Crack reinforcement of old steel structures using adhesively bonded composite

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ABSTRACT: Though the use of adhesively bonded composite reinforcement has not been extensively applied on steel structures, it may be a good alternative to existing methods regarding the repair of old cracked steel structures, being mainly built with mild steel or puddled iron. The proposed communication will present investigations led in the framework of a Phd thesis in collaboration with French Railway company SNCF. The studied aimed at first investigating experimentally the reinforcement capabilities of different adhesively bonded composite systems on both mild steel and puddled iron cracked elements. The influence of the length of the crack and the asymmetry of the reinforcement have been studied. In addition, some investigations have also been made on the use of prestressed bonded reinforcement. The obtained experimental results allowed obtaining stress intensity factors modification coefficients that may be used in the design process. These factors have also been compared to numerical results from a developed finite element modeling procedure. Such a procedure could be a basis for the determination of other stress intensity factors for other geometries.

1 INTRODUCTION

The major causes of deterioration of old metallic structures are corrosion and fatigue phenomenon. Furthermore, particular typologies of damage are recognized in these old structures, mainly due to the used materials (wrought iron and mild steel) and the riveted connections. In fact, fatigue cracks will initiate in the stress concentration areas, such as the rivet's hole, and propagates with an increasing rate until complete failure of the element or structure. Recent studies on the application of bonded Carbon Fiber Reinforced Polymer (CFRP) materials to cracked steel elements, have shown the efficiency of this technique to reduce the stress intensity factor (SIF) at crack tip, and thus to increase the fatigue lifetime of the elements (Zhao, 2014). Consequently, in order to assess the fatigue performance of CFRP-reinforced cracked steel elements, it seems necessary to investigate the effects of CFRP reinforcement on the SIF values.

Many literature studies have focused on center-cracked tensile (CCT) plates bonded with various CFRP reinforcements systems (low/high modulus, CFRP sheeting/plates) and various CFRP strengthening dimensions. For un-strengthened CCT plates, a classical solution of SIFs values at crack tip is available in several international standards and handbooks (Tada et al., 2000). Nevertheless, when CFRP-reinforced elements are considered, these expressions are no longer applicable, and the effects of CFRP reinforcement need to be incorporated to the SIF solutions.

Up to now, there are three types of methods to obtain SIF of cracked elements: experimental, analytical and numerical methods. For cracked elements reinforced with adhesively bonded composite, the analytical methods become very complicated due to the complex stress field existing at crack tip (CFRP and adhesive effects). In many studies, finite element method was thus widely adopted (Yu et al., 2012; Wu et al., 2013b) even if the damage of the bond and its effect during crack propagation still need further investigations. Experimental method mostly relies on the James-Anderson method, introduced in 1969, and used by Shen and Hou (2011) who proposed a SIF formula for CCT plates strengthened with single-sided CFRP composite. This SIF formula directly derived from the crack growth curves of the specimens, however, may not be applicable to different element geometry.

In this paper, the cracked metallic plate geometry was chosen to be representative of the riveted connections. Unlike the common CCT specimens, only one fatigue crack emanates from the center hole. Single and double-sided repaired specimens were studied with different initial crack lengths and for different CFRP reinforcement processes (non-pre-stressed and pre-stressed Normal Modulus (NM) CFRP, non-pre-stressed Ultra High Modulus (UHM) CFRP). Two metallic materials were also used for the metallic plates: S235 carbon steel and wrought iron. Firstly, experimental results showing efficiency of the CFRP reinforcement are presented. Then, these experimental results are used to determine the modified mode I SIF with both semi-empirical and FE method. Two SIF correction factors are proposed taking into account the mechanical properties and the geometry of the CFRP reinforcement, respectively.

2 EXPERIMENTAL STUDY

2.1 Fatigue test specimens

Experimental study on metallic plates with one fatigue emanating from a center hole has been conducted to investigate first the efficiency of the adhesively bonded CFRP reinforcement. Two metallic materials were considered: S235 carbon steel chosen due to its mechanical behavior similar to that of mild steel (Bassetti, 2001), and wrought iron originates from the dismantling of an old riveted bridge. Two types of CFRP laminates with their associated adhesive were also selected: Normal Modulus (NM) CFRP laminates and Ultra High Modulus (UHM) CFRP laminates (Lepretre et al., 2016a). The tested materials properties and dimensions are listed in table 1.

Table 1. Measured properties of metallic and CFRP materials

	S235 carbon steel	Wrought iron	NM CFRP laminate	UHM CFRP laminate
Tensile strength (MPa)	507 *(3.4)*	307 *(5.4)*	-	-
Yield strength (MPa)	244 *(2.4)*	186 *(4.4)*	-	-
Tensile Modulus (GPa)	199 135 *(1478)*	187 450 *(396)*	165 000	460 000
Thickness (mm)	10	7	1.2	2.3

The standard deviation is indicated in brackets
Properties indicated for wrought iron and CFRP laminates correspond to longitudinal direction

Specimens consist in metallic plates reinforced by CFRP laminates bonded on one side or both sides. The carbon steel plates are 510 mm-long, 90 mm-wide and 10 mm-thick. The wrought iron plates have the same dimensions except for the thickness with 7 mm-thick. An initial 0.6 mm-wide notch was made using the wire erosion technique. This allows to localize the crack initiation and to obtain a straight crack through thickness of the plates. From this initial notch, a fatigue crack is then initiated and propagated until a given length corresponding to the initial crack length a_0 for which the plate is reinforced by bonding CFRP laminates. Two different initial crack lengths were chosen for this study to simulate various stages of crack propagation: a_0 = 6 mm and a_0 = 13 mm. The first chosen length corresponds to a crack under rivet head, only detected using no destructive control technique, while the second initial length corresponds to a crack that has exceeded the rivet head and that can be detected by visual examination. For all reinforced specimens, the CFRP plate is bonded at a distance of 10 mm from the edge of the hole, taking into account the presence of the rivet head. Geometry of repaired plates, initial crack length and repaired configuration are shown in Figure 1.

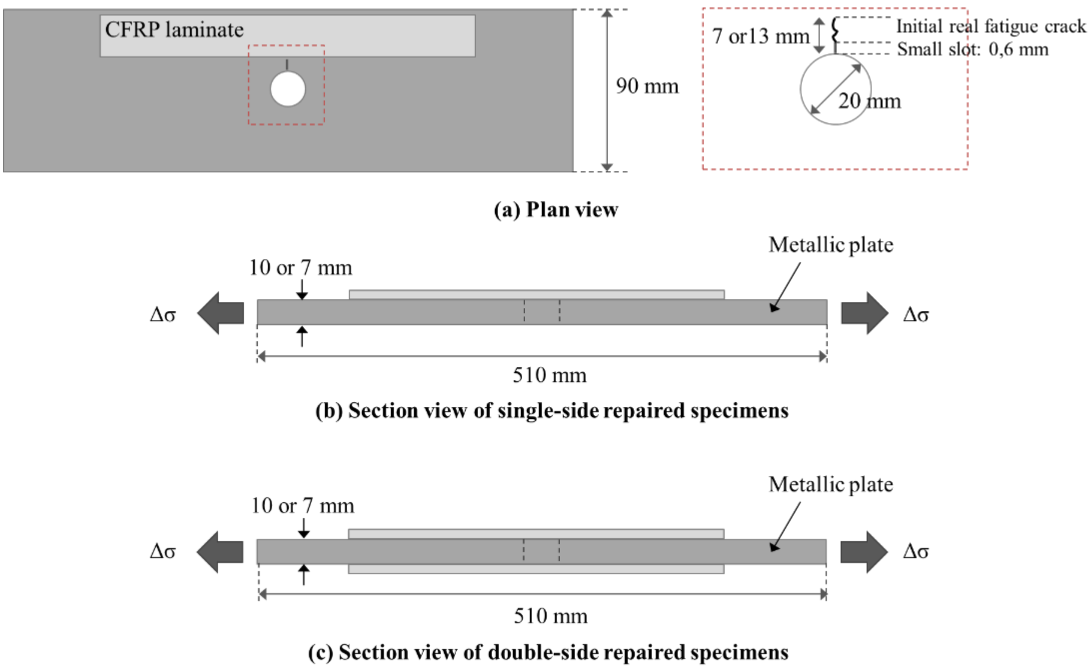

Figure 1. CFRP-reinforced cracked metallic plates (not to scale).

The specimens were tested under tensile cyclic loading with a stress ratio of 0.1 and a frequency of 10Hz, until complete failure of the specimens. The applied stress in the nominal section of the plates is similar for both carbon steel and wrought iron plates and varies from 100 MPa to 10 MPa. Crack propagation for all S235 carbon steel specimens was recorded using the "beach marking" technique. For wrought iron specimens, the "beach marking" technique cannot be applied due to the metallurgy of the materials, so it was decided to adopt a specific crack propagation sensor based on resistive technique bonded on the surface of the metallic plate.

2.2 Fatigue test results

2.2.1 Fatigue life extension

For mild steel plates, four reinforcement configurations were studied for both initial crack length (6 mm and 13 mm):

- non-pre-stressed NM CFRP laminates bonded on one side (un-symmetric reinforcement), named MN_NT_NS;
- non-pre-stressed NM CFRP laminates bonded on both sides of the plate (symmetric reinforcement) named MN_NT_S;
- pre-stressed NM CFRP laminates bonded on one side, named MN_T(10kN)_NS;
- UHM CFRP laminates bonded on one side, named UHM_NT_NS.

In order to ensure the repeatability of the results, three identical specimens were done for each reinforcement configuration. The fatigue cycle number is counted until complete failure of the specimen and the fatigue life increase ratio corresponds to the ratio between the average fatigue life of CFRP-reinforced specimens, N_{CFRP}, and those of the reference specimens (un-reinforced ones), N_P. For wrought iron specimens, based on the first results obtained for mild steel specimens, only UHM CFRP reinforcement was investigated for both initial crack lengths. Unlike carbon steel, wrought iron specimens exhibit wide variability of results mainly due to the non-homogeneity of the materials (Lepretre et al., 2016a). For this reason, results of each specimen within the same reinforcement configuration are presented separately.

Figures 2 left and right describes the relationship between initial crack length (damage degree) and fatigue life improvement for the different strengthening configuration, for mild steel and wrought iron specimens respectively. For mild steel specimens, an average increase of fatigue life by a factor ranging from 1.25 to 2.27 is observed. The maximum increase lifetime is obtained for double-sided repaired specimens with NM CFRP. Nevertheless, in practice, it is often difficult to make a double side repairing (complex geometry of the cracked elements, angle elements, and lot of rivets). For single sided repaired specimens with NM CFRP, the non-pre-stressed specimens show a non-significant increase of lifetime contrary to the pre-stressed NM specimens (for which crack closure phenomena are intensified by pre-stressing CFRP laminates). Nonetheless, pre-stressing technique still raises numerous questions regarding the durability of the bonded joint (losses of pre-stress with time, stress concentration areas …) (Wang et al., 2014). For these reasons, use of UHM CFRP laminates seems to be a good solution, see Figure 2 left (increase fatigue lifetime ratio of 2.18 and 1.75 depending on the initial damage degree).

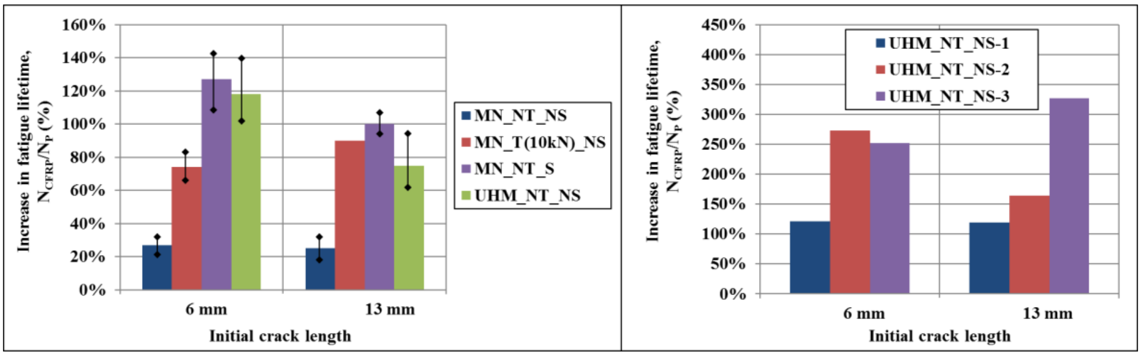

Figure 2. Fatigue life improvement ratio versus initial crack length for mild steel specimens (left) and wrought iron specimens (right).

For wrought iron specimens, only UHM CFRP laminates bonded on one side was investigated (see Figure 2 right). As expected, the non-repeatability of the tests is clearly visible. Nonetheless, for all reinforced specimens, the fatigue life increase ratio is significant with an increase lifetime ratio ranging from 2.19 to 4.27.

2.2.2 Crack propagation curves

Microscope observations of the crack surfaces for mild steel specimens are presented in Figure 3. These fracture surfaces with visible beach marks have been used for plotting all crack propagation curves. As expected, more striations are visible for CFRP-reinforced specimens, depending on the reinforcement configuration. For un-symmetric reinforcement, it is interesting to note an un-symmetric crack front shape about the mid-thickness of the plate. This phenomenon is mainly due to reinforcement configuration which cause load eccentricity and the establishment of an out-of-plane bending (Ratwani et al., 1979).

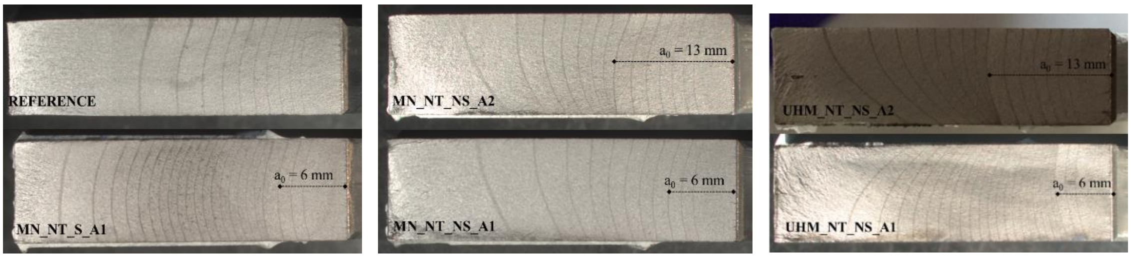

Figure 3. Fracture surface with beach marks.

Figure 4 shows crack propagation curves for mild steel specimens reinforced by non-pre-stressed NM CFRP laminates (symmetric (left) and un-symmetric (right) reinforcement configuration). A significant decrease of the crack propagation rate is observed for symmetric CFRP-reinforced specimens. Moreover, for all specimens, it is interesting to note the immediate effect of reinforcement corresponding to a decrease of the crack propagation rate even before the crack has reached the edge of the bonded CFRP laminate.

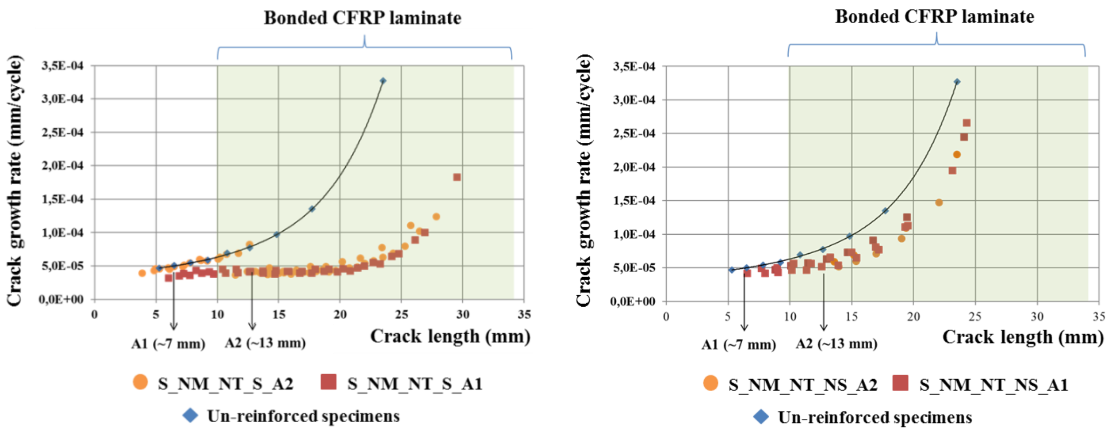

Figure 4. Crack propagation curves for mild steel specimens: MN_NT_S specimens (left); MN_NT_NS specimens (right).

The propagation curves obtained for all specimens (mild steel and wrought iron) are available in Lepretre, 2017. For mild steel specimens, these curves were later used to implement a modelling approach presented below.

3 STRESS INTENSITY FACTOR DETERMINATION

3.1 Semi-empirical analysis

The Stress Intensity Factor (SIF) is a key factor of the LEFM (linear elastic fracture mechanics). It is used to predict the crack propagation rate and thus assess the fatigue life of a cracked element. The semi-empirical method developed here to determine the mode I SIF is based on the well-known Paris law (Paris and Erdogan, 1963) and the James-Anderson method developed in 1969:

(1) Paris law parameters *C* and *m* are determined by fatigue test on reference specimens (R) (e.g. the un-repaired specimens in the present paper). *a* corresponds to the measured crack length, and *N* to the counted cycle number:

$$\left(da / dN\right)_R = C \cdot \Delta K^m \tag{1}$$

(2) The same fatigue tests are then performed on the CFRP-reinforced specimens with different reinforcement configuration (CFRP):

$$\left(da / dN\right)_{CFRP} = f(a) \tag{2}$$

(3) Assuming the *da/dN*-Δ*K* relationship from reference specimens can be used directly for CFRP-reinforced specimens (same Paris law parameters only depending on the metallic material, see Shen et Hou, 2011), the SIFs for each reinforcement configuration can be obtained:

$$\Delta K_{CFRP} = \left[1/C \cdot \left(da/dN\right)_{CFRP}\right]^{1/m} \tag{3}$$

Following this first step, a primary empirical factor, F_{CFRP} corresponding to the ratio $\Delta K_{CFRP}/\Delta K_R$, can be proposed. Nonetheless, this factor do not currently take into account of the different reinforcement parameters (modulus, thickness, wide of the metallic plate and the CFRP laminate, CFRP bonded location from the initial notch).

Similarly to study led by Wu et al., 2013a, two reduction factors, F_P and F_{GD}, were proposed. The first factor F_P was determined by writing the equilibrium equations (use of equivalent cracked steel plate with reduced far field stress range); it only considers the CFRP material properties. Since it is obvious that the SIF will also depend on the CFRP bond geometry, the second factor F_{GD} was proposed and determined with the semi-empirical factor F_{CFRP}. This factor only depends on the CFRP laminate wide and its position from the initial notch (Lepretre, 2017). Nonetheless, the implementations of these factors and their formulation have to be verified and validated for different parameters values. Therefore, the next step consisted in establishing a FE model extrapolated to others element geometries. This FE model is done with MSC Marc Mentat software.

3.2 Validation with FE model

Two steps are necessary to model the behavior of CFRP-reinforced specimens. First, only un-repaired specimens are considered in order to establish a reliable fracture model. This first model is based on the Paris law with thanks to the material parameters *C* and *m* determined previously. The fatigue crack propagation and the SIF calculation are realized using the VCCT method (Virtual Crack Closure Technique) described in more details in Kruegger et al., 2002 and Lepretre, 2017.

After validation, the different CFRP reinforcements are added to the fracture model and it then becomes necessary to consider the different materials, particularly the bonded joint. Two cases were considered: one model considers a linear-elastic behavior for all materials (mild steel plate, CFRP laminate and bonded joint); the second one considers a linear-elastic behavior for mild steel plate and CFRP laminate and a cohesive zone model is used for the bonded joint. In all cases, materials are isotropic, the first model is named ‘classical model’ while the second is named ‘cohesive zone model’. This latter is based on the use of a traction-separation law allowing damage of the joint during the crack propagation (Lepretre et al., 2016b).

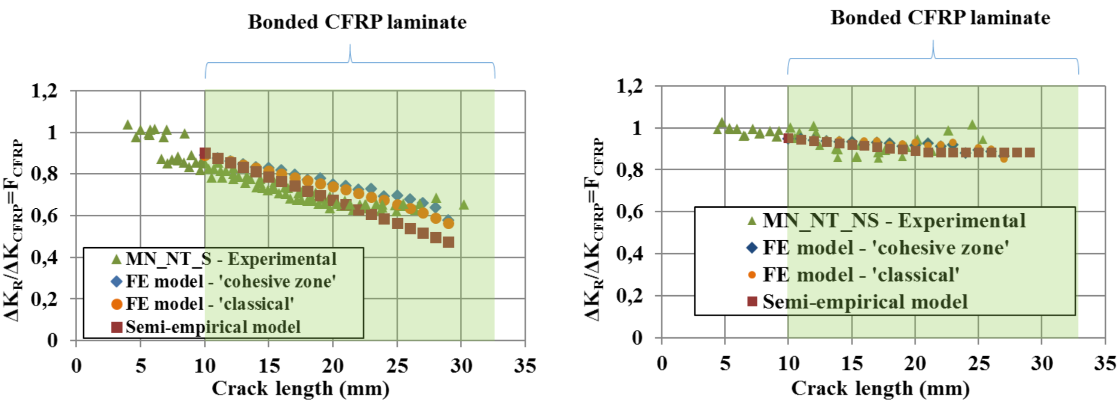

Figure 5. Comparison of obtained results from experimental, semi-empirical and numerical analysis: MN_NT_S specimens (left); MN_NT_NS specimens (right).

Figure 5 show a comparison of the results obtained from experimental, semi-empirical and numerical analysis for two CFRP reinforcement configuration : symmetric (left) and un-symmetric (right) NM CFRP reinforcement. It can be found that the FE results are very close to the experimental and semi-empirical ones, which tends to validate the model. It is also interested to note that the choice between ‘classical model’ and ‘cohesive zone model’ has a minor impact on results. The main advantage of the ‘cohesive zone model’ is the possibility to observe damage of the bonded joint. Similar debonded areas were obtained between numerical and experimental results as we can see in Figure 6. All these results show that a quick evaluation and assessment of the CFRP effects, on mode I SIF of studied cracked steel plates, become possible. Even if additional studies are still needed especially relating the influence of the various parameters and elements geometries.

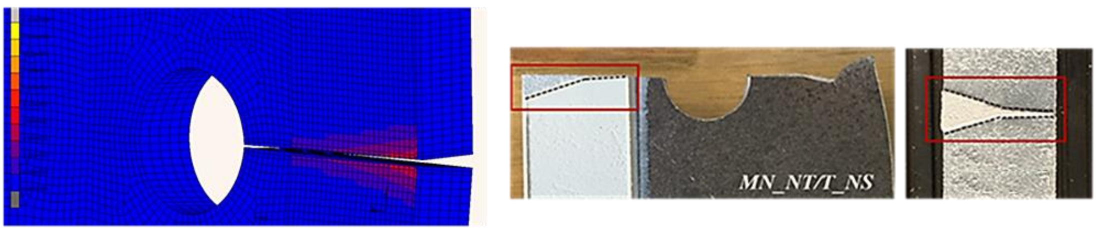

Figure 6. Damage of the bonded joint: numerical analysis (left); experimental results (right).

4 CONCLUSIONS & PERSPECTIVES

In this paper, NM CFRP laminates (pre-stressed or non-pre-stressed) and UHM CFRP laminates were used to extend the fatigue life of cracked metallic elements consisting of one single crack emanating from a center hole. Single sided and double sided repaired specimens were investigated for mild steel plates while only UHM CFRP laminate bonded on one side was studied for wrought iron plates. The results show an average increase of fatigue life by a factor ranging from 1.25 to 2.27 for mild steel specimens and from 2.19 to 4.27 for wrought iron specimens, substantiating efficiency of CFRP reinforcement even for old metallic structures.

Thereafter, in order to evaluate and assess the CFRP reinforcement effects, mode I SIF evolution for each mild steel specimen was investigated. Good agreement between semi-empirical, numerical (FE model) and experimental analysis was obtained, validating the proposed modelling approach. The next step is now to study the influence of various parameters on the results and to extrapolate the model to different cracked element geometries.

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