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Prediction of operating time of steel wire ropes using magnetic NDT data

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Summary

A strength assessment model is proposed for predicting the working time of wire ropes that have deteriorated. The distributed losses of the sectional metallic area and local wire breaks as measured by a magnetic flux detector are used as input data for the strength evaluation. A residual safety index for the damaged rope is treated as the parameter for working capacity. The following rope inspection and the corresponding strength state relative to the empirical permissible level are predicted. Several examples of the forecasting procedure are presented.

1 Introduction

Strict requirements for the reliable operation of steel wire ropes are accepted for practically all load-lifting machines. Regular periodic inspections by NDT instruments enable the rope condition to be monitored while the rope is in service [2]. Two main features of deterioration are usually registered by a magnetic flux detector: distributed losses of the metallic area (LMA) and localised faults (LF), such as wire breaks. These data correlate to some extent with the endurance of the degraded rope, but they do not indicate its strength in the quantitative sense. Therefore they must be interpreted using an appropriate mechanical model to obtain the generalised parameter that specifies the residual strength of the rope [3]. This parameter may be used as a diagnostic indicator for predicting the technical state of the rope up to the following inspection. The residual strength forecast gives warning of the risk of breakage, especially when approaching the permissible strength level during the operating history.

2 Assessment of rope residual strength

The residual strength of the rope is estimated by means of the criterion for the stress state of the wire. This gives a stress safety factor of n , which is treated as a ratio $n = \sigma_u / \sigma$ of the material ultimate stress σ_u and von Mises working stress σ that is at its maximum around the wires. Relative rope strength loss is defined by the parameter $\chi = 1 - \tilde{n} / n$, where $\tilde{n}$ and n are the stress safety factors of damaged and non-damaged rope, respectively, under the same working conditions.

The input parameters for the mechanical strength model – metallic cross-section loss ΔA and number of wire breaks B – do not account for the distribution of faults over the wires, and are in general of a random nature. Thus statistical modelling of wear locations in the rope cross-section has been performed and the residual strength calculated as a probabilistic assessment. The details of the procedure and the features of the mechanical model are described in [3, 4].

In the absence of a true account of the combined effect of local and distributed faults on rope strength, the statistical assessments of the decrease in strength due to metallic-section loss $\chi_{\Delta A}$ and wire breaks χ_B are determined independently. The total strength loss $\chi(x,t)$ in the rope cross-section with the longitudinal co-ordinate x at operating time t is estimated by superposition $\chi(x,t) = \chi_{\Delta A}(x,t) + \chi_B(x,t)$. The residual strength parameter $\eta(x,t) = 1 - \chi(x,t)$ is defined as a diagnostic index for predicting the technical state of the rope during operation.

The theoretical strength model has been verified by tensile experiments with ropes containing artificial wire breaks that were made initially. Initial breaks ranging from 4 to 20 in number were distributed more or less uniformly throughout the outer strands in the same section of each rope specimen. The failure load P_q was detected for the specimen with q initial breaks when the first rupture had occurred. The tensile test arrangement and one of the partly ruptured specimens are shown in Figure 1. The typical load-strain diagram of the whole step-like failure process is plotted in Figure 2.

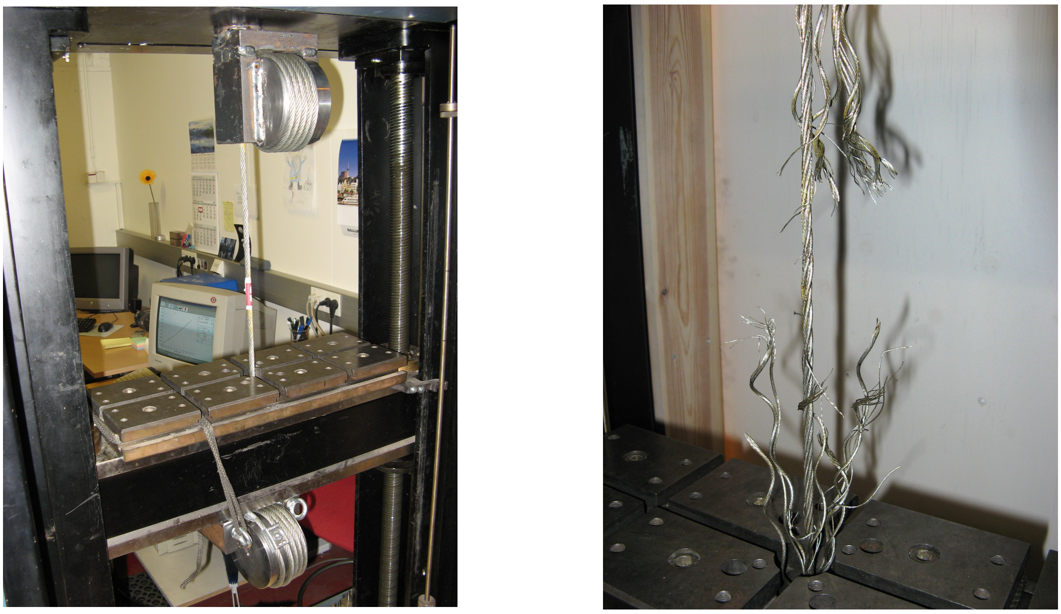


Figure 1: Tensile test arrangement and broken specimen

The strength of the defective specimen has been estimated using the parameter $\eta_{q,test} = P_q / P_0$, where P_0 is the failure load for a non-defective rope. The empirical value $\eta_{q,test}$ was compared with the theoretical assessment $\eta_{q,theory}$, evaluated for a rope with the proper q initial wire breaks according to the model [3].

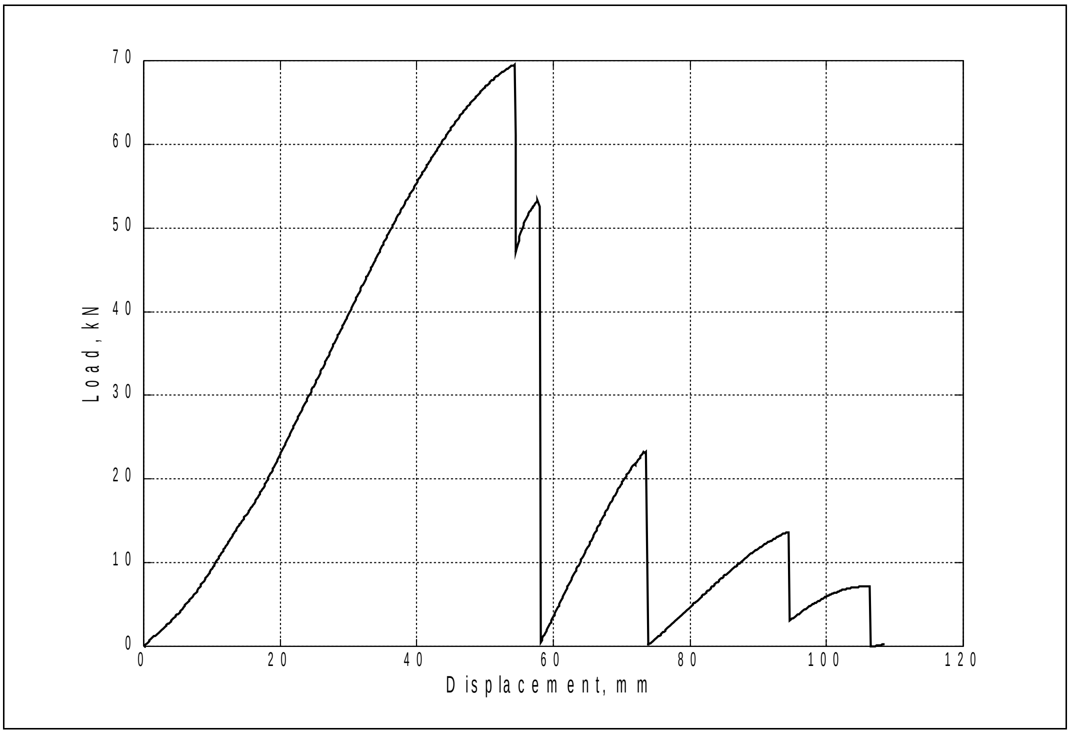


Figure 2: Load-strain diagram of the failure process

Test and calculation results (in percentages) are presented in Figure 3 for the rope PYTHON 8xK19S-PWRC(K) 2160 B sZ ISO 17893:2004 with diameter D 8 mm. Three specimens were tested for each number q of artificial breaks. The failure loads P_q have been correlated to the certified actual breaking load $P_0 = 72.56$ kN.

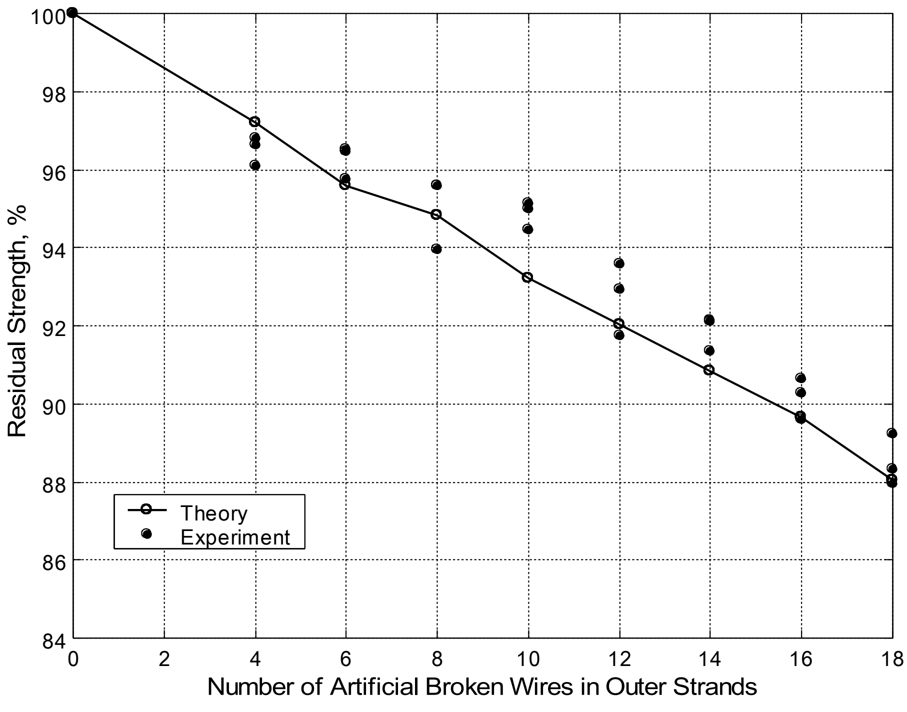


Figure 3: Comparison of theoretical and experimental results for ropes with artificial breaks

The theoretical line is not straight in Figure 3 because some of wire breaks (4, 8 etc) are distributed symmetrically around the eight strands and others (6, 10 etc) – not. This circumstance affects the strength assessment.

3 Principles for predicting rope strength

The parameter $\eta(x,t)$ of the residual strength of a damaged rope is a non-increasing function of the operating time t – i.e. $\eta(x,t+\Delta t) \le \eta(x,t)$ when $\Delta t > 0$. The safe state condition of the rope appears as

$$\min_x \eta(x,t) \ge \eta_* \quad . \qquad (1)$$

The permissible strength level η_* $(0 \le \eta_* \le 1)$ is an empirical value estimated from specified rope lifetime experiments, or it may be set with regard to the existing normative safety requirements. At the beginning of the service life $t = t_0$ (for a new rope) $\eta(x,t_0) > \eta_*$. An upset in condition (1) signifies rope failure. The LMA and LF charts are detected along the tested section of the rope with magnetic NDT inspections at the operating times t_j $(j = 0,1,2,...)$. Decoded records serve as the input data for calculating spaced strength estimates $\eta(x,t_j)$. The corresponding minimum values $\eta_j = \min_x \eta(x,t_j)$ are the parameters for the prediction algorithm.

Predicting the degrading of the residual strength of a rope requires answering two questions:

1) Whether to stop or to continue the work of the rope at the achieved operating time, factoring in all previous inspection history?
2) If the decision is to continue, at what operating time should the next testing be conducted and what value for residual strength is then expected?

The prediction algorithm at a given operating time t_J is similar to a least squares extrapolation $f(t)$ of the m points $\eta_{J-(m-1)},...,\eta_J$ evaluated from the NDT data of the last m inspections. The rope inspector sets the intervals between several initial tests to start the procedure.

The simplest choice – linear approximation $f(t,a_1,a_2) = a_1 + a_2 t$ for $m = 3$ points η_{J-2}, η_{J-1}, η_J – is shown in Figure 4. The coefficients a_1, a_2 are defined by the least squares criterion:

$$\sum_{i=1}^{3} \rho_i \left[f\left(t_{J-3+i}, a_1, a_2\right) - \eta_{J-3+i} \right]^2 \rightarrow \min_{a_1,a_2} .$$

Here $\rho_i = 1/\varepsilon_i > 0$ are the weight factors, given the various inaccuracies ε_i of the estimates η_{J-3+i}.

The step Δt_J for the next rope diagnostic time (or discard time) $t_{J+1} = t_J + \Delta t_J$ depends on the relationship between the previous step $\Delta t_{J-1} = t_J - t_{J-1}$ and the interval $\Delta t_* = t_* - t_J$ when the fitting curve $f(t)$ reaches the permissible strength level η_*. If $\Delta t_* > \Delta t_{J-1}$, then the prediction step is equal to $\Delta t_J = \Delta t_{J-1}$ and the expected strength estimate is $\eta_{J+1} \approx f(t_J + \Delta t_J)$.

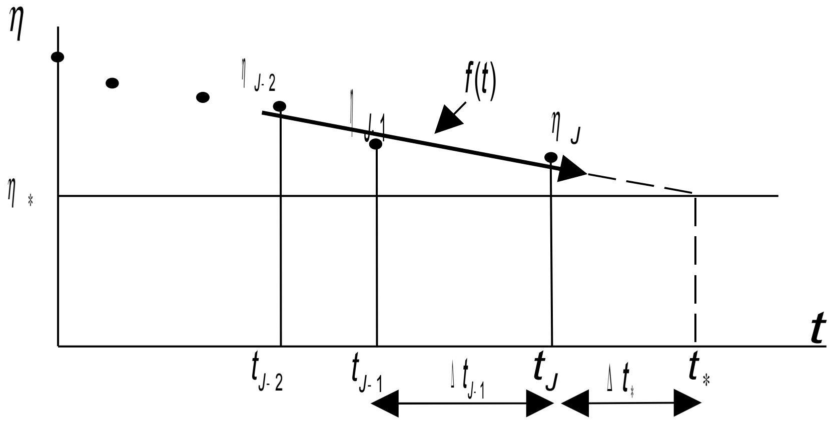
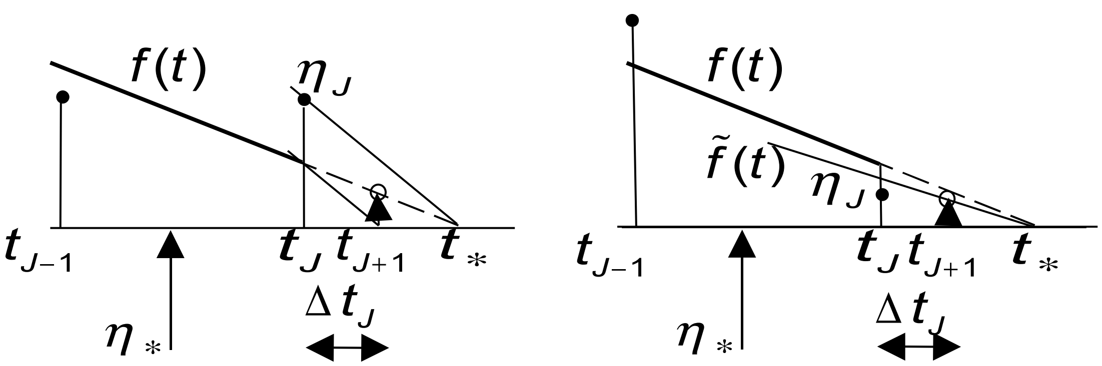


Figure 4: Approximation of residual strength estimates

The failures progressively accumulated in the strands of a rope bring about avalanche-like rupture. Therefore the prediction path must approach the permissible level η_* very carefully. When $\Delta t_* < \Delta t_{J-1}$ the prediction step Δt_J is set considering the degradation rate of the rope, roughly estimated by the slope $s = \left(\eta_* - \eta_J\right) / \Delta t_*$. If $|s| > |a_2|$ $\left(\eta_J > f(t_J)\right)$ the step Δt_J is assumed to be equal to $\Delta t_J = \alpha \left(\eta_* - f(t_J)\right) / s$. The factor α lies within the range $0.5 \le \alpha \le 1$ and in this way regulates the prediction risk near the permissible strength η_*. The expected strength value for a new inspection at the predicted operating time t_{J+1} is marked in Figure 5a as a light circle.

Provided that $|s| < |a_2|$ $\left(\eta_J < f(t_J)\right)$ the half step $\Delta t_J = 0.5 \Delta t_*$ is assigned and a standby approximation $\tilde{f}(t) = \tilde{a}_1 + \tilde{a}_2 t$ with slope modulus $|s| \le |\tilde{a}_2| \le |a_2|$ is used. The expected strength for a new inspection is estimated using the value $\eta(t_{J+1}) \approx \tilde{f}(t_J + \Delta t_J)$ (marked as a light circle in Figure 5b).



(a) (b)

Figure 5: Variants of the predicted inspection steps and rope strengths (light circles)

In any case the theoretical prediction must be treated only as a proposal 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 taken.

4 Examples

The ropes PYTHON 8xK19S + PWRC(K) with diameters D8 and D11 were periodically tested by the magnetic device INTROS along the length $X = 10$ m during lifetime experiments under the state similar to the pure tension when twisting is restricted. Some representative LMA and LF charts, respectively, are shown in Figures 6 and 7.

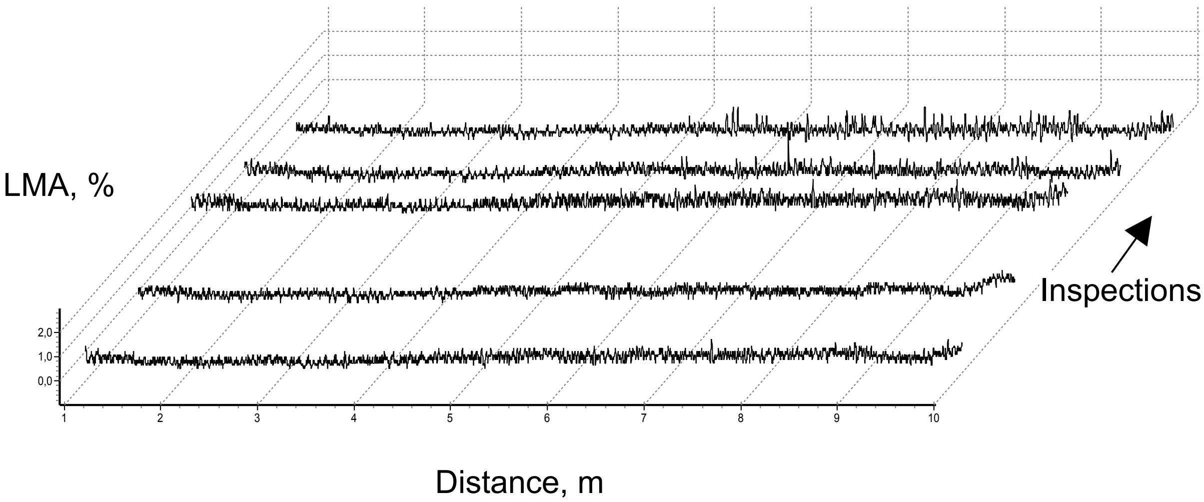


Figure 6: Periodic LMA charts for rope PYTHON D8

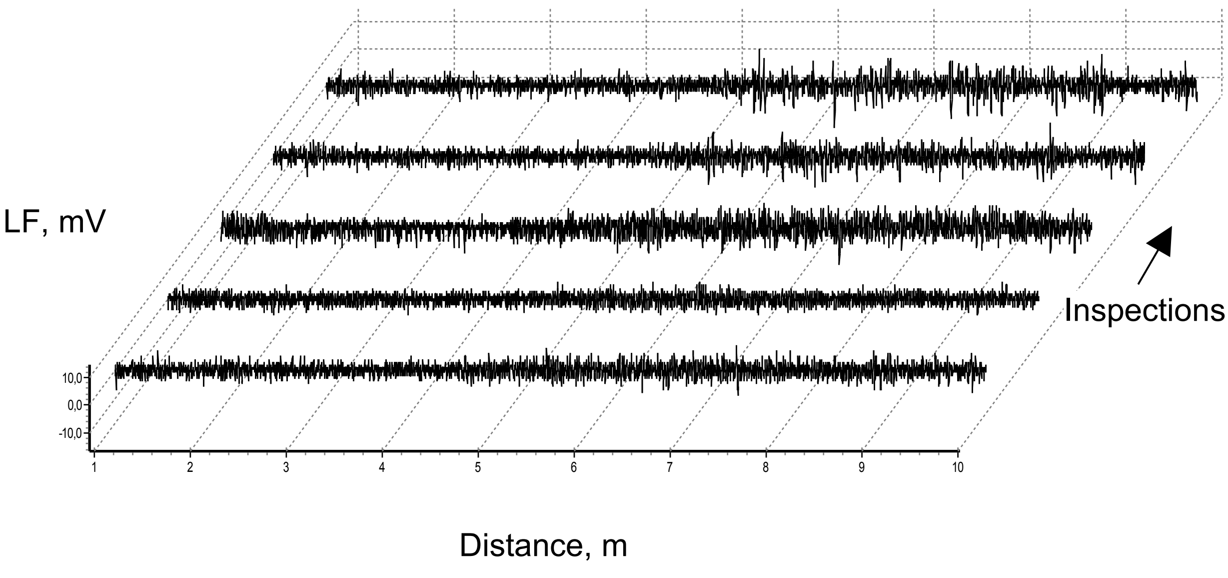


Figure 7: Periodic LF charts for rope PYTHON D8

The number of loading cycles was considered as the operating time t. A calculation of the residual strength was made with the proposition that the bending deformations at some parts of the ropes are negligible. Strength losses $\chi_{\Delta A}\left(x,t_j\right)$ and $\chi_B(x,t_j)$ have been evaluated at $0 \le x \le X$ for each time t_j by averaging over 200 samples with an assessment reliability of 0.997.

Figure 8 presents the strength index distributions along the rope PYTHON D8 segment $0 \le x \le X$ as it changes with inspection dates\cycles. The corresponding minimum values (marked as circles) are the prediction parameters $\eta_j = \min_x \eta(x,t_j)$. On the practically uniform background level they become more distinguishable at later deterioration phases because of the progressive accumulation of wire breaks. Local faults indicate the intervals where rope failure develops and will probably occur.

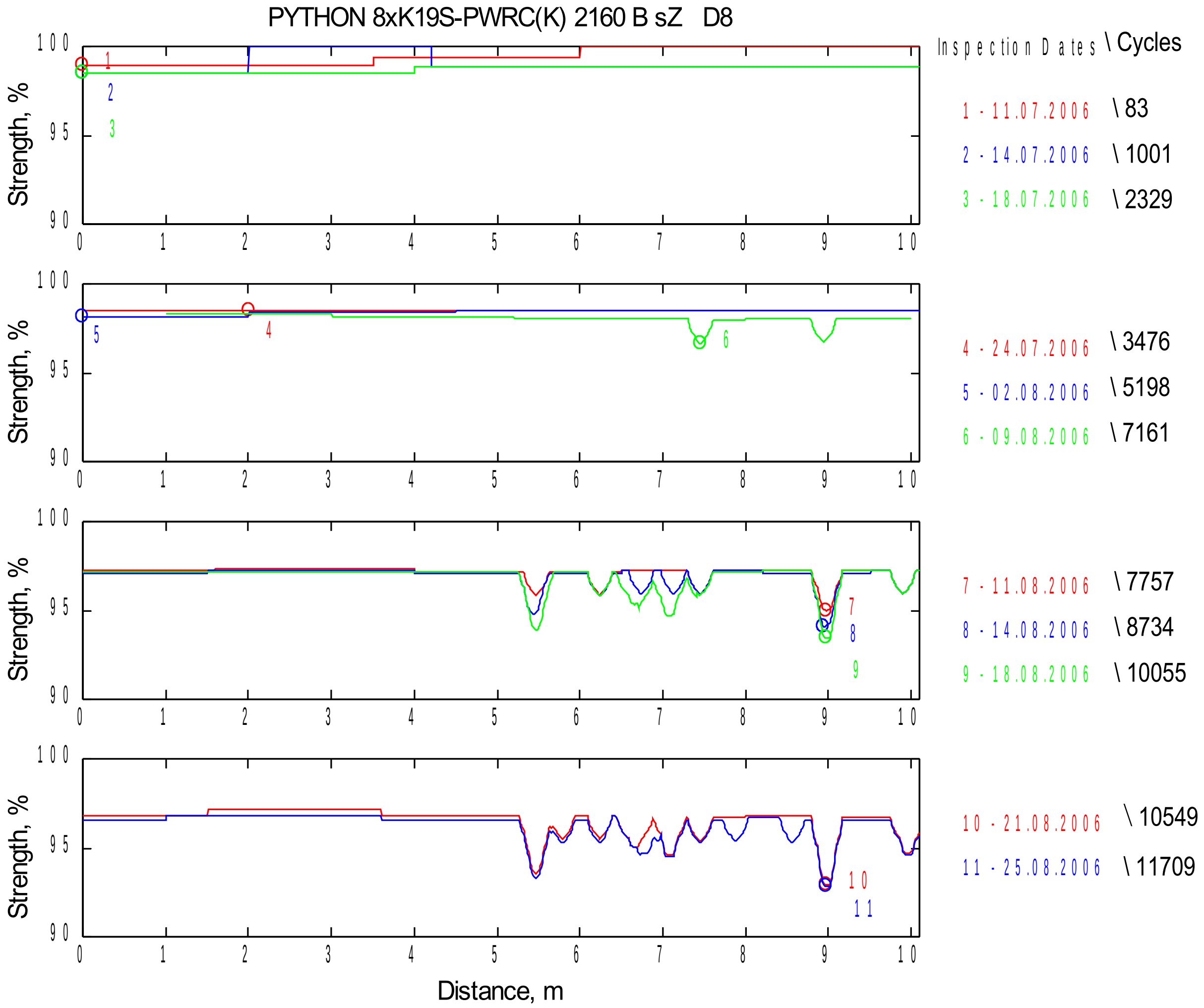


Figure 8: Time-quantified strength index distributions along the rope PYTHON D8 segment

Figure 9 demonstrates the changes in both the minimum estimates η_j and the prediction path $f(t_j)$ (marked in green) as functions of the operating cycles t_j for the test history of the rope. The permissible level η_* has been set for the situation just before failure of the rope when the measured LMA/LF magnitudes start to increase significantly. The assumed value $\eta_* = 92\%$ correlates with the normative discard criteria [1]. In general, this parameter has a stochastic nature. It must be detected carefully from the specific deterioration experiments. The integral strength estimate $X^{-1}\int_X \eta(x,t_j)dx$ that lies higher describes the degradation caused mainly by development of the distributed faults.

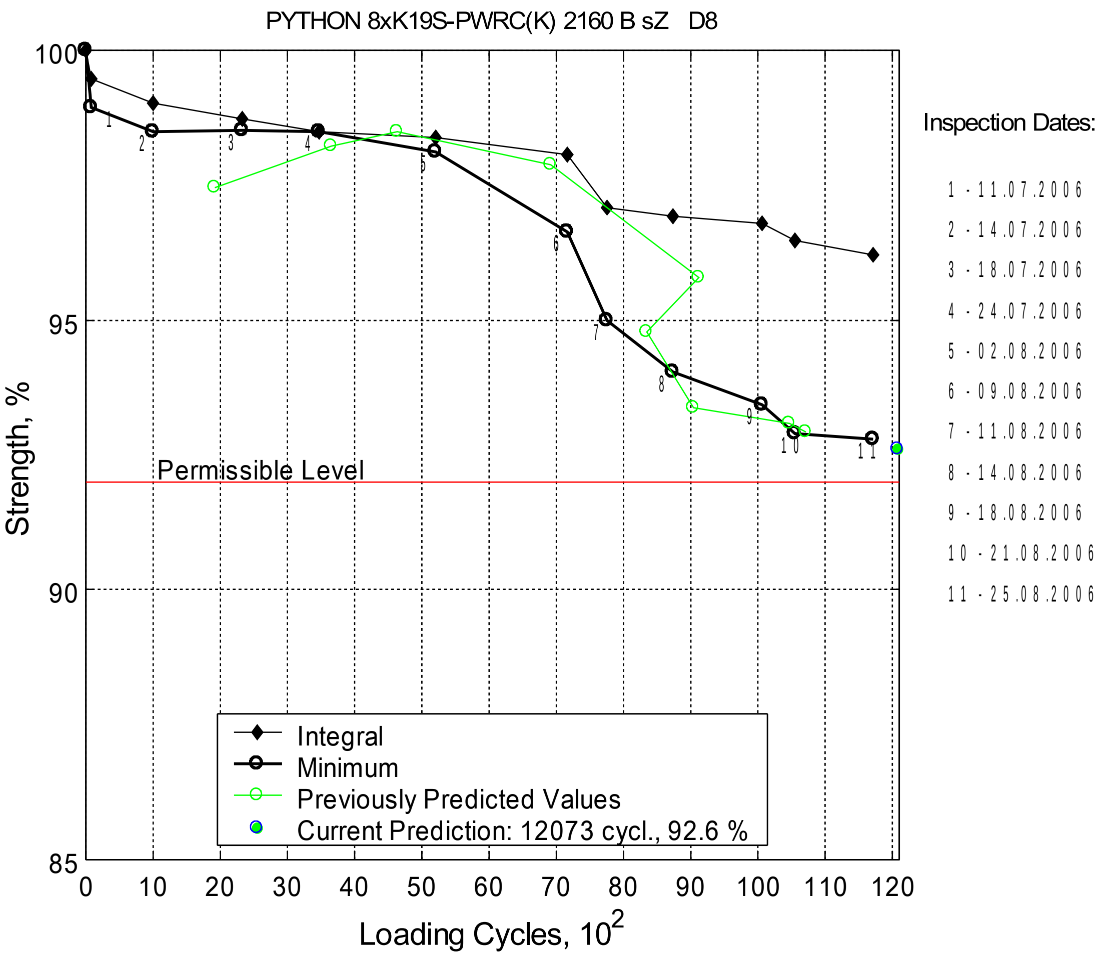


Figure 9: Changing of the rope strength estimates and predicted values (green) for progressively deteriorated rope PYTHON D8

Figure 10 presents similar results for rope PYTHON D11 with an empirical permissible level of 93%. Some degradation instability may be seen in initial inspections.

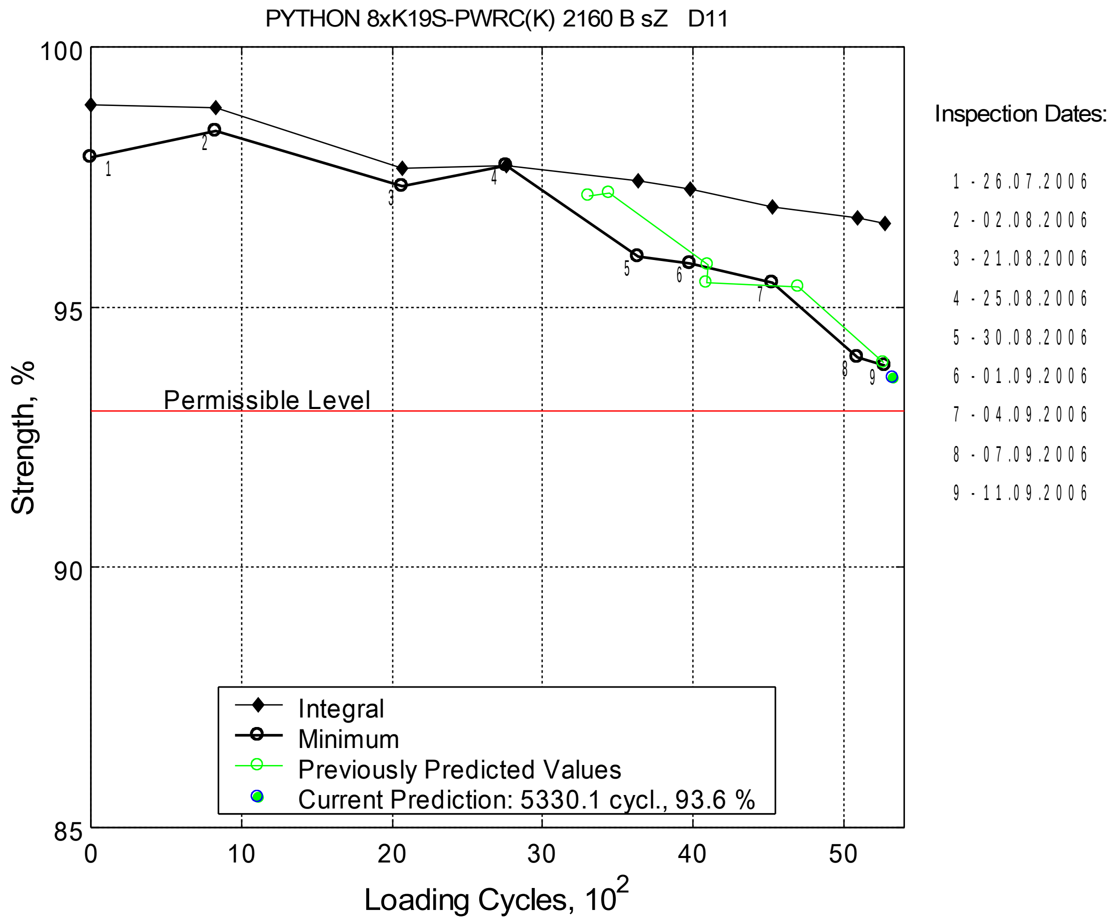


Figure 10: Changing of the rope strength estimates and predicted values (green) for progressively deteriorated rope PYTHON D11

Note that both examples are only apt illustrations of the forecasting procedure, because in each of them the prediction path $f(t_j)$ appears after all test history η_j has been generated.

5 Conclusions

The strength assessment model using NDT data estimated accurately the strength level of the tested ropes. In practical use the predicted successive diagnostic times and strength estimates give the NDT operator further information that will help in making a valid decision on testing policy.

The proposed approach increases the reliability of rope inspection because the successive test dates are dependent upon the condition of the rope.

6 References

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