Reliable model of mechanic behavior of lifting wire ropes

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Abstract. Wire ropes are used for different applications in many industrial domains, for instance, lifting system. Depending on the conditions of use, wire ropes are being degraded with direct consequences are significant changes of geometric and mechanical characteristics of its components. This results in a reduction in the resistance capacity of the wire rope with time, which could bring failure. Our work consists of studying the impact of the breaking of the wires which constitute the wire ropes on its duration, and develop models to determine the reliability of wire ropes to plan preventive maintenance actions and to change them in the appropriate time. We are equally proposing to develop a model which permits providing the resistance capacity of a wire rope in multiple levels of damage of its components and an analytical model of the relation of the reliability- damaging to illustrate the fatigue of the wires ropes' lifting phenomenon . The approach adopted is a multi-scale approach with a total decoupling between the scale of the wire and the wire rope.

1 Introduction

A wire rope (figure 1) is generally constituted of many strands helically arranged around the central core in a layer or multiple overlying. The strand itself is composed of a lot of steel wires regularly disposed around a central core in a layer or multiple overlying. A wire rope could be composed of one strand, and then we are talking about a mono-strand wire rope, or a helical wire rope.

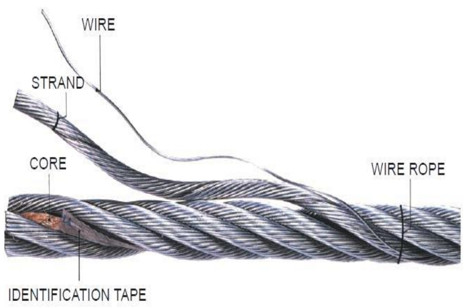


Fig.1. Schema illustrating the different component of the wire rope

The wire ropes are very available in the industrial domain. They constitute the essential element of the lifting systems. Their mechanical characteristics change during its use. In this respect, the security of people who use them directly depend on their states [1].

The sudden breaking of the wire ropes results in major disorders related to many aspects like the loss of humans or materials .Consequently, it is very important to predict their mechanical performance before using them. In this study, our purpose is essentially reliable with the use of a mathematical model based on a probable approach. Therefore, our objective is being able to describe the fatigue behavior of every wire to deduce that of the wire rope.

2 probabilistic Model of a wire rope behavior

2.1 multi-scale approach of a wire rope

A wire rope is a group of interconnected or interdependent elements so that the state of the wire rope depends on the states of its components, in this way it is related to the most complex composed systems. This signifies that all modeling approaches of the wire rope will be a multi-scale approach.

According to the study realized by Al achachi [2], a suspension wire rope can be considered as a system made of a group of strands disposed in parallel. A strand is itself made of a group of stub in which the length of each equals the length of the re-anchor. Each stub of wires is disposed in parallel. The study of the behavior of a wire rope is consequently a multi-scale study in which we can distinguish the scale of a wire, the scale of a strand and the scale of a wire rope.

The systemic schema of a suspended wire rope is therefore a system: parallel (n strands) – series (p stub of strands) – parallel (n' wires). The choice can be justified as follow:

- The behavior of a wire governs the behavior of the wire rope;
- The wires are twisted together, a broken wire has the capacity to re-anchor on a given length, called re-anchor length, and which defines the stub's dimension
- The behavior of the strand is profoundly linked to the behavior of the weakest stub (the series system);

- Since the strands are disposed in parallel, the resistance of a wire rope depends on their individual resistance and the distribution of the mechanical load.

On the other hand, the realized study by Kolowrocki [3] consists of developing a modeling allowing the estimation of a wire rope's duration of life, where we can distinguish the scale of the strand, the scale of the layer of strands and that of the wire rope. He considers that the wire rope is a mixed system (parallel-series).the choice of the parallel-series system is justified by:

- The exterior layer of a wire rope is made of strands having diameters superior than those of the interior layer;
- The failure of one of these strands leads to the failure of the wire rope (series system). These are connected in parallel with the interior layer (parallel system). Thus, we can say that the wire rope make a series parallel system.

3. The reliability of the composed system

The reliability of a material is a statistic parameter, it represents the probability of the survival of this material, that is to say the probability of not facing any kind of failure (the accomplishment of the function required) in relation to the conditions of use given, during an interval of time given, we represent it R (t).

Considering the components of a system E_i $i = 1,2,...,$ n, $n \in N$ having a functions of reliability: $R_i(t) = P\ (T_i > t)$, $t \in (-\infty, \infty)$, where T_i, $i = 1,2,...,$ n, are random independent variables representing the lives of the components E_i with the functions of the distribution :
$Fi(t) = P\ (T_i \le t)$, $t \in (-\infty, \infty)$.

The functions of reliability of simplest systems are defined as follow [4, 5]:

- For a series system :

$$R_n(t) = \prod_{i=1}^{n} R_i(t), t \in (-\infty, +\infty). \quad (1)$$

- For a parallel system:

$$R_n(t) = 1 - \prod_{i=1}^{n} F_i(t), t \in (-\infty, +\infty) \quad (2)$$

- For a series-parallel system: $R_{SP} = \prod_{j=1}^{S} R_j$ (3)

With j the number of the parallel bloc

- For a parallel-series system : $1 - R_{PS} = \prod_{j=1}^{P} 1 - R_j$ (4)

With j the number of the series bloc

- For a majority logic system m/n (m material among n functions), the reliability function is :

$$R(t) = \sum_m [\prod_{i \in A_m} R_i] * [\prod_{i \in A_m} (1 - R_i)] \quad (5)$$

With A_m all arrangement (1,2….m) include at least k materials in service

4. Law of probability used in reliability [6-7]

For predicting the life cycle of wire ropes, it is necessary to choose the appropriate statistic model to describe the duration of life of test samples. Three models are generally used for the description of wire ropes's life duration. These models are respectively the Gauss law, the exponential law and the Weibull law. The first law where the distribution of the failure is centered around by an average value in the third phase of their life. The exponential law is used only if we have a rate of constant failure that is to say in the second phase of the components's life. The Weibull law which is the most used one in representing the wire ropes's duration of life, because it is a flexible law that can adjust with all sorts of experimental results, it covers the case where the rate of failure is variable and thus allows adjusting with periods of "youthfulness" and to different forms of aging.

- Reliability according to the Weibull law

$$R(t) = \exp\left[-\left(\frac{t-\gamma}{\eta}\right)^{\beta}\right] \quad (6)$$

With β: parameter of form
η : parameter of scale
γ : Parameter of position

- Density of probability: $f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} . e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}}$ (7)

For t > γ

- Function of dividing: $F(t) = 1 - e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}}$ (8)

-Instant rate of failure:

$$Z(t) = \frac{f(t)}{R(t)} = \frac{f(t)}{1-F(t)} = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} \quad (9)$$

5. Application of equations of reliability and damage to wire ropes [8-9]

5.1 Reliability in function of fraction of life

We can express the reliability in function of fraction of life as (β) which has as an expression: β = n/Nf

Therefore we will consider the time like an increment succession of period ***(τ)*:** T =n. **τ**
Thus: η = Nf. **τ**
n: instant cycle's amount.
τ : Time between two successive cycles of loading.
η : spreading of the distribution.
Nf: number of cycles cumulated in the breaking

Exploiting this discretization of time T= n. **τ;** η =Nf. **τ** with γ = 0 and replacing it in the model of **Weibull** [7-9] which has appeared as the most capable one for adjusting with the failure's emergence phenomenon, we take as an expression of reliability :

$$R(t) = e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \quad (10)$$

We signal to the factor of form β with λ so as not to mix it with the fraction of life (β =n/Nf).

We take: $R(t) = e^{-\left(\frac{t-\gamma}{\eta}\right)^{\lambda}}$

Thus: $$R(t) = exp(-\beta)^{\lambda} \quad (11)$$

The figure 2 illustrates the graphic representation of the reliability in function of the fraction of life (β):

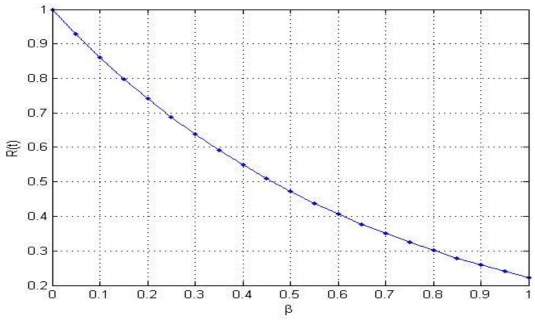


Fig.2. Graphic Representation of the reliability in function of the fraction of life (β)

This curve describes well the decreasing of the reliability during functioning in such an element, we also remark that for a fraction of life β=1 the reliability is equal to a non-zero value. This value can be attributed to a residual reliability just before the breaking of the material.

5.1.1 series-parallel system

Considering a series system which has some components or some sub systems in parallel, the system becomes series-parallel [11] in which the reliability equation in function of the fraction of life is the following:

$$R_{SP} = \left[1 - \left(1 - exp(-\beta)^{\lambda}\right)^{p}\right]^{s} \quad (12)$$

With s: the number of blocs in series
p: the number of blocs in parallel

In what follows, we will consider a steel wire rope of 6 mm diameter of a 6*7 type (6strands 7 wires) with a core in textile.

Fig.3. Steel wire rope of a 6*7 type with a textile core

In the first case we consider that the wire rope (6*7) is a series-parallel system. We take **S=6**, the number of series branches which correspond to the number of the strand, and considering **P=7** the number of parallel branches which is the number of wires. The figure 4 represents the reliability in function of fraction of life of this wire rope according to the series-parallel model.

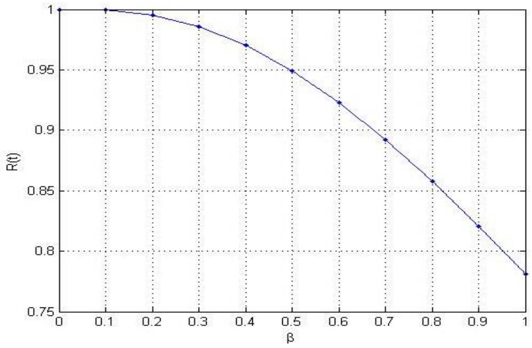


Fig.4. Reliability in function of fraction of life of the wire rope of (6*7) type according to the series-parallel model

5.1.2 parallel-series system

A parallel system which has components or sub systems in series are called a parallel series system [11] in which the reliability in function of fraction of life is the following:

$$1 - R_{PS} = \left[1 - exp\left(-S.(\beta)^{\lambda}\right)\right]^{P} \quad (13)$$

Considering that the number of branches in series **S = 7** which is the number of wires, and the number of branches in parallel **P=6** which is the number of strands. The figure 5 represents the reliability in function of fraction of life of the last wire rope according to the parallel-series model.

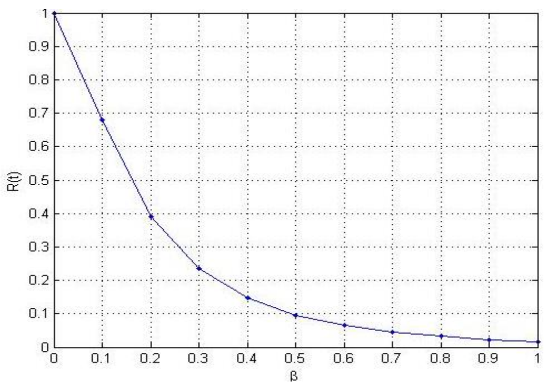


Fig.5. Reliability in function of fraction of life of the wire rope of (6*7) type according to the parallel-series model

5.2 Modeling of the failure of wire ropes

In the contrary of the reliability, we find the failure (Q) which evolves in the opposite sense white R (t) which will be the probability of the end of the capacity of the system to accomplish its requirements. Therefore, we will have: **R+ Q= 1** (14)

As the material is stressed, the micro-cracks develop and the probability of failure rises as a function of time. Consequently, we will have: **Q (t) = 1- R (t)** (15)

According to the two last models of reliability, the figures (6and7) show the superposition of the curves of reliability and failure of the last wire ropes according to the series-parallel models and parallel-series respectively.

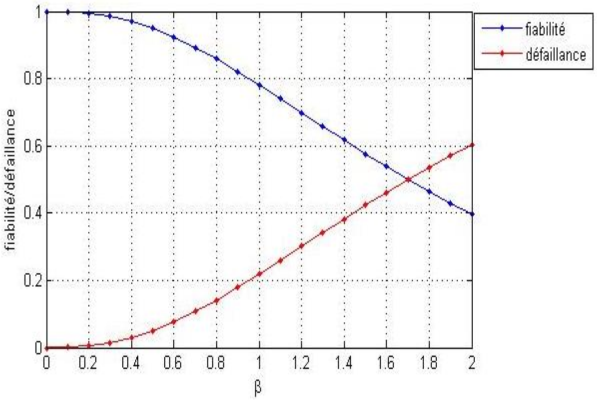


Fig.6. Superposition of curves of reliability and failure of the last wire rope according to the series-parallel model

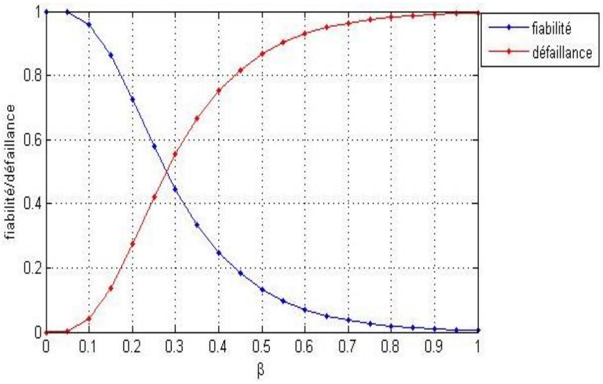


Fig.7. Superposition of curves of reliability and failure of the last wire rope according to the parallel-series model

5.3 Reliability in function of damage [12]

The theory of united damage in function of β fraction of life is the mechanic model chosen to translate the damage of the wire rope through fatigue [4,6], based on a synthesis profounded in different theories which describes the damage under loads of fatigue, and which has as an expression:

$$D = \frac{\beta}{\beta + (1-\beta)\left(\frac{\gamma - \left(\gamma/\gamma u\right)^{8}}{\gamma - 1}\right)} \qquad (16)$$

We put $\alpha = \left(\frac{\gamma - \left(\gamma/\gamma u\right)^{8}}{\gamma - 1}\right)$

This gives the expression of the reliability in function of time:

$$R(t) = \exp\left(-\left(\frac{\alpha . D}{1 - D(1-\alpha)}\right)^{\lambda}\right) \qquad (17)$$

The figure 8 illustrates the graphic representation of the reliability in function of the damage for γ= 1.5, γu=1.8 and λ=2.

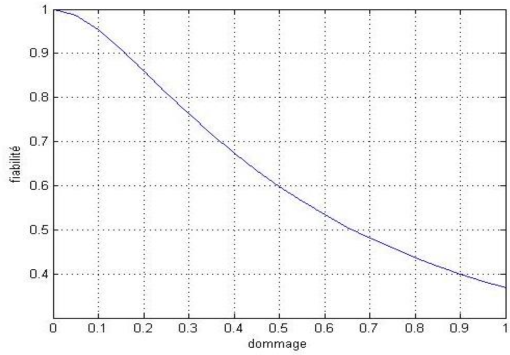


Fig.8. Graphic representation of the reliability in function of damage

After graphic reading of this curve, we remark that for a damage that equals 1, the reliability is not zero value. Thus, the damage theory considers that the damage reaches its maximal value "1" when it has appearance of a macroscopic crack, but the material keeps a certain resistance translated by a non zero reliability.

5.3.1 series-parallel system

The expression of the reliability in function of the damage of a series-parallel system is written as follow:

$$R_{SP} = \left[1 - \left(1 - exp\left(-\left(\frac{\alpha D}{1 - D(1-\alpha)}\right)^{\lambda}\right)\right)^{p}\right]^{S} \qquad (18)$$

For $\gamma = \frac{\Delta\sigma}{\sigma_0}$ = 1.5; $\gamma_u = \frac{\sigma_u}{\sigma_0}$ =1.8; λ=2, S = 6 (number of strands) and P = 7 (number of wires)

The figure 9 represents the reliability in function of the damage of the last wire rope according to the series-parallel model.

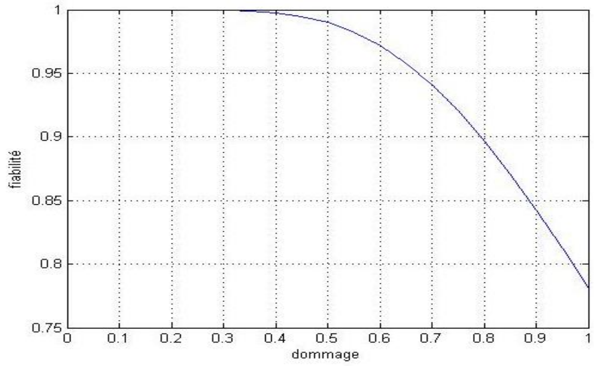


Fig.9. Reliability in function of the damage for the wire rope (6*7) type according to the series- parallel model

5.3.2 parallel-series system

The reliability in function of the damage of a parallel-series system is expressed as follow:

$$1 - R_{PS} = \left[1 - exp\left(-S.\left(\frac{\alpha D}{1-D(1-\alpha)}\right)^{\lambda}\right)\right]^{P} \qquad (19)$$

For $\gamma = \frac{\Delta\sigma}{\sigma_0}$ = 1.5; $\gamma_u = \frac{\sigma_u}{\sigma_0}$ =1.8; λ=2, S = 7 (number of wires) and P = 6 (number of strands).

The figure 10 shows the reliability in function of the damage of the same wire rope according to parallel-serie model.

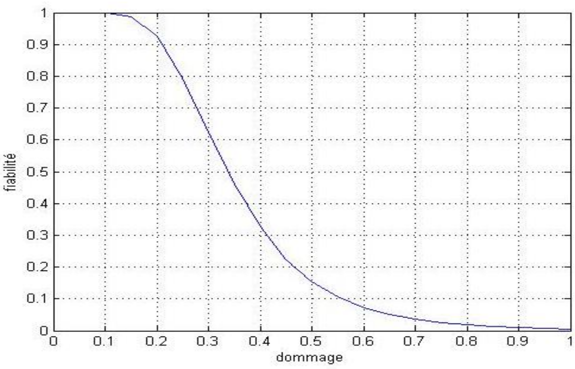


Fig.10. Reliability in function of the damage for the wire rope (6*7) type according to the parallel-series model

After studying these curves (Figures 4, 5, 9 and 10), we remark that the reliability of the system is influenced by the parallel branches. The opposite is observed: the system is more reliable if we increase the number of parallel blocs, and less reliable if we increase the number of series blocs.

6 Proposal of a new reliable modeling of a wire rope

A wire rope can be considered as a system constituted of a group of strands disposed of a majority logic system, each strand is itself constituted of a group of wires disposed in parallel. The approach adopted is a multi-scale approach where we distinguish the scale of wire, the scale of strand and that of the wire rope.

The schema of a suspended wire rope proposed is then a system: majority logic / parallel. The choice of this system is justified by:

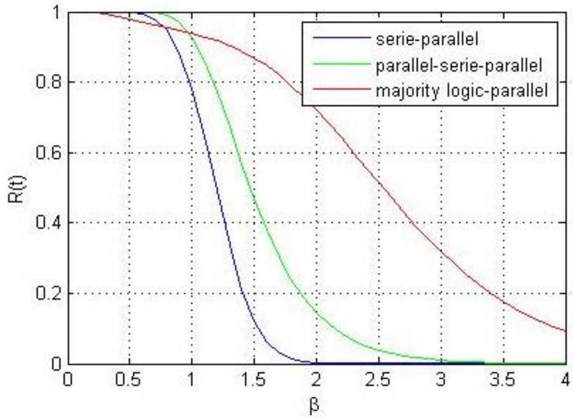
- The wires are twisted together, a broken wire has the capacity to re-anchor on a given length, called re-anchor length, and which defines the stub's dimension
- A broken strand does not lead to the failure of the wire rope. However, starting from a certain number of broken strands, the wire rope can be declared as being failed. Therefore, The system is a majority logic:

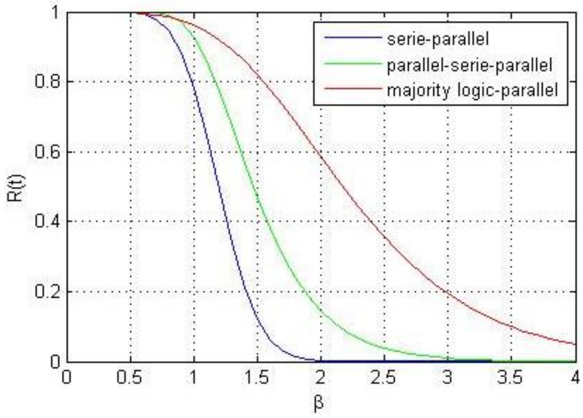
$$R(t) = 1 - \left(1 - \sum_{k=m}^{n} C_n^k R_i^{k}.(1-R_i)^{n-k}\right)^{p} \qquad (20)$$

With p: number of wire*number of stubs; n: total number of strands and m: minimal threshold of the number of functional strands.

7 comparison of models

In order to show the failure criteria based on the number of unacceptable broken wires, we proceeded to a comparison of our model with the those models proposed by Al Achahchi [2] who considers that the wire rope is like a parallel-series-parallel system, and Kolowrocki [3] who considers it as a series-parallel system, on a steel wire rope of (6*7) type (6 strands 7 wires) of 6 mm diameter. The figures 11, 12 and 13 illustrate this comparison taking the number of unacceptable broken wires as a criteria of failure.





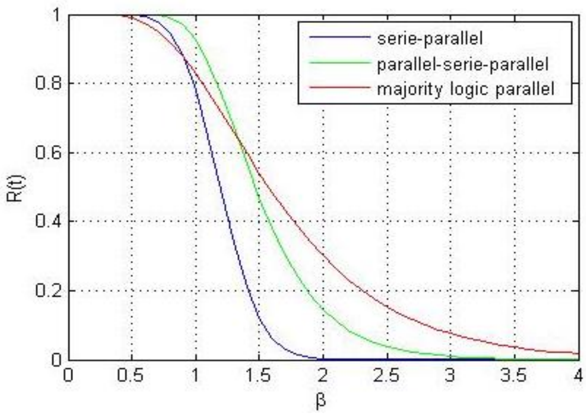


Fig.11. Case where the criteria of failure is six broken wires
Fig.12. Case where the criteria of failure is three broken wires
Fig.13. Case where the criteria of failure is one broken wire

These curves show that the two first models (those proposed by AL Achachi and Kolowrocki) do not change and consequently do not take into consideration the failure criteria. Yet the proposed model appears as being well adapted to the real situation of wire rope's use and takes into consideration the degradation of the wire rope in function.

Conclusion

The optimization of damage through the reliability is a technique that promotes knowledge and a continuation of an entity's condition under loads during time. This can have the interest for an eventual application in industrial maintenance. In this framework, this word is elaborated to make a link between reliability and damage through fatigue. this link which allows associating at each stage of damage the corresponding reliability; as a matter of fact, the damage theory considers that the damage reaches its maximal value "1" when it has an appearance of a macroscopic crack, but the wire rope keeps a certain resistance translated by a non zero reliability. This latter becomes when the wire rope is totally broken.

For each particular type of wire rope application, the occurrence of the number of unacceptable broken wires is the action adopted for the damage of fatigue evaluation. Consequently, our study's purpose was developing a modeling which allows predicting the resistance capacity of a wire rope in different levels of damage of its components. Our contribution is essentially reliable by the use of a new model which determines the reliability of the wire rope taking into account the number of tolerated broken wires in a strand, and that of the strands in the wire rope. In this respect, our objective is to be able to describe the mechanic behavior of each wire so as to deduce that of the wire rope.

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