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CRACK PROPAGATION IN CIVIL ENGINEERING BRIDGE CABLES: COUPLED PHENOMENA OF FATIGUE AND CORROSION

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Abstract. This paper deals with the propagation of a crack initiated by fretting-fatigue in bridge cables. They are submitted to traffic loads and exposed to environmental conditions (rain, wind, marine environment, de-icing salts …). These loads can lead to two main damage causes: fretting-fatigue and corrosion. These both phenomena can be coupled and lead to premature failures of drawn steel wires. In fact, at specific contact points, cracks are often initiated by fretting-fatigue. Fretting-fatigue is due to the cable bending. Near anchorages, the bending deformations are the highest and can generate damage (wire cracks). Cracks may propagate under traffic or wind fatigue load. They are also often submitted to a severe environment. Indeed, even if cables are initially protected, these protections can deteriorate and then cables are subject to corrosion. Experimental results show that wire cracks are often initiated by fretting-fatigue and crack propagation is due to fatigue or fatigue corrosion. In this study wire crack is initiated by fretting-fatigue first and fatigue tests are set up after with several environments in order to evaluate their influence on the crack propagation. The studied corrosive environments are: distilled water, sodium chloride solution and thiocyanate ammonium solutions with different concentrations. Lifetimes of specimens are compared. Metallographic and fractographic observations show the influence of the different solutions on the crack propagation. Indeed, since the microstructure of the steel wires is fully oriented in the longitudinal direction, corrosion changes the crack propagation modes and favours mixed mode propagation or longitudinal propagation.

1 INTRODUCTION

Wires of civil engineering cables are submitted to two main damage mechanisms: fretting-fatigue and corrosion. Fretting-fatigue is generally observed near the anchorage where the cable is submitted to the most important free bending deformations. Usually, wires are protected against corrosion in several ways such as lubrication, zinc coating, etc. However, if these means of protection disappear during the cable life, and if corrosive solution is in contact with the cable, then the wires would be submitted simultaneously to fretting-fatigue and corrosion. The wires of cables are generally elaborated by cold drawing. Those wires are cylindrical with a diameter ranging between 3 to 7 millimetres. They have a high-grade of carbon (about 0.8%) and are obtained by cold drawing. These cable wires have a high tensile strength and a low ductility.

The different types of cables are described in [1] and [2]. Due to cable geometry, inter-wires contacts are subject to stress concentration which can lead to crack initiation. Indeed, stay cables are submitted to vibrations induced by climatic loads (wind, rain, etc.) and traffic loads. These vibrations lead to bending deformations which are maximal near the anchorages and then there are small relative displacements between wires (fretting-fatigue).

Studies of fretting-fatigue phenomena were already conducted by several authors (Fouvry [5], Siegert [4], Zhou [6], etc.). They concluded that the fatigue limit is highly reduced for specimens undergoing fretting-fatigue. In the case of cables [4], this reduction is mostly due to contact friction forces between wires. In order to study this interwire contact mechanism, Siegert [6] determined normal contact force in a multilayer strand and the relative displacement amplitude between wires. Then, a fretting-fatigue device was developed; it aims at reproducing the contact fatigue conditions in spiral strands undergoing free bending deformation.

Aging cables are also subjected to severe environmental conditions and can undergo corrosion damage. There are three main types of corrosion for cables: uniform corrosion, localized corrosion and mechanically assisted corrosion as stress corrosion cracking or fatigue-corrosion. In stay cables with low tension, corrosion appears generally only after a certain age. However, for aging bridge cables where protective coatings are damaged, corrosion is an important source of cables degradation [2].

A previous study aimed at investigating the influence of a sodium chloride (NaCl) solution on the behaviour of wires undergoing fretting-fatigue [1]. In this paper, coupled phenomena between fatigue and corrosion are studied in wires of bridge cables. After initiating cracks in a wire by fretting-fatigue, their propagations are realized by fatigue-corrosion in several environments.

2 MATERIAL

The material used for the tests is mechanically a high strength steel and chemically a low alloy steel.

Table 1 : Mechanical properties and characteristics of test wires and strands

	E (MPa)	UTS (MPa)	σ_{Rg} (MPa)	$\sigma_{RP0,02}$ (MPa)	ε (%)
Wire	202 000	2 020	1 860	1 750	5,5
Strand	193 000	1 940	1 860	1 480	5,2

Those wires are manufactured by cold drawing process, which consists in reducing the wire section by passing through decreasing section dies. This process improves the wire resistance by hardening. The mechanical properties and characteristics of a wire and of a strand are reported in Table 1. They were obtained by carrying out several tension tests. Figure 1 shows the stress-strain curves obtained from these tests.

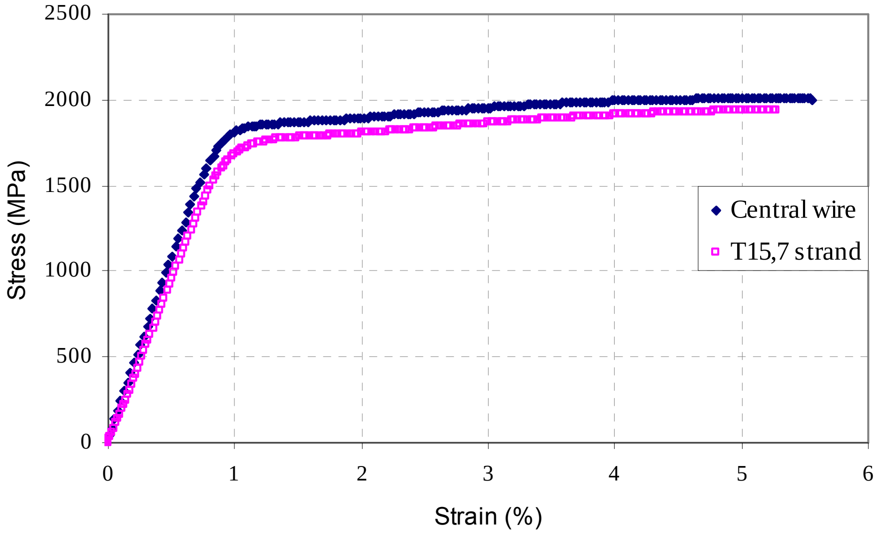


Figure 1: Tensile test on a wire and on a strand

Tested specimens are low alloy steel wires whose chemical composition is given in Table 2. They are cylindrical with a diameter of about 5.4 millimetres. They exhibit a pearlitic structure with fully oriented grains in the longitudinal direction.

Table 2: Chemical composition of cold drawn wires (main elements)

Fe	C (carbon)	Si (silicon)	Mn (manganese)	S (sulphur)	P (phosphor)
Balance	0,8 %	0,23 %	0,52 %	0,018 %	0,017 %

3 EXPERIMENTAL TEST DEVICE

For the tests, a fatigue machine is used: it is associated with a fretting grip for fretting-fatigue tests and with corrosive cells for fatigue-corrosion tests.

The fretting-fatigue testing device is shown in Figure 2. This experimental device is used to reproduce the loading conditions of wires in a spiral strand like the free bending of stay-cables. The tested specimens consist of steel wires which are subjected to a tensile fatigue loading with a mean stress value of 600 MPa, corresponding approximately to 30% of the wire UTS (1860 MPa), and a stress variation $\Delta\sigma$. The constant normal contact force F_c is added perpendicularly to the cable length, using two pairs of pads made up with the same material that crossed perpendicularly the tested specimen. The two pairs of pads were fixed in a rigid way at a distance L on a pair of supports. δ is the amplitude of the relative displacement between the pads and the tested wire.

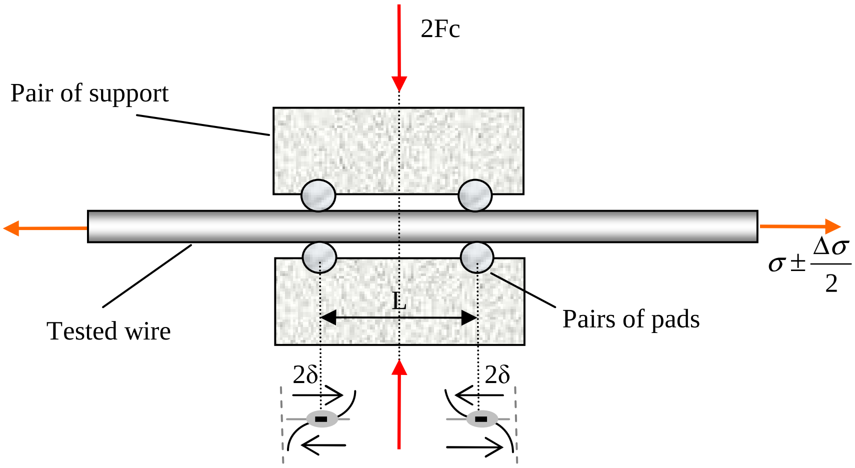


Figure 2: Schematic of the fretting-fatigue test set-up (side view)

The modelling of the mechanical behaviour of a strand subjected to bending deformations makes it possible to calculate the local contact between wires under simplified conditions (Siegert [7]). Moreover one first experimental study made possible to identify value ranges of the test parameters representative of the inter wire contacts in the strand which lead to an important reduction of the stress limit for bare wires (not galvanized and not lubricated). The tests were carried out with a contact force of 200 N, a distance between pairs of pads of 20 mm and a variation of tensile stress of 200 MPa at a frequency of 2 Hz.

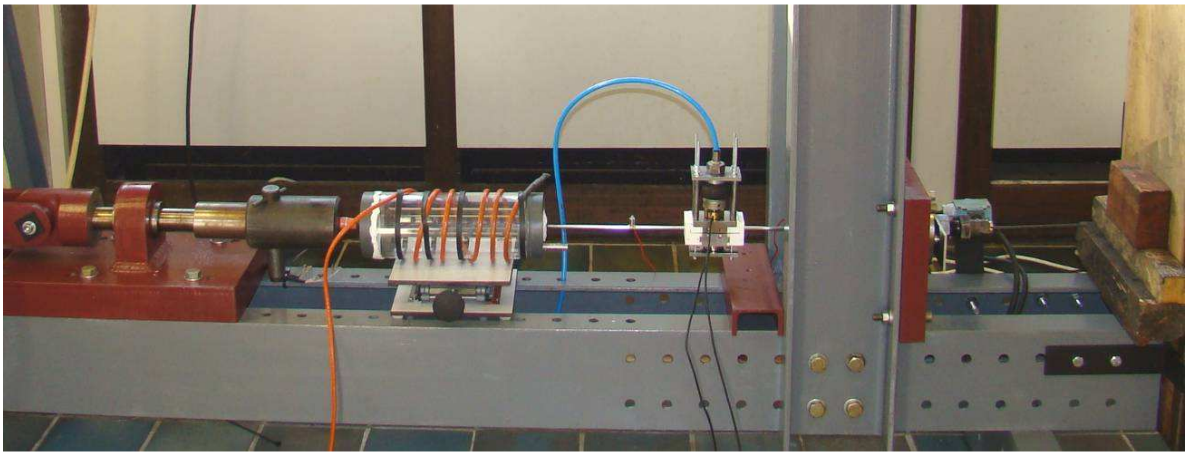


Figure 3 : Experimental device: fretting-fatigue test under realization and a corrosive cell which is translated after the fretting-fatigue

For the fatigue-corrosion test, the fretting grip is removed and a cell, which contains a corrosive solution at 50 °C is translated on the contact scars. The fatigue parameters are the same as for the fretting-fatigue test (mean stress of 600 MPa, stress variation of 200 MPa), excepted for the frequency which is reduced to 1 Hz (Figure 3).

So, the tests consisted in two steps. The first step aims at initiating a crack by fretting-fatigue. The second step consists in propagating the crack by fatigue-corrosion.

For the first step, 350 000 cycles of fretting-fatigue are sufficient to initiate cracks. The presence of these cracks is controlled with a ultrasonic device.

For the second step, the pre-cracked tested wire is submitted to fatigue-corrosion, and corrosion cells are added. For tests in distilled water or sodium chloride (NaCl) solutions, two cells are added, one cell is placed around the tested wire, and there is another cell in which the solution is aerated. For tests in thiocyanate ammonium (NH_4SCN) solutions, only one cell is added around the wire.

4 RESULTS AND DISCUSSION

The main results of the tests are the lifetimes of the tested specimens and their metallographic observations. The results are compared for the different studied environments: air, distilled water, NaCl solution and NH_4SCN solutions.

Lifetimes are given on the histogram of the figure 4. The pink part of the bars represents the fretting-fatigue phase (350 000 cycles). The blue part corresponds to the fatigue phase in each environment. The dispersion of the results is also reported.

For tests in air, the average lifetime is about 600 000 cycles, and it can be seen a large dispersion of the results, this dispersion is inherent of fretting-fatigue phenomena.

In distilled water, the average lifetime is about 750 000 cycles and in NaCl solution, the mean lifetime is about 800 000 cycles.

In NH_4SCN solutions, the average lifetime is between 370 000 and 500 000 cycles depending on the concentration.

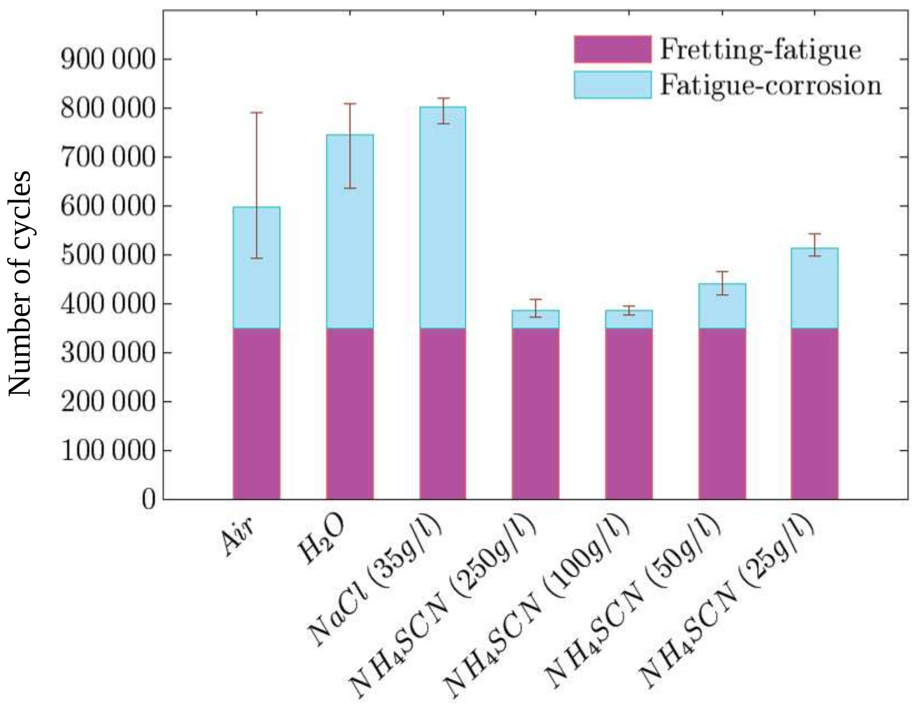
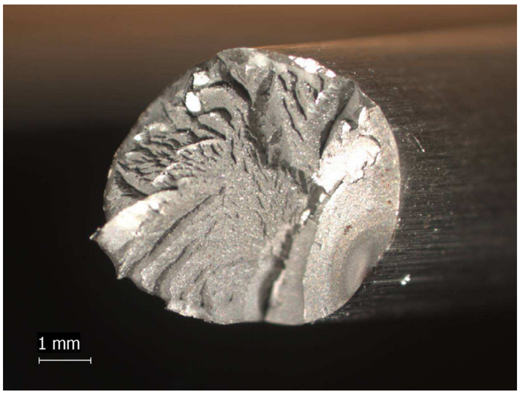


Figure 4 : Lifetimes of specimens submitted to fretting-fatigue first and then to fatigue in several environments

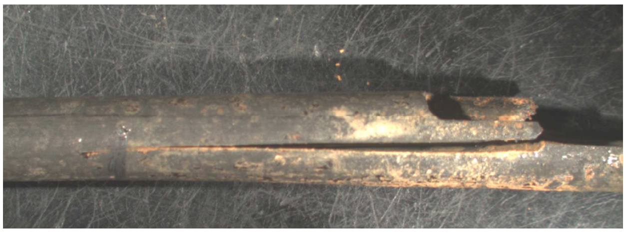
In NH_4SCN solutions, the lifetimes are reduced compared to air, more significantly for the concentrations of 100 and 250 g/l. This result means that hydrogen accelerate the crack propagation by a Hydrogen-Induced Stress Corrosions cracking (HI-SCC) mechanism.

On the contrary, in distilled water or in NaCl solution, lifetimes increase. These solutions seem to reduce the crack propagation. These results are obtained in the retained conditions and may not be representative of what happens on bridges.

However, some authors made similar observations. For example, Pao *& al.* [8] noticed that for low values of the variation of the stress intensity factor ΔK, the crack growth rate in an aluminum alloy can be slower in a NaCl solution than in air.



(a) Air



(b) Distilled Water

(c) NaCl solution

(d) NH_4SCN solution – 50g/l

(e) NH_4SCN solution – 100g/l

Figure 5: Fractures surfaces of specimens submitted to 350 000 cycles of fretting-fatigue and to fatigue until rupture in different environments

For each type of tests, the specimen rupture surfaces were observed with binocular, optical and/or scanning electron microscopes.

The fracture surfaces for tests in air are quite smooth in the crack area (Figure 5 (a)). The crack initiation and the beginning of its propagation are influenced by the fretting loading and make an angle of about 45°. The crack propagation is then due to the fatigue loading and is perpendicular to the wire until the final shear rupture.

For the tests in distilled water or in NaCl solution, the crack propagates transversally to the wire first and then longitudinally (Figure 5 (b) and (c)).

For tests in NH_4SCN solutions (Figure 5 (d) and (e)), after the transversal part of the crack, the crack propagates in a mixed mode (modes I and II).

The increase in lifetime of specimens immersed in distilled water or NaCl solution may be explained by the changes in the propagation of the crack. Indeed, there is a very long longitudinal propagation which is not observed for specimens undergoing fatigue in air. Moreover, some authors [8],[9] also made similar observations for aluminum alloys and they made hypothesis that may explain this effect. Three hypotheses are given by Menan [9]. The first one consists in the blunting of the crack tip which results from a competition between mechanical kinetic and anodic dissolution kinetic under the action of chloride ions. The second one supposes crack closure effects which might be due to corrosion products as said by Pao *et al.* [8]. The third one is the passivation of the crack tip which would protect the steel and then slow down the crack growth rate.

5 CONCLUSIONS

Cables of bridges have two main damage causes: fatigue and corrosion. In this paper, coupled phenomena are studied. Indeed cracks are initiated by fretting-fatigue and then propagate under fatigue-corrosion. Several environments are studied and compared. Air is chosen as a reference environment. An increase of lifetime is observed in distilled water or in NaCl solutions. This increase may be due to changes in the propagation of cracks in these environments (changes of modes, of crack growth rate, etc.). Indeed, there is a very long longitudinal propagation (mode II) which is not observed in air, and chloride ions may induce crack tip blunting. A reduction of lifetime is observed in the more aggressive corrosion solutions, it is probably due to hydrogen embrittlement.

The study of interaction between these phenomena may contribute to improve the management of bridges which are getting older. This study might be completed by pure fatigue-corrosion studies with different level of stress.

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