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The in Situ Application of a New Approach to Experimental Estimation of Tensile Forces in Prestressed Structural Elements by Method Based on the Magnetoelastic Principle

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Abstract. The important structural elements loaded by great tensile forces (prestressed reinforcements of concrete bridges for example) significantly affect the reliability of the whole structure. The force in such element fluctuates considerably in time. Accurate information about the current force value is very important for exact assessment of the structural reliability at any of the life cycle stages of the structure. The five experimental approaches are most often applied for determination of axial tensile forces in civil engineering practice. They are the direct measurement of the force by a pre-installed load cell, the approach founded on a strain measurement with strain gauges, the force determination in a flexible structural element based on the relation between the transverse force and the caused transverse displacement, the vibration frequency method and the magnetoelastic method. At first, the advantages and disadvantages of the above mentioned approaches have been discussed in the paper. Subsequently, the basic principles, results of the experimental verification and the in situ application of the new approach to experimental estimation of tensile forces by the method based on the magnetoelastic principle are described.

Introduction

The significant structural elements of civil engineering structures loaded by large tensile forces (prestressed reinforcements of concrete bridges, stays of cable stayed bridges, suspension cables of suspended roofs, ground and rock anchors for example) significantly affect the reliability of the whole structure. The force in such element fluctuates considerably in time. Accurate information about the current force value is very important for exact assessment of the structural reliability at any of the life cycle stages of the entire structure.

The five experimental approaches are generally used for evaluation of axial tensile forces in civil engineering practice. They are the direct measurement of the force by a pre-installed load cell, the approach founded on a strain measurement with strain gauges, the force determination in a flexible structural element based on the relation between the transverse force and the caused transverse displacement [1, 2], the vibration frequency method [3, 4] and the magnetoelastic method [5, 6, 7]

The main objective of the research work described in the paper was a solution of the issue that could be named as “an accurate experimental estimation of the current value of the tensile force in a prestressed structural element on an existing concrete structure”. The need to solve this problem is very frequent in praxis. Nevertheless, it is not often soluble by any other experimental or theoretical method.

The Brief Description of the Experimental Approaches Generally Used in the Practice

In this chapter, the brief description and the discussion of advantages and disadvantages of the five above mentioned approaches are summarized that are generally used in the civil engineering practice for experimental estimation of axial tensile forces in significant structural elements.

The Direct Measurement of the Force by a Pre-Installed Load Cell. The professionally made force sensor is usually used by this experimental approach. The transducer has to be connected in series between the investigated structural element and its anchoring to the structure. The basic advantage of this approach is the possibility to calibrate properly the force sensor and so increase the accuracy of the force measurement. The two fundamental disadvantages are that the sensor has to be installed on the element before a start of activation of the element and that the experiment has to be terminated in case of a sensor failure. The potential sensor replacement is tied to deactivation and reactivation of the observed element. For the mentioned disadvantages, the approach is unusable for a task of the experimental estimation of the current value of the tensile force in a prestressed structural element on an existing concrete structure.

The Approach Founded on a Strain Measurement with Strain Gauges. This approach is unusable for the stated main research objective too. The measurement with strain gauges fixed on the element surface is realized comparatively. The initial reading has to be realized on unloaded investigated structural element if the total force is to be determined. A damage of the installed strain gauges or a failure of the used datalogger lead to termination of the experiment.

The Force Determination in a Flexible Structural Element Based on the Relation between the Transverse Force and the Caused Transverse Displacement. This experimental approach [1, 2] can be used for the precise determination of the total force in the structural element at any of its life cycle stages. However, the applicability of the approach is significantly limited only for the flexible elements with a relatively small cross section and with a relatively long free length. The measurable transverse displacement increase substantially the tensile force in the considerably short element. It means, the approach is unusable for the embedded prestressed reinforcement which is minimally uncovered only.

The Vibration Frequency Method. The total force in the investigated structural element at any of its life cycle stages can be determined by this experimental approach too [3, 4]. However, the method needs relatively long free vibrating length of the studied element and the evaluated force uncertainty is significantly dependent on the element bending stiffness, the vibrating length and the element boundary conditions. Especially, the boundary conditions cannot be sometimes reliably specified, particularly for very short elements. The uncertainty of an evaluated force in some embedded prestressed reinforcement, which is minimally uncovered, is evidently greater than for the new approach based on magnetoelastic principle described in the paper.

The Magnetoelastic Method – Standard Approach. Measuring equipment, that is based on the magnetoelastic principle and that is standardly used at present [5, 6, 7], evaluates measured data in a relatively simple way. The standard magnetoelastic sensors, that have hitherto been used in civil engineering practice, are composed from the primary and secondary coils only (compare with the Fig. 1). Based on the author's knowledge, the standard magnetoelastic sensors [5, 6] are situated on an unloaded observed element before its activation. The sensitivity of the used measuring equipment, which is usually composed from the data logger and the sensors, is specified during tensioning of the element using the information about the actual prestressed force from a tension hydraulic jack. The evaluation of the measured signal is based on observation of one selected parameter in the specific magnetic conditions around the sensor in which its sensibility was specified. There is a risk of an inaccurate determination of the results that is attached to the possible change of magnetoelastic characteristic of the standard magnetoelastic sensor caused by a variation of sensor magnetic surroundings in the time between its sensibility specification during the observed element activation and a carried out force measurement. The changeability in the sensor magnetic surroundings is common during building of a civil engineering structure. It could be caused by a concreting of steel-fibre concrete or a removal of a steel massive falsework from the sensor surroundings after concrete hardening or the simple removal of the tension hydraulic jack after tensioning for example. The standard approach is only useable for the observation of the comparative change of the tension force compared with the realized initial reading which has to be carried out in the unloaded state of the element.

The Brief Description of the Physical Principle of the Magnetoelastic Method

The magnetoelastic method is based on an experimental estimation of the magnetic response of the tensile stressed structural element on an external magnetic field. It means, the method is applicable for elements made from ferromagnetic materials only, as the steel used for production of prestressed reinforcement for example.

The magnetic field intensity H and the magnetic flux density B are ones of the fundamental physical quantities describing the magnetic field arrangement. The magnetic flux density B compared to the magnetic field intensity H describes a force effect of the magnetism.

The relation between B and H, that is characterized by a curve called the hysteresis loop, depends on the quantity named the magnetic permeability of material μ that is influenced by particular materials subjected to the effect of the magnetic field and by momentary state of these materials. Certain materials or surroundings amplify the force effect of the magnetic field more or less, some others on the other hand waken it.

As was mentioned above, the permeability is given by the type of material exposed to the magnetic field influence, its features and current conditions. Usually, the value of permeability depends on the grade of the affected magnetic field, and not only on its actual value, but also on its history and rate of change, on the actual material temperature and on the current material stress. The ferromagnetic materials are the typical example of ones with this general dependence.

The Basic Principle of the Magnetoelastic Method and the New Approach

As was already stated above, the magnetoelastic method is based on the magnetoelastic principle. It is known, the magnetic characteristics of the ferromagnetic materials are dependent on the level of their mechanical stress among other things. The practical effect is that the permeability of steel is the function of the tension stress or the force straining the investigated steel element and this matter of fact is applied by the magnetoelastic method for determination of its mechanical stress or tension force.

The principle of the newly designed arrangement of the magnetoelastic sensor consisting of the four basic parts is shown in Fig. 1. The first segment of the sensor is the controlled source of the variable magnetic field, as is the primary coin supplied by changing current. The second one is the appropriately structured system of Hall sensors for detailed investigation of the magnetic field intensity H in the investigated cross section of the observed prestressed structural element. The third one is the secondary coil scanning the magnetic flux density B in the investigated cross section. The fourth one is the careful sensor shielding made from steel that significantly reduces the influence of the sensor magnetic surroundings.

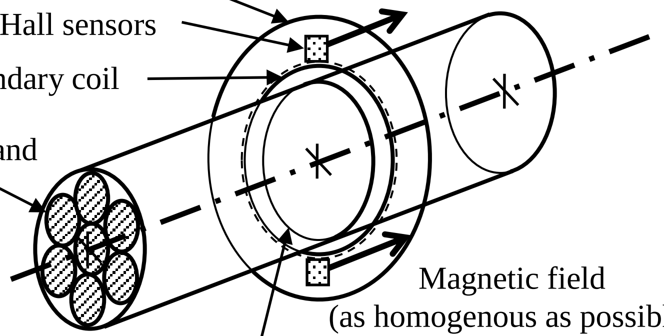

Fig. 1 The principle of the newly proposed arrangement of the magnetoelastic sensor

The Hall sensor is an electronic component that is applied for measurement of the magnetic field intensity H. The modern Hall sensors are small in size and they are satisfactory sensitive for accurate enough observation of the tangential component of the magnetic field close to the surface of the observed prestressed element. According to manufacturer's catalogs, the manufacturing tolerances of the sensitivity of the commonly available Hall sensors vary by up to about +/- 5%. Therefore, for a more precise measurement, the more accurate sensitivity has to be specified for each Hall sensor before its application by a special calibration device.

The magnetic flux density B in the observed element cross section is evaluated base on the analog integration of the voltage induced in the secondary coil.

The Verification of the New Approach

Several laboratory experiments were carried out during the verification process of the new approach to experimental determination of tensile forces in prestressed structural elements based on the magnetoelastic principle. Various sensor configurations and variants for measurement characteristics were studied during the verification experiments. For example, an appropriate time behavior and time duration of the changing current signal supplying the primary coil, a dimensionless parameter P characterizing most suitably a measured hysteresis loop, that can be applied for determination of experiment final results, a suitable placement of the Hall sensors around the investigated structural element for the appropriate description of the magnetic field intensity H in the close proximity of the element, a consequence of the sensor shielding and an effect of the sensor magnetic surroundings were analyzed.

In November 2016, the verification process of the new approach was finalized by a laboratory experiment concentrated on the systematic study of variations in the magnetic behavior of selected standard prestressed elements in dependence on its immediate temperature and rate of the mechanical stress. The laboratory experiment was realized in the experimental centre of the Klokner institute (the Czech Technical University in Prague).

The magnetoelastic parameters of several standard prestressed elements were investigated in the course of the experiment. Four currently used elements (one prestressed strand

Lp15.7/1860 MPa and three prestressed bars 15/17 made by companies Dywidag and Mikusol) and three formerly applied prestressed elements, that were obtained by demolitions of old prestressed concrete structures, (three patented wires P4.5 of different age) were studied.

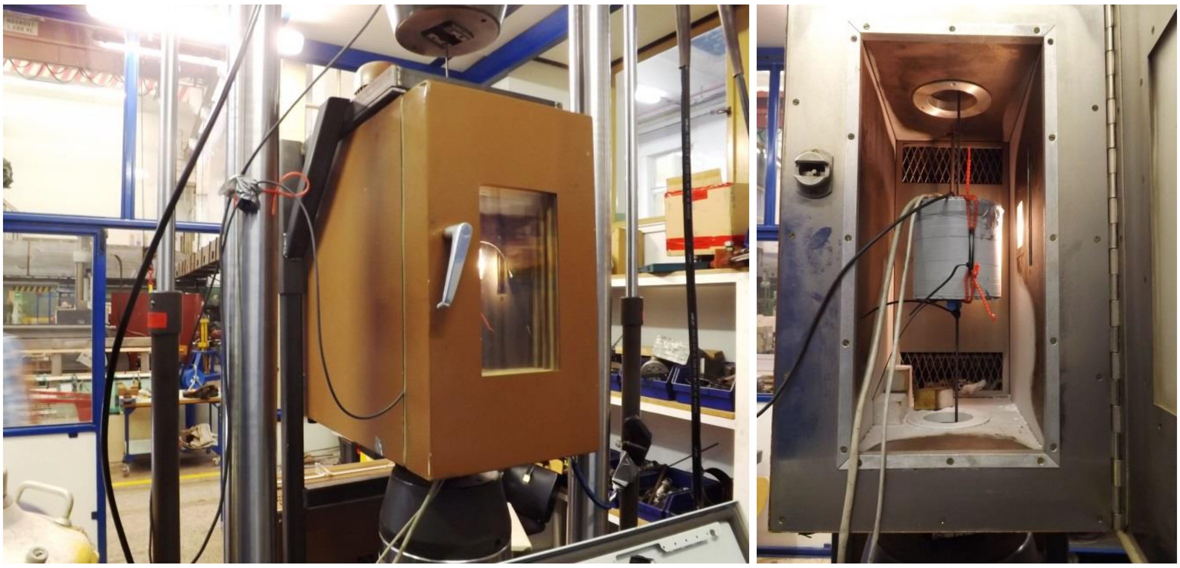

Fig. 2 The exterior view on the climatic chamber and the steel tensile testing machine (on left) and on the magnetoelastic sensor installed on the prestressed wire inside the chamber (on right).

In the course of the experiment, the investigated elements were placed in a climatic chamber (see Fig. 2) and loaded in a steel tensile testing machine. The magnetic features of the studied elements were investigated in four temperature steps namely, at -20^o C, at ±0^o C, at +20^o C and at +40^o C. The studied prestressed elements were loaded in a defined number of force steps for each temperature step. The used number of the force steps was nine or seven and it was chosen differently for each particular investigated element according to its design resistance.

For each element, each particular temperature and force step, the hysteresis loop was measured and determined. It was not effective to evaluate the measured hysteresis loops in their whole range because of the quantity and complexity of the obtained experimental results. In the course of the verification experiments, several various definitions of the dimensionless parameters P were defined and studied that represented in a simple way the character and shape of every measured hysteresis loop. The sensitivity to the variation of the mechanical stress and temperature was evaluated and critically assessed for each particular evaluated dimensionless parameters P. Base on this rating, the resultant dimensionless parameter P was selected that is defined as the difference between two values of the quantity B in exactly determined points of the hysteresis loop divided by the greater quantity B. It has been used for finally evaluation of all measured data.

The example of two evaluation curves resulting from the verification experiment for the patent wire labelled D1, that describes the dependence between the stress in the wire and the resultant dimensionless parameter P for two defined temperatures, is shown in Fig. 3.

The evaluated magnetoelastic characteristics for the particular wires are slightly different. But their differences are small and the values of the stress evaluated based on the average relation between the stress and resultant dimensionless parameter P deviate from the actual values about ±3% of the largest stress at maximum.

In the course of the verification experiments, the magnetoelastic characteristics of the prestressed strands were investigated only for one kind of this material which is used in the civil engineering practice at present. Though, several different test samples of this material were used during different verification experiments. The stress values were afterwards specified for almost all previously studied samples based on the final evaluation curve similar to the one shown in Fig. 3 that describes dependence between the stress and resultant dimensionless parameter P for the prestressed strands. The obtained results deviate from the actual stress values about ±2.0 % of the largest stress at maximum. The actual stresses in the studied strand samples were determined from the measured force values.

On the other hand, the large differences between the magnetoelastic characteristics of the prestressed bars made from various steel materials were identified. Moreover, it was found, the screw thread of the bar influences negatively the experiment. For obtaining the acceptably accurate results by the magnetoelastic method, the screw thread has to be removed from the bar surface in the proximity of the cross section, where the magnetoelastic sensor would be installed. And it is practically not feasible on an existing structure in a real situation.

The sensitivity of the dimensionless parameter P on the mechanical stress in the studied prestressed bars is considerably less than these ones evaluated for the prestressed strands or wires. This matter of fact is caused partially by the notably lower design resistance of the bar materials and also by their partly different chemical compositions.

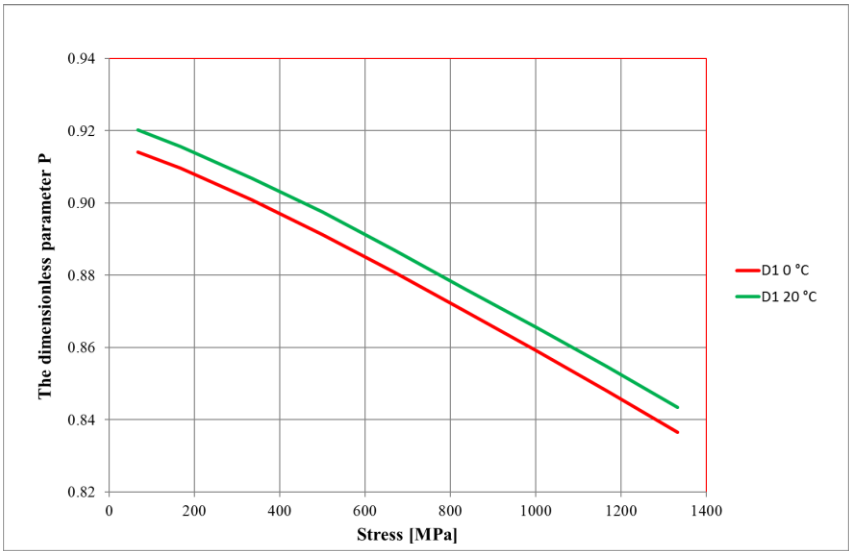

Fig. 3 The evaluation curve resulting from the verification experiment for the patent wire D1 and for the temperature steps ±0°C and +20°C, that describes the relation between the stress in the observed wire and the resultant dimensionless parameter P.

Another issue, that had to be solved during the evaluation of the experimental results, was the transformation of the magnetic field intensity H measured in the discrete specific positions by the system of the Hall sensors to a continuous field in the whole cross-section area. For the more accurate result evaluation, it is significant to know the value of the magnetic field intensity in the cross section sectors where the Hall sensor cannot be placed, as is the cross-section center of the strand for example.

The interpolation of measured values H for the significant points in the cross-section can be significantly improved by a numerical analysis. A suitable computing tool base on the finite element method (FEM) should be used for this activity. Rotationally symmetrical (see Fig. 4) and also general problems were solved during the new approach verification.

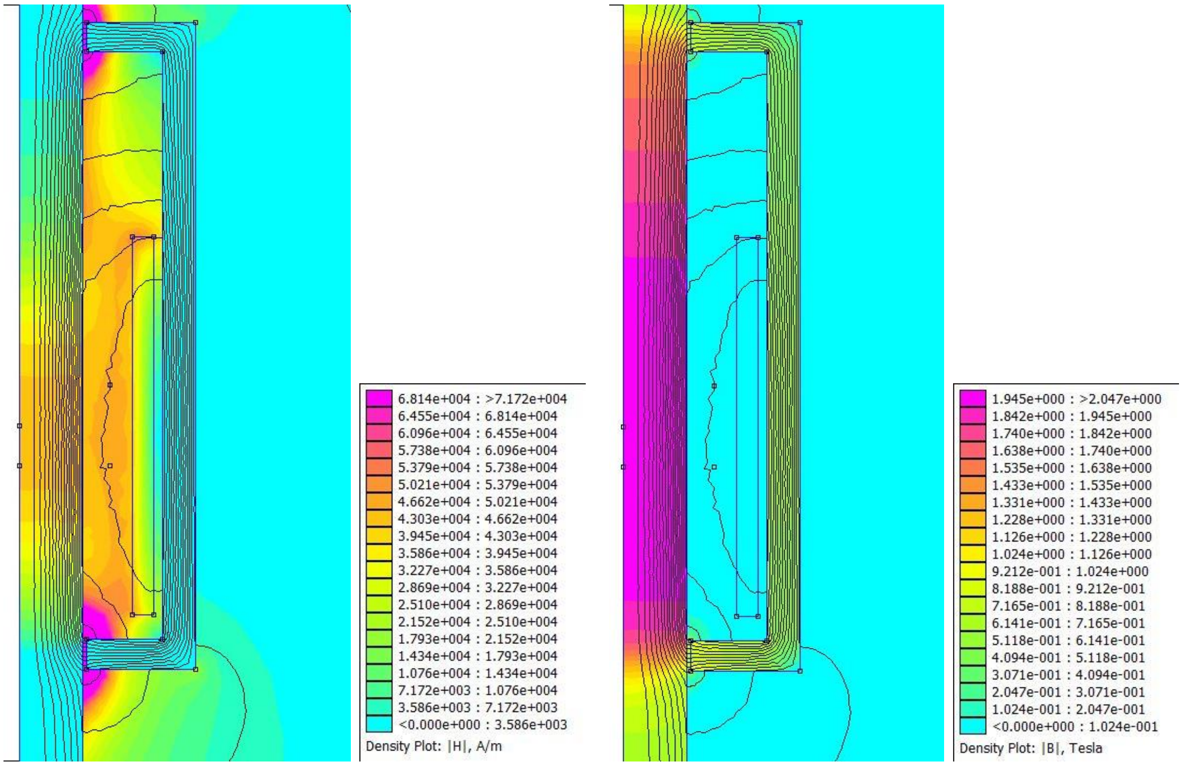

Fig. 4 The graphic visualization of the arrangement of the magnetic field calculated by the software FEMM [8] for the FEM model of the rotationally symmetrical magnetoelastic sensor (the axis of symmetry is in the left part of both images), the magnetic field intensity H (on the left) and magnetic flux density B (on the right).

The Application of the New Approach on the Existing Structure

The applicability of the new approach described in the paper was realized by an implementation on a prestessed concrete structure, namely on the existing footbridge across Vltava River in Prague constructed in 1984 (see Fig. 5). The footbridge load bearing structure is built as the precast segmental construction and its static system is the stress ribbon bridge with three spans 85.5 m, 96.0 m and 67.5 m.

Fig. 5 The overview on the investigated footbridge (on the left) and on the footbridge section, where the magnetoelastic sensors were installed (on the right).

The substantial part of the footbridge deck was overflowed by two great floods that occurred in August 2002 and in June 2013. Subsequent diagnostics of the footbridge detected several serious problems of the load bearing structure. Especially, justified doubts about the real actual value of the prestress in the prestressed cables were the basic reason for the realization of the verification experiment on this specific footbridge. It was supposed, the strong local corrosion of several prestressed cables and the partial deterioration of the construction conditions of the load bearing structure both detected by diagnostics could significantly affect the cable prestressed forces.

The archived footbridge design documentation was used to obtain the basic knowledge about the load bearing structure geometry, about the used fundamental structural elements and about the installation procedure of the footbridge structure.

Two types of the steel cables were used in the course of the footbridge construction process. At first, the cables of type A were situated. They are the carrying ones of the stress ribbon bridge. Afterwards the installation of the footbridge concrete parts, fourteen cables of type B assembled from six strands (see Fig. 6 and Fig. 7) were activated. They are the prestressed ones preventing the dilatation of transversal gaps between the concrete segments of the footbridge deck.

Fig. 6 The view on the created hollow, the studied cable, the coiler, the black plastic sensor body, the partially reeled secondary coil (on the left) and the partially reeled primary coil (on the right).

Fig. 7 The view on the completed magnetoelastic sensor (on the left) and on the sensor covered by the steel shielding (on the right).

In November 2016, the first magnetoelastic sensor designed for the assembly on the existing structure was installed on the prestressed cable of type B. In April 2017, the next three magnetoelastic sensors with the same parameters as the first one were made on another three cables of type B. The positions for the installation of all four sensors on the selected cables were chosen not to be significantly affected by cable corrosion in these places. All four observed cables were studied as the whole because of there was not gaps between the strand wide enough for the sensor installation on the individual strands.

At first, the adequately large hollows (see Fig. 6 and Fig. 7) were created carefully around the selected cables in which the sensors could be assembled. Secondly, the sensor bodies were assembled on the cable from two segments. Thirdly, the secondary coils were reeled on the sensor bodies by the help of the specially made coiler rotating with the plastic sensor body (see Fig. 6). Fourthly, the primary coils were made in the same way as the secondary ones (see Fig. 6). Next, the systems of the calibrated Hall sensors were placed inside the cables in small free hallows between strands and then their positions were specified accurately relative to both coils. One Hall sensor has always touched the surface of the middle strand. At the end, the thorough sensor steel shieldings were positioned (see Fig. 7) that were assembled from two segments again. Both experiments in situ were completed with the measurement of the hysteresis loops obtained as the primary experimental results. The results measured in April 2017 are still being processed.

The dimensionless parameter P was evaluated from the hysteresis loop measured in November 2016 and then the resulting value 825 MPa of the normal stress in the studied cable was obtained from the evaluation curve similar to the one depicted in Fig. 3.

The assessment of acceptability of the determined normal stress in the cables was realized based on comparison with expected stress in the prestressed cables of type B that was determined from the available information about the footbridge structure. The study of the static calculation of the footbridge showed that the normal stress in the cables of type B could be anticipated in the interval from 680 MPa to 1000 MPa. The large range of the stress interval is related to the prestress losses due to successive prestressing of the subtle footbridge structure by fourteen cables of type B. A protocol about the correct procedure of the successive prestressing of the prestressed cables in the course of the footbridge construction enabling a more exact assessment of the stress in the observed cables has not been found unfortunately. The experimentally determined resulting value of the normal stress in the first observed cable is practically located in the center of the anticipated interval taken from the static calculation. It means that the resulting value specified experimentally for the first investigated cable may be characterized as reliable.

Conclusions

The paper introduces the concise description of the principle of the new approach to the experimental determination of tensile forces in prestressed structural elements of civil engineering structures and the basic validation of its results. The new approach is based on the magnetoelastic principle and was designed and developed especially for application on existing structures built from prestressed concrete.

The applicability of the method was confirmed by the experiments performed both in the laboratory and on existing prestressed concrete structures in situ. This method is especially suitable for a supervision of the stress in the steel prestressed elements assembled from wires or strands on the existing structures made from prestressed concrete on which another nondestructive method [1, 2, 3, 4] cannot be used as it is in most of actual cases in the civil engineering praxis.

On the other hand, the supervison of the presstressed bars using the new approach does not seem appropriate. These bars are usually used on civil engineering structures as temporary mounting prestressed elements. In these cases, another experimental tools can be easily used for the tensile forces monitoring e.g. a strain gauge measurement or a professionally made force transducer.

Based on the author's knowledge, the standard magnetoelastic sensors [5, 6] composed from the primary and secondary coils only, that have been used to the present days, are placed usually on an unloaded monitored element before its activation. Then the actual prestressed force from a tension hydraulic jack during tensioning of the element is used for the sensitivity specification of the used measuring equipment. It usually consists of the data logger and the sensors. The disadvantage of the standard approach is that it is only useable for the observation of the tension force compared with the initial reading which has to be realized in the unloaded state of the element. Based on the above mentioned knowledge, the total normal force in the prestressed structural elements on an existing concrete structure cannot be determined with enough precision by this approach.

The described new approach also provides an advantage for experiments carried out on newly built prestressed concrete structures compared to experiments performed by standard magnetoelastic sensors [5, 6, 7].

In the performed experiments, another advantage of the new approach was found. It is the possible significant elimination of risks of an inaccurate determination of the current stress in the prestressed elements monitored already in the moment of their activation. These risks are particularly attached to the possible change of magnetoelastic characteristics of the standard magnetoelastic sensor [5, 6, 7] caused by a change of sensor magnetic surroundings in the time between its calibration during the prestressed element activation and a performed stress measuring. The changeability in the sensor magnetic surroundings is usual during construction of a civil engineering structure. It could be caused by concreting of steel-fibre concrete, a removal of a steel massive falsework from the sensor surroundings after concrete hardening or the simple removal of the tension hydraulic jack after tensioning for example.

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