EUROPEAN NDT&CM2021 PRAGUE, CZECH REPUBLIC OCTOBER 4-7, 2021
BETTER CM & NDT – WARRANTY OF QUALITY, RELIABILITY AND SAFETY
FOUR NDT, CM AND SHM EVENTS IN ONE WEEK IN THE MIDDLE OF THE EUROPE
WE GO HYBRID!

Use of Non-destructive Techniques to Detect Damage Induced by Corrosion of Pre-stressing Steel Strands

Josef STRYK[1], Monika MANYCHOVÁ[2], Marta KOŘENSKÁ[1], Aleš FRÝBORT[1], Václav SVOBODA[3]

[1]CDV -Transport Research Centre, Líšeňská 33a, 636 00 Brno, Czech Republic, +420 549 429 330; josef.stryk@cdv.cz, korenska.m@email.cz, ales.frybort@cdv.cz
[2]Brno University of Technology, Faculty of Civil Engineering, Veveří 331/95, 602 00 Brno, Czech Republic; manychova.m@fce.vutbr.cz
[3]Preditest Ltd, Pod višňovkou 23, 140 00 Praha 4, Czech Republic; svoboda@preditest.cz

Abstract

The aim of this work is to provide confirmation of the possible use of two non-destructive techniques to detect damage of pre-stressing steel strands due to corrosion. For this purpose accelerated corrosion procedure has been conducted on these strands in laboratory conditions. Corrosion consequences were analyzed for various duration of accelerated corrosion process. The ultrasonic techniques and metal magnetic memory (MMM) method were used in this experimental study. The results show the application potential of ultrasonic techniques to analyze the effect of damage induced by accelerated corrosion on the nonlinear elastic behaviour of a steel strands. A new parameter, based on sensing of the magnetic field strength in the form of residual magnetization on the surface of the material, has been used in this study. Appraising parameters of measurement by the metal magnetic memory method were presented in the form of magnetogram – dependence of the magnetic field strength and field gradient on the measured distance. The changes of the magnetic field strength proved different stress concentration zones in the steel strands due to corrosion consequences. Subsequently, the differently corroded strands were subjected to tensile tests in order to determine their mechanical properties to verify and complement results of non-destructive tests.

Keywords: Pre-stressing steel strands, electrochemical corrosion, cracking, nonlinear ultrasonic testing, metal magnetic memory method.

1. Introduction

Pre-stressed concrete is a complex material taking advantage of the combination of concrete and steel reinforcement. There is a need to study how pre-stressed concrete structures react to damage processes in the build environment. Steel reinforcement corrosion belongs to these damages very often. This paper is a continuation of our previous work on the analysis of damage effects induced by corrosion on the linear and nonlinear elastic properties of a pre-stressing steel strand during the accelerated corrosion process [1]. Having gained first results and experience we switched our focus on combination of two non-destructive methods for this purpose. The ultrasonic techniques and metal magnetic memory (MMM) method were used in our experimental study. The aim of this contribution is to analyze the effects damage induced by corrosion on the nonlinear elastic properties and metal magnetic memory parameters of the prestresing steel strand after accelerated corrosion process. Precisely the combination of these two methods may contribute to a great deal to further improvement of the defectoscopy and analysing steel corrosion consequences in reinforced concrete structures.

2. Preparation of specimens for experiment

Commercially available seven-wire steel strand of 15.7 mm in diameter was object of our experiments. The strand consists of a steel central straight wire surrounded by six helical wires. Eight strand pieces of 1.3 m in long were the subject of the experiment. The strands were divided into two groups, labelled L9 and L10. One piece was left in its original state and three pieces of strands were subjected to different degrees of electrochemical corrosion in each group. The duration of the corrosion process was set for individual strands for 2, 6 and 12 hours. The strands labels were following: L90, L100 - strands were not subjected to corrosion, L92, L96, L912 and L102, l06, L1012 - strands according to the duration of their accelerated corrosion. The electrochemical corrosion process has been described in detail in [1] and is briefly described here. The cylindrical corrosion cell was replaced by a box with a removable top, allowing visual inspection of the progressive corrosion of the strand during the corrosion process, which was accelerated by an electric current of a constant value of 3 A. The strand central part of 50 mm length was only subjected to corrosion; remaining steel surface in corrosion box has been coated with an electric insulator. An illustration of the corrosion process realization, including the detail of the corrosion box is shown in Fig. 1.

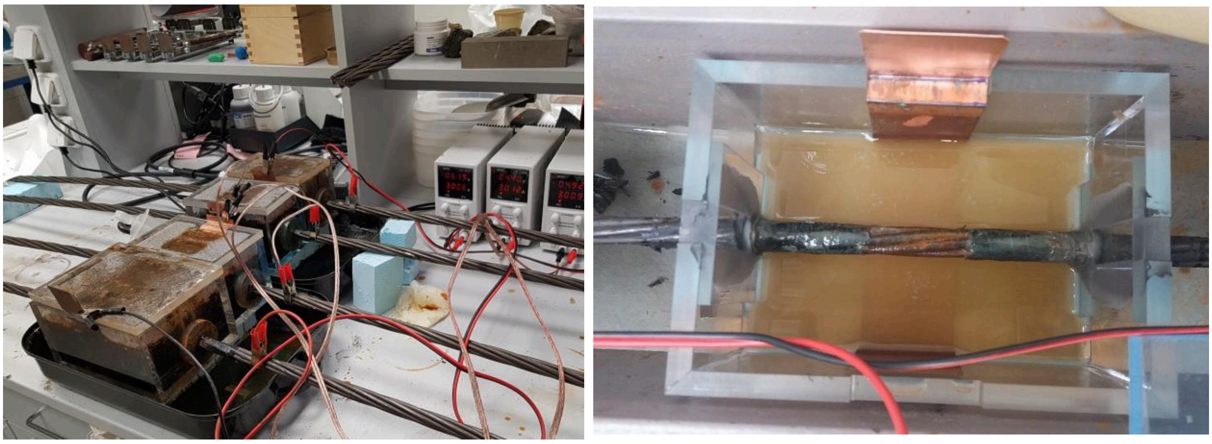

Figure 1. Illustrative record of prestressing strands subjected to accelerated corrosion: on the left - four strands exposed to corrosion process; on the right - detail of the corrosion box

The corroded strands were measured by non-linear ultrasonic spectroscopy in CDV laboratories and after that had drive transport to Preditest company for MMM measurement and tensile testing. The visual condition of all measured strands is documented in Fig. 2. The strands are sorted according to the increasing duration of the corrosion process: L90 to L912; L100 to L1012.

Figure 2. Two groups of measured strands: on the left L9 group; on the right L10 group

2.1 Nonlinear measurements

As results, when an ultrasonic wave propagates through material and interacts with the micro-structural defects, non-linear effects linked to these higher order waves are generated. As the micro-damage grows, non-linearity should increase. Nonlinear dynamic response may manifest itself in a variety of manners.

Nonlinear methods focusing on the material response nonlinearity have been described in many papers for example [2]. A single harmonic ultrasonic signal measurement method which has been applied to the experiment is briefly described below.

This method analyses the effect of nonlinearities on acoustic signals propagating through the specimen. The nonlinearity gives rise to additional signals featuring different frequencies according to Fourier expansion. In general, the amplitudes of these additional components decrease with natural number *n.* In this case, where the excitation is accomplished by a single frequency f_1 (Fig. 3) the nonlinearity gives rise to other harmonic signals, whose frequencies f_v obey the Fourier series formulas:

$$f_n = n \cdot f_1 \quad \rightarrow \quad \big|\, n = 0, 1, 2, \ldots \infty \tag{1}$$

In general, these frequency component amplitudes are falling when the harmonic order natural number, *n*, is increasing. If the nonlinearity effect is not entirely symmetrical, there can arise low-amplitude second and higher even-numbered harmonic components, whose amplitudes may be lower than those of the odd-numbered ones. Among these emerging components, the third harmonic is the most distinctive one, see Fig. 3. Therefore, its amplitude is pursued most frequently [3].

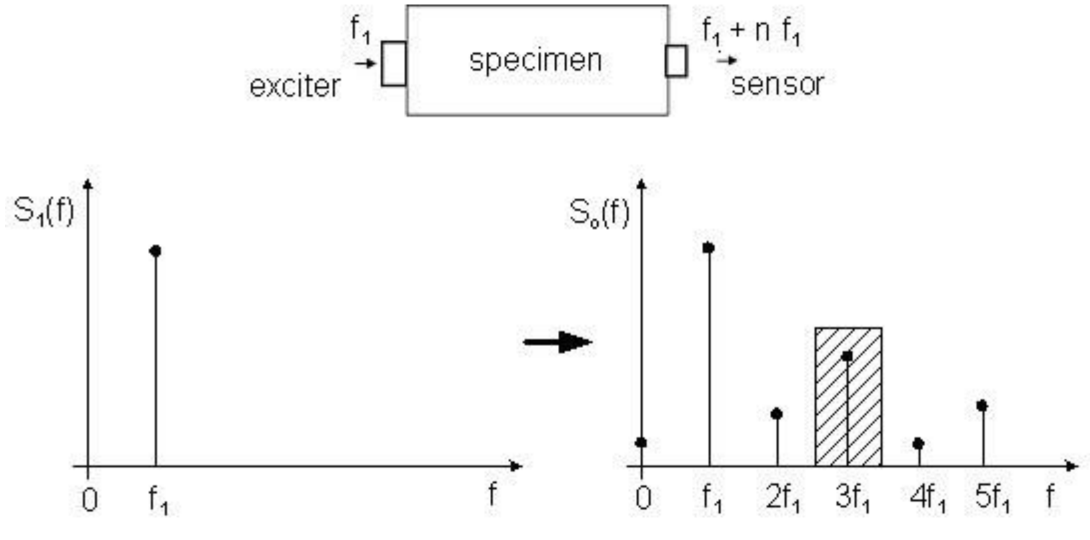

Figure 3. Frequency spectrum of a nonlinear medium response

In the framework concerned the degradation of the strands, in the act of the corrosion process consequences, is linked to a nonlinear mechanical behaviour. As a result, when an ultrasonic wave propagates through the strand and interacts with microstructural defects, nonlinear terms linked to these higher order waves are generated. As the microdamage grows, nonlinearity should increase.

Two different strategies have been used in this study to put evidence the appearance of nonlinear features due to damage of distinct corroded strands. First, the observation of the frequency spectrum of the received signal, which may allow direct observation of the higher harmonic generation or intermodulation distortion features, see Fig. 3. In second place the nonlinearity parameter can be derived from the amplitudes of the fundamental and harmonic frequencies. Assuming that changes in the wave propagation velocity and the attenuation are small, and in experimental conditions like those used in this work (nonlinear measurements done with an input signal of fixed frequency, and the transducers located always at the same positions), the parameter of nonlinearity can be approximated as: $Bpn = A_3 / A_1^3$, being A_1 amplitudes of the fundamental and A_3 third harmonic waves [4]. In practice, the variation of these ratios relative to the initial undamaged conditions is used as an indicator of the microstructural damage [5].

2.1.2 Measurement results

Measuring results from the first strategy are represented by the following Fig. 4 showing the values of higher harmonic frequency amplitudes as a percentage of the 1st harmonic (exciting frequency f_1) amplitude for both groups.

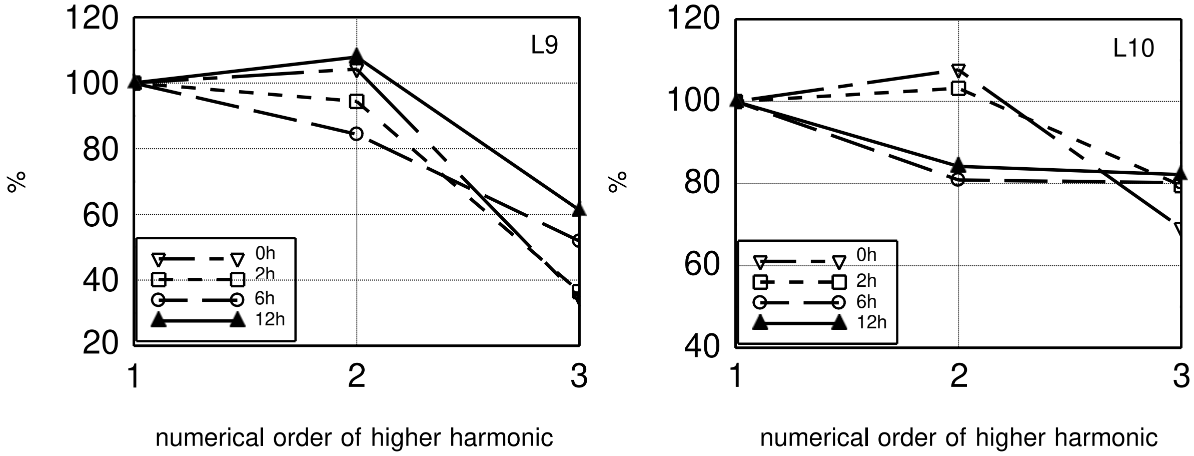

Figure 4. Higher harmonic frequency amplitudes expressed as a percentage of the first harmonic amplitude; on the left - group L9, on the right - group L10

It is apparent from Fig. 4 that the amplitudes of the third harmonics (A_3) are always lower than the fundamental amplitude (A_1) in all frequency spectra. Anomalies are evident in some spectra; the second harmonic amplitude (A_2) exceeded the fundamental amplitude in the case of non-corroded strands L90 and L100, strand L912 (after 12 hours of corrosion process action) and strands L102 (after 2 hours of corrosion process action). The consequences of corrosion manifested by a growing in the amplitude values of the third harmonics after 6 and 12 hours of corrosion action, as can be seen in both graphs in Fig. 4. This observation point out to the possibility that nonlinear ultrasonic measurements may provide an early warning of the damage due to strand corrosion.

Figure 5 shows the variations of the relative values of the parameter *Bpn* from tests of strands which were subjected corrosion process for differed time (0, 2, 6 and 12 hours). Any value in the figure is normalized to its corresponding value at zero time (0 hours). A linear increase in the value of this parameter is evident from 2 hours of the corrosion process. It must be recalled that the values of this *Bpn* parameter is proportional to those of the rigorously defined nonlinearity parameters, Sect. 2.1. Previously it was proposed a tenfold increase relative to the initial values of these parameters, as the arbitrary threshold for considering a critical increase of the nonlinear elastic features, which in turn would be indicative of the presence of significant defects or damage in the material medium [6].

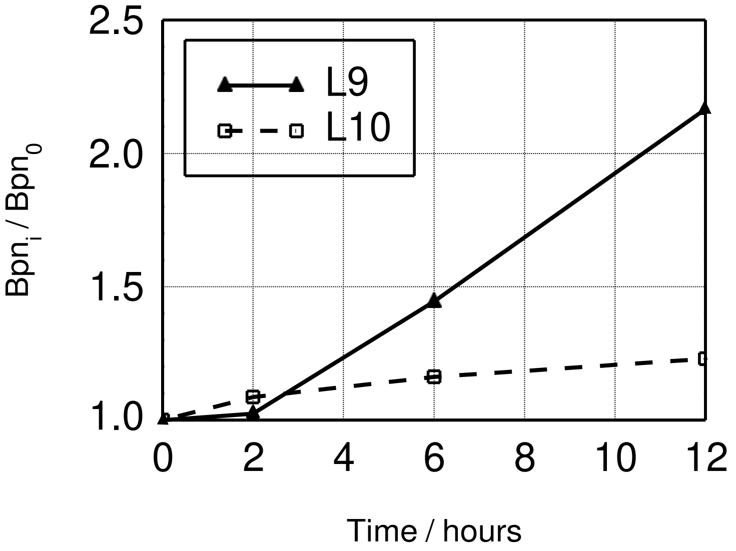

Figure 5. Evolution of the parameter *Bpn* normalized to this initial values (at the time = 0 hours)

2.2 Metal magnetic memory method

The metal magnetic memory (MMM) method is an NDT method based on sensing of the magnetic field strength *Hp* in the form of residual magnetization on the surface of the material. It uses one or more probes, each sensing the magnetic field in three on perpendicular planes, see Fig. 6. The residual magnetization of the material is affected by the production process, machining, cutting, welding, bending, heat treatment, cooling, operational stress, corrosion of the material, etc. A very important factor influencing the magnetic memory of a material is the degradation process caused by the operational stress and conditions to which the structure is exposed.

In the case of steel reinforcement in a concrete beam, the degradation processes are further approached by corrosion processes, stress corrosion and possible negative effects from the assembly process, which in turn reduce the life of the object. The MMM method use can detect these effects in the form of a magnetogram, i.e. the dependence of the magnetic field strength on the distance of the probe *Lx* from the beginning of the measurement.

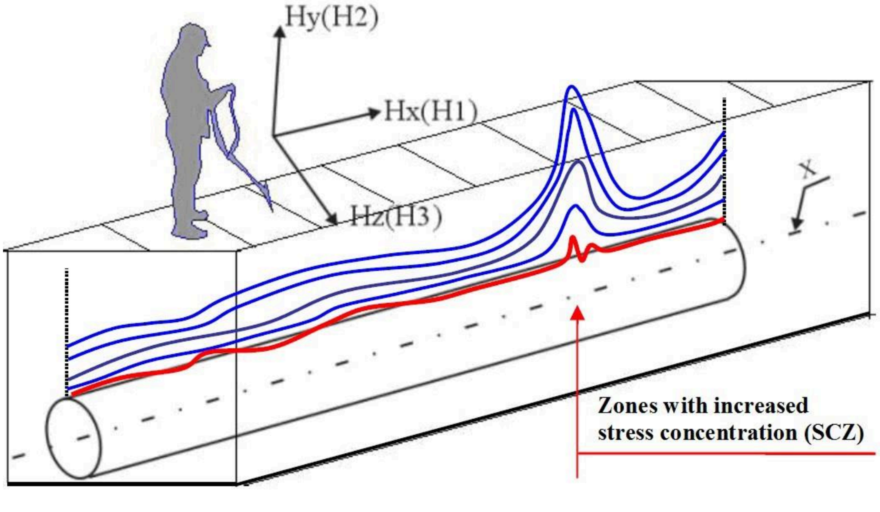

Figure 6. Scheme of measurement by the metal magnetic memory method above a steel pipe in the ground in the longitudinal direction [7]

The MMM method can detect these effects from a magnetogram, i.e., dependence of the magnetic field strength on the distance of the probe from the beginning of the measurement.

A special cart, on which the probes are placed, is moved above the surface of the measured area (e.g., in a pipe or beam axis) and the wheel of the device measures the driven distance. The signal from the each individual channels, together with the distance, is recorded in digital form in the device's memory and displayed graphically either directly as *Hp* or in the form of gradient *dHp/dx*. The recorded data are presented in the form of a graph (so-called magnetogram). Based on the evaluation, we can then determine the zones with increased stress concentration (SCZ), where there is an increased probability of changes or defects in the material structure. The stress concentration is proportional to the measured magnitude of the magnetic field strength gradient around the given position.

A significant advantage of this NDT method is the measurement speed and also the high sensitivity. Used measurement technique has been described in [7].

2.2.1 Measurement results

The steel strands were arranged in the line on the ground, Fig. 7. The indicative contactless measurement was applied in the distance 100 mm from the surface of the strands.

Figure 7. Intact steel strand L90

The measurement was repeated three times to verify the repeatability of the measurement results. The measurement results are presented here in the form of the magnetograms from measurements of group L9. Black rectangle indicated in magnetograms corresponds to evaluated strand central part subjected to corrosion process. A magnetogram in Fig. 8 illustrates the results of the continuous scanning of intact (uncorroded) strand L90.

Figure 8. Magnetogram 10913.mms corresponds to undamaged steel strand L90

The magnetogram shows graphically the field strength *Hy* and the field gradient *dHy/dx* as a function of the distance *Lx*. The uniform distribution of the field strength *Hy* in the magnetogram confirms that the structure of the strand is uniform throughout its length.

Fig. 9 presents the magnetogram from scanning the strand L92 after 2 hours of corrosion process. The magnetogram shows zone of slight increased stress concentration of field strength in the range of coordinates x, correspond to corroded part of strand L92. Max value of the field gradient *dHy/dx* amounts to 9.0 (A/m)/mm.

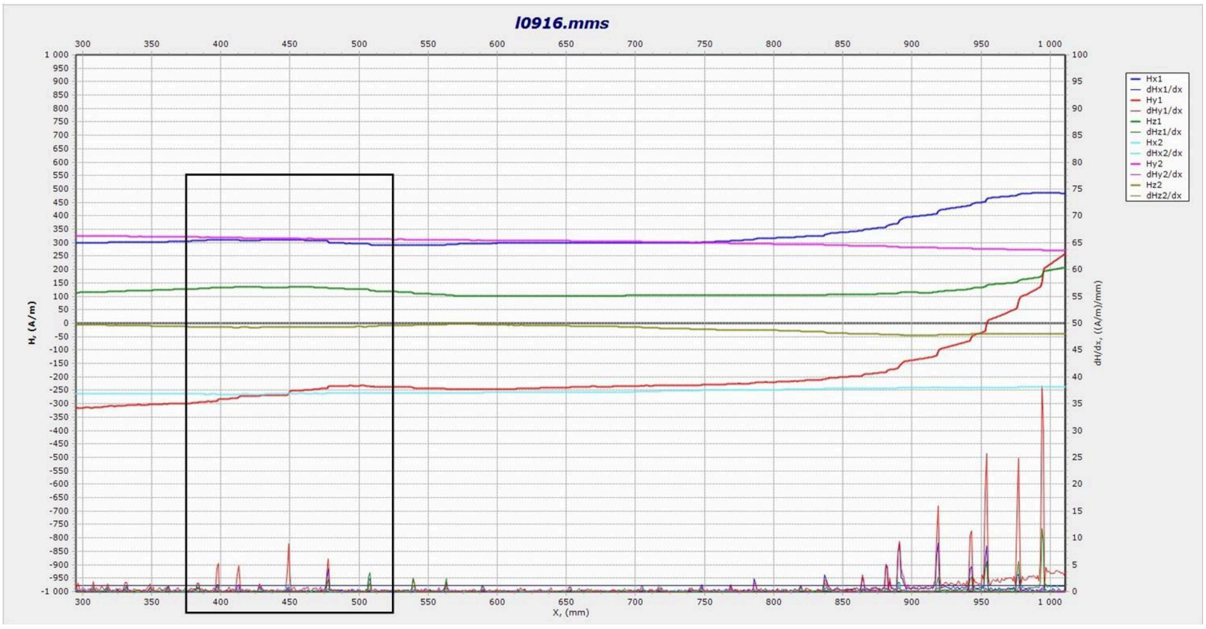

Figure 9. Magnetogram 10916.mms correspond to strand L92 – after 2 hours of corrosion process

Next Fig. 10 presents the results of the continuous scanning of strand L96, after 6 hours of corrosion process. In the magnetogram is evident further increased stress concentration of field strength in comparison with magnetogram in Fig. 9. Max value of the field gradient *dHy/dx* amounts to 43.0 (A/m)/mm.

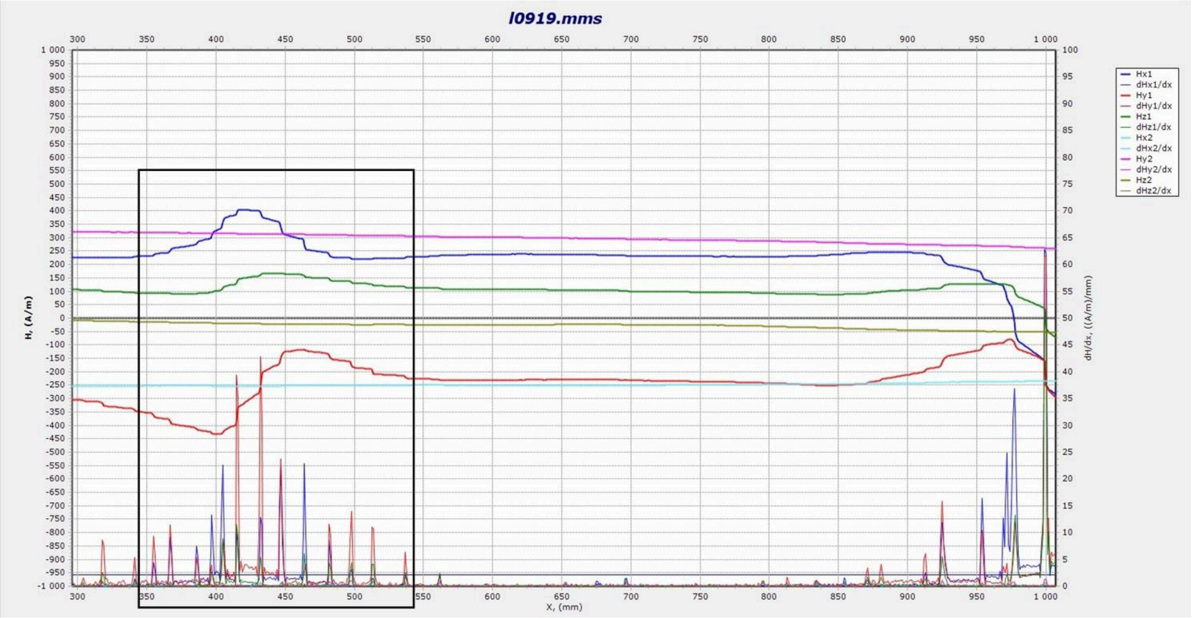

Figure 10. Magnetogram 109169.mms correspond to strand L96 – after 6 hours of corrosion process

Fig 11 presents measurement results of strand L912 after 12 hours of corrosion process. The magnetogram shows higher value of the field gradient *dHy/dx* in comparison with strand L96. It amounts to 100.0 (A/m)/mm.

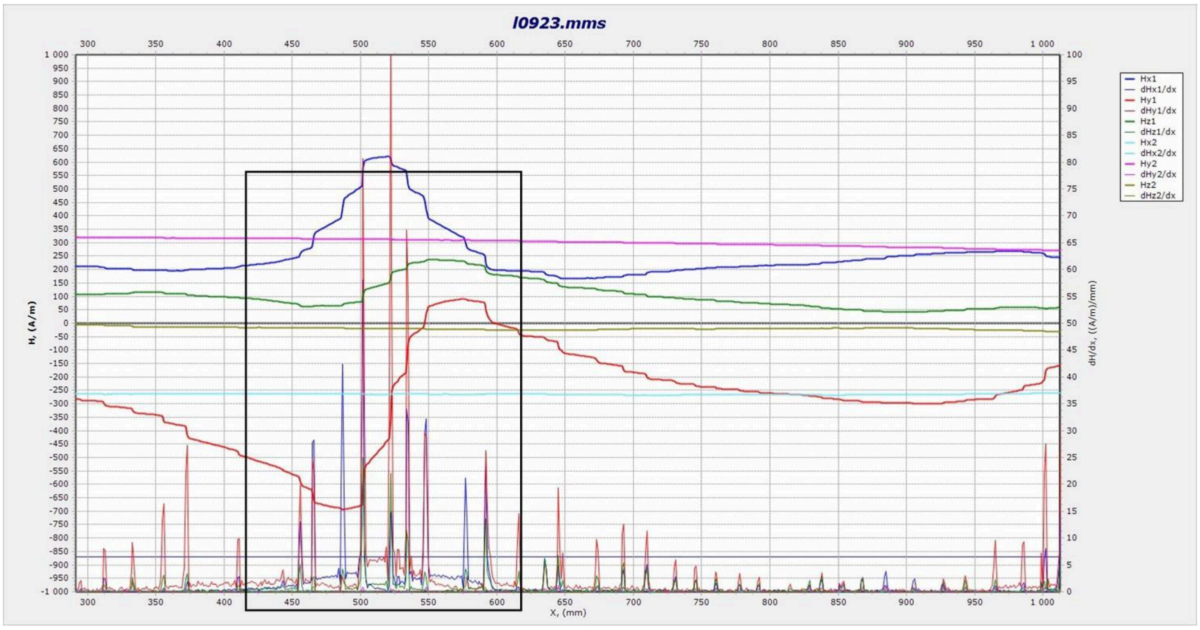

Figure 11. Magnetogram 10923.mms correspond to strand L912 – after 12 hours of corrosion process

The values of the field gradient *dHy/dx* are graphically shown for both groups (L9, L10) in Fig. 12.

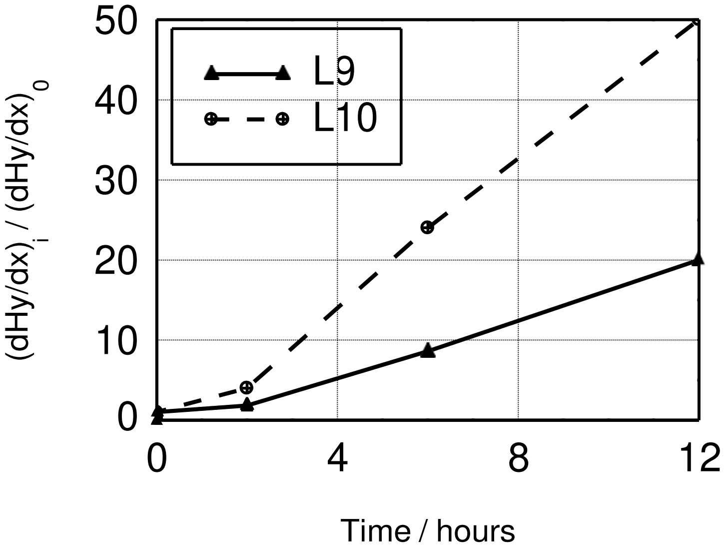

Figure 12. Evolution of the parameter *dHy/dx* normalized to this initial values (at the time = 0 hours)

Graph shows the variations of the relative values of the parameter *dHy/dx* from tests of strands which were subjected corrosion process at differed time (0, 2, 6 and 12 hours). Values in the figure are normalized to its corresponding value at the time = 0 hours. A linear increase in the value of this parameter is evident from 2 hours of the corrosion process action, similarly as in the case of parameter *Bpn* in Fig. 5.

Finally the tested strands were subjected to tensile strength tests in order to determine their mechanical properties and verify and complement measurement results. Appraising parameters of strand damage were following: normalized values of strand diameters in affected area and force F_{max} corresponding to failure of strands during the tests. These parameters are compared graphically in Fig. 13.

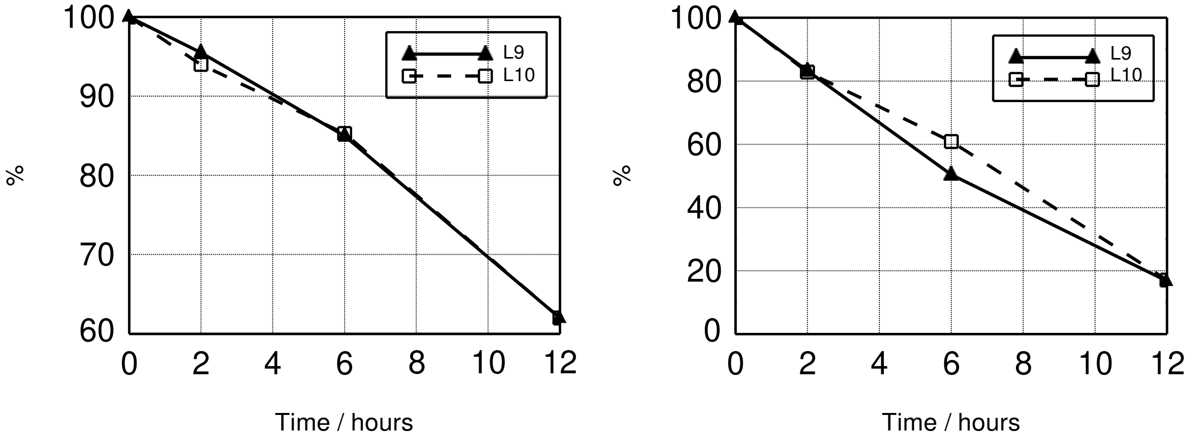

Figure 13. Consequences of corrosion on strands: on the left - normalized values of strand diameters; on the right - normalized values of force F_{max} corresponding to failure of strands during tensile strength tests

Both graphs show a deterioration of mechanical properties of corroded strands. The normalized values of the parameters (strand diameter and breaking force F_{max}) show a linear decrease with increasing time of subjecting the steel strands to the corrosion process.

3. Conclusions

The results obtained in this work provide confirmation that it is possible to use ultrasonic techniques and metal magnetic memory method for the damage detection of pre-stressing strands caused by corrosion. In cause of ultrasonic techniques damage consequences were observed in the form of strong nonlinear features of the received signal. Harmonic distortion was clearly observed. The parameter of nonlinearity was approximated as $Bpn = A_3 / A_1^3$. The variation of these ratios relative to the initial undamaged condition was used as indicator of the structural damage. Regarding the results corresponding to both specimen groups (L9, L10) the relative parameter values increase with time of corrosion process. The growing trend is linear from two hours duration to twelve hours of accelerated corrosion process.

Similar trend is evident in the case of use of magnetic memory method and observation of the magnetic field gradient dHy/dx. Its magnitude shows similarly linear increase from two hours duration until twelve hours of the corrosion process action.

Finally, the strands were subjected to tensile strength tests in order to determine changes of their mechanical properties due to impaired diameter of strands as a consequence of corrosion. The values of strand diameters and corresponding forces F_{max} at failure of the strands proved linear decrease with increasing corrosion.

More research is necessary to confirm the findings and interpretations of this study, and to advance on the proposal of practical procedures for routine engineering surveys of pre-stressed or post-tensioned concrete structures suspected to be affected due to steel corrosion.

Acknowledgments

This paper was prepared as a part of research project No. CK01000108, which was financed from the state budget by the Technology agency of the Czech Republic and the Ministry of Transport of Czech Republic under the DOPRAVA 2020+ Programme.

References

1. J. Stryk, K. Pospisil, M. Korenska, A. Frybort, M. Manychova, 'An Initial Investigation on the Potential Applicability of Ultrasonic Testing to Assess Effects of Corrosion on Linear and Nonlinear Elastic Behaviour of Pre-stressing Steel Strands', In Proceedings of Xth NDT in Progress, October 2019, pp. 75-84.
2. M. Korenska, M. Manychova, L. Pazdera, 'Experimental Study of the Nonlinear Effects Generated in a Concrete Structure with Damaged Integrity', Russian Journal of Non-destructive Testing, 2013, 49(9), pp. 530-537.
3. K. Hajek, J. Sikula, 'Testing of Low-Current Contacts Quality and Reliability by Using Third Harmonic Distortion', In Proceedings of 45th- IEEE Holm Conference, pp. 211-213, September 2003.
4. D. R. Raichel, 'The Science and Applications of Acoustics', AIP Series in Modern Acoustics and Signal Processing, 2006, pp. 625-626.
5. A. A. Shah & Y. Ribakov, 'Non-linear ultrasonic evaluation of damage concrete based on higher order harmonic generation', Materials & Design 30, 2009b, pp. 4095-4102.
6. M. A. Climent, M. Miró, J. Carbajo, et al., 'Use of non-linear ultrasonic techniques to detect cracks due to steel corrosion in reinforced concrete structures', *Materials* 2019, *12*(5), 813; https://doi.org/10.3390/ma12050813.
7. K. Pospisil, M. Manychova, J. Stryk, et al.: 'Diagnostics of reinforcement condition in concrete structures by GPR, metal magnetic memory method and impact-echo method', Remote Sensing, 2021, 13, 952. pp. 1-15; http://doi.org/10.3390/rs 13050952.