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Corrosion Monitoring of Steel Bridge Ropes

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Abstract: Corrosion monitoring of steel bridge cables is treated below. Simulation model adopting the Washizu's variational principle and backpropagation neural network approach is used for numerical analysis of the problem. The numerical treatment of nonlinear problems appearing is made using the updated Lagrangian formulation of motion. The feasibility of parallel processing combined with backpropagation neural network is established. Adoption of EM-sensors for experimental testing in situ. Numerical and experimental verifications are submitted.

Key words: corrosion monitoring, EM-sensors, neural network, parallel processing, steel ropes, ultimate behavior

1. Introduction

Corrosion monitoring of steel bridge cables has recently become the focus of intense efforts in structural engineering. This is because of pressing problems of disaster prevention after long-termed exploitation of steel cables in slender structures, such as space and offshore facilities, guyed masts, cable roofs, bridges or lines of high voltage air conductors subjected to heavy dynamic loads. Required is treatment of questions associated with the ultimate behavior and reliability of such cables.

The cables are simulated by models adopting the wave analysis on the micromechanical level considering the behavior of their multi-string elements configurated in backpropagation neural network mesh adopted.

In this paper the following is presented below:

1) mathematical formulation of the governing wave equations for the analysis of steel ropes,

2) brief description of the ultimate analysis adopting the parallel wave processing and EM-sensors testing approach,

3) actual application with numerical and experimental verifications in situ.

2. Behavior of Steel Rope

When a steel cable specimen consists of densely packed inclusions, the interaction effects of inclusions may play a dominant role in the behavior of the resulting continuum. The concept of transformation strain can be used when an elastic medium contains periodically distributed inclusions or voids in the material. Because of the periodicity, the transformation strains as well as other field quantities entering into the estimate of elastic moduli are periodic functions of space, time and temperature. The periodicity is exploited in an effort to obtain accurate estimates for transformation strains used to approximate mechanical properties of the steel ropes studied.

The Washizu's variational principle [1] is adopted in order to include initial stress and strain components due to the isothermal deformation in time. The stress in the microelement of the simulation model adopted at the beginning of time increment studied is considered as initial stress and strain increments. The variational principle under consideration is then written in the terms of time rate quantities given by

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$I = \{\int_V [S_{ij}\, \varepsilon_{ij} + 0.5\, W_{ij}\, u_{ki}\, u_{kj} - (\varepsilon^o_{ij} + 0.5\, \varepsilon'_{ij})\, S_{ij}]\, dV - \int_{A1} r_i^{(\cdot)}\, u_i\, dA1 - \int_{A2} s_i\, (u_i - w_i)\, dA2\}(dt)^2 + \{\int_V W_{ij}\, \varepsilon_{ij}\, dV - \int_{A1} r_i\, u_i\, dA1 - \int_{A2} p_i\, (u_i - w_i)\, dA2\}dt$ (1)

where W_{ij} and S_{ij} are the Piola-Kirchhoff stress tensors for initial stress and strain rate states, respectively, p_i and s_i are the Lagrangian surface traction and its time rate quantity, respectively, r_i and $r_i^{(\cdot)}$ are prescribed on surface area A1 and w_i on area A2 and V is the volume bounded by surface area A=A1+A2. The total strain rate ε_{ij} is composed of the initial strain rate, thermal expansion coefficient at temperature T be $\alpha(T)$ and at temperature T+dT be $\alpha(T+dT)$. By expanding $\alpha(T+dT)$ into Taylor series, the average thermal strain rate is obtained.

The governing wave equation for the treatment of the ultimate fatigue behavior of the elastic continuum of steel ropes is then given by

$$\mu\, \eta(u_t) + (\lambda + \mu)\, \mathrm{grad}(\mathrm{div}\, u_t) + f = \rho\, \partial^2 u_t/\partial t^2 \quad (2)$$

where λ and μ are Lame's constants, mass density is ρ, corresponding Laplace operator is η, the body force vector is f and the vector of displacements is u_t.

In the terms of derivatives of displacement components u_t, the governing wave equation is modified by

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

with propagation velocities for dilatational and shear waves

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

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

Strain and stress components are defined by

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

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

with Kronecker delta function δ_{ij}.

Further numerical analysis of the problem, adopting the backpropagation neural network approach and taking into account the feasibility of the parallel processing technique, is to be made on the basis of references [2-6].

3. Corrosion Monitoring

The EM-sensors combined with the spectral resonance analysis are used for the assessment of forces in corroded steel ropes and their wires.

The measuring rate is specified by the magnetization process in the rope and by the inductance of the EM-sensor magnetizing coil. In static model the EM-sensor allows precise measurement of the static load. Simple physical principle allows the utilization of EM-sensors also for dynamic measurement. During static measurement a large current pulse flows through the magnetizing coil of the EM-sensor and after reading the measured steel remains magnetized (residual magnetic flux density). The dynamic load affects the stress σ in the steel rope and consequently also the magnetic flux $\Phi(\sigma)$ in the cross-sectional area of the rope. In such a way in the coil around the rope the change of the magnetic flux will induce the voltage given by

$$U_{ind} = -d\Phi(\sigma)/dt. \quad (8)$$

At the output the electronic integrator specifies the change of stress (or force). The EM-sensor can be calibrated in dynamic mode in the same way as in static mode by application of the static load. The remaining magnetic field in the rope decays in accordance with stress changes. For stable readings the rope after certain time must be magnetized again by the current pulse or permanently magnetized using strong permanent magnet. For processing in the spectral approach the output voltage is to be logged with data logger capacity at least 43000 samples with more than 35 minutes record and with a minimum sampling interval 0.05 sec.

Above approach is to be combined with resonance analysis technique in order to specify the variability of resonance frequencies due to the cross-sectional decrease associated with corrosion of the rope [2-6].

4. Measurement and Application

In scope of the assessment of the rope stayed steel bridge crossing Danube in Bratislava (Fig. 1) the above testing approach for corrosion assessment of cables was adopted. The bridge has the 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 anchor chamber. The bridge is subjected to regular testing in order to obtain all necessary data for virtual assessment of its reliability and safety.

Fig. 1 View of the bridge studied.

The EM-sensors in dynamic mode were installed at the ropes in the splain chamber (Figs. 2 and 3) of the bridge. Stays were anchored in the chambers inside of thin-walled bridge box main girder. The assessments of stays were focused on two problems:

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

The resonance frequencies of the main ropes anchored in thin-walled box girder were calculated in scope of spectral analysis taking into account the P-Delta as well as the P-Delta + Large Displacements nonlinearities.

The corrosion of the rope results in decrease of its cross-sectional area. The EM-approach can be used for estimation of the changes of such cross-sectional area.

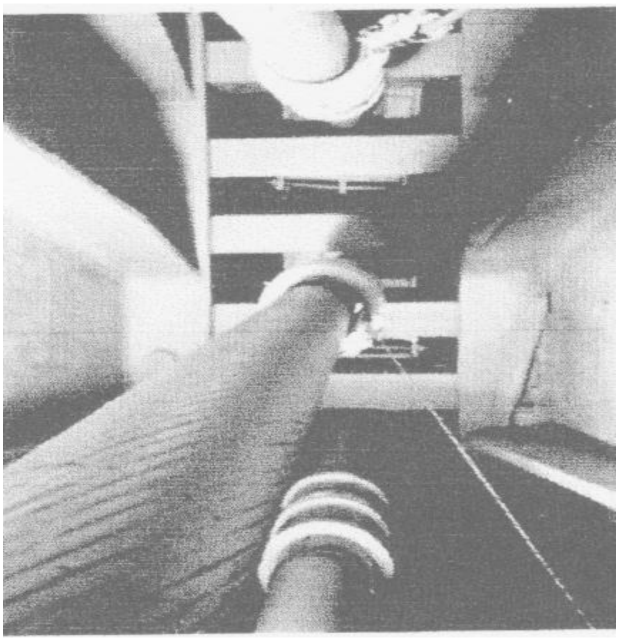

Fig. 2 The EM-sensors located near the bottom anchor inside bridge box girder.

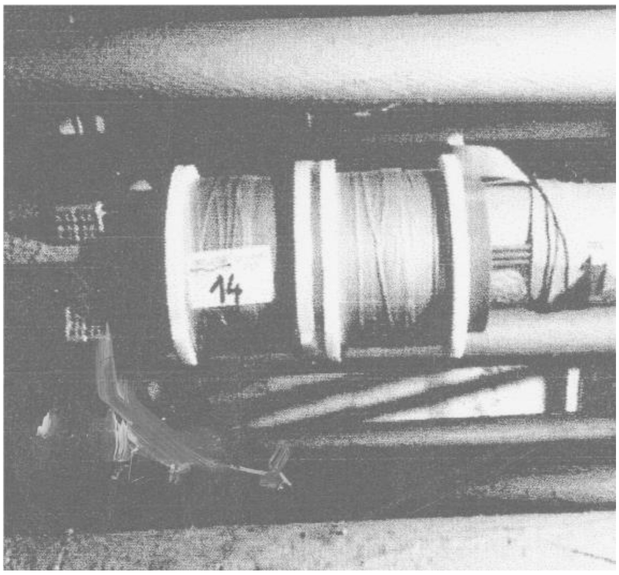

Fig. 3 The EM-sensor calibration in situ.

The EM-sensor allows the estimation of magnetic permeability of the rope depends on stress σ and temperature T by

$$\mu(\sigma,T) = 1 + A_0/A_f\,(\Phi_{out}(\sigma,T)/\Phi_o - 1) \qquad (9)$$

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

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

$$\mu(\sigma,T) = \mu(0,0) + m.\sigma + \alpha.T \qquad (10)$$

where m is the elastic-magnetic coefficient and α is the temperature coefficient. Under constant load (F = const.) and temperature the output is the magnetic flux depends only at cross-sectional area of the cable A_f.

According to experiences obtained the substitution to above relationship specifies the change of the magnetic flux given by A_f in mm^2 and F in kN,

$$\Delta\Phi_{out}(F,T,A_f) = \Phi_0\,(0.0017.\Delta A_f + 0.00016.\Delta F_f) \qquad (11)$$

Equivalent change of cross-sectional area was found to be 9 mm^2 or 0.27% of nominal cross-sectional area of the rope studied.

The EM-sensors were installed at selected ropes (Figs. 2 and 3) and were manufactured in situ using special winding rig and bobbins. All EM-sensors were identical, with the same number of turns.

The EM-approach is a relative method like a resistive strain gauge. Without measuring the elastic-mechanic characteristics of the rope in laboratory is possible to compare magnetic properties of the ropes with installed EM-sensors. The EM-sensor and corresponding packages measure the magnetic flux in cross-sectional area of the sensing coil. The magnetic flux is affected also by ferromagnetic surrounding of the EM-sensor. Therefore it is important to compare the magnetic properties of ropes in the same package.

Measured vibration of shortest rope of the bridge has submitted its resonance frequency 26.855 Hz. Calculated resonance frequency of the same rope is 26.318 Hz. It is ca. 2% lesser value and corresponds with additional averaged cross-sectional decrease of 0.37%. Similar evaluations pay also for other ropes of the bridge.

5. Conclusions

Above EM-sensor approach can be used for evaluation of corrosion decrease in cross-sectional area of steel ropes utilized as load-bearing members of thin-walled steel bridges. Uncertainty of measurement can be affected not only by manufacturing tolerances of steel ropes but also by dispersion of magnetic properties of steel.

The EM-sensors are now permanently installed at the ropes of the bridge studied above and will allow not only repeated testing of the ropes in future but can be used in scope of regular testing of the bridge for direct measurement of stress in ropes.

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