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Engineering Failure Analysis 10 (2003) 223–235

ENGINEERING FAILURE ANALYSIS

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Bending fatigue tests on a metallic wire rope for aircraft rescue hoists

Marco Giglio*, Andrea Manes

Department of Mechanics, Politecnico di Milano, Via La Masa 34, 20158 Milan, Italy

Received 29 July 2002; accepted 24 August 2002

Abstract

During normal operation, the ends of helicopter rescue hoist ropes, to which a hook is attached, can be subject to bending stress caused by vibrations. This happens in the event of partial or total recovery of the hook into its lodging without a spring-loaded blocking system. The swinging of the rope end consequently causes bending of the rope near the terminal, with resultant fatigue stress that can lead quickly to breakage or damage of the rope. A series of alternating bending fatigue tests using a constant load, similar to those known as BoS (bending over sheave) tests, were carried out. These simulate the effective working conditions of a rescue hoist. This paper describes modifications to test machinery, the test method and the data obtained; statistical analysis of this data enabled us to make a rope life prediction which was then experimentally confirmed by run-outs on test ropes.

Keywords: Wire ropes; Sheave: Fatigue; Hoists; Aircraft

1. Introduction

Wire ropes, like ropes in general and also chains, are commonly used for traction load transmission. 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 investigate the behaviour of rope used on a helicopter rescue hoist. We analyse the circumstance in which the hook attached to the end of the rope has been totally or partially recovered into its lodging and is left free to swing. Incorrect hook lodging or insufficient pre-loading of the spring blocking system result in bending of the end section of the rope, which may then hit

* Corresponding author. Tel.: +39-02-399-47354; fax: +39-07-063-8377.
E-mail address: marco.giglio@polimi.it (M. Giglio).

1350-6307/03/$ - see front matter
PII: S1350-6307(02)00043-2

the guide wheels of the winch (see Fig. 1). Breakage and damage to rope without the application of any traction load, and therefore not otherwise explainable, have been attributed to this particular operating condition.

This wire rope, like all aeronautical components, must be optimised for weight; the rope has a safety factor of 5 on the static failure load (less than ropes for civil and industrial use) but must be replaced after 1500 complete lower-raise cycles under operating loads. It is, therefore, reasonable to assume that wear and damage due to vibrational swinging, even when the hoist is not in use, can lead to progressive and marked weakening of the resistant section. Assuming a constant preload (equal to the weight of the hook multiplied by an appropriate factor, which takes into account inertia forces), we studied the bending fatigue behaviour of wire rope during cyclically repeated swinging on the guide wheels, at a fixed alternating angle, in order to establish whether there exists an angular variation below which no damage to the rope occurs. The instrumentation used was designed and constructed specifically for these tests: it reproduces the swinging of the rope end and the consequent alternating bending fatigue stress of the rope at the sheave.

2. Background

We found no previous published studies concerning bending tests carried out with the methods used in this experiment. In published research on bending, rope has been wound off and onto a pulley of a given diameter and thus assumes the bending radius for a defined length. In the experimental tests performed, the bending radius of the rope on the sheave differs from point to point. Moreover, the alternating bending of the rope end induces a variable sign bending loading in every section of the rope (in every cycle), thus determining alternating fatigue stress of the wires in contact with the sheaves.

Fatigue tests on pulleys are foreseen under the Mil-W-84140 standard [1] for helicopter rescue hoist ropes. The rope (in our case, a rope with a nominal diameter of 3/16 inches), suitably conditioned, must

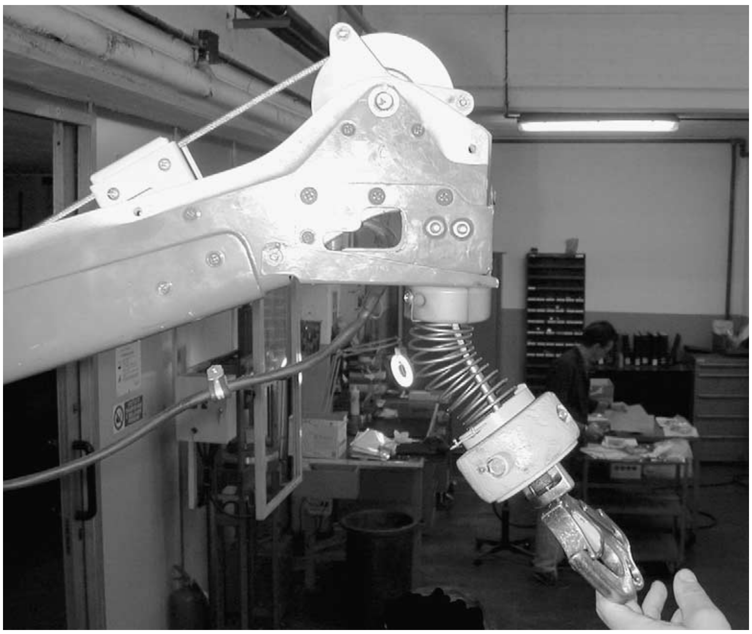

Fig. 1. Terminal bending.

perform 150,000 cycles on a pulley with a throat diameter of 1.781 inches (45.23 mm), with a preload of 22.5 pounds (100.08 N), and must subsequently have residual mechanical characteristics to allow a tensile strength of over 2000 pounds (8896.44 N). A similar test (in terms of test system), aimed at obtaining more detailed information on deformations in the wires making up the rope, is that carried out by Ridge et al. [2,3]. In this article, measurements are taken using strain gauges placed on the wires (thicker than 1 mm) of a complex section rope during winding over a test pulley. The diameter of the pulley is 18 times that of the rope and the preload is 20% of the tensile strength of the rope. It can be seen how, initially, when the rope is only axially loaded, wires that should give similar measurements actually display different strains (probably due to imperfections in the rope construction), and how these differences tend to disappear quickly during the bending fatigue tests. The amplitude and the shape of the strain cycles recorded do not change significantly during the fatigue test. The authors show experimentally how degradation and impaired quality due to wrong use, wear and the manufacturing process, considering the configuration and load used by Ridge et al., have only a limited influence on bending fatigue life, which depends mainly on the rope's nominal construction and on the rope/sheave diameter ratio. Nabijou and Hobbs [4] analyse, in a wide variety of cases, the fatigue behaviour of a rope wound on small drum, subjected to a preload proportional to its tensile strength (40–60%). Their study looks into the influence of parameters including the geometry of the groove in which the rope rests, the type of working of the pulley throat and the treatment carried out on the wires of the rope, as well as the effect of the diameter of the rope and of any lubricating or contaminating agents such as water or sand. It is interesting to note how two identical sheaves made by two different manufacturers produce different rope fatigue endurance. This confirms that fatigue life can also therefore depend on the microscopic characteristics of the surfaces with which the rope comes into contact. From Nabijou and Hobbs' work, it can be seen that for low load and high sheave curvature compared to the rope diameter, the predominant form of breakage is that due to wear caused by contact with the pulley. In the case of high load and small diameter sheave, on the other hand, the first type of wear to appear is that due to sliding between wires. The internal sliding between wires, in such a configuration, has also been observed analytically by Nabijou and Hobbs [5].

The two groups of articles outlined above are not conflicting but help provide a more thorough understanding of the complex phenomenon of BoS. The fatigue life and the consequent failure of a BoS-tested rope depend, unequivocally, on fretting (wire–wire, wire–sheave). Fatigue life seems, however, to be influenced mainly by the nominal load conditions and diameter ratios, and only slightly by particular unfavourable initial conditions or progressive initial yielding.

These conditions underline a substantial difference of the BoS from the axial fatigue load where notches and wear result in a considerable reduction in the fatigue life.

The importance of wear due to fretting was first highlighted by Starkey and Cress [6]. Their study was, in fact, the first to identify the existence of two different 'critical regions' in a rope: the first one relative to the linear contact between adjacent strands in the same layer, the second relative to local and, therefore, more dangerous contact between two wires belonging to two adjacent layers.

In static tests, the effect of wear has a considerable influence on tensile strength. De Silva and Fong [7] analyse the significant residual load reduction in ropes subject to wear both in the laboratory and during actual operation, and compare their results with current standards on the replacement of rope subject to wear, in particular ISO 4309. In a similar way, Kuruppu et al. [8] analyse the same reduction in mechanical characteristics and reach similar (but less drastic) conclusions to those of the study by De Silva and Fong. In both studies, however, it can be seen how a metallic area loss of a few percentage points results in tensile strength reductions of about 10%.

As previously stated, published research contains no studies on fatigue behaviour when the winding angle of the rope on the sheave is limited and when there is a very low constant preload, in other words, under the conditions applied in this test project.

3. The rope tested

The rope tested corresponds to Mil-W-83140 specifications as Type I, 19×7 stainless steel, preformed, non-rotating for helicopter rescue hoists. Cables of this construction consist of one core of seven strands of seven wires each for a total of 49 wires and an outer layer of 12 strands of seven wires each for a total of 84 wires. The inner core is lang lay, left lay; the outer layer is regular lay, right lay. The total number of wires in the cables is 133. The rope diameter is 3/16 inch (4.76 mm).

4. The test machine

4.1. Description of the machine before modification

The machine used for the tests, the METRO COM T6AL (test frequency 0.5 Hz, maximum angular variation 180°), was made to perform alternating torsion fatigue tests. The test ropes are placed between two clamps, one of which turns around its axis; the other is fixed (see Fig. 2). The machine was modified to be able to carry out the alternating bending tests. The machine's mobile clamping head was replaced by a rope terminal support specially designed for the tests, and a service structure, necessary to create the desired test conditions, was added.

4.2. Rope terminal support

The support allows both an optimal locking of the rope terminal and the creation of actual load conditions. The support (Fig. 3) was designed with the aim of maintaining the machine's ability to perform rotations with a maximum angular variation of ±180°. Two sheaves are mounted on the support, symmetrically placed near the machine drive shaft axis. They are an exact reproduction of the sheaves of a helicopter rescue hoist and, thanks to an assembly with two degrees of freedom, their position is the same as that which they have when in operation; during bending, the rope lies over these sheaves (see Fig. 4). The support is fixed to the test machine by means of a hub-shaft coupling with tangential key and blocking screw. The two sheaves between which the rope runs are mounted on shafts with Teflon bearings in order to limit the effects of wear; the sheaves have been hardened and polished to avoid the possibility of surface damage (see Fig. 5). A surface hardness test gave an HRC of 63. The support was designed and built with tolerances to guarantee:

- parallelism between drive shaft and sheave axis;
- perpendicularity between the axis of the cable and that of the sheaves;
- flatness of the support fixing hole axis.

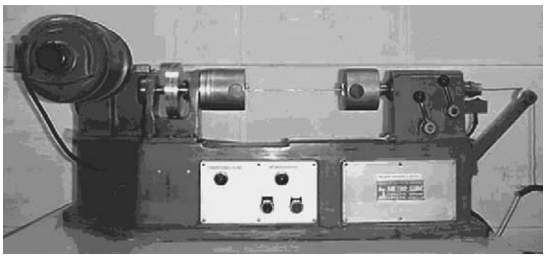

Fig. 2. METRO COM T6AL before modification.

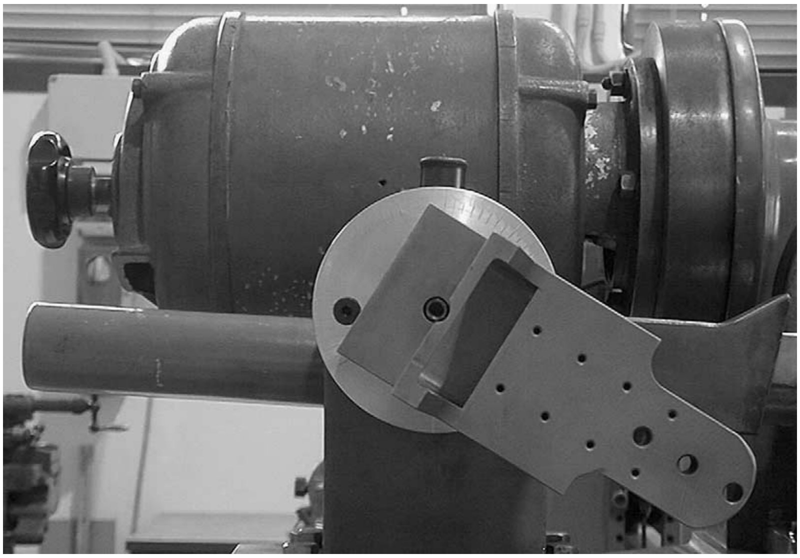

Fig. 3. Wire terminal support on the machine.

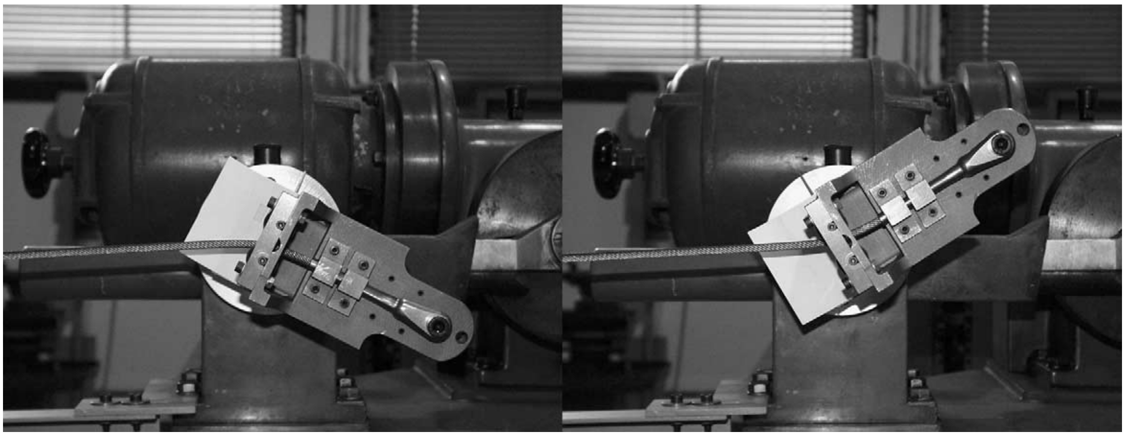

Fig. 4. Wire rope arrangement on the sheaves during a test.

4.3. Service structure

In order to apply an axial preload that did not influence the test zone of the rope bent over the sheave, a service structure was built. The structure is formed of a reticular beam frame, which is bolted to the test machine. This creates a single test structure, regardless of the type of support on which the machine is placed. The shaft around which the back gear pulley rotates was positioned on this service structure (see Fig. 6). The pulley must be placed so that when the angle of the rope end support is zero, the rope axis is perpendicular to the plane on which the two sheaves' axes lie and is equidistant from them. This position guarantees that the rope axis corresponds to the centre line of the sheaves, simulating the condition of a hanging rope and subject only to the force of gravity, a neutral condition in relation to the bending stress.

The construction of the service structure allows three degrees of freedom for the positioning of the pulley (see Fig. 7). Four grooves (two per side) allow pulley axis movement which is normal or tangential to the

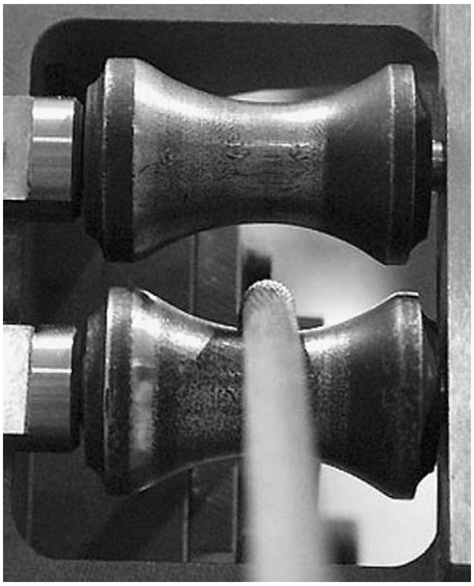

Fig. 5. Particular of the sheaves.

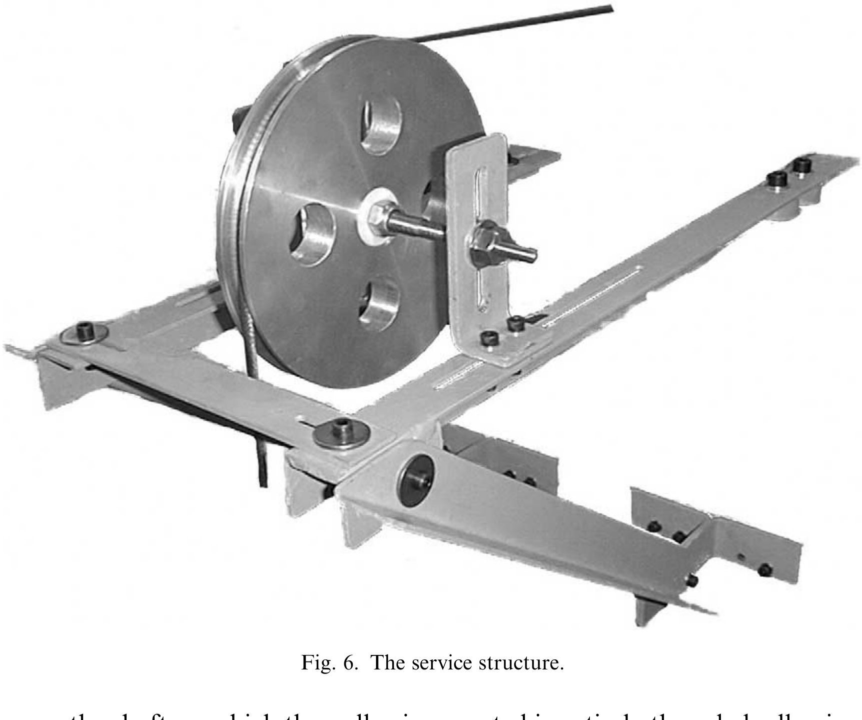

Fig. 6. The service structure.

rope axis. Moreover, the shaft on which the pulley is mounted is entirely threaded, allowing movement also in a binormal direction. The pulley is mounted on the shaft using a Teflon bearing that allows free spinning around the axis. The pulley is set to work with the support in a neutral position (zero angle) and with preload applied. The pulley axis is, furthermore, positioned as far as possible from the sheaves (compatibly with the end cross beam and the load connector) in order to increase the rope length for the test.

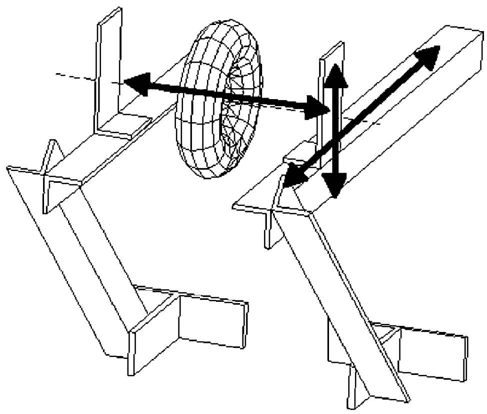

Fig. 7. Degrees of freedom of the service structure.

5. Test methodology

5.1. Test ropes

We used 1000-mm lengths of rope with a terminal at one end. The bending fatigue tests were carried out on rope sections close to this terminal.

5.2. Preload

The rope was subjected to a preload of 98.1 N, obtained by considering the mass of the hook that normally weighs on the terminal (5 kg) and a multiplying coefficient of 2 which takes into account the inertia force (see Fig. 8).

5.3. Terminal locking

The rope terminal was fixed to the service structure by means of a screw. Three screw holes on the service structure make it possible to carry out tests on sections of rope which are 1, 5 and 9 diameters (respectively 4, 24 and 44 mm) from the end of the terminal; for the purposes of this test, the mid-position was used.

5.4. Rope bending

The bending stress of the wire rope occurs through rope deformation near the sheave, that is the bending of rope sections next to the sheave with respect to an axis perpendicular to the rope axis. This condition of stress reproduces the real operating condition of swinging of the rope with its terminal free (with the hook suspended).

5.5. Rope failure

We consider the test finished when breakage of an entire strand on the outer surface of the wire rope occurs; we also reported in the test diary the progressive breaking of single wires, observed through visual inspection. The breakage of an entire outer strand, easily noticed during inspection, was chosen as the failure condition. Ropes for helicopter rescue hoists are generally subject to operating conditions that cause

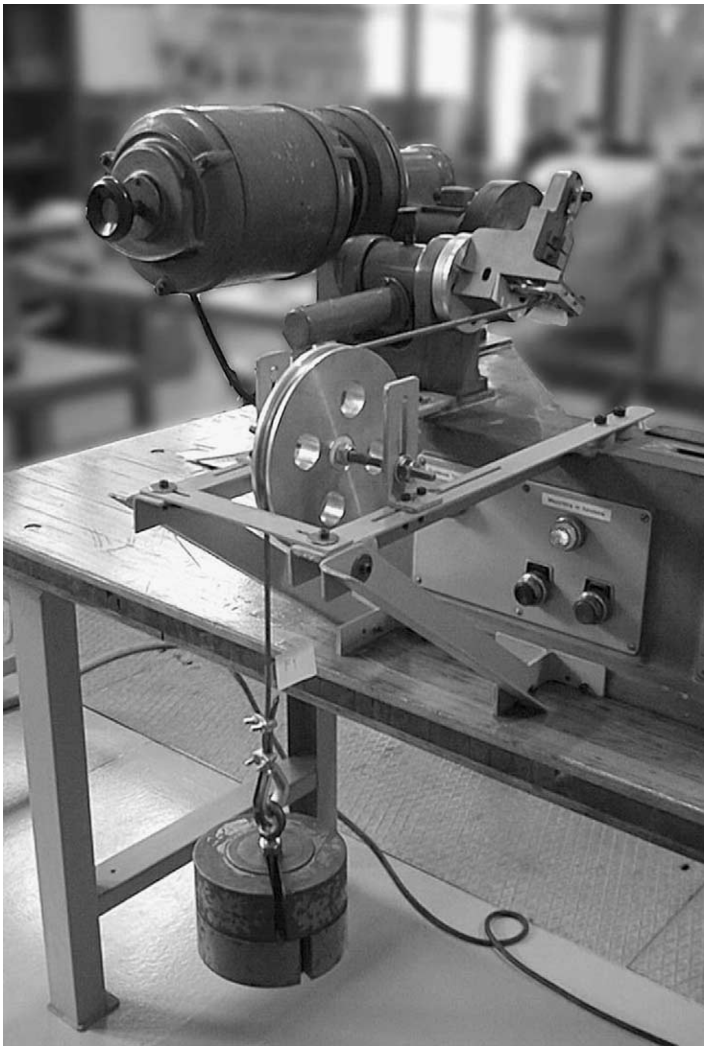

Fig. 8. Modified test machine during a test.

considerable wear of the outer wires because of contact with the sheave (and, of course, with other parts of the helicopter and with objects on the ground). The breakage of an entire strand is an indication of more serious and extensive failure due to bending on the sheaves (wire-wire fretting due to relative sliding, bending fatigue cycles on single wires), which is the subject of this study. The breakage of an entire strand in the outer layer is also considered in the rope replacement criteria of the UNI ISO 4309 standard.

5.6. Test rope inspection during testing

The machine does not have an automatic rope breakage monitoring system; consequently monitoring was carried out visually. Visual inspection of test rope was carried out at variable intervals, depending on the test angle. The interval was set so as to limit data error to a maximum of $\pm 5\%$.

5.7. Temperature control

During the first test, the temperature of both the test environment and the rope surface was measured in order to see whether the test induced overheating of the rope with consequences on its internal lubrication. We observed that the temperature increase is limited and does not, therefore, influence the lubrication characteristics.

6. Experimental results

6.1. Observations on rope damage

Before reaching complete strand breakage, progressive damaging of the wires in contact with the sheaves during the cycles can be seen; this damage leads to a progressive breaking of the wires involved. The breakage of the wires occurs in different ways, depending on the test angle. In particular, for angles from $\pm 60^{\circ}$ to approximately $\pm 40^{\circ}/\pm 35^{\circ}$, there is a progressive failure of the external wires in contact with the sheaves. The damage also involves adjacent strands and becomes more and more noticeable as the number of cycles increases. By increasing the angle, it is also possible to observe a progressive separation of damaged wires and strands, probably due to internal breakage. Furthermore, during the cycles, more and more marked sliding of the strands involved in the damage can be seen. In these cases, imminent failure of the strand can be expected. For smaller angles, the progressive failure become less and less marked, until it disappears altogether; or rather, there is an initial failure of some wires belonging to the strands in contact with the sheaves during the bending cycles but, subsequently, no further failure was observed for the duration of the test. In these cases, breakage of the strand is not foreseeable. In all the tests, there was a noticeable seeping out of lubrication near the sheave-rope contact points. Moreover, this lubrication seepage was greater where wire breakage had occurred. Test rope 4 (angular variation $\pm 60^{\circ}$) was tested until complete breakage into two parts, which happened after 16,847 cycles. This test rope was kept under constant observation in order to obtain indications about the damage mechanisms of the rope. We observed the following:

- 800 cycles after the breakage of one strand (the end of the first part of the test), we observed the breakage of another two surface strands, which were progressively expelled. This allowed us to observe considerable inner strand breakage;
- 4000 cycles after the end of the first part of the test, a lot of external strand breakage took place (at the point of maximum bending imposed by the sheaves, only two strands per side remained intact, near the ‘neutral axis’ of the rope section) and we noticed breakage of the inner strands involving nearly all wires;
- 5000 cycles after the end of first part of the test, there was complete breakage of the inner strands, which were progressively expelled. In the remaining cycles, resistance of the rope will be due to the external strands that are still partially intact.

From these observations, we can deduce that, at bigger angles, there is probably much more extensive, though not visible, inner breakage, going on in parallel with the visible, but less extensive breakage of outer wires.

6.2. Microstructural analyses

Microstructural analyses were performed on test rope 5 (angular variation: $\pm 40^{\circ}$; cycles of strand breaking: 235,553) using a scanning electron microscope. We observed crack nucleation zones of fatigue failure on the wires of the broken strand, and, in one case, two nucleation fatigue zones opposite each other on the same wire. In the section of the wire, one can see the zone affected by fatigue propagation (about 50% of the section) and the presence of microdimples in the rest of the section (see Figs. 9, 10).

6.3. Obtained results

The data obtained from the tests has been grouped into Table 1 as follows:

- *Test rope number*: progressive numbering, in chronological order, of the ropes tested.
- *Test angle*: rotation, in degrees, imposed on the rope terminal by the support. The value refers to the angular semi-amplitude and is therefore preceded by the sign $\pm$.
- *Number of cycles*: arithmetic mean values of the number of cycles recorded at test curtailment due to failure (last inspection) and at the penultimate inspection; this is the assumed number of cycles to failure.

$$\text{Number\_cycles} = \frac{\text{Number\_cycles}_{\text{last\_inspection}} + \text{Number\_cycles}_{\text{penultimate\_inspection}}}{2} \tag{1}$$

- *Percentage error*: maximum percentage error of the assumed number of cycles to failure compared to the real value.

$$\text{Percentage\_error} = \left(\frac{\text{Number\_cycles}_{\text{last\_isp}} - \text{Number\_cycles}_{\text{penultimate\_isp}}}{2}\right)\frac{1}{\text{Number\_cycles}}\cdot 100 \tag{2}$$

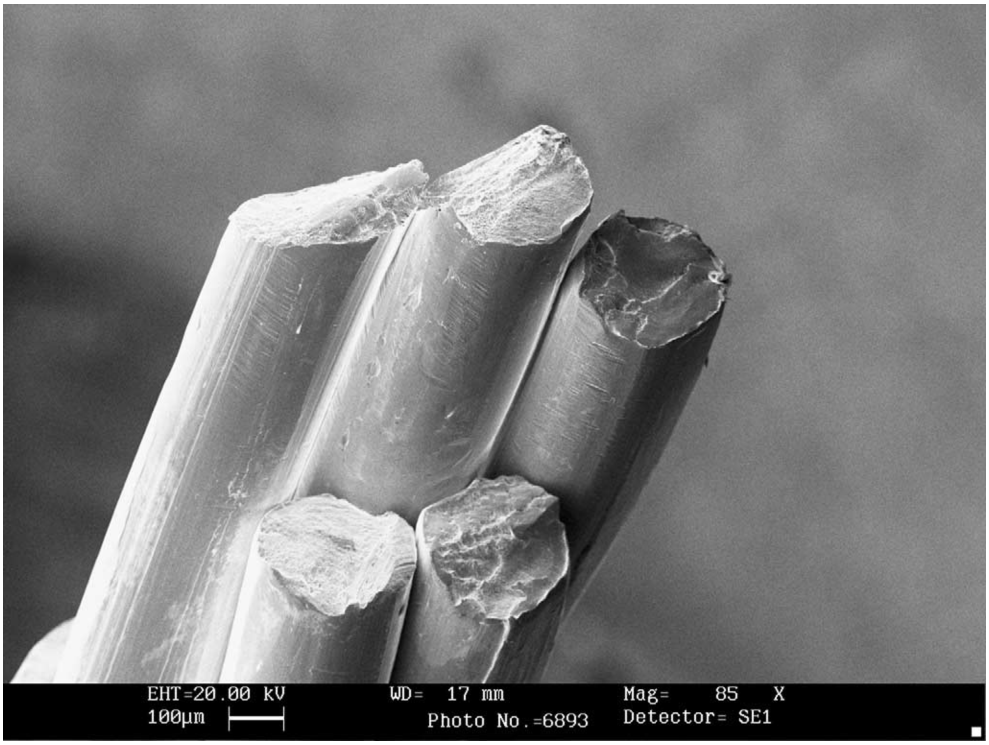

Fig. 9. SEM image of broken wires with crack initiation fatigue zone.

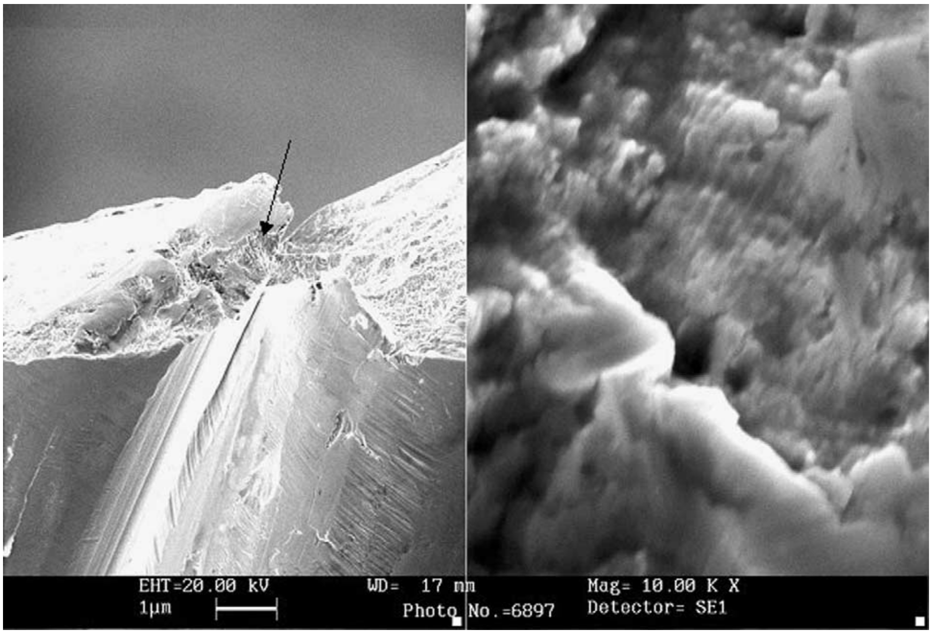

Fig. 10. SEM images of crack initiation fatigue zone near wire-wire contact.

Table 1

Test rope number	Test angle (°)	Number of cycles	Percentage error (%)	Condition of test ropes
1	±60	10,072	8.3	Broken
2	±50	47,731	0.7	Broken
3	±50	41,599	0.7	Broken
4	±60	10,660	0.8	Broken
5	±40	235,553	0.1	Broken
6	±40	117,668	N.A.	Broken
7	±35	289,220	4.6	Broken
8	±35	540,519	0.5	Broken
9	±30	> 1,300,000	–	Run-out
10	±30	> 6,000,000	–	Run-out
11	±40	339,497	3.5	Broken

- *Test rope condition*: condition of test rope at the end of the test. As previously established, the test was considered to have ended when breakage of an entire strand was observed on the outer surface of the rope. A duration of over 1,300,000 cycles was considered as the run-out condition, the endurance fatigue limit.

6.4. Statistical analyses of results

The data obtained from the tests was elaborated through a series of least-square method interpolations, as specified under the ASTM E739-91 standard. We plotted both linear and quadratic Angle versus N interpolation curves (number of cycles to failure) and, in both cases, with distribution of both semi-logarithmic [Angle-log(N)] and bilogarithmic [log(Angle)-log(N)] variables.

The curves were constructed using only broken test rope results, with the aim of describing the short-term behaviour of the rope. The run-out test ropes were used to confirm the predictions obtained from previous elaborations.

Moreover, every curve is characterised by a standard error, S, defined as:

$$S = \sqrt{\frac{\sum_{i=1}^{8}(\text{Number\_cycles}_i - \text{Number\_cycles\_estimated}_i)^2}{n}} \tag{3}$$

where: Number cycles$_i$ is the number of cycles obtained from the ith test; Number of cycles estimated $_i$ is the value obtained from the interpolation curve for the test angle of the ith test; n is the total number of test ropes (eight) used to construct the interpolation curve.

Through standard error optimisation, it is therefore possible to establish the best interpolation curve.

In particular, the quadratic law in semi-logarithmic scale [Angle-log(N)] was chosen; this curve makes it possible to describe short-term behaviour completely and foresees an endurance fatigue limit

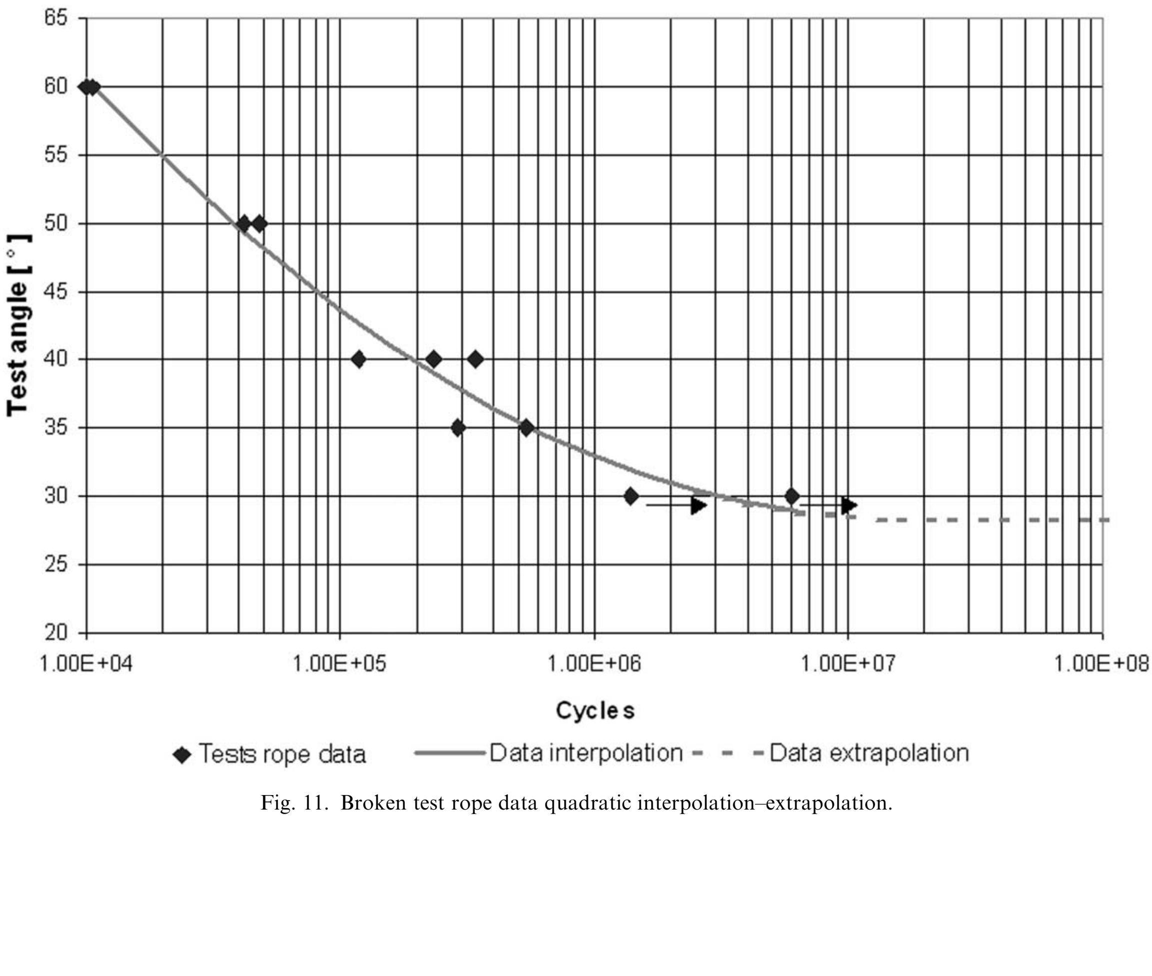

Fig. 11. Broken test rope data quadratic interpolation–extrapolation.

corresponding to an angular variation of $\pm 28°$ (see Fig. 11). The quadratic interpolation law has the following equation:

$$\begin{aligned} y &= ax^2 + bx + c \\ a &= 0.03117 \cdot 10^2 \\ b &= -0.4499 \cdot 10^2 \\ c &= 1.9906 \cdot 10^2 \end{aligned} \tag{4}$$

with $y = [°]$ and $x = \log(N)$ [cycles]

7. Conclusions

Through a series of experimental tests, requiring lengthy preparation and even longer completion, we confirmed the initial hypothesis that the particular circumstance in which the hook, mounted on the end of the rope, has been totally or partially recovered in its lodging and left free to swing, can cause damage to the rope. The loss of mechanical characteristics for limited test angles causes less and less damage and we found, by conservative extrapolation, an angle of $\pm 28°$, below which no damage should occur.

It was not possible to carry out internal strand failure analysis, even though observation of test rope 4 (tested until the complete separation of the rope into two parts) suggests that the breakage of inner strands not only happens but, at high angles, involves most of the inner rope.

Acknowledgements

The authors wish to express their appreciation to Ing. Riccardo Rossi for the design of the support, and to C4 laboratory staff at the Polytechnic of Milan for their assistance during the experimental work.

References

[1] Military specification MIL-W-83140. Wire rope: steel (stainless steel) preformed, non-rotating, for aircraft rescue hoist and cargo handling (winching). 1969.
[2] Ridge IM, Zheng J, Chaplin CR. Measurement of cyclic bending strains in steel wire rope. Journal of Strain Analysis 2000;35(6): 545–58.
[3] Ridge IM, Chaplin CR, Zheng J. Effect of degradation and impaired quality on wire rope bending over sheave fatigue endurance. Engineering Failure Analysis 2001;8(2):173–87.
[4] Nabijou E, Hobbs R. Fatigue of wire ropes bent over small sheaves. Fatigue 1994;16:453–60.
[5] Nabijou E, Hobbs R. Relative movement within wire ropes bent over sheaves. Journal of Strain Analysis 1995;30(2):155–65.
[6] Starkey WL, Cress HA. An analysis of critical stress and mode of failure of a wire rope. Journal of Engineering for Industry 1959.
[7] de Silva ART. Long Woon Fong, Effect of abrasive wear on the tensile strength of steel wire rope. Engineering Failure Analysis 2002;9(3):349–58.
[8] Kuruppu MD, Tytko A, Golosinski TS. Loss of metallic area in winder ropes subject to external wear. Engineering Failure Analysis 2000;7(3):199–207.