Fast and Effective Solution for Steel Bridges Life-Time Extension

D5.5 FASSTbridge technical, environmental and cost benefit report – Study case

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Glossary

Acronym	Full name
AASHTO	American Association of State Highway Transportation Officials
CFRP	Carbon Fiber Reinforced Polymer
FASSTbridge	FASt and efficient methodology for STeel Bridges Life-Time Extension
FCG	Fatigue Crack Growth
FE	Finite Element
HM	High Modulus
NM	Normal Modulus
UHM	Ultra-High Modulus
ULS	Ultimate Limit State
SLS	Serviceability Limit State
BR	Bonded Reinforcement
UR	Un-bonded Reinforcement
PUR	Pre-stressed Un-bonded Reinforcement
PBR	Pre-stressed Bonded Reinforcement

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 is the result of the works developed within *task 5.4 Results and conclusions: technical, environmental and economic assessment of the FASSTbridge solution.*

This Deliverable 5.5 links directly to D5.3 and D5.4:

D5.3 Implementation of FASSTbridge strengthening system in Jarama Bridge (M28-DRAGADOS): describes the strengthening process carried out on site in the Jarama Bridge.

D5.4 Test and monitoring layout. (M28-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) panel.

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

This deliverable aims at giving main conclusions regarding the on site application of FASSTbridge solution for Jarama bridge and applying some of the methods proposed in the work package 4 for cost benefit and life cycle assessment of such operations.

It is important to note that a part of Jarama bridge has been reinforced and that the application is mainly intended to assess the ease of application of the reinforcement solution and to check its efficiency. Different reinforcement configurations have been tested on six locations of one span. Therefore, it must be pointed out, that FASSTbridge methodology has not been completely applied, as it would have implied working on the entire structure.

Yet, the completed operations allowed gathering better data for:

- The duration of FASSTbridge reinforcement application on site,
- The cost of FASSTbridge reinforcement application,
- The needed conditions for such application,
- The efficiency of the reinforcement in comparison with the expectations,
- The advantages and drawbacks of the operations,
- The issues that still need to be solved for on site applications.

This is presented in the first two parts. The third and the fourth parts are dedicated to the applications of cost-benefit and life cycle assessment methodologies to Jarama case.

3 Major findings during prototype application

3.1 Duration of application

As was detailed in derivable D5.3 of this same WP, the schedule of works finally accomplished had some deviations from the original program (Figure 1), but at the end it was possible to maintain the milestone for the second load test.

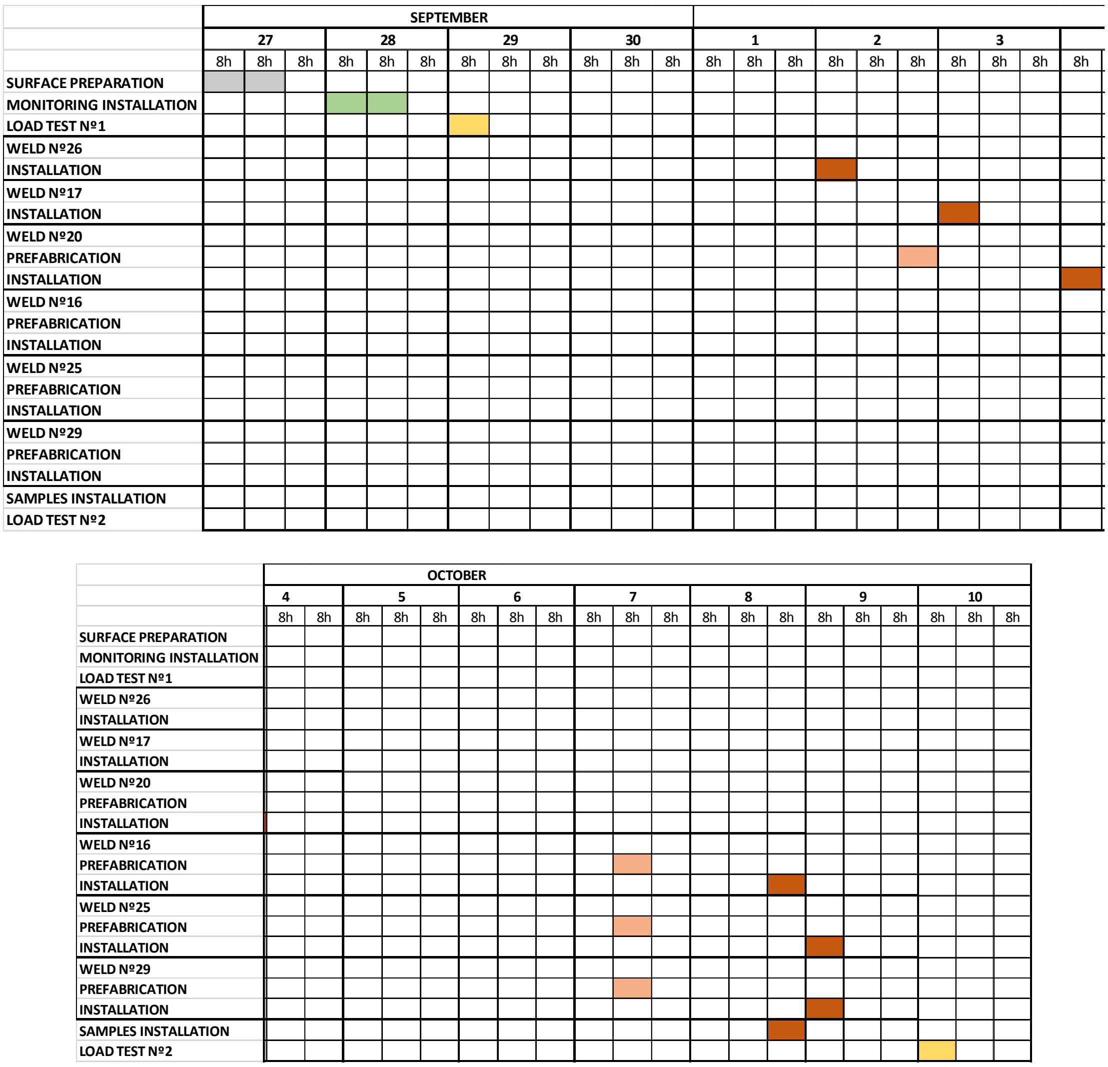

Figure 1: Real schedule.

The duration of the different activities was:

- Surface preparation: 16 hours.
- Monitoring installation: 16 hours.
- Load test nº1: 4 hours.
- WELD 26:
    - Installation weld nº26: 6,5 hours.

- WELD 17:
    - Installation weld nº17: 6,5 hours.
- WELD 20:
    - Prefabrication weld nº20: 2,0 hours.
    - Installation weld nº20: 6,0 hours.
- WELD 16:
    - Prefabrication weld nº16: 2,5 hours.
    - Installation weld nº16: 5,5 hours.
- WELD 25:
    - Prefabrication weld nº25: 2 hours.
    - Installation weld nº25: 5,0 hours.
- WELD 29:
    - Prefabrication weld nº29: 1,0 hour.
    - Installation weld nº29: 4,5 hours.
- Load test nº2: 3 hours.

The equivalent in working days is: 9 days, including:

- surface preparation: 1 day.
- monitoring installation: 1 day.
- load tests: 1 + 1 = 2 days
- CFRP prefabrication and installation: 5 days.

3.2 Cost of application

The next table (Table 1) includes the costs associated with the strengthening intervention in Jarama Bridge.

Table 1 Strengthening intervention costs

FASSTBRIDGE STRENGTHENING INTERVENTION		
Strengthening implementation	Material costs	
	Carbon fiber	13.101 €
	Adhesive	207 €
	Minor materials	775 €
	Labor costs	10.415 €
	Machinery	7.410 €
	Fuel for the machinery	1.780 €
	Post curing heat application	3.750 €
	Traffic diversion (4 nights)	4.400 €
	Health and safety coordinator	374 €
Load test 1	Machinery	1.800 €
	Traffic diversion	1.100 €
Load test 2	Machinery	1.800 €
	Traffic diversion	1.100 €
Total costs		**48.012 €**

The strengthening implementation costs cover all the associated costs:

- Material costs:
    - Carbon fiber: Carbolam THN450 from Epsilon Composite (Gaillan en Medoc, France). 100 mm width and 4 mm thickness. Total length used: 66.4 m.
- Adhesive: UREPOX EXTRA 2C and UREPOX EXTRA B.
- Labor costs: works were carried out by 3 workers.
- Machinery used:
    - Two compressors
    - Lighting system
    - Lifting platform
    - Sandblasting equipment
    - Small tools

3.3 Production rates

The quantities involved in the demonstration retrofitting were:

- Surface preparation: 7,56 m^2.
- Weld grinding: 4,2 m.
- CFRP installation: 58 m of 100 mm width laminates (5,8 m^2)

With the durations indicated previously in this document (Table 2):

Table 2 Works duration

	m2	m	days	hours		m/day	m/hour	m^2/day	m^2/hour
Surface preparation	5,8	58	2	16		29,00	3,63	2,90	0,36
Installation	5,8	58	5	41,5		**11,60**	**1,40**	1,16	0,14
TOTAL	5,8	58	7	57,5		**8,29**	**1,01**	0,83	0,10

It is important to note that this is the first application, and this data (duration and rates) should decrease for next applications as the applicants will get more used to it and as specific tools and procedures may ease the process.

4 Analysis of the system. Technical appraisal

This paragraph will gather the encountered main advantages and drawbacks of FASSTbridge solution after Jarama application. It will also propose possible improvements of the solution, and present main conclusions regarding the efficiency with regards to strain measurements and theoretical expectations.

In order to be able to compare in next steps more traditional solution with FASSTbridge solution, a reinforcement design with additional steel plates instead of bonded UHM CFRP plates was realized by LAP. Steel plates solution design to obtain an equivalent stress reduction in the 6 locations is given in Figure 2.

Configuration with steel plates (S 275, EN 1993)

Weld No.	Weld code	thickness of steel plates [mm]	width of steel plates [m]	Length of steel plates [m] *2
29	B1 - W1	11	0,6	1,2
26	B1 - W4	7	0,6	1,2
25	B1 - W5	12	0,6	1,2
20	B2 - W2	11	0,6	1,2
17	B2 - W5	7	0,6	1,2
16	B2 - W6	12	0,6	1,2

Figure 2: Proposed reinforcement with steel plates.

4.1 Advantages of FASSTbridge reinforcement solution

The retrofitting system design, developed, tested and demonstrated in this project is the alternative to the standard system which would be a retrofitting based on additional welded or bolted steel plates. Here we try to explain the different advantages of FASSTbridge solution, mainly compared to structural steel welded and bolted solution.

FASSTbridge solution is **less intrusive** to existing bridge structure compared to steel bolted or welded retrofit. In FASSTbridge solution the retrofit is attached with an adhesive to the existing steel plates, with no affection to the conditions of the existing material, element or fatigue detail. On the contrary, welded or bolted steel plate solution are intrusive, with potential of significant affection to existing material, element or fatigue detail.

CFRP can be utilized on mild steel or iron with **poor weldability**. Structural steel used in the past, especially before 1970s, usually have very poor weldability, which directly discards the possibility of considering a retrofit based on additional welded steel plates. In this cases, FASSTbridge solution is clearly a serious alternative, as the only parameter which has to be considered and prepared of the existing structure is the surface in order to guarantee a minimum bonding properties.

Lightweight CFRP does not introduce significant additional weight to existing bridge structure compared to additional steel plates.

CFRP laminates are around 80% lighter than structural steel. In addition, young modulus is double. As a result, taking into account the quantity of material needed, FASSTbridge retrofit system is much lighter than the one with welded or bolted additional steel plates.

In the case of the demonstration in Jarama bridge, the figures are as follow in the next figures (Figure 3, Figure 4, Figure 5):

	t/m^3
Steel	7,85
CFRP	1,57
Adhesive	1,8

Figure 3 Density of materials

CFRP				
L	b	t	V	p
[m]	[mm]	[mm]	[m^3]	[kg]
1,2	100	4	0,00048	0,7536
1,4	100	4	0,00056	0,8792
1,6	100	4	0,00064	1,0048

Adhesive				
L	b	t	V	p
[m]	[mm]	[mm]	[m^3]	[kg]
1,2	100	2	0,00024	0,432
1,4	100	2	0,00028	0,504
1,6	100	2	0,00032	0,576

Option	FASSTbridge		
	Weight	nº laminates	Total weight
	[kg]	[ut]	[kg]
5x1	1,19	5	5,93
4x2	2,57	4	10,28
3x3	4,15	3	12,45

Figure 4 FASSTbridge configuration. Weight of the solution

Option	Structural welded steel							
	L	b	t	V	p_{steel_plate}	p_{fillet_weld}	P_{TOTAL}	Comparison
	[m]	[mm]	[mm]	[m^3]	[kg]	[kg]	[kg]	[%]
5x1	1,2	600	7	0,00504	39,56	0,69	40,26	679%
4x2	1,2	600	11	0,00792	62,17	1,71	63,88	622%
3x3	1,2	600	12	0,00864	67,82	2,03	69,86	561%

Figure 5 Structural steel welded plates solution

As it can be observed in the previous figures, FASSTbridge solution is between 500% and 700% lighter than additional structural steel welded plates. This can has a huge impact in the additional weight introduced into the existing structure (which in some cases could be significant), and also in construction, where CFRP retrofit requires lighter equipment for erection.

Durability is another positive advantage for CFRP solutions. No risk of corrosion compared to traditional steel plates. In FASSTbridge system, as well as any other CFRP based retrofit system, there is the need of some kind of external protection (paint or similar) against external weather conditions (UV rays, rain, etc.) to ensure an adequate durability of the solution. Some kind of inspection and maintenance activities are also necessary, similar to what is necessary for a steel welded or bolted solution.

Faster construction schedule for CFRP retrofit. The production rates which were achieved at the end of the installation of the demonstration, close to 3 to 4 hours per weld, are much higher than the ones expected for a structural steel welded or bolted solution. In the case of the welded solution, the number of hours needed for installation, surface preparation apart, but including plates preparation, plates presentation, plates pre-fixation and welding, the duration could be around 7 to 8 hours, double than for FASSTbridge solution. In addition, an inspection (the day after) of the welds would be necessary (non-destructive, such as magnetic particle or ultra-sound), which would imply not only more time, but also could imply the need for some reparation works (quite common when welding onsite), which again would imply extra time and extra cost. As a conclusion, steel welded solution could be between 2 to 3 times slower than FASSTbridge solution.

Faster means not only a reduction in time, but also a reduction in costs, risks, traffic disruptions, etc.

Several layers of CFRP can be prefabricated and/or used. This implies efficiency in terms of logistic, time and risks management.

4.2 Drawbacks

Adhesive workability. During installation of the solution the adhesive developed for this project has been found to be difficult to work with. The pot life is short, but also the consistency is variable depending of the thickness, and during installation was too fluid at some points. Additional research on the adhesive may help improve workability.

Surface geometry. During installation of the solution, it has been found that the CFRO plates are very rigid, in which case the surface geometry of the plates to be retrofitted and the length has a direct impact in the application, having to deal with different adhesive thickness and adaptable fixation systems to deal with this issue.

Post-curing treatment. This necessity implies extra time and extra cost, in addition to the fact that nowadays there is no commercial system directly applicable at a reasonable scale to this solution.

Ultra High Modulus CFRP. The necessity of UHM (>460 GPa) CFRP laminates implies not only more cost for the solution but also some potential problems with supply of material (fewer suppliers, fewer stock available).

4.3 Possible improvements

During design, testing and demonstration of FASSTbridge solution and methodology some possible improvements have been detected, some of which are listed below.

- Initial results indicate CFRP retrofit may be applied with no interruption to traffic.
- More research needed to improve workability of adhesive and possible use of standard modulus CFRP plates
- Further adhesive refinement may eliminate need for post-curing treatment (on-site heating).
- Possibility to utilize pre-stressed CFRP retrofit.
- Development of a standardized installation system.
- Possibility of developing a pre-fixation and adhesive injection system.

4.4 Analysis of the measurements and comparison with the expectations

The main results from the monitoring, stress range in every weld, were the following:

Table 3: Monitoring results. Point 1 (near the weld)

Weld	Static before	Static after	Difference	Dynamic before	Dynamic after	Difference
16-1	71	56	-21 %	60	45	- 25 %
17-1	68	56	-18 %	75	62	- 17 %
20-1	84	59	-30 %	80	56	- 30 %
25-1	69	51	-26 %	65	53	- 18 %
26-1	84	67	-20 %	84	77	- 8 %
29-1	77	58	-25 %	71	51	- 28 %

Table 4: Monitoring results. Point 2 (out of reinforced length)

Weld	Static before	Static after	Difference	Dynamic before	Dynamic after	Difference
16-2	69	59	-14 %	60	52	- 13 %
17-2	82	71	-13 %	92	80	- 13 %
20-2	77	66	-14 %	74	62	- 16 %
25-2	63	55	-13 %	60	55	- 8 %
26-2	85	72	-15 %	91	88	- 3 %
29-2	71	63	-11 %	64	61	- 5 %

Actual reduction of average strain/stress of 22%; larger than calculated theoretical decrease of 13% in the previous design of the retrofitting.

Table 5: Comparison between expected and monitored.

	PREVIOUS DESIGN			DEMONSTRATION		
Weld	**Before**	**After**	**Difference**	**Before**	**After**	**Difference**
16-1	16,61	13,08	**-21%**	71	56	**-21%**
17-1	24,07	22,3	**-7%**	68	56	**-18%**
20-1	36,13	30,62	**-15%**	84	59	**-30%**
25-1	16,52	12,83	**-22%**	69	51	**-26%**
26-1	26,26	25,21	**-4%**	84	67	**-20%**
29-1	28,13	25,72	**-9%**	77	58	**-25%**
		Average	-13%		Average	-23%

Altough there is some dispersion in the results, from 18% reduction in weld 17 to 30% reduction in weld 20, there is a better correlation between similar arrangements of retrofittings:

- 5 x1 : 18% and 20% reduction. Average 19%.
- 4 x 2: 30% and 25% reduction. Average 28%.
- 3 x 3: 21% and 26% reduction. Average 23%.

In this sense, it seems that the multi-layer solution is more effective than the one-layer solution.

Also, the multi-layer solution results of monitoring are more similar to the ones expected from theoretical design compared to one-layer solution results.

There are several variables that could affect the retrofitting performance and therefore the resuts of the monitoring, most of them during installation. For this reason, during installation different parameters were registered, in order to be able to analyse its influence in the retrofitting permormance during monitoring and load test nº2.

In the following tables, an excercise of analisys and correlation of the results with some of the variables during installation is made.

The variables included are:

- Adhesive thicness.
- Order of installation.
- Traffic on the bridge.
- Ambient temperature.
- Ambient humidity.

Adhesive thickness: due to the difference surface geometry of the steel plates where the CFRP laminates had to be attached, different thickness of adhesive were applied in the different locations. Altough at laboratory tests the thickness of the adhesive was not found to be affecting the performance of the system, during installation it was considered that this could affect final behaviour.

In the table below (Table 6) we can find the results ordered from the minimun thickness applied (2 mm) to the higher (4 mm). It can not be found a clear correlation between adhesive thickness and results of the monitoring, which would be coherent with the laboratory tests, with the expception of weld 26 which had a 8% improvement in dynamic behaviour with 4 mm adhesive thickness.

Table 6: Results analysis and correlation. Adhesive thickness.

THICKNESS											
	Static			Dynamic			Thickness	Order of	Traffic	Temp	Humidity
Weld	Before	After	Difference	Before	After	Difference	[mm]	installation	yes/no	[ºC]	[%]
17-1	68	56	-18%	75	62	-17%	2	2	NO	18	73
20-1	84	59	-30%	80	56	-30%	2	3	NO	20	50
29-1	77	58	-25%	71	51	-28%	2	6	At the end	12	58
16-1	71	56	-21%	60	45	-25%	3	4	YES	18	50
25-1	69	51	-26%	65	53	-18%	3	5	NO	14	58
26-1	84	67	-20%	84	77	-8%	4	1	At the end	18	64

Order of installation: while installation is progressing the learning curve can have an impact not only in duration of the application but also in the quality and final performance of the reinforcement. In this case, there is a little correlation, improving the results while progressing the installation, but as it can be observed there is a coincidence between the order of installation and the arrangement of the retrofitting, commented before, so it is not possible to establish a clear correlation between the order of installation and the results of the monitoring, tough it could have had a small influence.

Table 7: Results analysis and correlation. Order of installation.

ORDER OF INSTALLATION											
	Static			Dynamic			Thickness	Order of	Traffic	Temp	Humidity
Weld	Before	After	Difference	Before	After	Difference	[mm]	installation	yes/no	[ºC]	[%]
26-1	84	67	-20%	84	77	-8%	4	1	At the end	18	64
17-1	68	56	-18%	75	62	-17%	2	2	NO	18	73
20-1	84	59	-30%	80	56	-30%	2	3	NO	20	50
16-1	71	56	-21%	60	45	-25%	3	4	YES	18	50
25-1	69	51	-26%	65	53	-18%	3	5	NO	14	58
29-1	77	58	-25%	71	51	-28%	2	6	At the end	12	58

Traffic on the bridge: from the beginning of the project the absence of traffic on the bridge while installation of the retrofitting (installation and post-curing) was imposed, based on previous experience with epoxy adhesive based retrofitting. The reason behind this is that the stress range and/or vibrations in the structure caused by the traffic could affect the bonding of the adhesive while curing. With this premise, the installation of the demonstration was designed.

The first obstacle found was that it was not possible to obtain permission for total traffic diversion on the structure during day nor during night. The only permission obtained was a partial diversion, from 2 carriageways to only 1 carriageway, during night periods of 6 to 7 hours. This condition was consulted to the rest of the partners of the project for approval.

The facts were:

- As there are two beams, one under each carriageway, although they are cross-connected the traffic of one carriageway has greater impact in the beam underneath it that in the other beam.
- During night the traffic on the bridge was expected to be very light. In any case, it was decided to monitor the traffic while installation to confirm this point.

After this analysis, the approval was obtained and it was decided to work with only partial diversion on the bridge.

A second obstacle was found during installation, with adhesive quantity and the need to order an extra shipment. As a consequence, the last 3 welds had to be retrofitted in just one day, the last one before the milestone of the second load test. Although a detailed installation programme was developed and prefabrication was done at workshop prior to onsite installation, one of the welds, nº16, had to be installed with full traffic over the structure.

Also, for some other welds, the first ones to be installed, welds nº26 and nº29, it was not possible to fulfil the total post-curing treatment within the traffic diversion window give, so the last minutes of post-curing and of course the cooling had to be done with full traffic over the structure.

Looking at the table below (Table 8), there is no clear correlation between traffic on the structure during installation and/or post-curing and structural behaviour of the retrofitting. In fact, weld nº16 had a reduction in stress of 21%, same as expected in previous design, with no negative impact from the fact that it was fully installed and cured with full traffic over the structure. Welds nº26 and 29 have also good behaviour.

With the support of these results, it is possible to think that the system developed in this project could be installed with no traffic restriction at all, at less in structures with a minimum stiffness and a limited stress range due to traffic loading, which would result in a very interesting system for infrastructure owners and at the end for infrastructure users.

Table 8: Results analysis and correlation. Traffic on the bridge.

TRAFFIC											
	Static			Dynamic			Thickness	Order of	Traffic	Temp	Humidity
Weld	Before	After	Difference	Before	After	Difference	[mm]	installation	yes/no	[ºC]	[%]
16-1	71	56	-21%	60	45	-25%	3	4	YES	18	50
26-1	84	67	-20%	84	77	-8%	4	1	At the end	18	64
29-1	77	58	-25%	71	51	-28%	2	6	At the end	12	58
17-1	68	56	-18%	75	62	-17%	2	2	NO	18	73
20-1	84	59	-30%	80	56	-30%	2	3	NO	20	50
25-1	69	51	-26%	65	53	-18%	3	5	NO	14	58

Ambient temperature: temperature of installation is always relevant when working with epoxy-based adhesives. Low ambient temperatures can have a negative effect in the behaviour of the adhesive and as a result a negative effect in the structural behaviour of the retrofit. In this case, the ambient temperature varied from 12 degrees to 20 degrees. In the table below (Table 9) is not possible to establish a clear correlation between the structural behaviour of the retrofit and the ambient temperature during installation. The fact that the system developed in this project includes a final post-curing treatment consisting in 1 hour at controlled temperature of 80ºC could be a fact which would reduce possible negative effects of different, especially low, temperatures during installation.

Table 9: Results analysis and correlation. Ambient temperature.

TEMPERATURE											
	Static			Dynamic			Thickness	Order of	Traffic	Temp	Humidity
Weld	Before	After	Difference	Before	After	Difference	[mm]	installation	yes/no	,	[%]
29-1	77	58	-25%	71	51	-28%	2	6	At the end	12	58
25-1	69	51	-26%	65	53	-18%	3	5	NO	14	58
16-1	71	56	-21%	60	45	-25%	3	4	YES	18	50
17-1	68	56	-18%	75	62	-17%	2	2	NO	18	73
26-1	84	67	-20%	84	77	-8%	4	1	At the end	18	64
20-1	84	59	-30%	80	56	-30%	2	3	NO	20	50

Ambient humidity: also humidity was controlled and registered during the installation of the different retrofitting. The values registered range from 50% to 73%, mainly influenced by the presence of the river nearby. In this case, there is a kind of correlation, where the behaviour of the retrofitting decreases as the humidity increases. This has sense as high humidity can have a negative effect in the structural behaviour when working with epoxy-based adhesives.

Table 10: Results analysis and correlation. Ambient humidity.

HUMIDITY											
	Static			Dynamic			Thickness	Order of	Traffic	Temp	Humidity
Weld	Before	After	Difference	Before	After	Difference	[mm]	installation	yes/no	[ºC]	[%]
16-1	71	56	-21%	60	45	-25%	3	4	YES	18	50
20-1	84	59	-30%	80	56	-30%	2	3	NO	20	50
25-1	69	51	-26%	65	53	-18%	3	5	NO	14	58
29-1	77	58	-25%	71	51	-28%	2	6	At the end	12	58
26-1	84	67	-20%	84	77	-8%	4	1	At the end	18	64
17-1	68	56	-18%	75	62	-17%	2	2	NO	18	73

As a conclusion, after all these analysis, the following considerations are extracted:

- Traffic on the structure does not appear to have any negative impact in the retrofitting structural behaviour.
- The arrangement of each solution seems to have some impact in the behaviour, having better results in the multi-layer solutions.
- Ambient temperature does not appear to have any negative impact in the retrofitting structural behaviour, while humidity could have a negative impact.
- Adhesive thickness should not have any impact in the retrofitting structural behaviour.

5 Cost benefit analysis

On the basis of the presented data, the proposed methodology (in WP4) for cost benefit analysis of the solution was applied. It intended to:

- Assess the direct cost,
- Assess the indirect cost,
- Compare more traditional solution with FASSTbridge solution.

5.1 Appraisal of the direct economic gain

Table 11 summarizes the gain in remaining fatigue life for the different locations of interest of the Jarama Bridge on the basis of the application of the remaining service life tool developed in Task 2.1.

Table 11: Remaining fatigue life assessment.

Weld No.	Weld code	Remaining Fatigue Life (years)	
		Unstrengthened Girders	CFRP Strengthened Girders [1]
29	B1 - W1	> 100+ years	> 100+ years
26	B1 - W4	> 100+ years	> 100+ years
25	B1 - W5	> 100+ years	> 100+ years
20	B2 - W2	40 - 50 years	120 - 130 years
17	B2 - W5	> 100+ years	> 100+ years
16	B2 - W6	> 100+ years	> 100+ years

[1] Using 20% lower stress range with CRFP retrofit

It is observed that the most critical location is B2-W2 (with a remaining fatigue life estimated at 40-50 years before strengthening). For the other 5 locations, there was no real issue with fatigue concerning CFRP reinforcement and strengthening was performed more to test different strengthening configurations and check mechanical behaviour.

Even if only one location was critical for the Jarama Bridge, fatigue failure of one girder in 40-50 years (in this case B2-W2) may lead to the replacement of the entire bridge for safety reasons and considering the age of this bridge at that time. Postponing the end of service life by extending the remaining fatigue life can represent a significant challenge in this perspective. The increase of service life from 40-50 years to 120-130 years is considered thereafter as illustration.

Moreover, to determine the minimal direct gain, 50 years and 120 years with unstrengthened Girders and CFRP Strengthened Girders, are considered as remaining fatigue service life respectively (see Table 3).

The "Do Nothing" strategy (DN) is characterized by the net present value (NPV) (discounted demolition/reconstruction costs assumed to occur at T_f^0) :

$$NPV_0 = \frac{C_f}{(1+r)^{T_f^0}} \qquad (1)$$

The "CFRP strengthening" strategy is characterized by the net present value (NPV) (discounted demolition/reconstruction costs assumed to occur at T_f) :

$$NPV_1 = \frac{C_f}{(1+r)^{T_f}} + C_{M,CFRP} \qquad (2)$$

Where $C_f =$ cost of demolition/reconstruction of the entire bridge, $T_f^0 =$ end of life time of the bridge with doing nothing, $T_f =$ end of life time of the bridge with CFRP strengthening, $C_{M,CFRP} =$ cost of the strengthening action (calculated in this case study by using information of Table 1).

Assuming $T_f^0 = 40$ years, $T_f = 120$ years, a unit demolition/reconstruction cost of 800€/m² with an average area of 1093m² for the Jarama Bridge, $NPV_0 \approx 325{,}000€$, $NPV_1 \approx 130{,}000€$, and the direct gain in postponing the end of service life (with a strengthening cost of 48,000€ at the current time, see Table 1) is then $NPV_1 - NPV_0 \approx 195{,}000€$.

5.2 Indirect costs

Indirect costs include traffic delay, vehicle operating and accident costs when traffic congestion occurs due to the loss of service level during maintenance works. Traffic delay is due to the decrease of bridge capacity (in case of lane closure). Vehicle operation costs are due to the level of service loss caused by the maintenance operations on highway structures. The disruption of normal traffic causes speed reductions, increase of fuel and oil consumptions, tire wear and vehicle maintenance. Accident costs are due to the increase of accident risks, healthcare and deaths related to the change of traffic condition.

All these additional costs can be significantly decreased, even avoided when maintenance works are performed at night or if no lane closure during works.

In the case of the Jarama Bridge, the absence of traffic was needed to install FASSTbridge solution. Consequently, one traffic direction was closed alternately during night.

Figure 6 to Figure 9 show the low volume of traffic during works. No traffic congestion was observed (capacity in normal conditions can be assumed around 6,500 vehicles per hour and per lane).

Indirect costs can be seen therein as the additional costs for the bridge owner to perform works at night. In the case of the Jarama Bridge, one can consider that additional costs are due to traffic diversion (4,400€, see Table 1) and additional labour costs between night shift and day shift teams (around 3,000€).

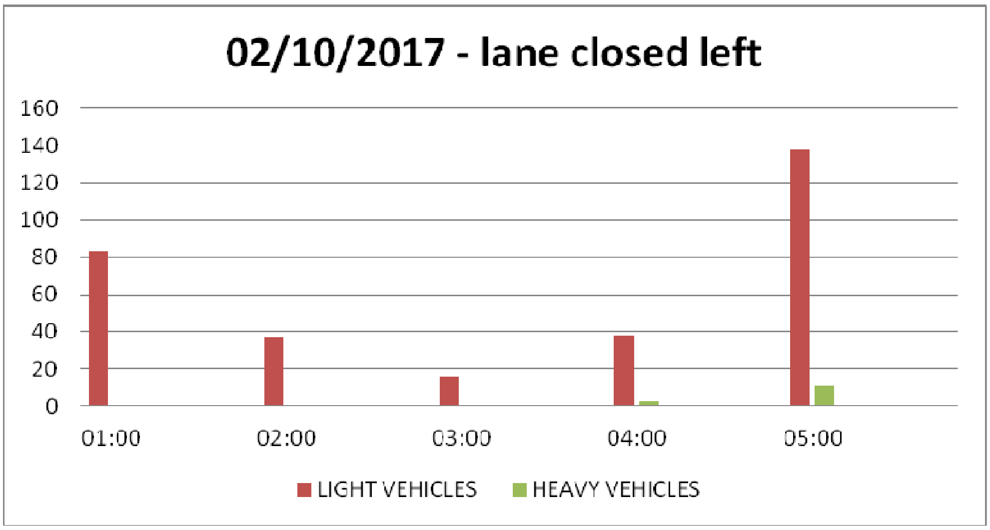

Figure 6: Traffic volume on Jarama bridge on 02/10/17 from 01:00 AM to 06:00AM.

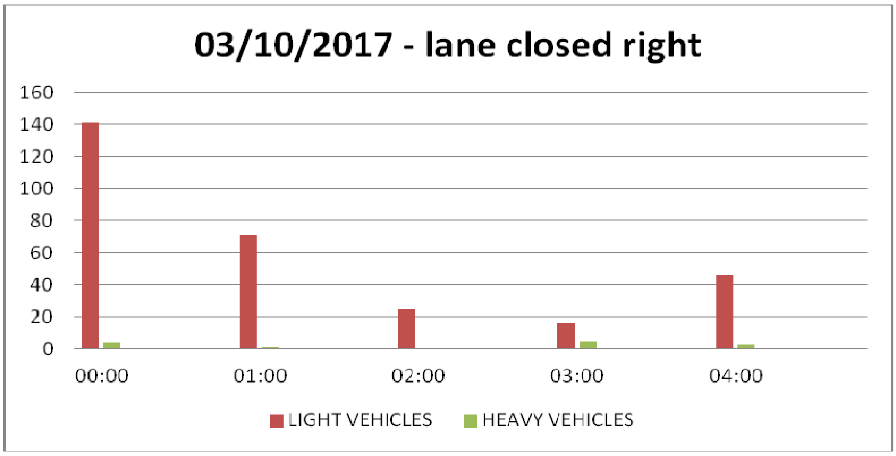

Figure 7: Traffic volume on Jarama bridge on 03/10/17 from 00:00 AM to 05:00AM.

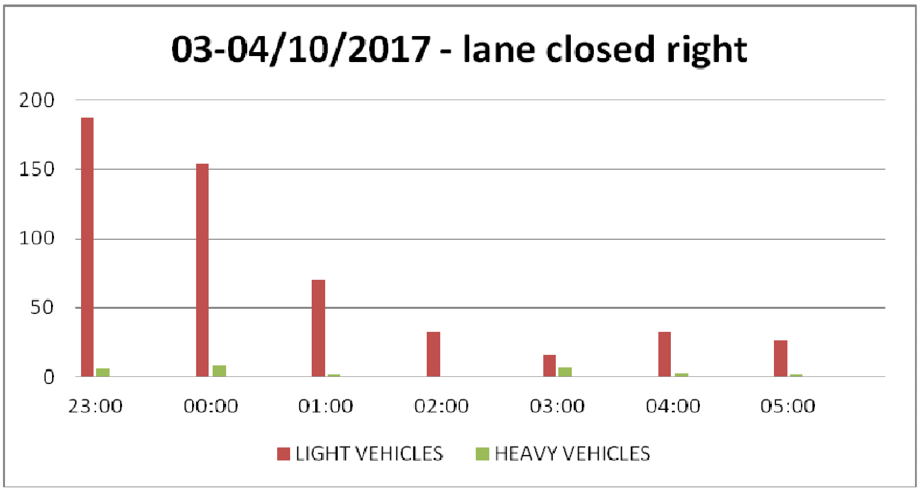

Figure 8: Traffic volume on Jarama bridge on 03-04/10/17 from 23:00 AM to 06:00AM.

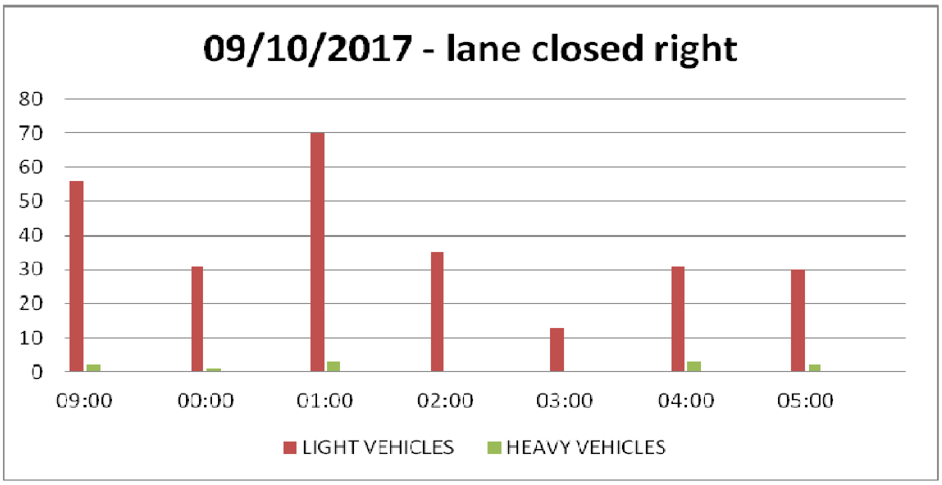

Figure 9: Traffic volume on Jarama bridge on 09/10/17 from 09:00 PM to 06:00AM.

5.3 Comparison with welded solution

Figure 10 compares labour costs between welded and steel plates solution. Labour costs in this figure details the costs of specialist workers and field engineer during night shift (NS), during extra hours of night shift (ANS) and day shift (ADS).

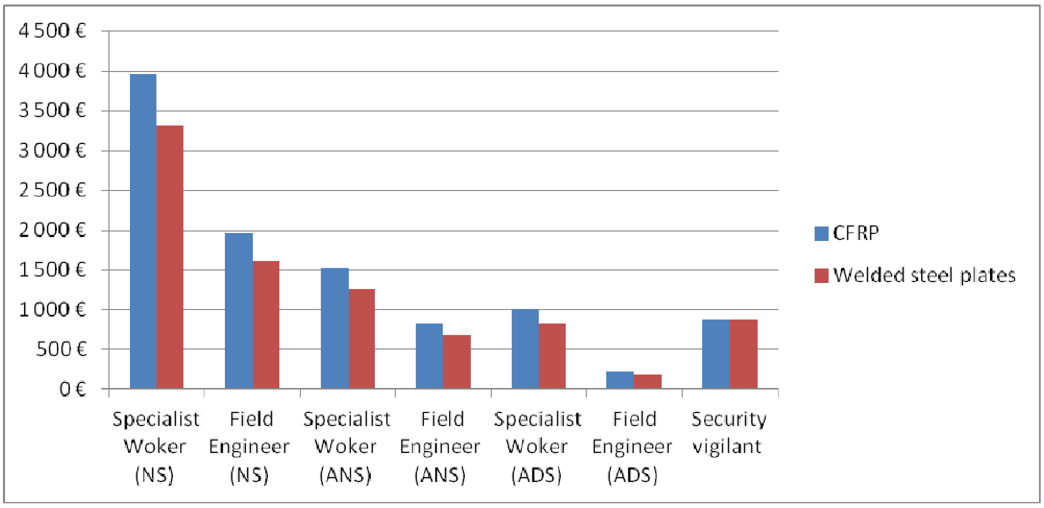

Figure 10: Comparison of manpower costs for CFRP and welded steel plates solutions.

Total labour costs is 10,415€ for CFRP against 8,760€ for welded steel plates.

Figure 11 compares the cost of equipment needed for each case of strengthening action. 7,411€ are needed for the CFRP solution against 13,620€ for welded steel plates. It is noted that there is no operated crane needed in work site when using CFRP.

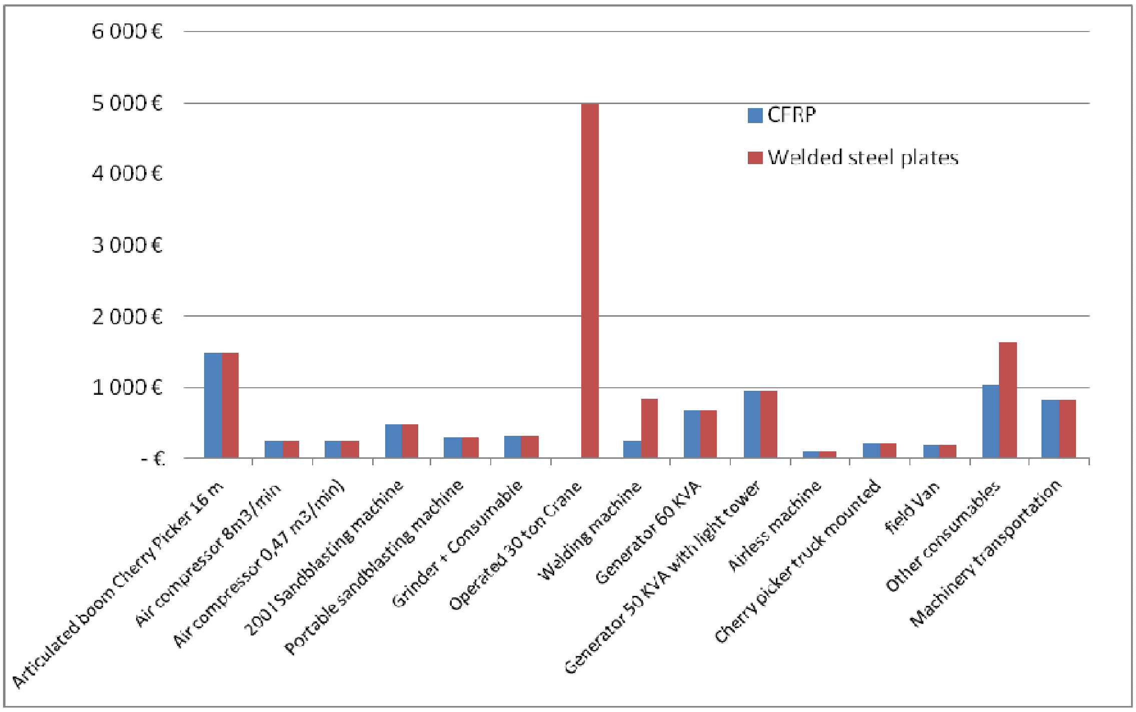

Figure 11: Comparison of equipment costs for CFRP and welded steel plates solutions.

Figure 12 shows the difference in material costs for the two considered solutions, knowing that selling price for adhesive is estimated at 207€ for the Jarama Bridge works.

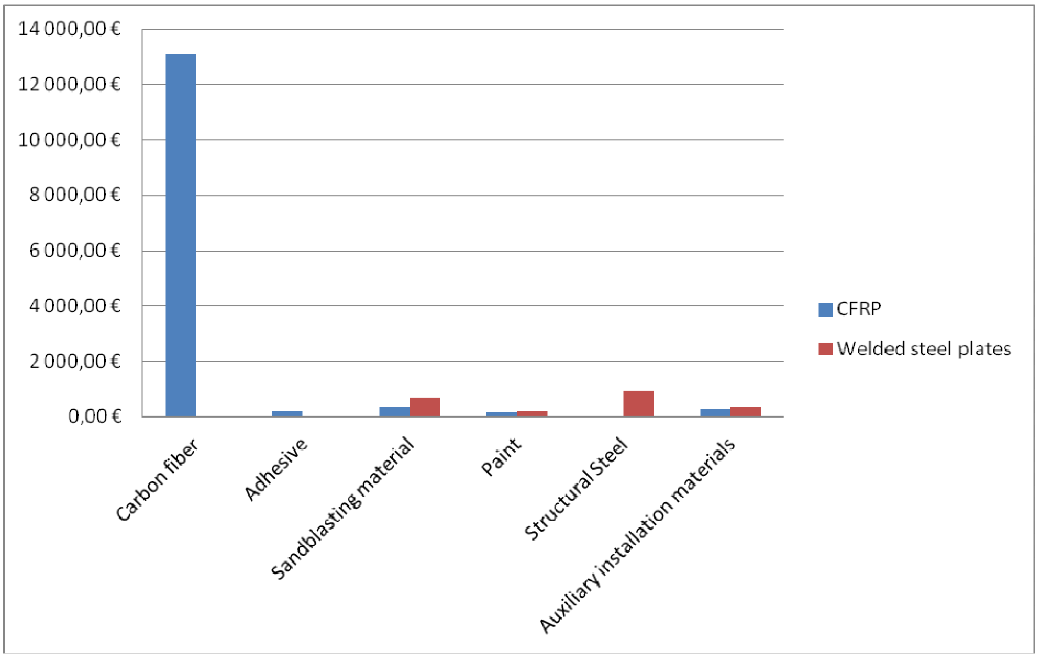

Figure 12: Comparison of material costs.

Figure 13 compares the heating system costs (3,750€ for CFRP and 3,582€ for steel plates). Differences in costs are observed, sometimes at the advantage of CFRP, sometimes at the advantage of welded steel plates. Total heating system costs are relatively similar though. Besides, the cost of fuel is the same for two maintenance solutions (1,781€).

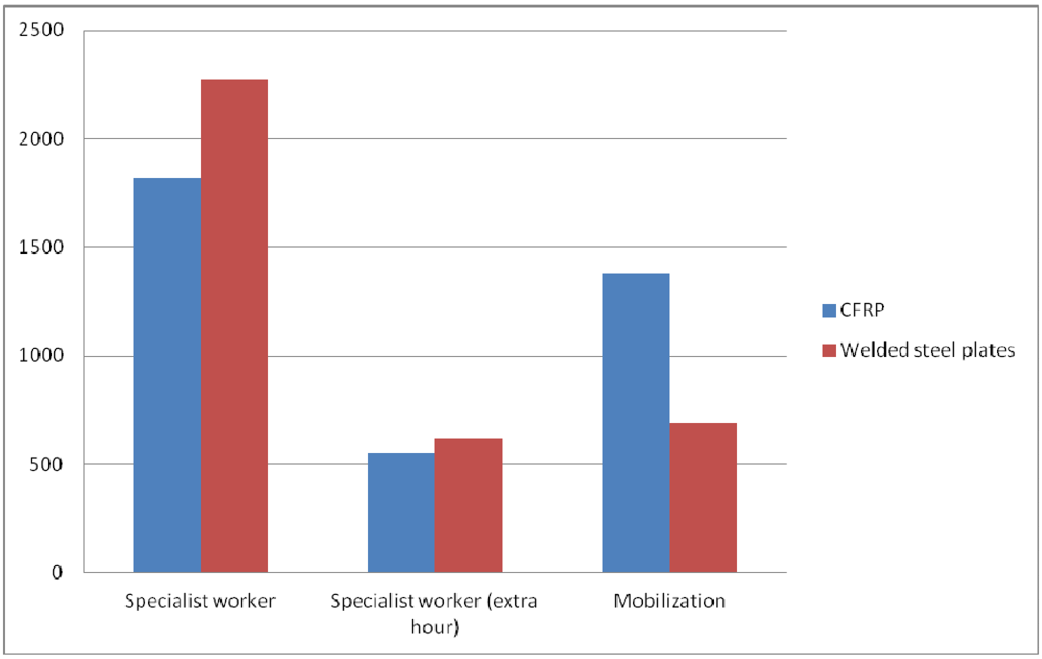

Figure 13: Comparison of heating system costs.

Finally, it appears from this economic analysis that the cost of CFRP is slightly higher than for steel plates (37440€ against 29900€). However, the former solution can find some advantage in terms of the entire execution process (swiftness of the intervention, no crane needed), making easier the transport (steel plates are heavy and difficult to handle in the worksite) and some of labour costs (when welding requires qualified and experienced workers).

More generally, experience shows that even the use of higher cost materials and methods can be very effective if they allow the repair work to be carried out with minimal or zero interruption to traffic flow, especially on bridges with intensive heavy transport circulation. For this reason, it can be stated that bridges are major structures for which decisions are dominated by traffic and commercial considerations much more than by the basic cost of executing the structural repair. These considerations are measured for each situation due to the dynamic nature of the indicators (importance of the bridge, number of users, existence of alternatives, etc.).

6 Life cycle analysis

Similarly to the cost benefit analysis, the life cycle analysis methodology was applied on the case of Jarama. Due to lack of data, only the comparison between more traditional method and FASSTbridge solution was carried out. But, from an environmental point of view, it is clear that extending the service life of a structure is highly beneficial.

6.1 Work hypotheses and data

As in the deliverable D4.6, manpower is not taken into account in LCA. The only way environmental balance of manpower can be taken into account is through the transportation of each person. In this case we don’t have this information.

We want to compare two solutions. Let’s have a look to Figure 11 and Figure 12. Differences are noted for operated 30t crane and welding machine in Figure 11 and obviously on material used and quantity of sandblasting material in Figure 12.

The following table gives the differences between the two evaluated structures.

Table 12: Assumptions of the two solutions compared.

CFRP	**Welded steel plates**
CFRP : 66,4 m	Steel : 508,68 kg
Sandblasting : 750 kg	Sandblasting : 1500 kg
	Operated 30 t crane : 40h Consumption : 30 l/hour Total : 1200 l

As in deliverable D 4.6, LCA calculations will be performed on OpenLCA software supported by Ecoinvent database, the most complete environmental database.

For each material and process in Table 4 the ecoinvent process equivalent is given in the following, except for CFRP evaluated though a home made process which was detailed in deliverable D 4.6. All these data include all upstream activities.

Sandblasting: *"gravel production crushed";* this datum is made from mined gravel round, crushed and sand.

Steel: "*Steel, low-alloyed, hot rolled*"; This datum is made using a mix of differently produced steels and hot rolling

Operated 30t crane: "*diesel burned in building machine" ;* This datum includes the inputs "building machine" for infrastructure, lubricating oil and fuel consumption, and some measured air emissions as output. We consider a PCI of 38MJ/l.

An important assumption is made because we have no informations on the fabrication process of the adhesive: we don't consider the 22,5 kg of adhesives used in the Jarama bridge.

6.2 Comparison with welded solution

Results regarding the comparison between the use of additional welded steel plates and the FASSTbridge system are shown in Figure 14. It's not the evaluation of the whole system but it is based on the differences between these two solutions.

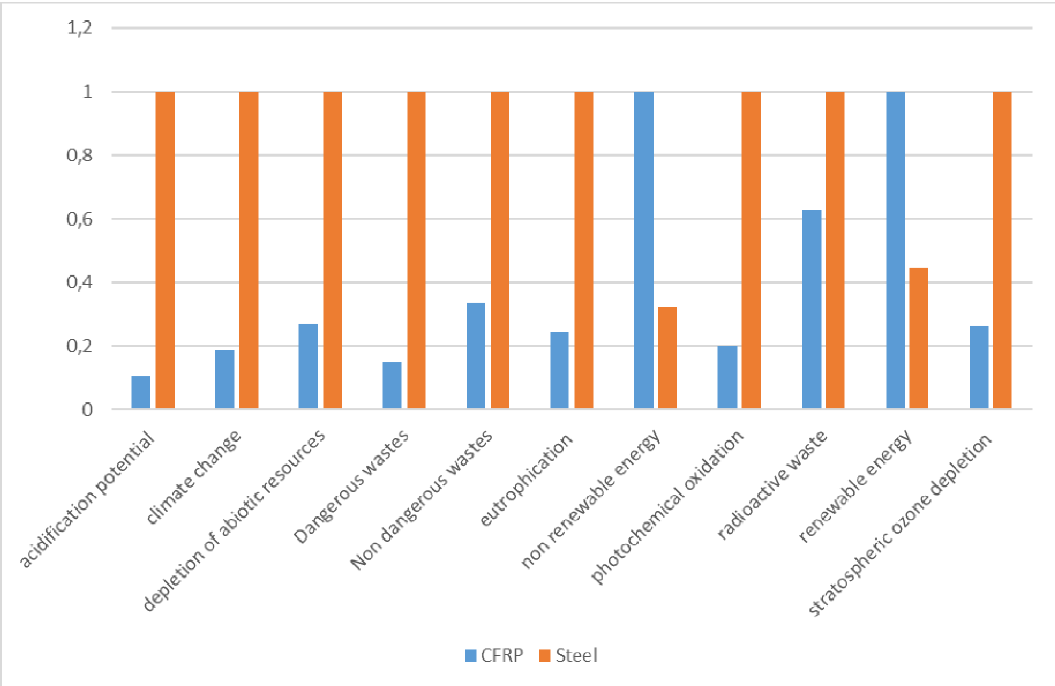

Figure 14: Comparison of the two solutions from an environmental point of view.

Results obtained show that the CFRP solution is interesting from an environmental point of view under the made assumptions. The fact that less material is used play an important role.

We have made the same analysis using a process with an adhesive which we know is not perfectly adapted but is present in Ecoinvent "*adhesive production for metal*". Results shown in the following figure are not so different.

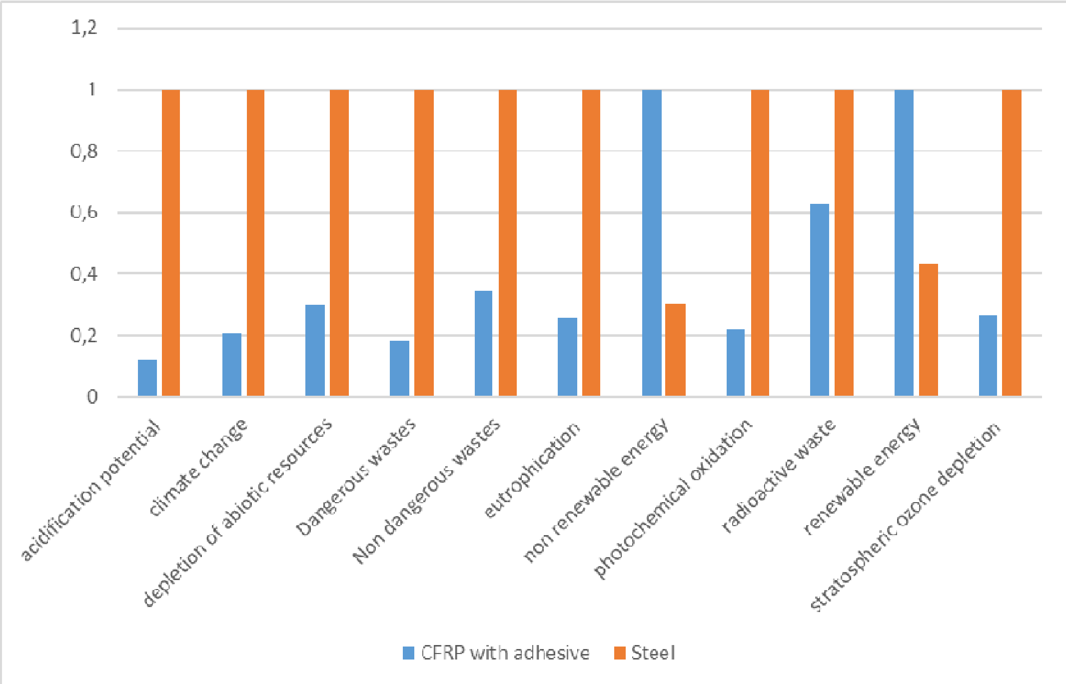

Figure 15: Comparison of the two solutions from an environmental point of view, with a non adapted process of adhesive.

In conclusion, the comparison of both solutions from an environmental point of view does not show clear discrepancy, and results are different regarding the considered environmental impact.

7 Conclusions

The presented deliverable aimed at giving main conclusions regarding the application of FASSTbridge solution on Jarama bridge. It is closely linked to most of the deliverables of work package 5 that concerns this application, but also with some deliverables of work package 4 especially regarding the used methodologies for cost benefit and life cycle assessment analyses.

It is important to note that the application of FASSTbridge methodology to Jarama bridge was only partial as it concerned only one part of the structure and as it was decided to reinforce several locations with different reinforcement configurations to study its effectiveness. Yet, this proved to give a lot of information regarding the developed reinforcement solution based on the use of adhesively bonded CFRP. Additional applications are however needed to carry out the exact complete methodology to a real structure in order to refine the obtained data and validate the whole methodology. Several issues have been studied in this report:

- The technical conclusions on the developed solution,
- Some cost benefit results,
- Some environmental conclusions.

Regarding the technical conclusions, it was shown that the reinforcement system was efficient in decreasing stress ranges. The measured decrease was more important than what was forecast theoretically certainly in reason of the local asymmetry caused by the reinforcement on only one side of the flange. Several application parameters were studied (adhesive thickness, order of application, humidity, order of installation, traffic on the bridge). Interestingly, no decrease of the efficiency of the reinforcement was observed for the location reinforced under traffic. A comparison was led with a more traditional solution (additional steel plate) and gave the main advantages of FASSTbridge solution (lightweight, durability, faster application) and also its drawbacks (mastering adhesive workability, surface geometry, post-curing treatment). Additional work could certainly improve the proposed solution by, for instance, developing specific tools to ease application and post-curing, or trying to formulate other adhesive with better workability or having higher glass transition temperature value with cold-curing.

On the basis of Jarama application data, a cost benefit analysis was led accordingly with the proposed methodology of D4.5. The direct economic gain was assessed to be around 195 k€ thanks to the postponing of the end of service life of the bridge. Several hypotheses had to be made as the reinforcement has been only led on one part of the bridge but this allows highlighting the gain that such a preventive action would have if it was applied on the steel structures stock. It can also be noted that this gain could be increased if the reinforcement was applied under traffic as no traffic diversion would be needed (that represented 10 % of the cost during Jarama application). The indirect costs of the reinforcement operations proved to be low, and should be even null if the reinforcement was appied with no traffic diversion. The led comparison with the alternative more traditional solution (welded steel plate) allowed highlighting the big differences with FASSTBridge solution: FASSTbridge solution seems to be a little more expensive than traditional solution, but the ease of application allows economic gain on the execution process. If it was well proved that there is no impact of traffic during application, this would make the proposed FASStbridge solution much more economic than the traditional ones.

Finally, a life cycle analyses was led to compare FASSTbridge solution with additional welded steel plate solution. With the presented hypotheses, the results revealed no main discrepancy between both solutions. Depending on the considered environmental impact, the results are indeed different. For instance, focusing on climate change, FASSTbridge solution appears to have less impact, while it is the inverse for energy. Though the data on the developed adhesive was not available, the study led with another adhesive did not show any differences than the one led without taking into account the adhesive. This tends to prove that the adhesive quantity has a very small influence on the overall impact of the solution.

The completed analyses allowed for checking that the developed solution was efficient, cost effective and comparable with more traditional methods in terms of cost and environmental impact. The preliminary investigations led on one of the studied zones on Jarama bridge regarding the application under traffic revealed that there was no damage of the bonded reinforcement. This could highly increase the cost efficiency of the solution taking into account both direct and indirect costs. It would worth checking that for encountered on site stress ranges in laboratory. Additional applications are also needed to fine-tune the application methodology, developing if possible specific equipment for application and post-cure.