

The Inspection of Crane Wire Ropes in Moroccan Service: Discard Criteria and Monitoring Procedure

A. El Barkany, A. Benali, M. El Ghorba, A. Choukir

Abstract—The reliable and safe use of wire rope is crucial for crane operations. Wire rope is a very useful and long lasting structural element when properly used and maintained. Therefore, wire rope safety is (or should be) a constant concern of wire rope operators and safety authorities. Safe use of the crane wire ropes depends directly on the rope condition, and on the in-time and reliable rope inspection. This study is focused on the failure analysis of crane wire ropes in service in Morocco. Wire defects and condition of a lifting rope have been studied and presented in this paper. Special attention is given to conditions that can lead to internal damage such as broken wires, wear as well as corrosion. Various nondestructive tests methods have been used in this application for wire ropes control such as visual inspection, radiographic and electromagnetic. The results of the nondestructive testing have made it possible to determine the safety status of a rope and establish preventive maintenance procedures to extend the useful life of a rope. It is concluded that maintenance, inspection and discard policy must be determined in recognition of the degradation mechanisms that operate in different rope applications.

Index Terms—Wire rope, Degradation mechanisms, Nondestructive methods, Electromagnetic inspection, Discard criteria, Safety, Maintenance.

I. INTRODUCTION

Wire rope is a group of strands laid helically and symmetrically, with uniform pitch and direction around a central core of natural or synthetic fiber, or wire (fig. 1). Generally, there is combination of steel wire and textile elements. The basic material of the wire ropes is in a traditional way steel with strong high percentage of carbon. Carbon steel wire ropes are by far the most abundant, due to their high strength and relatively low cost. Typically, the steel used has a very high strength, which may be a factor of five greater than the strength of typical structural steels. Wire ropes are identified by several parameters including size, grade of steel used, whether or not it is preformed, by its lay,

the number of strands and the number of wires in each strand [1].

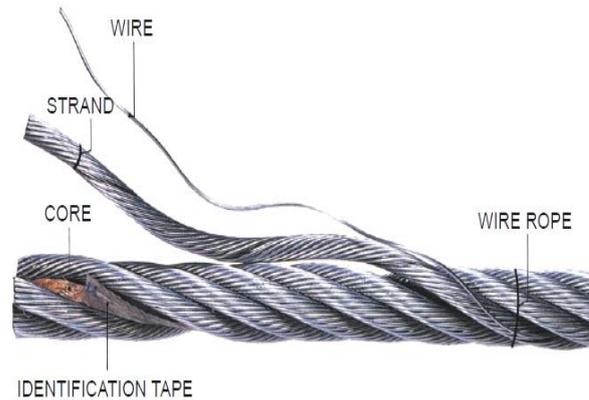


Fig.1. Schematic of wire rope composed of different strands of wound steel wires

Wire rope service is typically categorized as static or dynamic. Many types of machines and structures use wire ropes, including draglines, cranes, elevators, shovels, drilling rigs, suspension bridges and cable-stayed towers. Steel wire ropes constitute the essential element carrying the lifting devices. Each application has specific needs for the type and size of wire rope required. The producers of wire rope offer a wide range of rope types, in which the wires can be organized in according to different configuration for achieving an acceptable performance in a wide range of safety critical applications. Wire ropes are long lasting when properly used and maintained.

Despite its widespread use, a wire rope remains an extremely complex and little-known piece of lifting equipment. Wire ropes are tough in the sense that it is tolerant of local damage, particularly in the form of broken wires. Wire ropes operate at high stress levels and are almost invariably subject to fluctuating loads. Lifting wire ropes are subjected to variable constraints and cyclic deformations. They are the seat of displacement of their components (wires) or/and additional (anchoring, final fasteners, etc.). They are at the origin of a large number of serious accidents. The continual process of degradation associated with operational service will ultimately lead to failure, and a lifting rope must therefore be replaced before the risk of such failure becomes unacceptable. In many cases, failure of a wire rope could lead to expensive damage to equipment or even to loss of life.

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The inspection of crane wire ropes in Moroccan service: Discard criteria and monitoring procedure

Nondestructive test method of a wire rope plays a significant role in the process of evaluation of its operating conditions. So, the state of the wire ropes can be apprehended with one or more of the following methods:

- Visual inspection;
- Electromagnetic method of evaluation of abrasive wear, corrosion and detection of the wire-breaks;
- Radiographic methods;
- Acoustic emission method (detection of the shock wave emitted during the brutal broken wire).

Steel wire rope is deteriorating gradually throughout its entire service life. To keep abreast of degradation, wire ropes must be periodically inspected. Because moderate degradation is normally present, the mere detection of rope deterioration does not usually justify rope retirement. There are two major nondestructive inspection methods for the detection and assessment of rope degradation: visual and electromagnetic inspections.

The objective of this work is to show the importance of the nondestructive inspections methods applied on wire ropes in order to be able to estimate and predict their residual lifetime. We propose to study and analyze the state of deterioration of the ropes after one period of operation. This work presents principal degradations which affect the wire ropes, their typical scenarios accidents and the losses of mechanical resistance which they generate in service. A test campaign electromagnetic wire rope was also performed. Finally, a monitoring procedure of crane wire rope has been proposed.

II. EVALUATION OF ROPES CONDITIONS: FAILURES MECHANISMS

Steel wire ropes are most significant part of lifting. Frequent inspection of wire ropes is required to attain maximum service life avoiding costly, and possibly inconvenient, replacement. It is necessary to observe excessive wear on the outside wires resulting in marked reduction of rope diameter, broken wires, corrosion and pitting, state of lubrication, core condition, etc. During the diagnosis of a wire ropes structure, the following question arises systematically: what is the current capacity of the ropes and which must we conclude to the security of lifting device and what are the exploitation cautions to be considered?

Indeed, the principal goal of examination of a wire rope is to supervise the development of the increase amongst wire-breaks, so that a rope can be deposited in good time, before its state becomes too dangerous for the service. The second goal is the possibility of recognizing the damages, which are often produced by mechanical external influences.

According to the normative regulations [3], a wire rope must undergo periodic examinations to check the safety of its exploitation. The frequency of these examinations is shorter after the appearance of the first damages on the wire rope.

Each rope will have to be examined before the resumption of work of an elevating lifting device which was put except service for a given period. In the same way, in the event of displacement of the equipment facility or damage related with the mechanism, or after an accident. Besides the rope, all the parts of kinematics in contact with this it must be controlled.

A wire rope in service is subjected to several mechanisms of normal or abnormal degradation that may occur alone or in

combination. The wire-breaks by cracking, deformation or corrosion are a much answered problem.

Several detailed investigations were conducted with the Public Laboratory of Studies and Tests (LPEE) on wire ropes in service of the cranes and gantries of the main ports of Morocco (MARSA Morocco). This research is the result of collaboration between the Laboratory of Control and Mechanical Characterization of Materials and Structures (LCCMMS) of the National Higher School of Electricity and Mechanics (ENSEM) in Casablanca and the Experimental Center of Materials and the Industrial Engineering (CEMGI) of LPEE.

To define the chemical compositions of crane wire ropes, a metallographic examination has been carried out on a sample of a cable diameter of 35 mm (Table 1). Before metallographic sample preparation, dirt and lubricant residues were removed from the wires by washing in alcohol. Additional cleaning in an ultrasonic bath was performed. Samples for optical microscopy were prepared by grinding and polishing, and were etched in 2% Nital (2% H₂NO₃ solution in demineralised water applied for 10 seconds). The observations were performed on longitudinal and transverse. Figures 2 and 3 obtained with a magnification of 400x with attack "nital" show that the metallurgical of the cable is ferritic-perlitic microstructure.

An extract of the pathologies observed on Moroccan sites affecting the wires or the strands of the cables is described below (Figures 4 to 14) [4]–[8].

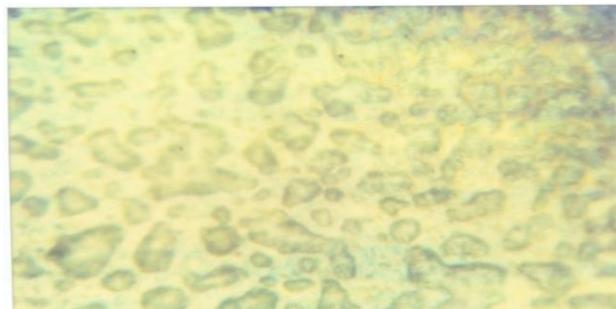


Fig. 2. Optical metallography of the cross-section of sample 1 featured by a very fine ferritic and perlitic microstructure

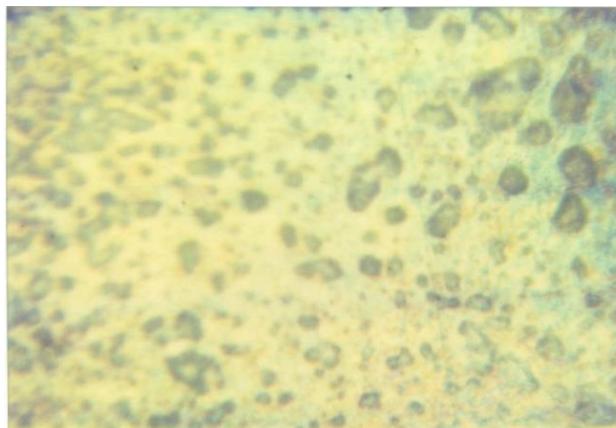


Fig. 3. Optical metallography of the longitudinal-section of sample 1 featured by a very fine ferritic and perlitic microstructure



Fig. 4. Internal inspection of damage rope: The opening of this cable has revealed that there are actually five internal wire breaks in one section and 10 internal wire breaks in total



Fig. 7. Corkscrew-type deformation in rotation-resistant hoisting rope



Fig. 5. Birdcaging caused by a sudden release of tension in rotation-resistant hoisting rope: Strand protrusion/distortion



Fig. 8. Broken aluminum sleeve during a tensile and torsion test of rotation-resistant hoisting rope

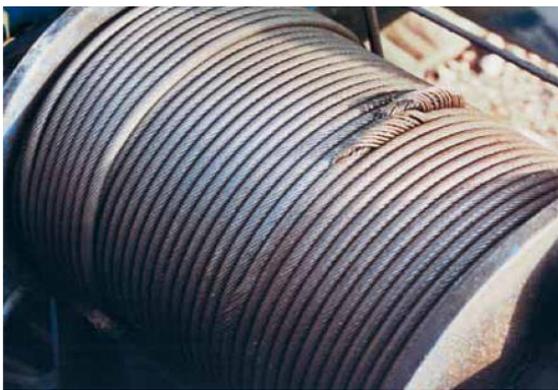


Fig. 6. Rope deformed forming a hull with hernia of the fiber core



Fig. 9. Wire rope subjected to internal and external corrosion. Wire rope with indication of crack wires. The cracks produced during the service are the only marked ones



Fig. 10. Failing rope following corrosion, wear and fatigue

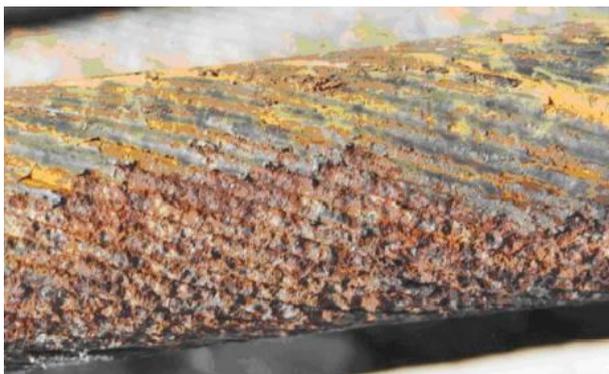


Fig. 11. Homogeneous dissolution of the wires with losses of section [5]



Fig. 12. Broken wires of fretting tiredness on multi-layer strand [5]



Fig. 13. Effect of external corrosion on the rotation-resistant hoisting rope and the drum

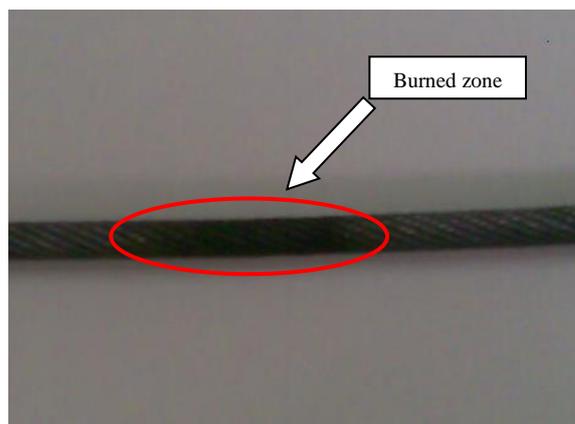


Fig. 14. Zone Burned during fatigue tests at a frequency of 15Hz [8]

A. Discussions and interpretations [4]–[10]

Details are presented of specific degradation mechanisms observed on the crane wire ropes. In each case the mechanisms are analyzed and steps outlined to alleviate the problems.

The measurements are intended to identify rope wear and other deterioration so that a wire is removed from service before it becomes hazardous to use. Application of visual inspection procedures makes it possible to improve the reliability of detecting broken wires over the available rope length for evaluation.

The main reasons for the failure of the wire rope were fatigue and poor inspection. The process of service degradation is complex and different for each installation, reflecting the local operating parameters and the characteristics of the rope employed. The periodic visual controls that we have started show that the damages reported above are of mechanical and environmental origins. These degradations result in the wear of the steel wire ropes, which appears by local reductions of cross-sectional area of the wires (flat, indentations), wire-breaks or local deformations. It is relatively rare to be able to separate wear, and corrosion, the second enemy of the steel wire ropes. Corrosion is responsible for the retirement of a great number of the hoisting wire ropes.

Visual checks shall decide on the possible need to make additional destructive testing. Let us note that fractographic examinations and tensile tests on wires of service rope were carried. The whole of these data makes it possible to make “reasonable” evaluations of the following points:

- State of the internal strands of the starting from the examination of the external strands;
- State of the internal layers starting from the state of the visible layer;
- Many pre-fissured wires starting from the report amongst already broken wires;
- Residual resistance.

In running ropes, broken wires develop primarily in sections that move over sheaves, pulleys and winch drums. Typically, they are caused by bending-over-sheave fatigue cycling. Usually, breaks develop in segments of the rope surface that come into direct contact with the sheave. Here, various contact phenomena compound the fluctuating bending stresses. Breaks in these areas are external and usually visible. However, internal breaks also can develop depending on the loading and, especially, the rope construction. Following laboratory tests, it was found that the capacity of a cable decreases with the growth of his broken wires. We note that the number and distribution of wire breaks were, in turn, responsible for the rope being retired prematurely. Any broken wires in close proximity to termination points should be fully analyzed for their effect on the continued safe operation of the rope and monitored regularly for further deterioration.

Once deterioration of a rope is evident, all destructive tests should be accompanied by testing of individual wires from a variety of rope samples. Tests should include torsion, wrap or bend and weight of zinc loss tests.

It was also noted that the damage due to wear can reduce the force and the resistance of the wire rope. External wear usually occurs on the working surface of a rope. Wear results in loss of cross-sectional area of the wires. The problems related to external and internal wear require special attention. Severe external wear can indicate that internal wires are similarly worn. Often, severe wear can cause outer wires or clusters of outside wires to break abruptly. Rubbing between wires of strand can cause internal wear.

Mechanical damage can have many causes such as a solid object hitting the rope, improper handling during rope installation, overloading or shock-loading. In parallel, all the parts of kinematics to the contact with the rope require an attention. Indeed, the bases and the various final fasteners can be the seat of damages of mechanical origin of the rope. A bad alignment in the beginning can create a strong tensile heterogeneity in the wires of the rope (this phenomenon being worsened by the inflection, the traction and the torsion combined of the rope). Usually, mechanical damage is clearly visible and easy to detect. However, some forms of mechanical damage, such as wire plucking, can be more difficult to locate. Corkscrew-type deformations (fig. 7) can be caused by sheave grooves that are too tight, through manufacturing errors or as a result of severe wear. Corkscrew-type deformations can cause rope damage by increased exposure to wear. Therefore, they increase the pressure between adjacent strands, which will eventually cause broken wires. Filled by moisture or rainwater, this tank allows feed the water penetrations through the fasteners which finally cause a corrosion of the rope. Wires can also corrode uniformly over their entire surface. This may reduce their cross-sectional area and cause loose unstressed wires. Rust can cause shallow pitting on the working surfaces of a rope where the steady rubbing action of the sheave prevents deep cavities. This mechanism accelerates wear. Furthermore, deep corrosion pitting on the internal surfaces of wires can severely shorten service life. The severity of corrosion often varies along the length of a rope. Then, external and internal corrosion and wear reduce the strength of wires. During fatigue tests at a stress amplitude $\Delta\sigma$ equal to

50% of the breaking load and a frequency of 15 Hz, there was a remarkable heating of the sample causes the burn the fat that is inside the loop (fig. 14) [8], [9].

In addition, most cables have a fat incorporated during manufacture. It has a dual purpose: to prevent corrosion and reduce internal friction. However, if desired in an optimal service, lubrication applied by the manufacturer must be followed by lubrication during operation.

In summary, the reduction in rope diameter due to excessive wear of outside wires should be thoroughly investigated and its cause determined. In case of broken wires, their number and distribution over a distance should be taken into account to calculate their effect. Where corrosive conditions exist, the inside wires and core should be controlled by correct and sufficient lubrication. An understanding of the degradation processes is important in realizing the potential rope life. This understanding is important in the context of inspection and discard.

In addition, during a visual inspection of a rope, only the contracting state of visible of the external wires can be evaluated. The metallic section of the external wires accounts for however only approximately 40% of the metal section of the rope and only half the length of these visible wires. This means that during visual inspection, a controller can examine only 20% of the metal section of the rope. It can only hope that the 80% remainders are in a condition at least as good.

It is however not rare that the visible 20% of the metal section are in good state, whereas a large number of wire-breaks is hidden in the not visible part of the rope. The ropes with internal broken wires and any sign external of damages are extremely dangerous. Core damage may be invisible, including IWRC or WSC fatigue cracking, internal corrosion attack, insufficient lubrication, and other potentially serious types of degradation [4], [5]. We can nevertheless have an outline of the interior of the rope by untwisting it but this operation is only possible for small rope diameters (figs. 9 and 10). Most wire ropes are covered with grease, which makes visual inspection – even for surface deterioration – impractical. Visual inspection is the simplest nondestructive examination method for wire ropes. Unfortunately, visual inspection can only include the exterior strands. Electromagnetic wire rope inspection is used now-a-days to scan the ropes in-situ to assess the condition of ropes. Electromagnetic wire rope inspection allows detecting broken wires occurring over time. In the following work, we will look beyond that the visual inspection on wire ropes remains essential and complementary methods, including electromagnetic monitoring, are always supplemented by visual examination.

III. ELECTROMAGNETIC WIRE ROPES INSPECTION METHODS

Electromagnetic wire rope inspection methods have been developed over the past 100 years. The first research on the electromagnetic control of the steel wire ropes goes back to 1907 (deposit of a patent in Germany by A. PEUKER). This it used the wire rope such as a transformer core.



Whatever the nature and frequency of electromagnetic controls, inspections of the entire length of the cables are designed to identify, record and assess the progress of any defects that may affect safety, such as [11]–[13]:

- Surface defects (abnormal appearance of the son, abrasion local general wear, corrosion);
- Geometrical defects (diameter reduction, modification of lay, ripple, distortion of the splice);
- Internal defects (local distortion, corrosion, dents wire, wire loose, broken wire);
- Sliding the cable to the end attachments.

A. Control principle

The electromagnetic control principle consists in magnetizing the rope, during its passage through the testing device over a length of a few tens of centimeters using a sufficiently important magnetic field to obtain the saturation of the rope so that the field is homogeneous and to thus measure the field of dispersion (figures 15 to 17) [12].

In this study, the control method is used with electromagnetic reels made up of two half-hulls which are close again around a wire rope [14], [15].

In the absence of defects, the tension fields of the magnetic field are parallel to the axis of the rope. When a defect exists, for example broken wire or loss or sudden variation in the metal section, the magnetic field lines are no longer parallel, they are deflected and induction B resultant is represented by its two components, tangential B_t and normal B_n (field of dispersion). Basically, a magnetic head encircles a rope. A constant flux magnetizes a length of rope as it passes through the head (magnetizing circuit). Variations in a constant magnetic field are sensed and electronically processed to produce an output voltage proportional to the change in metallic cross sectional area within the region of influence of the magnetizing circuit. Magnetic flux leakage created by a discontinuity in the rope, such as a broken wire, is also sensed, processed and displayed.

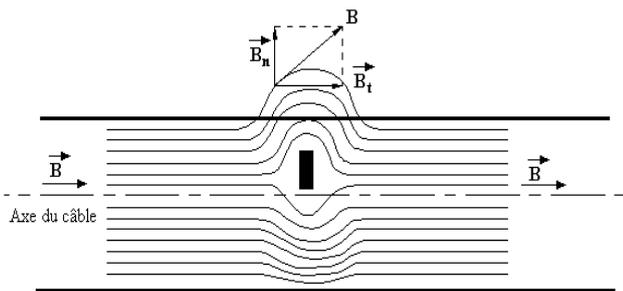
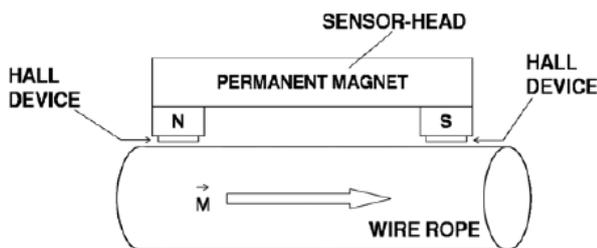


Fig. 15. Principle of electromagnetic wire rope inspection



M: MAGNETIZATION

Fig. 16. Schematic representation of a Permanent Magnet Equipped Sensor-Head Using Hall Devices to Measure the Loss of Cross Sectional Area

LEAKAGE FLUX AND TYPICAL SENSOR LOCATION

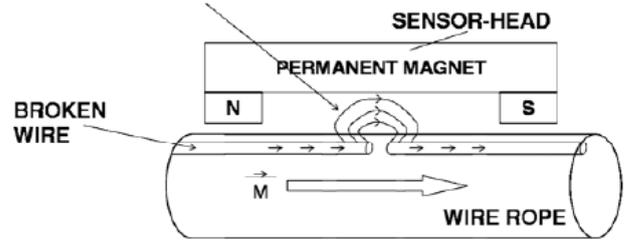


Fig. 17. Illustration of the Leakage Flux produced by a broken wire

B. Dispersion magnetic flux measure

We have seen that in this type of control, the rope is magnetized to saturation over a certain length. Thus, the voltage induced in the measuring coil is proportional to the flux derivative with respect to time: Faraday's law. That is to say:

$$U = \frac{d\phi_r}{dt} \tag{1}$$

We can also write:

$$U = \frac{d\phi_r}{dx} \cdot \frac{dx}{dt} = \frac{d\phi_r}{dx} \cdot V \tag{2}$$

Where:

U : Impulse voltage;

ϕ_r : Radial magnetic flux leakage;

t : Time.

In the last expression, x represents the abscissa counted along the rope and V is linear speed of the test wire rope. It is seen by there the produced impulse, indicated on the instrument – is proportional to the linear speed of the test. It results from it that to record defects of the rope, there must be a relative movement between the rope and the reels of measurement. Thus, voltage induced by the rope is then continually recorded.

The functional block diagram of figure 18 illustrates the signal generation process. This figure shows the rope's cross-sectional area – including variations caused by broken wires, corrosion, abrasion, etc. – as the input to an electromagnetic (EM) wire rope inspection system. From this input, the sensor head produces one or several electrical signals. These signals are electronically processed to produce the Localized Faults (LF) and Loss of Metallic Cross-Sectional Area (LMA) signals, which are then recorded by a chart recorder and/or stored by a data acquisition system [12].

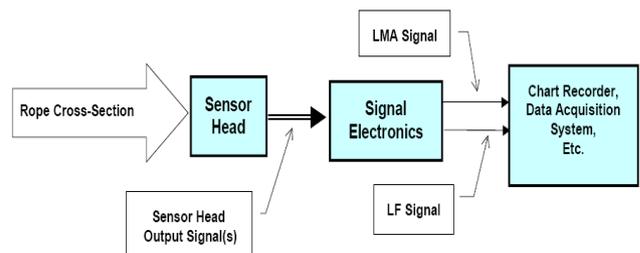


Fig. 18. Functional Block Diagram of the Signal Generation Process



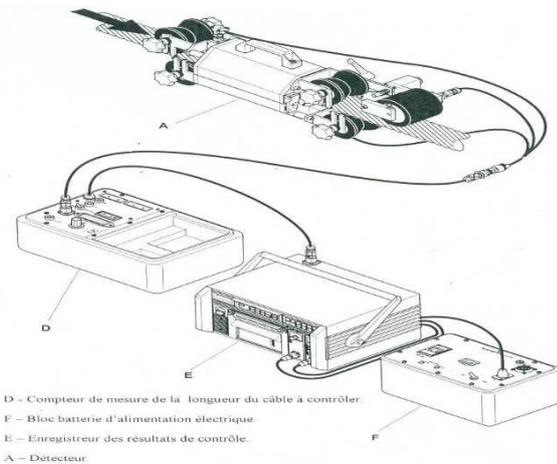
C. Measurement and control device

“Cable Test Halec SA” Magnetic Defectograph (fig .19) of French origin [14] was used for scanning the entire ropes length. For this device, the signals are electronically processed to produce the LF signals, which are then recorded by a chart recorder.

This measurement device consists of four principal parts: the system of magnetization (reference A) which constitutes the essential part of the apparatus. It is in two parts to allow its installation around the rope. The meter (reference D) is intended to measure the position of the points of the rope. The recorder (reference E) is equipped with the ordering of training to record the control results. Lastly, the block battery (reference F) is used for the power supply.



(a): Photograph Electromagnetic measurement Instrument [14]



D - Compteur de mesure de la longueur du câble à contrôler
F - Bloc batterie d'alimentation électrique.
E - Enregistreur des résultats de contrôle.
A - Détecteur

(b): Measurement and control device

Fig. 19. Photograph electromagnetic measurement instrument [14]

This equipment uses “permanent magnet method”. The method is based on magnetization of the rope with permanent magnets and detection of rope anomalies indirectly by magnetic sensors. This method is used direct current excitation coils. This instrument provides simultaneous readings of rope’s metallic cross-sectional area (both in total and relative terms) and localized faults, such as broken wires, wire ends, wire nicks, and corrosion.

D. Electromagnetic control parameters

Rope in a new state presents a defect of homogeneity which is translated on the recording by the background noise. Besides a recording with its commissioning will constitute the original answer of the rope known as “recording of zero” (figure 20). The signals which appear incontestably above

background noise result from the defects in the wire rope.

The identification and classification of local defects depends largely on the subjective interpretation of an analogue signal by an experienced operator coupled with the information from rope traces (figure 21 shows a typical trace obtained from testing a degraded rope).

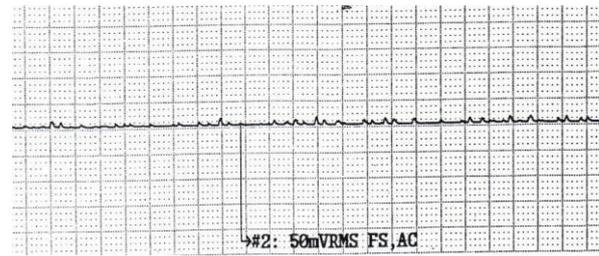


Fig. 20. Background noise of a new rope



Fig. 21. Typical Local Fault (LF) traces for severely degraded rope

The shape of the recorded signals depends on various factors:

- Magnetization of the rope: intensity and stability of the magnetic field;
- Design of the sensor coil;
- Relative speed between rope and the sensor;
- Relative speed variation;
- Sensor sensitivity;
- The defect nature;
- Section change;
- Defect length;
- Defect depth;
- Overlap between defects.

During controls on the same rope, we will preserve permanently, in what follows, the values of the first two factors so that from the signals rise only from the other factors which are inherent in the speed of measurement, the recorder sensitivity and rope defects.

E. The theoretical signals shapes

1) Broken or fissured wires

The shape of the signal for a broken wire should be compared with the idealized signal. The figure 22 depicts the rope cross-section as the input signal and the idealized corresponding LMA and LF output signals [12], [16]. It is quite obvious that in practice, the breaks can follow one another very quickly in the rope. It results from that the superposition of several types of defects and the detection of the smallest defects depend on the power of separation of the apparatus. This power of separation also depends on the width and the diameter of the reels and the capacity of the amplifier.



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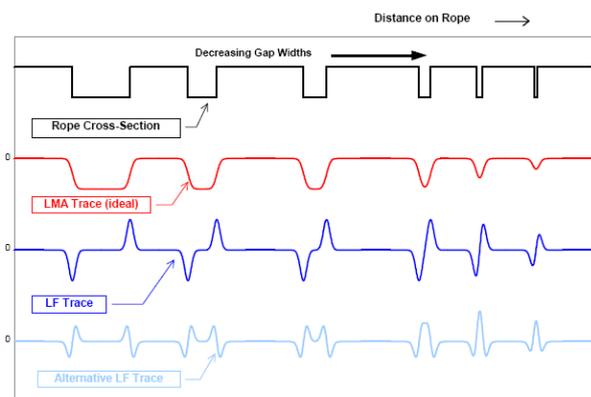


Fig. 22. Input and Output Signals of an Idealized Rope Test Instrument

F. Laboratory test results and experimental approach

1) Material and method

The analyses wire-breaks of the various layers of the rope during exploitation show that part of the breaks is the consequence of phenomena of tiredness associate with frictions. Under the conditions of employment determined, ropes can support the creation of internal wire-breaks. Independently of the visual observations, the electromagnetic method allows a nondestructive testing and a judgment on the internal and external state of the rope.

Considering the significant number of the control parameters, we built a device which makes it possible to carry out tests on ropes with variable speeds in order to establish a catalog of defects and criteria of demounting. The tests were carried out using an original assembly (fig. 23) [15] designed and carried out in the Experimental Center of Materials and Industrial Engineering (CEMGI) of the Public Laboratory of Tests and Studies (LPEE).

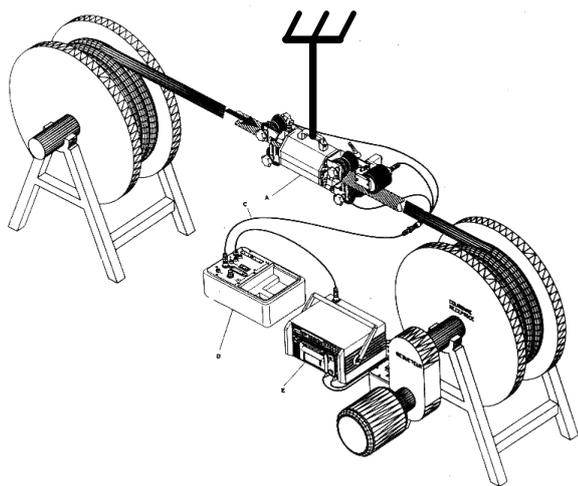


Fig. 23. Electromagnetic device of laboratory

The laboratory tests described in this paper were conducted with HALEC NDT (Non Destructive Testing) instrumentation employing coils and integrating circuitry. To assure repeatability of the examination results, two or more operational passes are required.

2) Working procedure

The steel wire rope used for this investigation was 35.0 mm in diameter and of construction 6*36 (14/7+7/7/1) IWRC (fig. 24). The main features of magnetic rope testing are shown in Table 1.

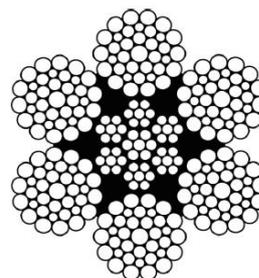


Fig. 24. Cross section of a 6*36 IWRC of rope of rotation-resistant

We carry out creation, over the length and the various sections of the rope, the principal defects recognized on the wire ropes namely:

- Localized defects:
 - Wire-breaks of space variables;
 - Wire-breaks superimposed or brought closer;
 - Superposition of the wires end;
 - Notches;
 - Cracks.
- Continuous defects:
 - Wear;
 - Crushings (indentations);
 - Corrosion.

After calibration of the detector, electromagnetic measures are carried out. The signals delivered by the magnetic sensor were detected by a transitory recorder for a secondary treatment.

Table 1. Main features of the experimental rope study

Cable diameter (mm)	$D_c = 35$ mm
Design	6×36 (14/7+7/7/1) IWRC
Nature and direction of wiring	Steel, ordinary lay on the left
Twisting direction	Right
Surface quality of the wires	Ungalvanized steel
Strength class of the wires (MPa)	$R_0 = 1900$ MPa
Length of the rope (m)	20 m
Use	Hosting and handling
Young modulus of the wire (MPa)	$E = 200\ 000$ MPa
Poisson's ratio	$\nu = 0,3$

3) Electromagnetic results

In this paragraph, we will present and comment on the various results got by the electromagnetic tests from the point of view of the factors of influence. The recordings obtained during the tests are presented below.

a) Measurement influence speed

A broken wire of 20 mm opening was caused on a wire of the upper layer of the rope to be tested. For a fixed sensitivity (VRMS = 100 mVDC), we have varied the speed of measurement from 0.1 to 2 m/s. Figure 25 presents the results got after optimization the measurement conditions.

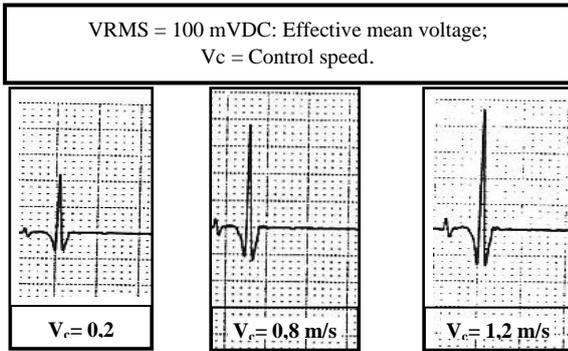
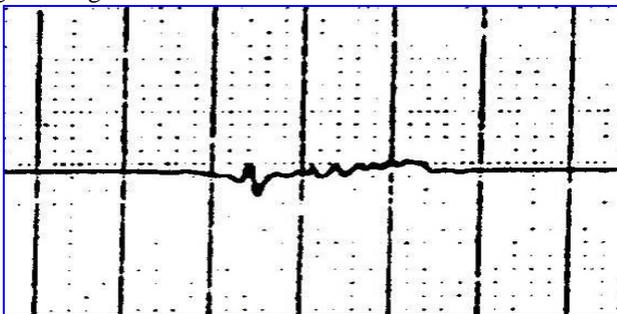


Fig. 25. Diagrams of signals due to a broken wire opening 20 mm

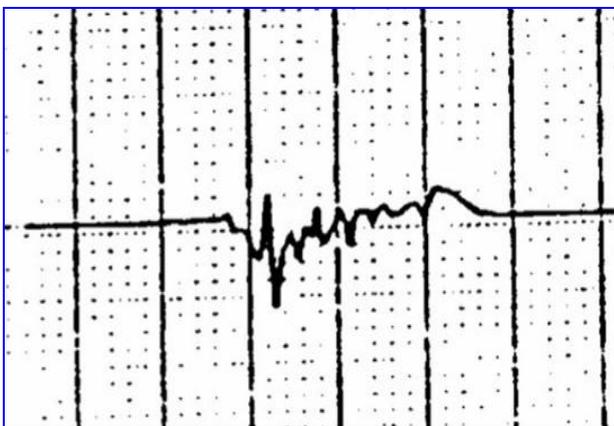
It is noticed, for fixed conditions of control that the amplitude of the impulse increases with the measurement speed. Consequently, the amplitude of the impulse is proportional to the measurement speed. Indeed, the graphic signal given by the magnetic sensor is very close to that envisaged by the theoretical study (equation 2).

b) Recorder sensitivity Influence

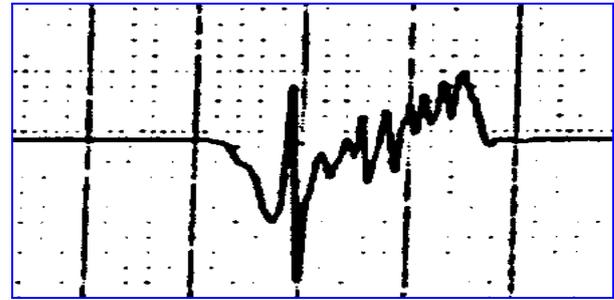
In order to determine the influence of the Recorder sensitivity Influence on the obtained amplitude of the signal, we have proceeded by its variation (VRMS varies from 50 to 500 mVDC). The broken wire represents for the following configurations of the rope a percentage of broken section equalizes to 1% compared to the total cross section of the rope. Figure 26 shows the influence of this one. The control speed is fixed at 0.5 m/s. After optimization of the measurement conditions, we note that more the recorder sensitivity decreases more the amplitude of the obtained signal is significant.



(a): VRMS= 250 mVDC



(b): VRMS= 100 mVDC



(c): VRMS= 50 mVDC

Fig. 26. Charts showing the broken wire of 20 mm opening with: $V_c = 0.5 \text{ m/s}$ for different values of VRMS

c) Length broken wire influence

A geometrical defect involves distortion lines of force of the magnetic field. Under the same conditions of measurement, we have varied the length of the broken wire on the top layer of rope to be controlled from 20 to 50 mm. Figure 27 illustrates the influence of this opening. The fixed control speed is fixed at $V_c = 0.5 \text{ m/s}$.

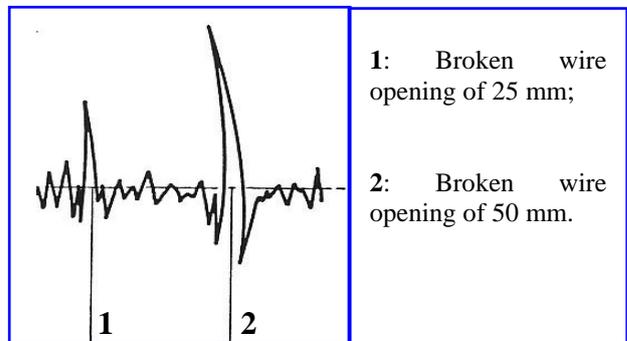


Fig. 27. Signature due to the variables openings broken wire

d) Defect depth influence

An example of the obtained signals is given on figure 28 for the rope above. The measurement speed is fixed at 0.5 m/s. The defects undertaken are:

- (R_i): Internal broken wire opening equal to 20 mm;
- (R_m): Intermediate broken wire opening equalizes to 20 mm;
- (R_e): External broken wire opening equalizes to 20 mm.

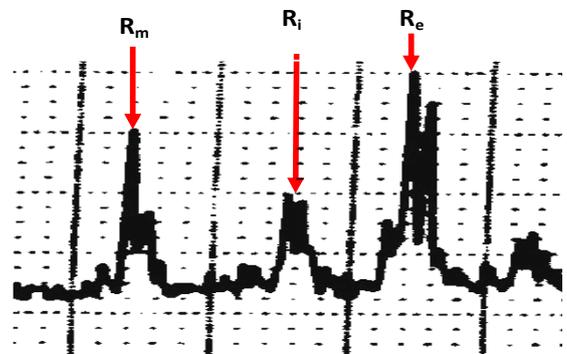


Fig. 28. Signal showing the influence of the depth of a the broken wire: $V_c = 0.5 \text{ m/s}$ and VRMS = 50 mVDC

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It is observed that the break is more profound than the signal amplitude is low. Therefore, we used a simulation of the signal obtained by improving the sensitivity of the recorder.

e) Corrosion and wear influence

Wear and corrosion are characterized by a reduction in the cross section of the rope. If external or internal wear in steel wire ropes is in general uniform, corrosion is local and often overlaps to other anomalies. Figure 29 shows the results obtained on the hoisting rope of 52 mm in diameter [14]. This is an area of high pressure fingerprints combined with signs of corrosion. As a result, the background noise which characterizes the "total response of the rope" is modified by the phenomena of corrosion. In this case, the experience of the operator becomes essential in interpreting signals.

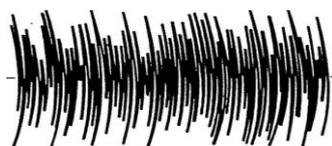


Fig. 29. Pressed area combined with signs of corrosion

In addition, wear is classified into external or internal depending on whether it is on the outside of the rope or inside. Internal wear is due to the contact and movement which occurs between wires. In the field the extent of wear of a wire rope is normally measured as a reduction in rope diameter. However, since the rope is not a rigid body, a reduction in rope diameter can be a summation of wear and other factors such as collapse of the core. In the case of abrasive wear, true external wear of the rope can be assessed by measuring either the loss in diameter of the outer wires, stated as a loss in their depth, or by measuring the width of the flats formed on the outer wires by wear [17]. The former requires prising open the outer wires which can be difficult. The latter is convenient to measure in practice but care must be taken to ensure that the measurement is accurate.

4) Discussions and interpretations

This work consisted in applying electromagnetic inspections methods which would be applicable to detect, especially, broken wires of the ropes. Electromagnetic Inspection is a reliable non-destructive evaluation procedure used for the in-service inspection of wire ropes [11]–[18]. More dependable than visual inspections, non-destructive inspection methods allow the detection and evaluation of external as well as internal rope deterioration. This allows the inspection of a rope's entire cross-section to the core.

All wire ropes wear out eventually, gradually losing work capability throughout its useful life making periodic important that the wire surface be sufficiently clean so that the broken wires are visible.

Electromagnetic inspection methods and their role for lifting applications are discussed and illustrated by examples, which include crane ropes. Electromagnetic wire rope characterization is used to confirm the control parameters influence on the results. We are based primarily on the amplitude of the impulse charts to interpret the signals. To conduct a quantitative interpretation, we must first classify defects:

- Geometric heterogeneities;
- Localized defects: broken wires, nicks, cracks caused by tensile-torsion fatigue [6]–[8] and other local lesions;
- Continuous defects: wear, crushing, corrosion;
- Magnetic heterogeneities: changes in the texture, welding.

It is advisable to compare readings with a "signature" trace taken when the rope was new or first installed, and then subsequent traces, to assess more accurately any degradation which has developed in the rope.

We examine initially the defects located using a standard chart. One recognizes the broken wires and the isolated notches with the particular form of the impulses which they cause.

The amplitude of the impulse is all the more large that the defect is less remote from the measuring coil. Using the calibration curves, one can determine the number of broken wires, as the reduction in section which is proportional to the decrease in tensile strength.

When defects are uniformly distributed, the diagram provides a "level of disturbance or noise". We can say that we have a series of tight peaks having almost the same height. We observe this "background" even on new ropes, but with low intensity. It is caused by very small distortion of the rope, d magnetic heterogeneities, and design of the cable. On ropes in service, this "minimal background" rises as a result of wear, corrosion, and crashes.

It was also confirmed that the amplitude of the impulse is proportional to the reduction in the cross section area and the measurement speed.

The practical use of the diagrams supposes that we initially interpret the isolated impulses. The calibration curves refer to a loss of given section, for a fixed measurement speed. The impulses appeared on the diagrams must then be converted linearly. Knowing the wires diameters in rope, we can finally determine, using a catalog of the defects, the number of broken wires as well as the percentage of reduction of the section of the rope.

The interpretation of the disturbance level is based on experimental values obtained by examining ropes with the same design or from similar constitution presenting to the various degrees of deterioration. We determine here, either a loss of section or a reduction in the tensile strength.

In summary, Electromagnetic inspections are particularly effective when they are combined with visual examinations as part of a comprehensive inspection program. Electromagnetic and visual wire rope inspections complement each other. Both are essential for safe rope operation, and both methods should therefore be used for maximum safety. Because Electromagnetic nondestructive examinations provide an important additional element of lifting wire rope inspection, the thrust of evolving regulations is clearly toward combined periodic electromagnetic and visual inspections. We also performed radiographic test to decide on the possible realization of discard criteria.

An operator should be aware of the situations and/or conditions which may occur at the site of an examination (fig. 30) and which could potentially complicate interpretation of the results, but may not necessarily invalidate the test. These may include:

- Heavy lubrication: In some cases lubricant may cause slippage in the distance measurement system. Errors in distance measurement will make it impossible to determine the position of a defect along the length of the wire rope, preventing further examination;
- The distance measurement system should be monitored to verify that it continues to operate. If the equipment on which the wire rope is installed has a line-out meter, this can be used to confirm the accuracy of the distance measurement;
- Metallic contamination: Metallic (ferrous) contaminants on the surface of the wire rope will increase the noise trace and create anomalous indications. Larger pieces of debris could cause damage to the machine and excessive lubricant can hold metallic contaminants;
- External interference: The presence of powerful magnetic sources, large pieces of ferromagnetic material, close to the magnetic head may affect the trace. If there is relative movement between the magnetic head and the source of the interference then its effect will be variable and potentially significant;
- Continuity of examination: The configuration of the wire rope and access restrictions may prevent the wire rope being examined in a single uninterrupted test. The operator should ensure that part tests are correctly reassembled to provide a single trace that accurately identifies the position of any defects.

A competent operator who is aware of likely conditions in the field should have no difficulty differentiating between real and spurious indications.



Fig. 30. Situations and/or conditions which may occur at the site of an examination

5) Limitations of electromagnetic testing

To assure maximum NDT reliability and accuracy, it is important to know the capabilities and limitations of the NDT instrumentation. The limitations of NDT Instruments to detect defects in wire ropes include the following [13]:

- It can only be used for ferromagnetic ropes;
- It is difficult, if not impossible, to detect flaws at or near rope terminations and ferromagnetic steel connections;
- Deterioration of a metallurgical nature (eg. Embrittlement, plastic deformation or fatigue) is not detectable until wires break;
- The instrument is limited to rope speeds specified by the manufacturer;
- The sensitivity of NDT method decreases with the depth of flaw from the surface;
- External electrical sources or magnetic fields may cause interference and hence affect the results;
- The % loss of area as measured by NDT does not necessarily indicate % loss of rope breaking force;
- Lack of experience / care / knowledge by the operator;
- Accuracy of the NDT equipment;
- Type and size of faults in the rope.

IV. WIRE ROPE DISCARD CRITERIA

Periodic examination should be carried out by a competent person and will involve the complete length of wire rope. The detail of the examination must conform to the statutory requirements of local legislation. The great majority of safety critical rope applications involve fatigue coupled with other degradation processes, which together determine a finite service life. This combination is reflected in the inspection and discards policies employed on rope systems, as well as in system design and operation. The function of wire rope discard criteria is to ensure that a rope will not fail before the next inspection.

Wire rope inspection and retirement standards are becoming simpler. Two different policies are used to decide on rope retirement:

- A statutory life policy that mandates rope retirement at certain prescribed intervals. (This means, the statutory life policy places a maximum on the time a rope can be in service), or
- Retirement for cause based on retirement conditions that are evaluated periodically by nondestructive inspections. (This means, the retirement-for-cause approach requires that the rope must be retired when the deterioration exceeds a certain limit.).

Otherwise, the following consideration can be used. The discard criteria of rope are related to the type of use and its structure, so, obviously they cannot be transposed directly. We can base the safety of exploitation of the wire ropes in service on the following criteria [3]:

- Nature and number of the broken wires;
- broken wires at the termination;
- Concentration of broken wires;
- Broken strand;

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- Reduction of the diameter of the rope, including by broken core;
- Elasticity reduction;
- External and internal wear;
- External and internal corrosion;
- Deformation;
- Deterioration produced by heat or an electric phenomenon;
- Rate of increase in permanent elongation.

International standard ISO 4309 “Cranes - Wire ropes -Care, maintenance, installation, examination and discard“ provides a framework for an examination and many of the considerations that are required when determining how often they should be carried out. Its scope includes deck, gantry, mobile, overhead and travelling cranes as well as derricks with both guyed and rigid bracing. The application of the wire and how often it is used, referred to as the number of work-cycles must also be taken into account.

International standard ISO 4309 refines the analysis criteria, simplifies the classification of cable breaks tolerated on the corresponding cable constructions, determines specific divergences closer and takes into account the discard criteria cumulatively. The following data for the verification of the security service of steel cables are in line with the technical level.

Any damage and / or any wear on one point of the cable are critical to the evaluation of steel cables. Therefore, different factors influence wear and damage must be assessed as a percentage and added to each other. If this value is greater than 100% at one point, the cable must be removed, because safe use is no longer assured. Figures 31 to 41 show a typical example of each defect [3], [6].

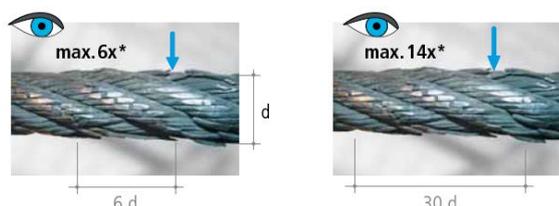


Fig. 31. Number of broken wires requires the removal of a length



Fig. 32. Local reduction in rope diameter



Fig. 33. The ruin of broken wires on the rope



Fig. 34. Broken Strand of rope caused by an electric arc



Fig. 35. Internal examination: internal wire breaks



Fig. 36. External wear



Fig. 37. Degree of internal or external corrosion



Fig. 38. Deformations prominent on multi-strand cables



Fig. 39. Output wires of the external strands caused by mechanical damage

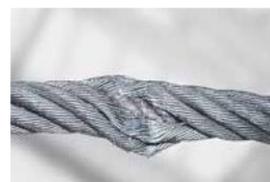


Fig. 40. Crushing



Fig. 41. Kink, node

In this work, the states involving the immediate reform of the lifting or crane wire rope are:

- Fractured strands;
- Existence of a hull, node, hernia and birdcaging;
- Broken wires at termination points;
- Localized reduction Abnormal of the diameter:
- When the reduction in diameter of the rope at any point reaches 10% in diameter;
- When the number of visible broken wires reaches 20% of the full number of wires in rope on 2 times the length of the step of wiring;
- When the reduction in strand section measured on a step of wiring reaches 40% of the total section of the strand.

All these criteria must be examined individually. However, the juxtaposition of certain zones can present a cumulative effect whose qualified person must take account in the decision of demounting or start-up of the rope. Lastly, certain Lifting equipment work under conditions where the steel wire ropes are exposed to accidental deteriorations and the initial choice of the rope must take account of this factor. Under such conditions, the rope examination must be done particularly carefully, the rope having to be replaced immediately as of the appearance of least deterioration. The criteria of demounting above make it possible to preserve, until the final stage of employment, a reasonable safety margin. The non-observance of these criteria is dangerous.

V. MONITORING PROCEDURE OF WIRE ROPES IN SERVICE

As a result of its arduous service, rope can be worn out, compromising safety and structural properties, so specific inspection procedures should be implemented to prevent tragic failure.

Wire rope inspection takes an important place with rope deterioration is increasingly frequent. A thorough evaluation must consider all aspects of a rope's condition, including:

- The findings of visual inspection,
- The results of an electromagnetic rope inspection,
- The rope's operating conditions and related damage mechanisms,
- The history of the rope under test and that of its predecessors.

A program of periodic evaluations is especially effective. To establish baseline data for subsequent inspections, such a program should commence with an initial evaluation of the installed rope after a certain break-in period. The following inspections should be performed at regular intervals. In particular, periodic electromagnetic inspections allow the documentation of a rope's deterioration over its entire service life. The establishment of such a procedure is necessary when the report of damage of the wire ropes, suggests that the lifting device is exploited with a degraded security level. Logically it must go through the following steps.

A. Historic record analysis of the aircraft and calculations

The objective of this stage is to examine the level security in wire ropes by considering the current conditions of operating. This work is based on an exhaustive examination of the file of archives of the steel wire ropes. It is very interesting to make a list dated from the interventions and work on the apparatus and to examine the reports carried out during maintenance work. These reports can inform us on the real state of hosting steel ropes.

B. State of the ropes and degraded safety coefficients

It is possible to have an idea of the state of the rope and its capacity and to establish an "estimation" (which can be only one order of magnitude) security level of the cable according to the conditions of operating. Minimal acceptable level of the safety coefficient degraded is difficult to estimate. It depends in particular on the following points:

- Precision of stress evaluation (knowledge of the loads, etc.);
- Precision of the degraded capacity evaluation in wire rope;
- Degradation level and appearance of the rope (it is possible in certain cases to fix or at least to slow down degradation by anticorrosive system restoration and/or the addition of a dehumidification);
- Possibilities of monitoring (visual monitoring, electromagnetic rope monitoring: period and effectiveness?);
- Effects of accidental breakage of a strand.

C. Procedure of high surveillance based on visual inspections and an electromagnetic monitoring

The procedure sets up several successive levels of answer which can be as follows:

- An pre-alarm before prohibition of use of the rope which

calls a visual inspection, a meeting of the technicians and possibly complementary investigations;

- A prohibition of use of the rope. This measurement has only one influence moderated on maximum traction in the steel wire ropes which is theoretically usually reduced from 10 to 20% by such an experimental measurement [4], [12];
- An pre-alarm before total ban calling a visual inspection, a meeting of the technicians and possibly complementary investigations;
- Total ban of use of the lifting device.

The determination of the thresholds is based on a complete analysis of the operating hoisting device and its components to evaluate the actual position of the ropes. Several thresholds are fixed for each level of pre-alarm then alarm on the basis as of following principles:

- Nature and number of the wire-breaks;
- Broken wires to the right of the termination;
- Concentration of wire-breaks;
- Broken strand;
- Reduction of the diameter of the rope including broken core;
- Increased frequency of broken wires breaks on the rope's length corresponding to a few pitch of rope. This frequency is considered as a periodic number of broken wires.

Visual observation of a broken strand should always be considered a serious sign insofar which reflect the general condition on the strands and thus be the symptom of a rope to the breaking strength. Significant number of broken wires in internal or external terminals rope must be considered with the same caution.

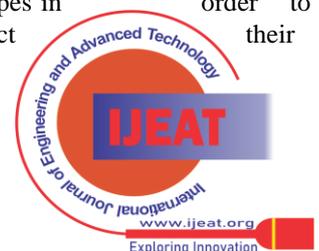
Moreover, dependable inspection procedures, using combined visual and electromagnetic methods, can detect rope deterioration at its earliest stages. Therefore, wire ropes users can employ them as an effective preventive maintenance tool. To illustrate, here are some practical examples.

- The early detection of corrosion allows immediate corrective action through improved lubrication;
- Accelerating wear and inter-strand nicking can indicate a need to reline sheaves to stop further degradation;
- Careful inspections can monitor the development of local damage at the crossover points of the rope on a winch drum. This, the operator can determine the optimum time for repositioning the rope on the drum.

Finally, users as well as regulatory authorities recognize that careful inspections can significantly increase the safety of wire ropes.

VI. CONCLUSION

Wire rope is a very useful and long lasting structural element when properly used and maintained. Safe use of the crane wire ropes depends directly on the rope condition, and on the in-time and reliable rope inspection. The objective of this work is to show the importance of the nondestructive test methods applied to the wire ropes in order to be able to estimate and predict their residual lifetime.



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The main rope degradation mechanisms are reviewed. The results of the NDTs have made it possible to determine the safety status of a rope and establish preventive maintenance procedures to extend the useful life of a rope. To specify and standardize the electromagnetic ropes inspections, a catalog of the defects and their discard criteria was established for the members of the CEMGI/LPEE, with the HALEC equipment.

Electromagnetic rope inspections are particularly effective when they are combined with visual examinations as part of a comprehensive evaluation program. Non destructive testing will give a better indication of the condition of most of the rope. Visual examination shall be used in addition to testing to ensure ropes remain in a safe condition.

It is concluded that maintenance, inspection and discard policy must be determined in recognition of the degradation mechanisms that operate in different rope applications. Nondestructive testing, incorporated into a preventive maintenance program, reduces costs and enhances safety.



Management, Engineering Management and Quality Management.

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