D5.2 Implementation of FASSTbridge methodology:
Bridge Service Life recalculation and Strengthening design

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D5.2 Implementation of FASSTbridge methodology

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Glossary

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1 Executive summary

This report is part of the Infravation research project “Fast and effective solution for steel bridges life-time extension”. Within Work Package 5 “Real case demonstration of the methodology”, the adopted strengthening system for Jarama Bridge in Madrid, Spain, is to be validated by means of a well-defined experimental campaign regarding static, dynamic, application and durability topics of the assembly.

This Deliverable uses the results from WP2 and WP4 to assess the condition of the existing bridge and to determine its remaining service lifetime. Then, the extended service life according to given repair and strengthening actions is calculated. Repair and maintenance costs will be accounted for in each of the proposed actions. The most suitable option from this analysis will be selected for implementation in task 5.3.

This Deliverable 5.2 links directly to D5.3 and D5.4:

D5.3 Implementation of FASSTbridge strengthening system in Jarama Bridge (M23-DRAGADOS) describes the actual strengthening process as carried out on site. Identifying possible drawbacks found during the repair of the bridge.

D5.4 Test and monitoring layout. (M23-USTUTT) Results and analysis of the data collected. Configuration of the test and sensors network for monitoring. Gathers the data collected from the bridge sensor network.

To assist the reader a summary of objectives for all six Work Packages (WPs) are presented below:

Work Package 1

The main objective of this WP is to define, manage and achieve the project goals while staying within the required technical, financial, quality, and timing guidelines.

Work Package 2

The objectives of this WP are to design the FASSTbridge methodology for assessing remaining fatigue life and to develop the strengthening and maintenance approaches.

Work Package 3

The main objective of this WP is to determine the most suitable materials for the strengthening system, which is comprised of an adhesive and a carbon fibre reinforced polymer (CFRP) plate.

Work Package 4
The aim of this WP is to validate the adopted strengthening system, developed in work package 3, through a well-defined experimental approach.

Work Package 5

The main goal of WP 5 is to demonstrate the FASSTbridge solution by applying it in the field, in a real case study using a bridge in Madrid, Spain.

Work Package 6

The main goal of this WP is to ensure that the project's practical outcomes are widely disseminated to the appropriate target individuals and communities.

2 Introduction

Key stages of the FASSTbridge methodology for existing steel bridges prone to fatigue loading based on the following 3+1 stages:

Stage 1 – Diagnosis

Stage 2 – Safety Evaluation

Stage 3 – Design of Intervention

Stage 4 – Monitoring and Maintenance

The first step is the “Diagnosis” of the given steel bridge, evaluating the input parameters and the building history of the bridge, based on the available material e.g. documents, static calculation, reports, drawings, photos. From studying this data, information can be gathered about the building type, kind of connections and especially fatigue-prone details. The result of the Diagnosis is to have all information to model the bridge in a comprehensive and complete way in consideration of the diagnostic range.

On the basis of the results of the “Diagnosis” the safety level of the existing bridge is evaluated in the second step “Safety Evaluation”. For FASSTbridge methodology this includes especially the estimation of the remaining life time. The necessity of re-evaluating the safety level, in detail the remaining life time, is given because of changed and raised load-conditions, altering of the material and environmental impacts. To do so static calculations, material valuation and monitoring procedures are used.

Design of Intervention includes the design of the strengthening system with regards of all the findings of “Diagnosis” and "Safety Evaluation". The aim is to develop a concept for a sustainable, easy-to-apply and effective strengthening system. With respect to the chosen CFRP-system the post-retrofit stress range to enhance the remaining fatigue-lifetime can be estimated and the increase of $N_i$ is derivable.
3 FASSTbridge Methodology

3.1 Diagnosis

3.1.1 Description of Bridge

Figure 1: Elevation Jarama Bridge

Jarama Bridge is located in 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 2: General views, Jarama Bridge

The three central spans form a continuous beam, while the lateral spans are simply supported separated by a joint, resulting in the following span distributions: 16,6 m – 24,2 m – 36,9 m -24,2 m – 16,95 m. The total length is 118.85 m. 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. The cross-section consists of two I-beams, which are connected by transversal cross-bracings to stiffen the bridge in transversal direction.

The design code of 1956 did not take into account a fatigue limit state. The adequacy of the structure for the project needs to be checked by carrying out a fatigue limit state check (see 3.2.3.1).
3.1.2 Condition of bridge

The results of the latest bridge inspections are summarized in the following.

3.1.2.1 April 2016
The maintenance status from a visit in April 2016 (carried out by DRAGADOS and VIAM) revealed minor affections on steel structure that occur as local corrosion and small impacts on secondary structural elements.

The accessibility is good. There is an easy access to roads and paths under the bridge. Furthermore the piers are relatively low (7 m max). The only problem is the access to the main span over the river Jarama.

3.1.2.2 February 2017
There was a detailed inspection carried out in February 2017. The visual inspection on site included the abutments and piers. Furthermore, the concrete deck was investigated. Most damages in the concrete deck are located at the cantilever and the parapets. Some cracks, efflorescence, deformations in concrete surface and many spall concrete areas with exposed rebar can be seen. Some minor problems have also been noted near expansion joints (moisture and cracks).

The steel-elements in Jarama-Bridge are 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 are 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 V-1 show important distortion, corrosion and some other defects probably caused by object impact. One angle in bottom lateral bracing member of span V-5 also presents small deformation.

The floor beams are 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.

There are two different types of bearings: neoprene bearings on the abutments and fixed and movable steel plate bearings on the piers. The neoprene-bearings are placed on concrete seats. They are generally in a good condition. They have some anti-corrosion coating. The concrete seat on abutment E-1 shows a spalling and a crack. All steel-plate bearings are heavily corroded.

Non-structural elements, like pavements, sidewalks, bridge-drains ... are in a fair condition. It was noted that most bridge-drains are clogged.
Summarizing the general defects and problems on the bridge, it is notable that most of the deficiencies are related to an accumulation of water, entering from the deck to the substructure elements through e.g. expansion joints.

3.1.3 Fatigue Details in Jarama-Bridge

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 analysed. 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).

From the 27 welds of the second type (in-shop-welds) that were analysed, eleven do not fulfil the quality standards (under AL2 UNE EN ISO 11666:2011).

The following table shows the classification of all welds in span 1 to 4.
### Table 1: Classification of the welds in span 1 - 4

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<td>4</td>
<td>S4_B2_W4</td>
<td>Span 4</td>
<td>Beam 2</td>
<td>23.88</td>
<td>Bottom flange butt weld</td>
<td>14.68</td>
<td>9.2</td>
<td>Workshop</td>
</tr>
<tr>
<td>5</td>
<td>S4_B2_W5</td>
<td>Span 4</td>
<td>Beam 2</td>
<td>23.88</td>
<td>Bottom flange butt weld</td>
<td>20.14</td>
<td>3.74</td>
<td>Workshop</td>
</tr>
<tr>
<td>14</td>
<td>S5_B1_W1</td>
<td>Span 5</td>
<td>Beam 1</td>
<td>16.63</td>
<td>Bottom flange butt weld</td>
<td>8.19</td>
<td>8.44</td>
<td>Workshop</td>
</tr>
<tr>
<td>12</td>
<td>S5_B2_W1</td>
<td>Span 5</td>
<td>Beam 1</td>
<td>16.63</td>
<td>Bottom flange butt weld</td>
<td>6.03</td>
<td>10.60</td>
<td>Workshop</td>
</tr>
<tr>
<td>13</td>
<td>S5_B2_W2</td>
<td>Span 5</td>
<td>Beam 2</td>
<td>16.63</td>
<td>Bottom flange butt weld</td>
<td>11.99</td>
<td>4.64</td>
<td>Workshop</td>
</tr>
</tbody>
</table>
3.2 Calculation

3.2.1 Methodology according to Eurocode

Traffic, especially trucks, on bridges lead to a stress spectrum that may cause fatigue. To estimate this fatigue loading in Eurocode there are five fatigue load models. In German codes it is implemented that only fatigue model 3 should be used [EC]. Fatigue model no. 3 includes four axle loadings of 120 kN each. These loadings should be placed in the most unfavourable position for each span of the bridge. The most critical position can be determined by evaluating the influence line in longitudinal direction of the bridge. It is then possible to derive the maximum and minimum stresses and calculate the algebraic difference.

3.2.2 Description of FEM-Modelling

3.2.2.1 System

To evaluate the strengthening action of CFRP laminates on the butt welds of span 2 of the continuous beam, a 3D-shell-model is created in FEM-Program SOFiSTiK. 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.

Figure 3: Full model of continuous beam, Jarama Bridge (top view)
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.

It was agreed that only span 2 of the continuous beam is investigated (the results may be adopted on span 4). The individual beams are named “beam 1” and “beam 2”. On each beam, four welds were interesting for the investigation. Of this 8 welds 2 were discarded from this selection. The welds no. 28 and 19 are too close to the kink of the bottom flange. From this it follows, that the welds no. 29, 26, 25, 20, 17 and 16 are investigated and the effect of strengthening action is evaluated.

These are marked in Figure 6 on the next page.
3.2.2.2 CFRP

It was decided not to model the adhesive layer. The CFRP-laminates are modelled as shell elements with following material parameters:

Thickness: $d_L = 4.0 \text{ mm}$
Width: $b_L = 100 \text{ mm}$
Young’s modulus: $E_L = 460 \text{ 000 N/mm}^2$

For a comprehensive investigation and consideration of different possible application options, various arrangements of the laminates were examined. Therefore, the numbers, length and layers of the laminates per weld were differentiated. Considering a distance to the edge from the bottom flange (width of bottom flange = 700 mm) of 40 mm and 30 mm minimum separation between the laminates, the number could be up to 5 CFRP plates per weld. It was defined that
the minimal length of the laminates is 1.20 m. For the arrangement of several layers, it was determined to stagger the length from layer to layer. In that case, an anchorage length of 100 mm on each end has to be added.

First, it was assumed that the same number of laminates and layers are arranged on each weld. After analysing different configurations, it was decided to provide the welds on each beam with different arrangements of laminates and layers. To line up the strengthening system, symmetric arrangements of the CFRP plates between "beam 1" and "beam 2" were decided. Consequently, the following configuration will be investigated.

<table>
<thead>
<tr>
<th>Weld No.</th>
<th>Weld code</th>
<th>Laminates</th>
<th>Layer</th>
<th>Length [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Layer 1</td>
</tr>
<tr>
<td>29</td>
<td>B1 - W1</td>
<td>4</td>
<td>2</td>
<td>1.4</td>
</tr>
<tr>
<td>26</td>
<td>B1 - W4</td>
<td>5</td>
<td>1</td>
<td>1.2</td>
</tr>
<tr>
<td>25</td>
<td>B1 - W5</td>
<td>3</td>
<td>3</td>
<td>1.6</td>
</tr>
<tr>
<td>20</td>
<td>B2 - W2</td>
<td>4</td>
<td>2</td>
<td>1.4</td>
</tr>
<tr>
<td>17</td>
<td>B2 - W5</td>
<td>5</td>
<td>1</td>
<td>1.2</td>
</tr>
<tr>
<td>16</td>
<td>B2 - W6</td>
<td>3</td>
<td>3</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Table 2: Configuration of laminates arrangement

The depicted figure shows the symmetric arrangement of the laminates on the investigated welds.
A closer investigation of the CFRP plates showed that the influence of the laminates length is negligible. The approach of using CFRP-laminate with a length of 1,20 m leads to nearly the same results as locating CFRP-laminate over the whole span. It is considered, that only normal longitudinal stresses are acting and that the CFRP and steel act fully compositely at the section.

### 3.2.3 Calculation of un-strengthened and strengthened system

To evaluate the effect of strengthening action to the given system (according to chapter 3.2.2), calculations were conducted, in order to derive the algebraic difference between the minimum and maximum stresses in the welds due to fatigue loading. Having the algebraic difference, an evaluation of the fatigue strength is possible.

Beforehand several more scenarios were investigated to estimate an interaction between the welds (is there any influence on the neighbouring weld if only one of the welds of the beam is strengthened?). Due to the results of this preliminary investigation, it was decided to strengthen all 6 welds as shown in figure 8.
Case 0 - Un-Strengthened System (for comparison)

Case 1 - Welds strengthened with the chosen configuration

For the six welds loaded with tensile stresses, the reduction of $\Delta \sigma_{\text{rat}}$ was derived. As expected, there is a reduction of $\Delta \sigma_{\text{rat}}$ 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 $\Delta \sigma_{\text{fat}}$ about 8 - 15 % can be achieved, the reduction of $\Delta \sigma_{\text{fat}}$ 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.

### 3.2.3.1 Fatigue resistance and Design Life Time of the unstrengthened system

According to the presented procedure in D2.2/Chapter 3.8, the fatigue resistance for the unstrengthened system may be estimated by using the regulations of Eurocode DIN EN 1993-1-9, 7.1(3). For detailed calculation, see Annex 1.

Fatigue strength:

$\Delta \sigma_{C} = 0,96 \cdot 112 \text{ N/mm}^2 = 107,99 \text{ N/mm}^2$

$\Delta \sigma_{C}/ \gamma_{C} = 107,99 / 1,25 = 86,39 \text{ N/mm}^2$

Fatigue stress rate:

$\Phi_{2} = 1,0$ (road bridges)

$\lambda = \lambda_{\text{max}} = 1,78$

$\Delta \sigma_{E2} = \lambda \cdot \Phi_{2} \cdot \Delta \sigma_{\rho} = 1,78 \cdot 1,00 \cdot \Delta \sigma_{\rho} = 1,78 \cdot \Delta \sigma_{\rho}$

Results:

<table>
<thead>
<tr>
<th>Case 0</th>
<th>$\Delta \sigma_{\rho}$</th>
<th>$\Delta \sigma_{E2}$</th>
<th>$\Delta \sigma_{C}/ \gamma_{C}$</th>
<th>Proof</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weld No.</td>
<td>Weld code</td>
<td>[N/mm$^2$]</td>
<td>[N/mm$^2$]</td>
<td>[N/mm$^2$]</td>
</tr>
<tr>
<td>29</td>
<td>B1 - W1</td>
<td>15,80</td>
<td>28,13</td>
<td>86,39</td>
</tr>
<tr>
<td>26</td>
<td>B1 - W4</td>
<td>14,76</td>
<td>26,26</td>
<td>86,39</td>
</tr>
<tr>
<td>25</td>
<td>B1 - W5</td>
<td>9,28</td>
<td>16,52</td>
<td>86,39</td>
</tr>
<tr>
<td>20</td>
<td>B2 - W2</td>
<td>20,30</td>
<td>36,13</td>
<td>86,39</td>
</tr>
<tr>
<td>17</td>
<td>B2 - W5</td>
<td>13,52</td>
<td>24,07</td>
<td>86,39</td>
</tr>
<tr>
<td>16</td>
<td>B2 - W6</td>
<td>9,33</td>
<td>16,61</td>
<td>86,39</td>
</tr>
</tbody>
</table>

Table 3: calculation results of the un-strengthened system

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) with following formulae (analogue formulae for shear):

$$N = \frac{\Delta \sigma_{\rho} \cdot 2 \cdot 10^6}{\Delta \sigma_{E2} \cdot \Phi_{2}} \approx 5 \cdot 10^6$$

for $m=3$ (longitudinal stresses) \hspace{1cm} (1)
D5.2 Implementation of FASSTbridge methodology

### Table 4: Remaining fatigue lifetime of the un-strengthened system

<table>
<thead>
<tr>
<th>Weld No.</th>
<th>Weld code</th>
<th>Case 0</th>
<th>Δσ_{E2} [N/mm²]</th>
<th>Δσ_{C}/γ_{C} [N/mm²]</th>
<th>N_R [10^6]</th>
</tr>
</thead>
<tbody>
<tr>
<td>29</td>
<td>B1 - W1</td>
<td></td>
<td>28,13</td>
<td>86,39</td>
<td>57,95</td>
</tr>
<tr>
<td>26</td>
<td>B1 - W4</td>
<td></td>
<td>26,26</td>
<td>86,39</td>
<td>71,18</td>
</tr>
<tr>
<td>25</td>
<td>B1 - W5</td>
<td></td>
<td>16,52</td>
<td>86,39</td>
<td>286,10</td>
</tr>
<tr>
<td>20</td>
<td>B2 - W2</td>
<td></td>
<td>36,13</td>
<td>86,39</td>
<td>27,33</td>
</tr>
<tr>
<td>17</td>
<td>B2 - W5</td>
<td></td>
<td>24,07</td>
<td>86,39</td>
<td>92,52</td>
</tr>
<tr>
<td>16</td>
<td>B2 - W6</td>
<td></td>
<td>16,61</td>
<td>86,39</td>
<td>281,52</td>
</tr>
</tbody>
</table>

Table 4: Remaining fatigue lifetime of the un-strengthened system

### 3.2.3.2 Increase of life time due to strengthening action

<table>
<thead>
<tr>
<th>Weld No.</th>
<th>Weld code</th>
<th>Laminates</th>
<th>Layer</th>
<th>Length [m]</th>
<th>Δσ_{P,0} [N/mm²]</th>
<th>Δσ_{E2} [N/mm²]</th>
<th>Δσ_{C}/γ_{C} [N/mm²]</th>
<th>Proof</th>
</tr>
</thead>
<tbody>
<tr>
<td>29</td>
<td>B1 - W1</td>
<td>4</td>
<td>2</td>
<td>1.4, 1.2</td>
<td>-</td>
<td>14.45</td>
<td>25.72</td>
<td>86,39</td>
</tr>
<tr>
<td>26</td>
<td>B1 - W4</td>
<td>5</td>
<td>1</td>
<td>1.2</td>
<td>-</td>
<td>14.16</td>
<td>25.21</td>
<td>86,39</td>
</tr>
<tr>
<td>25</td>
<td>B1 - W5</td>
<td>3</td>
<td>3</td>
<td>1.6, 1.4, 1.2</td>
<td>7.21</td>
<td>12.83</td>
<td>86,39</td>
<td>0.15 &lt; 1.0</td>
</tr>
<tr>
<td>20</td>
<td>B2 - W2</td>
<td>4</td>
<td>2</td>
<td>1.4, 1.2</td>
<td>-</td>
<td>17.20</td>
<td>30.62</td>
<td>87,39</td>
</tr>
<tr>
<td>17</td>
<td>B2 - W5</td>
<td>5</td>
<td>1</td>
<td>1.2</td>
<td>-</td>
<td>12.53</td>
<td>22.30</td>
<td>89,39</td>
</tr>
<tr>
<td>16</td>
<td>B2 - W6</td>
<td>3</td>
<td>3</td>
<td>1.6, 1.4, 1.2</td>
<td>7.35</td>
<td>13.08</td>
<td>89,39</td>
<td>0.15 &lt; 1.3</td>
</tr>
</tbody>
</table>

Table 5: Calculation results of the strengthened system with the chosen final configuration

<table>
<thead>
<tr>
<th>Weld No.</th>
<th>Weld code</th>
<th>Laminates</th>
<th>Δσ_{E2} [N/mm²]</th>
<th>Δσ_{C}/γ_{C} [N/mm²]</th>
<th>N_R [10^6]</th>
<th>Increase compared to case 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>29</td>
<td>B1 - W1</td>
<td>4</td>
<td>25,72</td>
<td>86,39</td>
<td>75,80</td>
<td>31%</td>
</tr>
<tr>
<td>26</td>
<td>B1 - W4</td>
<td>5</td>
<td>25,21</td>
<td>86,39</td>
<td>80,47</td>
<td>13%</td>
</tr>
<tr>
<td>25</td>
<td>B1 - W5</td>
<td>3</td>
<td>12,83</td>
<td>86,39</td>
<td>610,03</td>
<td>113%</td>
</tr>
<tr>
<td>20</td>
<td>B2 - W2</td>
<td>4</td>
<td>30,62</td>
<td>86,39</td>
<td>44,93</td>
<td>64%</td>
</tr>
<tr>
<td>17</td>
<td>B2 - W5</td>
<td>5</td>
<td>22,30</td>
<td>86,39</td>
<td>116,25</td>
<td>26%</td>
</tr>
<tr>
<td>16</td>
<td>B2 - W6</td>
<td>3</td>
<td>13,08</td>
<td>86,39</td>
<td>575,84</td>
<td>105%</td>
</tr>
</tbody>
</table>

Table 6: Remaining fatigue lifetime of the strengthened system

The comparison shows, with the formulae of Eurocode, that the increase in Design Life Time goes from 13 % to 113% due to strengthening action with “5 laminates / 1 layer” respectively “3 laminates / 3 layers” of CFRP-laminates on beam 1.

### 3.3 Design of Intervention. Execution plan

This section presents the description for the strengthening intervention procedure and maintenance of the strengthening system. As already described in D2.2, these guidelines have been developed based on two general guides on CFRP strengthening of steel structures, namely (CNR.DT 202/2005) and (Schnerch et al. 2007a). The intervention procedure and maintenance guidelines have been tailored to the FASSTbridge strengthening system based on the preliminary results
of the project, the partners’ experiences in previous projects, and results published in scientific literature.

The different steps of the installation process are summarized in the following sections.

3.3.1 Transport and storage of strengthening materials

General and Project-related determinations:

Transportation and storage of the strengthening materials (FRP plates and adhesives) will strictly follow the instructions provided by the producers and/or suppliers. The following general recommendations are to be followed:

- The CFRP plates should be transported in rigid containers to prevent impact from damaging the strips. Upon arrival at the site, the plates should be inspected to ensure they have no defects (cracks, notches or out-of-straightness). If the plates need to be replaced, the replacements should be provided before the preparation of the steel surface.

- The CFRP plates and the adhesive components should be stored in a cool, ventilated place, avoiding direct sunlight. The adhesive components should be stored in tightly closed containers to prevent moisture contamination.

- For the Adhesive storage preservation of the product not below +5°C protected from humidity and source of heat is needed.

3.3.2 Preparation of CFRP plates

General:

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

The CFRP plates should be cut to the required length, see table below, and their ends detailed as specified by the designer prior to the preparation of the surfaces for bonding. The plates will be cut by hand using a tooth saw blade and a miter box. To avoid the inhalation of dust particles, the operators performing the cuts should wear a dust mask and avoid cutting with power tools.
D5.2 Implementation of FASSTbridge methodology

<table>
<thead>
<tr>
<th>Units</th>
<th>Length (m)</th>
<th>total (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weld 29</td>
<td>4</td>
<td>1,40</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1,20</td>
</tr>
<tr>
<td>Weld 26</td>
<td>5</td>
<td>1,20</td>
</tr>
<tr>
<td>Weld 25</td>
<td>3</td>
<td>1,60</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1,40</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1,20</td>
</tr>
<tr>
<td>Weld 20</td>
<td>4</td>
<td>1,40</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1,20</td>
</tr>
<tr>
<td>Weld 17</td>
<td>5</td>
<td>1,20</td>
</tr>
<tr>
<td>Weld 16</td>
<td>3</td>
<td>1,60</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1,40</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1,20</td>
</tr>
<tr>
<td>QC</td>
<td>8</td>
<td>0,15</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7: Length of CFRP for unit and weld.

Project-related determinations:

It is proposed to cut, if possible the CFRP plates with an angle as recommended in (Schnerch et al., 2007). Such geometry should optimize the maximum force that may be transferred through the joint. It has not been investigated in the experimental investigations in laboratory as the thickness was too small (2.3 mm instead of 4 mm). Two different edge detailing geometries may be used (figures 9 and 10).

Yet, as resin may be difficult to apply in bigger thickness than 1 mm (WP4, task 4.2), it is proposed to adopt the alternative edge detailing (figure 9). The angle may be around 30° if possible.

Figure 9: Proposed edge detailing in (Schnerch, Dawood, & Rizkalla, 2007)
In addition, when several layers of CFRP reinforcement are considered, the adhesive bonding of the CFRP layers could be done in laboratory or at the workshop before being delivered on site (this would minimize the time and the number of operations on site).

3.3.3 Steel surface preparation

General:
The first operation to perform is the grinding of welds surface until a complete flat surface is obtained.

The following steps must be undertaken to correctly prepare the steel surface and ensure a good bond between the adhesive and the steel:

- **Remove coatings (painting) and corrosion products.** This operation must be carried out with grit blasting. It has to be avoided sanding or grinding instead because these processes leave the surface of the steel smooth and does not effectively remove the contaminants and can redistribute these contaminants into the surface. The grit should be angular, hard, properly graded, dry, and free of contaminants. Prior to grit blasting, a solvent should be applied to the steel surface to remove greases.

- **Cleaning the surface.** After grit blasting, any surface dust should be removed by brushing, vacuuming or blowing with a clean uncontaminated air supply. A final solvent cleaning after grit blasting may be completed.

- **Drying the surface.** If the surface is wet at the end of the abrasion and the cleaning phase, then it must be immediately dried in order to avoid the quick formation of oxide layers on the exposed surface.

**Project-related determinations:**
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 should be done before application of the adhesive. The level of surface preparation Sa should be determined using NF EN ISO 8501-1 (a minimum value of 2.5 is required). Roughness may be measured using NF EN ISO 8503-2. Surface cleanliness must also be assessed using NF EN ISO 8502-3.

### 3.3.4 CFRP surface preparation

**General:**

It is recommended to use CFRP plates with a peel-ply that protects the surface from contamination. The peel-ply should be completely removed right before applying the adhesive, without touching the side to be bonded to protect it from contaminants from the hands. No further surface preparation is required.

If a peel-ply is not available for the CFRP, or if it is in bad condition, the surface should be lightly abraded with sandpaper and cleaned with a solvent.

**Project-related determinations:**

For FASSTBridge solution, CFRP plates from Epsilon Composite have a peel-ply on both sides that should be removed.

Degreasing of the CFRP surfaces must be done after peel-ply removal. Then, at least 15 minutes must be waited for the solvent to evaporate and it must be check that no dust is present on CFRP surfaces.

### 3.3.5 Adhesive mix and application

**General:**

The adhesive is a hybrid two component epoxy-polyurethane adhesive (Urepox Extra 2C) with the following specifications:

- Pot life 45 minutes (workability)
- $T_g > 71{\degree}C$ after post-curing
- Tensile strength $\geq 35$ MPa, 5.1 ksi

For optimisation of the cure schedule, 2 hours at room temperature is needed and 1 hour at $80{\degree}C$ for post-cure.
Once all the surfaces are prepared, the adhesive must be mixed, applied to the bonding surfaces and the CFRP plates clamped within the pot-life of the adhesive.

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

It will be taken into account the environment temperature at the time of the application of the adhesive.

**Project-related determinations:**

*FASSTbridge* suggests that the application is carried out on both surfaces if possible (CFRP and steel). Then, a strong pressure on the CFRP to the steel surface must be done and a roller may be used to apply it along the reinforcement.

### 3.3.6 Installation of the CFRP strengthening system

**General:**

The CFRP plate with the adhesive on one side should be pressed into the steel starting from one end and gradually towards the other allowing air to escape. A laminate roller should be used from the centre of the plate towards the ends to remove as much air as possible and ensure a good contact between the CFRP, adhesive and steel substrate. The resin in excess that squeezed out must be removed letting a 45° fillet. Care must be taken to ensure that too much adhesive is not squeezed out of the ends of the plate and that the adhesive thickness in the end regions is consistent with the rest of the plate. Once the CFRP, adhesive and steel surface are completely in contact, the plates should be clamped, if necessary, to the steel. This procedure should be completed within the pot-life of the adhesive.

Heat must be applied to cure the adhesive as the designer has specified, an hour at 80°C is needed.

During the installation of the strengthening system, the following further precautions must be taken:

- Proper drainage must be ensured to minimize the accumulation of water due to condensation and rain, especially when the CFRP plates are used on the top surface of the tension flange of a beam.
- Proper protection against galvanic corrosion must be ensured by insulating steel from CFRP and the steel. For this purpose, a consistent adhesive
thickness must be obtained and will be coated with a water resistant sealant.

Project-related determinations:

Some temporary device may be used such as clamps for instance. The pot life is assessed to be around 25 minutes. It may be checked using Shore Hardness D measurement.

The time between the application and the application of heat may be assessed using viscosity measurements. It has been carried out by Karim Benzarti at IFSTTAR who found a minimum time of 2.5 hours before the application of heating.

After application, a strong care is 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.

3.3.7 Post-curing

General:

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.

Post curing will expedite the cross-linking process and properly align the polymer’s molecules. 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.

Project-related determinations:

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.

It would be also recommended to control the rate of temperature increase so that the post-curing temperature may be reached.

30 min to 1 h to reach the required temperature

$T_{\text{post-cure}} = 80^\circ\text{C}$
3.3.8 Environmental and site conditions

General:

The temperature ranges for the application and curing of the adhesive joint will be strictly satisfied to allow a correct development of the chemical reactions needed to reach the strength required for the adhesive joint. Excessive humidity may also affect the strength and durability of the adhesive joint. Therefore, the joint must be protected against contact with water during curing.

As for the application of anti-corrosion coatings, the Dew point must be measured before application to check that there is no risk of humidity entrapping. A security of 3 °C must be taken.

Appropriate job site conditions must be maintained to ensure a good quality in the application of the strengthening system. Particular attention must be paid to cleaning the substrate surface, avoiding the presence of particles that adversely affect the quality of the FRP-steel bond.

Project-related determinations:

Two-component epoxy-polyurethane adhesive characterized from a strong flexibility and a good adhesiveness on various materials.

Specific for bonding steel and Carbon Fibre Reinforced Polymer (CFRP), in projects of Steel Bridges Life Time Extension.

To achieve the maximum value of $T_g$, heating ($T = +80^\circ$C) the glue line for 60 minutes is necessary.

3.3.9 Quality control during installation

General:

Quality control during installation of the CFRP strengthening system may include semi destructive and non-destructive tests. Among the quality control procedures recommended in (CNR.DT 202/2005), the procedures that will be applied to the FASSTbridge strengthening system are described below.

Prequalification tests should be available from the producer of the CFRP plates and the adhesive mix.

Semi-destructive tests may be conducted in special testing zones strengthened with CFRP. The testing zones will be not less than 0.5% of the actual strengthened area, and in any case not less than 0.1 m². Strengthening testing samples will be
uniformly distributed. The testing regions should be prepared following the same procedures adopted for the actual strengthening system and exposed to the same environmental conditions. They must be placed in such a way that the semi-destructive tests do not affect the response of the strengthened member.

Project-related determinations:

The presence of bonding defects can significantly affect the structural performance and durability of the strengthening systems. Defects have then to be detected, located and evaluated in order to estimate if injection or replacement is needed. In these conditions, conformance checking of the bonded overlays through in situ non-destructive evaluation (NDE) techniques is highly suitable. The quality-control program should involve a set of adequate inspections and tests.

Quality-control program:

Visual examination

The visual examination of the CFRP is the primary inspection method were bridge inspectors are looking for the following surface deficiencies.

- Blistering (surface bubbles)
- Voids and delamination
- Discoloration
- Wrinkling
- Fibre exposure
- Scratches
- Cracking

As the "Bridge Inspector's Reference Manual" indicates, during a visual inspection may be helpful to incorporate a static or dynamic load to assist in detecting cracks and other deficiencies including vertical movement.

In this case the visual inspection will be performed during the load test that is to be.

Physical examination

Sound testing.

Physical examinations of CFRP are performed by sounding or tap testing for detecting areas of debonding or delamination in CFRP. With visual inspection, tap testing is the most widely in situ method used for inspection of bonded CFRP. That kind of examination is typically performed by using a small hammer tap to measure the difference in frequency between sound and delaminated areas. A disbonded region produces a sound that is markedly different than a region devoid of a disbond.
Pull-off adhesion test.

Moreover, adherence properties of CFRP systems installed on concrete or steel substrates can be evaluated by conducting on site pull-off adhesion tests on witness panels specifically bonded on test zones (ASTM, 2015, UNE EN 1015-12:2000).

It is to note that it has been proposed, to determine the bond properties of the adhesive layer within the reinforcement system, using a non-destructive testing
(NDT) method derived from the standard pull-off test. This innovative method consists in measuring, in the elastic domain, the displacement of the adhesive joint under the action of the tensile load, in order to determine a bond stiffness which may be used as a bond quality criterion.

This NDT method is an interesting tool to determine whether the reinforcement system satisfy the design requirements at the time of the strengthening works on site.

In this case the procedure was the same as it has been carried out in laboratory by TECNALIA (reference in document D 3.2, chapter 5).

There will be 8 samples disposed, 0,1 x 0,15 m in dimension, as shown in the figure below. The testing samples will be prepared following the same procedures adopted for the strengthening system and at the same time.

![Figure 13: Samples location](image)

After the post-curing process, the test will be done. The nose-tips will be attached to the samples, and after drying, tests will take place.
Results will be compared with those related in document D 3.2.

**Infrared Thermography**

For many years, the Pulsed Stimulated Infrared Thermography technique has been used to control aerospace structures, in particular to detect and characterize delamination in carbon/epoxy composites. A similar principle is used to locate bond defect of FRP systems bonded in RC or steel structures. It consists in heating the surface of the composite during a short period and measuring the temperature distribution on the sample surface with an infrared camera.

Despite the initial cost of a quality imaging system, thermal testing is considered to be one of the more favourable and practical advanced inspection methods for FRP.
3.3.10 Application of the protective coating

General:

The protective coating scheme to apply should be compatible to the existing one and with the CFRP.

Project-related determinations:

Primer coating: EPOXI-ZINC minimum dry film thickness 120 µm (2 layers of 60 µm applied with roller).

Finish: EPOXI minimum dry film thickness 120 µm (2 layers of 60 µm applied with roller).

The colour of the finish layer is “RAL 5024 Pastel blue”.

3.4 Fixed Load Tests

The objective of the test is to obtain a status Jarama bridge in Paracuellos del Jarama considering a controlled or "fixed load” condition.

This fixed load condition will allow, measuring strains before retrofitting the bridge and after retrofitting, to demonstrate the effectiveness of the CFRP retrofit.

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.

The following activities were undertaken:

TRAFFIC DISRUPTION:

The traffic has to be disrupted on the right lane first, then the static load (two trucks at three positions) and the dynamic load (one truck and one position for the timber plank) tests can be performed.

After that, the traffic diversion has to be moved to the left lane then the same tests on the other lane can be replicated.

Finally, once all is finished, the traffic diversion can be removed.

The permanent presence of the staff that ran the traffic diversion is required, and applicable regulations has to be follow during these works.

TRUCKS FOR LOADING:

We will use two three-axle trucks charged to its rated load.
They will be positioned on the bridge deck in a series of certain positions to induce a certain state of loads in the structure of the bridge.

Operation will first be made in the first cut lane, then do so on the other.

The same operation will be repeated on the second day, after the placement of the reinforcement, it is essential that the load of the second day was exactly equal to the ones of the first day, aspect that is verified by means of delivery of cargo from trucks (F1, F2 and F3)

In this way it has to be ensured that loads induced in the structure is exactly the same on two occasions.

**Table 8: Trucks Load data**

<table>
<thead>
<tr>
<th>Lengths (mm.)</th>
<th>Loads (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Truck 1</td>
<td></td>
</tr>
<tr>
<td>Truck 2</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Plate number</th>
<th>Total Weight (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>First day</td>
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<tr>
<td>Truck 1</td>
<td></td>
</tr>
<tr>
<td>Truck 2</td>
<td></td>
</tr>
</tbody>
</table>

**DEVELOPMENT OF THE TESTS**

It is recommended to make the test with different positions, first the static load, three positions, and then those of dynamic load, two positions.
Static test will be performed by placing the trucks in its positions, and after leaving stabilize the load, make the measurements of strains.

Dynamic test will be performed by placing a wooden plank, 4 cm in height, in the selected position, and passing above it to a single truck at a speed of 20 km/h and 50 km/h, the passage of the truck to hit with plank, will induce a dynamic impact load in the structure, during which there will be measurements of strains.

As already mentioned, it will be made first in the right lane and then in the left lane.

And also as mentioned above, it will be made before and after the placement of the reinforcement, with identical trucks, in identical positions and with the same operational.

The sketches that indicate the applied position for Jarama bridge are presented below.

**RIGHT LANE**

Figure 16: Static. Right Lane position 1. Example
Figure 17: Dynamic. Left Lane position 1. Example
3.5 Monitoring

The tasks of the FASSTbridge monitoring strategy are to determine the success of the strengthening intervention in terms of reduced fatigue stresses at the embraced welds and to ensure the continued integrity of the strengthening system itself by instrumentation of the glue layer as bond between the CFRP and the base steel in order to detect separation.

Two different but interdependent approaches are required for the tasks based on their specific technical requirements. A short-term performance monitoring under defined loading conditions both before and after the strengthening intervention affirms the success of the implementation.

A long-term instrumented monitoring of the bridge is required to ensure the continued operational reliability of the installed CFRP reinforcements, especially their bond to the steel via the glue layer. The assessment is achieved by the installation of the delamination sensors developed within this project.

3.5.1 Strain gauges monitoring

General:

Strain gauges for performance monitoring must be installed at all strengthened welds in order to assess the fatigue strain reduction. The chosen sensors must be suitable for measurements on steel. They must to be glued to the steel surface and protected from outside influence according to manufacturer’s specifications. Be aware that both the sensors and their fixations have to be able to withstand the elevated temperature of about 80 °C during curing of the CFRP glue. It is strongly recommended to use at least a half-bridge configuration in order to minimize influence of the ambient temperature. Additionally, the air temperature and the steel surface temperature should be measured, if applicable both in sunlit and shaded areas.

The measurement system (sensors and data acquisition) should allow a resolution of at least 5 µ-strain to be able to detect changes from the strengthening intervention. Different values can be agreed on if according calculations suggest so. In case of dynamic loading, either by targeted passage of a sufficiently heavy vehicle or through regular traffic and environmental loads, the measurement system must be able to sample the 10th fold value of the highest relevant bridge resonance frequency, but not higher than 500 Hz.

The data evaluation must include a comparison of strains before and after the strengthening. The environmental and loading conditions during the test must be stated.
The installed strain gauges may be re-used for later experimental investigations if sufficiently protected from the environment. It must be ensured before such measurements that the strain gauges are still properly glued to the bridge. Another possibility is the connection to an instrumented monitoring system, which continuously measures the strains.

Project-related determinations:

At the Jarama bridge demonstration site, all six welds specified will be monitored. Two pairs of one-axial strain gauges (Tokyo Sokki Kenkyuyo Co., Ltd. FLA-6-11) are installed at each weld. One sensor of each pair is glued (Tokyo Sokki Kenkyuyo Co., Ltd. ethyl 2-cyanoacrylate) on top of the bottom flange in longitudinal direction to measure the occurring strains in the girder. A second strain gauge is glued on a separate piece of metal, which can freely deform due to temperature changes and is not affected by the bridge loading.

Both sensor pairs do not interfere with the strengthening due to their location on top of the flange. The strain gauges, the glue and the covering are selected to withstand the epoxy curing at 80 °C.

3.5.2 Delamination monitoring

General:

The task of the FASSTbridge delamination sensor is to reliably detect separation between the steel base and the CFRP strengthening. It is composed of two coplanar copper sheets separated by a dielectric layer. An additional insulation layer seals the entire sandwich element to prevent moisture ingress and electrical contact to the steel and the CFRP. The sensor is self-adhesive and must be glued to the CFRP directly before the strengthening, after ply-peeling and cleaning.

More information could be found in D4.4.
The sensor is optimized regarding the impedance change upon separation, i.e. the initial impedance is minimized. This is achieved by reducing the thickness of the central dielectric film and by increasing its permittivity. The chosen dielectric features a good permittivity at low thickness and can withstand the high temperatures expected during the strengthening process. The sensor is adjusted that the separation will always occur between the two copper sheets and not between the copper and the insulation or the insulation and the CFRP.

The measurements can be carried out at different frequencies between 10 Hz and 100 kHz. During the laboratory tests, a frequency of 10 kHz has proven to be suitable. Six digital temperature sensors (I²C) can be additionally connected to the node to capture the temperature influence at each impedance sensor. A waterproof plastic housing protects the system. It is not substantially protected against vandalism or theft.

The device is battery powered and can run unsupported for up to two years at a measurement frequency of once every 15 minutes. The data is wirelessly send to a base station, from where it is transmitted to a central data server. The CE certified system utilizes the 2.4 GHz ISM band for the transmission. The base station transmits the measurement data from all wirelessly connected nodes to the central data server. The connection is possible both by Ethernet and mobile internet (2G/3G/4G). It requires an electric power connection (230 V).

The data volume transmitted via mobile internet is generally low, less than 1 GB per month, for small to medium sized projects with only a few sensors.
Project-related determinations:

The installation of the bond sensors on the readily prepared CFRP strips takes place immediately before the strengthening intervention. Three delamination sensors are installed on the center laminate stack at weld S2_B2_W6, one on each layer. Three are installed on the outer three laminates at weld S2_B2_W5.

Continuous bond monitoring is not scheduled within the project. The sensor data is manually collected after installation.
3.6 Plans

Figure 20: Top view and elevation on Span 2. Investigated welds (red)
Figure 21: Location of reinforcement
3.7 Inspection and maintenance of strengthening system

General:

After the whole intervention, a new protective coating system must be applied in the area that was blasted and/or retrofitted.

![Diagram of Original Paint, CFRP Plates, Grit Blasted Area, Original Paint]

**Figure 22: Reinforcement**

In case of surface resin lost, due to abrasion or environmental degradation, a compatible resin can be used to replace the layers. It is not specified special maintenance interventions for the composite material.

It is also recommended to renew the paint before it fails to avoid grit blasting, which will require an adequate protection of the CFRP. Aside from that, the structure should be subjected to normal inspection and maintenance operations.

The CFRP structure should preferably be provided with a maintenance and inspection plan. This plan should make it possible to:

- keep the structure in a functional state during its lifetime;
- achieve good and responsible inspection.

Project-related determinations:

The following Fiches could be used during inventory and inspection works:
### Inventory Fiche

<table>
<thead>
<tr>
<th>Weld</th>
<th>Description</th>
<th>Location</th>
<th>Nº Layers</th>
<th>Layer Id</th>
<th>Nº Laminates</th>
<th>Spacing (mm)</th>
<th>Edge distance (mm)</th>
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**Comments:**

- **Figure 23:** Inventory Fiche
### Inspection Fiche

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<th>Nº Layers</th>
<th>Layer Id</th>
<th>Nº Laminates</th>
<th>Spacing (mm)</th>
<th>Edge Distance (mm)</th>
<th>Length (mm)</th>
<th>Width (mm)</th>
<th>Thickness (mm)</th>
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<td>105</td>
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<td>1200</td>
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</table>

**Comments:**

- S2_B1_W1: Span 2/Beam 1/Bottom flange butt weld
- S2_B1_W4: Span 2/Beam 1/Bottom flange butt weld
- S2_B1_W5: Span 2/Beam 1/Bottom flange butt weld
- S2_B2_W2: Span 2/Beam 2/Bottom flange butt weld
- S2_B2_W7: Span 2/Beam 2/Bottom flange butt weld
- S2_B2_W6: Span 2/Beam 2/Bottom flange butt weld

---

**Figure 24: Inspection Fiche**
3.7.1 Maintenance issue

The maintenance of the CFRP parts consists of:

- inspection: every 2 years. This frequency could be increased if needed;
- cleaning of the surfaces;
- maintenance of connections: putting the debonding sensor in use;
- repair of superficial damage of coating, kit layers and laminates;

It is advised to clean (coated) surfaces on a regular basis. This could be done by cleaning with water or special cleaners. For monolithic (non-sandwich) CFRP structures, generally a high pressure washer could be used.

In case of surface damage on coatings and kit layers, it is advised to repair these. Structural adhesive layers should be sealed from dirt and moisture.

3.7.2 Periodic inspections of bonded areas

Routine inspection is based on the following evaluations:

- examination of defects such as discolorations and eventual local damage;
- possible differences of environment occurring during the use of the structure.

More detailed inspection results from an evaluation of:

- permanent deformations;
- integrity of the retrofit;
- general behaviour of the structure, for instance related to a 0-measurement at completion: monitoring strains during real traffic conditions;

3.7.3 Visual examination

Inspection that can be executed visually, whether or not supported by non-destructive techniques:

- surface condition, discolorations, crazing, tears, blistering;
- permanent deformations;
- visible damage caused by vandalism or incidents;
- tightness of connections;
- cracking, delamination, damage to adhesive layers;
- damage to insulation against galvanic corrosion.

3.7.4 Physical examination

Visual inspections can be supported by non-destructive techniques like:

- (coin) tapping;
- acoustic measurements;
- infrared thermography;
- laser shearography;
- ultrasonic tests;
- strain measurements: monitoring strains during real traffic conditions;

3.7.5 Repairs

In case of damage and defects of the CFRP structure, the necessary repairs should be determined in consultation with a qualified designer, CFRP engineer and/or CFRP supplier.

In case of adhesive repairs, the same guidelines and conditions as prescribed for adhesive connections should apply.

Possible repair methods:

- creation of a bypass through the application of plates (bonded or mechanically connected);
- filling with resin (in case of small superficial damages);
- removing of the damaged CFRP material and laminating of replacement CFRP material;
- laminating with CFRP (strengthening).

During the design and execution of the repair, the remaining lifetime of the structure should be taken into account. Any repair operation should be provided with appropriate inspection instructions.
The repair should meet at least a level of confidence and reliability in conformity with adequate renovation standards.

### 3.8 Skilled labour specifications

The production and realization procedures of CFRP structures have been described in the “Design of Intervention. Execution plan”.

Additional and general recommendations:

The production should be executed by producers and personnel with appropriate level of experience for the used CFRP materials and production techniques.

When determining the necessary level of experience, for all activities the complexity and consequence class of the structure should be taken into account.

The procedures involved in the assembly and installation of the CFRP structure should be described in the execution plan.

The assembly and installation of a CFRP structure should be executed under supervision of a professional with the required experience in working with FRP materials and CFRP structures, in line with EN 1990. The executing personnel should be provided with clear instructions on working with FRP, before the start of the installation process.

The general inspection of a CFRP structure should be executed by a well instructed expert, described in accordance with an included inspection plan. A detailed inspection should be executed periodically, in accordance with a pattern described in advance, and in case of ascertained deviations.

Detailed inspections should be executed by a CFRP expert.
4 Conclusions

Some conclusions after the implementation of FASSTbridge methodology and Strengthening design in Jarama Bridge can be included in this Deliverable:

About the Fatigue Assessment Tool:

- Definition of technical and economical properties of the optimum CFRP plates and assessment of existing commercial products
- Developed a preventive, reliable, easy-to-apply procedure
- Purpose is to assess remaining fatigue life of aging steel bridges using AASHTO and Eurocode
- Tool can be used by bridge owners for asset management and to prioritize repairs

About the Design:

- Strengthening of intact steel structures to increase the calculated life time with CFRP possible
- Methodology (Diagnosis, Safety Evaluation, Intervention) is approved at Jarama Bridge
- Design of different CFRP-configurations accordant to the geometry
- Calculated decrease of stresses and strains in bottom flange
- Calculated increase of life time of considered welds with CFRP

About the Adhesive:

- Definition of adhesive properties to achieve optimum long term performance of the strengthening action
- Design and production of the adhesive according to the established properties
- Rheological behaviour of the adhesive: pre-certification

About Jarama Bridge Retrofit:

- Successfully demonstrated at 6 locations on Jarama Bridge utilizing light equipment and short time
- Average reduction of strain/stress of 22 %
5 References


EN11666. (2010) *Non-destructive testing of welds - Ultrasonic testing - Acceptance levels*.


EN8503-3. (2008). *Preparation of steel substrates before application of paints and related products - Surface roughness characteristics of blast-cleaned steel substrates*
Annexes

5.1 Annex 1 – Fatigue Resistance of unstrengthened System (Eurocode)

The fatigue assessment partial factors are given with:

Fatigue strength: \[\Delta\sigma_C \quad \rightarrow \quad \gamma_C := 1.25\]

Fatigue stress rate: \[\Delta\sigma_{E2} \quad \rightarrow \quad \gamma_{E2} := 1.00\]

**FATIGUE STRENGTH**

Having a connection with butt welds, the corresponding design fatigue category is given in Eurocode DIN EN 1993-1-9, Table 8.3 with the fatigue strength:

\[\Delta\sigma_C := 112 \frac{N}{mm^2}\]

Since the bottom flange has a thickness bigger that 25 mm, the fatigue strength has to be reduced by applying the factor \(k_s\):

\[t_{bf} := 30\text{mm} > 25\text{mm}\]

\[k_s := \left(\frac{25}{t_{bf}}\right)^{0.2} = 0.964\]

\[\Delta\sigma_{C,k} := \Delta\sigma_C \cdot k_s = 107.99 \frac{N}{mm^2}\]

\[\Delta\sigma_{C,d} := \frac{\Delta\sigma_{C,k}}{\gamma_C} = 86.392 \frac{N}{mm^2}\]

**FATIGUE STRESS RATE**

The fatigue stress rate may be derived according to Eurocode with the factors \(\lambda\) and \(\phi_2\). While \(\phi_2\) is an oscillation coefficient which is given with 1.0 for road bridges, \(\lambda\) is an adjustment factor being determined as the result of multiplication of several values \(\lambda_1\) to \(\lambda_4\).

\[\Delta\sigma_{E2} := \lambda \cdot \phi_2 \cdot \Delta\sigma_p\]

\[\phi_2 := 1\]

**Adjustment factor \(\lambda\):**

\(\lambda_1\) - Span coefficient
\(\lambda_2\) - Traffic intensity coefficient \(\lambda := \lambda_1 \cdot \lambda_2 \cdot \lambda_3 \cdot \lambda_4\) < \(\lambda_{\text{max}} := 1.78\)
\(\lambda_3\) - Life-time coefficient
\(\lambda_4\) - Traffic line coefficient

\(\lambda_1\) - Span coefficient

The span coefficient takes into account, that small spans have more cycles (load changes) than elements with bigger spans. For continuous beams, the decisive length is the span of the field:

\[L_f := 24.2\text{m}\]

\[\lambda_1 := 2.55 - 0.7 \left(\frac{L_f}{m} - 10\right) \frac{1}{70} = 2.408\]
\( \lambda_2 \) - Traffic intensity coefficient
If there is no decified data for the traffic intensity, \( \lambda_2 \) may be chosen as:
\[
\lambda_2 = 1.1
\]

\( \lambda_3 \) - Life-Time coefficient
Simplified, the factor for Life-Time can be chosen as:
\[
\lambda_3 = 1.0
\]

\( \lambda_4 \) - Traffic Lane coefficient
With one truck lane, the coefficient is
\[
\lambda_4 = 1.0
\]

\[
\lambda := \lambda_1 \cdot \lambda_2 \cdot \lambda_3 \cdot \lambda_4 = 2.649 \quad > \quad \lambda_{\text{max}} = 1.78 \quad \rightarrow \quad \lambda := \lambda_{\text{max}} = 1.78
\]

\[
\Delta \sigma_{E2} := \lambda \cdot \phi_2 \cdot \Delta \sigma_p \quad \rightarrow \quad \Delta \sigma_p \text{ has to multiplied with: } \lambda \cdot \phi_2 = 1.78
\]

Beam 1/ Weld 29 (B1-W1):
\[
\Delta \sigma_{p,1.1} := 15.80 \cdot \frac{N}{\text{mm}^2}
\]
\[
\Delta \sigma_{E2,1.1,d} := \frac{\lambda \cdot \phi_2 \cdot \Delta \sigma_{p,1.1}}{\gamma_{E2}} = 28.124 \cdot \frac{N}{\text{mm}^2}
\]

\[
\frac{\Delta \sigma_{E2,1.1,d}}{\Delta \sigma_{C,d}} = 0.326 < 1.0 \quad \text{fulfilled}
\]

Beam 1/ Weld 26 (B1-W4):
\[
\Delta \sigma_{p,1.2} := 14.76 \cdot \frac{N}{\text{mm}^2}
\]
\[
\Delta \sigma_{E2,1.2,d} := \frac{\lambda \cdot \phi_2 \cdot \Delta \sigma_{p,1.2}}{\gamma_{E2}} = 26.273 \cdot \frac{N}{\text{mm}^2}
\]

\[
\frac{\Delta \sigma_{E2,1.2,d}}{\Delta \sigma_{C,d}} = 0.304 < 1.0 \quad \text{fulfilled}
\]

Beam 1/ Weld 25 (B1-W5):
\[
\Delta \sigma_{p,2.2} := 9.28 \cdot \frac{N}{\text{mm}^2}
\]
\[
\Delta \sigma_{E2,2.2,d} := \frac{\lambda \cdot \phi_2 \cdot \Delta \sigma_{p,2.2}}{\gamma_{E2}} = 16.518 \cdot \frac{N}{\text{mm}^2}
\]

\[
\frac{\Delta \sigma_{E2,2.2,d}}{\Delta \sigma_{C,d}} = 0.191 < 1.0 \quad \text{fulfilled}
\]
Beam 2/ Weld 20 (B2-W2):
\[ \Delta \sigma_{p1.1} := \frac{20.30}{mm^2} \]
\[ \Delta \sigma_{E21.1.d} := \frac{\lambda \cdot \phi_2 \cdot \Delta \sigma_{p1.1}}{\gamma_{E2}} = \frac{36.134}{mm^2} \]
\[ \frac{\Delta \sigma_{E21.1.d}}{\Delta \sigma_{C.d}} = 0.418 < 1,0 \quad \text{fulfilled} \]

Beam 2/ Weld 17 (B2-W5):
\[ \Delta \sigma_{p1.2} := \frac{13.52}{mm^2} \]
\[ \Delta \sigma_{E21.2.d} := \frac{\lambda \cdot \phi_2 \cdot \Delta \sigma_{p1.2}}{\gamma_{E2}} = \frac{24.066}{mm^2} \]
\[ \frac{\Delta \sigma_{E21.2.d}}{\Delta \sigma_{C.d}} = 0.279 < 1,0 \quad \text{fulfilled} \]

Beam 2/ Weld 16 (B2-W6):
\[ \Delta \sigma_{p2.2} := \frac{9.33}{mm^2} \]
\[ \Delta \sigma_{E22.2.d} := \frac{\lambda \cdot \phi_2 \cdot \Delta \sigma_{p2.2}}{\gamma_{E2}} = \frac{16.607}{mm^2} \]
\[ \frac{\Delta \sigma_{E22.2.d}}{\Delta \sigma_{C.d}} = 0.192 < 1,0 \quad \text{fulfilled} \]

5.2 Annex 2 – FEM-Model un-strengthened System

(See D4.4)
5.3 Annex 3 – Traffic control proposed during Fixed Load Testing