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Application of the Modified Magnetoelastic Method

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***Abstract* – In technical practice there is very often a requirement of axial force determination in important structural elements of a building or engineering structure during its construction or operational state. In civil engineering practice, five experimental techniques are usually used for evaluation of axial tensile forces in these elements. Each of them has its advantages and disadvantages. One of these methods is the magnetoelastic method. The paper presents general principles of the magnetoelastic method, the magnetoelastic sensor layout and actual information and knowledge about practical application of the new approach based on the magnetoelastic principle on prestressed concrete structures. Subsequently, recent results of the experimental verification and the in situ application of the method are described in the text. The described experimental approach is usable not only for newly built structures but in particular for existing ones. Furthermore, this approach is the only one effectively usable experimental method for determination of the prestressed force on existing prestressed concrete structures in many cases in the technical practice.**

Keywords – Concrete, Tensile Force, Magnetoelastic Method, Prestressed Strand, Prestressed Cable, Sensor.

I. INTRODUCTION

Five experimental techniques are usually applied in civil engineering practice for evaluation and verification of actual values of axial tensile forces in important structural elements on building constructions.

If the total value of the tensile force in the investigated structural elements must be determined, the two of these methods (namely, the direct measurement of the force by a pre-installed load cell and the approach based on a strain measurement with strain gauges) can be applied only for an experiment by which the applied sensors were installed before the investigated structural elements were activated.

Compared to that, the next three methods (namely, the vibration frequency method [1-2], the force determination in a flexible structural element based on the relation between the transverse force and the caused transverse displacement [3-4] and the magnetoelastic method [5–12]) can be used during newly started experiments on existing structures that have already been in service for some time. The basic advantage of these three methods is that the investigated structural elements remain activated all the time (namely, in the period of the structure service, the experiment preparation, the experiment realization and also after the experiment completion).

The results obtained by the vibration frequency method on a structural element with complicated boundary conditions can be improved using not only measured natural frequencies of the element but also measured mode shapes in the process of results evaluation [1-2].

The next advantages and disadvantages of all five above mentioned experimental techniques are discussed in more detail in the reference [9].

The selection of the most suitable experimental method for a particular practical application depends on specific element parameters and specific conditions in which the experiment must be performed.

According to the authors opinion, the modified magnetoelastic method is the only one that can be applied effectively and expediently for evaluation of the prestressed force on existing structures made from the prestressed concrete when the prestressed reinforcement is embedded inside the concrete.

II. RELATED RESULTS IN THE LITERATURE

In civil engineering practice, the utilization of the magnetoelastic method for experimental evaluation of axial tensile forces in structural elements made from ferromagnetic materials started about thirty-five years ago. The original inventors developed gradually the method theory, the magnetoelastic sensor (hereinafter the ME sensors) and their practical utilization. They published their obtained knowledge regularly, see [10] for example.

The ME sensors and their appropriate equipment that have been standardly used in civil engineering practice in the recent past and at present [10], [11], [12] evaluate measured prestressed forces in a relatively simple way. These standard ME sensors are composed from two basic parts only, from the primary and secondary coil. This is the minimal possible configuration of the ME sensor, as it is described below.

The basic advantages of the application of the ME sensor in its standard configuration are that the tensile force in the structural element is evaluated contactless using the standard ME sensor, the observed element is not locally deformed and its anti-corrosive layer is not abraded, the sensor body is robust, long lasting and resistant to accidental mechanical damage. It is possible to evaluate the instantaneous magnitude of the tensile force with high accuracy. However, the important requirement for high accuracy of the obtained results is the sensitivity assessment of each particular standard ME sensor in concrete conditions its practical application using an independent force sensor. In the case of the prestressed reinforcement (namely the strand or the cable), the force sensor is used as a part of a hydraulic jack and therefore it is necessary to install the ME sensor before the activation of the observed prestressed reinforcement is initiated.

An additional installation of the standard ME sensor on the activated prestressed reinforcement is, of course, technologically possible. However, it is time consuming and the sensor sensitivity assessment cannot be realized in the concrete conditions of the magnetic surroundings of the location where the ME sensor is installed.

The modified magnetoelastic method, its physical principle, the fully equipped magnetoelastic sensor, an experiment on a real structure and its result evaluation are described in more details in reference [7]. Other supplementary information about the method, its practical applications and about a removable ME sensor can be found in references [5-6] and [8-9].

III. DESCRIPTION OF THE METHOD

The method is based on an experimental estimation of the magnetic response of the tensile stressed structural element on an external magnetic field. The magnetic field intensity H and the magnetic flux density B are ones of the basic physical quantities describing the magnetic field arrangement. The relation between B and H in the form of the so called hysteresis loop is given by the kind of material exposed to the effects of the magnetic field, its properties and its current conditions (e.g. tensile stress, temperature).

For the purposes of applications of the modified magnetoelastic method, differently arranged ME sensors are used depending on the specific experiment and its concrete conditions.

A diagram of a fully equipped ME sensor is shown in Fig. 1 that was adopted from reference [7]. Fundamental components of this ME sensor variant are a controlled magnetic field source (for example, the primary coil that is drawn in Fig. 1), a sensor of magnetic field intensity "H" in a measured cross section (the system of Hall's sensors and/or the secondary coil 2), a sensor of magnetic flux that is closely related to the magnetic induction "B" in the measured section of the strand (the secondary coil 1) and the EM sensor protection against magnetic influences from its surroundings (the steel shield). The function and principle of Hall´s sensors were explained in more detail in the reference [8].

The fully featured ME sensor offers the greatest possibilities to increase accuracy and reduce uncertainties in evaluating of the tension force in the observed prestressed element. On the other side, the fully equipped ME sensor is spatially larger and that may restrict its applicability in some practical cases and it is also more complicated. This complexity affects its higher production time, higher requirements for its application in civil engineering practice and as well as higher requirements on the used measuring system and its equipment.

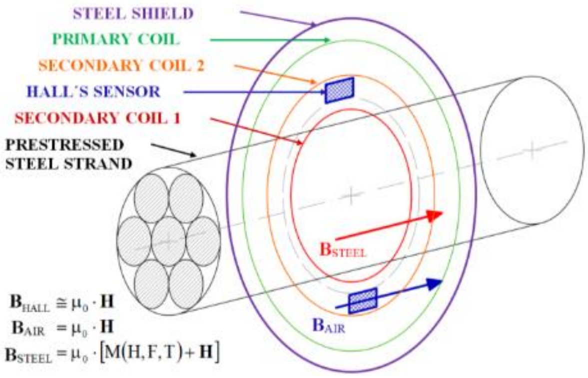

Fig. 1. Diagram of a fully equipped magnetoelastic sensor published also in [7]

The above described standard ME sensors (see chapter II) represent the minimalist variant of the EM sensor that consists of a primary coil and a secondary coil 1 only. The intensity of the magnetic field "H" is determined, in this case, indirectly from a completely different physical quantity, from the current flows through the primary coil. However, there is a risk that results from this approach in the case of application of the minimalist variant of the ME sensor.

Any change in the magnetic surroundings in the sensor vicinity (a removal of a massive steel falsework after concrete hardening for example) causes completely "silently" the substantial or even severe changes in sensor parameters.

The sensor's steel shielding reduces the impact of this effect on the obtained results. The quality of the ME sensor shielding influence the level of this reduction, however, it is never one hundred percent. For example, the application of the minimum ME sensor configuration on a prestressed prefabricated concrete structure reinforced by steel-fibre is completely unusable.

For the purpose of the modified magnetoelastic method, magnetic behaviour of the standard prestressed elements used both in the past and today is appropriate and necessary to know.

In November 2019, a laboratory experiment concentrated on the systematic study of variations in the magnetic behaviour of two selected standard prestressed elements (namely, the patented wire P7, that was applied in the past, and the prestressed strand Lp15.7 currently used by the Freyssinet company with right-handed threading) dependence on its immediate temperature and rate of the mechanical stress was realized in the experimental centre of the Klokner institute (the research institute at the Czech Technical University in Prague). Results of similar experiments realized for different standard prestressed elements are described in [8] (namely, for the patented wires P4.5, unknown prestressed strand Lp15.7 with left-handed threading, the prestressed bars 15/17 made by companies Dywidag and Mukusol) and in [6] (namely, for the full locked cable PV 150 and the Mukusol threadbar 15FS 0000).

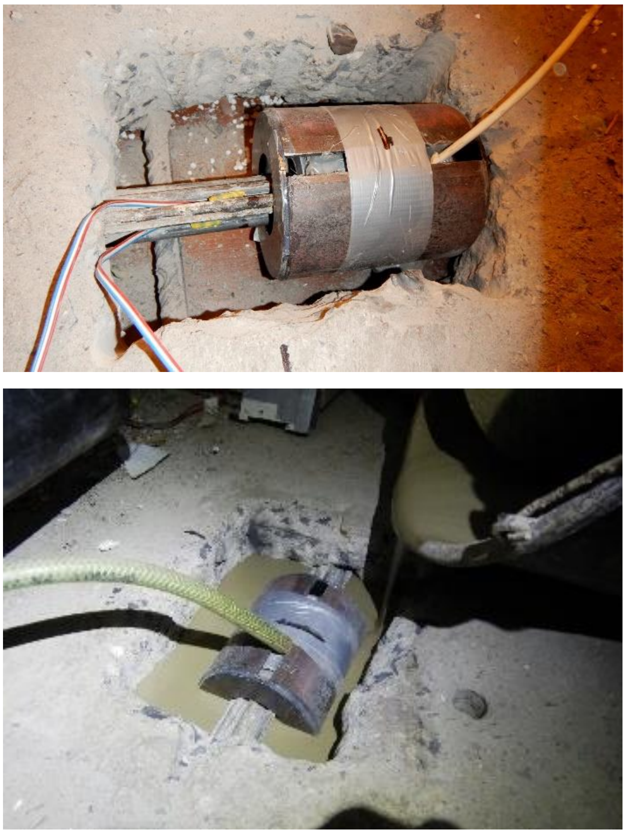

Fig. 2. The fully equipped ME sensor installed on the prestressed cable in the inspected bridge (above) and consequent filling of the created opening by the special grout (below)

A. *The experiment realized on the previously used patent wire P7*

The patent wire P7 used during the experiment described in this chapter was removed from the chamber of the existing prestressed concrete bridge in Prague that was put into operation in the year 1974.

In the course of the bridge inspection in the year 2019, the fully equipped ME sensors were installed on two selected prestressed cable assembled from twelve patent wires P7 (see Fig. 2). The opening created for the purpose of the ME sensor installation was consequently filled in by the special grout (see Fig. 2). The installed ME sensors are intended for long-term monitoring of the prestressed force in the selected cable.

The basic reason for realization of the experiment described in this chapter was to determine the accurate parameters of magnetic behaviour of the prestressed reinforcement used in the inspected bridge for more precise evaluation of the results. The fully equipped laboratory ME sensor used in the course of the experiment is shown in Fig. 3.

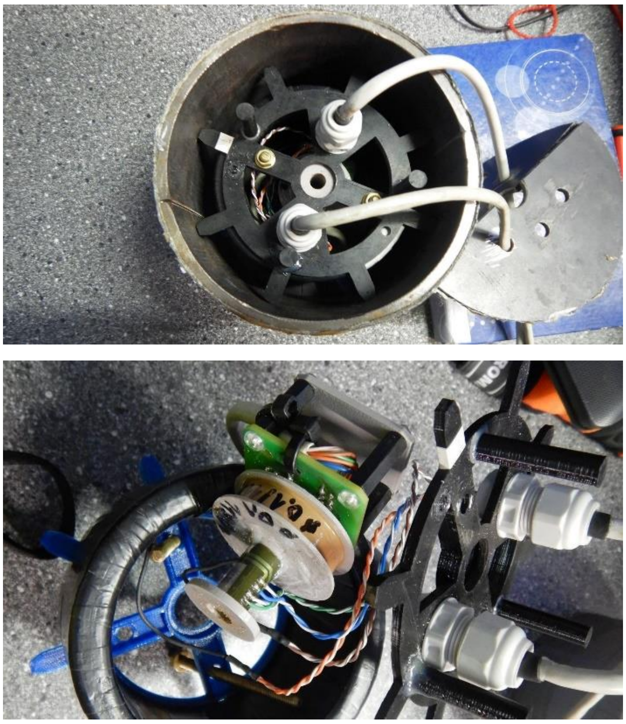

Fig. 3. The fully equipped laboratory ME sensor intended for the experiment on the patent wire P7, the assembled sensor inside the steel shield (above) and view on its disassembled basic parts (below)

In the course of the experiment, the investigated patent wire P7 was placed in a climatic chamber (see Fig. 4) and loaded in a steel tensile testing machine. The magnetic properties of the studied wire were investigated for two temperature levels of the wire surface, namely around 0° C and around +25 °C. The studied patent wire P7 was loaded in five force steps for each temperature level according to its design resistance, namely, 10 kN, 20 kN, 30 kN, 40 kN and 47 kN. It is roughly about 20 %, 40 %, 60 %, 80 % and 100 % of the design strength.

The temperature of the observed wire cross-section was evaluated as a linear interpolation between two measured temperature values. The first one was observed on the element surface in the close vicinity of the ME sensor and the second one was the temperature of the air measured inside the ME sensor.

The specific hysteresis loop was measured and determined multiple times for each particular temperature level and force step. The hysteresis loop, in general, characterizes the relation between magnetic flux density B and the magnetic field intensity H and it changes its shape depending on the actual force magnitude in the investigated prestressed element and also on its temperature. However, it is not effective and also necessary to evaluate the measured hysteresis loops in their whole range.

The dimensionless parameter P is used to convert a complex measured shape of the hysteresis loop, that depends on the actual force magnitude, to one simple numeric value. And this parameter is standardly evaluated for the purpose of a practical application of the modified magnetoelastic method. Same examples are published in [5-9].

Fig. 4. The exterior view on the climatic chamber and the steel tensile testing machine (on left) and on the laboratory ME sensor installed on the prestressed strand Lp15.7 inside the chamber (on right)

The particular parameter P is described as a fraction. The numerator is the most important value for evaluation of the parameter P and it describes the level of the magnetic field intensity "H" in the main node point. The lower values of the parameter P indicate the preference of the portion of the hysteresis loop close to the remanence (the intersection with the vertical axis in the B–H curve). On the contrary, its higher values prefer the loop portion near to the saturation. The more exact definition of the parameter P is an industrial secret.

The resultant regression fitting curve using polynomial regressions was calculated for the investigated patent wire P7 and the chosen resultant parameter P 15/45. The temperature effect on the parameter P was considered as linear and the force effect was considered as 3rd degree polynomial. Calculated curve is one of several ones, which is as “D7” shown in Fig. 6. The differences between the theoretical fitting curve and the used input experimental results are small. The maximal deviation between them is 1.6 % of the design strength of the investigated patent wire and the standard deviation of all particular results is 0.6 % of the design strength.

B. *The experiment realized on the currently used prestressed strand Lp 15.7*

The prestressed strand Lp 15.7, that was the subject of the experiment described in this chapter, is standardly used by the Freyssinet company at the present time.

The arrangement of the experiment, its procedure and results evaluation were similar to those described in the previous chapter.

In the course of the experiment, the investigated prestressed strand was placed again in a climatic chamber (see Fig. 4) and loaded in a steel tensile testing machine. The magnetic properties of the studied strand were investigated for three temperature levels of the wire surface namely, around 0° C, +20° C and +35° C. The strand was loaded in five force steps for each temperature level, namely, 40 kN, 80 kN, 120 kN, 160 kN and 200 kN. It is roughly about 20 %, 40 %, 60 %, 80 % and 100 % of the strand design resistance. The temperature of the observed strand was evaluated in the same way as for the patent wire P7.

The specific hysteresis loop was measured and determined again multiple times for each particular temperature level and force step as can be seen, for example, from the Fig. 5.

For the observed strand Lp 15.7, the example of evaluated dependence of the chosen resultant parameter P 15/60 on the strand temperature by the constant prestressed force 120 kN is shown in Fig. 5. The resultant regression fitting curves for the several chosen parameters P were also calculated using the same methods of mathematical analysis and statistics analogous with chapter A. The differences between the theoretical fitting curves and the used input experimental results are even smaller than for the wire P7. The maximal deviation between them is 1.4 % of the design resistance of the observed prestressed strand and the standard deviation of all particular results is 0.2 % of the design strength.

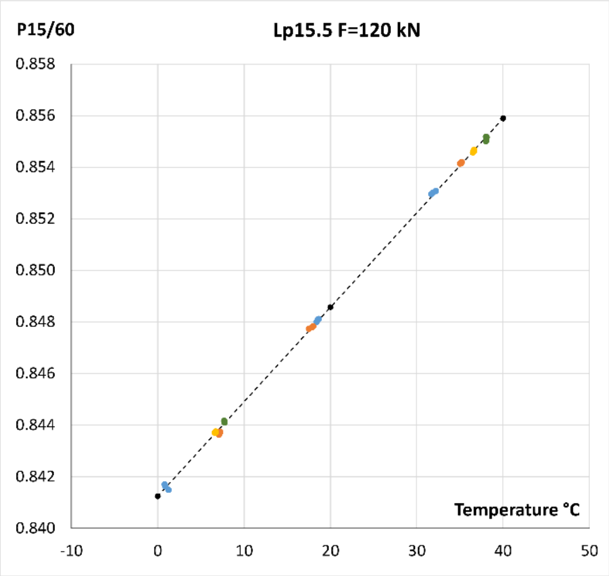

Fig. 5. The prestressed strand Lp15.7 – the relation between the temperature of the observed strand and the chosen resultant dimensionless parameter P 15/60 on the specific force step (120 kN)

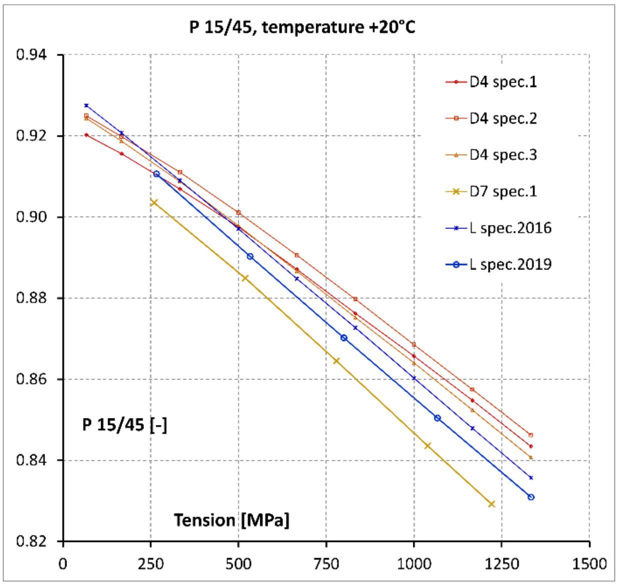

Fig. 6. The comparison of the relations between the stress in the six observed prestressed elements (three patent wires P4.5, one patent wire P7 and two strands Lp15.7 / 1860 MPa) and the chosen resultant dimensionless parameter P 15/45 for the strand temperature 20° C

The example of calculated regression fitting curve that expresses the dependence of the particular resultant parameter P 15/45 on the stress in the observed strand at the strand temperature 20° C is shown in Fig. 6 where the curve is labelled “L 2019”.

IV. RESULTS AND DISCUSSIONS

So far, as part of development of the modified magnetoelastic method, the experiments focused on the evaluating curves were realized for four specimens of the patent wires, three types of the prestressed bars and two prestressed strands Lp 15.7 / 1860 MPa from different producers.

The results obtained for six selected investigated prestressed elements (namely, three patent wires P4.5, one patent wire P7 and two prestressed strands Lp15.7) were compared mutually in detail. The resultant regression fitting curves for the particular elements at the element temperature 20° C are drawn in Fig. 6.

The analysis of the results shows the standard deviations of all measured data from the specific calculated evaluating curves are usually significantly lower than 1.0 % of the design strength.

The comparison of the corresponding evaluating curves for two different samples of the prestressed strands Lp 15.7 / 1860 MPa made by different producers is shown in Fig. 6 (specimens “L 2019” and “L 2016”). The difference between curves is roughly about 5 % of the design strength of the strands. It means the evaluating curves of the particular samples of the strand Lp 15.7 deviate roughly about 2.5 % from the averaging evaluating curve of this type of the prestressed strand.

Very similar results were obtained from the comparison of the corresponding evaluating curves for three different test samples of the patent wire P4.5 that were taken during the demolitions of three different existing bridges, which were built in the seventies and eighties. For example, three curves “D4 spec. 1”, “D4 spec. 2” and “D4 spec. 3” for the wire temperature 20° C are drawn in Fig. 6. The evaluating curves of the particular test samples of the patent wire P4.5 deviate roughly about 2.5 % from the averaging evaluating curve of this type of patent wire.

In contrast to the previously mentioned results, the significant difference roughly above 20 % of the design strength was found between the evaluating curves for the patent wires P7 and P4.5, as can be seen from Fig. 6.

V. CONCLUSIONS AND OUTLOOK

The results stated above demonstrate that the modified magnetoelastic method can be used for the experiments realized on the existing structures for the determination of the actual value of the tension force in steel prestressed structural elements using the available general evaluating curves. The result uncertainties of these experiments are then similar as for the alternative experimental methods, e.g. the vibration frequency method [1-2]. It should be noted here that the frequency method cannot be used for the prestressed elements embedded in the concrete.

In the cases when it is possible to remove the test sample of the specific prestressed element from the particular existing bridge then the evaluating curves for this observed element can be evaluated according to the above described procedure. The uncertainties of the evaluated prestressed forces are relatively small then and they are comparable with precision of the method based on a strain measurement with strain gauges.

The possibility of using the modified magnetoelastic method for the prestressed bars was also verified during previous experiments [6] and [9]. However, the ME sensor sensitivity, when it is applied on the bars, is substantially lower than for the prestressed wires and strands. The main reason of this fact is the significantly lower design strength of the bar materials.

According to the authors opinion, the modified magnetoelastic method is the only one that can be purposefully and effectively used for the prestressed force evaluation in the prestressed reinforcements embedded inside the concrete on the existing prestressed concrete bridges or similar engineering structures.

VI. ACKNOWLEDGMENTS

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