INFLUENCE OF CORROSION ON THE ENDURANCE LIMIT PREDICTION OF WIRE ROPE AND ITS COMPONENTS IN SHAPE OF WÖHLER CURVES

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Résumé

*Les câbles métalliques sont des structures hiérarchiques très complexes. Ils se composent de plusieurs fils torsadés ensemble pour obtenir une structure avec d'énormes propriétés mécaniques. Ces propriétés rendent le câble un élément essentiel et utilisé dans de nombreuses structures industrielles telles que le levage de charges, les structures flottantes, les ponts suspendus et l'industrie minière. Néanmoins, les câbles en service sont soumis à plusieurs chargements variables. Ils sont liés aux effets mécaniques, thermiques et environnementaux qui conduisent à différents mécanismes de dégradation, qui peuvent se produire seuls ou en combinaison. L'un de ces mécanismes est l'effet de corrosion, qui peut causer des dommages accélérés aux composants du câble et entraîner une rupture soudaine et inattendue. Dans ce contexte, des essais expérimentaux de traction ont été réalisés sur des échantillons vierges et corrodés de câble métallique non-rotatif 19*7 afin de prédire l'évolution du dommage et de la durée de vie de cette structure. De plus, l'influence de la corrosion sur la limite d'endurance a été étudiée en établissant les courbes S-N. Les résultats expérimentaux obtenus dans cet article montrent que la fatigue due à la corrosion peut entraîner une diminution de la résistance à la fatigue et accélérer l'endommagement par fatigue du câble. Ces nouvelles approches peuvent bien estimer la résistance à la fatigue des câbles métalliques à partir d'essais statiques.*

Mots-clés : *Câble métallique, Corrosion, Fatigue, Propriétés mécaniques, endommagement, Limite d'endurance, Courbes S-N.*

Abstract

Wire ropes are rather complex hierarchical structures. They consist of several wires twisted together to obtain a structure with enormous mechanical properties. These properties make cable an essential element and used in many industrial structures such as lifting loads, floating structures, suspended bridges and the mining industry. Nevertheless, the cables in service are subjected to several variable loadings. They are related to mechanical, thermal and environmental effects that lead to different *degradation mechanisms, which can occur alone or in combination. One of these mechanisms is the corrosion effect, which can cause accelerated damage to cable components and lead to sudden and unexpected failure. In this context, experimental tensile tests were carried out on virgin and corroded samples of 19*7 non- rotating wire rope in order to predict the damage evolution and the lifetime of this structure. Furthermore, the influence of corrosion on the endurance limit was investigated by establishing S-N curves. The experimental results obtained in this paper, show that corrosion fatigue can lead to a decrease in fatigue strength and accelerate fatigue damage in the rope. This new approach can estimate well the fatigue life of wire ropes from static tests.*

Keywords: *Wire rope, Corrosion, Fatigue, Mechanical properties, Damage, Endurance limit, S-N curves.*

Nomenclature

D	Damage function
β	Life fraction
t_i	Immersion time
T	Total immersion time
σ	Applied stress
σ_u	Ultimate stress
σ_{ur}	Ultimate residual stress
σ_a	Stress just before the failure
R_s	Static reliability
γ_e	Instantaneous nondimensional endurance limit
n	Instantaneous number of cycles under an applied stress
K_a	Material constant
b	Material constant
N_f	Number of cycles to failure
γ	Nondimensional ultimate residual stress
γ_u	Nondimensional ultimate stress
σ_0	Endurance limit of the virgin strand
γ_e^*	Nondimensional endurance limit at failure
σ_e	Instantaneous endurance limit of a virgin material
σ_0^*	Endurance limit at the failure
m	material constant is equal to 8 for metallic

1 Introduction

Wire ropes are structural elements that have a complex geometric form. The construction process follows a rigorous hierarchy that can be described by passing through the sub-elements of the whole system. The basic element is the wire that is wrapped in a strand. This latter consists of a straight central wire (core wire), and other wires twisted around the core in shape of a single helix curve (outer wires) [1]. These wires are assembled in layers with the same distance between the centreline axis and the strand axis. The strand is the new basic element for the rope construction and depends on how it is inserted into the whole system, which is the support of a wire rope on which several strands are wound [2]. Wire ropes can be considered as composite structures. Their main characteristic is their relatively high tensile strength compared to their bending and torsional strengths [3]. Moreover, they are often regarded and designed as perfectly flexible structures. In fact, wire ropes have very little stiffness in bending if it related with the axial stiffness. This property is important when the element must be wound up [4], as in lifting systems where the cable is forced to follow the radius of a pulley or winch. Indeed, Wire rope contains various elements that can be affected in the long term by environmental effects, stresses or natural aging of materials. These degradations are evolving and can lead to some more dangerous disorders that guide the evolution of technologies. These degradation mechanisms indicate the concept of damage, which is also a major tool for predicting the service life of all mechanical components [1]. Many researchers from literature based their investigations on the concept of damage models to estimate the service life of wire rope and to evaluate the risk of failure of its components. Meksem et al [5] studied the reliability of a rope damaged by fatigue at different percentages of its wires. Tijani et al [6] examined the effect of the combined degradation modes of accelerated corrosion and wire rupture on the mechanical properties of a wire rope. In addition, Molnár [7] conducted research on a rope sample as a whole and on individual wire samples to examine the process of degradation of the mechanical properties of ropes in the corrosive environment. Moreover, Meknassi et al [8] investigated the corrosion of wires extracted from a wire rope. After that, Mouradi et al [9] conducted an experimental study to track the damage evolution of the 19*7 non-rotating wire rope, and identified the different stages of damage. As many mechanical components subjected to cyclic loadings of varying amplitude are subject to fatigue failure. Predicting the fatigue life of these mechanical components became a major research topic. Prediction of fatigue life under loading of variable amplitude is a complex problem against a loading of constant amplitude in engineering operations. This type of problem is more challenging to deal with. One of the most important and rudimentary problems in predicting fatigue life is the modelling of the accumulation of fatigue damage [10]. It is therefore important to develop simple but robust approaches for prediction of fatigue life using the available material properties. For this reason, many research studies were done to estimate the fatigue curves from simple and fast monotonous tensile tests, or techniques that link the fatigue parameters to static tests. The most famous methods are the methods for predicting the Coffin-Manson's curve [11], such as the four-point correlation method [12], which estimates the fatigue curve of a given material from characteristics determined by a monotonous tensile test. The universal slope method developed by Manson and Hirschberg [13], which accepts that a tensile test is a very short fatigue test under plastic loading.

The main objective of this study is to investigate the mechanical behaviour of cable components in service. In fact, the evolution of the damage to the strand and wire of the 19 ×7 non-rotating wire rope is tracked as a function of the immersion time as well as the evolution of the loss of their sections. This method is widely used by industrial companies to predict the useful life of this structure and to ensure that it can be deposited in the appropriate time. For this purpose, an experimental study is carried out to trace the evolution of the damage to the strand and wire constituting the 19 ×7 non-rotating rope and to identify its different stages as well as the critical fraction of life that can lead to the failure of these components. In addition, the influence of corrosion on fatigue life under Wohler diagram is studied and its different fatigue zones are defined. This investigation is based on tensile tests performed on virgin and other samples that are damaged by corrosion at different levels.

2 Theory

The models used to characterize the accumulation of fatigue damage can be categorized into two types: the linear and the nonlinear approach.

2.1 Miner's law

The Miner's rule is the most effective approach to linear accumulation of damage and is widely used in engineering machines because of its simplicity [14]. The damage of the wire rope being progressive, its variation is largely influenced by the loading level. Various theories representative of this damage are given by the linear model initiated by Miner's law according to which the damage evolves linearly as function of the life fraction β [15].

$$\beta = \frac{t_i}{T} \tag{1}$$

This approach overestimates the damage D and indicates that material failure happens when the solicitation histories it exposed, caused partial damage such that their sum is equal to one.

$$D = \beta = \sum_{i=1}^{P} \frac{t_i}{T_I} = 1 \tag{2}$$

2.2 Nonlinear Fatigue Damage Accumulation Model Based on unified theory

To correct the Miner rule inconvenience, several methods of fatigue damage accumulation were developed and the majority of these models are based on nonlinear accumulation laws. One of these nonlinear models is the theory unified [16]. Loss of strength may be associated to static tensile strength or fatigue strength under the effect of damage due to cyclic loading. The concept of damage caused by energy associated to cyclic plastic deformation, for stresses above the endurance limit was originally suggested by Henry [17], then taken up by Gatts [18]. Using some characteristics of the theories of Shanley [19] and Valluri [20]. Dubuc [21] have suggested an expression deriving the loss rate of the endurance limit of the material subjected to cyclic loading as a function of life fraction, it is written as below:

$$\gamma_e = \gamma - \frac{1}{\dfrac{1-\beta}{\gamma - 1} + \dfrac{\beta}{\gamma - \left(\dfrac{\gamma}{\gamma_u}\right)^m}} \tag{3}$$

where $\gamma_u = \frac{\sigma_u}{\sigma_e}$ and $\gamma = \frac{\sigma}{\sigma_e}$ is the loading level defined according to the unified theory as a nondimensional cyclic load, it reflects the influence of the loading and the mechanical characteristics of the material on the damage.

In the case where the average stress is zero, the expression of the variation rate of nondimensional endurance limit γ_e as a function of number of cycles applied n is:

$$\frac{d\gamma_e}{dn} = -\frac{1}{K_a}\gamma^b\left(\gamma-\gamma_e\right)^2 \tag{4}$$

By integrating Eq. (4) with the boundary conditions, we obtain an approach to the $(\sigma - N)$ fatigue curve at a constant amplitude and for a number of cycles as:

$$N_f = K_a \frac{1}{\gamma^b}\left[\frac{1}{\gamma-1} - \frac{1}{\gamma-\left(\frac{\gamma}{\gamma_u}\right)^m}\right] \tag{5}$$

which leads to nonlinear damage depending on the level of applied stress to cable, this damage varies according to life fraction, it is represented by a series of curves, each curve associated with a loading level:

$$D = \frac{\beta}{\beta + (1-\beta)\left[\frac{\gamma-(\frac{\gamma}{\gamma_u})^m}{\gamma-1}\right]} \tag{6}$$

3 Experimental procedure

3.1 Material

The examined specimens are wires and strands extracted from wire rope of the 19*7 non- rotating construction type of 10 mm diameter, with a metallic central core strand and crossed to the right. Its components are mechanically high-strength and chemically low-alloy steel wires. The rope is composed of two layers of strands twisted in opposite directions, which makes possible to avoid the rotation of the suspended load when the hoisting heights are important and the load is not guided. This cable construction is widely used in lifting applications, mechanical and marine industries Fig. 1.

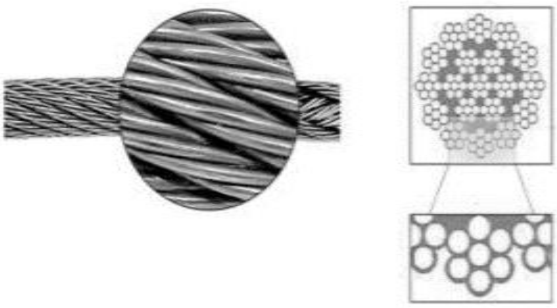

Fig. 1. Cross-section of a 19*7 non-rotating wire rope

The main geometric and mechanical characteristics of the studied rope are presented in Table 1.

Table 1. Mechanical and geometric characteristics of the 19*7 non-rotating rope

Nominal rope diameter	$D_n = 10\ mm$
Cable construction	19*7 (1*7+6*7+12*7)
Strand construction	1*7 (6+1)
Wiring direction	Left wiring in the inner layer Right wiring in the outer layer
Outer layer strand diameter	$1.8\ mm$
Strand wire diameter	$0.52\ mm$
Core nature	Metallic
Material Category	Galvanized
Mass per unit length	$0.404\ kg/m$
Lubrication	$A2/W-3$
Minimum breaking force	$68.6\ KN$

The percentage composition of this rope is indicated in Table 2.

Table 2. Chemical composition of cable

C	Mn	Si	P	S	Fe
0.8	0.52	0.22	0.019	0.018	Balance

The mechanical properties of the rope are reported in Table 3.

Table 3. Mechanical properties of cable

Elastic Modulus E(GPa)	Poisson's Ratio ν	Yield Strength σ_y(MPa)	Ultimate Strength σ_u(MPa)	Strain ε(%)
171	0.3	1568	1786	2.1

3.2 Preparation and tensile tests on specimens

The objective of this experimental study is to track the mechanical behavior of wire rope in operation. Thus, static tests were carried out on virgin and corroded samples of wires and strands constituting the cable that are damaged by corrosion at different levels (from 4h to 32h with a time length of 4h). This corrosion damage was realized by immersing the specimens in 30% concentration sulfuric acid solutions. In order to obtain a specimen of strand and wire, a length of 300 mm was cut from the cable as the test length for all samples according to ISO 6892 1984 [22]. The specimens were tested in monotonous tensile according to standard NF EN 10002-1 with imposed displacement corresponding to a strain rate of 1.5 mm/min. The tests were carried out under ambient conditions of air and temperature on a Zwick Roell tensile machine with a capacity of 10 kN Fig. 2 [23, 24].

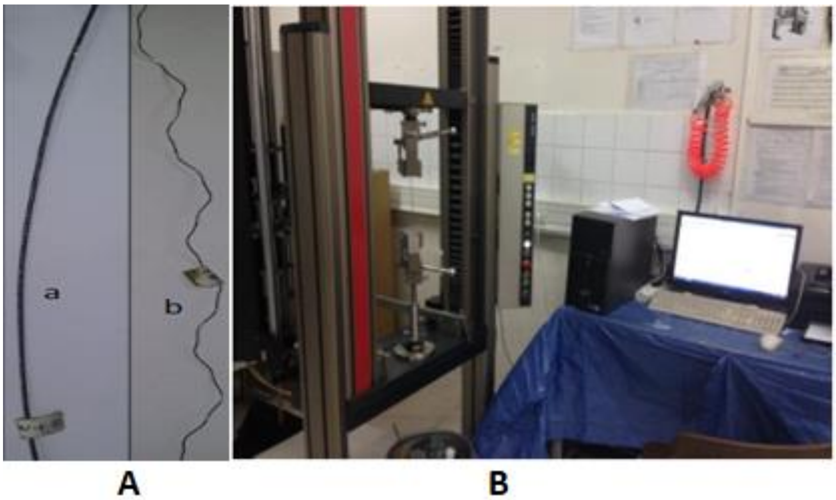

Fig. 2. (A) Specimens: (a) strand (b) wire (B) Mounting the sample in the ***Zwick Roell*** tensile machine

4 Results and discussions

4.1 Mechanical behavior characterization

The tensile curves of virgin specimens are illustrated in Fig. 3. The Stress-Strain curve of the test pieces was measured using true stress and true strain relationships. In fact, the virgin specimens has an ultimate stress σ_u that gradually decreases as the immersion time increases to reach a value corresponding to the total damage of the specimens (Table 6).

The mechanical characteristics of specimens are indicated in the following table.

Table 4. Values of ultimate stress of damaged specimens

Immersion time (h)	0	4	8	16	24	32
Residual ultimate stress of wire (MPa)	1853	1747	1529	1095	763	512
Residual ultimate stress of strand (MPa)	1948	1838	1637	1020	605	439

4.2 Loss of the ultimate stress during static tensile tests

Fig. 4 presents the residual ultimate stress as a function of the life fraction. The virgin specimens supports an ultimate stress of σ_u, which gradually decrease as the immersion time of specimens increases until critical values are reached (total damage of the specimens).

4.3 Loss rate of the endurance limit

The rate of the endurance limit as a function of life fraction for different loading levels of γ (Eq. (3)) is presented in Fig. 5. When the rate of the endurance limit is zero, there's no stress applied, the fraction of life must be equal to one. When the rate of the endurance limit is equal to one, the material has been 100% damaged, the endurance limit must be zero, and therefore the life fraction becomes zero. The concavity of the loss rate curves of the endurance limit is accentuated for low load levels.

4.4 Quantifying damage by the unified theory

The damage evolution calculated from Eq. (6) according to the unified theory as a function of the life fraction for different loading levels of γ of wire and strand are presented in Fig. 6. The concavity of the damage curves is accentuated for the low load levels. However, they gradually tend towards (Miner Rule) linearity for higher loads. For this reason, the Miner's rule overestimates the damage that can justify the simplicity and security of the Miner's law in relation to other theories.

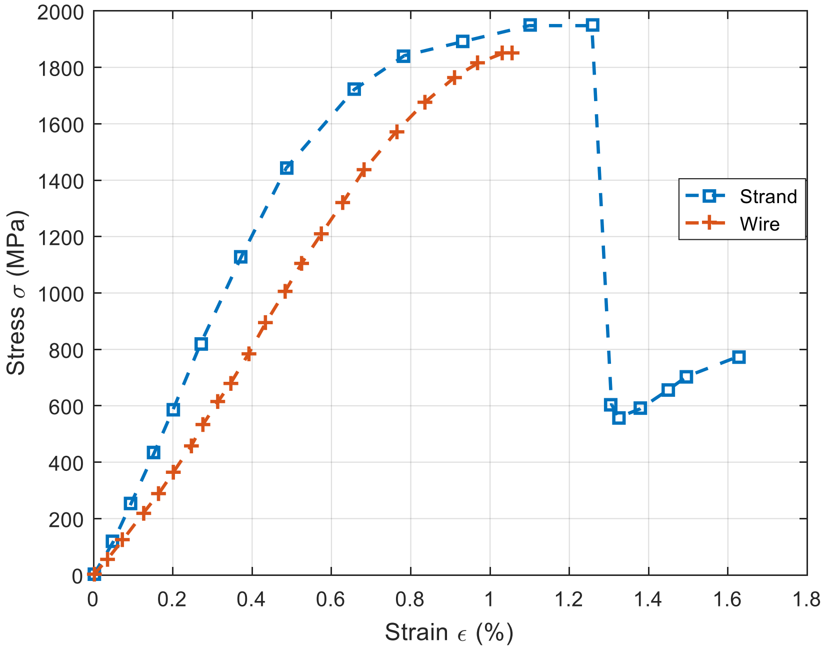

Fig. 3. Tensile curve for virgin specimens

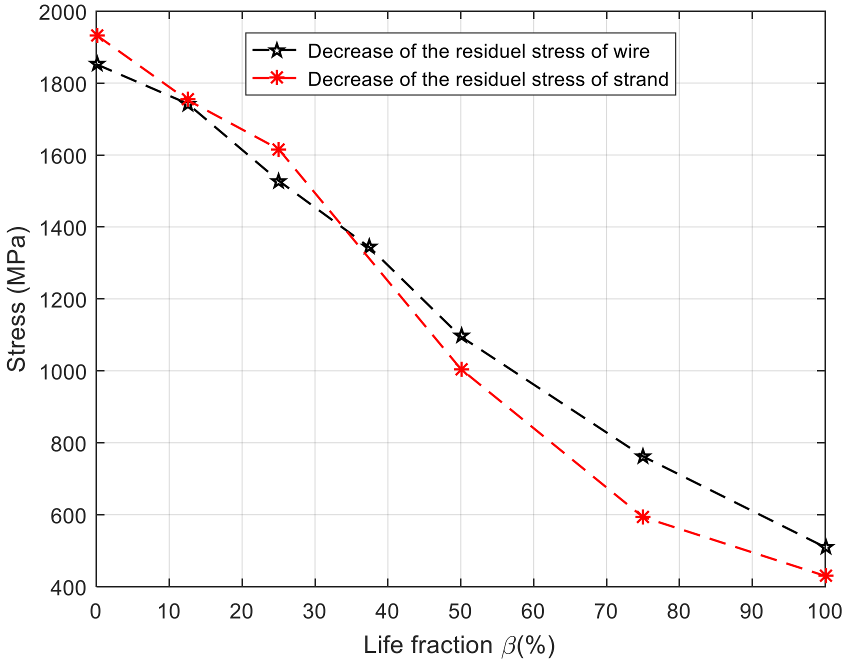

Fig. 4. Corrosion effect on the variation rate of the endurance limit

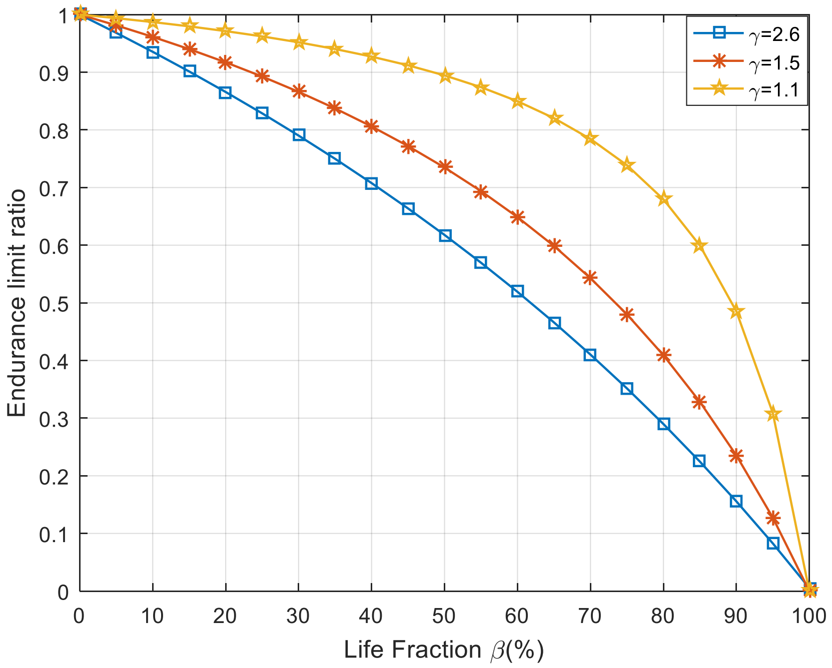

Fig. 5. Corrosion effect on the variation rate of the endurance limit

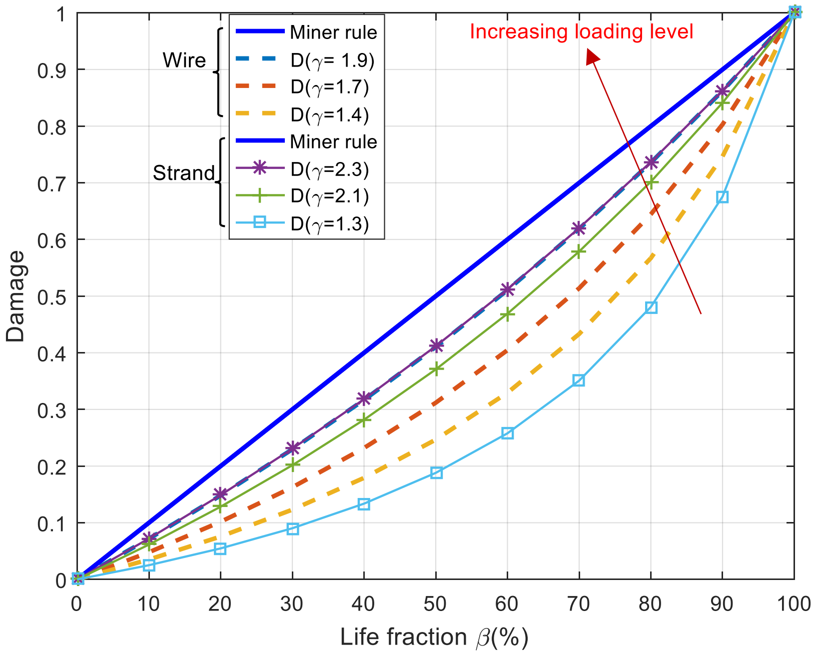

Fig. 6. Variation of the damage according to the unified theory for different loading levels γ of the cable components.

4.5 Prediction of number of cycles N_f at failure

In order to be able to predict and to plot the rope fatigue curve, we must determine the material constants K_f and b using the experimental results and the Coffin-Manson's $(\sigma-\varepsilon)$ curve. Then we took two characteristic stress points used in the experiment, which gives $K_f = 1.57 * 10^4$ cycles and $b = 1.53$.

The value of σ_0 is determined experimentally or estimated from the ultimate stress: $\sigma_0 = \alpha * \sigma_u$. The evaluation of the $(S - N_f)$ curve from the maximum stress to the endurance limit of wire rope components according to Eq. (5) is depicted in Fig. 7. The fatigue curve shows well the three regions of Wohler diagram:

- Low-cycle fatigue regime, the failure of rope components occurs after $2*10^3$ cycles under the effect of plastic deformation.
- Limited endurance or fatigue regime, the failure of cable components is reached after a limited number of cycles,
- Unlimited endurance regime or safety zone, the failure of cable components does not occur after $1.5*10^6$ cycles, which means that the stresses applied are too low; the curve has a horizontal asymptote.

The fatigue life of this structure was reduced due to friction and contact between the multi-components and the effect of corrosion on components of the wire rope.

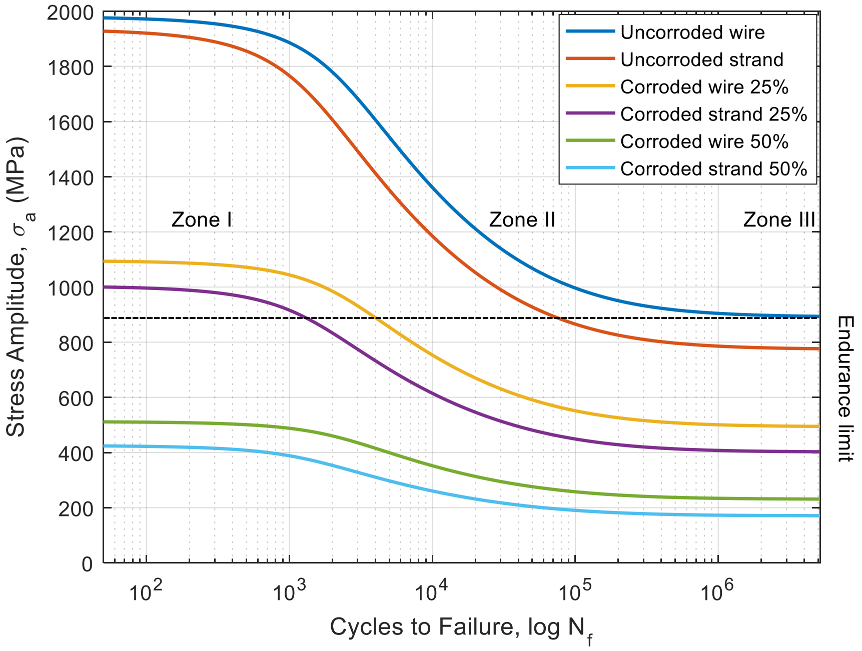

Fig. 7. Comparison of fatigue behavior of corroded and uncorroded samples

5 Conclusion

In this study, we were able to track the fatigue damage evolution of wire and strand constituting the wire rope, based on two damage models, that is, the Miner's rule and the unified theory model. The concavity of the damage curves was accentuated for the low load levels. However, they were gradually tended towards (Miner Rule) linearity for higher loads. For this reason, the Miner's rule overestimates the damage that can justify the simplicity and security of the Miner's law to other theories. Subsequently, we estimated the fatigue curves of the rope components by using the unified theory approaches, as well as we defined the different zones of fatigue of these components. The first zone I, corresponding to low cycle fatigue $N = 2*10^3$ cycles under the effect of plastic deformation. Then the zone II, which is the limited endurance or fatigue $2*10^3 \prec N \prec 1.5*10^6$ cycles. Finally, the unlimited endurance regime or safety zone $N \succ 1.5*10^6$ cycles, the failure of rope components does not occur, which means that the stresses applied are too low; the curve has a horizontal asymptote. The fatigue life of this structure was reduced due to friction and contact between the multi-components and the effect of corrosion on components of the wire rope. This new approach can be a reliable and useful tool for the fatigue life estimation of wire ropes from static tests in the field of design and maintenance.

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