Magnetic NDT and computer modeling of steel ropes deterioration in suspended bridges

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Abstract. A combined approach to strength assessment of stay ropes in suspension bridges is considered. The rope working condition is being analyzed by following steps: *in-situ* magnetic testing of rope structure, computational assessment of ultimate breaking load and evaluation of residual margin of safety. The diagnostic parameters – distributed and/or local faults in wires – are used as input data for mechanical model of rope structure. The model enables to calculate the stresses in each wire and to simulate the step-wise degradation process thus estimating the rope residual breaking tensile load. The safety factor of deteriorated rope is considered as a generalized parameter that specifies the rope safe operation as an element of bridge stay arrangement. Examples of integrity analysis of stranded stay ropes and locked coil stay ropes are presented.

Introduction

The safe operation of suspension bridges requires the periodical monitoring of health state of numerous structural elements: stay ropes, guys, anchorage components etc. The main stay steel ropes are usually subjected to aggressive environments. Hidden corrosive wear and fatigue-induced deterioration in tensed wires decrease an operational reliability of stay system.

Several methods are used for control the strength condition of stay ropes [1]. A number of technologies are based upon detection and location failures in steel wires through continuous remote monitoring. On-site data-acquisition unit processes the events information and applied software converts it into set of variables that describe the mechanical state of examined object.

Some of stayed constructions do not require the continuous monitoring. The alternative way is an occasional inspection of ropes working under the hard environments by external non-destructive test (NDT) equipment. As well as in continuous monitoring the diagnostic information is transferred into rope state parameters by embedded processor and software support. The load factor of safety seems to be the most appropriate indicator specifying the technical condition of stay rope. The paper considers an approach to evaluate the residual bearing capacity (residual strength) of main stay steel wire ropes based on non-destructive diagnostic data. The mechanical model of heterogeneous rope structure along with computational simulation of deterioration process is employed to achieve this purpose.

Principles and features of stay ropes magnetic testing

Magnetic flux detection is the diagnostic method used most commonly for non-destructive testing of steel wire ropes. Two-channel flux detector estimates the magnetic flux along the tested rope length and measures the flux leakage caused by two kinds of defects: metallic cross-section area loss (LMA) and local faults (LF). Record of the LMA channel represents LMA value due to corrosive or/and abrasive wear in percents relative to a standard value of metallic area as a function of distance along the rope. The LF channel records sensor signals that appear due to local wear like broken wires, local corrosion etc. along rope under test.

The steel rope magnetic flux detector INTROS designed and manufactured by INTRON PLUS Ltd. is adopted for various applications: mine hoist ropes, elevator ropes, stay ropes (guys), crane ropes etc. It consists of a universal electronic unit and different magnetic heads to test ropes of various constructions and dimensions [2]. The microprocessor unit is used as data logger with memory sufficient to save testing data of (2-12) km of rope in the LMA and LF channels simultaneously. Due to portability and self-containing power supplying the electronic unit can be fixed at magnetic head to work as full independent instrument moving along the rope far away from inspector. This is particularly convenient for testing the stays and guys of bridges or buildings.

Stay ropes at five bridges were controlled by INTROS instrument since 2009. Fig.1 demonstrates the inspection of stay wire ropes of suspension bridge across the river Ob' in Western Siberia.

Figure 1: Stay ropes inspection by INTROS device

The diagnostic system should have a significant mass for provide the magnetic saturation along the ropes having large diameters. The heads supplied by wheel traction allow examining the stay ropes with diameters up to 150 mm (Fig.2).

Figure 2: Testing the large diameter stays

The magnetic head with electronic unit is drawn along the stay rope by trailing cable pulling over two crown blocks by electric hauling winch or manually. The layout of diagnostic equipment is shown in Fig.3.

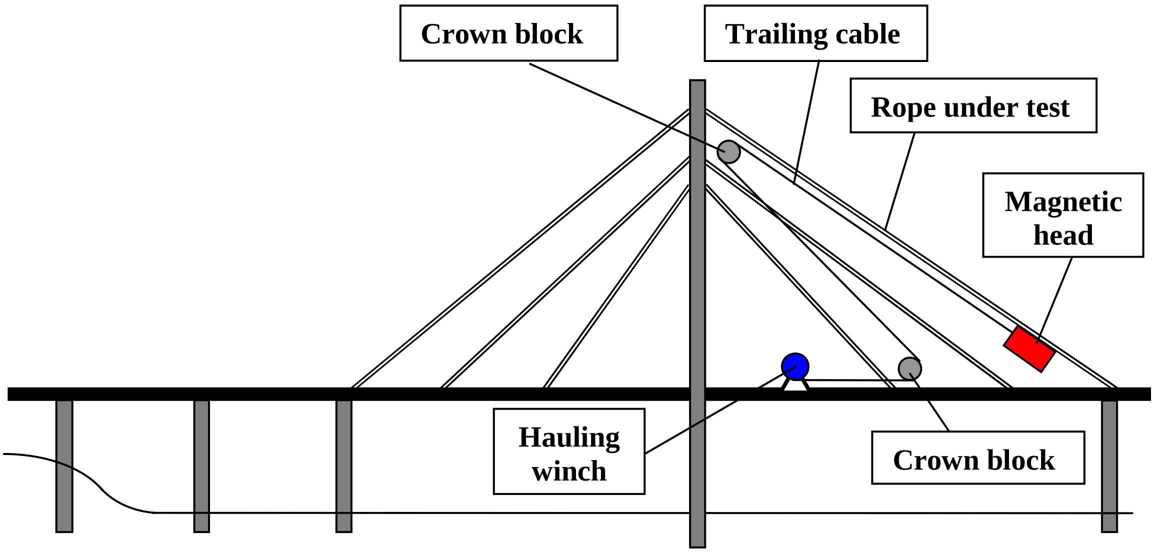

Figure 3: Layout of stay rope diagnostic equipment

The software Wintros is intended for test data processing after they are downloaded into an embedded computer [3]. The software provides a broad spectrum of functions: different kinds of filtering, noise cutting-off, zero level displacing, amplitude and distance zooming, auto-scaling, aligning the signal traces from several inspections and others. The last function is very helpful to observe the changes in rope condition within its lifetime. Typical LMA- and LF-traces obtained by INTROS instrument for locked-coil stay rope are presented in Fig.4.

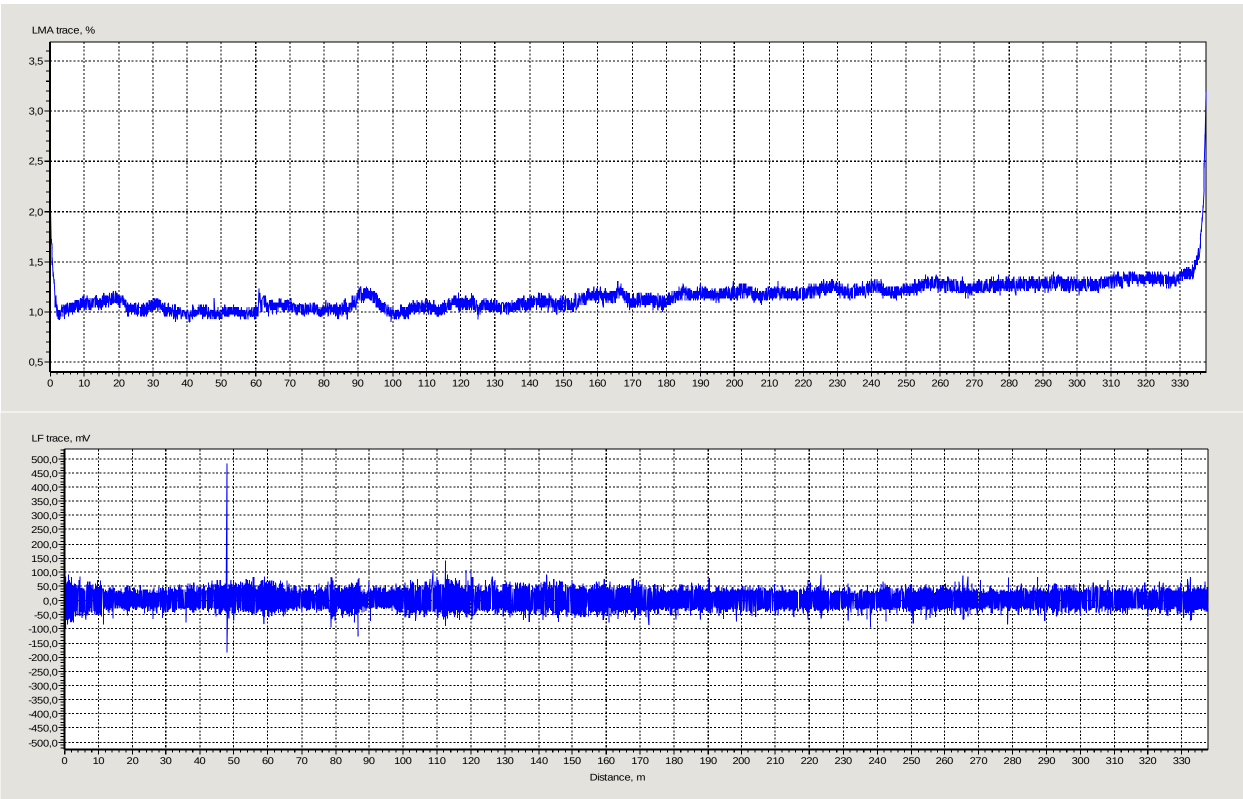

Figure 4: LMA- and LF-traces of stay rope inspection

The locked coil rope under test had a core of round wires similar to helical strands while three outer layers were of Z-shaped wires. These wires interlock when stretched and therefore provide substantial protection for inner layers. The rope structure is notified as 1+7+7/7+14+20+34Z+41Z+41Z where the initial six numbers are amounts of round wires in core layers.

As may be seen from LMA-trace the active cross-section is decreased insignificantly. The distinctive raising of LMA values near the terminations of tested rope are caused by the influence of bottom and top anchor zones and do not relate to rope strength. A sharp peak is recognized at the distance of 47.5 meters from the ground end at the LF-trace. This signal corresponds to a sole Z-wire break in outer layer. Constant monitoring is not necessary at this time but the bridge maintenance staff should pay more attention if this rope section proves to be reduced due to future damage accumulation.

Strength indicators of stay ropes structural capability

Rated steel wire ropes subjected to tensile loads are selected according to the rule $F \geq \max T \cdot [n]$, where F is a certified rope breaking force, $\max T$ is a project operating tension, $[n]$ is a required factor of safety imposed by law or standard [4]. We will refer to this structural capacity parameter as to design factor. In engineering practice the breaking force F is usually estimated by the simplest procedure: the calculated total ultimate tension of parallel wires assembly is reduced by correction factor $k = 0.83 \div 0.90$ granting the helical rope structure [5].

An actual rope load safety factor n is specified as a ratio between the ultimate breaking tension T_u and nominal working tension T :

$$n = \frac{T_u}{T} . \qquad (1)$$

Ultimate tension T_u is a non-damaged rope strength quality of similar nature than a rated certified value F .

Traditional structural safe criteria require that $n \geq [n]$. During the service life the bearing capacity of stay ropes reduces due to wear accumulation therefore an actual factor of safety n may become less than required design factor $[n]$. From the conventional point of view when this event has been occurred the rope should be immediately rejected. But partly deteriorated stay rope remaining a statically indeterminate system is able to keep its functions until the actual factor of safety reaches a certain minimal allowable value n_*. Parameter n_* defines the rope's margin of survivability as for partially failed structure. It specifies a reasonable risk when operating the rope with worn-out elements and is called *"vitality"* factor in theory of reliability [6]. The value of n_* is estimated from rope lifetime experiments or it may be evaluated with use of appropriate mechanical model regarding the corresponding normative rules [7]. The allowable vitality factor is a main indicator the rope lifetime prediction procedure is based upon [8]. It may also be used for planning the operating times of stay ropes testing.

A real safety factor $\tilde{n}$ of deteriorated rope still in service is defined by relation

$$\tilde{n} = \frac{\tilde{T}_u}{T} . \qquad (2)$$

Here $\tilde{T}_u$ is an ultimate breaking tension for stay rope with certain defects. The endurance of working rope may be estimated in regard to safety factor n of new (delivered) rope or to allowable vitality factor n_*. Two corresponding parameters may be assigned: the actual relative residual strength of rope structure

$$\eta = \frac{\tilde{n}}{n} \leq 1 \quad (3)$$

and relative residual vital ability of deteriorated rope structure

$$\psi = \frac{\tilde{n}}{n_*} \geq 1. \quad (4)$$

Parameter ψ indicates how much of the rope structure's capacity is held "in reserve". When condition (4) gets upset this signifies the structural endurance fail so the rope must be discarded.

Stay ropes failure simulation and strength assessment

One needs to know reliable values of ultimate tensions (breaking loads) T_u or $\tilde{T}_u$ for judgment upon the rope safety. A statistical assessment of these parameters may be derived from tensile experiments. But such experiments are of a great expense for a wide range of different ropes, especially with large diameters. Therefore, as was mentioned above, the theoretical estimates, evaluated by means of simplifying assumptions, took place in ropes catalogues. The empirical helical structure correction factor k is rather uncertain. It does not account for details of combined stress state in wires, particularly for locked coil ropes. For deteriorated ropes with reduced active cross sections the ultimate tension $\tilde{T}_u$ is not identified by existent methods at all. Hereinafter an attempt is being performed to define the values of ultimate tensions for typical stay rope constructions with the aid of step-by-step failure simulation.

Two kinds of main stays in suspension bridges were considered as the objects of analysis: the locked coil rope 1+7+7/7+14+20+34Z+41Z+41Z (diameter of 72 mm) and the stranded rope 37+9x7+9x36(WS) (diameter of 84 mm). Abbreviation WS denotes the outer strands construction of type Warrington-Seale [5].

The steel wire ropes theory [9] is a background of strength assessment for both ropes. The constitutive equations of rope treated as a 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:

$$\left.\begin{aligned} T &= C_{11}\varepsilon + C_{12}\theta \\ M &= C_{12}\varepsilon + C_{22}\theta \end{aligned}\right\} . \quad (5)$$

Here 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 geometries of wires and strands. Expanded expressions for stiffness parameters, strains and stresses are rather complicated so only the general procedure of stress calculation in wires will be mentioned.

The rope deformations ε and θ are determined from equations (5) for given loads T, M and known structural parameters C_{jk}. The constraints at rope terminations also should be taken into account. These deformations are double-transformed to strand lay axes and wires lay axes. The tensile, bending, 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 a wire is reduced to uniaxial equivalent stress σ_{eq} by proper strength criterion e.g. $\sigma_{eq} = (\sigma^2 + 4\tau^2)^{1/2}$. Fig. 5 demonstrates the diagrams of equivalent stresses σ_{eq} plotted across the wires sections for tensed locked coil rope and stranded rope. The bar ordinates are normalized to maximal stresses taking place in cores' center wires for both ropes.

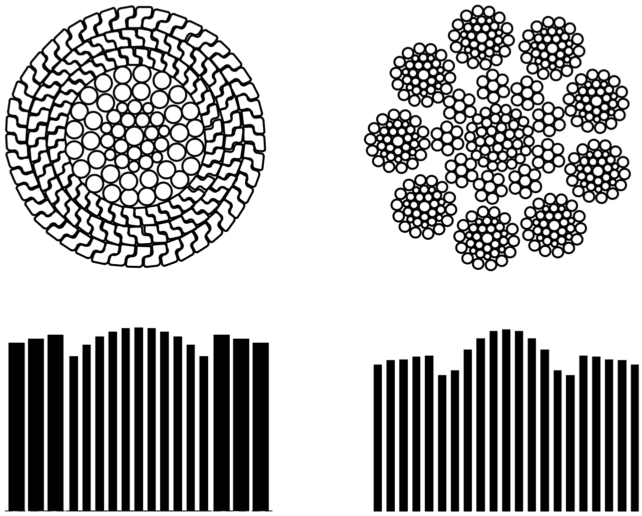

Figure 5: Equivalent stresses over cross-sections for tensed locked coil rope (left) and stranded rope (right)

The stay rope failure is simulated at step-by-step loading with the assumption that only tension T increases and external torque M remains equal zero. The maximal stress σ_{eq} over all wire layers is compared with ultimate tensile stress σ_u at each load step ΔT. If the strength condition $\max \sigma_{eq} \leq \sigma$ is upset, the corresponding wire layer is considered ruptured and removed off the rope structure. Loading step procedure is repeated until the survived wires are still able to take a raised tension. The event when the rope elements start to fail one by one at a constant tension purely due to strain energy release should be recognized as an exhaustion of rope strength. The achieved tensile load is an estimate of rope ultimate tension T_u.

Results of failure simulation for two kinds of initially safe ropes are shown in Fig.6. The load step was set of $\Delta T = 10$ N. Tensile strength of wires in stranded rope was equal to 1770 MPa. Wires in locked coil rope had different strength: core wires – 1570 MPa, Z-shaped wires – 1270 MPa. Dotted lines in Fig.3 mark the certified ultimate tensions T_u evaluated by simplified structure models as was mentioned above. The corresponding values are: 6080 kN for stranded rope and 5100 kN for locked coil rope.

Numbers nearby the signs denote the successive rupture of ropes' elements (wire layers). This process appears in accumulating of active metallic cross-section loss. The failure progress for stranded rope looks as follows: 1÷4 – core layers fail starting with centre wire; 5÷7 – outer strands layers fail starting with center wires. The failure of locked coil rope goes as that: 1÷3 – three core layers fail starting with center wire; 4 – inner Z-shaped layer break; 5 – outer core lay break and so on the fails come of the rest Z-layers. Note that numerical procedure was limited by 30-percentage of cross-section loss when there is a good reason to assume the ropes were really destroyed.

Failure of locked coil rope has an avalanche manner that is a result of rather homogeneous distribution of stresses in wires across the rope section (Fig.5, left). After the first rupture of central core wire the rest wires are loaded additionally and the stresses in all wires come above the tensile strength under the steady tension of 4580 kN. This value is what should be considered as an ultimate tension T_u (breaking load) of rope structure.

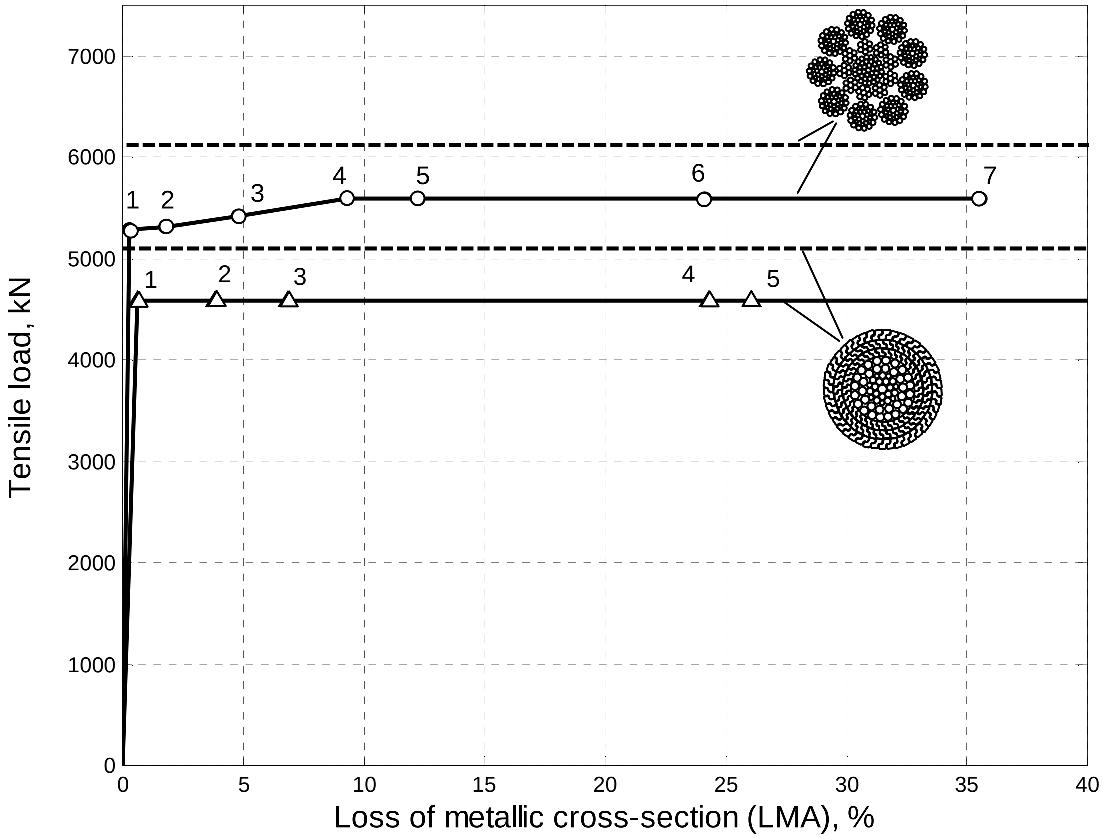

Figure 6: Failure courses of locked coil rope D 72 mm and stranded rope D 84 mm

The stranded rope fails gradually due to initially non-uniform distribution of stresses round the wire layers (Fig.5, right). At initial ruptures the survived loaded wires are able yet to take an increasing tension. As the stresses grow in wires, there comes a moment when a certain layer break (point 4 in Fig.6) leads to strain energy release sufficient to destroy all rest rope elements at stationary load of 5590 kN. This value is a simulated estimate of the rope ultimate tension T_u.

Table 1 contains a summary of different calculated ultimate loads for stay rope types under consideration (in parentheses – the terminology used in current assortments and catalogues).

Ultimate breaking loads for two types of stay ropes

Table 1

Stay rope	Ultimate tension (Breaking Load – BL)		
	Total strength of parallel wires (Calculated BL), kN]	Calculated BL adjusted for helical structure (Minimal BL), [kN]	Simulated BL by refined steel ropes theory [9], [kN]
Locked coil D 72	5850	5100	4580
Stranded D 84	7007	6080	5590

Note that the safety factor (1) related to the lowest of ultimate tensions in Table 1 takes into account the virtual vague factors that could reduce potentially the bearing capacity. Therefore it gives the estimate of rope technical condition with some extra margin of safety.

The residual strength of partially deteriorated rope is defined by actual safety factor $\tilde{n}$ according to expression (2). The corresponding ultimate tension (residual breaking load) $\tilde{T}_u$ for defected rope is not the same as for rated new rope. The presented concept allows assessment of strength parameter $\tilde{T}_u$ by numerical modeling the failure process for given initial damage location. It should be noted that diagnostic parameters LMA and LF are the generalized indexes of degradation. As a matter of fact they are of a random nature and in general do not account for the distribution of faults over the wires. So the statistical modeling of wear locations in the reduced rope cross-section was done and the residual strength parameter $\tilde{T}_u$ was evaluated as a probabilistic assessment. The details of the Monte Carlo procedure are described in [10].

Assessment of breaking load for locked coil rope was performed using the magnetic NDT data shown in Fig.4. The desired value of $\tilde{T}_u$ was of 4500 kN and corresponding relative rope strength loss $\chi = 1 - \tilde{T}_u / T_u$ was equal to 2%. The strength decrease seems completely accessible. However the hazard is that single outer Z-wire break may promote a breakdown of whole layer interlock.

Summary

The proposed combined NDT-theoretical approach is adapted for particular rope subjected to specific working conditions. Several diagnostic parameters are transformed into single indicator – factor of safety that specifies the residual strength of tested deteriorated stay rope as a mechanical structure. The technical state parameter of this kind is habitual for engineers giving the additional argument that may be helpful to suspension bridge maintenance staff.

If a sequence of NDT data is available during the operating time, the possibility appears to plan a moment for future inspection and to predict the residual life-time of stay rope under test.

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