, nuisance from noise, vibration dust, and air pollution). Moreover, problems derived from their improper functionality are also cause of important impacts in the economic activities of the affected area (transportation, job accessibility, development strategies). In Europe 15% of the 300 000 bridges are made of steel or they have concrete-steel composite structures (Ye et al., 2014). Of this number, it is considered that approximately 68% need structural interventions. In the USA, 34% of the 599 000 bridges are made of steel. Of this number, approximately 9% are classified as structurally deficient, 15% are functionally obsolete and 9.5% are both structurally deficient and functionally obsolete (Lee, 2012). Many of these bridges were constructed using old standards and for a design service life of 50 years, which is coming to its end or has already been exceeded.

Fatigue is the second main cause of damage after corrosion for steel bridges, limiting their load-carrying capacity and residual life, and is one of the main causes involved in fatal mechanical failure of this kind of asset. The increase of traffic flows and loads in the last decades has a direct influence on this issue, especially on structures designed and erected many years ago for which fatigue was not taken into account during design (Palmer, 2014). Fatigue is a progressive and local weakening process in which structural damage is accumulated due to the continuous and repetitive application of external loads (vehicles and trucks in the case of steel bridges). The process of fatigue consists of three steps: crack initiation, crack propagation and failure. This phenomenon is extraordinarily dangerous and difficult to identify with a conventional structural stress analysis, which might lead to a misleading result of safety. In addition, there is no mean to measure fatigue damage on site before crack initiation. Damage can only be assessed using either fatigue design loading from the standards, or long-term on-site strain measurement (Kühn et al., 2008). The corresponding methods, that allow the determination of the remaining service life, can be based on the characteristics of the studied asset (deterministic methods) or in existing statistics (probabilistic). The latter require a considerable amount of data, which is still scarce. Therefore, deterministic methods are commonly used.

Currently, the mainstream strategy concerning fatigue has been a reactive strategy. Maintenance or repair indeed has mainly occurred after the appearance of cracks in the structure. With a bridge stock that is inevitably ageing, it is necessary to widely adopt a preventive strategy to enable road administrations to enlarge the service life of steel and composite steel bridges in a cost-effective and sustainable manner to avoid the high economic and environmental costs of following the current strategy in the years to come. The prevention of fatigue is thus a high priority. To provide such a strategy, it is essential to seek an easy-to-apply solution which includes an engineering analysis methodology for assessing the fatigue damage status and the application of fast, cost-effective and sustainable retrofitting strengthening techniques that enable the wide adoption of the preventive approach, avoiding difficult, resource-consuming and costly retrofitting and repair interventions and demolitions of the steel and composite steel bridges stock.

Once fatigue damage has been identified, normally by visual inspection for crack detection, various methods are frequently used to strengthen steel bridges. The most popular among engineers is the attachment of steel plates to the tension flange of the girders (FHWA, 2013) (Fig.1). However, this method has several disadvantages: plates are usually bulky, heavy, difficult to fix and prone to corrosion and fatigue. In general, conventional strengthening techniques are labor-intensive and disruptive to traffic flows, thus limiting their application in the wide network of European and American steel bridges. Carbon Fibre Reinforced Polymers (CFRP) composites, although more expensive than steel plates in terms of price per unit/$m^2$, have several and relevant advantages that make them suitable and cost effective for steel bridges retrofitting: their application is less time consuming than traditional solutions (i.e. from one month to a few days, therefore less traffic disruptive), have a high strength-to-weight ratio, excellent fatigue properties, low space disruption, high durability and versatility, and are easy to transport, handle and apply (without heavy equipment) (Tavakkolizadeh et al., 2003; Bocciarelli, 2009;  (Figure 1). Despite their wide application on indoor concrete structures, where CFRP is progressively replacing the traditional techniques, CFRP has not been broadly used for steel structures yet, especially in bridges. The main technical barrier for the adoption of CFPR is the durability of existing commercial adhesives in outdoor environments, which is still limited for this kind of interventions, where high functional periods with minimum maintenance are expected. When exposed to outdoor environments and fatigue conditions, in order to ensure cost-effective and durable strengthening interventions, high quality adhesives are necessary

(Zhao, 2014).
These different statements motivated the proposal to the ERA-Net European Resarch call Infravation of the project called FASSTbridge (FASt and effective solution for STeel bridges life-time extension). The project is coordinated by the Spanish research centre Tecnalia, and implies the contribution of two expertise and research organisms (IFSTTAR from France, and MPA Stuttgart from Germany), one Italian company specialized in polymer formulation and production Collanti, two engineering offices (LAP-Consult from Germany and Altavista from United States), the Spanish international building company Dragados SA and a public owner: the Community of Madrid. The project started on November 2015 and has duration of 30 months.

This paper will first describe main objectives of the project, and will then focus on the issue of the development of an adapted strengthening system. This system is currently being experimentally assessed and first results will be given.

Figure 1. Photo of a repair using additional bolted steel plate on the left (FHWA, 2013), and adhesively bonded CFRP on the right (On site application in France)

## 2 OBJECTIVES OF FASSTBRIDGE PROJECT

FASSTbridge aims at drastically reduce the economic and environmental costs of ownership of the steel bridges stock in Europe and the USA by providing a reliable preventive, cost-effective and sustainable solution for steel bridges life-time extension. The preventive nature of the solution is the key to cost-effectiveness and sustainability, since it will allow the timely design and implementation of innovative, competitive CFRP-based strengthening actions that will reduce the overall costs and environmental impact of life-time extension.

This solution will stand on two pillars. The first will be dedicated to the proposal of a FASSTbridge methodology to prevent the evolution of irreversible fatigue derived problems at a pre-cracking scenario. The second will concern the development of a FASSTbridge strengthening system to preventively extend life-time of steel bridges.

### *2.1 FASSTBridge metholodology*

The methodology will address the development and validation of a preventive and easy-to-apply procedure to assess the remaining life of steel bridges. Such a procedure should be in agreement with existing methods presented in (AASHTO, 2012; Kühn et al., 2008), and should propose a clear strategy between the classical nominal stress method and the local stress approach. It should also be supported by indicators from non-destructive or monitoring methods.

If insufficient remaining service life is determined, a proposal will then be made regarding the design and the application of adhesively bonded composite reinforcement for fatigue strengthening operations. This will be based on existing guidelines and previous investigations (CNR, 2007; DNV, 2012; Schnerch et al., 2007; Cadei et al., 2004).

The methodology will also include a strategy regarding the maintenance of the strengthening, and the monitoring to verify the efficiency of the structural reinforcement and to contribute to databases for the assessment of steel bridges in fatigue.

### *2.2 FASSTBridge strengthening system*

The proposed strengthening system will rely on the development of a specific adhesive for the considered application. The adhesive should be durable and allow a correct force transfer between CFRP plate and steel adherend. It should also have good rheological performance before curing to allow an easy on site application. The obtained mechanical properties of the cured adhesive should be durable and in agreement with existing standards. Associated to this adhesive, a commercial CFRP plate will be chosen according to the requested technical and economical properties needed for the project.

The compatibility of both parts (adhesive and CFRP plate) will be verified through different tests on the assembly and under different environmental conditions relevant with the design codes recommendations (AASHTO, 1989; EN1990, 2002; EN 1991, 2003). The experiments will also check the compatibility of different monitoring devices with the assembly. The led experimental investigations will be followed by the definition of a pre-certification plan for the studied system.

### *2.3 FASSTBridge solution*

In addition to the assessment tools and strengthening system, the FASSTbridge solution will be completed with a method to evaluate the effectiveness and efficiency of the interventions based on cost-benefit analysis and life cycle analysis.
An on-site application will be carried out at the end of the project to demonstrate the applicability of the complete solution. This will be done on a composite steel/concrete bridge from the community of Madrid. It will include the application of complete methodology (determination of the remaining life-time, design of the reinforcement, cost-benefit and life-cycle analyses, application of the reinforcement and monitoring on site) (Figure 2).

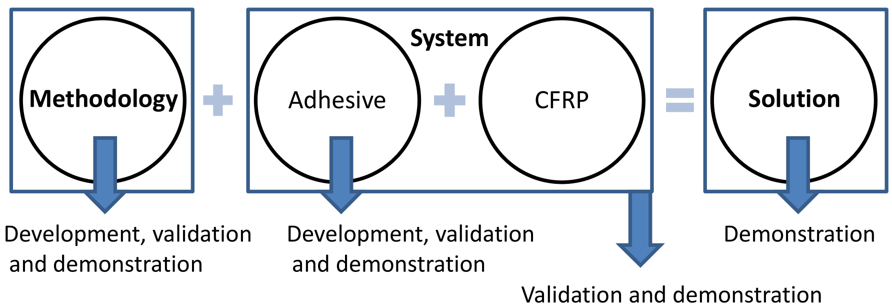


Figure 2. Scheme of the objectives of FASSTbridge project

## 3 DEVELOPMENT OF THE STRENGTHENING SYSTEM

FASSTbridge project's strengthening system relies on the formulation of a new adhesive in regards with constraints encountered on steel bridges and the use of an adapted composite plate. Both materials must be compatible and the final system should comply with the requirements of civil engineering steel structures.

### *3.1 Choice of the composite plate*

The project being focused on the use of adhesively bonded composite reinforcement, preliminary investigations proved that two main options could be investigated for the definition of the strengthening system to obtain cost-effective solutions (Ghafoori et al., 2015): either the use of ultra-high modulus reinforcement or the use of prestressed composite. Due to concerns regarding creep of the adhesive (Houhou et al., 2014), it was decided to choose a strengthening system based on the use of ultra-high modulus composite. Epsilon composite decided to support the project providing 460 GPa carbon fiber reinforced polymer. Such a composite material has already been used in other studies dedicated to the reinforcement of cracked elements (Lepretre et al., 2016).

### *3.2 Development of the adhesive*

Extensive literature review was carried out in order to define the adhesive and the system specifications. Main additional constraints in regard with applications on concrete structures are related to the temperature service range that was assessed to be between -35°C to 56 °C according to North American and European guidelines. This implies the use of an adhesive with a glass transition temperature superior to this value. The glass transition should be measured on samples cured in on site conditions and with Differential Scanning Calorimetry method (Michels et al., 2015). It was decided to adopt 15°C safety margin in agreement with existing recommendations (the glass transition temperature of the adhesive must then be superior to 71°C).

The adhesive has been developed by Collanti accordingly through a trial and error method. It is a two-component cold-curing epoxy-polyurethane that needs post-curing (1 hour at 80°C) to raise glass transition temperature above the required value. The results obtained on the final formulation in terms of glass transition before and after post-curing are given in Table 1. It can be checked that the measurement method has a strong impact on the result and that the formulated adhesive reaches the required glass transition temperature value after post-curing.

Table 1. Results of glass transition measures

| Sample | Glass transition temperature (*measured by DSC*) | Glass transition temperature (*measured by DMA*) |
|---|---|---|
| Resin before post-curing | 49°C | 60°C |
| Resin after post-curing | 72°C | 80°C |

### *3.3 First investigations on the assembly*

Preliminary mechanical investigations have been realized on the assembly to check the compatibility of the adhesive and the CFRP plate and to assess the reached ultimate stresses in different configurations. The presented investigations have been realized with the final resin but with a different catalyst than the one that will be finally used. The obtained results may then slightly evolve due to the recent change in the catalyst.

It was chosen to adopt three different mechanical test configurations as described in figure 3: a double lap shear test commonly used to characterize shear transfer, a flexure test, and a double strap test as proposed in (DNV, 2012). The samples were prepared in laboratory: sanding of steel surfaces, removing of the peel ply of the 45 mm-wide CFRP, degreasing, application of the adhesive on steel surface, squeezing of the resin in excess, realization of adhesive spew fillet. The samples have then been post-cured with the process described in previous paragraph. For each configuration, three tests have been realized at the speed advised in (DNV, 2012): 0.5 mm/min.

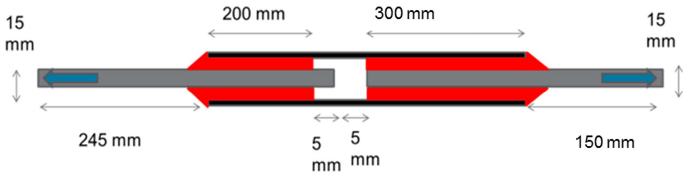


Figure 3. Scheme of the double lap shear test

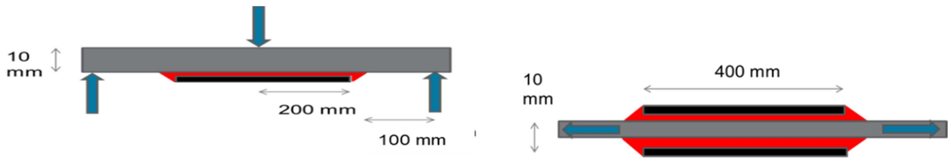


Figure 4. Scheme of the flexure test and the double strap test (from left to right)

All the tested samples failed in cohesive manner in the adhesive. The results in terms of ultimate capacity, dispersion and ultimate CFRP strain (measured by resistive strain gages) are given in Table 2. It can be checked that all the tests proved to have good repeatability (around 5%). In addition, it is important to note that the obtained ultimate strains are well above the required strain in the case of old steel structures. This may indicate that the proposed system is suitable for our application.

Table 2. First experimental results on assembly

| | Double lap shear test | Double strap test | Flexure test |
|---|---|---|---|
| Average ultimate capacity, in kN | 119,6 | 214,3 | 5,1 |
| Standard deviation, in kN | 5,7 | 2,1 | 0,3 |
| Dispersion, in % | 4,7% | 1,0% | 5,4% |
| Ultimate CFRP strain, in microstrain | 1204 | 1670 | 962 |

## 4 CONCLUSIONS

Main issues of FASSTBridge project have been presented in this article. It aims not only at proposing a preventive strengthening system for steel bridges based on the use of composite materials, but also a complete methodology including evaluation of remaining fatigue life, design, application, maintenance and monitoring of the strengthening system and environment and cost analysis of the proposed solution at the service life scale. The presented results concern the choice of the reinforcement system.

It was chosen to propose an adhesively bonded composite reinforcement system with ultra-high modulus CFRP plates with the support of Epsilon Composite to obtain a cost-effective solution.

After the definition of the required properties for the adhesive and the whole system, and after several trials, an adhesive has been formulated by Collanti. It is a cold-curing two component epoxy-polyurethane resin that requires post-curing to reach the desired glass transition temperature. Preliminary mechanical investigations allowed checking the properties of the system in terms of failure mode, repeatability, and ultimate strain in CFRP plate. Yet, these tests must be carried out again as the catalyst has been slightly modified. Additional double lap shear tests will also be done to study the influence of different application parameters. The results will then be exploited in terms of cohesive zone model as described in (Chataigner et al., 2011).

An extensive review has been made regarding durability of such solution (Linghoff et al., 2009; Zhao et al., 2007; Dawood et al., 2010; Benzarti et al., 2011; Chataigner et al., 2012; Hesmati et al., 2015;). Based on these results, it was decided to build an experimental plan to assess the durability of the proposed system. The experimental campaign will be based on recommendations from (Ascione et al., 2016) and (EOTA, 2012) and is currently under progress.

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