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Adhesively bonded composite reinforcement against fatigue crack propagation in the case of old steel structures

E. Lepretre¹, S. Chataigner², L. Dieng², L. Gaillet²

Introduction

After corrosion, fatigue phenomenon is the main cause of damage in old metallic structures. Fatigue cracks appear in stress concentration area subject to high stresses, and can lead to the ruin of the bridge. The main objective of the present work realized in the framework of the Phd Thesis of E. Lepretre (Lepretre, 2017) was to study the effectiveness of adhesively bonded carbon fibre reinforced polymer (CFRP) laminates in reinforcing fatigue crack emanating from rivet hole. Thus, investigations on small-scale specimens were done. These specimens consist of metallic plates with center hole from which one single crack emanates. Two metallic materials, puddled iron and mild steel, and different reinforcement processes were used. First, the quality of stress transfer on old steel materials was assessed. Then, specific experimental procedures were set up in order to investigate the ability of such technique to reinforce steel elements against crack propagation. Different schemes of reinforcement have been assessed and the obtained results are given in the last part.

Adhesive bonding in the case of old steel materials

First of all, specific investigations have been carried out regarding the ability of adhesive bonding to transfer stress on old steel materials. The work has been made using single lap shear test as described in (Chataigner et al., 2011). Two steel materials have been tested: puddled iron coming from a deconstructed bridge and mild steel (S235). Three different commercial reinforcement processes have been tested: two normal modulus ones (A and B) and one ultra-high modulus (C). For each configuration three tests have been carried out.

Main results are given in Table 1 it can be observed that the obtained failure modes (Figure 1) indicate good surface preparation (good adhesion between the adhesive and both steel material and composite) and no influence of the heterogeneity of puddled iron. Good repeatability has also been remarked. Finally, it is interesting to note that the obtained ultimate stresses are far above the ultimate stress of old steel materials. This proves the adequacy of such a technique for this kind of application. Finally, additional investigations have been made to assess the characteristic anchorage length and are presented in (Lepretre et al., 2016). 80 mm anchorage lengths have been found in the case of normal modulus processes and 140 mm have been determined in the case of ultra-high modulus reinforcement process. This is in agreement with existing literature on this topic.

Table 1: Obtained single lap shear test results

Sample	Steel adherend	Reinforcement process	Average ultimate capacity (kN)	Average ultimate stress (MPa)	Failure mode
S_NM_A	S235	A	44,5	741,1	Cohesive in the adhesive
S_NM_B	S235	B	39,7	660,9	Cohesive in the adhesive
S_UHM_C	S235	C	93,6	782,7	Composite delamination
I_NM_A	Wrought iron	A	40,6	675,9	Cohesive in the adhesive
I_NM_B	Wrought iron	B	40,8	679,4	Cohesive in the adhesive
I_UHM_C	Wrought iron	C	>90	751,1	Composite delamination

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Figure 1: Photos of the obtained failure modes (reinforcement processes A, B and C)

Experimental set-up for the study of the reinforcement against fatigue crack propagation

After a thorough literature review to identify the existing studies on the topic and the lack in terms of tested configurations (Colombi et al., 2003; Jones et al., 2003; Zheng et al., 2006; Liu et al., 2009; Täljsten et al., 2009; Yu et al., 2012, Wu et al., 2012), it was decided to realize 30 tests to investigate the ability of adhesively bonded reinforcement processes to reinforce cracked steel elements. 24 were realized on mild steel and 6 were realized on puddled iron. The plate with centre hole was adopted and a crack was initiated on one side of this hole (using erosion technique, and decreasing fatigue loading to obtain realistic crack tip). Two different initial crack lengths before reinforcement have been investigated: A1 corresponding to a crack that would not be visible if there was a rivet head (detectable from non-destructive technique only), A2 corresponding to a visible crack detectable by visual inspection. More details on the adopted geometry is given in figure 2 a. The reinforcement laminate is 300 mm long, 24 mm wide, and bonded 10 mm far from the hole.

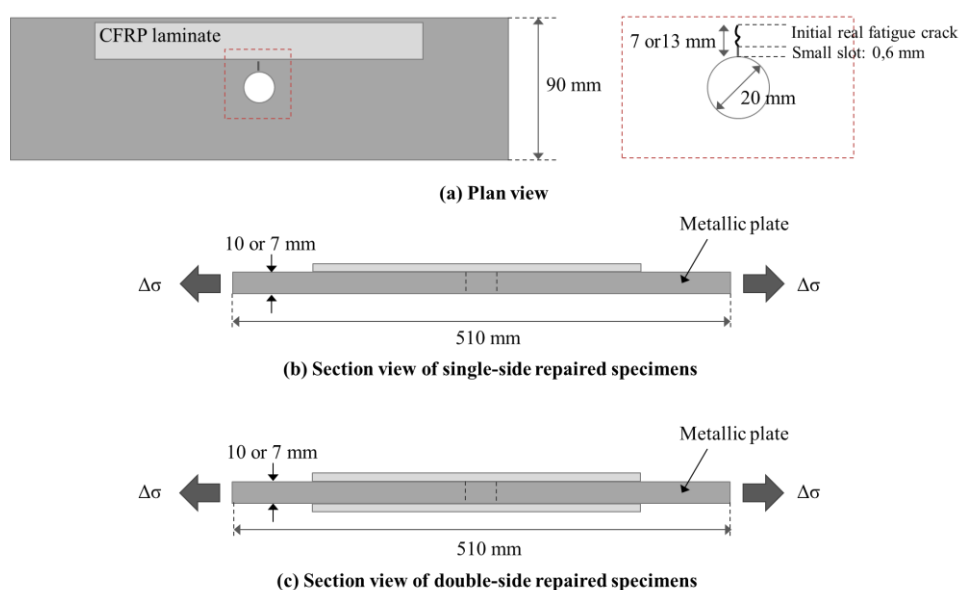


Figure 2: Geometry and configuration of the tested samples to study reinforcement against crack propagation

Two different reinforcement processes (1.2 mm thick Normal Modulus (NM): 165 GPa, and 2.3 mm thick Ultra High Modulus (UHM): 460 GPa) have been investigated for mild steel. Furthermore, symmetrical (S) (figure 2 b) and un-symmetrical (NS) (figure 2 c) reinforcement configurations are considered as well as pre-stressing NM laminates before application (T) (at 350 MPa). In the case of puddle iron samples, only the ultra-high modulus reinforcement was investigated in the unsymmetrical case to allow the monitoring of the crack length.

For mild samples, the crack propagation was monitored using the well-known “beach-marking” technique (Figure 3 a). In the case of puddled iron, its brittleness does not allow such a technique to be used. A specific technique relying on the use of crack gage bonding at the surface was then used to follow crack propagation (Figure 3 b). All the tests were realized at a stress ratio of 0.1 at 10 Hz with a maximum stress range of 90 MPa (close to maximum stress range encountered in real structures).

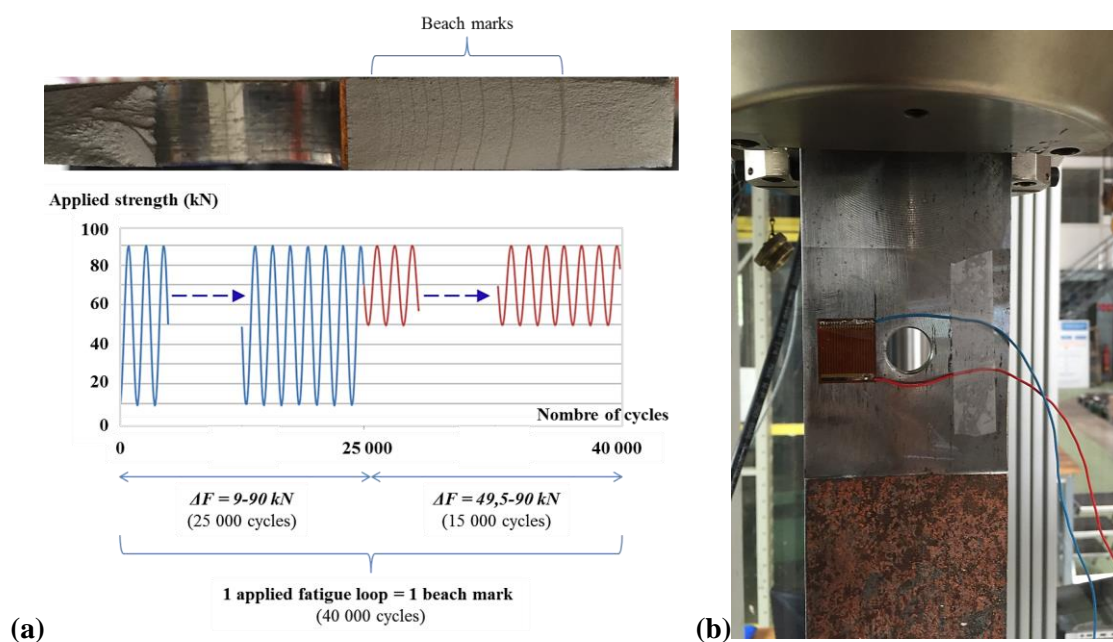


Figure 3: Measurement of crack propagation: a) beach marking technique for mild steel, b) crack gage for puddled iron

Experimental results

The results in terms of fatigue life increase are given in table 2 for mild steel samples and table 3 for puddled iron samples. The indicated fatigue life corresponds to the number of cycles counted from the initial precrack until complete failure.

In the case of mild steel, improvement of fatigue life has been validated and has reached more than 100 % increase in the case of symmetrical reinforcement or the use of ultra-high modulus composite. The reached improvement is of course dependent on the crack length but the rather good repeatability (maximum dispersion around 15%) of the tests seem to indicate that predictive approach may be used to design such reinforcement.

Table 2: Obtained results for mild steel samples (3 tests for each configuration)

	<i>CFRP laminate</i>	<i>Initial crack length (mm)</i>	<i>Failure mode</i>	<i>Average fatigue life</i>	<i>Average fatigue life increase ratio</i>
Un-reinforced specimens	-	-	-	416 720	-
S_MN_NT_NS_A1	MN	7	CF	528 455	1.27
S_MN_NT_NS_A2	MN	13	CF	520 185	1.25
S_MN_T_NS_A1	MN	7	CF	725 950	1.74
S_MN_T_NS_A2	MN	13	CF	790 656	1.9
S_MN_NT_S_A1	MN	7	CF	947 680	2.27
S_MN_NT_S_A2	MN	13	CF	832 105	2
S_UHM_NT_NS_A1	UHM	7	CF + CD	907 955	2.18
S_UHM_NT_NS_A2	UHM	13	CF + CD	730 080	1.75

CF = cohesive failure in adhesive layer
 CD = CFRP delamination (separation of some carbon fibers from the matrix)
 CR = CFRP rupture

In the case of puddled iron, an improvement in fatigue life has also been observed but dispersion is much higher and it was decided to give the results for all the samples. The minimum increase in fatigue life was assessed to be around 120 %. Such a value is already satisfactory and proves that the technique may be applied to old steel structures. A conservative approach will have however to be adopted in order to take into account the heterogeneity of puddled iron material.

Table 3: Obtained results for puddled iron samples (details of each realized test)

	CFRP laminate	Initial crack length (mm)	Failure mode	Fatigue life	Fatigue life increase ratio
I_REF_1	-	-	-	286 011	-
I_REF_2	-	-	-	406 497	-
I_UHM_NT_NS_A1-1	UHM	7	CF + CD	897 170	2.21
I_UHM_NT_NS_A1-2	UHM	7	CF + CD	1 542 085	3.79
I_UHM_NT_NS_A1-3	UHM	7	CF + CD	1 432 910	3.53
I_UHM_NT_NS_A2-1	UHM	13	CF + CD	889 044	2.19
I_UHM_NT_NS_A2-2	UHM	13	CF + CD	1 074 692	2.64
I_UHM_NT_NS_A2-3	UHM	13	CF + CD	1 737 567	4.27

CF = cohesive failure in adhesive layer
CD = CFRP delamination (separation of some carbon fibers from the matrix)

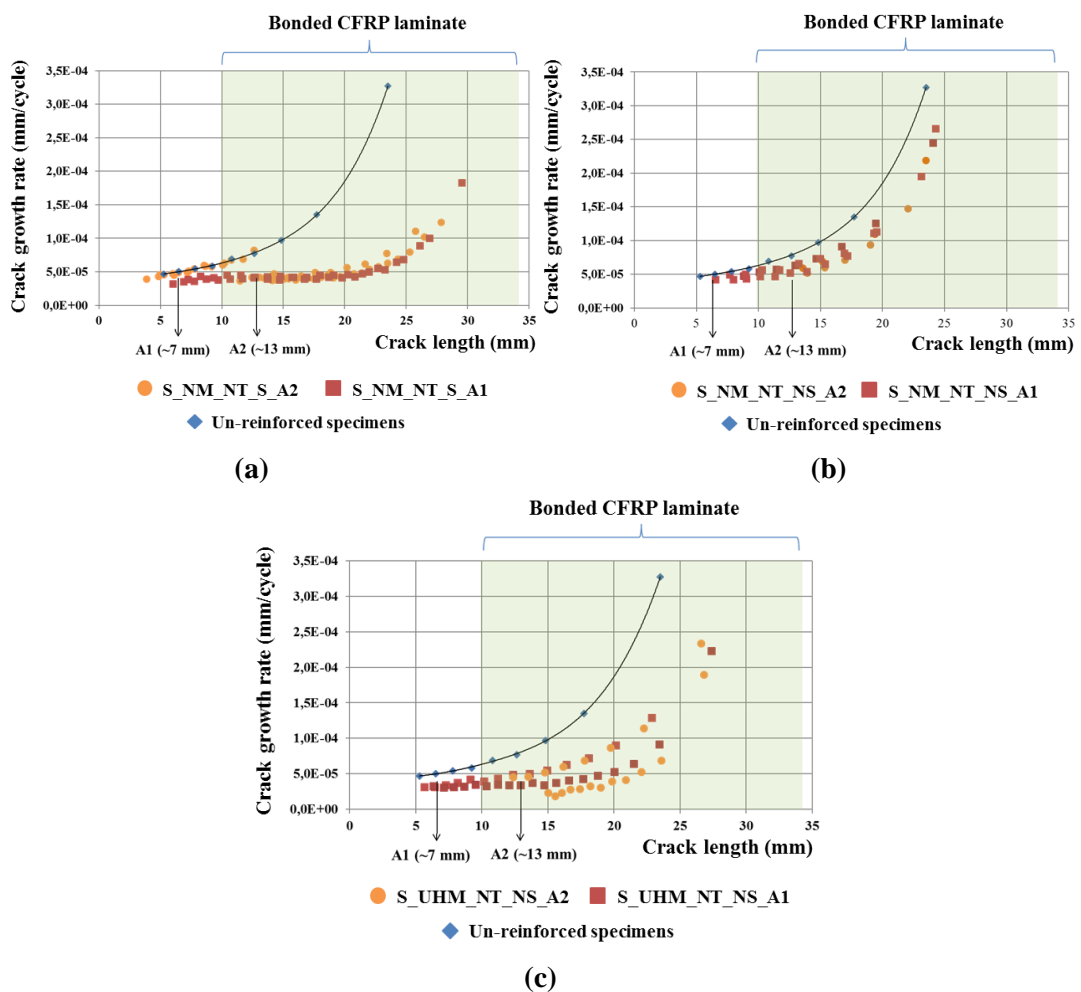


Figure 4: Crack propagation curves for mild steel specimens: (a) S_NM_NT_S specimens; (b) S_NM_NT_NS specimens; (c) S_UHM_NT_NS specimens

From the study of beach patterns after failure or from the monitoring of crack gage during the tests, it is possible to determine crack growth rate curves for the different samples to exploit results according to Paris law. This is done in figures 4 and 5 for respectively mild steel and puddled iron. Such a technique allows identifying the modification of stress intensity factors thanks to the reinforcement. This identification was carried out in (Lepretre, 2017), but it is important to note that it is adapted to the studied geometry and that new geometries will need therefore new identification of these stress intensity factors.

Having a closer look at the obtained curves, it is interesting to note that the effect of the reinforcement is effective even before the crack propagates under the applied reinforcement. In addition, it allows checking that the procedure does not depend on the size of the initial crack at reinforcement application.

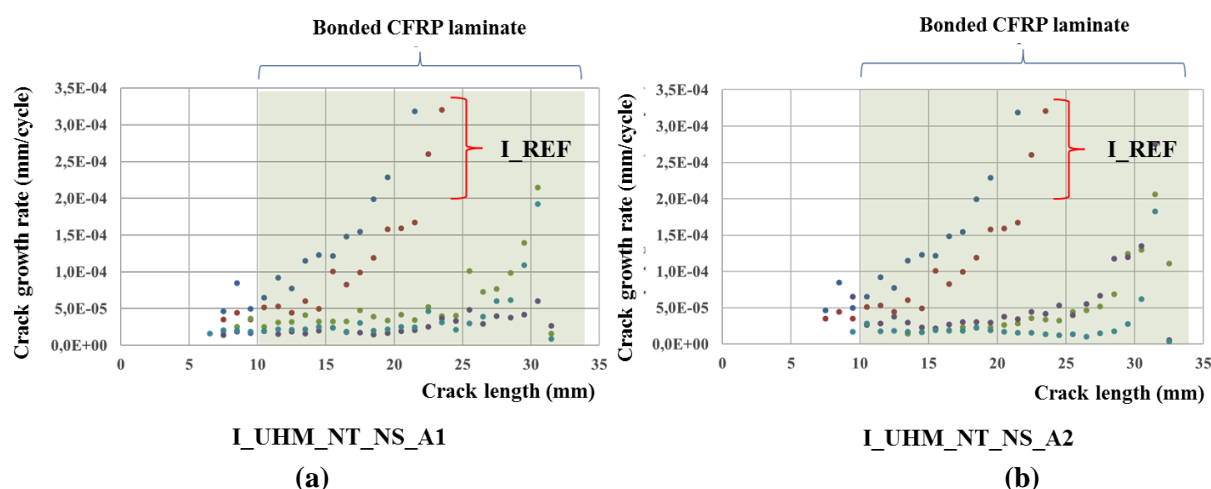


Figure 5: Crack growth curves for wrought iron specimens: (a) I_UHM_NT_NS_A1 specimens; (b) I_UHM_NT_NS_A2 specimens

Conclusions and Points for Discussions

The led investigations led in collaboration with SNCF (French Railway Company) and realized during the Phd Thesis of E. Lepretre (Lepretre, 2017) allowed getting interested in the use of adhesively bonded composite reinforcement for cracked steel elements, and more particularly riveted elements.

The experimental work first dedicated to the characterization of the adhesive joint behaviour proved that the technique was suitable for old steel materials (in particular puddled iron) and for the encountered stress levels on site as the ultimate capacities are well above the yield limits of old steel materials. Besides it allowed designing the required anchorage length.

Then, a protocol was proposed to check the adequacy of the technique to reinforce cracked elements for both mild steel and puddled iron, and to work on geometries that had been rarely tested in the literature and that are close to geometries encountered on site (single-side reinforcement, plate with center hole, access to the edge of the plate). The obtained increase in life expectancy proved that the technique may be suitable in particular when using ultra-high modulus reinforcement. The results may also be used to determine the modifications of the stress intensity factors. Yet, as stated, the obtained new stress intensity factors will be only suitable for similar geometries. That's the reason why the results are currently being analysed using a finite element tool to be able to propose a method to assess the reinforcement abilities for different geometries, reinforcement processes, or reinforcement configurations.

Finally, it was observed that reinforcement had actually a role even before the crack propagates under the composite plate. Such a reinforcement could thus be used in a preventive way before crack initiates

in fatigue. That's the topic that is currently investigated in Infravation project FASSTBridge (Chataigner et al., 2016). This should result in a complete methodology for the reinforcement regarding fatigue of steel structures.

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