

Combined approach to damaged wire ropes life-time assessment based on NDT results and rope mechanics

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Abstract. Principles of strength assessment and life-time prediction of deteriorated wire ropes based on magnetic NDT technique are presented. The measured loss of metallic cross-section area due to abrasion, corrosion etc. and local wire breaks are treated as input data for mechanical model of rope structure. The rope is interpreted as a system with two degrees of freedom that enables to calculate the strains and stresses in each wire when the rope is subjected to tension, torsion and bending. Stress safety factor is considered as a generalized parameter that specifies the rope degradation and may be used for predicting the instant life-times during the rope operating history. The rope discard criterion refers to residual life-time calculated with respect to minimal allowable strength factor. Examples of integrity analysis of mine hoisting rope and jib crane rope under tension-bending fatigue loading are demonstrated. The residual strength estimates give the rope inspector further information that helps to make a valid decision on testing policy.

1. Introduction

The steel wire ropes used in hoisting mechanisms are expendable components. They should be renewed when examination shows that the strength of the wires has been depreciated to unsafe levels or after the assigned working life-time has passed. The life time of wire rope depends on the hoist type, the materials, design and construction of the rope, how it is used to lift cargo and the environment it works in. It can either be required by international conventions or selected according to the rope manufacturer's recommendations.

Predetermined wire ropes discard criteria belong to following main groups. First one refers to empiric fatigue life-time regression model that defines the ultimate number of tension/bending cycles as function of operating parameters [1]. That sort of expressions may be used for fatigue life prediction of idealized rope at design stage of the load lifting machine.

Second group implies discard standards related to limit values of typical defects, most often to limit number of wire breaks on a reference rope length [2]. These criteria are used if any diagnostic information about the rope damage is available. This approach is suitable for individual rope life-time prediction during actual operation.

Evident dependence between the number of fatigue cycles and amount of broken wires was found out by laboratory tests in special loading conditions [1]. But relations of this kind are of a little use in practice because of the multitude of factors acting on the rope endurance in real duty. As a result it is difficult to associate the on-line diagnostic information with the generalized life-time formulae.

Magnetic rope testing is the diagnostic method used most commonly for wire ropes [3]. Magnetic flux sensors enable to detect two kinds of rope defects – distributed losses of cross-sectional metallic

area (LMA) due to abrasive/corrosion wear and localized faults (LF) such as wire breaks. These data correlate with the endurance of degraded rope, but they do not indicate its strength in the quantitative sense. The question is that standard discard criteria do not account for combined action of that sort of defects on rope's strength. Furthermore, LMA and LF rates may differ significantly so it is hard to predict the life-time of the rope and make decision on its discard by two diagnostic indicators. The solution consists apparently in relevant interpretation of NDT data from the strength point of view.

Aim of study is to develop a new way of looking on wire ropes discard problem. A combined approach lies in considering the LMA and LF charts as input data for applicable rope's mechanical model to obtain the generalized parameter that specifies the rope degradation rate varying in time. The stress safety factor seems to be an appropriate indicator for estimation the technical state of degraded rope. It can be used for planning the test periods and for predicting the instant life-times during the operating history of individual rope. In this way the assumed discard criterion refers to remaining life-time calculated with respect to permissible strength level of deteriorated rope under investigation.

Real life duration problems have, as a rule, a probability meaning. For the lack of individual ropes failure statistics and prior probabilities of service conditions this study is restricted to deterministic life-time prediction approach.

2. Elements of rope mechanics and strength analysis

The steel wire ropes theory of Glushko-Malinovsky [4] is a background of the rope strength assessment. The constitutive equations of rope treated as system with two degrees of freedom are derived from Kirchhoff thin bar relationships. Mechanical state equations of straight ropes connect a tensile force T and torque M with generalized axial deformations of the rope – relative elongation ε and relative angle of twist θ :

$$\left. \begin{aligned} T &= C_{11}\varepsilon + C_{12}\theta \\ M &= C_{12}\varepsilon + C_{22}\theta \end{aligned} \right\}, \quad (1)$$

where C_{11} , C_{12} and C_{22} are the effective stiffness coefficients of the rope considered as a heterogeneous structure. They depend upon the wires stiffness and helixes geometry of wires and strands. Expanded expressions for stiffness parameters, strains and stresses are rather complicated so we shall note only the general procedure of strength assessment.

The rope deformations ε and θ are determined from equations (1) for given loads T , M and known stiffness values C_{jk} . These deformations are double-transformed to strand lay axes and wires lay axes. The tensile, bending and torsion strains and corresponding normal σ and shear τ stresses are evaluated in helix co-ordinate system of each wire. The combined stress state in wire is reduced to uniaxial equivalent stress σ_{eq} by proper strength criterion e.g. $\sigma_{eq} = (\sigma^2 + 4\tau^2)^{1/2}$. The stress safety factor relative to the wire ultimate tensile strength σ_u is defined as that:

$$n_s = \frac{\sigma_u}{\sigma_{eq}}.$$

For ropes working on sheaves and drums the maximal resulting normal wire stress σ is a superposition of ordinary tensile stress σ_t , bending stress σ_b due to wire curvature on sheave surface and secondary tensile stress σ_{ts} caused by constrained displacement of different wire layers [1]. The bending stress σ_b may be estimated as following:

$$\sigma_b = \frac{\delta}{D} E \cos^2 \alpha \cos^2 \beta.$$

In this equation, δ is the wire diameter, D is the middle curvature diameter (diameter of the rope axis bent over a sheave), E is the elastic modulus of material and α, β are the helix lay angles of wires and strands respectively.

The secondary tensile stress σ_{ts} depends on multitude of rope parameters therefore its detailed expression is highly complicated. In practice the simplified calculation for the case of uniformly bent strands may be carried out by formula

$$\sigma_{ts} = \sigma_t \left(e^{\mu(\varphi_0 - \varphi)\sin\alpha} - 1 \right).$$

In this equation σ_t is the ordinary tensile stress, μ is the friction coefficient, α is the wire lay angle, φ is the wire winding angle and φ_0 is the winding angle for that the secondary tensile force is zero. This angle is a little greater than $\pi/2$.

When the wire ropes are subjected to fluctuating loading during their service life (e.g. the ropes running over the sheaves) the fatigue endurance must be taken into account [5, 6]. If characteristic stresses of loading cycle are constant in time and the endurance limit exists, the fatigue safety factor n_f is entered as

$$n_f = \frac{\sigma_{-1}}{k\sigma_a + \psi\sigma_m}. \quad (2)$$

Here σ_{-1} is the reference fatigue endurance at symmetrical cycle; σ_a, σ_m are the stress amplitude and mean stress respectively, k is so-called effective stress concentration factor and ψ is an empirical tangent factor of the straight line in Haigh's diagram. For lack of proper data the factor k has been roughly estimated by finite element simulation. Its value was varied from 1.02 to 1.05 for non-damaged (new) ropes and from 1.1 to 1.6 for ropes with abrasion/corrosion and wire breaks.

When tensile stress σ and shear stress τ are combined the resulting fatigue safety factor follows the rule

$$\frac{1}{n_f^2} = \frac{1}{n_\sigma^2} + \frac{1}{n_\tau^2}.$$

The partial safety factors n_σ and n_τ are calculated from (2) for tension/bending and torsion separately.

In case of unsymmetrical stress cycle the ultimate strength may be attained, so the actual safe state of the structure should be characterized by the minimal factor

$$n = \min(n_s, n_f).$$

The required rope safety factor is suggested as a minimal value of n around all wires according to "weak component" hypothesis [5].

3. Assessment of damaged rope strength using magnetic NDT data

Above mentioned procedure may be carried out to calculate the safety factor for damaged rope. In this case one needs to evaluate all structure parameters for the prescribed distribution of rope defects. This way reveals two main features when magnetic NDT data are available.

Input parameters for mechanical strength model – the measured metallic cross-section loss ΔA and number of wire breaks B – are varying along the rope line with operating time. This changing is specified by LMA- and LF- charts being recorded from periodic magnetic inspections. It should be noted that diagnostic parameters ΔA and B are the generalized indexes of degradation for particular rope cross-section. As a matter of fact they are of a random nature and do not account for the distribution of faults over the wires. So the statistical modeling of wear locations in the rope cross-section is performed and the residual strength factor is calculated as a probabilistic assessment. The details of the Monte Carlo simulation are described in [7].

Relative strength loss $\chi(x,t)$ in the rope cross-section with the longitudinal co-ordinate x at operating time t is defined by

$$\chi(x,t) = 1 - \tilde{n}(x,t)/n.$$

Here n is a stress safety factor of non-damaged rope and $\tilde{n}(x,t)$ is a similar strength indicator of damaged rope. Both ropes are proposed to work under the same conditions.

The true account of the combined effect of local and distributed faults on rope durability is unknown. So the statistical estimates of strength depreciation due to metallic-area loss $\chi_{\Delta A}$ and due to wire breaks χ_B are determined independently. The total strength loss $\chi(x,t)$ is evaluated by superposition

$$\chi(x,t) = \chi_{\Delta A}(x,t) + \chi_B(x,t).$$

The corresponding generalized strength parameter

$$\tilde{n}(x,t) = n(1 - \chi(x,t))$$

may serve as a theoretical indicator of rope technical state during operation.

4. Predicting the rope life-time

Minimal value of $\tilde{n}(x,t)$ along the inspected rope segment has the meaning of safety factor of deteriorated rope at operating time t . The safe state condition of the rope is given by

$$\min_x \tilde{n}(x,t) \geq [n]. \quad (3)$$

The permissible safety factor $[n]$ defines the rope's margin of survivability as for partially failed structure. It is an empirical value estimated from specified rope lifetime experiments or it may be set regarding corresponding normative rules [8].

When condition (3) does not hold, this signifies the actual rope's failure. The near future of degraded rope right now the last inspection depends upon answering three questions:

1) Whether to stop or to continue the work of the rope at the achieved operating time, factoring in recent testing history?

2) If the decision is to continue, at what operating time should the next examination be conducted and what value for safety factor is then expected?

3) What operating time does it left for the rope?

Life-time prediction method is based on the least-square extrapolation from several previous safety factor estimates to the 'vital' limit $[n]$. Details of algorithm are described in [9].

5. Examples

5.1. Cargo crane rope PYTHON 8xK19S+PWRC(K)

The rope has been operating under tension-bending fatigue loading. It was five times examined by magnetic tester INTROS. Rope diameter – 8 mm, sheave diameter – 350 mm, nominal tension – 10 kN, tensile strength – 2160 MPa. Any noticeable losses of metallic area were not detected. The wire breaks have been revealed only since the third inspection. The 3^d, 4th and 5th LF-charts are shown in figure 1. Processed LF-data were imported to the RopeStrength application and corresponding distributions of strength parameter $\tilde{n}(x,t)$ along the rope distance were evaluated (figure 2).

Strength parameter $\tilde{n}(x,t)$ has been calculated in rope cross-sections with given numbers of wire breaks by averaging over 100 samples with an assessment reliability of 0.997. Local faults indicate the interval where rope failure develops and will probably occur. The minimum values (marked by circles) may be adopted as implicit discard parameters of deteriorated rope. Also they serve as rope state indicators for planning the dates of next inspections and predicting the remaining life-time. The number of operating (loading) cycles is considered as the operating time t .

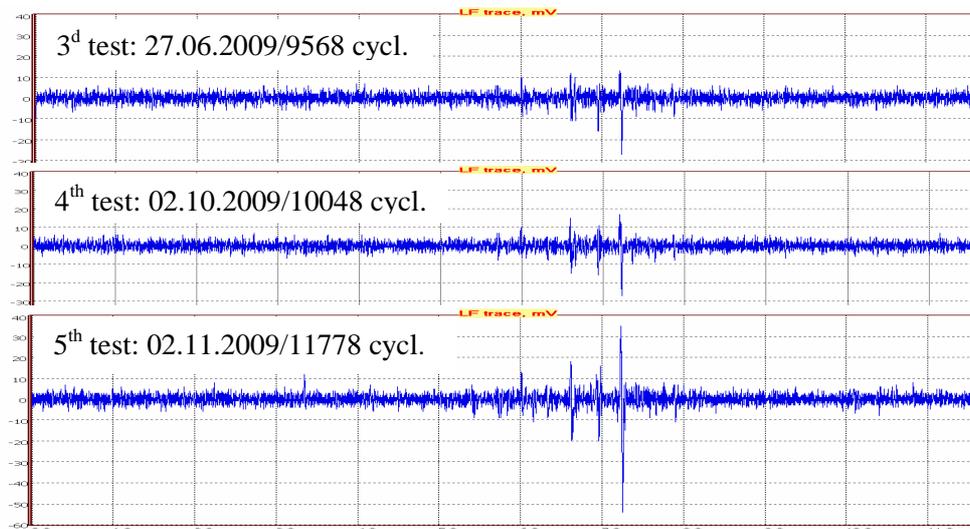


Figure 1. LF-charts for lifting crane rope PYTHON D8

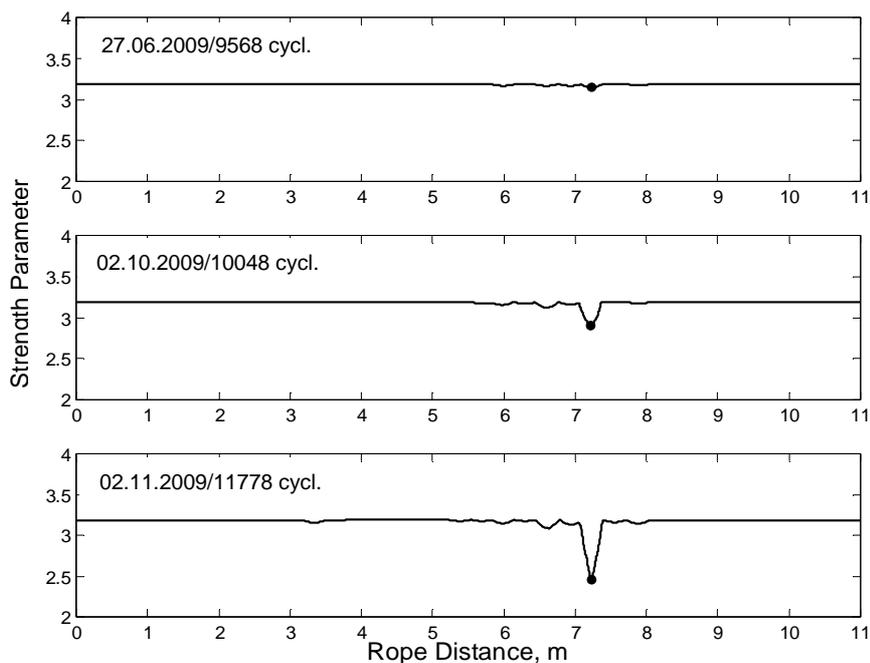


Figure 2. Time-quantified distributions of crane rope PYTHON D8 strength parameter

Figure 3 demonstrates the changes in both the minimum estimates treated as safety factors and expected values for planned inspections as piecewise-linear functions of operating cycles for all NDT history of the rope. The non-defective rope has the safety factor of 3.2. The permissible level $[n] = 1.5$ was evaluated with respect to normative LF-standards for rope type under examination [8]. Planned quantity of operating cycles to the next inspection is equal 13508 with expected safety factor of 1.91.

Predicted remaining life-time tendency of progressively degraded rope is presented in figure 4. Forecasting procedure starts after second testing when three safety factor estimates at least are available. The rope could have reached a defined discard condition of 1.5 in 2850 operating cycles after the last inspection. That rope was not reduced to failure so its real life-time is unknown.

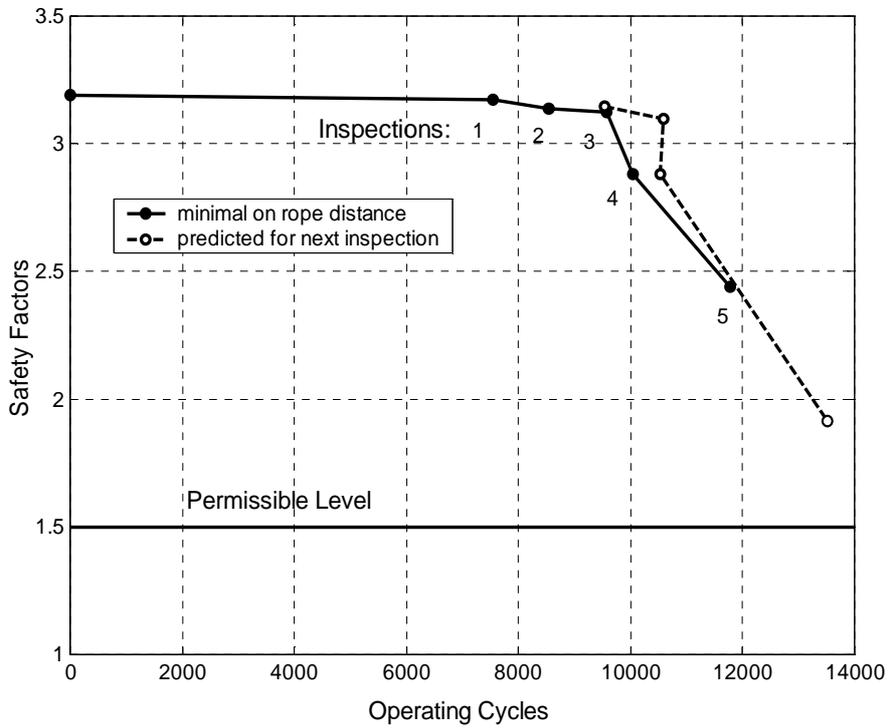


Figure 3. Safety factors and prospective estimates for rope PYTHON D8

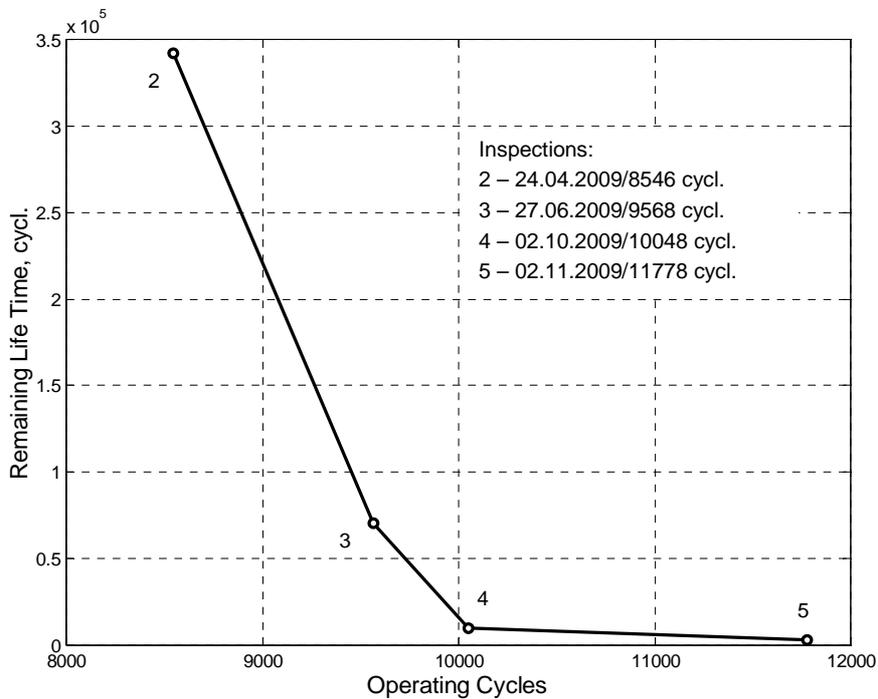


Figure 4. Remaining life-time estimates for crane rope PYTHON D8

Note that theoretical prediction should be considered purely as a suggestion for the rope inspector, who is the only person to make the final decision concerning the technical state of the rope and what future actions should be undertaken.

5.2. Jib crane rope DIEPA 15xK7-WSC 1315 at offshore platform

The rope was subjected to fluctuating tension. Rope diameter is of 32 mm, nominal tension – 162 kN, tensile strength – 2160 MPa. Series of LM- and LF-charts measured by magnetic tester INTROS are presented in figure 5. Only one broken wire was detected at 149.6 m but increasing reduction of metallic cross-sectional area may be recognized in tested distance.

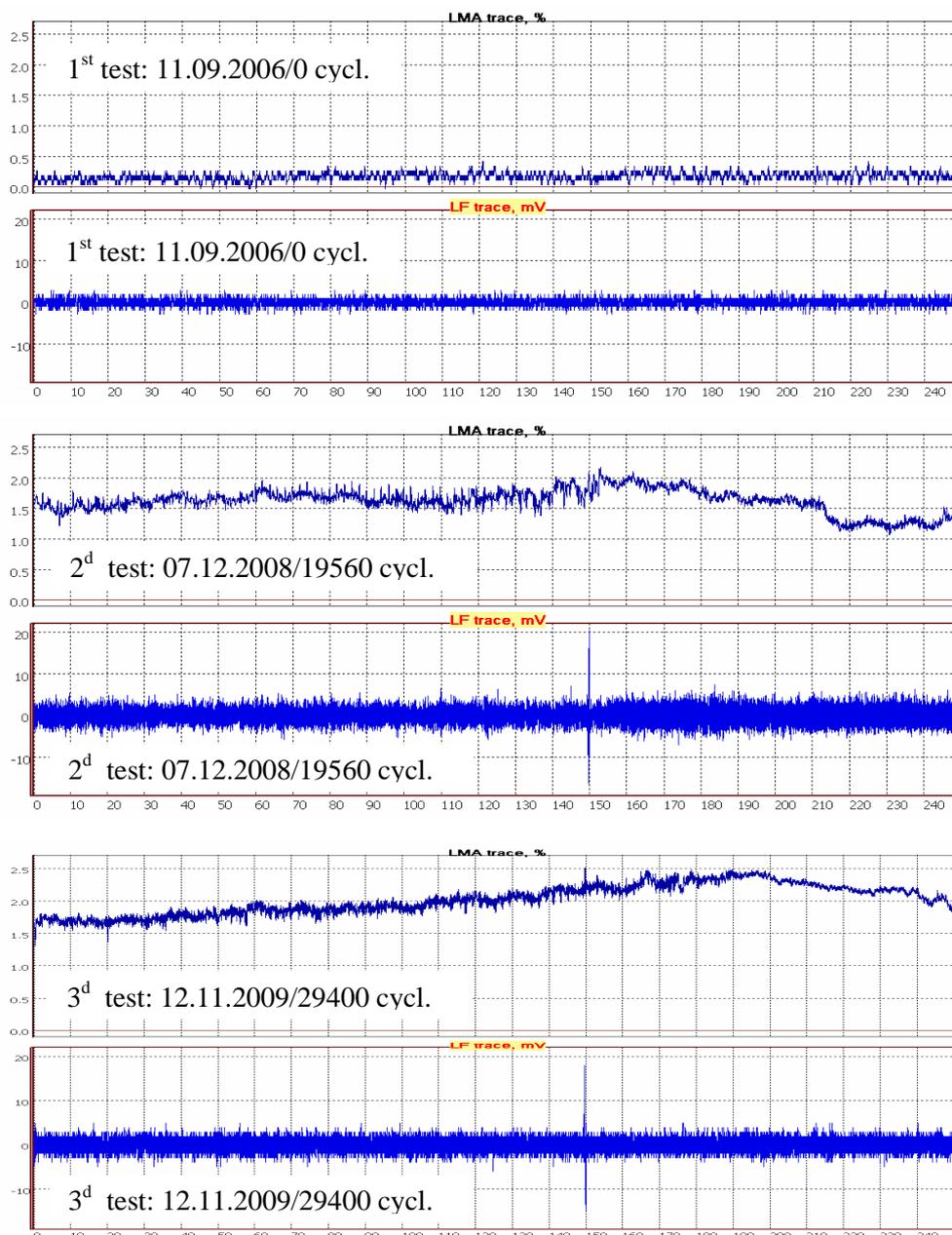


Figure 5. Successive LMA- and LF-charts of rope DIEPA 1315 D32

Corresponding rope strength estimates are shown in figure 6 and in figure 7. The rope was reliable in operation because the degradation has been sloping mildly so that factor of safety kept sufficiently above the discard (permissible) level of 3.5.

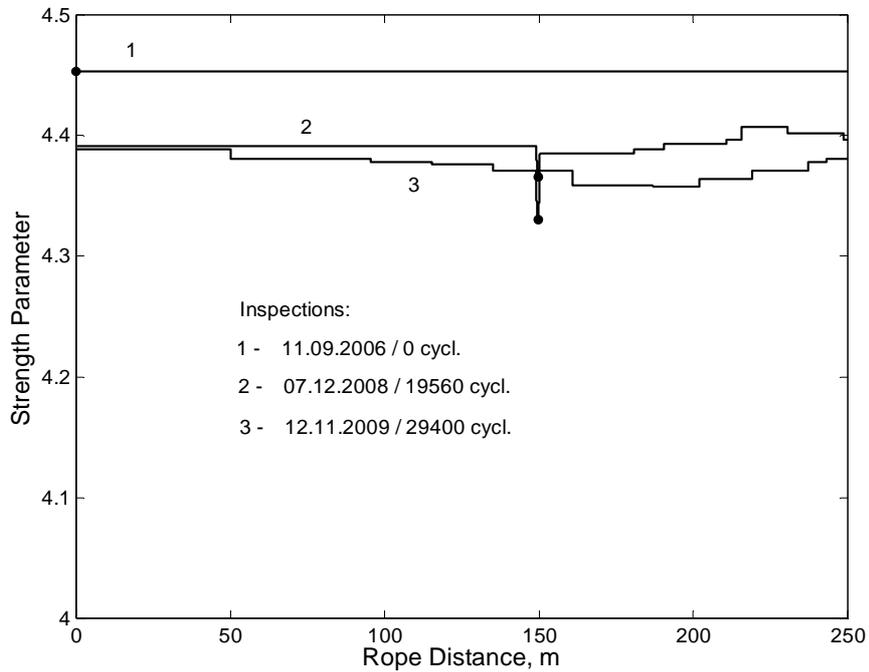


Figure 6. Distributions of strength parameter along the segment of jib crane rope DIEPA 1315 D32

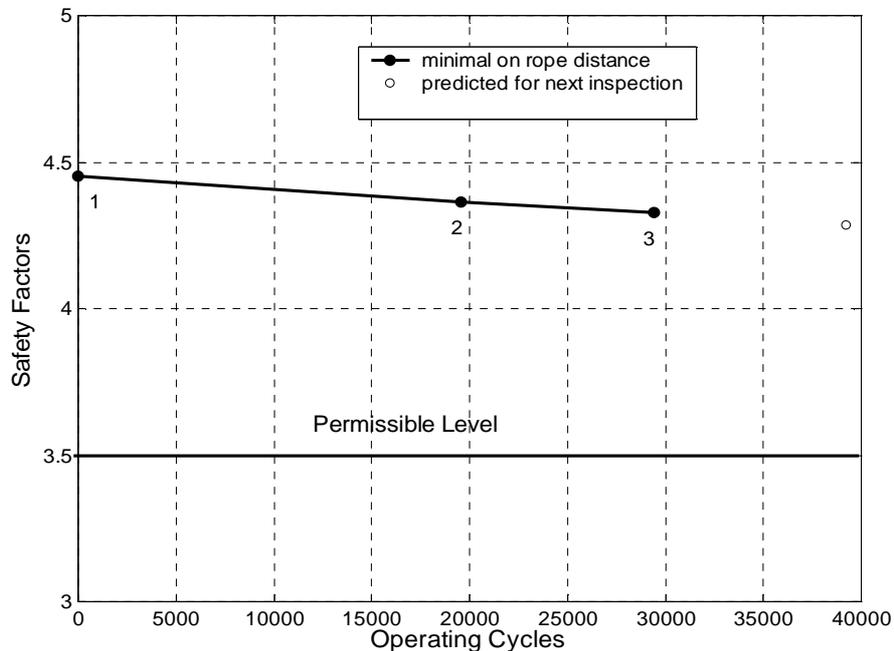


Figure 7. Changing of safety factors and expected value for next inspection the rope DIEPA 1315 D32

Next inspection is planned on 39240 operating cycles with expected safety factor of 4.29 (light circle in figure 7). Remaining life span has been predicted around of 195300 operating cycles with regard to given permissible level.

6. Conclusions

Strength assessment model with input magnetic NDT data makes possible to estimate accurately the strength state of deteriorated ropes. It may be used for wide range of rope constructions and service conditions.

The proposed approach increases the reliability of rope inspection because the successive test dates are dependent upon the condition of the rope. The NDT-mechanical-discard procedure is adapted for particular rope subjected to specific working conditions. In practical use the predicted diagnostic times and working life spans give the NDT operator further information that will help in making a valid decision on testing and unfailing maintenance policy.

7. References

- [1] Feyrer K 2007 *Wire Ropes: Tension, Endurance, Reliability* (Berlin: Springer-Verlag)
- [2] Kashyap S, Laxminarayna G, Tewathri S and Sinha A 2005 Non-destructive testing of steel wire ropes and their discard criteria *Proc. 8th Int. Conf. on Non-Destructive Testing in Engineering (Portoroz, Slovenia, 1-3 September 2005)* pp 229-235
- [3] Sukhorukov V 2001 Steel wire ropes NDT: new instruments *Proc. 6th Int. Conf. on Non-Destructive Testing in Engineering (Portoroz, Slovenia, 13-14 September 2001)* pp 225-230
- [4] Malinovsky V 2001 *Stal'nye Kanaty 1* (Odessa: Astroprint)
- [5] Gere J M and Timoshenko S P 1990 *Mechanics of Materials* (Boston, Mass.: PWS-Kent)
- [6] Bolotin V 1999 *Mechanics of Fatigue. Series: Mechanical Engineering* (Boca Raton, Florida: CRC Press LLC)
- [7] Volokhovskiy V, Vorontsov A, Kagan A and Sukhorukov V 2003 Stochastic assessment of steel rope strength using magnetic NDT results *Experiences with Ropes: OIPEEC Technical Meeting (Lenzburg, Switzerland, 30 August – 3 September 2003)* pp 137-144
- [8] *ISO 4309:2010 Cranes – Wire Ropes – Care, Maintenance, Installation, Examination and Discard* 2010 (Berlin: Beuth Verlag)
- [9] Vorontsov A Volokhovskiy V Halonen J and Sunio J 2007 Prediction of operating time of steel wire ropes using magnetic NDT data *How to get the most out of your ropes: OIPEEC Conf. Proc. (Johannesburg, South Africa, 11-15 September 2007)* pp 145-154