The 2012 World Congress on
Advances in Civil, Environmental, and Materials Research (ACEM' 12)
Seoul, Korea, August 26-30, 2012

Corrosion Monitoring of Steel Bridge Cables

*Alexander Tesar[1)] and Andrej Jarosevic[2)]

[1), 2)] *Institute of Construction and Architecture, Slovak Academy of Sciences, Dubravska cesta 9, 845 03 Bratislava 45, Slovakia*
[1)] *alexander.tesar@gmail.com*

ABSTRACT

Corrosion monitoring of the steel cables supporting rope stayed or suspension bridges is dealt with in present paper. The monitoring is based on numerical and experimental assessment of dynamic testing. The wave approach is used for numerical analysis of the problem. The development and utilization of the EM sensor package is adopted for experimental testing. Submitted is the assessment and evaluation of the results obtained.

1. INTRODUCTION

As significant topic in the assessment of the reliability of rope stayed and suspension bridges appears the corrosion monitoring of the steel cables as classical problem of bridge engineering. Some new approaches, techniques, results and conclusions obtained are submitted in this paper.

The steel bridge cable consists of wires and surface skin. The analysis takes into account the behavior of single wire in interaction with other wires and surface skin. A long-standing difficulty in the assessment of corroded wires of bridge cables is the specification of a consistent theory that describes their failure behavior under non-uniform stress fields. As problem appears there the discrepancy between the bend and simple tensile test data. The bend specimens fail at higher strain compared with the tensile specimens. When the bend and tensile data are analyzed using classical linear elastic theory, the bend stress at any strain prior to failure of a tensile test specimen is 20 - 35 % higher than corresponding axial tensile stress. Such strength discrepancy

[1)] Professor
[2)] Associate Professor

remains unresolved even when corrections are made for the nonlinearity of the stress-strain curves. By attempts to explain such discrepancy only very limited success has been achieved with failure theories, including the Weibull`s statistical model and the fracture mechanics approach. Similar experiences also appeared by the application of linear fracture mechanics or couple-stress theory.

The failure process of corroded wire elements is treated in this paper. The failure analysis is adopted together with formulation of governing equations for modeling and numerical treatment of the problem. Submitted are the results of numerical and experimental assessment of cables on actual bridge.

2. ANALYSIS

In corroded wire members the transformation strains and other field quantities appearing in the elastic modulus are periodic functions of space, time and temperature. The periodicity is exploited in an effort to obtain accurate estimates for the transformation strains used to approximate mechanical properties of wires (Simo 1990).

The Washizu´s variation principle is adopted in order to include initial stress and strain components into the analysis. The stress in the wire element at the beginning of time and temperature increments studied is considered as initial stress with thermal strain increments. The variation principle under consideration is then written in the terms of time rate quantities given by

$$I = \{\textstyle\int_V [S_{ij}\, \varepsilon_{ij} + 0.5\, W_{ij}\, u_{ki}\, u_{kj} - (\varepsilon^o_{ij} + 0.5\, \varepsilon'_{ij})\, S_{ij}]\, dV - \int_{A1} r_i\, u_i\, dA1 - \int_{A2} s_i\, (u_i - w_i)\, dA2\}(dt)^2$$

$$+ \{\textstyle\int_V W_{ij}\, \varepsilon_{ij}\, dV - \int_{A1} r_i\, u_i\, dA1 - \int_{A2} p_i\, (u_i - w_i)\, dA2\}dt \quad ,$$

(1)

where W_{ij} and S_{ij} are the Piola-Kirchhoff tensors for initial stress and strain rate states, respectively. The symbols p_i and s_i are the Lagrangian surface traction and its time rate quantity, respectively. The symbols r_i and $r_i^{(.)}$ are prescribed on the surface area $A1$ and w_i on area $A2$. V is the volume specified by surface area $A = A1 + A2$. The total strain rate ε_{ij} consists of initial strain rate ε^o_{ij} and ε'_{ij}, corresponding to the instantaneous stress rate S_{ij}. In order to evaluate the thermal strain rate, the thermal expansion coefficient at temperature T is $\alpha(T)$ and at temperature $T + dT$ is $\alpha(T + dT)$. By expanding $\alpha(T + dT)$ into Taylor series, the average thermal strain rate is obtained.

The governing equation is given by

$$\mu\, \Delta(w_t) + (\lambda + \mu)\, grad(div\, w_t) + f = \rho\, \partial^2 w_t / \partial t^2 \quad ,$$

(2)

where λ and μ are Lame´s constants, the mass density is ρ, corresponding Laplace operator is Δ, body force vector is f and the vector of displacements is w_t (Tesar 1993).

In the terms of derivatives of displacements w_t the governing equation of motion is given by

$$c_2^2\, w_t + (c_1^2 - c_2^2)\, w_t + f_i/\rho = a_t \quad ,$$
(3)

with propagation velocities for dilatation waves

$$c_1 = \sqrt{[(\lambda + 2\mu)/\rho]}$$
(4)

and shear waves

$$c_2 = \sqrt{(\mu/\rho)} \quad .$$
(5)

Strain and stress components are given by

$$\varepsilon_{ij} = (w_{i,j} + w_{j,i})/2$$
(6)

and

$$\sigma_{ij} = \lambda\, \varepsilon_{kk}\, \delta_{ij} + 2\, \mu\, \varepsilon_{ij} \quad , \quad i,j,k = 1,\, 2,\, 3$$
(7)

with Kronecker delta function δ_{ij}. When neglecting the body forces and using the divergence of each term, then equation (2) specifies the shear waves by

$$\Delta\Phi = \Phi/c_1^2 \quad ,$$
(8)

with

$$\Phi = div\, w_t \, .$$
(9)

The rotation of each term in Eq.(2) states the shear waves by

$$\Delta\psi = \psi/c_2^2 \quad ,$$
(10)

with

$$\psi = (rot\, w_t)/2 \quad .$$
(11)

An idea appears here to adopt the micromechanical modeling of wires by strings in order to study the problem (Budiansky 1983). Adopting the above approach the ultimate analysis of corroded bridge cables is given by

1. Micro-mechanical modeling of the wire material and corrosion damages as well as macro-mechanical modeling of the cable configuration in space, time and temperature.
2. Updated calculation of stress and strain in space, time and temperature.
3. Automatic comparison with ultimate strength of the steel material adopted.
4. Initiation of cracks in all micromechanical elements trespassing the ultimate strength.
5. Updated calculation of the crack distribution in space, time and temperature until total failure of the cable (Tesar 1988).

The regime of the crack initiation and distribution is rather complex. One or several cracks develop and propagate along the critical regions of the cable. In the case of the shear the cracks turn inside of the cable body in a direction being quasi-perpendicular to the tension.

3. MEASUREMENT AND APPLICATION

In scope of the assessment of the rope stayed steel New Bridge crossing Danube in Bratislava, Slovakia (Fig. 1) the new testing approach for the corrosion monitoring of the steel cables was developed. The bridge has main span 303 m and is supported by steel cables anchored in the main field. The cables are led over the skew pylon with height 90 m into the end anchor chamber. The width of the bridge is 22 m. As significant topic there appears the corrosion monitoring of the steel cables.

The bridge is subjected to regular testing in order to obtain all necessary input data for virtual assessment of its reliability and safety (Tesar 2008). The testing is made adopting the trucks moving with smooth runs as well as crossing the artificial barriers located on the runway of the bridge. In scope of dynamic testing the natural frequencies, the dynamic coefficients, the logarithmic decrements of damping, maximal amplitudes, velocities and accelerations of deformations are measured. The numerical assessment of all above data submits the conclusions concerning actual reliability and safety of the bridge.

The EM sensors were used for the assessment of forces in steel cables (Jarosevic 2008). The measuring rate is limited by a magnetization process in cable and by inductance of the EM sensor magnetizing coil. For small EM sensors (single strands) the maximum measuring rate is about one reading in 5 seconds. For the EM sensors (cables), due to slow current decay, the measuring rate is one reading in 60 seconds. In static mode the EM sensor allows precise measurement of the static load but is not applicable for dynamic measurement.

Very simple physical principle, however, allows the utilization of the same EM sensor for dynamic measurement. During the static measurement a large current pulse flows through the magnetizing coil of the EM sensor and after taking reading the measured steel remains magnetized (residual magnetic flux density). The dynamic load affects the stress σ in the steel cable and consequently also the magnetic flux in the cable. It means that in the coil around the cable the change of the magnetic flux will induce the voltage given by

Fig. 1. New Bridge crossing Danube in Bratislava

$$U_{ind} = - d\Phi(\sigma)/dt \quad . \qquad (12)$$

At the output of the electronic integrator with the time constant RC there is obtained the voltage being proportional to the change of the stress (or force). The integrator should have very low drift. In the experimental assessment was used the integrator with low offset LTC1051. The EM sensor was calibrated in the dynamic mode by the same way as in the static mode by application of the static load. The remaining magnetic field in the cable slowly decays (due to stress changes) and approaches the an-hysteretic curve. For stable readings the cable must be after certain time again magnetized by the current pulse or permanently magnetized using strong permanent magnet.

For further processing, especially in the spectral analysis, the output voltage was logged by the multimeter EXTECH ML720, with data logger capacity 43000 samples (more than 35 minutes record) and a minimum sampling interval 0.05 s.

The EM sensors were installed at the cables of the New Bridge. The dynamic testing of the bridge was used for the experiments with the EM sensor in dynamic mode. Some results obtained by such test are submitted below. The EM sensors for the test were located at steel cables (locked coil, diameter 70 mm) in the splain chamber, where all 64 cables are anchored. The static force in each cable is about 1200 kN.

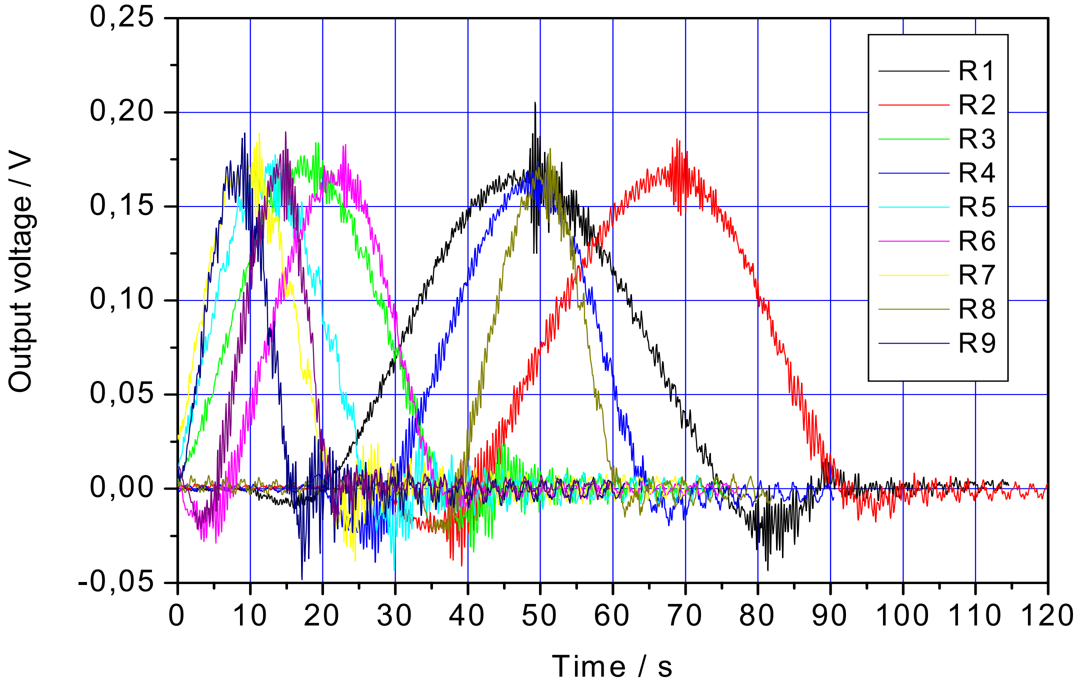

Fig. 2. The overview of all time records taken during dynamic testing (truck and artificial barrier)

The view of all time records taken during dynamic testing of the bridge is plotted in Fig. 2. Stays are assembled of 4-16 locked coil cables with diameter 70 mm and with cross-sectional area 3390 mm^2. The cables are anchored in the chambers inside of thin-walled bridge box girder. The assessment of stays was aimed on two problems:

- force distribution between cables of the whole stay and
- comparison of the cross-sectional area of the measured cables in order to find possible corrosion damages.

The natural frequency of the free length L [m] of the cable with cross-sectional area A [m^2], with density m [kg.m^{-3}] and loaded by the force F [N], is given by equation

$$v = 1/(2L) \sqrt{(F/(A^2 m))} \quad . \qquad (13)$$

Eq. (13) allows to estimate roughly (precise equation contains also the stiffness) the acting force in order to compare all forces in the cables.

The corrosion of the cable results in decreasing of the cross-sectional area of the steel material adopted. The EM method can be used under certain conditions also for estimation of the changes in the cross-sectional area of the cable. The EM sensor allows the estimation of the magnetic permeability of the cable depending on stress σ and temperature T by

$$\mu(\sigma,T) = 1 + A_0/A_f\,(\Phi_{out}(\sigma,T)/\Phi_0 - 1) \quad , \tag{14}$$

where

A_0	is the cross-sectional area of the coil,
A_f	is the cross-sectional area of the measured steel cable,
$\Phi_{out}(\sigma,T)$	is the magnetic flux in the area of the coil with the measured cable inside and
Φ	is the magnetic flux in the area of the coil without cable (empty EM sensor).

The relationship between magnetic permeability, stress and temperature is for working conditions available by approximating the linear dependence given by

$$\mu(\sigma,T) = \mu(0,0) + m.\sigma + \alpha.T \quad , \tag{15}$$

where m is the elastic-magnetic coefficient and α is the temperature coefficient. The initial permeability μ(0.0) depends on the magnetic properties of the measured cable. For practical purpose there holds

$$\Phi_{out}(F,T,A_f) = \Phi_0\,(1 + A_f/A_0\,(\mu(0,0) - 1) + m\,F/A_0 + A_f/A_0\,\alpha.T) \quad . \tag{16}$$

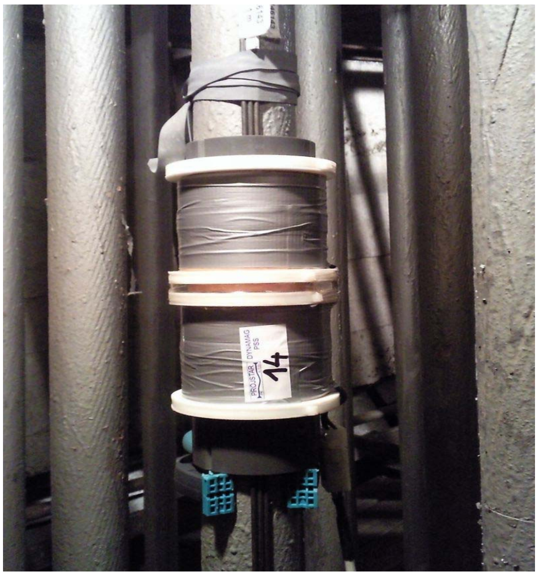

Fig. 3. EM sensor calibration in situ

Under constant load (F=const) and temperature the output magnetic flux depends only on the cross-sectional area of the steel cable A_f .

According to experiences obtained for high tensile steel, the elastic-magnetic coefficient is approximately given by $m=10^{-3}$/MPa. The cross-sectional area of the cable is A_f = 3390 mm^2 and the area of the sensing coil is A_0=6362 mm^2. Initial magnetic permeability for the used EM sensor is approximately 12 and correspoding magnetic flux is Φ_0=8 mWb. The temperature coefficient for high tensile steel is approximately $\alpha = -10^{-3}$/°C. The substitution to the above relationship shows that the change of the magnetic flux in mWb is given by A_f in mm^2 and F in kN

$$\Delta\Phi_{out}(F,T,A_f) = \Phi_0\,(0.0017\,\Delta A_f + 0.00016\,\Delta F_f) \quad . \tag{17}$$

The acting force is around 1000 kN (or stress 300 MPa). The change of 1 mm^2 in the cross-sectional area of the steel cable (what is about 0.03%) results in the change of the magnetic flux 0.014 mWb (stated by calibration). The change of 100 kN in the force (what is about 10%) results in the change of the magnetic flux 0.128 mWb. The equivalent change of the cross-sectional area is 9 mm^2 or only 0.27% of the nominal cross-sectional area of the cable.

To exclude the magnetic “memory” of the cable – hysteresis – the examined free length of the cable is to be magnetized to deep saturation in the steps by 10 cm in direction from deviator to the anchor beam.

This approach allows the comparison of the cross-sectional area of all 15 measured cables near the bottom anchor. The corrosion of the cable (due to possible penetration of water inside the cable) should be most significant in the bottom of the cable.

The EM sensors were installed at selected 15 cables – 13 inside of the bridge box girder and 2 inside of the splay chamber. The EM sensors were manufactured in situ using special winding rig and splitted bobbins. All EM sensors including the reference sensor are identical with the same number of turns.

The EM method is a relative method, like a resistive strain gauge. Without measuring the elastic-magnetic characteristics of the cable sample in the laboratory it is possible only to compare the magnetic properties of the cables with installed EM sensors. Cables used at the New Bridge were produced more than 40 years ago and no samples of them are available today.

The EM sensor and the package DYNAMAG measure the magnetic flux in the cross-sectional area of the sensing coil. The magnetic flux is affected also by the ferromagnetic surrounding of the EM sensor. From this point of view it is important to compare the magnetic properties of the measured cables in the same package. The most suitable position is near the bottom anchor where the arrangement of all cables is practically the same.

The first step was to calibrate EM sensor sensitivity to steel cross-sectional area in the laboratory using the reference EM sensor with the sample of commonly used steel cables. The cross-sectional area sensitivities are 0.0124 mWb/mm^2 and 0.0184 mWb/mm^2, what allows to find the change of the steel cross-sectional area in scope of more as 2 mm^2.The same approach was applied also at the bridge as shown in Fig. 3. Estimated sensitivities are 0.0141 Wb/mm^2 and 0.0189 mWb/mm^2. The magnetic flux is slightly affected by the traffic load what decreases the minimum detectable change in the cross-sectional area of the cable in scope of 5 mm^2.

In Fig. 4 is shown the magnetic flux along the cable for two working points. The first part responds magnetizing from the deviator to the anchoring bar with the step 100 mm. The second part of the plot corresponds to the magnetic flux during movement from the anchoring bar to the deviator with the step 200 mm. In each location were taken 5 readings. The change of the magnetic flux at the free length of the cable is affected by the ferromagnetic surrounding – other cables, ribs, etc. Only massive steel cover around the EM sensor could reduce this influence.

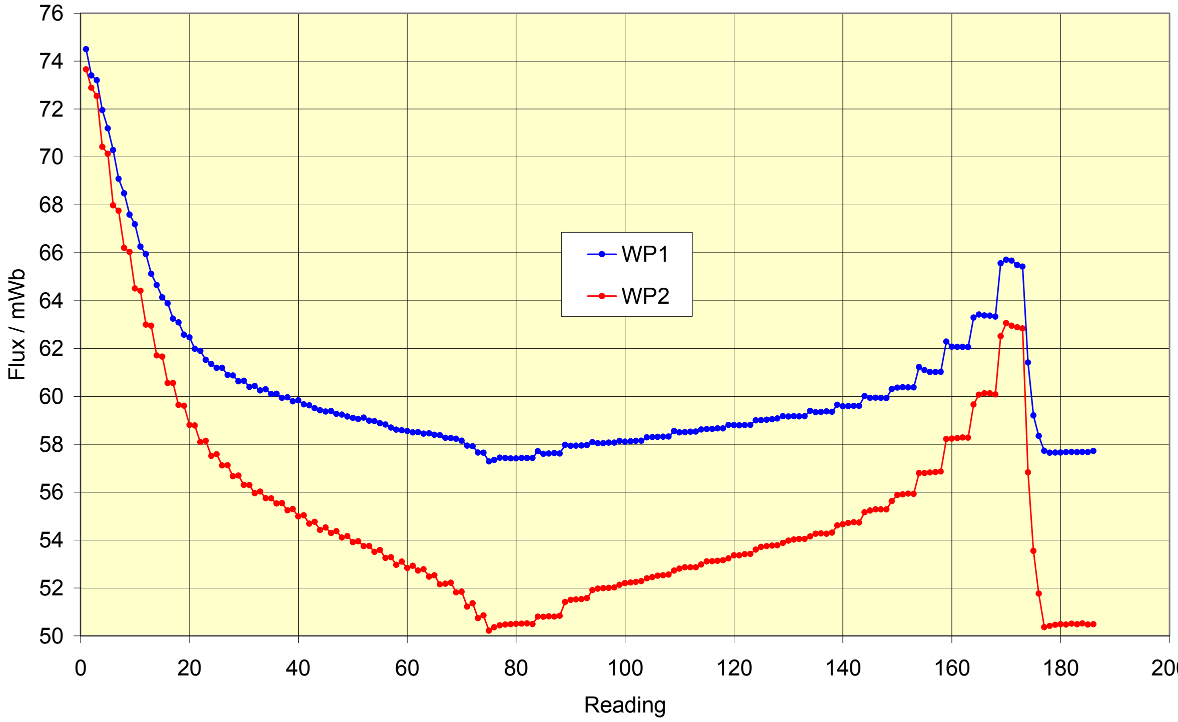

Fig. 4. Magnetic flux during moving the EM sensor along the free length of the cable

In Table 1 are summed up some results obtained – the number of the cable studied, its free length, measured magnetic flux in the bottom position (EM sensor at the anchor bar) for both working points, measured natural frequency of the free length, calculated force (from the string equation) and stress.

Table 1

Measured magnetic flux [mWb] in position near the anchor. Measured own frequency [Hz] of the cable. Force [kN] and stress [MPa], estimated from the own frequency.						
Cable	Length / m	Flux_2 / mWb	Flux_1 / mWb	Own frequency / Hz	Force / kN	Stress / MPa
1	4.05	56.381	51.195	26.611	1244	367
2	4.05	56.041	50.604	26.855	1267	374
3	5.15	57.029	49.309	24.902	1762	520
4	5.15	56.685	48.953	22.705	1465	432
5	7.20	57.518	50.673	15.625	1356	400
6	7.20	57.720	50.482	14.648	1192	351
7	4.05	55.824	50.795	26.123	1199	354
8	4.05	55.463	49.781	27.344	1314	388
9	5.15	56.273	48.477	23.682	1593	470
10	5.15	56.290	49.527	23.193	1528	451
11	5.15	56.011	48.132	25.879	1903	561
12	7.20	56.651	50.319	15.381	1314	388
13	7.20	56.385	50.050	15.625	1356	400
14		56.634	51.276	8.057		
15		54.808	50.605	7.813		

CONCLUSION

The EM sensor can be used also for estimation of the change in cross-sectional area of the free length of the steel cable under load. Uncertainty of the measurement is affected not only by manufacturing tolerances of steel cables (up to 2%) but also by the dispersion of the magnetic properties of steel. This was not tested during production. But in the most cases uncertainty of several % is acceptable.

The EM sensors are now permanently installed at the cables of the bridge studied and allow not only repeated testing of cables in the future but are used also during regular testing of the bridge for direct measurement of the longitudinal stress in cables. The assessment of the results measured has stated no problems with actual corrosion damage of the cables.

Numerical evaluation of the results obtained by adoption of above theoretical approach, has stated full reliability and safety of the bridge from the aspects of the corrosion monitoring of cables.

REFERENCES

Tesar, A. (1988). "Transfer Matrix Method", KLUWER Academic Publishers, Dordrecht, Boston, London.

Tesar, A. and Svolik, J. (1993). "Wave distribution in fibre members subjected to kinematic forcing", *Int. Journal for Communication in Numerical Mechanic*s, 9, 32-40.

Simo, J.C. (1990). "On a fully three-dimensional finite strain viscoelastic damage model - formulation and computational aspects", *Compuct. Meth. Engng*. 29, 1990, 140-160.

Budiansky, B.(1983). "Micromechanics". *Computers & Structures*, Vol. **16**, No. 1-4.

Tesar, A. and Bencat, J. (2008). "Dynamic testing of the New Bridge crossing Danube in Bratislava". *Technical Report, TESAR & PARTNER Engng.*, Bratislava.

Jarosevic, A. and Chandoga, M. (2008). "Corrosion monitoring of cables of New Bridge crossing Danube in Bratislava". *PROJSTAR Consulting Engineers*, Bratislava.