Estimated loss of residual strength of a flexible metal lifting wire rope: Case of artificial damage

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Abstract—In lifting equipment, risks due to failure of structures are magnified by the nature of components that are designed to operate in extreme environments. In addition, due to passage rates on equipment and successive decelerations and accelerations, the cables for hanging ponds and handling are considered among the most difficult and the most critical services in the field of construction and engineering civil.

In this context, the wire ropes are a prime target of brutal damage, compared to conventional structures. More generally; the sudden failure is the major cause of cables degradation. Industrial experience shows that the failure of much of their hoisting ropes in use is most commonly due to cumulative damage of wires. This is particularly insidious due to its hidden nature; it can lead to significant reduction in strength capacity of wire ropes over time, which can sometimes lead to their total or partial rupture.

Analysis to assess the effect of brutal damage affecting the performance of hoisting ropes in the long term is the essence of this work. This consists of developing a model to predict the strength capacity of a cable at various levels of damage of its components, and exposing a mechanical model describing the state of damage depending on the number of broken wires.

In order to optimize the residual resistance loss of a lifting wire rope, we propose a study of rupture impact of its wires on the loss of residual strength elastic.

Keywords—Failure, accelerations, wire ropes, brutal damage, degradation, partial rupture, broken wires, residual strength elastic.

I. INTRODUCTION

The base material of metal wires is typically a low alloy steel containing a carbon content close to eutectoid, with as main alloying elements manganese and silicon (Fig.1). These steels are formed by a drawing process [1]. Other production processes also exist as the bainitic and martensitic hardened, but they are less used for wires [2].

To ensure the characterization of cables under optimal conditions, an analysis of its security must be combined with well-defined inspection procedures [3] [4] [5].

Unfortunately, many cables have never been subject to inspection or otherwise, only very partially, due to the limitations of inspection techniques.

The safety analysis is to connect the estimation of residual strength of cable using inspection data, this link is difficult to establish, even if we admit that the concept of safety factor of cable is a little insufficient to characterize its present state [6]. The majority of works related to determining the bearing of a suspension cable capacity are statistical models that do not fit the complexity of mechanical description (non-linear behavior, the distribution of load, friction between the strands ....).

Fig.1.Component parts of a metal wire
The choice of these scales is given that a relevant portion of a wire behavior governs the behavior of entire cable. The physico - chemical processes such as the rate of degradation, due to the environment (corrosion) are different for each layer, the outer layers is more exposed [9].

Indeed, when the wires are twisted and wound together, a broken wire has the ability to recover its strength in a specific length; this length defines the size of effective segment, its value is 1 to 2.5 times cast length.

II. DEGRADATION MECHANISMS OF CABLES

Cables suffer from continued aggression of environment (urban, industrial, marine….). The effects of the aggression manifested through various events, including the direct effects are strong changes in geometrical and mechanical characteristics of the components, which indicate a significant reduction in the strength capacity of the cable over time, which can sometimes lead to partial rupture.

In general, the defects of the hoisting ropes are classified into four categories:
1. Reduction of the section by wear, corrosion or abrasion;
2. Rupture of wires steel;
3. Strains such as bird cages, shell, crush....;
4. Fatigue.

This part presents a recall of main degradation mechanisms that affect the cables, their typical scenarios of accidents and losses they cause mechanical strength and discard criteria.

A. Breakage of wire ropes

Wire break evolves disproportionately. This fact must be taken into consideration when determining the control intervals (Fig.2).

![Fig.2. Breakage of strand cables](image)

The sudden termination of cables is often the result of interactions between two contacting wires, subjected to relative displacements of low or high amplitude. Several phases can be distinguished in the behavior of cable breakage. First, a more or less significant degradation and rapid wires with the formation of wear debris (third body) part of which may be ejected from the contact. During the second phase, there is the appearance of microcracks initiated at the contacts which involved in the formation of larger debris thereby increasing degradation strands. The last phase is the crack of contact when toughness cable reaches a critical value.

Siegert [10] studied the fatigue mechanisms that are causing ruptures wires in the steel cables, used for bracing of structures. For this, he relied on many experimental results. He also proposed a criterion to predict the initiation and endurance of fatigue cracks in the interfilaires contacts cables. This criterion is based on the concept of critical facet amplitude maximum shear.

Contact materials which reduce the wear of cable and their strands cracking are wear materials such as zinc or aluminum alloy and lubricant materials such as high density polyethylene. Studies by Urvoy [11] were used to compare the change in wet or galvanized wires, strands of contact and mechanical stresses at interfilaires contacts subjected to friction between wires. These tests demonstrate that the 100 MPa fatigue endurance limit ( Δσ peak/peak ) obtained by Siegert [10] on uncoated dry wires is raised to 170 MPa for dry galvanized strands for 200 MPa on uncoated lubricated .

B. Friction interfilaire

The study of interfilaire contacts is essential for modeling the behavior of cables. In general, two types of contact exist in multilayer cables: the linear contact between the wires of a single layer and the point contact between two strands belonging to adjacent layers (Fig.3). The side contact is considered as a line contact when the initial contact area is a curve. This contact also exists between core wire and strand of first wire [12].

The other type of interfilaire contact is present between wires of successive layers which are extended in opposite directions. Therefore, wires in both layers cross at an angle, where a line contacts rather than point. The contact pressures are clearly higher in the case of a point contact as in the case of linear contact [13].

In general the behavior of the cable in axial load is characterized by a coupling between traction, torsion and bending. In the literature there are various models that describe the behavior of the cable tension. Costello [14] and Hruska [15] have modeled the behavior of strands subjected to different tensile forces. They confirmed that the Poisson effect, friction and geometric nonlinearities have a negligible influence on the overall behavior of cables in tension. Moreover, the radial contact between the core and outer wire are the only contacts that exist during an axial loading.

Yan Shen [16] studied the influence of applied loading and lubrication strands on characteristics of cable (18*6) analyzed.

The variations of the friction coefficient according to the movement of steel in relatively stable wires stage at different loads of contact are shown in the fig.4.

It can be seen that the coefficient of friction increased by the applied loads and gradually decreased with increasing amplitudes of displacement.
C. Localized corrosion

Dissolving wires may also take the form of craters, in addition to bearing capacity, reduce the strain at break of strands and also promote fatigue cracking (Fig.5).

Elachachi [17] developed a model to predict the load-carrying capacity of a corroded cable, at various levels of damage to its components in order to estimate the residual life and the risk assessment of broken wires for a given level of stress.

The effect of corrosion on the behavior of a section of strand is presented with the average effort (1000 simulations) as a function of displacement which is given for 8 deadlines (the time increment is 20 years). It is found that the corrosion influences the initial stiffness of section and on the maximum resistive force which decreases with time (here 27% of 100 years).

III. MATERIAL, EXPERIMENTAL TECHNIQUES

In our study, we will look at tests to be performed on cables of type 19 * 7 (7 wires 19 strands) of non-rotating structures (1 * 7 + 6 * 7 + 12 * 7) 6 mm in diameter, composed of steel light greased, metal core, right cross, preformed, used especially in tower cranes and suspension bridges (Fig.6).

They are composed of two layers of strands wired in opposite directions, which avoids the rotation of the suspended load when the lift height is important and that the burden is not guided. Their use requires a certain amount of caution at rest and during operation. This construction, robust nature, is widely used for common applications and especially for lifting heights reduced.

The sample length of the cable is equal to 10 times the pitch of 20 mm reancrage more necessary to mooring. Therefore, the length of 700 mm was taken as the length of tests for these cables. The accuracy of measurement in a length of ± one millimeter for all samples studied.

The base material is steel from which wires are formed. They are twisted to form the assembled strand. Then the strands are wound in spirals around describing core (type 1 +6). The cable is finally obtained from the strands with a structure of 19 x 7 (1 +6).

<table>
<thead>
<tr>
<th>Table 1. Main features of the experimental rope study</th>
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<tbody>
<tr>
<td><strong>Cable diameter (mm)</strong></td>
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<td><strong>Design</strong></td>
</tr>
<tr>
<td><strong>Nature and direction of wiring</strong></td>
</tr>
<tr>
<td><strong>Minimum breaking strength</strong></td>
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<tr>
<td><strong>Surface quality of the wires</strong></td>
</tr>
<tr>
<td><strong>Twisting direction</strong></td>
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<tr>
<td><strong>Mass per unit length (kg/m)</strong></td>
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<tr>
<td><strong>Use</strong></td>
</tr>
<tr>
<td><strong>Young modulus of the wire (MPa)</strong></td>
</tr>
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<td><strong>Poisson’s ratio</strong></td>
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IV. RESULTS AND RECOUNTS

A. Static tensile test on degraded cables (19*7)

In order to calculate the damage of broken wire ropes, a graphical interface is performed using a library destined especially to complex systems whose functional description can be translated into a block diagram that combines, in series or in parallel, components (or failure modes). The characteristics of the components (relative difference, endurance limit, loss of elastic resistance ...), are saved in a library.

Recall that our goal is to calculate the damage elastic and ultimate through the unified theory and compare the results of damages to quantify the energy reserve between the two types of damage.

The curves of experimental trials of force in function of the elongation for cables at different number of broken thread are given in the (Fig.7) relatively to the cable of 6 mm.

A virgin cable has a residual ultimate force of 26, 35 KN which fall gradually, as and when extent, that the number of thread broken increases, until the value of 13 KN, for a cable 90% of thread broken.

For broken wires at 30%, 50% and 70%, the maximum force of break successively diminished from 20 KN to 17,50 KN and 14,33 KN at the end; this can be translated into a loss of resistance of the cable depending on number of thread broken (Fig.6).

B. Calculation of the conventional strength

According to the tensile curves of broken cables at different levels of degradation (Fig.7) we calculate the ultimate strength and the elastic strength conventional, and then we determine the standardized section to derive the residual stress of the cable studied (19 * 7).

The ultimate conventional strength values of various cables broken simultaneously at 30%, 50%, 70% and 90% of threads are given in Table 2.

Table 2. Values of elastic and ultimate residual strength

<table>
<thead>
<tr>
<th>Number of broken thread (%)</th>
<th>0%</th>
<th>30%</th>
<th>50%</th>
<th>70%</th>
<th>90%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{e}(0.2%)$ (KN)</td>
<td>24,75</td>
<td>19,27</td>
<td>16,50</td>
<td>14,06</td>
<td>11,79</td>
</tr>
<tr>
<td>$F_{ar}$ (KN)</td>
<td>26,10</td>
<td>20,57</td>
<td>18,00</td>
<td>15,35</td>
<td>13,10</td>
</tr>
</tbody>
</table>

The elastic force is calculated for a conventional elongation of the slope of traction. Force for different levels of artificially broken cable (virgin, experienced in 30%, 50%, 70%, 90%) successively diminished by 24.75 KN for a virgin cable, to 11.79 KN for a broken cable at 90% of its thread.

C. Calculation of the standardized section

We use the following formula (1) to calculate the area of the standardized section of wire rope 19 * 7:

$$A_n = \frac{\pi d^2}{4}$$  \hspace{1cm} (7)
Where: \( d \) is the diameter of the cable and \( f \) a coefficient equal to \( f = 0.55 \) for multi-strand cables. The wire rope 19 * 7 is a cable multiple strand therefore the standardized section will be equal to 15, 54 mm².

D. Loss of residual strength according to the number of broken wires

The experimental results are shown in fig.8. This figure shows the change of the loss of tensile strength as a function of number of broken thread.

![Fig. 8. Loss of residual strength based on the number of broken thread of the cable diameter 6 mm](image)

The cable has an ultimate tensile strength of 1680 MPa and static yield strength of 1593MPa. The yield of residual degrades continuously as the number of cyclic loading amplitude \( \sigma_e \) reached 843 MPa \( \sigma_{ea} \) is the elastic applied stress which attain 759 MPa in our case.

Furthermore, we note that the two curves have a decreasing pace, depending on the level of constraint imposed only for a number of relatively large broken threads (Fig.8).

V. Conclusion

Metal cables are primordial elements and should be checked regularly by qualified personnel. The frequency of tests shall be chosen so as to detect the damage in time.

The failure criteria for the cable are more complex than those applied to continuous structures, where the measurement of crack length or the simple observation of the loss of integrity may suffice. Generally, these criteria are based on a mixture of past experience, personal preference and prejudice for each particular type of application. The occurrence of unacceptable number of wire breaks is by the most common adopted for the assessment of damage to the cable action, which justifies our choice.

Analysis to assess the impact of factors affecting the reliability of hoisting ropes which constituted the essence of this work. It developed a model for predicting the reliability and dependability of a cable at various stages of his period in service. In this study, our contribution is essentially reliability engineer through a system based on a mathematical approach that determines the reliability of the cable, taking into account all its parameters and its physical and chemical characteristics model.

REFERENCES