Proyecto FASSTBRIDGE. Refuerzo preventivo frente a fatiga de estructuras de acero con fibra de carbono.

FASSTBRIGDE Project. Preventive fatigue strengthening of Steel structures with adhesively bonded CFRPs – Efficiency demonstration on Jarama bridge.

Luis Sopeña Corvinos [a], Elena Martín Díaz [b], Mazen Wahbeh [c], David Garcia-Sanchez [d], Sylvain Chataigner [e], Michael Fischer [f]

[a] PE MSc Civil Engineering. Senior Structural Engineer. gGravity Engineering. lsopenac@ggravityeng.com

[b] Ingeniera de Caminos, Canales y Puertos. R&D Department. Dragados S.A. emartind@dragados.com

[c] PhD PE MSc Civil Engineering. Executive Chairman. Alta Vista Solutions. mwahbeh@altavistasolutions.com

[d] PhD MSc Civil Engineering. Senior Researcher. TECNALIA. david.garciasanchez@tecnalia.com

[e] PhD MSc Civil Engineering. Senior Researcher. IFSTTAR. sylvain.chataigner@ifsttar.fr

[f] ppa. Dipl.-Ing. Senior Structural Engineer. Leonhardt, Andrä und Partner. michael.fischer@lap-consult.com

RESUMEN

FASSTBRIDGE, un proyecto perteneciente a INFRAVATION ERA-NET Plus, con objeto de desarrollar una metodología sólida y completa incluyendo un nuevo método de cálculo de la vida útil remanente de un puente de acero considerando la fatiga, una metodología de diseño del refuerzo necesario, y un sistema de refuerzo basado en fibras CFRP adheridas al acero. Algunas innovaciones relevantes fueron desarrolladas para el proyecto FASSTbridge, dando como resultado una solución integral, completa y competitiva que abarca el proceso completo, consiguiendo una estrategia de extensión de la vida útil de puentes de acero sostenible y eficiente económicamente. Todo el sistema fue aplicado a un puente en España para verificar su adecuación y comportamiento.

ABSTRACT

FASSTBRIDGE project, an INFRAVATION ERA-NET Plus project, aimed at developing a complete and solid methodology including a new calculation method for assessing the remaining life of steel bridge due to fatigue, a designing methodology for the strengthening intervention, and a strengthening system based on adhesively bonded CFRP. Some relevant innovations where developed for FASSTbridge, resulting in an integral, complete and competitive solution which embraces the whole process, achieving a sustainable and cost-effective preventive strategy for life time extension of steel bridges. The whole concept was applied on a steel bridge in Spain to verify its adequacy and performance.

PALABRAS CLAVE: acero estructural, fatiga, fibra de carbono, adhesivo, refuerzo preventivo.
KEYWORDS: steel structures, fatigue, adhesively bonded CFRP, preventive reinforcement.

1. Introduction

FASSTbridge methodology is an evolution of the existing probabilistic and deterministic methods. It means an advance from the analysis based on the standard load model to the more precise load approaches getting an easy assessment with satisfactory accuracy level facilitating a real preventive assessment of existing steel bridge. The innovation of FASSTbridge is to provide an integral and complete solution which embraces the whole process, from the assessment of possible fatigue damage to the maintenance of the applied strengthening system to achieve a sustainable and cost-effective preventive strategy for life time extension of steel bridges.

2. Development of the project.

Up to date, very few research and real case applications of CFRP retrofitting in civil work structures has been accomplished. FFASTbridge is aimed to develop a cost-effective and easy to apply solution. First analysis showed that, in order to achieve an effective reduction in stress that would have a significant positive impact in fatigue behavior and extend the service life of the structure, standard CFRP plates had not the enough capacity. Two main alternatives were investigated, pre-tensioned CFRP plates solutions, and UHM (Ultra High Modulus) CFRP plates. The first one, with standard CFRP plates, implied a more complex installation of the retrofit, and also some additional cost as well as higher risk of affection to traffic. In addition, anchorage points have shown to be a weak point in this type of systems. On the other hand, UHM CFRP plates are more expensive and complex to acquire, but the installation is as simple as for the standard plates. Structural wise, UHM CFRP plates solution demonstrated to have the required structural properties, mainly strength and stiffness, to be suitable for the purpose of the project.

3. Structure for the application. Description and inspection.

Jarama Bridge (Figure 1) is located near the city of Madrid in Spain over Jarama river on road M-111 (Ch 5+0). It was designed in 1962 (Design Code 1956) and erected around 1965.

Figure 1. General view, Jarama Bridge

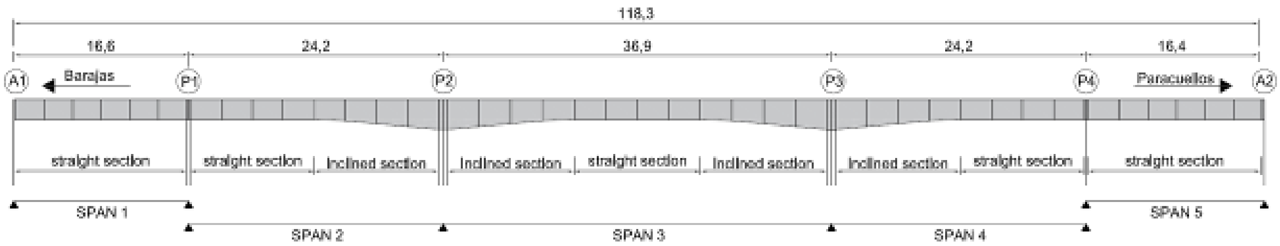


Figure 2: Jarama Bridge Elevation

The three central spans form a continuous beam, while the lateral spans are simply supported separated by a joint, resulting the following span distributions: 16.6 m – 24.2 m – 36.9 m -24.2 m – 16.95 m. The total length is 118.30 m (see Figure 2). The main structure is made with structural steel whereas the top slap is reinforced concrete with a width of 9.20 m. The whole structure is welded (see details in Figures 3 and 4). The cross-section consists of two I-beams, which are connected by transversal cross-bracings to stiffen the bridge in transversal direction.

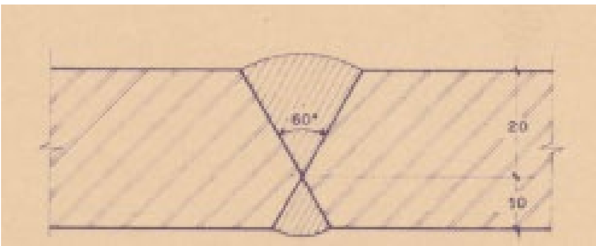


Figure 3. Flange weld detail, Jarama Bridge

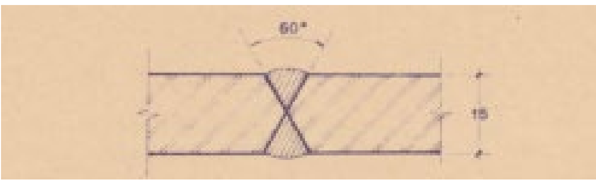


Figure 4. Web weld detail, Jarama Bridge

Also a detailed inspection of the structure was carried out to determine its adequacy for the demonstration. As one of the principals of the project is a preventive intervention, the structure for the demonstration must not have already developed fatigue damages and must be in good condition for the retrofit.

The steel-elements in Jarama-Bridge were generally in a good condition. Still, there was moisture, moss, corrosion and some other local and punctual deficiencies detectable. On the top flange of the main girders there was general corrosion notable. In some cases the corrosion already progressed into the web plates. In some other cases, efflorescence and pealing problems have been noted. The same deficiencies were also present on the bottom flange. Crosses or x-bracing seem in good condition and no visual defect has been noted. Nevertheless, bottom lateral bracing members of span 1 show important distortion, corrosion and some other defects probably caused by object impact. One angle in bottom lateral bracing member of span 5 presented small deformation also.

The floor beams were in a good condition. Moisture, efflorescence and corrosion on the top flange have been noted locally. Some areas of peeled coating can be seen in the bottom flange. Larger areas affected by moisture and corrosion are located in floor beams over piers and abutments.

4. Weld selection for the intervention.

There were two types of butt welds occurring in the main girders: welded on site and welded in shop. In the framework of the second bridge-inspection in 2017, 4 out of 8 welds of the first type (on-site-welds) have been analyzed. Beside visual inspection works, ultrasonic tests were carried out. The result of these investigations was, that the selected welds do not fulfil quality standards according to level B UNE EN ISO 5817:2014 neither AL2 UNE EN ISO 11666:2011. From the 27 welds of the second type (in-shop-welds) that were analyzed, 11 do not fulfil the quality standards (under AL2 UNE EN ISO 11666:2011).

In order to meet project budget, also accessibility and installation cost must be taken into account. Main span over the river may be the most interesting from a structural point of view, but resulted to be too expensive for the demonstration of the project.

Focused was then set on side spans of the continuous structure, being finally selected span number 2 (Barajas side, see Figure 5).

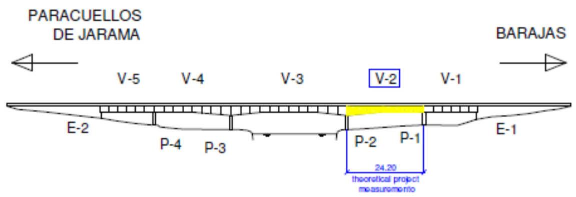


Figure 5: Span 2 selected for the intervention.

On each beam, onsite welds and 1 workshop weld did not full-fill weld inspection requirements. Among the rest of the welds, 3 of each beam were selected, taking into account also geometry and location (structural solicitations), trying to keep some simetry between the two beams.

In order to obtain as much information as possible from the demonstration, it was decided to apply three different plate layer arrangements: 1 layer, 2 layer and 3 layer arrangement.

5. Theoretical calculations and design of intervention.

To evaluate the strengthening action of CFRP laminates on the butt welds of span 2 (first span of the continuous beam), a 3D-shell-model is created in FEM-Program (Figures 6 and 7). Therefore, both of the main girders are modelled as composed shell elements. The deck slab carries out the connection between both of the girders. For the modelling, the slab induces no loadings into the system and the stiffness in longitudinal direction was set to zero. It is there to guarantee a realistic load distribution on both of the girders.

The stiffness in transversal direction is achieved in reality by cross-bracings. In order to simplify the model, these cross-bracings are idealised by bearings fixed in y-direction.

To represent the welds, the height of the bottom flange was reduced on a small segment with a width of 1-2 cm. By correlating these small segments with different group numbers, it is possible to get precise results on the stresses with and without strengthening action.

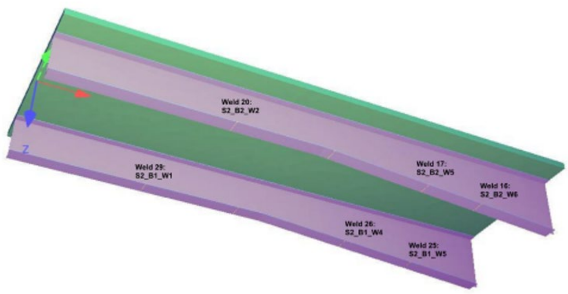
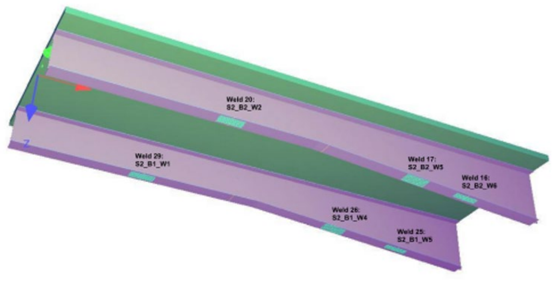


Figure 6: Case 0- Un-strengthened System (for comparison).



For the six welds loaded with tensile stresses, the reduction of Δσ was derived. As expected, there is a reduction of Δσ due to the amount of laminates and layers. The more laminates next to each other are applied, the higher is the reduction of the stress variation range. The same occurs with more layers of laminates.

While with the option "4 plates / 2 layers" per weld a reduction of Δσ about 8 - 15 % can be achieved, the reduction of Δσfat when using option "5 plates / 1 layer" is 4 – 7 % and with option "3 plates / 3 layers" a reduction of 21 – 22 % can be achieved. It is to be taken into account that the position of the welds on the beam 1 is not fully symmetrical to beam 2. This leads to the different percentage range of the reduction.

Fatigue resistance and Design Life Time of the un-strengthened system

The fatigue resistance for the un-strengthened system may be estimated by using the regulations of Eurocode DIN EN 1993-1-9, 7.1(3).

The un-strengthened system is sufficiently resistant against fatigue damage. Therefore, FASSTbridge methodology for undamaged steel details may be applied.

The estimation of remaining fatigue lifetime is done according to the regulation of Eurocode EN 1993-1-9 7.1(3).

Increase of life time due to strengthening action

The estimation of remaining fatigue lifetime for the strengthened system (Table 1) is done according to the regulation of Eurocode EN 1993-1-9 7.1(3).

Weld No.	Weld code	$\Delta\sigma_{E2}$	$\Delta\sigma_C/\gamma_C$	N_R	Increase
		[N/mm²]	[N/mm²]	[10^6]	compared to case 0
29	B1 - W1	25,72	86,39	75,80	31%
26	B1 - W4	25,21	86,39	80,47	13%
25	B1 - W5	12,83	86,39	610,03	113%
20	B2 - W2	30,62	86,39	44,93	64%
17	B2 - W5	22,30	86,39	116,25	26%
16	B2 - W6	13,08	86,39	575,84	105%

Table 1: Remaining fatigue lifetime of the strengthened system

6. Implementation of the retrofit

6.1 Preparation of CFRP plates

The Carbon Fibre Reinforced Polymer was Ultra-high modulus CFRP (460 000 N/mm2, 66 700 ksi).

The CFRP plates were cut to the required length and their ends detailed as specified by the designer prior to the preparation of the surfaces for bonding.

Yet, as resin may be difficult to apply in bigger thickness than 1 mm, it was proposed to adopt the alternative edge detailing (figure 8). The angle was around 30° aprox.

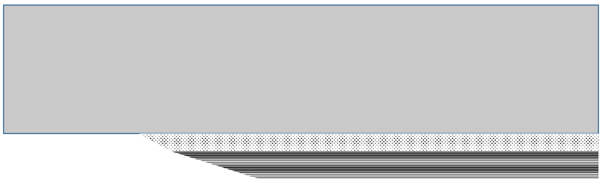


Figure 8: Alternative proposed detailing

In addition, when several layers of CFRP reinforcement were considered, the adhesive bonding of the CFRP layers was done at the workshop (Figure 9) before being delivered on site (this would minimize the time and the number of operations on site).

Figure 9: CFRP preparation

6.2 Steel surface preparation

In FASSTbridge solution, no primer is needed provided the adhesive application is sufficiently rapid after steel surface preparation. A control of the surface preparation quality was done before application of the adhesive. The level of surface preparation Sa was determined using NF EN ISO 8501-1 (a minimum value of 2.5 is required). Roughness was controlled using NF EN ISO 8503-2. Surface cleanliness was also assessed using NF EN ISO 8502-3.

6.3 Adhesive mix and application

The adhesive used is a hybrid two component epoxy-polyurethane adhesive (Urepox Extra 2C) with the following specifications: (1) Pot life 30-45 minutes (workability); (2) Tg> 71ºC after post-curing; (3) Tensile strength ≥35 MPa, 5.1 ksi. This adhesive was developed specifically for this project, and the parameter that governed the mix design was the Tg. At the end, the only way of achieving the target Tg (fixed at the beginning of the project), it was necessary to introduce a post-curing at high temperatures, 1 hour at 80ºC controlled constant temperature. Implementing this post-curing process on site was challenging regarding installation and schedule.

Once all the surfaces were prepared, the adhesive was mixed, applied to the bonding surfaces and the CFRP plates clamped within the pot-life of the adhesive.

Figure 10: CFRP preparation.

In this case the adhesive mix was applied directly to the surface of the CFRP plate. The final thickness of the adhesive layer was within the guidelines established by the designer. In general, the target thickness for metal and FRP joints should be 0.5-2.0 mm. To spread the adhesive uniformly, recommend using a trowel with a v-notch (Figures 10 and 11).

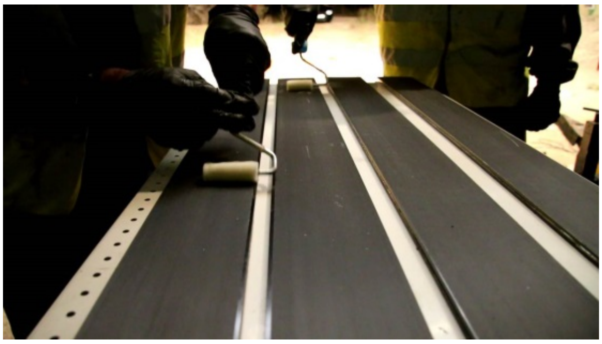


Figure 11: CFRP preparation.

It was also taken into account the environment temperature at the time of the application of the adhesive.

The application was carried out on CFRP surface, then pressure on the CFRP to the steel surface was done and a roller was used to apply it along the reinforcement.

6.4 Installation of the CFRP strengthening system

It is easy to understand, that some temporary device may be used such as clamps for instance. The pot life is assessed to be around 25 to 45 minutes. The time between the application and the application of heat was also assessed using viscosity measurements.

After application, a strong care was needed for the removal of the excessive resin both on sides and extremities of the joint. The resin edges should be at around 45° to obtain smooth stress transitions in the adhesive layer.

6.5 Post-curing

Post curing is the process of exposing a part or mold to elevated temperatures to speed up the curing process and to maximize some of the material's physical properties (from 80% to 100% of adhesive properties), specially Tg temperature.

Post curing will expedite the cross-linking process and properly align the molecules of polymer. Much like tempering steel, post curing thermosets can increase physical properties (e.g., tensile strength, flexural strength, and heat distortion temperature) above what the material would normally achieve at room temperature. Post curing is extremely important if hundred percent of capability of retrofit is needed, regarding Tg temperature.

It is necessary to measure temperature on top of the reinforcement, and to limit in any case the maximum temperature to the glass transition temperature of the CFRP plate itself.

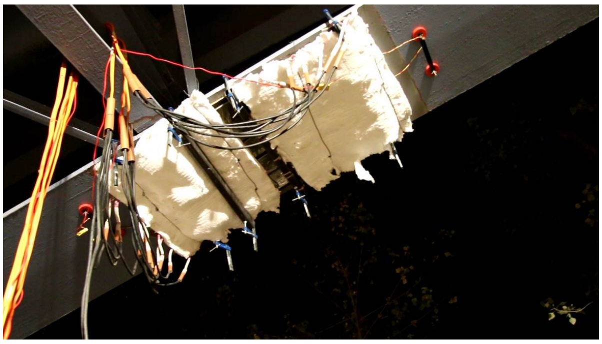


Figure 12: Heating procedure for post-curing.

During Jarama Bridge retrofitting it was mandatory to control the rate of temperature increase so that the post-curing temperature may be reached: (1) 30 min to 1 h; (2) Tpost-cure= 80ºC. The heating system was formed by ceramic pad units, isolating blankets, and a fixing structure (Figure 12). Other heating systems could be used, applied or developed for this purpose.

6.6 Fixed Load test

FASSTbridge team considered it would be useful to obtain a status of Jarama bridge considering controlled or "fixed load" condition. This fixed load condition will allow, measuring strains before retrofitting the bridge and after retrofitting, demonstrating the effectiveness of the CFRP retrofits.
Tests took place during two nights, from 23.00 to 06.00 (before and after the retrofitting) in September 29th 2017 and October 10th 2017. We proceed to make the test, first the static load, three positions, and then those of dynamic load, two positions (two examples in Figures 13 and 14).

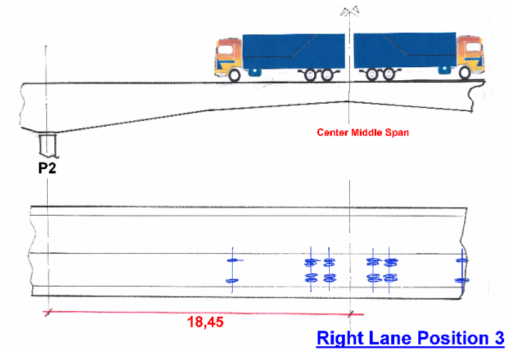


Figure 13: Position 3 in Right Lane for static test.

Static test was performed by placing the trucks in its positions, and after leaving stabilized the load, make the measurements of strains.

Dynamic test was performed by placing a wooden plank, 4 cm in height, in the selected position, and driving above it to a single truck at a speed of 20 km/h and 50 km/h, the passage of the truck hitting the plank, induces a dynamic impact load in the structure, during which there are measurements of strains.

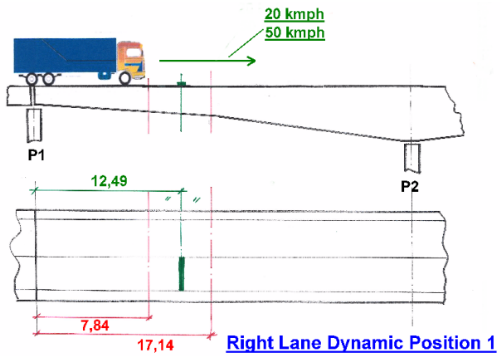


Figure 14: Position 1 in Right Lane for Dynamic test.

7. Main results and conclusions.

The fixed load test described above, before and after the intervention, and the monitoring system installed at each retrofitted weld (see Figure 15), enabled to develop a comparison with sufficient detail and accuracy so the results can be considered trustfull.

In general, it is interesting to highlight the strain reduction in monitored sections included in Table 2 and figure 16.

The final results allow FASSTbridge partners to be optimistic, although deeper analysis and case-studies should be performed.

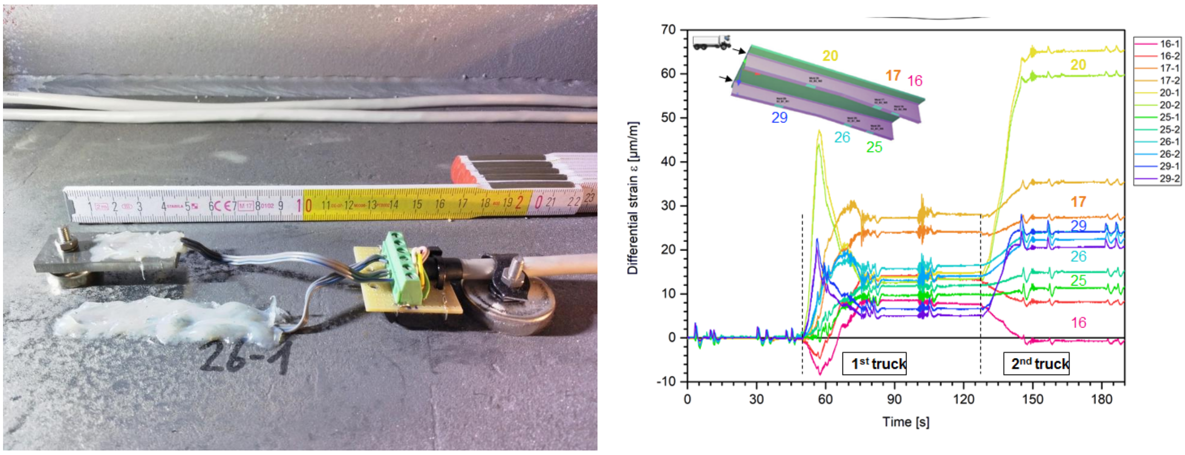


Figure 15: Strain gauges installed for monitoring and data acquisition during test performance.

Sensor	Laminates	Static before	Static after	Difference	Dynamic before	Dynamic after	Difference
16-1	3 x 3 (9)	71 με	56 με	- 21 %	60 με	45 με	- 25 %
17-1	1 x 5 (5)	68 με	56 με	- 18 %	75 με	62 με	- 17 %
20-1	2 x 4 (8)	84 με	59 με	- 30 %	80 με	56 με	- 30 %
25-1	3 x 3 (9)	69 με	51 με	- 26 %	65 με	53 με	- 18 %
26-1	1 x 5 (5)	84 με	67 με	- 20 %	84 με	77 με	- 8 %
29-1	2 x 4 (8)	77 με	58 με	- 25 %	71 με	51 με	- 28 %

Table 2: Strain reduction above retrofitted sections.

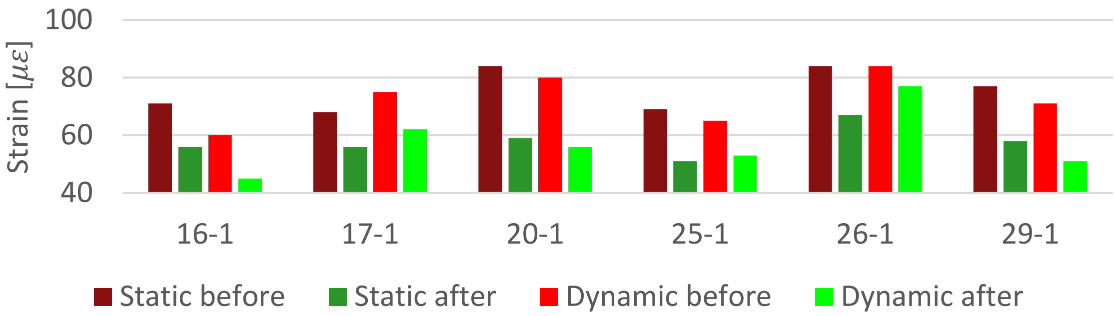


Figure 16: Strain reduction above retrofitted sections (before and after intervention).

Some conclusions after the implementation of FASSTbridge methodology and strengthening design in Jarama Bridge can be summarized as follows:

The Fatigue Assessment Tool is useful for defining technical and economical properties of the optimum CFRP plates and for the assessment of existing commercial products, it assess about remaining fatigue life of aging steel bridges using AASHTO and Eurocode and it can be used by bridge owners for asset management and to prioritize repairs.

Regarding design, the project was successful at developing a strengthening methodology to increase the calculated life time with CFRP. This methodology (Diagnosis, Safety Evaluation, Intervention) has been tested at Jarama Bridge. Some different CFRP configurations have been tested accordant to the geometry. The decrease of stresses and strains in bottom flange after retrofitting has been demonstrated. Therefore, the increase of life time of considered welds with CFRP has been demonstrated.

About the adhesive, during the project a new adhesive was developed successfully achieving the requirements of strength, Tg temperature and pot life established at the beginning of the project.

Finally, demonstration of the system, Jarama Bridge Retrofit, the system was successfully demonstrated at 6 locations utilizing light equipment, short time installation and low affection to traffic, with an average reduction of strain/stress of 22 %.

As a summary, the project was successful at developing a preventive, reliable, easy-to-apply and cost effective procedure and solution.

Also, some improvement areas have been detected, for possible future developments of the system:

Adhesive viscosity and pot life. During application of the adhesive, some difficulties were found related to its viscosity along time. POT life was not an issue, instead viscosity during installation was. A system were the adhesive is injected once the plates are in place could be investigated and found interesting.

Post-curing. Tg temperature for the adhesive of 71 ºC, fixed at the beginning of the project, as a result of 56 ºC some codes apply to structural steel plus 15 ºC margin, at the end resulted too conditioning for the adhesive, forcing to a post-curing process at the end of the installation which endangers some of the targets of the project such as easy-to-apply and cost-effective. Reducing the Tg required or developing an adhesive that does not require post-curing could be the answer.

Traffic over structure. As a first approach, it was established that application should be done with no traffic over the structure, in order to avoid vibration which could affect the bond between steel and CFRP plates. This implies night installation and traffic disruption. During the installation, one of the welds had to be retrofitted before traffic closure, which at the end did not have negative effects on the results. This also could be further investigated to establish in which cases (type of decks, type of traffic, intensity of traffic,…) the system can be applied without affecting traffic over the structure, which would end in many benefits in terms of cost of installation, schedule and traffic disruption.

Necessity of UHM CFRP plates. This endangers one of the targets of the project, cost-effective. A system able to achieve similar results in terms of strain reduction using standard

CFRP plates would be a significant improvement.

Acknowledgments

This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 31109806.0008.

FASSTbridge is co-funded by Funding Partners of the ERA-NET Plus Infravation and the European Commission. The Funding Partners of the Infravation 2014 Call are: MINISTERIE VAN INFRASTRUCTUUR EN MILIEU, RIJKSWATERSTAAT, BUNDESMINISTERIUM FÜR VERKEHR, BAU UND STADTENTWICKLUNG, DANISH ROAD DIRECTORATE, STATENS VEGVESEN VEGDIREKTORATET, TRAFIKVERKET – TRV, VEGAGERÐIN, MINISTERE DE L'ECOLOGIE, DU DEVELOPPEMENT DURABLE ET DE L'ENERGIE, CENTRO PARA EL DESARROLLO TECNOLOGICO INDUSTRIAL, ANAS S.p.A., NETIVEI, ISRAEL - NATIONAL TRANSPORT INFRASTRUCTURE COMPANY LTD, FEDERAL HIGHWAY ADMINISTRATION USDOT.

Special acknowledgment to Comunidad de Madrid (Pedro Berruezo and Concepción Iborra, Dirección General de Carreteras e Infraestructuras), owner of Jarama bridge structure, making everything related to the intervention and the monitoring possible.

Also special acknowledgment to Frank Lehmann (Dipl.-Ing.), Head of Unit Non-destructive testing and building monitoring, and his team from Materials Testing Institute University of Stuttgart (MPA Stuttgart), for the work developed related with monitoring.

References

Chataigner, S., & Caron, J. (2011). Optimization of the shear transfer in structural bonded assemblies using a curved bonded geometry. Construction and Building Materials , 442-451.

Chataigner, S., Aubagnac, C., Quiertant, M., & Benzarti, K. (2010). Méthode d'essai LPC N°72 - Essai de cisaillement à simple recouvrement pour caractériser l'adhérence de renforts composites collés sur supports béton. LCPC.

Chataigner, S., Caron, J., Diaz Diaz, A., Aubagnac, C., & Benzarti, K. (2010). Non-linear failure criteria for a double lap bonded joint. International Journal of Adhesion and Adhesives, 10-20.

Chataigner, S., Caron, J.-F., Benzarti, K., Quiertant, M., & Aubagnac, C. (2011). Use of a single lap shear test to characterize composite-to-concrete or composite-to-steel bonded interfaces. Construction and Building Materials, 25(2), pp. 468–478.

Chataigner, S., Gagnon, A., Quiertant, M., Benzarti, K., & Aubagnac, C. (2012). Adhesively bonded composite reinforcements for steel structures : durability of the stress transfer. Proceedings of composites in civil engineering.

CNR-DT_202/2005. (2007). Guidelines for the design and construction of externally bonded FRP systems for strengthening existing structures. Rome: National Research Council.

DNV-RP-C301. (2012). Design, fabrication, operation and qualification of bonded steel repair of steel structures, Det Norske Veritas.

EN13887. (2003). Structural adhesives. Guidelines for surface preparation of metals and plastics prior to adhesive bonding.

EN14869-1. (2011). Structural adhesives. Determination of shear behavior of structural adhesive bonds. Torsion test method using butt-bonded hollow cylinders.

EN14869-2. (2011). Structural adhesives. Determination of shear behavior of structural bonds. Thick adherend shear test.