A life cycle analysis approach applied to the strenghtening of steel bridges

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A LIFE CYCLE ANALYSIS APPROACH APPLIED TO THE STRENGTHENING OF STEEL BRIDGES

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ABSTRACT

This paper presents some results obtained in the Infravation research project called "Fast and effective solution for steel bridges life-time extension" (FASSTbridge). The aim of this project is to develop and demonstrate a reliable, preventive, cost-effective and sustainable solution for steel bridges fatigue life-time extension.
Original sustainable preventive strengthening techniques will be tested to help postpone difficult, resource-consuming and costly retrofitting and repair interventions and demolitions of the steel and composite steel bridges stock. This paper addresses the definition of the needed data and the methodology for the realization of an actual cost-benefit analysis and a life cycle analysis of the CFRP solution compared with traditional techniques (use of steel plates) and considering the economic and environmental profit of the preventing policy.

KEYWORDS

Strengthening and repair, CFRP, Life Cycle Cost, Life Cycle Analysis.

INTRODUCTION

Various methods exist to strengthen steel bridges once fatigue damage have been identified. The most popular among engineers is the attachment of steel plates to the tension flange of the girders (Figure 1). However, this method has several disadvantages: plates are usually bulky, heavy, difficult to fix and prone to corrosion and fatigue. In general, conventional strengthening techniques are labor intensive and disruptive to traffic flows, thus limiting their application in the wide network of European and American steel bridges. Carbon Fibre Reinforced Polymers (CFRP) composites, although more expensive than steel plates in terms of price per unit/m2, have several and relevant advantages that make them suitable and cost effective for retrofitting of steel bridges: their application is less time consuming than traditional solutions (i.e. from one month to a few days, therefore less traffic disruptive), have a high strength to weight ratio, excellent fatigue properties, low space disruption, high durability and versatility, and are easy to transport, handle and apply (without heavy equipment) (Figure 2).

Figure 1. Additional riveted plate

Figure 2. Adhesively bonded composite reinforcement

The use of CFRP strips for fatigue strengthening is not only justified by its optimum mechanical performance, proven in several research studies and projects (Fawzia et al. 2010, Chataigner et al. 2011, Ghiassi et al. 2012, Jiao et al. 2012, Lepretre et al. 2016). It is also cost-effective in terms of the entire execution process. The swiftness of the intervention, compared to the traditional attachment of steel plates, reduces considerably traffic disruptions: reducing the costs of auxiliary means (platform, scaffolds), making easier the transport (steel plates are heavy and difficult to handle in the worksite) and the labour (welding requires qualified and experienced

workers). In a report from the National Cooperative Highway Research Program (NCHRP 503, 2003), the findings of a study to develop a strategic plan for guiding the application of fibre reinforced polymer composites in the highway infrastructure are presented and discussed. Among all the elements in the proposed strategic plan to create widespread understanding and application of FRP materials in highway infrastructure, it was recommended to perform a study of the relative costs of FRP versus traditional materials. Some of the key issues regarding the use of FRP composites for rehabilitation of steel components the authors mentioned in the report were:

- costs of strengthening deteriorated steel components are largely labor and societal costs,
- costs of materials in rehabilitation projects are usually less significant,
- higher initial costs of FRP composites can be offset by reduced labor, reduced construction time, and reduced traffic disruptions during construction,
- cost-effectiveness of rehabilitation of steel components with FRP composites would be mainly due to durability of FRP, reductions in construction time and traffic delays.
- Based on the strategic plan outlined in the NCHRP 503, this report not only aims to look at the material/labor costs and environmental impact but also at the costs associated with traffic disruptions/delays during the repair or retrofit of the bridge.

These aspects are considered in this paper which introduces a cost-benefit and life-cycle analysis to perform the comparison of costs of implementing traditional repair strategies and the use of FRP composites. Such analysis should make a link between the variables in the design of the strengthening action, the cost and the gain on performance and life-time extension. The data needed were introduced and a database with unit cost was elaborated in the realm of the project FASSTbridge (2017a,b). This project aims at developing and demonstrating a reliable, preventive, cost-effective and sustainable solution for steel bridge fatigue life-time extension. FASSTbridge is co-funded by Funding Partners of the ERA-NET Plus Infravation and the European Commission.

INFORMATION USED IN LIFE CYCLE ANALYSES

Input data

This section provides impacts information when using welded steel plate (Table 1), bolted steel plate (Table 2) or CFRP (Table 3) to increase the fatigue remaining life. These estimations are based on actual interventions made by the partners of FASSTbridge consortium.

Table 1: Steel S275JR, welded structure (1 kg).

Item	Unit	Quantity	Ecoinvent Process	Unitary Cost	Cost
Workmanship	h	0.018		18.96	0.34
Workmanship (auxiliary)	h	0.018		17.83	0.32
Qualified welders	h	0.018		24.5	0.44
Laminated steel S275 JR	kg	1.05	*steel. low-alloyed. hot rolled*	0.99	1.04
Electrolytic coating	l	0.01	*Zinc coating*	7.59	0.08
Crane 30m. span. 750 kg capacity	h	0.005		18.92	0.09
Diesel Welder	h	0.018	*Diesel burned in building machine*	3.62	0.07
Fungible material	%	0.019		5	0.1

Table 2: Steel S275JR, Bolted structure (1 kg).

Item	Unit	Quantity	Ecoinvent Process	Unitary Cost	Cost
Workmanship	h	0.028		18.96	0.53
Workmanship (auxiliary)	h	0.028		17.83	0.5
Laminated steel S275 JR	kg	1.05	*steel, low-alloyed, hot rolled*	0.99	1.04
Electrolytic coating	l	0.01	*Zinc coating*	7.59	0.08
Crane 30m. span. 750 kg capacity	h	0.01	*Diesel burned in building machine*	18.92	0.19
Fungible material	%	0.023		5	0.12

Table 3: CFRP laminate strengthening (1m).

Item	Unit	Quantity	Ecoinvent Process	Unitary Cost	Cost
MasterBrace P 3500. 5 kg (primer)	kg	0.048	*epoxy resin production. liquid*	MasterBrace P 3500. 5 kg (primer)	kg
MasterBrace ADH 4000 (adhesive)	kg	0.374	*epoxy resin production. liquid*	MasterBrace ADH 4000 (adhesive)	kg

Carbolam THM 450	m	1.1	"home made » CFRP process[2]	Carbolam THM 450	m
complementary material and special pieces	%	0.306		complementary material and special pieces	%
Electrogen group INS 40 KVAs	h	0.03	*Diesel burned in building machine*	Electrogen group INS 40 KVAs	h
Sander	h	0.2	*Diesel burned in building machine*	Sander	h
Crew Type B	h	0.2		Crew Type B	h

To the unit costs in Tables 1 to 3 should be added the costs of scaffolding and rental equipment such as forklift in work site, when necessary (Table 4). The average work duration for such a strengthening project is assessed at 12 days for welded and bolted solutions and 5 days for CFRP. It is noted that there is no forklift location in work site when using CFRP.

Table 4. Additional costs/m2.

Item	Description	Welded solution	Bolted solution	CFRP
Scaffold and platforms	Rental equipment - 400€/day	4800	4800	2000
	Installation + dismantling	350	350	350
	Installation certificate	300	300	300
	Transport	400	400	400
Forklift in work site	Rental equipment - 80€/day	960	960	-
	Transport	1200	1200	-

Despite the fact that the unitary cost of material is higher for CFRP than for steel plates (welded or bolted), the former solution seems cost-effective in terms of the entire execution process. The swiftness of the intervention, compared to the traditional attachment of steel plates can reduce the costs of auxiliary means (platform, scaffolds), making easier the transport (steel plates are heavy and difficult to handle in the worksite) and the labour (welding requires qualified and experienced workers, see Table 1).

Performance analysis

The estimation of the remaining fatigue life time is done according to the regulation of Eurocode EN 1993-1-9 7.1 (3) with following formulae (analogue formulae for shear):

For nominal stress spectra with stress ranges above and below the constant amplitude fatigue limit $\Delta\sigma_D$ the fatigue strength is based on the extended fatigue strength curve as follows:

$$N_R = \frac{\Delta\sigma_c^m \times 2.10^6}{\Delta\sigma_R^m} \text{ with } m = 5 \text{ for } N \le 5.10^6 \quad (1)$$

$$N_R = \frac{\Delta\sigma_D^m \times 5.10^6}{\Delta\sigma_R^m} \text{ with } m = 5 \text{ for } N \le 5.10^6 \quad (2)$$

The fatigue detail category 50 (reference value $\Delta\sigma_C$ =50N/mm^2 for the fatigue strength at 2 million cycles) is considered for illustration in the following. The properties of the steel section and fatigue design life configuration are provided in Table 5.

Table 5. Properties of steel section and axial stress considered for illustration.

		Cross section	
Thickness t = 35mm	Width b = 550 mm	A = 19250 mm^2	
		Axial stress	
σ_{max} = 30.5N/mm^2 σ_{min} = -5.6N/mm^2	If stress relieved $\Delta\sigma = \lvert\sigma_{max}\rvert + 0.6\lvert\sigma_{min}\rvert$ $\Delta\sigma$ = 33.86 N/mm²	If not stress relieved $\Delta\sigma = \lvert\sigma_{max}\rvert + \lvert\sigma_{min}\rvert$ $\Delta\sigma$ = 36.1 N/mm²	$\Delta\sigma_C$ =50N/mm^2 $\Delta\sigma_D$ =36.85N/mm^2

To simplify the illustration of the methodology, the strengthening project is based on this fatigue assessment configuration, extended to the scale of the structure. The design life in number of cycles is then $N_R = 6{,}439{,}900$ if stress relieved and $N_R = 5{,}313{,}961$ if not stress relieved.

As mentioned previously, three options are taken into account in this report for fatigue service life increase:

- welded steel plates,
- bolted steel plates,
- CFRP strips.

In order to make a comparison based on the function or performance equivalent the solutions are compared keeping the product of the Young modulus (E) by the section constant. The characteristics associated with each of the three solutions are provided in Tables 6, 7 and 8.

Table 6. Steel S275JR, welded structure, cost/m for several design life increase configurations.

n	a	b	E	Al	Al/A	Stress reduction	Stress range	Design life	Design life increase	Weight	Cost/m
	mm	mm	GPa	mm²						Kg	
1	145	6	210	870.00	0.05	0.96	32.4	7353107	1.14	6.699	13.7
2	145	6	210	1740.00	0.09	0.92	31.1	8348804	1.30	13.398	27.3
3	145	6	210	2610.00	0.14	0.88	29.8	9430559	1.46	20.097	41.0

Table 7. Steel S275JR. bolted structure. cost/m for several design life increase configurations.

n	a	b	E	Al	Al/A	Stress reduction	Stress range	Design life	Design life increase	Weight	Cost/m
	mm	mm	GPa	mm²						Kg	
1	145	6	210	870.00	0.05	0.96	32.4	7353107	1.14	6.699	16.5
2	145	6	210	1740.00	0.09	0.92	31.1	8348804	1.30	13.398	33.0
3	145	6	210	2610.00	0.14	0.88	29.8	9430559	1.46	20.097	49.4

Table 8. CFRP. cost/m for several design life increase configurations.

n	a	b	E	Al	Al/A	Stress reduction	Stress range	Design life	Design life increase	Cost/m
	mm	mm	GPa	mm²						
1	100	4	460	876.19	0.05	0.96	32.4	7359896	1.14	233.8
2	100	4	460	1752.38	0.09	0.92	31.1	8363586	1.30	466.7
3	100	4	460	2628.57	0.14	0.88	29.8	9454615	1.47	699.5

To these costs above need to be added the additional costs due to the scaffold and platform rent, installation/dismantling, transport, and to the use of forklift in work sites (rental equipment and transport). The corresponding unit costs for the welded/bolted steel plates and use of CFRP are provided in Table 4.

COST ANALYSIS

Materials

The proposed methodology assesses the NPV at $T_{s,0}$ of all future costs including strengthening ones that can occur at different years. Doing this, the "Do Nothing" strategy (DN) is characterized only by the discounted demolition/reconstruction costs assumed to occur at T_f^0 (year 100 in this example):

$$NPV_0\left(T_s\right) = \frac{C_f}{\left(1+r\right)^{T_f^0 - T_{s,0}}} \tag{3}$$

The alternative strategies with some strengthening actions (use of welded or bolted steel plates or use of CFRP) are applied at $T_{s,0} \le T_s \le T_f^0$ and added to the end of life costs which occur at $T_f^1, T_f^2, T_f^3 \ge T_f^0$ in case of maintenance (when G_s = 14% or 30% or 46%, respectively) since the residual fatigue remaining life is

increased (the effect being dependent on G_S and the effective year of strengthening action). The total cost for each type of repair project can be calculated with information previously provided on unit cost $c_{S,u}^j$, additional cost C_w^j and length L_S of strengthening. The net present value at $T_{S,0}$ for strengthening solution j and gain of fatigue service life i applied at year T_S can be obtained as follows:

$$NPV_{j,i}(T_S) = \frac{C_f}{(1+r)^{T_f^i - T_{S,0}}} + \frac{c_{S,u}^j \times L_S + C_w^j}{(1+r)^{T_S - T_{S,0}}} \quad \text{with} \quad T_{S,0} \le T_S \le T_f^0 \tag{4}$$

Such an approach reflects a decision making process where one investigates at a specific year (here $T_{S,0}$) the interest to postpone some strengthening action and to find the optimal year for it in the future. In this approach, $T_{S,0} \le T_S \le T_f^0$ but the decision is always considered at year $T_{S,0}$.

Figure 3 illustrates the cost NPV_j obtained with different solution ($j = 1,2,3$ for welded, bolted steel plates and CFRP, respectively), with $L_S = 50m$, $G_S = 14\%$ ($i = 1$), $T_f^0 = 100$ and $T_{S,0} = 50$. It is observed that $NPV_{1,1}$ gradually decreases until year 69, then grows again over time until $T_S = T_f^0$. $NPV_{2,1}$ follows the same trend with the same inflection point at year 69. The inflection point for $NPV_{3,1}$ is reached sooner at year 52. Tthe "Do nothing" cost (NPV_0) is fixed for any T_S as it is always expressed in reference to year $T_{S,0}$ and is equal to 325,000€.

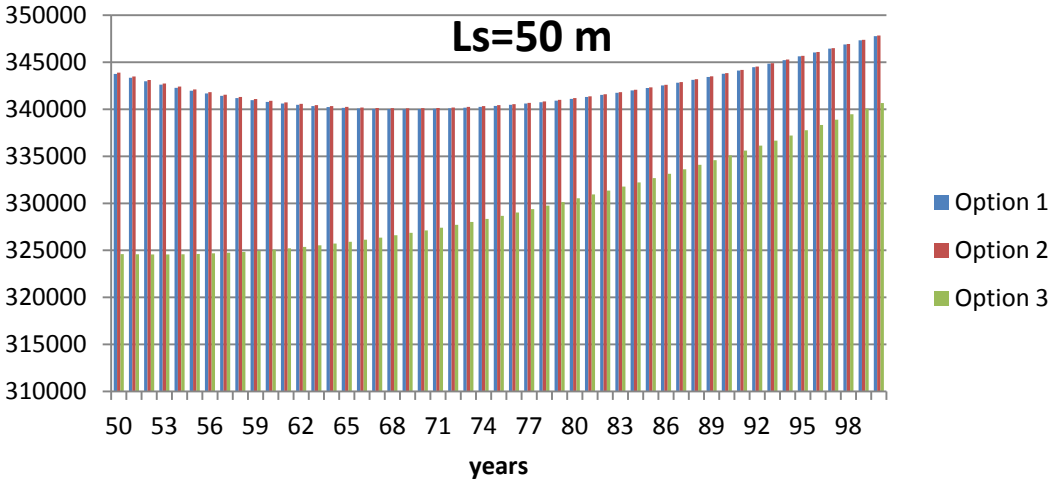

Figure 3. Net present value $NPV_{j,1}$ ($j = 1,2,3$) of different solutions with $L_S = 50m$ and $G_S = 14\%$.

Similarly, Figures 4 and 5 illustrate the net present value obtained with different solutions ($j = 1,2,3$ for welded, bolted steel plates and CFRP, respectively), with $G_S = 30\%$ and 46%, respectively. In both cases, $L_S = 50m$. In Figure 4, as corresponding cost values increase with T_S, it is more interesting not to wait at year 50 to strengthen the bridge. Since $NPV_0(T_S) = 325000$€, the use of welded and bolted steel plates ($j = 1$ and 2) is more interesting than DN option until year 81. It is more interesting until year 85 for CFRP ($j = 3$).

In Figure 5 when $G_S = 46\%$, it is more interesting not to wait at year 50 to strengthen the bridge and that for any of strengthening options. The net present values for each option are very close. Indeed, additional costs C_w^j are more interesting when using CFRP. However, this advantage is neutralized when $G_S = 46\%$ as the unit costs for CFRP are larger than those for steel plates and necessary quantities of materials are more significant than when $G_S = 14\%$ and 30% (see Tables 6, 7 and 8).

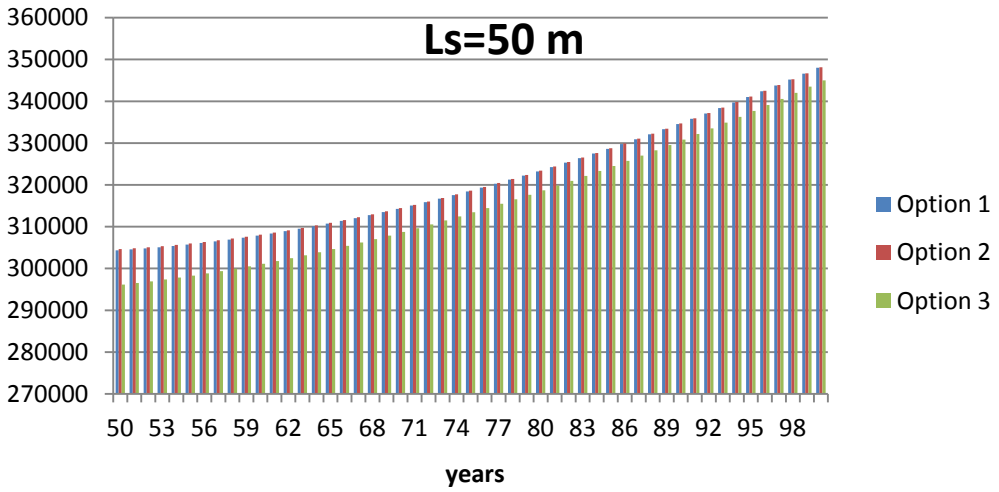

Figure 4. Net present value $NPV_{j,2}$ ($j = 1,2,3$) of different solutions with $L_s = 50m$ and $G_s = 30\%$.

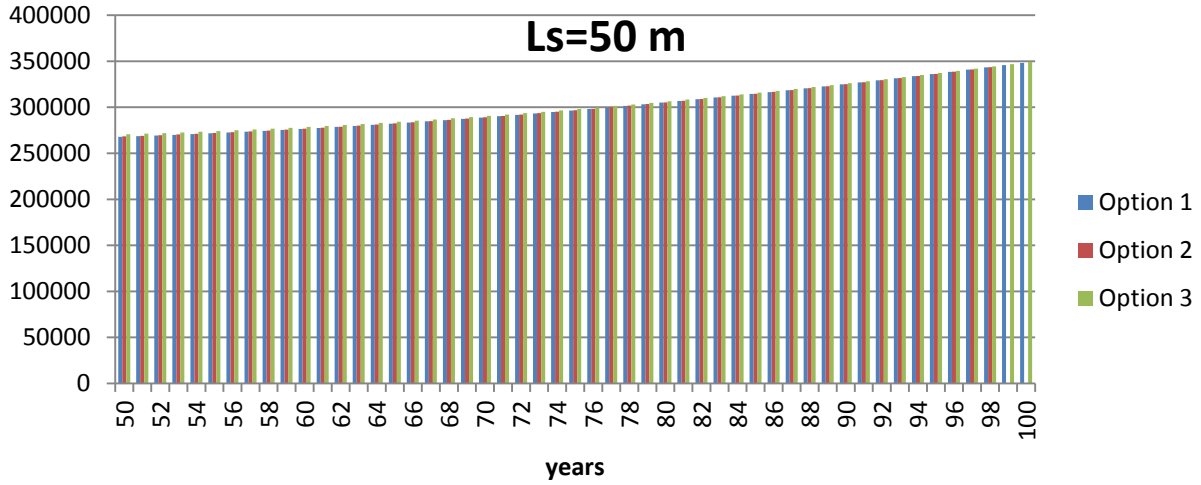

Figure 5. Net present value $NPV_{j,3}$ ($j = 1,2,3$) of different solutions with $L_s = 50m$ and $G_s = 46\%$.

ENVIRONMENTAL ANALYSIS

LCA methodology

LCA methodology enables the evaluation of the product on its entire life cycle, that is from cradle to grave, calculating different impact indicators, such as climate change, eutrophication… It is important to note that the fact that LCA is multicriteria allows to avoid a pollution transfer from one environment to another. LCA method has been undertaken complying with the standards 14040 at 14044 of the lnternational Organization for Standardization (lSO). The indicators in Table 9 are assessed according to the European standard EN 15804 regarding the construction products.

Table 9: Environmental impact indicators calculated in the following study and calculation methods used (CML, EDIP and CED); these methods have been chosen for their international representativeness.

Environmental indicator	Unit	Calculation method used
Consumption of energy resources Renewable energy Non renewable energy	MJ	Cumulative Energy Demand (CED)
Depletion of abiotic resources	kg eq antimony	Impact-oriented characterisation (CML 2001)
Wastes	kg	Environmental Design of Industrial Products (EDIP)
Radioactive wastes	kg	Environmental Design of Industrial Products (EDIP)

Climate change	Kg eq CO_2	Impact-oriented characterisation (CML 2001)
Acidification potential	Kg eq SO_2	Impact-oriented characterisation (CML 2001)
Stratospheric ozone depletion	Kg eq CFC	Impact-oriented characterisation (CML 2001)
Photochemical oxidation	Kg eq ethylene	Impact-oriented characterisation (CML 2001)
Eutrophication	kg eq PO^{3-}_4	Impact-oriented characterisation (CML 2001)

Table 10 present the environmental results obtained for the solution with for a life cycle increase of 14%, 30% and 46%. Similar tables can be obtained for the two other solutions. It's important to note that these results have been obtained with the hypothesis described and with generic environmental data which might not be representative of the type of materials used in the FASSTbridge project. If more representative data were obtained in the near future, the methodology to be applied would be the same, but the results of the calculations of impact indicators at material scale should be updated.

Table 10: Environmental impacts for 1m of CFRP.

Indicator impact	Unit	14%	30%	46%
Acidification potential	Kg eq SO_2	0.30079	0.398780726	0.496767694
Climate change	Kg eq CO_2	39.44833	57.52334768	75.59836625
Depletion of abiotic resources	Kg eq Sb	0.32011	0.495088248	0.670066297
Dangerous wastes	kg	0.41127	0.65697567	0.902684559
Non dangerous wastes	kg	3.56786	5.9002119	8.232565633
Eutrophication	kg eq PO_4^{3-}	0.06949	0.104183964	0.13888189
Non renewable energy	MJ	590.35404	1143.250925	1696.147813
Photochemical oxydation	kg eq ethylene	0.00808	0.01194248	0.015804783
Radioactive waste	kg	0.00723	0.012315639	0.017397316
renewable energy	MJ	22.72660	43.72423107	64.72186321
Stratospheric ozone depletion	Kg eq CFC-11-	0.00001	1.13534E-05	1.5118E-05

In order to be able to compare different reinforcement solutions, we propose to focus on the climate change just to be more readable.

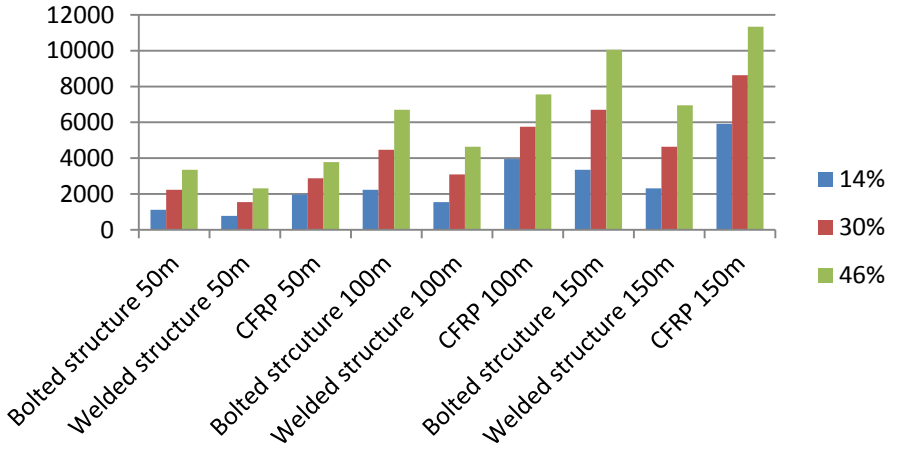

Figure 6: Climate change in kg eq CO_2 for each solution of reinforcement while reparing 50m, 100m or 150m.

Concerning CFRP and under the assumptions of this study, the climate change impact has been the most important in all cases. Welded structure is always the one with the less impact comparing with the two other solutions. It is noted that uncertainties have not been calculated in this case but may be important in LCA, given the uncertainty of the data but also the methods of calculating the impact. Thus CFRP could be competitive regarding bolted structure.

An LCA study has been performed on a bridge by Cimbeton (CT 87). It is a concrete bridge so it is not the same case as ours, but it takes into account the whole life cycle or this bridge for a lifetime of 100 years. As there is not any other bridge case LCA studied we will consider this as a first approximation in order to compare

different reinforcement solutions for this bridge along all its life cycle. In the publication of Cimbeton for the whole life cycle, climate change is equal to 677,000 eq CO2. Figure 7 shows the representative fraction of the strengthening action on the whole life cycle considering climate change indicator. It is observed that even in the worst case this fraction does not exceed 1.7% of the total life cycle of the bridge chosen as a reference.

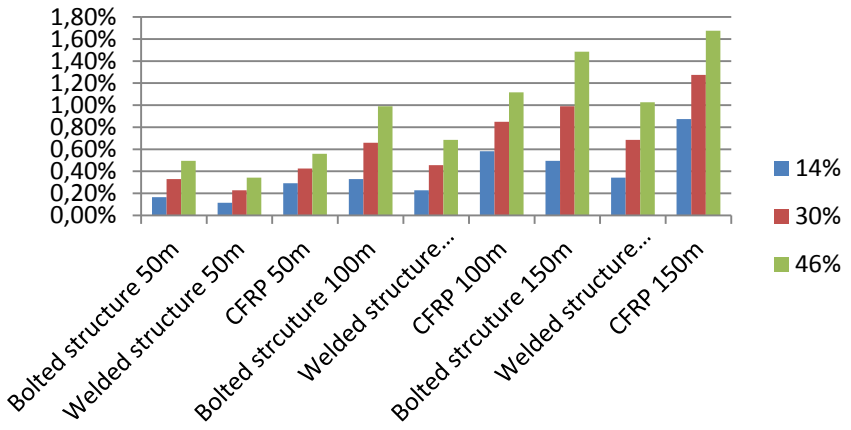

Figure 7: Part of the reinforcing solution compared to the total bridge for climate change.

CONCLUSIONS

This paper proposes economic and environmental analyses for highlighting the benefits of different strategies for fatigue strengthening. The aim is to provide a general framework that gathers precise information on unit costs to assess the overall cost of traditional strengthening projects (use of welded and bolted steel plates) and also original repair techniques (use of CFRP). Impacts include the cost of the strengthening action for the bridge owner and the corresponding impact on the end of the service life, and consequently the effective year for demolition/reconstruction.

The general framework is highly dependent on input parameters and enables the comparison of several strengthening strategies. In particular, it is shown how several parameters can significantly influence the comparison results both for direct costs (yearly discount rate of money, costs of maintenance works, area of the bridge deck concerned by strengthening, end-of-life costs). The perspectives for future work is to apply this framework to the Jarama Bridge located in the city of Madrid in Spain over Jarama river and to analyze the effect of uncertainties on input parameters.

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