STRENGTH ASSESSMENT OF WORKING CAPACITY OF STEEL WIRE ROPES

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1. Introduction

The steel ropes of load-lifting machines are usually being chosen considering the certified breaking load F_0 from the condition $F_0 \geq S \cdot z_P$, where S is the highest tensile load of the rope and z_P is "rope's service factor", which is similar to normative factor of safe $[n]$ in structural mechanics. The limit load F_0 is determined from tensile rope testing or by simple calculation when the rope is treated as homogeneous bar.

In practical situations the stress state in wires is combined and therefore the load F_0 may not be considered as appropriate parameter for rope's assortment. It appears especially when the axial deformation is accompanied with twisting or the rope is under tension/bending deformations on the sheave. Some kinds of inaccurate actions may happen. High values of prescribed safety factors $[n]$ commonly lead to ill-founded rope sizes. From the other hand, if customer does not know the reliable safety factor of the new rope he cannot estimate its life-time so increasing the failure risks.

Actual ropes discard criteria are of unclear empirical origin. They do not include any notes concerning the strength concept. If the rope is periodically inspected by NDT instruments the decision about its working safe state is often uncertain. Customer may stand the questions: how much strength did the rope loose up to the last inspection? what is a residual safety factor of deteriorated rope? when should the next inspection be conducted?

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 with the endurance of the degraded rope, but they do not indicate its strength in the quantitative sense. The point is to interpret the NDT results using the proper mechanical model and to obtain the generalised parameter that specifies the residual strength of the rope. This parameter may be used as a diagnostic indicator for predicting the operating times for the following successive inspections and life-time of the rope depending of operating history. The residual strength forecast gives warning of the risk of breakage, especially when approaching the given permissible strength level.

2. Strength parameters of steel wire ropes

The strength of wire rope subjected to nominal tensile load S may be characterized by the following parameters:

stress safety factor relating to the most strained wire

$$n_\sigma = \frac{\sigma_u}{\sigma_{von\ Mises}}$$

(σ_u is a tensile strength of material of wires (MPa), $\sigma_{von\ Mises}$ – the inter-wires maximum von Mises working stress (MPa);

load safety factor relating to the most strained wire

$$n_{Sw} = \frac{S_w}{S}$$

(S_w is the load when rupture starts in the most stressed wire i.e. when $n_\sigma \leq 1$);

load safety factor for the rope

$$n_S = \frac{S_u}{S}$$

(S_u is an ultimate breaking load for the rope as a whole structure – an analogue of certified breaking load F_0).

Safety factors n_σ and n_{Sw} are similar because they both relate to primary rupture of the most strained element of the rope. The distinction between them should be taken into account if the rope is considered under different working conditions. Parameter n_σ is used when stresses are proportional to tensile load (rope is only tensed) and n_{Sw} - if stresses in wires are not proportional to tensile load (rope is tensed and bended over the sheave so that its bending stiffness depends on the tension).

In present study strength assessment was being performed for the rope PYTHON 8xK19S+PWRC(K) 2160 B sZ ISO 17893:2004 with diameter $D = 8$ mm. Details of procedure based on steel ropes theory of Glushko were described in [1].

3. Breaking loads of rope structure

Owing to irregular stress distribution over rope's cross-section the most stressed wire fails at smaller load than the ultimate breaking load for the entire rope. The first case means the strength of material, the second – strength of construction. The results of modeling the simultaneous breaking processes for three working conditions of the same rope are presented in Figure 1. At pure tension twisting is restricted; at free tension the rope is tensed and twisted. In both cases the stresses are assumed to be continuous in time. The rope running on and off the sheave is subjected to repeated loading and fatigue endurance is accounted for. The circles mark the values of breaking load and loss of metallic area of corresponding broken rope's elements like single wire, groups of wires and strands. The points are straight-line interpolated for clearness. Safety factors n_σ, n_{Sw} and n_S were estimated with respect to nominal tensile load $S = 12$ kN.

In straight ropes subjected to pure or free tension the failure starts with the centre core wire, then the core progressively fails and at last the outer strands are being broken. The ultimate loads S_u and corresponding safety factors n_S are defined by the strength of the metallic core. Initial (minimal) values of breaking loads are related with stress safety factors n_σ. The calculated ultimate load at pure tension is a little lower than certified breaking load thus referring to margin of safety.

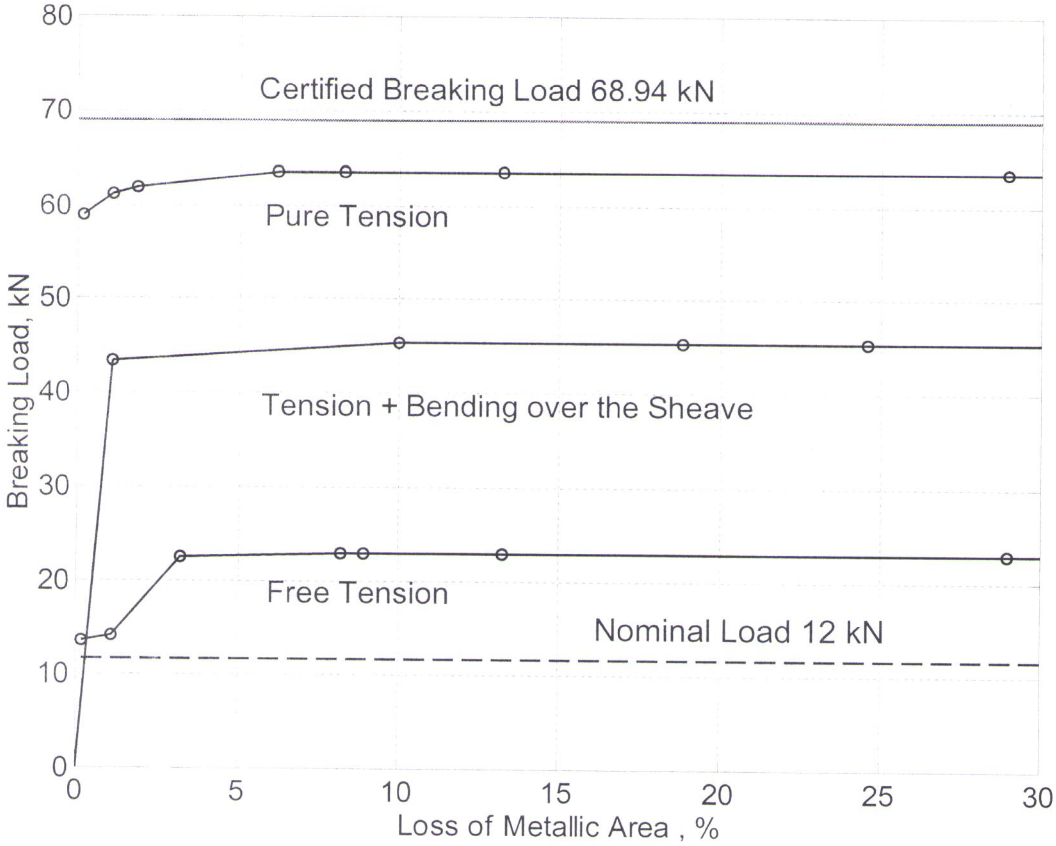


Figure 1 Failure phases of rope PYTHON D8

Strength of the rope on the sheave was analyzed with account of fatigue endurance of wires material at run-on/run-off branches [2]. The endurance limit was taken equal $0.4\sigma_u = 0.4 \cdot 2160 = 864$ MPa. The stress concentration factors near broken wires were estimated by finite-element model. Their values vary from 1.2 to 1.55 at distinct failure phases. The rupture starts with the central strand of metallic core at tensile load S_w . This act is associated with load safety factor n_{Sw} . This indicator is not equal to stress safety factor like n_σ because the bending stiffness of the rope depends on tensile load S and the problem of stress evaluation is nonlinear. After primary rupture the breaks of outer strands and breaks of core strands are taking place progressively one after another. The limit load S_u relates to the failure of outer strands which are in contact with the sheave.

In all situations the rope limit loads are only slightly higher comparing the primary breaking loads when failure begins. This fact is rather confirmed by the load-strain diagram of the rope PYTHON D8 which was obtained from tensile testing (Figure 2).

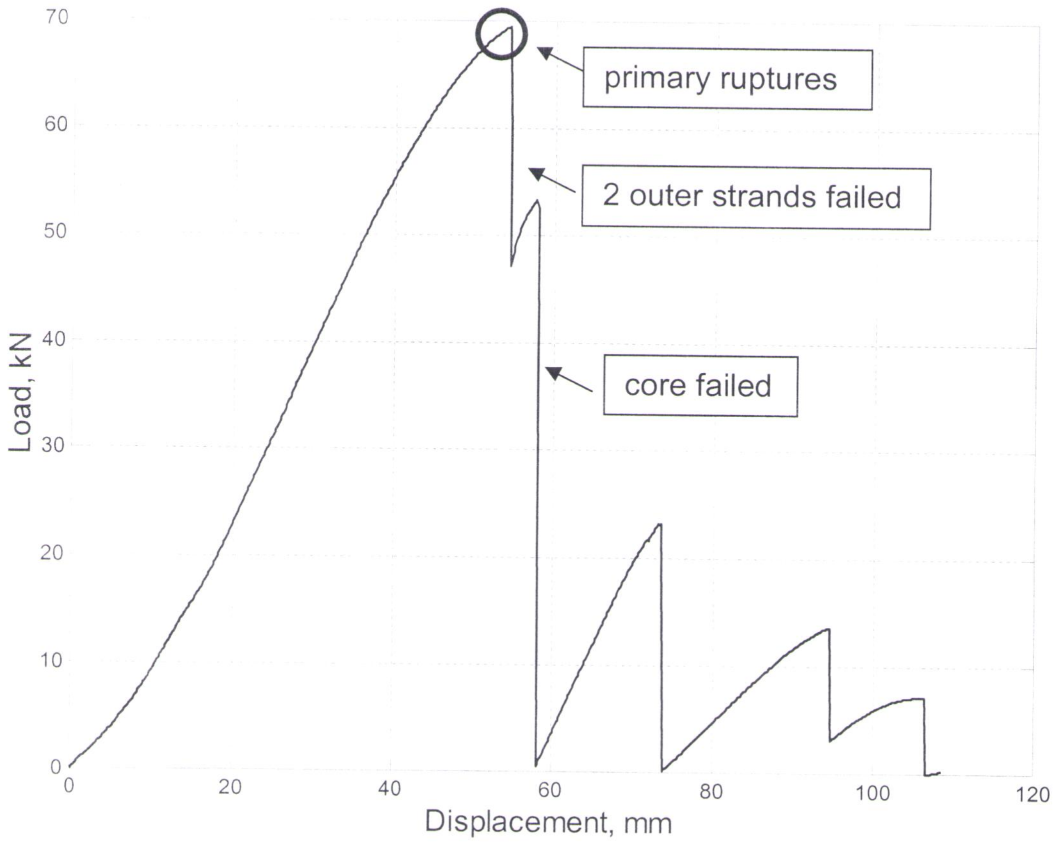
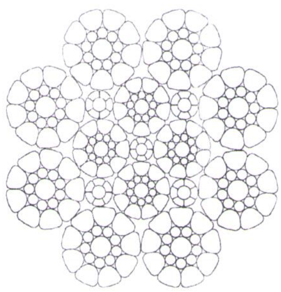


Figure 2 Load-strain diagram of rope PYTHON D8

The numerical results for originally new ropes and ropes with one initially cut outer strand are summarized in Table 1. It may be seen that relative strength estimates of initially damaged ropes are close to each other for distinct cases. But the absolute values of corresponding safety factors differ significantly. So the strength parameters of such kind may be treated as realistic indicators of rope technical state in special practice.

Table 1

 PYTHON D8		New Rope	Initially Defected Rope – 1 cut outer strand (LMA= 9 %)	$\frac{\text{Defected}}{\text{New}}$
Pure Tension	n_σ	4.9	4.49	0.92
	n_S	5.3	4.84	0.91
Rope on the Sheave	n_{Sw}	3.61	3.27	0.91
	n_S	3.78	3.69	0.97
Free Tension	n_σ	1.13	1.06	0.94
	n_S	1.91	1.78	0.93

4. Prediction of operating time of wire ropes using magnetic NDT data

The strength changing of rope in service may be estimated using the results of regular periodic rope inspections. Two NDT data – the loss of metallic area and number of wire breaks are input parameters for mechanical model of degraded rope. Assume the stress safety factor $n_\sigma(x,t)$ to be a generalized diagnostic indicator that specifies the residual strength in the rope cross-section with longitudinal coordinate x at operating time t. For ropes running over sheaves it is reasonable to consider the number of bending cycles as the operating time t.

Parameter $n_\sigma(x,t)$ may serve for predicting the times of successive inspections and corresponding technical states of deteriorated rope. Particulars of forecasting algorithm are described in [3]. Here we point only to problem statement. The safe state condition of the rope appears as

$$\min_{x} n_{\sigma}(x,t) \geq [n]. \tag{1}$$

The permissible safety factor $[n]$ is an empirical value estimated from rope lifetime experiments or it may be set regarding existing normative safety requirements. When condition (1) does not hold, this signifies rope failure. 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 rope PYTHON D8 was executed to failure on the sheave under tensile load $S = 12$ kN. Its original normative safety related to the specified breaking load $F_0 = 69.0$ kN was equal $z_P = 69/12 = 5.75$. The rope was periodically tested by the magnetic device INTROS along the length 10 m and corresponding strength assessments were derived.

Figure 3 demonstrates the changes in rope strength estimates $n_j = \min_{x} n_{\sigma}(x,t_j)$ (marked by triangles) and predicted values (marked by circles) as functions of operating cycles t_j for the test history of the rope. Undamaged rope under bending fatigue conditions has the safety less than supposed value $z_P = 5.75$ given by homogeneous bar approach. The defects progressively accumulated in the strands of a rope bring about avalanche-like rupture. Therefore the predictions approach the tentative permissible level $[n] = 1.5$ very carefully. An example is only illustration of forecasting procedure because the prediction trace (in green) appears after all test history n_j has been obtained. In practice each forecast follows each next in turn strength estimate evaluated after processing the corresponding LMA and LF charts.

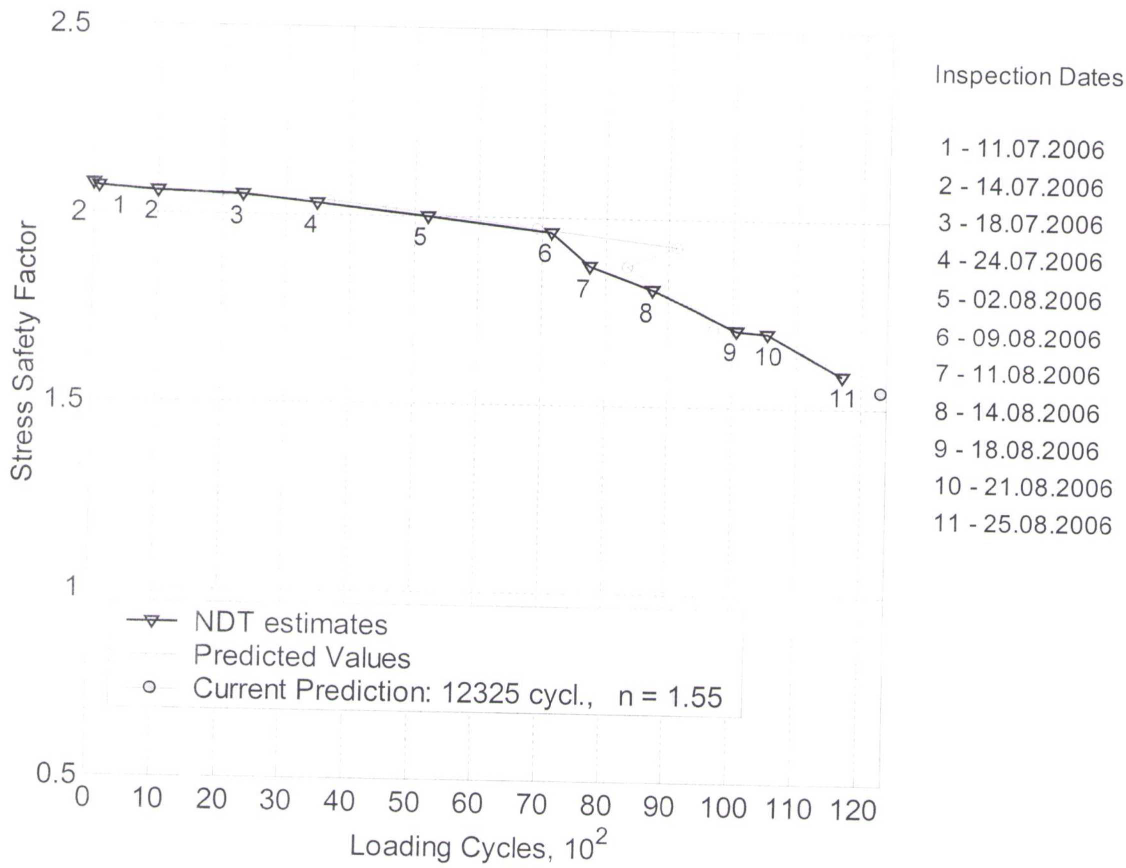


Figure 3 Changing of the strength estimates for progressively deteriorated rope PYTHON D8

Note that theoretical prediction must be realized simply as a proposal for the rope inspector, who is the only person to make the final decision concerning the technical state of tested rope.

References

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2. Feyrer K. Wire Ropes: Tension, Endurance, Reliability. Springer-Verlag, Berlin, 2007. – 322 pp.

3. A.Vorontsov, V.Volokhovsky, J.Halonen, J.Sunio. Prediction of operating time of steel wire ropes using magnetic NDT data. OIPEEC Conference, Johannesburg, 2007, p. 145-154.