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EXPERIMENTAL MEASUREMENTS IN THE FIELD OF PRESTRESSING FORCE MONITORING

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Abstract

In recent years, lots of researchers have given attention to prestressing evaluation in existing prestressed concrete structures. In Europe, many existing prestressed concrete bridges are about to reach their limit of service life and exhibit signs of deterioration. Therefore, reliable, and effective methods for determining the actual state of prestressing are needed. Indirect methods represent a valuable tool for the structural assessment of prestressed concrete members in service. These methods include, e.g., Saw-cut method, Structural response method, Barkhausen noise technique, or Wire-cutting method. The presented paper summarises indirect measurements focused on prestressing force monitoring using the aforementioned techniques performed in the Laboratory of Civil Engineering of the University of Žilina.

Keywords:

Prestressed concrete;
Assessment;
Saw-cut method;
Structural response method;
Barkhausen noise technique.

1 Introduction

Prestressed concrete has successfully established as one of the most used construction materials in the field of civil engineering. First applications date back to the early 20th century and are attributed to French engineer Eugène Freyssinet [1]. However, lots of prestressed concrete structures built in the 1950s and 1960s are approaching the limit of their service life as their structural condition is inappropriate. The state of these structures is closely related to insufficient maintenance and certain design pitfalls of technology that was used in the time of construction [2, 3]. As A Result, significant corrosion losses of prestressing steel decrease the actual prestressing force value in the assessed member. Within the next few years, the assessment of existing prestressed concrete structures is likely to become a crucial element in civil engineering [4]. In the case of bridges on road networks, the Slovak Road Administration statistics database and available sources show that about 34.2 % of existing bridges do not satisfy the current criteria for reliability and 2.5 % are in very poor or breakdown condition [5]. For these reasons, the research activities of the Department of Structures and Bridges are focused on reliability assessments and investigation of existing steel and concrete bridges, along with their possible rehabilitation [5, 6]. Consequently, the presented paper aims to introduce some methods for prestressing force monitoring which could be used as an effective tool in the field of structural assessment [7].

Currently, several methods for the monitoring of the actual level of prestressing are available. Generally, these techniques can be classified according to their influence on the investigated structure or approach to the prestressing force evaluation [4]. The techniques with none or only negligible impact on the structure's integrity are usually considered non-destructive or semi-destructive. On the other hand, destructive methods cause severe damages to the investigated structure. Direct approaches typically fall into a group of non-destructive methods and enable the quantification of residual prestressing force directly from the results of the measurement. On the contrary, using indirect methods inevitable leads to the calculation of prestressing force value indirectly from the measured values such as deflection, normal stress or strain change, a width of the crack, etc.

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2 Monitoring of prestressing force

This chapter presents an overview of some possible approaches for determining the residual prestressing force in existing prestressed concrete structures. All mentioned methods were performed in situ or laboratory as a part of the research focused on verification of prestressing force monitoring.

2.1 Saw-cut method

Saw-cut method falls into the group of so-called Stress relief methods. Its principle is based on normal stress relief initiated by sawing of two or more cuts into a prestressed concrete member. This sawing initiates local change in strain (normal stress) whereas this strain (normal stress) relief is monitored in the adjacent area, see Fig. 1. Eventually, performed saw-cuts isolate concrete block from the acting forces. Based on knowledge of the material properties, characteristics of the investigated beam, and applied load in the time of test, it is possible to indirectly calculate the initial normal stress value. Subsequently, if the normal stress distribution in the member is linear (uncracked structure), we can determine prestressing force value $P_{mt,actual}$ using (1).

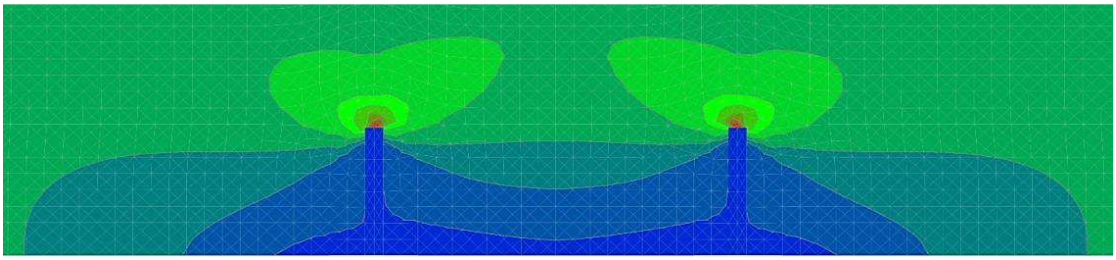


Fig. 1: Saw-cuts – local normal stress relief from the FE numerical model (contour areas).

$$P_{mt,actual} = -\frac{\sigma_{c,0} - \frac{M_G}{I_{yi}} \cdot z_i}{\frac{1}{A_i} + \frac{e_{pi}}{I_{yi}} \cdot z_i}, \tag{1}$$

where:
$\sigma_{c,0}$ - initial normal stress in concrete,
M_G - bending moment due to dead load,
I_{yi} - second moment of inertia of the cross-section,
z_i - position of the neutral axis of an ideal cross-section from the edge,
A_i - ideal cross-sectional area,
e_{pi} - ideal eccentricity of prestressing force from the neutral axis.

When using Saw-cut method, it is essential to avoid cutting of reinforcement bars because such intervention could lead to affecting structural integrity. Therefore, the maximum depth of saw-cuts is limited by the concrete cover which can be especially in the case of elder bridges very low in comparison to today applicable standards. However, a remarkable benefit of this technique is that provided results describe the state of prestressing in the whole structure and not only in certain prestressing wire (or strand). Saw-cut method can be an effective tool in structural assessment. Especially, if the prestressed concrete structures are composed of individual beams [3, 8, 9]. Moreover, if the tested member is not loaded by an external load, the determination of additional normal stress value resulting from the dead load is not complicated. Consequently, the measurement can be performed quickly and easily in situ and does not require expensive tools [3]. Importantly, this approach was experimentally tested mainly in the case of compressive stress relief. Tensile stress relief should be, therefore, further investigated. The verification of Saw-cut method in laboratory conditions can be seen in Fig. 2 and experimentally recorded stress relief in Fig. 3 where abrupt changes in normal stress reading represent the gradual application of saw-cuts.



Fig. 2: Saw-cuts – side view (left), bottom view with a foil strain gauge (right).

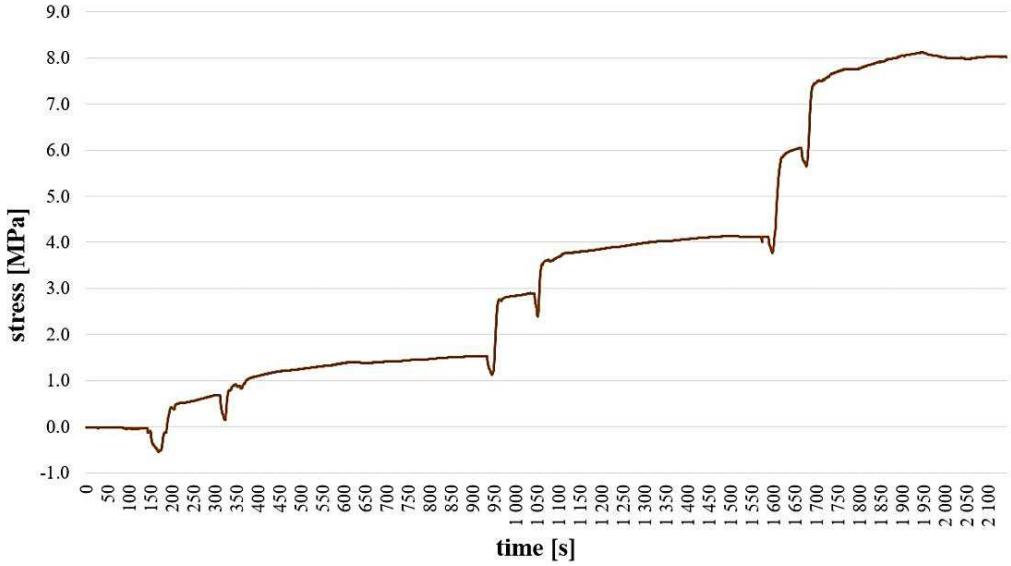


Fig. 3: Saw-cut method – experimentally recorded normal stress relief after gradual sawing.

2.2 Structural response method

Structural response method is based on the measurement of quantities which enables subsequent determination of residual prestressing force. Measured quantities include, for example, deflection, normal stress or strain, and crack width. Prestressing force can be evaluated according to the relation between average strains ε_{cm} in concrete and steel ε_{sm} and mean curvature κ_m considering Navier beam theory. This relation is presented in (2). The drawback of this method is a requirement to apply load which will initiate a crack in prestressed concrete structure (critical bending moment). Correspondingly, in the case of already precracked prestressed concrete structures, decompression bending moment has to be reached [9]. Furthermore, in the case of prestressed concrete bridges composed of several individual girders, the determination of the ratio of distributed load can be sometimes difficult. Structural response method performed on the post-tensioned beam can be seen in Fig. 4.

$$\kappa_m = \frac{1}{r_m} = \frac{M}{(E \cdot I)_m} = \frac{\varepsilon_{sm} - (-\varepsilon_{cm})}{d}, \tag{2}$$

where:
r_m - mean radius of curvature,
d - the effective depth of a cross-section,
M - bending moment,
$(E \cdot I)_m$ - girder stiffness.



Fig. 4: Structural response method performed on post-tensioned beam in the laboratory.

2.3 Barkhausen noise technique

Magnetic Barkhausen noise can be found in ferromagnetic bodies as a result of the discontinuous motion domain walls [10 -11]. The principle of the evaluation is a combination of in situ measurement on stressed wires which are still part of the prestressed concrete structure. Subsequently, the wire is removed and tested in the laboratory under predefined levels of stress. Thus, the obtained calibration curve enables the comparison of detected values of rms of MBN from in situ and laboratory measurements. The relation obtained from the test on prestressing wire in prestressed concrete sleeper is displayed in Fig. 5.

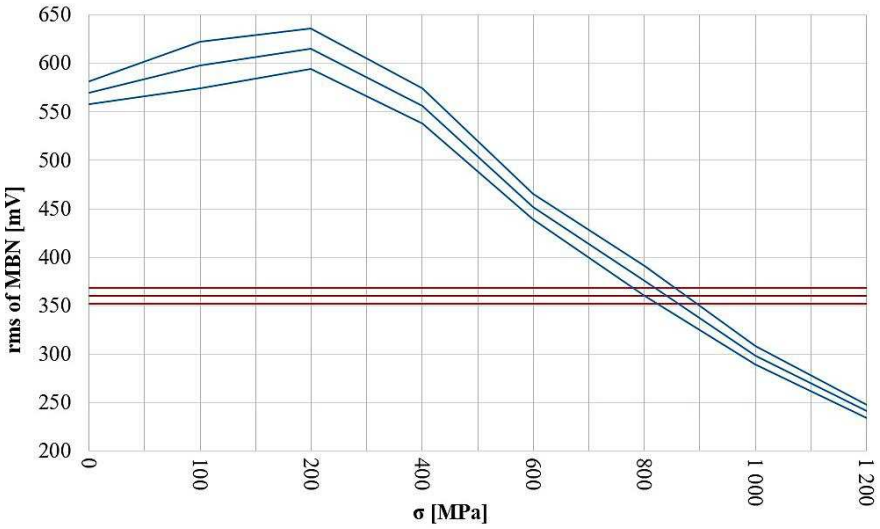


Fig. 5: Barkhausen noise measurement output – measurement (red), calibration (blue).

It is recommended to perform the evaluation at multiple points on prestressing steel specimens. One of the crucial pitfalls of this technique is that sensitiveness against surface damages which affect the stress state. In the case of existing prestressed concrete structures, both surface and microstructural damages of prestressing steel are not unusual. Therefore, at least a visual inspection of the tested wire or strand is required. On the other hand, an important advantage of the Barkhausen noise technique is that its application is time-saving and portable. An example of the application of this method on prestressed concrete sleeper is shown in Fig. 6.



Fig. 6: Barkhausen noise measurement applied on wires of prestressed concrete sleeper.

2.4 Wire-cutting method

Wire-cutting method (or strand-cutting method) belongs to the group of so-called strain-based methods and its principle is established on the measurement of change in the strain that develops when the wire (or strand) is cut after the exposure. Determination is possible due to the relationship between strain and stress in the linear elastic range. This method can be used only in the case of bonded prestressed concrete members. Eventually, the results of performed measurement facilitate determining the value of the corresponding residual prestressing force in the investigated wire. Strain change is recorded by strain gauge installed on wire prior to cutting. The drawback of this technique is the need for prestressing steel exposure [9, 12]. Eq. (3) describes the relationship between change in strain and residual prestressing force in investigated wire or strand. Wire-cutting method applied on prestressing wires of the post-tensioned bridge is shown in Fig. 7. Disadvantages of this technique include difficult measurement of the strain change peak $\Delta\varepsilon_p$ after the cut is applied which is crucial for correct evaluation of prestressing force $P_{mt,actual}$. Similarly, as in the case of the Barkhausen noise technique, generalization of prestressing force in one prestressing wire on the whole structure could be incorrect as the state of prestressing wires can differ. An example of strain change measurement performed on prestressing wire is presented in Fig. 8, where a sudden change in strain reading can be seen after the application of the cut. Subsequently, it is needed to wait until the strain reading is sufficiently stabilized.

$$P_{mt,actual} = \Delta\varepsilon_p \cdot E_p \cdot A_p, \tag{3}$$

where:
$\Delta\varepsilon_p$ - measured strain change in prestressing steel,
E_p - modulus of elasticity of prestressing steel,
A_p - actual cross-sectional area of prestressing steel.



Fig. 7: Wire-cutting method – prior cutting (left), after cutting (right).

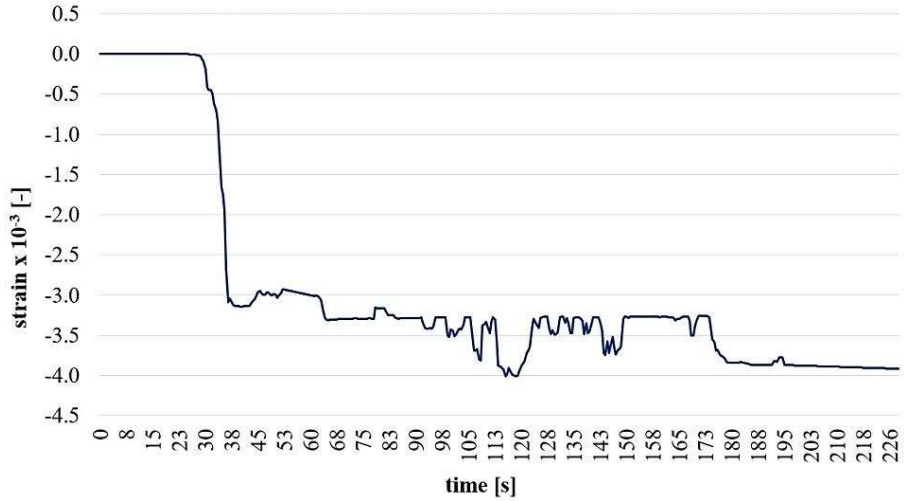


Fig. 8: Wire-cutting method – example of strain change measurement.

3 Conclusions

The presented paper introduced some methods which could be possibly used in the field of prestressed concrete structures assessment. In practice, it is important to choose a suitable method regarding its applicability, availability, and affordability. Another important factor is the type of output from the performed measurements. Application of methods that provide information about the state of prestressing in the individual prestressing wires or strands, such as the Barkhausen noise technique and Wire-cutting method, can lead to incorrect overall determination of load-carrying capacity and remaining service life of the investigated structure. Hence, using methods that provide the general value of residual prestressing force (Saw-cut method and Structural response method), seem to be a more suitable option. Consequently, all aforementioned methods should be further studied in situ and laboratory conditions. Especially, the determination of factors that could negatively influence the accuracy of these techniques is a big challenge for future research.

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References

[1] BONOPERA, M. – KUO-CHUN, CH. – ZHENG-KUAN, L.: State-of-the-Art Review on Determining Prestress Losses in Prestressed Concrete Girders. Applied Sciences, 10, 2020, No. 20, 7257, https://doi.org/10.3390/app10207257.

[2] BUJŇÁKOVÁ, P.: Anchorage System in Old Post-tensioned Precast Bridges. Civil and Environmental Engineering, Vol. 16, Iss. 2, 2020, pp. 379-387, https://doi.org/10.2478/cee-2020-0038.

[3] KRAĽOVANEC, J. – MORAVČÍK, M. – BUJŇÁKOVÁ, P. – JOŠT, J.: Indirect Determination of Residual Prestressing Force in Post-Tensioned Concrete Beam. Materials, 14, 2021, No. 6, 1338, https://doi.org/10.3390/ma14061338.

[4] KRAĽOVANEC, J. – MORAVČÍK, M. – BAHLEDA, F. – PROKOP, J.: Experimental and Numerical Study of Saw-cut Method on Concrete Beams. FIB Symposium 2021, Concrete Structures: New Trends for Eco-Efficiency and Performance, held online from Lisbon, Portugal, June 14–16.

[5] KOTEŠ, P. – VIČAN, J. – NIKOLIČ, R.: Evaluation of Elder and Historical Bridges. 9th International Conference Bridges in Danube Basin 2016, BDB 2016. Procedia Engineering, Vol. 156, 2016, pp. 186-190, https://doi.org/10.1016/j.proeng.2016.08.285.

[6] PONECHAL, R. – KOTEŠ, P. – MICHÁLKOVÁ, D. – KRAĽOVANEC, J. – BAHLEDA, F.: Effect of Water Condensate on Corrosion of Wires in Ungrouted Ducts. Materials, 2021, 14, 7765, https://doi.org/10.3390/ma14247765.

[7] VIČAN, J. – GOCÁL, J. – MELIŠ, B. – KOTEŠ, P. – KOTULA, P.: Real Behaviour and Remaining Lifetime of Bridge Structures. Communications - Scientific Letters of the University of Zilina, 10(2),

2008, pp. 30-37. Retrieved from http://komunikacie.uniza.sk/index.php/communications/article/view/1042.

[8] KRAĽOVANEC, J. – MORAVČÍK, M. – JOŠT, J.: Analysis of Prestressing in Precast Prestressed Concrete Beams. Civil and Environmental Engineering, Vol. 17, Iss. 1, 2021, pp. 184-191, DOI: 10.2478/cee-2021-0019.

[9] BAGGE, N. – NILIMAA, J. – ELFGREN, L.: In-situ Methods to Determine Residual Prestress Forces in Concrete Bridges. Engineering Structures, 2017, https://doi.org/10.1016/j.engstruct.2016.12.059.

[10] PASTOREK, F. – DECKÝ, M. – NESLUŠAN, M. – PITOŇÁK, M.: Usage of Barkhausen Noise for Assessment of Corrosion Damage on Different Low Alloyed Steels. Appl. Sci. 2021, 11, 10646, https://doi.org/10.3390/app112210646.

[11] VARGA, R.: Domain Walls and Their Dynamics. Košice, Slovakia, 2014, Pavol Jozef Šafárik University.

[12] ABDEL-JABER, H. – GLISIC, B.: Monitoring of prestressing forces in prestressed concrete structures - an overview. Struct. Control Health Monit., 2019, 26, e2374, https://doi.org/10.1002/stc.2374.