RESEARCH INVENTY: International Journal of Engineering and Science
ISSN: 2278-4721, Vol. 1, Issue 1 (Aug 2012), PP 21-30
www.researchinventy.com

Analytical approach of availability and maintainability for structural lifting cables using reliability-based optimization

A. Chouairi[1], M. El Ghorba[1], A. Benali[1]
[1] *Laboratoire de Contrôle et Caractérisation Mécanique des Matériaux et des Structures, B.P 8118, Oasis-Route El Jadida – ENSEM, Casablanca, Maroc*

ABSTRACT:--*In industrial settings, the risks due to wire ropes failure are important and have much challenge for engineering and design, especially if costs are assessed in terms of human lives. Frequently the extent of damage and the carrying capacity of ropes are closely related to the sense of safety by staff and equipments, therefore the failure prediction has become so essential for optimal use of all industrial facilities.*

The aim of this article is to introduce a practical method for reliability modeling wire ropes subjected simultaneously to tensile loads in order to ensure the exploitation of wire ropes under optimal conditions.

In order to optimize the relation reliability-maintainability and availability of metallic wire ropes, an extensive analytical modeling study has been performed in order to estimate the reliability-related to damage in the case of mixed systems, series-parallel or parallel-series configuration with symmetrical applied. The adopted approach is an approach multi-scale with a total decoupling between the scale of the wire and that of the cable.

Keywords - *Wire ropes, damage, reliability-maintainability, availability, mixed systems.*

I. INTRODUCTION

Ropes, due to their capacity to support large axial loads with comparatively small bending or tensional stiffness, have been widely used in many industrial applications, like structural elements (reinforcement for tires and bridges brace) or as elements for transporting purposes (cranes, lifts, ropeways, ski lifts and mine hoists) [1]. In this latter application, steel wire ropes have played a vital role in mine hoisting systems because their endurance strength and fatigue life have great effect on the safety of miners and the mine production [2-3].

A wire rope consists of many wires twisted together to make a complex structure combining axial strength and stiffness with flexibility under the bending action [4]. 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. These elements are long lasting when properly used and maintained.

The rope is constructed by laying several strands around a core (Fig.1). These strands have a central wire around which single metallic wires are helically wrapped [5]. The larger fraction of load is carried by a strand. On the other hand, wires are the basic elements of a rope; they are made by patented high strength steel, realized through the application of carbon steel featured by carbon content generally close to eutectoid composition. The choice of such steel grade is related to the aim of slowing or completely avoiding the growth process of fatigue cracks through the obstacle role opposed by the alternate lamellas of ferrite and iron carbide that features the perlite and characterizes these eutectoid steels.

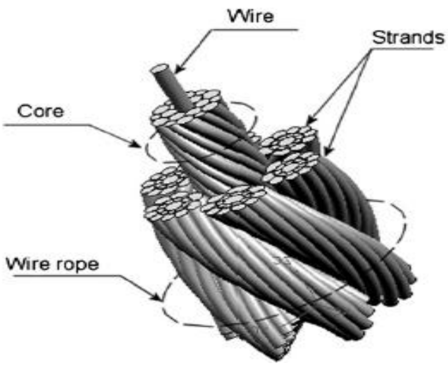

Fig.1. Schematic of wire rope composed of different strands of wound steel wires

Despite its widespread use, wire rope remains an extremely complex and little-known piece of equipment. Its construction, the considerable and diverse internal contact forces, the wear due to these forces and to contact with drums, pulleys or sheaves, all make a completely analytical approach to reliability extremely difficult.
Even today, experimental testing plays an important role in the analysis of rope subjected to a particular load, especially as regards fatigue analysis where the breaking of strands results from varying types of test and load.

The purpose of this paper is to study the relation between maintenance and availability of lifting cables, based on the influence of reliability on the uptime. This is in particular to establish a system analysis of series-parallel cables, using the relations for calculating reliability. The results are then used to determine the fraction of critical life Bc, which provides information on the time course of action in order to remove the cable.

II. MULTI-SCALE APPROACH BASED ON RELIABILITY

Like all structural suspension cables wire ropes are subjected to the action of time and consequently to the damage which is one of the main causes of reduction of their bearing capacity and their reliability. This issue is important for suspension bridges and in particular for their main suspension cables. If the reliability of these systems has been widely studied, only a few works account for durability effects, using for modeling data obtained in the field [6–11].
In order to ensure the exploitation of the structure under optimal conditions, a fine analysis of its safety must be combined with procedures of inspection defined consequently. Unfortunately, many cables have never been subjected to an inspection or, in the contrary case, only in a very partial way, because of the limits of the inspection techniques (visual, acoustic, etc.).

The safety analysis consists in connecting the estimation of the residual cable strength to the data of inspection (when they are available). This link is difficult to establish, even if one agrees that the concept of safety factor of the cable is somewhat insufficient to characterize its present state. The majority of works related to the determination of the bearing capacity of a suspension cable are statistical models which do not integrate the complexity of the mechanical description (non-linear behavior, load redistribution, etc.).

Crémona [9] proposed a more mechanical approach to the problem, but without describing degradation. In order to have models being able to assist the manager in his choices, for instance when he must decide to limit traffic on the bridge, we have chosen to work according to two objectives: on one side, to evaluate the effect of the factors affecting the long term performance of the cable. This requires to develop a model of the strength of a cable with various levels of damage of its components, and to connect the response of the wire with that of a set of wires considered then collectively (strand) and finally with that of a set of strands. On the other side, to develop a model of the residual lifespan (for a requirement of given service), since the physical and behaviors at the various scales to the form and kinetics of degradation. The statistical data related to the temporal development of damage, obtained through monitoring, can be integrated as well at the scale of wire as at the scale of strand section in a cable.

The study of the behavior of a cable is consequently a multi-scale study where one can distinguish three scales: the scale of the wire, the scale of the strand and the scale of the cable. The systemic diagram of a suspended cable is thus a system: parallel (K strands) – series (M sections in each strand) – parallel (N wires in each section) [16]. The choice of these three scales is relevant knowing that firstly the behavior of a wire governs the behavior of the whole of the cable. The physic-chemical processes like rates of degradation due to the environment (corrosion, etc.) are different for each layer, external layers being more exposed. Secondly, when wires are twisted and rolled up together, a broken wire has the capacity to recover its strength over a recovery length; this length will define the effective segment size for a strand. Its value, according to Raoof [18], is from 1 to 2.5 times the lay lengths. The behavior of a strand is related to the behavior of its weakest section (system is in series).Thirdly, the strands being laid out in parallel, the resistance of the cable depends on their individual resistances and the type of sharing load redistribution (local, global).

Meng [15] has compared the MTTF of four series–parallel and parallel–series redundant systems which contained 2n independent components. General ordering relations between four different systems arising in standby redundancy enhancement in terms of their MTTF are proposed by Meng [16]. Lewis [14] first introduced the concept of the standby switching failures in the reliability with standby system. Kuo and Zuo [13] introduced many of the system reliability models such as parallel, series, standby, multistate, maintainable system, etc. Gaikowsky et al. [12] and Wang and Liou [20] examined the series systems with cold standby components and warm standby components, respectively. Wang and Pearn [19] investigated the cost and probabilistic analysis of series systems with mixed standby components. Wang and Liou [20] studied the probability analysis of a repairable system with warm standbys plus balking and reneging for which no cost–benefit analysis is considered. Recently, Wang and Liou [20] proposed cost–benefit analysis of series systems with warm standby components and general repair time.

Giglio and Manes [21] reported several analytical formulations to estimate the state of stress in the internal and external wires of a rope. Siegert [22] determined the normal contact load and relative displacement amplitude between wires in a multilayer strand.

Leissa [23] extended the case of a rope made up of six strands, each of seven wires. Leissa sought a relationship between the stresses in the single wires and the geometry of the rope and the load applied, also as regards the stresses due to contact between the single wires and the strands. Starkey and Cress [24] developed a simplified mathematical model for the calculation of the contact stresses; the importance of this work is the introduction of the fretting problem, in other words the fatigue due to contact and relative slipping between wires.
Meksem [25] developed an analytical model to analyze the mechanical behavior of lifting wire ropes with different percentages of broken wires subjected to tension and fatigue. The model developed determine the reliability of a cable degraded at different levels of damage and the corresponding maximum tensile strength, to help in the planning and organization of preventive maintenance.

Chouairi [26] proposed a practical method for system reliability analysis. Among the existing methods for system reliability analysis, reliability graph theory which is particularly attractive due to its intuitiveness, which is an extension of the conventional reliability graph.

III. Equations Of Reliability Systems

III.1. Relation reliability-maintainability

The basic model for describing the relation reliability-maintainability is to study the intersection between the MTBF (Mean time between failures) which is the predicted elapsed time between inherent failures of a system during operation (1) [26]:

$$MTBF = \int_0^1 R(t)dt \tag{1}$$

The MTTR (Mean time to recovery) is the average time that a device will take to recover from any failure (2).

MTTR = (Amount of time repair) / (Number of repairs) (2)

Generally Total elapsed time from initial failure to the reinitiating of system status is approximately equal to Mean Time To Restore includes Mean Time To Repair (3).

$$\text{MTTR} = (\text{MTBF})^{-1} \tag{3}$$

III.2. Availability

The availability of a production tool is a very broad concept, encompassing human aspects, business organization, but also purely technical (statistical calculation type chosen to analyze the data).
Among the concepts that contribute to good availability, maintainability is of particular importance, especially as it affects policy maintenance of the company. Equation (4) gives the expression of the availability for function of the MTBF and MTTR.

$$D = \frac{MTBF}{MTTR + MTBF} \tag{4}$$

IV. Parallel series system

IV.1. Relation between reliability-failure and fraction of life

We consider a system of n blocks characterized by the same reference law, but experiencing different levels of stress. In the case of a configuration composed by S series blocks, each block is composed by P single elements connected in parallel where the reference law is a reliability-series law; we will have an expression of reliability as (5):

$$R_{ps} = 1 - \left[\left(1 - \exp\left(-S.\beta^{\lambda} \right) \right)^{p} \right] \tag{5}$$

R_{ps}: Reliability of parallel series system
S: number of components in series

P: number of components in parallel
β: form parameter
γ: position or origin parameter

The failure of a series system is based on the fraction of life, and given by (6):

$$Q_{ps} = \left[\left(1 - \exp\left(-S.\beta^{\lambda} \right) \right)^{p} \right] \tag{6}$$

Q_{ps}: Failure of parallel series system
S: number of components in series
P: number of components in parallel
β: form parameter
γ: position or origin parameter

IV.2. Relation between reliability and damage

Concerning the mechanical damage model that reflects the behavior of the component toward the failure mode that is the fatigue, is based on the reduction of strength and endurance limit, these features are results of the different damage that the metal may has, this model is the unified theory which was established after a thorough overview of the different theories that describe the damage in the solicitation of fatigue.

According to the equation for parallel series system, reliability is given by (7):

$$\begin{cases} R_{ps} = 1 - \left[\left[1 - \exp\left(-S.\left(\dfrac{\alpha.D}{1 - D(1-\alpha)} \right)^{\lambda} \right) \right] \right]^{p} \\ 1/e \le R \prec 1 \\ D = 0 \, pour R = 1 \end{cases} \tag{7}$$

The failure of a series system based on the damage is given by the relation (8):

$$Q_{ps} = \left[\left[1 - \exp\left(-S.\left(\frac{\alpha.D}{1 - D(1-\alpha)} \right)^{\lambda} \right) \right] \right]^{p} \tag{8}$$

IV.3. Relation reliability-maintainability

The Mean time between failures (MTBF) and the Mean time to recovery (MTTR) are given by relations (9) and (10).

$$MTBF_{ps} = \int_{0}^{1} 1 - \left[1 - \exp\left(-S.\beta^{\lambda} \right) \right]^{p} dt \tag{9}$$

$$MTTR_{ps} = (MTBF)_{ps}^{-1} \tag{10}$$

IV.4. Availability

For a parallel series system availability is given by (11).

$$D_{ps} = \frac{MTBF_{ps}}{MTTR_{ps} + MTBF_{ps}} \tag{11}$$

V. SERIES PARALLEL SYSTEM

Similarly we consider that all blocks are equivalent and simultaneously solicited in the same way, and their damages are therefore identical.
So is now the case of a series parallel configuration composed by S series blocks, each block is composed by P single element connected in parallel.
Forms of reliability and failure are presented in Table 1:

Table 1. Relation reliability and failure

Failure	**Reliability**
$1-Q_{sp}=\prod_{j=1}^{S}(1-D_j)=(1-D_j)^S$ j : the number of parallel blocs	$R_{sp}=\prod_{j=1}^{S}R_j$ j : the number of parallel blocs
$Q_{sp}=1-\left[1-\left(1-\exp(-\beta^{\lambda})\right)^p\right]^S$	$R_{sp}=\left[1-\left(1-\exp(-\beta^{\lambda})\right)^p\right]^S$

By replacing the fraction of life β expressed in terms of damage D, we have (Table 2):

Table 2. Relation damage and reliability in term of failure

Reliability	**Failure**
$R_{sp}=\left[1-\left(1-\exp\left(-\left(\frac{\alpha.D}{1-D(1-\alpha)}\right)^{\lambda}\right)\right)^p\right]^S$	$Q_{sp}=1-\left[1-\left(1-\exp\left(-\left(\frac{\alpha.D}{1-D(1-\alpha)}\right)^{\lambda}\right)\right)^p\right]^S$

Table 3 gives the relations of Mean time between failures (MTBF) and the Mean time to recovery (MTTR).

Table 3. Relation MTBF and MTTR

$\mathbf{MTBF_{sp}}$	$\mathbf{MTTR_{sp}}$
$MTBF_{sp}=\left[1-\left(1-\exp(-\beta^{\lambda})\right)^p\right]^S dt$	$MTTR_{sp}=(MTBF)_{sp}^{-1}$

Availability for a series parallel system is given by (12).

$$D_{sp}=\frac{MTBF_{sp}}{MTTR_{sp}+MTBF_{sp}} \qquad (12)$$

VI. NUMERICAL DETAILS

VI.1. 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 steel light greased, metal core, right cross, preformed, used especially in tower cranes and suspension bridges (Fig. 2).

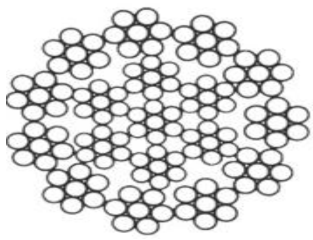

Fig. 2. Cross section of a 19*7 wire rope

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.

VI.2. Estimation of reliability and damage

In order to calculate the damage of wire ropes, a graphical interface is performed 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.

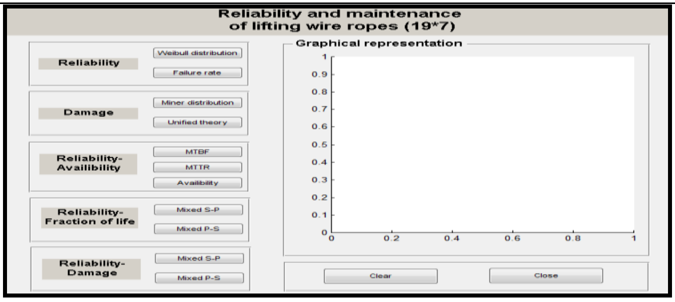

Fig. 3. Graphical interface for estimating the residual strength

To treat the model, we use an algorithm derived from graph theory, which generates digitally function of damage systems.
The interface module of calculation and presentation of results is shown in Fig. 3. This interface allowed us to summarize all the steps and tests to study the damage produced by wire ropes.

VI.3. Failure rate for a cable (19*7)

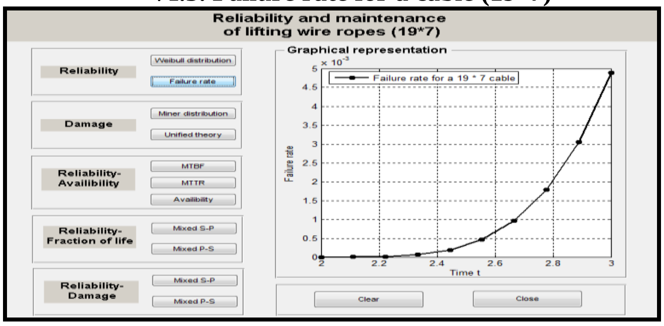

Fig. 4. Failure rate for a lifting wire rope (19*7)

Fig. 4 shows the shape of the failure rate for a (19*7) metallic cable according to unit time t for weibull parameters: $\beta = 3.2$, $\eta = 2.5$, $\gamma = 2.6$, we notice that the failure rate which describes the probability of failure per unit time t (Fig. 2) increases progressively as:
- To $2 < t < 2{,}38$: the failure rate is constant, preventive maintenance has no effect.
- To $2{,}38 < t < 3$: the failure rate is linearly increasing, therefore, changes in the maintenance period is proportional to changes in reliability.

VI.4. Unified theory

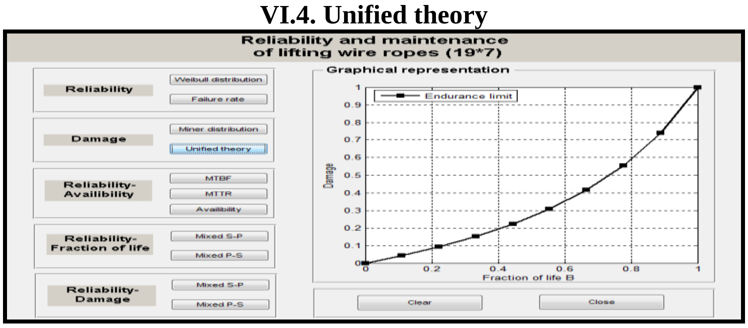

Fig. 5. Damage depending on the fraction of life for a 19*7 wire rope

The variation of damage depending on the fraction of life according to the unified theory is given in Fig. 5, the parameters of the lifting wire rope type (19 * 7) are:
- Endurance limit: γ=2.6,
- Ultimate residual stress: γ_u=3;

we notice that the damage of the cable reaches 25% of the damage for a fraction of life equal to 50% of the total life of the cable which corresponds to the initiation stage of the damage, or the damage increases to 75% for a fraction of life equal to 90% of the cable which is the point of brutal damage.

VI.5. Relation reliability- fraction of life

VI.5.1. Mixed s-p

In the case of a series-parallel system, for the metallic cable (19 * 7), we considered that the number of series branch matches the number of strand S = 19, or the number of parallel branch is the number of wires per strand P = 7.

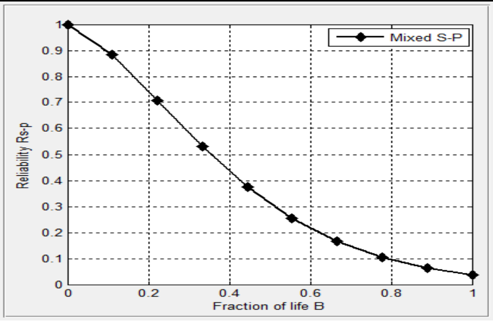

Fig.6. Curve representing the reliability Rs-p based on fraction of life B

Reliability according to fraction of life B (Fig. 6), ensure that there is a rapid decrease of reliability for the curve of reliability, proportionally to fraction of life B , This is because we have favored the trend series at the expense of the parallel trend. Also, the failure of the strands that are parallel is slower than that of the branches in series; this reflects the behavior of the cable towards its reliability. We also note that the cable maintains some internal resistance resulted in a reliable non invalid (B= 1), this resistance becomes when the cable is completely broken.

VI.5.2. Mixed p-s

In the case of a parallel-series system, for the metallic cable (19 * 7), we considered that the number of parallel branch matches the number of strand P = 19, or the number of series branch is the number of wires per strand S = 7.

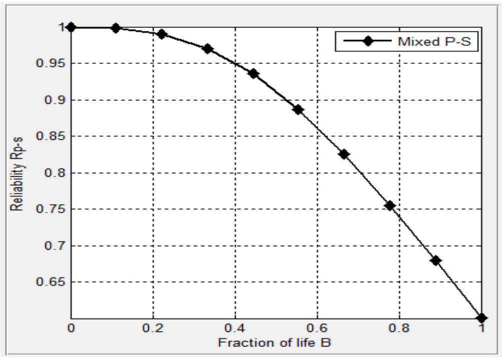

Fig.7. Curve representing the reliability Rp-s based on fraction of life B

Fig. 7 represents the reliability Rp-s depending on the fraction of life B; we notice clearly that the curve is influenced by the tendency of parallel components on system reliability. The reverse is observed: the system is less reliable if we increase the number of series blocks, and we keep the same number of parallel components. The parallel-series system keeps a significant reliability even in failure, the decrease of reliability is not important, and this is exacerbated each time we raise the number of components arranged in parallel, that is to say every time we raise the number of components; we will have as result an increasing system reliability.

VI.6. Relation reliability-damage

VI.6.1. Mixed s-p

For: $\gamma = \Delta\sigma/\sigma_0 = (2.6)$; $\lambda = (2.8)$; $\gamma_u = \sigma_u/\sigma_0 = 3$, S = 19 (number of strands); P = 7 (number of wires per strand).

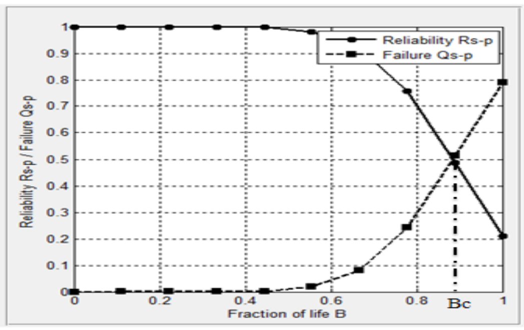

Fig. 8. Superposition of the curves reliability and failure for series parallel cables

The superposition of the curves of reliability and failure shows a point of intersection (Fig. 8) which coincides with a reversal of situations.
Indeed, the reliability was initially higher than the failure and becomes weaker beyond this point which corresponds in fact to the acceleration of the damage, and thus a fraction of critical life Bc, where the intervention of preventive maintenance.

For the cable studied which is considered as a series parallel system, in this case-sensitive fraction (Bc) is equal to 90% of the total life of the cable, which is 50% of the reliability and failure of the cable.

VI.6.2. Mixed p-s

For: $\gamma = \Delta\sigma/\sigma_0 = (2.6)$; $\lambda = (2.8)$; $\gamma_u = \sigma_u/\sigma_0 = 3$, S = 7 (number of wires per strand); P = 19 (number of strands)**.**

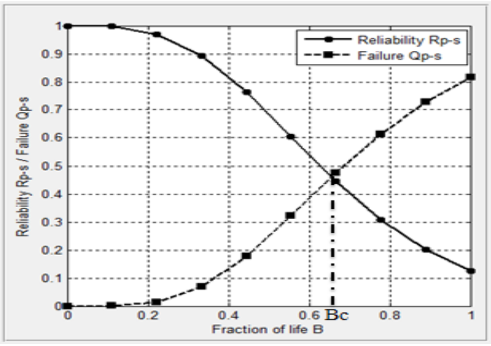

Fig.9. Superposition of the curves reliability and failure for parallel series cables

In the case of a parallel series, the fraction of life for critical cable (Bc) is equal to 0.64 of its total life; this value is smaller than the system serial parallel, which requires preventive maintenance in the case of parallel series cable before the case of a series parallel cable (Fig.9).
So the series parallel system is most compatible for the study of a cable or any complex system.

VI.7. Reliability-maintainability for the 19*7 wire ropes

In this part to calculate the MTBF, MTTR and availability of cable, we will consider that the cable corresponds to a parallel series for his particular interest as continues system to function, even if some of its components are completely ruined.

For: $\gamma = \Delta\sigma/\sigma_0 = (2.6)$; $\lambda = (2.8)$; $\gamma_u = \sigma_u/\sigma_0 = 3$; S = 7 (number of wires per strand); P = 19 (number of strands).

VI.7.1. MTBF

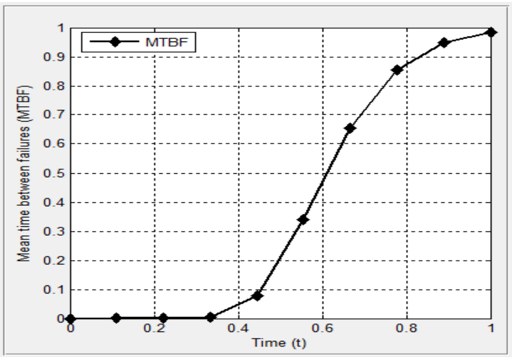

Fig. 10. Mean time between failures (MTBF) for a parallel series cable

Fig. 10 shows the curve of mean time between failures (MTBF) for a (19*7) metallic cable according to unit time t .We notice that the MTBF which describes the efficiency of the cable per unit time t which increases progressively as:
- To 0 < t < 0,34 : the MTBF is constant, and have a null value.
- To 0,34 < t < 1: the MTBF is linearly increasing, therefore, changes in the maintenance period is proportional to changes in reliability.

VI.7.2.MTTR

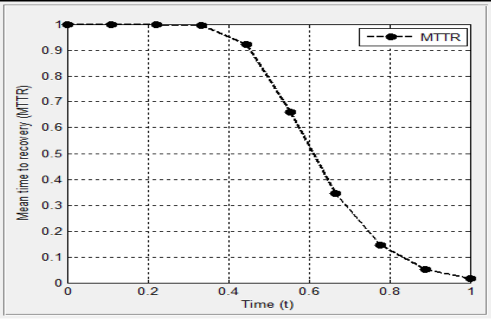

Fig.11. Mean time between failures (MTTR) for a parallel series cable

The Fig. 11 represents the mean time to recovery (MTTR) as a function of time t, we deduce clearly that there is a rapid decrease of reliability for the curves, and this decrease is greater at 0.34 of the time of cable in service.

VI.7.3.Relation MTBF /MTTR

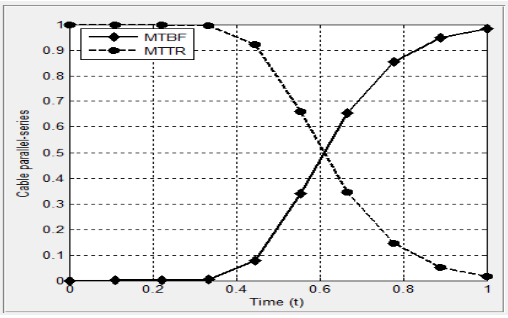

Fig.12. Relation reliability-maintainability for a parallel series cable

In Fig. 12 the superposition of curves of MTBF and MTTR shows a reversal of situation at intersection of the two curves. The system reached set point at a fraction of 50% with a time of 0.61. This approach allowed us to predict the critical moment of the damage, and thus to intervene in a suitable time to maintain the cable.

VI.7.4. Availability

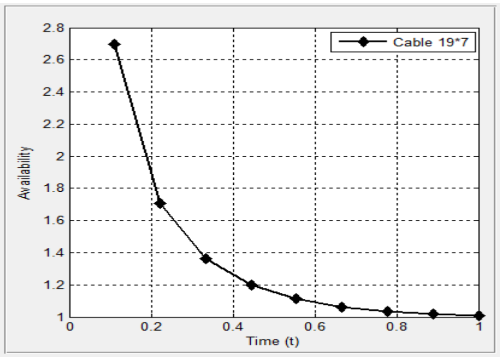

Fig.13. Availability in function of time for a parallel series cable

According to Fig. 13 we deduce clearly that there is a rapid decrease in availability, this decrease is increasingly proportional to the function of time.

VII. Conclusion

Cables are often fundamental to the maintenance of structures and the safety of users depends on their condition. This security is directly related to the ability to monitor and detect their degradation.

In this work, we linked to the reliability of damage through the fraction of life. We can associate to each point of damage the reliability corresponding to a lifting cable type 19 * 7. Other shares, this approach allow us to predict the critical moment of the damage, and therefore the response time to maintain the system.

A comparison between parallel and series system a parallel series showed that the second is the most reliable. On an industrial scale, this work finds its interest in any company that uses regular or occasional lifting devices. Its first objective is to avoid accidents caused by cables. The second objective is to predict the timing of intervention for preventive maintenance.

REFERENCES

[1] Kaczmarczyk S, Ostachowicz W. Transient vibration phenomena in deep mine hoisting cables. Part 1: Mathematical model. Journal of Sound and Vibration 2003; 262:219–44.

[2] Hoeppner DW, Chandrasekaran VW, Elliot CB. Fretting fatigue: current technology and practices ASTM STP 1367. 3rd ed. Philadelphia: ASTM; 2000.

[3] Ge SR, Qu RL, Xie WY. Reliability of hoisting ropes. In: Chen YH, Jiang ZF, editors. Reliability Technology of Mine Hoist. Xuzhou: China University of Mining and Technology Press; 1994.

[4] G. Simonnet, Tube, steel, technology and engineering. Metallic materials, 1996, Vol.MC2, N.M645, p. M645.1-M645.12.

[5] Canadian Centre for Occupational Health and Safety "Wire rope lifting" in February 2010.

[6] Matteo J, Deodatis G, Billington DP. Safety analysis of suspension-bridge cables:Williamsburg bridge. ASCE J Struct Eng 1994;120(11):3197–211.

[7] Haight RQ, Billington DP, Khazem D. Cable safety factors for four suspension bridges. ASCE J Bridge Eng 1997;2(4):157–67.

[8] Camo S. Probabilistic strength estimates and reliability of damaged parallel wire cables. J Bridge Eng 2003;8(5):297–311.

[9] Crémona C. Probabilistic approach for cable residual strength assessment. Eng Struct 2003;25(3):377–84.

[10] Elachachi SM, Breysse D, Yotte S. Strength capacity of suspension cables. Final report, CDGA, University of Bordeaux I; 2004.

[11] Faber MH, Engelund S, Rackwitz R. Aspects of parallel wire cable reliability. Struct Safety 2003;25:201–25.

[12] C. Galikowsky, B.D. Sivazlian, P. Chaovalitwongse, Optimal redundancies for reliability and availability of series systems, Microelectronics and Reliability 36 (1996) 1537–1546.

[13] W. Kuo, M.J. Zuo, Optimal Reliability Modeling: Principles and Applications, John Wiley & Sons, New York, 2003.

[14] E.E. Lewis, Introduction to Reliability Engineering, second ed., John Wiley & Sons, New York, 1996.

[15] F.C. Meng, On comparison of MTBF between four redundant systems, Microelectronics and Reliability 33 (1993) 1987–1990.

[16] F.C. Meng, Comparing the MTBF of four systems with standby components, Microelectronics and Reliability 35 (1995) 1031–1035.

[17] K.-H. Wang, J.-C. Ke, Probabilistic analysis of a repairable system with warm standbys plus balking and reneging, Applied Mathematical Modelling 27 (2003) 327–336.

[18] K.-H. Wang, C.-C. Kuo, Cost and probabilistic analysis of series systems with mixed standby components, Applied Mathematical Modelling 24 (2000) 957–967.

[19] K.-H. Wang, W.L. Pearn, Cost benefit analysis of series systems with warm standby components, Mathematical Methods of Operations Research 58 (2003) 247–258.

[20] K.-H. Wang, Y.-C. Liou, W.L. Pearn, Cost benefit analysis of series systems with warm standby components and general repair times, Mathematical Methods of Operations Research 61 (2005) 329–343.

[21] Giglio M, Manes A. Life prediction of a wire rope subjected to axial and bending loads. Eng Fail Anal 2005;12:549–68.

[22] Siegert D. Initiation of fretting fatigue cracks in spiral multilayer strands. OIPEEC Bull 1999; 78:27–44.

[23] Leissa AW. Contact stresses in wire ropes. Wire Wire Products 1959;34:307–14. 872–873.

[24] Starkey WL, Cress HA. An analysis of critical stresses and mode of failure of a wire rope. J Eng Ind, Trans ASME 1959;81:807–16.

[25] A. Meksem, Probabilistic approach and experimental characterization of the behavior of wire rope hoist, Ph.D. Thesis, ENSEM, University Hassan 2, Ain Chock, Casablanca, 2010.

[26] A. Chouairi, E. Boudlal, M. El Ghorba, A. Benali «Estimating the relation reliability-maintainability and availability performance of complex systems with the method of accelerated tests » International Journal of Research and Reviews in Mechatronic Design and Simulation (IJRRMDS), Vol. 2, No. 2,pp .165-174,June 2012