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Investigation on the Main Degradation Mechanisms of Steel Wire Ropes: A Literature Review

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Abstract: Steel wire ropes consist of several steel wires twisted together to make complex structures with huge mechanical properties combining axial strength and stiffness with bending flexibility. In the great majority of applications, a rope is subjected to repeated bending, fluctuating loads and cyclic deformations. Therefore, it is prone to several degradation mechanisms that may occur alone or in combination. The results of expertise showed that the main mechanisms leading to wire ropes degradation are fatigue, fretting fatigue, wear and corrosion which all reduce the strength of wires and accelerate the failure of the rope. This study aims to establish a broad and comprehensive bibliography on the main degradation mechanisms that affect steel wire ropes after a period of service as well as their causes and loss of strength that these very mechanisms engender. This literature review allows us to shed light on a quiet interesting point which was not previously widely approached, for the ultimate goal of increasing the reliability of steel wire ropes.

Key words: Steel wire ropes, geometrical problems, degradation mechanisms, failure, energy losses

INTRODUCTION

A wire rope is generally made of several strands laid helically and symmetrically in one or multiple layers with uniform pitch and direction around a straight central core strand. The strand itself consists of several wires regularly disposed around a central wire in one or multiple layers. A wire rope could be composed of one strand; here, we are talking about a mono-strand wire rope, or a helical wire rope. The basic material of wire ropes is initially steel with an elevated strength thanks to its high carbon content and its very fine grain structure. Wire ropes are identified by several parameters including size, grade of steel used, minimum breaking load, metric mass, the number of strands and the number of wires in each strand (Fig. 1).

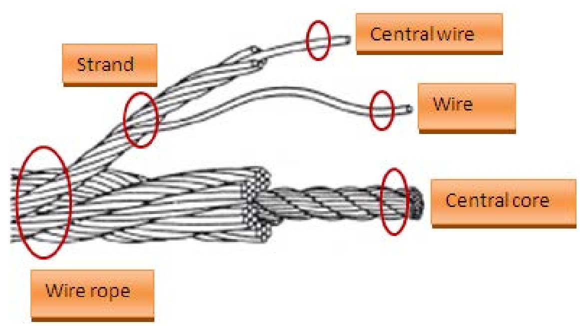

Fig. 1: Schema illustrating the different components of steel wire rope

The effective use of steel wire ropes goes back to 1836 thanks to Wilhelm Albert engineer. Ever since, the use of these ropes has known tremendous growth and has had significant effect on several industrial applications. Due to their mechanical properties (bending flexibility and torsional stiffness) and their ability to relatively resist large axial loads, wire ropes have been widely used in fulfilling difficult tasks such as lifting loads, suspended bridges, elevators, electricity transmission and boat caching. On the other hand, in the great majority of applications, a rope is subjected to repeated bending and fluctuating loads. It is also subjected to high contact stresses and longitudinal sliding at point contact with sheaves or drums whose direct consequences are the significant changes of geometrical and mechanical characteristics of its components. This results in a reduction of the wire rope bearing capacity leading, eventually, to its failure (Meksem, 2010). In this respect, the security of people who use wire ropes directly depends on the states of these latter. Thus, companies have interest in eliminating or controlling the risk of accidents that are linked to the wire rope use so as to guarantee a smooth running of their activities but most importantly, ensure the staff security.

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Therefore, it is quiet important to predict their mechanical performance before using them, to plan and organize actions of preventive maintenance and to change them at the appropriate time.

A wire rope in service is subjected to several degradation mechanisms that may occur alone or in combination. The results of expertise showed that the steel wire ropes deterioration phenomena originated initially from mechanical and environmental causes. The wires' breakings that are caused by fatigue, fretting fatigue, wear or corrosion are widespread problems. It is been known for a quite long time that the wire rope has a limited lifespan; the continuous process of degradation associated to its operational service lead finally to its failure. The wire rope should thus be replaced for fear of such breaking to occur and become unacceptable. Some serious damages, such as those caused by lightning strikes, are sufficient to warrant discard. However, over the long-term, in the case of well maintained and exploited installations, the fatigue plays an essential role (Chaplin, 2005), it is a process which when under the action of variable stress and deformation, edits the properties of the employed wire rope, engenders cracks and the eventual breaking of the wire rope. Thestressvalues that cause such damage may be much less than theultimate tensile stress limit of the wire rope. Nevertheless, a wire's fatigue is not always related to stress variation, for there is generally another process which worsens and accelerates fatigue and makes it condensed in well determined areas. This process can be known as: fretting fatigue. It results out of the frictionbetweenneighboringwires leading to a reduction of the steel wires fatigue lives and an acceleration of the rope's failure.

The great majority of safety critical rope applications involve fatigue coupled with other degradation processes such as wear or corrosion which together reduce the strength of wires and determine a finite service life of the rope. 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. This mechanism accelerates wear.

Preferably, for a better design and maintenance of lifting systems and for both enhanced safety in hoisting and improved efficiency in rope utilization, a better understanding of the degradation processes is important in optimizing the potential rope life. This understanding is important in the context of inspection and discard. The present research aims to establish a broad and comprehensive bibliography on the main degradation mechanisms that affect the steel wire ropes after a period of service as well as their causes and loss of strength that these very mechanisms engender while introducing the results of recent investigations relevant to different applications of steel wire ropes.

MATERIALS AND METHODS

In order to make a well structured and rich research of our thesis topic we decided to follow a simple methodology. Our topic is important and a large field of study, therefore we have chosen to compress such a lengthy and detailed subject into a simplified and manageable form. Like any other, our research is based on references taken from articles, conference papers and reports of master and doctoral theses which have been searched by specific researchers and which are to be found in different databases like: Scopus-Elsevier; Springer link; OIPEEC; Science direct; Thomson, British ropes ltd. All this in order to establish a broad and comprehensive bibliography on the main damage mechanisms that affect the steel wire ropes after a period of service as well as their causes and loss of strength that these very mechanisms engender. We have also based our research on other papers by making research in Google using the keywords: Steel wire ropes, geometrical problems, degradation mechanisms, failure, energy losses. Figure 2 and Table 1 present, respectively the

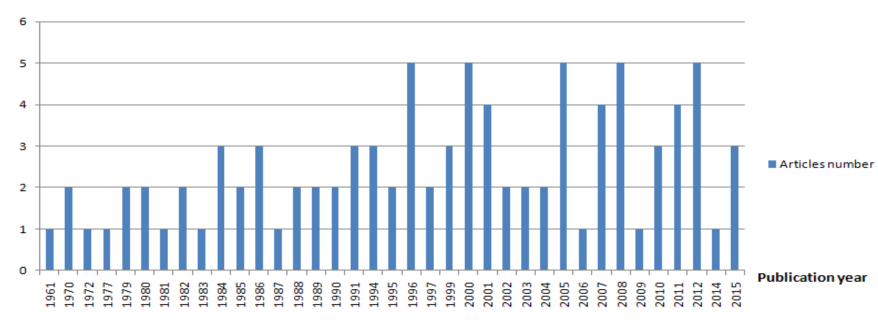

Fig. 2: Classification of examined articles per year of publication

Table 1: percentage of journals used for publications

Source	Number	Percentage
Engineering failure analysis	7	9.33
Journal of strain analysis	6	8.00
International Journal of Mechanical Science	5	6.66
International Journal of Solids and Structures	4	5.33
Journal of Engineering Mechanics	4	5.33
Annual offshore technology Conference, OTC	4	5.33
Structural Engineering and Mechanics	3	4.00
OIPEEC Technical Meeting	3	4.00
Computers and structures	2	2.66
International Journal of Mechanical Engineering	2	2.66
International Journal of Fatigue	2	2.66
Metallurgist	2	2.66
Theory of wire rope (Springer)	2	2.66
Applied Mechanics and Materials	2	2.66
Journal of Applied Mechanics: ASME DC	2	2.66
British ropes Ltd	2	2.66
Proc. Institution of Civil Engineers.	2	2.66
wire ropes: tension, endurance, reliability (Springer)	1	1.33
Tribology International	1	1.33
European Journal of Mechanics A/Solids	1	1.33
Journal of Engineering Mechanical Division	1	1.33
Journal of Mechanical Science and Technology	1	1.33
Journal of Materials in Civil Engineering Technology	1	1.33
Transactions of the ASME, Journal of Mechanical Design	1	1.33
Trans. ASME, Journal of Engineering Resources Technology	1	1.33
Journal of Naval Science and Engineering	1	1.33
Journal of Materials Engineering and Performance	1	1.33
Materials Science Forum	1	1.33
Journal of Engineering for the Maritime Environment	1	1.33
Wire industry		
Mathematical and computational Applications	1	1.33
International Journal of Advanced	1	1.33
Manufacturing Technology	1	1.33
Bulletin of Materials Science		
International Journal of Electrochemical Science	1	1.33
Indian Journal of Engineering and Materials Sciences	1	1.33
Wear	1	1.33
Wire Journal International	1	1.33
Wire World International	1	1.33

number of examined documents classified per year of publication and the percentage of journals used for publications.

Geometrical problems related to wire ropes: The geometry of steel wire ropes is hugely complicated that the definition of contact area between wires or that of curvatures and torsions in wires requires lengthy mathematical developments. Various theoretical models and analytical studies have been developed to solve this purely geometrical problem. Hence, in their study, Karamchetty and Yuen (1979) have interestedly searched the contact points between wires in a multi-strand wire rope. They have noticed that the rope loading edits the number and the distribution of the contact areas. Lee *et al*. (1987) have tried to express geometrically the curvature and the torsion before loading in the wires of a rope wound around a drum or a sheave. In literature, most analytical studies are available for wire ropes with an independent wire rope core IWRC. These studies are based on the superposition method which takes core strand and outer strands as a straight wire and single helical wires respectively to model IWRC as if a simple straight strand and then solve the whole system. Costello and Sinha (1977) have studied the static response of a simple straight strand using the theory of research. Costello (1990) has also presented in his reference book variety of studies concerning the frictionless theory of wire ropes. Velinsky *et al*. (1984) Velinsky (1985) developed a general nonlinear theory as an extension of the frictionless theory of Costello, to analyze complex wire rope as a Seale IWRC. Hobbs and Raoof (1994) have noticed in their study that there are more breakings on quasi-punctual contacts than on linear contacts. In their research, Brevet and Siegert (1996a) showed that the interwire fretting core-wires leads to the initiation of cracks localized in the lines contact (Table 2).

Various modeling approaches have been proposed by Costello (1997), so as to model the complex cross-section of multi-strand constructions. These models gave a good approximation of the mechanical response of the rope. However, to obtain the behavior of each wire, it was necessary to establish models that explicitly take into account the double helix configuration of individual wire. This was essential for predicting rope stiffness, strength, fatigue, wear and overall mechanical response of all the rope from the individual wire's data. In this context, some theoretical studies have been developed by Elata *et al*. (2004) where they gave parametric equations which provide the double-helix configuration of individual wires of IWRC. Then, Usabiaga and Pagalday (2008) introduced an analytical procedure for modeling wire ropes subjected simultaneously to tensile and torsional loads, taking into account wire by wire analysis of the double helical wires. A new model which considers the double-helix structure in multi-strand configuration was presented by Xiang *et al*. (2015) to estimate the local deformation and stresses in the wires subjected to axial tension and axial torque.

Table 2: Main degradation mechanisms of steel wire rope

Degradation mechanisms	Main Causes	Dominant parameter	Application areas
Tension-tension fatigue	Changes in the axial tensile loading	Tensile load range	Lifting and hoisting application including mine hoisting.
Bending-over-sheaves fatigue	Local changes in wire curvature as the rope. adapts to the radius of a sheave or drum	The D/d ratio (the ratio of sheave diameter to rope diameter), Tensile load	Lifting and hoisting application.Mooring ropes
Free bending fatigue	System dynamics or lateral oscillation	Tensile load	The cables of cable-stayed suspension bridges
Torsion fatigue	Absence of restriction from rotating by virtue of the attachments at either end, No compliance of the restraint	Twist amplitude	Moorings of floating offshore systems, Lifting and hoisting application
Fretting-fatigue	Friction between contacting wires	Coefficient of friction	All rope application
Corrosion	Temperature, pollutants in the air and water.	Water temperature	Mooring ropes. The cables of cable-stayed suspension bridges
Wear	Friction between wires; Bending of the rope	coefficient of friction; bending stresses over sheaves or drums	Lifting and hoisting application Mooring ropes

On the other hand, some researchers have adopted the finite element method to get the results at any specific point of the generated model. An early finite element approach was given by Jiang and Henshall (1999) in which they tried to analyze the termination effects and the frictional behavior of a wire strand. They, thereafter, presented a concise finite element model for a simple straight wire rope strand (Jiang and Henshall, 1999) and for a wire rope with three layers strand (Jiang *et al*., 2000) taking into consideration the helical symmetry features. In their work, they compared the results of their finite element model to those reported by Costello (1997) and Utting and Jones (1988)'s theory. Later on, in another work they looked into the contact problem of simple wire strand using a finite element model (Jiang *et al*., 2008). Then, they discussed the influence of several geometric parameters of the rope on the resulting contact stresses. Sun *et al*. (2005) have presented a finite element model for a simple straight strand in order to solve the contact problem between the helical wire and the centre wire of multilayered strand. Thereafter, Ghoreishi *et al*. (2007) developed and validated an analytical model for steel wire strands under axial loading with infinite friction between the wires and the core. Imrak and Erdonmez (2010) developed a finite element modeling of wire ropes with IWRC by using the double helical geometry. They provided in their study a division of the percentages of the applied load wire by wire. They concluded from their study that the center wire of the core strand carries the major portion of axial load.

Main degradation mechanisms

Fatigue: Fatigue is a process which occurs when a material is subjected to repeated loading and unloading. It initially takes place in the areas where the stress concentration exists. The nominal maximumstressvalues that cause such damage may be much less than theultimate tensile stress limit of the wire rope. Generally, wire ropes function at high stress levels and are almost invariably subject to fluctuating loads and cyclic deformations. Some serious damages, such as those caused by lightning strikes are sufficient to warrant discard. However, over the long-term, in the case of well maintained and exploited ropes, the fatigue plays an essential role. In running ropes, a significant source of fatigue is the repeated bending as ropes run over sheaves (Chaplin, 2005).

Steel wire ropes are comprised of an assembly of steel wires. Basically, the steel used has an elevated strength thanks to its high carbon content and its fine grain structure. The division of the load bearing capacity between many parallel wires assures the essential combination of high axial strength and stiffness with bending flexibility. In fact, the helical nature of rope construction causes a radial load component under applied tension. This leads to normal contact stresses between wires such that broken wires rapidly recover their share of applied load on a given length from the break; this point is pretty important to ensure that the wire rope is tough in the sense that it is tolerant to have local damages, particularly in the case of broken wires (Chaplin, 1995; Torkar and Arzensek, 2002).

In practice, in each solicitation, wires go through a micro damage which has no consequences whatever on the wire rope in the short run. However, rope failure occurs when the accumulation of wire breaks in a locality is sufficient to precipitate total failure. An approach was adopted by Palmgren-Miner regarding this to evaluate the cumulative effect of cycles at different levels of loading until the breaking of the material; it is called: "the palmgren-Miner cumulative damage approach'' and which also works well with wire ropes.

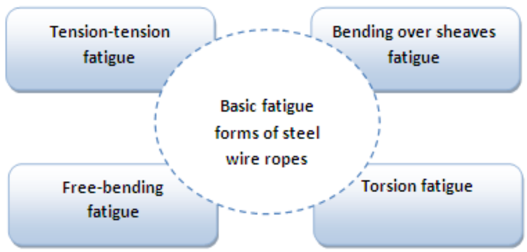

Fig. 3: Basic fatigue forms of steel wire ropes

The basic fatigue forms of ropes can be grouped under four headings as illustrated in the Fig. 3: tension-tension fatigue, bending over sheaves fatigue, free bending fatigue and torsion fatigue.

Tension-tension fatigue: This type of rope fatigue is generally the simplest involving stress fluctuations that result from changes in axial tensile loading. In fact, even for a static rope which does not work on a sheave or drum has a limited lifespan. It is found considerably in every application in which attached mass changes, acceleration and deceleration are the principal sources of axial load fluctuation, such as mooring ropes, lifting and hoisting application. The rope quality issue relates to the variation in load sharing both between wires and along any one wire which derives from the dynamics of the manufacturing process (Chaplin, 2005). This can significantly influence the relative performance of initially identical ropes (from different makers, or from different lengths) along with affecting fatigue life by an order of magnitude (Chaplin, 1995). The quantitative aspects of this functionality of rope manufacture were carefully explored by Evans *et al.* (2001). Without forgetting the beneficial effects of overloading on the rope lifespan which by generating a uniform load distribution, can improve the tension-tension fatigue endurance, notably in a rope of initially poor quality. In addition, it should be ensured that the terminations are correctly applied so the rope performance does not get affected during their employment.

Several tension-tension fatigue test studies have been performed on steel wire ropes. Matanzo (1972) evaluated the effect of several parameters such as rope construction and environment as well as the effect of the applied mean load and the tensile load range on this type of fatigue. He concluded that, the most dominant parameter is the tensile load range. Fatigue tests have been made by Hanzawa *et al.* (1981) on steel wire ropes of which the results showed that the cuts in the free length of wires occur on high stress whereas those in sockets occur on low stress and they are due to stress concentration. Hobbs and Ghavani (1982) have presented their fatigue testing results that were made on multilayer strands. They have concluded that the number of cycles of the first break of the wire until the total failure of the rope increases in line with the number of wires of which the rope is composed. Chaplin and Potts (1988) have published a synthesis report on fatigue testing made in England in the eighties on ropes that are dedicated to offshore applications. Zhang and Costello (1996) on the other hand have shown interest in the most constraints wires in the rope and in calculating their life in order to give a lower bound of the fatigue life of the entire rope. Siegert (1997) has studied fatigue mechanisms which represent the main cause for the wire's breakings in guying ropes. He relied on numerous experimental results in order to suggest a criterion predicting the initiation and the endurance of fatigue cracks in interwire contacts. Giglio and Manes (2003) reported several analytical formulations to estimate the state of fatigue in internal and external wires of steel wire ropes for aircraft rescue hoists. From the tests that they have performed, they found that for high oscillation angles, there was appearance of internal cracks but they are not observably visible to the eye. These remarks were confirmed by other experimental tests (Giglio and Manes, 2005) which showed that the last strands which break are substantially those constituting the external layer of the wire rope which is the least stressed. Urvoy *et al.* (2005) performed tests to compare the contact fatigue of galvanized, lubricated and virgin (uncoated and non-lubricated) wires. These tests allowed them to quantify the benefits of the zinc coating and the presence of lubricant on the endurance limit and thus on the wire rope's fatigue life. On the other hand, Meksem (2010) carried out some tests on accidentally damaged ropes and on others which are damaged by fatigue. These tests showed that a rope which incurs an accidental damage loses its strength much faster than that which incurs damage by fatigue. He thus concluded that an accidently damaged rope is more dangerous than a rope damaged by fatigue.

Bending-over-sheaves fatigue: Bending over sheaves fatigue is a topic which was object of most published wire rope endurance research and of considerable experimentations done by Muller (1961), Gibson (1980), Ridge *et al.* (2001) and also by Onur and Imrak (2011). Wire ropes working dynamically in bending (i.e., bending over sheaves) always have a limited lifespan. The primary sources of the stress fluctuations in this mechanism are the local changes in wire curvature as the rope adapts to the radius of a sheave or drum (Chaplin, 2005). Whenever, a rope section passes over sheave it makes a complete bending cycle (passage from a straight state to a flexed state and a return to a straight state). The number of bending cycles which a rope is capable of making in a hoisting system depends on several parameters. Amongst these parameters are those which tend to influence more on this type of fatigue: The D/d ratio (the ratio of sheave diameter to rope diameter) and tensile load.

The bending life of a rope running on and off a multi-layer winch drum may be far too much reduced compared to that of a rope running over a sheave having a similar D/d ratio. An experiment done at the University of Stuttgart, simulating a rope winding on and off drums on crane, showed that endurances may be reduced by factors as high as 50 (Chaplin, 1994).

The rope construction plays a relevant role in bending fatigue namely because of the response to transverse loading on sheaves or drums. In ropes that have within their construction 'equal layers' and a single layer of outer strands, there is a transmission of forces between wires by line contacts, while in the case of compound strands; the transmission involves point contacts between wires. In the latter case, this tends to induce internal wire fatigue failures that are not externally visible (Chaplin, 2005). This characteristic must be properly taken into account as for the definition of inspection policies and the rope discard criteria. In addition to this, there is also the lubrication criterion which basically says that a well lubricated rope will attain a higher number of bending cycles than that of a poorly lubricated rope of the same design.

This form of fatigue loading has been the subject of different wire rope endurance research. Ridge *et al*. (2001) evaluated the effects of simulated degradations (wire breaks, corrosion, abrasive wear, plastic wear, slack wires, slack strands and torsional imbalance) on the fatigue endurance of steel wire ropes subject to repeated bending at constant tension. Torkar and Arzensek (2002) performed bending fatigue tests on wires located in outer strands of 6*19 Seale rope. Feyrer (2007) presented in his book a literature review and experimental test results of steel wire ropes subjected to Bending over Sheaves (BoS) fatigue. Urchegui *et al*. (2008) inspected wear evolution in a 6*19 seale stranded rope subjected to bending fatigue. Erdonmez and Imrak (2009) made a realistic structural model of a strand bending over sheave using the finite element method. They deduced from the numerical results that the maximum stress and maximum displacement positions of the strand were respectively positioned over the upper midpoint of the sheave and at the fixed edge of the strand. Other researchers investigated the effects of various parameters (rope core type, tensile load, sheave diameter, bending length, sheave geometry and material, lubrication, zinc coating, winding angle) on the BoS fatigue life of steel wire ropes. In this context, Experimental studies have been performed by Onur and Imrak (2012) to show the effects of tensile load and sheave diameter parameters on BOS fatigue lifetimes of 6*36 warrington-seal steel wire ropes. They concluded that the BoS fatigue life reduces as tensile load increases and as the sheave with smaller diameter is used. Giglio and Manes (2003) searched for the effect of winding angle parameter between the rope and the sheave on the bending fatigue life of non rotating ropes used in aircraft rescue hoists. Gorbatov *et al*. (2007) examined effects of some parameters (core type of wire rope, lubricant type and tensile load) on the bending fatigue life of 6*36 warrington-Seale rope. Argatov (2011) got interested by fretting wear degradation of wires under cyclic bending of wire ropes. Kurashov *et al*. (2008) conducted comparative tests to evaluate bending fatigue life of steel wire ropes with various types of core. Zhihui and Jiquan studied fatigue failure behavior of wire ropes caused by bending over sheave, together with analyzing damage mechanisms of wire rope caused by fleet angle and angle of wrap.

Free bending fatigue: The rope's bending fatigue is not always bound to their passage over drums or sheaves, for there is also the free bending fatigue case which involves fluctuating bending deformation of the rope without getting in touch with other bodies. This category of fatigue is typically excited by system dynamics and it can be significant in the case of lateral oscillation of the cables of cable-stayed suspension bridges (Siegert and Brevet, 2003). The developed curvatures in this mechanism are less serious than those found in ropes running over sheaves or drums in which frequency is much higher. This type of bending often takes place adjacent to a termination in fixed rope applications, introducing additional local problems and life may then be a concern (chaplin, 2005). In this respect, some research has been performed on the fatigue behavior of ropes in free bending near terminations. Hobbs and Smith (1983) have both examined the effects of small amplitude free bending near socketed terminations under constant tension. On the other hand, Lucht and Donecker (1982) proposed the use of long plastic boots at mooring rope terminations so minimizing the effects of free bending fatigue. Hobbs and Smith (1983) carried out a series tests on spiral strand mast guy ropes which were subjected to a cyclic transverse displacement at the centre. It has been deduced that wire breaks started in outer wires and then made their way to the second layer leading to total failure of the strand. In another research, Raoof and Hobbs (1984) more precisely stated that the first wire breakages invariably occurred not at the extreme fiber in bending terms but rather the wires very close to the neutral axis.

Torsion fatigue: The construction of wire ropes with a group of combined wires so they share the tensile load, results in overall properties that combine axial strength and stiffness with bending flexibility. One of the consequences of this construction is that the rope has also a low torsional stiffness which can lead to low natural frequencies for torsional oscillations. If such oscillations are excited and have the opportunity to achieve high amplitude this can lead to local "de-stranding" of the construction and if the line slackens the de-stranding will be followed by kinking of individual strands (Chaplin and Potts, 2008). This example of torsional fatigue can be found in the moorings of floating offshore systems with hybrid mooring lines (Chaplin *et al*., 2000). A failure analysis of a broken multi strand wire rope removed from an offshore platform crane was performed by Shaiful and colleagues. They concluded that the large size wires were fractured by cyclic torsional stresses as characterized by the presence of fatigue cracking originating from the outer surface of wires. Whereas the smaller wires were fractured in a ductile manner under excessive load after the larger wire broken out due to the fatigue mechanism. Another consequence of the geometry of several categories of rope would be the fact that, if a rope is not restricted from rotating by virtue of the attachments at either end, or if the restraint is not compliant, there will be rotation until equilibrium is achieved. Coupling components with different tension-torsion characteristics can lead to counter rotation and this can be damaging.

There are certainly other rope constructions specially designed to reduce this tendency to rotate but these latter often have other disadvantages that can include a propensity to break up internally (BSI, 1986; Dohm, 2000) and an expensive cost. This type of ropes is called non-rotating ropes; they are composed of multiple layers of strands wired in opposite direction from one layer to the other. They prevent the rotation of the suspended load under important hoisting heights. The geometric composition of non-rotating ropes is chosen so that the turning torque of the steel cores and the outer strands cancel each other in a wide load range. It avoids in this way the kinking of ropes. In certain applications and particularly when the components presenting different torsional characteristics are joined end to end, torsional oscillations may be generated in response to tensile fluctuations. This example of torsional fatigue is a particular concern in mooring lines which combine six-strand wire rope and torque-balanced polyester ropes (Bradon *et al*., 2005). In this specific application, the rope can experience torsional mode of fatigue for which the prevailing parameter seems to be the twist amplitude.

Fretting fatigue: Wire ropes function at high stress levels and are almost invariably subject to fluctuating loads and cyclic deformations. Given time and a sufficiently high fluctuation in stress range, fatigue is inevitable. However, a wire's fatigue is not always related to stress variation, for there is generally another process which worsens and accelerates fatigue and makes it condensed in well determined areas. This process is known as: fretting fatigue. It results out of the friction between neighboring wires leading to a reduction of the steel wires fatigue lives and an acceleration of the rope's failure. Due to cyclic loading, the interwire contact area increases. Therefore the interwire friction generates more heat and hence a decrease in the viscosity of the grease, facilitating thereby its exhaust to the outer layers of the rope. At this time, the fretting wear between contacting wires increases and the sample degradation accelerates until complete rupture. Thus, the phenomenon of fretting fatigue plays an important role in the degradation of the ropes in use.

Several researchers conducted studies for the determination of fretting parameters of wire ropes. Further to the study that was made by Hobbs and Raoof (1994) and in which they have noticed that there were more breakings on quasi-punctual contacts than on linear contacts, they have concluded that the smaller the contact area, the higher are the contact stresses. Raoof and Kraincanic (1995) had studied the distribution of Von Mises stresses in two wires of successive layers in punctual contact with fretting. Brevet and Siegert (1996b) showed in their work that the interwire fretting core-wires leads to the initiation of cracks localized in the lines contact. They also observed that the fatigue breaks are located in the bending plane. Siegert (1999) determined the normal contact load and relative displacement amplitude between wires in a multilayer strand. Nawrocki and Labrosse (2000) developed a finite element model of a simple straight wire rope strand based on a Cartesian isoparametric formulation. They demonstrated that it is the interwire pivoting and the interwire sliding which governs the rope response, respectively, for cases of axial and bending loads. In their study, Kumar and Botsis (2001) employed the linear deformation derivative results to obtain analytical expressions for the maximum contact stresses for the multilayered wire rope strands under tension and torsion. Sun *et al*. (2005) have presented a Cartesian isoparametric formulation to model a simple straight strand using the finite element analysis in order to solve the contact problem between the helical wire and the centre wire of multilayered strand. Thereafter, Ghoreishi *et al*. (2007) developed and validated an analytical model for steel wire strands under axial loading with infinite friction between the wires and the core. In the same year, a finite element analysis was performed by Virginie *et al.* (2007) on virgin and corroded wires in order to model the contact fatigue of steel wires of a rope already corroded using in their study the experimental device of fretting fatigue that was developed by Siegert (1997). They concluded that the shear stress and the hydrostatic pressure play a predominant role in the fatigue behavior ropes; the shear stress is at its utmost near the edges of the contact while the hydrostatic pressure is so in the contact center. Jiang *et al.* (2008) examined the contact problem of simple 1*7 wire strands using a finite element model. Meriaux *et al.* (2010) performed a fretting fatigue test using acoustic emission device in order to identify the crack propagation steps. Argatov (2011) used the method of matched asymptotic expansions to solve the nonlinear model interwire contact deformation and obtained the constitutive equations for a helical wire rope strand subjected to axial and torsional loads. On the other hand, Wang *et al.* (2012a) examined the effect of various kinematic parameters of mine hoist on fretting parameters of the hoisting rope.

Corrosion: The wire ropes, during use, are dynamically complex systems composed of numerous moving parts that operate in multiple environments (such as hostile environment). Not only are they subject to both internal and external abrasion, but they are also prone to the corrosive effects that reduce both the wire's load-carrying capacity and serviceable life. Filled by moisture or rainwater, this tank supplies the water penetrations through the fasteners which lead to an eventual corrosion of the rope. Corrosion is a chloride reaction process in which rate is increased by temperature, pollutants in the air and water. Corrosion of an unmaintained wire rope is not limited to its external surface but rather, attacks all the wires individually. The result is a constant reduction of the metallic area of each wire and the susceptibility of the wire to corrosion fatigue during bending over a sheave. Furthermore, deep corrosion pitting on the internal surfaces of wires can severely shorten their service life. However, the application of lubricants to working ropes provide a dual form of protection in that the friction between individual wires is reduced to minimum and the whole wire is preserved against the corrosive action of sea water.

The corrosive effects of sea water on wires that are immersed for lengthy periods of time have been an area of interest for a while. It has been observed that the rates of corrosion vary from location to another in the ocean when the wire in use is unprotected by either a lubricant or rust preventive. The analysis performed by the Woods Hole Oceanographic Institution and Grignard Chemical Company indicated that water temperature was the main factor involved in the accelerated corrosion rate that had been observed; Experimental investigations have been carried out by Suzumura and Nakamura (2004) who were interested in zinc dissolution rates of galvanized wires extracted from suspension bridge cables. The tests at different temperatures indicate an order of magnitude increase in dissolution rate from 5°C (considered typical for ground wire in deep water of the North Sea) to 30°C (representing the conditions at the Kumul terminal).

Research works have been developed to study the endurance performance of steel wire rope mooring lines in seawater. Lennox and colleagues conducted a study on totally and partially immersed wire ropes at Marine corrosion research laboratory in the warm waters off key West, Florida. They found that the galvanization protected the rope only for 12 months. Then, Seawater exposure tests on wire ropes were performed by Swam (1970). He reported the lives for different thicknesses of galvanized coating in a seawater environment. The 12 month exposure life concluded by Lennox and colleaues concurs with his results. British Ropes Ltd (1979) have chosen a number of samples from galvanized six strand mooring rope during its ten year service life as a mooring line and tested for the rope's residual breaking load. They thereby noticed that, in spite of the large loss in zinc coating on the outer wires of strands, the residual breaking load after 10 years' service was only some 6% less than the original breaking load and only marginally less than the manufacturer's rated. On the other hand, Rajan (1986) examined discard mooring ropes from exploration semi-submersible rigs and concluded that firstly, wires galvanization and good penetration by lubricant protect the rope to a wide extent from significant corrosion. Secondly, the sections of mooring rope which were continuously immersed in seawater were virtually free of external corrosive attack.

The zinc coating has a limited life essentially determined by its rate of dissolution. However, on an experimental word conducted by Li *et al.* (2012), it was indicated that a useful extension may be obtained by using alternative zinc-aluminum alloys as an alternative to zinc. Much longer term protection is more effectively provided by plastic sheathing which is practically applied only for spiral strand. In recent years, Dongsheng adopted the Acoustic Emission (AE) technology to monitor the fatigue damage evolution process for corroded and non-corroded steel wires. They noticed that the mechanical performance of corroded cables is changed considerably in comparison with non-corroded cables. Wang *et al.* (2012b) in their study, examined stress corrosion behaviors of steel wires in coalmine under different corrosive mediums by using Slow Strain Rate Tests (SSRT). On the other hand, repeated bending tests were performed by Sung on corroded wire ropes used in elevators using a bending fatigue tests. They concluded that an increase in accumulated corrosion fatigue and repeated bending cycles may yield a rapid decrease in fracture strength and an increase in the number of broken wires and therefore the decreases of the life expectancy of wire rope. Recently, Meknassi *et al.* (2015) carried out an accelerated test, to evaluate the effect of corrosion on the mechanical properties of steel wires. From the tensile tests on virgin and corroded specimens, they noticed a decrease in strength as function of immersion hours.

Wear: Amongst steel wires ropes main modes of degradation, there is wear. It occurs in two forms; internal wear resulting from friction between the wires of the rope and external wear resulting from the bending of the rope over sheaves or drums. The latter form is the most common in the majority of ropes applications. The bending stresses cause point contacts and much undue wear and directly shorten the safe working life of the rope. Generally, the abrasive wear takes place between the wire rope and the sheave and between the wire rope and the drum but the greatest cause of abrasion is often through interference at the drum. Another cause of severe wear in wire ropes is reverse bending over sheaves which reduces the life of the rope by approximately a half. It is to be noted that reverse bending refers to the bending of a rope over sheaves, first in one direction then in another. Moreover, in the case of sheaves that have become worn or in which the grooves have become irregular in shape, a new wire rope may be damaged and not work suitably. It is also more reasonable to renew the sheaves rather than to allow excessive wear on the wire rope for worn or damaged sheaves. In the hoisting application, one of the causes leading to severe rope wear is twisting of the hoisting rope. Once the rope is twisted and a hoist is made, the wear produced is equal to more than that produced from weeks of normal use. Therefore, the person in charge of hoisting operations should guard against twisting of the rope and should not allow a hoist to be made if the rope is twisted.

Table 2 represents the main degradation mechanisms of steel wire ropes after a period of service, their causes and their application areas.

Energy losses by friction and damping: Several demonstrations of friction in ropes are touched upon in literature. In his study, LeClair (1989) was interested in energy losses during the crossing of a monolayer rope over a sheave. The results of his study showed that the losses are reduced only if the outer wires get in contact with the core without, however, getting in mutual contact with each other which may be provided by an appropriate design of the rope. In the case of a monolayer coreless rope or a rope with fiber core, the external wires rub against each other, during axial loading, giving rise to energy losses. This very phenomenon was studied by Blakeborough and Cullimore (1984) in which they have analyzed the rope's hysteretic response during a cycle including loading and unloading. They have also determined interwire shifting which can represent the source of fatigue with fretting. An attempt to relate the internal friction due to twist to the damping properties of a bent cable was made by Vinogradov and Atatekin (1986). Huang and Vinogradov (1994) were interested in energy losses in a monolayer rope during cyclic bending in compelled curvature. They concluded that losses caused by dry friction occur due to the twisting and the bending of an individual wire and the energy dissipation is linearly proportional to bending curvature. They have also developed in another work a model based on dry friction losses during interwire sliding in axially loaded cables (Huang and Vinogradov 1996a, b).Their model showed that the energy losses are proportional to the cube of the axial tension and inversely proportional to the interwire friction forces. Lanteigne (1985) examined the response of multi-layered strand to the problem of interlayer slippage. Ramsey (1990) has sought to study interwire friction in multilayered strands under uniform extensions and twisting using the 'thin rod' model. Labrosse *et al.* (2000) investigated the frictional dissipation properties of axially loaded straight steel ropes. The numerical results indicated that a larger lay angle lead to a lower damping and the energy dissipated by pivoting friction is very small and negligible compared to other sources of dissipation. Other works have been conducted by Raoof and Huang (1991, 1992) on multilayer ropes to study the axial damping, torsional damping and damping under cyclic bending in a compelled curvature. In another research, Raoof (1991) developed a theoretical formulation to obtain upper bounds of single layer helical strand damping under cyclic bending to a constant radius of curvature. They later investigated the damping mechanism of axially multi-layered sheathed spiral strand under cyclic free bending. The results showed that the damping ratio decreases with the mean axial strain and the length of cable. Raoof and Davis (2006) conducted theoretical studies on the maximum axial and torsional energy losses of axially preloaded spiral strands.

CONCLUSION

Wire ropes are used for different applications in several industrial domains. As a result of its arduous service, the rope inevitably degrades during use. This degradation is more often due to the four following phenomena: fatigue, fretting fatigue, wear or corrosion that may occur alone or in combination. The sudden breaking of wire ropes can endanger people's health and safety and cause costly work stoppages. Thus, the accidents due to the failures of these ropes present the major concern and challenge for the design offices, especially if the cost is measured in terms of human lives. Therefore, for enhanced safety in hoisting and improved efficiency in rope utilization, a good understanding of the degradation processes is important in optimizing the potential rope life. In this study, the aim was to establish a literature review including different work research dealing with the main degradation mechanisms that affect the steel wire ropes after a period of service as well as their causes and loss of strength that these very mechanisms engender. This research has allowed us to shed light on a quiet interesting point which was not previously widely approached. It basically touches on the rope overloading beneficial effects on the fatigue life and its role in improving the tension-tension fatigue endurance. This point will be the subject matter of an ulterior analytical and experimental work.

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