Andrzej JURKIEWICZ
Piotr MICEK
Marcin APOSTOŁ
Dariusz GRZYBEK

O POTRZEBIE MONITOROWANIA PROCESU SPRĘŻANIA KONSTRUKCJI MOSTOWYCH

ABOUT THE NEED OF THE MONITORING OF THE BRIDGE CONSTRUCTION PRESTRESSING PROCESS

W artykule przedstawiono koncepcję systemu monitorowania i rejestrowania przebiegu procesu sprężania z wykorzystaniem układu mikroprocesorowego. W agregatach hydraulicznych stosowanych w technologii sprężania i nasuwania konstrukcji mostowych ASIN (opracowane w KAP AGH) stosowane są nowoczesne sterowniki programowalne, dzięki czemu rozbudowa ich o system monitorowania i rejestrowania przebiegu siły i wydłużenia nie wymaga dużych nakładów. Opracowanie i wdrożenie systemu monitorowania i rejestrowania parametrów procesu sprężania pozwoli, oprócz poprawy jakości i bezpieczeństwa konstrukcji, na zbudowanie bazy wiedzy. Baza ta jest niezbędna dla opracowania metod diagnozowania procesu sprężania. Dla opracowana koncepcja systemu wykorzystano wieloletnie doświadczenie autorów artykułu zdobyte przez udział w sprężaniu kilkunastu obiektów mostowych.

Słowa kluczowe: konstrukcje sprężone, system sprężania, monitorowanie, diagnostyka

The article presents the system conception of the monitoring and course logging prestressing process wit the use of the microprocessor system. In the hydraulic supplying units, which are elaborated by AGH, are used the modern programming controllers which can be used like the base of the elaborating monitoring system.
The elaboration and application of the monitoring and logging system enables the improvement of construction quality and safety as well as the building of the knowledge base. The base is needed to the elaboration of the diagnostic method of the prestressing process. To the elaboration of this conception was used the experiences of the author of this article. This experience was earned by the participation in the prestressing ten or more bridge construction.

Keywords: prestressing, post-tensioning system, monitoring, diagnostic

1. Introduction

Quality of the carrying out of the structure post-tensioning process is one of the most important factor which decide about the operating characteristics as well as the safety of the structure. Nowadays the monitoring of the post-tensioning process as well as documentation of its course is leaded by check of the tendon elongation after the prestressing force reaches the level of 20, 40, 60, 80 and 100% of the design value. Assessment of process quality is leaded by comparison of real value of the tendon elongations and design value (it is correct if the differences are smaller than 10 %). Appeared during post-tensioning realization dynamic transitory states aren't analyzed if its effects don't cause the exceed permissible difference between real and design force value. On the other hand the analysis of the causes of exceed permissible value is very difficult because the prestressing team have only one information about the exceed of this value. The dynamic states like the step change of post-tensioning force are the standard phenomena which results from the friction between the tendon and the tendon channel. The value of the amplitude of this vibrations is depended from the friction coefficients and the channel shape. The vibration don't effect on quality of post-tensioning process. The decrease of post-tensioning force caused by the scarifying of the tendon or the tendon slip in the anchored block is the emergency state. The definition of the damage kind isn't usually possible, from there the next decisions are made on

the basis of the hypothesis. The approval of the post-tensioning process carrying out is leaded on the basis of the post-tensioning journal which is described by the prestressing team which want to get the positive decision from supervision inspector. From there the prestressing team can want to hide the prestressing mistakes.

The conception of monitoring and registration system with use of microprocessor for prestressing process is presented in this article. The modern programmable controllers are used in the hydraulic units which are applied in ASIN technology for prestressing and slide over of bridge structures. Hence, its development for the elaboration of the monitoring and registration system of the force course and string elongation doesn't require a big costs.

In the most applied prestressing systems the control of prestressing force value is realized by hand by the setting of throttle valve on the basis of the manometer indications. Hence, the elaboration of the independent microprocessor system monitoring the parameter values of prestressing process without the interference to this process as well as the prestressing devices construction is needed for these systems.

The elaboration and application of the monitoring and registration system of prestressing process parameters enables, apart from the quality correction and the structure safety correction, the building of the knowledge base. The base is needed to the

elaboration of the monitoring methods of prestressing process. Many years experience of authors was used to the elaboration of the system conception.

2. The influence of prestressing process monitoring on the quality of the structure carrying out

2.1. The verification of prestressing program

Suitable stress distribution in the structure (minimization of the tension stress) is the target of prestressing process. Modern design systems using the advanced analysis methods of the stress and displacement distribution (FEM, modal analysis) enable to the optimal choice of the tendon channel shape and the force distribution on the tendon length. The distribution of the prestressing forces is the function of the tendon canal channel as well as coefficients of friction between the tendon and the wall of channel. Defined by norms parameters of the constructions materials and simple models of the structure load are established in the design process of new object. The prestressing process is elaborated on the basis of this ideal assumption. The prestressing process contains: sequence of the cable tension, prestressing forces values, the way of input of prestressing forces (unilateral, bilateral) as well as established elongation of tendons. The real parameters are different from established parameters. The course of the cable channel is different than established because of the carrying out inaccuracy as well as the displacements at the place the concrete stage. The friction coefficients for applied prestressing system are usually established as material constants depend on the applied cable shields and the kind of strings. The state of the shields and strings (rust, dirtiness, cracks, protective coats etc) and atmospheric conditions (humidity, temperature) can effect on friction coefficients values. These differences cause a big divergences between the real distribution of prestressing forces and established distribution in the project. The variety and randomness of factors effecting on prestressing process make impossible its definition in the laboratory research. Hence, the conducting of the research on real object is only possibility.

Verification of prestressing program is carried for the definition of real friction coefficients. Verification is carried out by the experimental prestressing of chosen (characteristic for some object) cable with measurement of prestressing forces on the active and passive side. The prestressing is carried out without the active anchored (on the side of prestressing press) in order

Fig. 1. The force sensor during verification

to obtain the cable lightening, which enables the disassembly of the measurement sensor. The active forces are defined on the basis of characteristic of the tension press. A special, usually strain gauge, force sensors are applied for the forces measurement on the passive anchorage (Fig. 1). The load cycle of tendons during the verification is similar to prestressing process. The measurement of the cable elongations is realized after the active force value reaches value of 20, 40, 60, 80, 100% of design value of the prestressing force.

The determined real coefficients enable to the correction of the prestressing program.

The losses of prestressing forcen (ΔP_{tk}) caused by the cable friction in the shield are determined on the basis of the registered course of the prestressing force on the passive side:

$$\Delta P_{tk} = P_C - P_b \qquad (1)$$

The exemplary force courses on active and passive sides are presented in Fig. 2a.

Percentage part of the prestressing force losses is calculate:

$$\eta_{tk} = \frac{P_C - P_b}{P_C} \cdot 100\% = \frac{\Delta P_{tk}}{P_C} \cdot 100\% \qquad (2)$$

The exemplary diagrams of the percentage part of the force losses according to prestressing force for two tendons which have different course route is presented in Fig. 2.
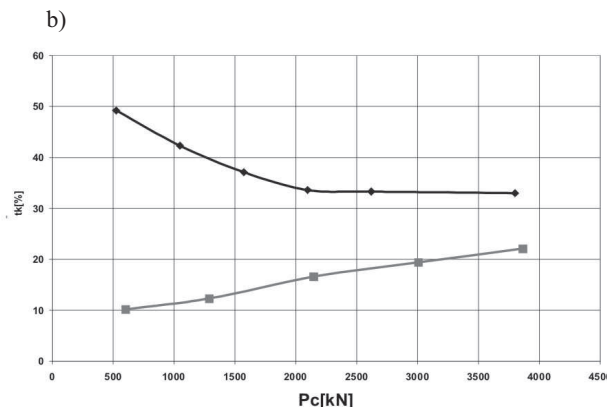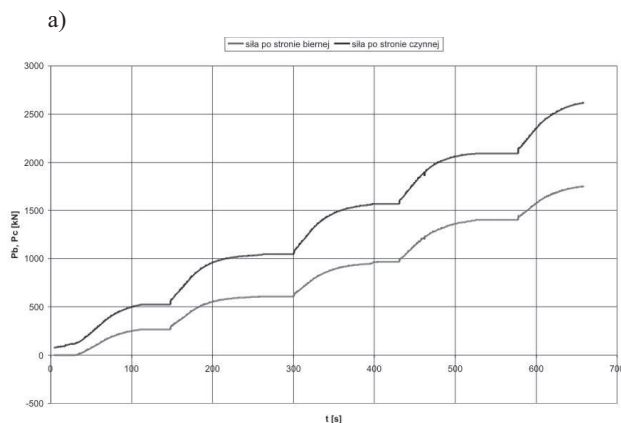
a)

b)

Fig. 2. a) Courses of prestressing force on active and passive sides, b) Force losses according to prestressing force value

A substitute friction coefficients can be determined after the input of measured force courses to the established model (3) of object

$$\Delta P_{tk} = (1 - e^{-(\alpha\mu + \lambda x)})\, P_o + Tx \tag{3}$$

λ − friction coefficient per unit of cable length, μ − coefficient of friction between the cable and wall channel on the curving, T − the losses of the cable tension force per length unit, independently on the tension value (kN/m), e − Euler function, Po − initial prestressing force, $x = \Sigma a_i + \Sigma \varphi_i r_i$ — cable length from the impose a force point to the section, in which the prestressing force is determined, φ_i − middle angle of i-arch in radians, r_i − radius of i-arch, $\alpha - \Sigma\varphi_i$ [radian].

Presented above mathematical model has infinite number of the solution because it contains 2 unknown coefficients α i λ. The optimization methods are used to the determination of the coefficient values.

The designer can verify the prestressing process on the basis of the real value of the friction coefficients. Histograms of the distribution of the cable elongations for two bridge objects are presented in Fig. 3 and Fig. 4.
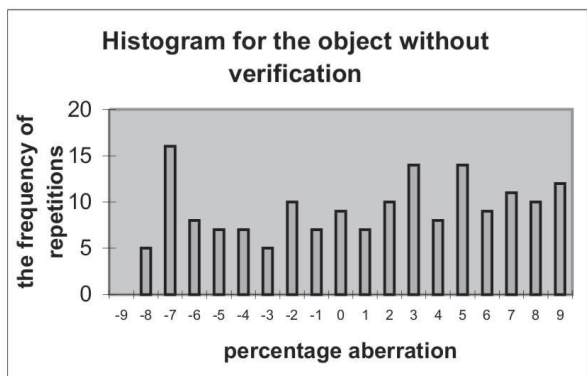

Fig. 3. Histogram of distribution of tendons elongations for object without verification of prestressing program
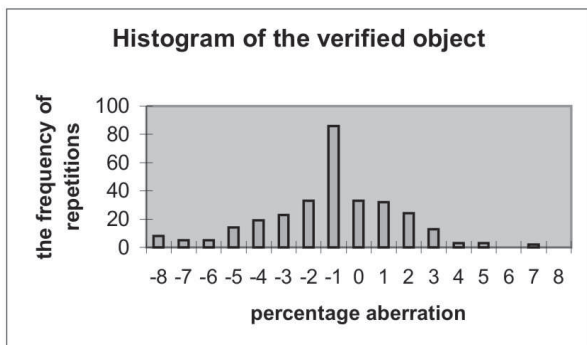

Fig. 4. Histogram of distribution of tendons elongations for object with verification of prestressing program

In the first case the real value of friction coefficients, which was determined in researches, wasn't applied in project. In the second case these coefficients was applied in the project and the prestressing program was verified (Wielicka-Kraków).

The lack of verification of the prestressing program caused the big dispersion of the real cable elongations according to the design value.

The most of results are bigger than the range of ±4%. It means that the part of tendons was overloaded or low-loaded. It can effect on prestressing and the operating parameters of the structure.

2.2. Monitoring of the damages of the prestressing system

The differences between the static friction and kinetic friction as well as the cable elasticity cause the step decrease of the prestressing force during the prestressing of the cable.

This decreases can amount to several percent of the force value. The course of the prestressing force value isn't registered in the most systems. The value of this force is determined on the basis of the indication of manometers which measure the pressure in the input conduit of prestressing press. The force decrease resulting from the string slip according to anchorage as well as the scarifying of the string is comparable with the decrease resulting from change of friction coefficient (relaxation vibrations) in the system consisting of ten or more cable. In this case, the cable and anchorage damages couldn't be notice by operator of the prestressing system. The damage of one or several strings in the cable couldn't be notice in the analysis of the whole cable elongation because the differences between real and design elongation amount to up 10%. The rest of strings are overloaded because it carry this differences. The registration of the prestressing force course and its analysis can solve this problem.

The elaboration of method detecting the system damages enables the analysis of prestressing force course.

2.3. Monitoring of the structure damages

The exemplary damages of the bridge structure caused by misuse prestressing of the object I presented in Fig. 5. The dynamic processes proceeded in the concrete structure during prestressing process as well as the operating of this structure are the sources of acoustic waves emission. The occurrence of acoustic emission don't be researched well. It can be take assumption that the processes of the formation and propagation of micro and macro gaps as well as reciprocal effect of the materials having different parameters (strength, elasticity modulus, hardness) are the sources of the acoustic waves emission.

The diversification of strength and acoustic characteristic of the materials creating the prestressing system (concrete – prestressing steel) have an effect on the diversification of the acoustic wave parameters as well as the modulation of the vibroacoustic signals (different models of the vibroacoustic wave propagation).

Fig. 5. The view of the object damages resulting from the mistakes in the prestressing process

The research of the possibility of the acoustic emission using to the detection of damage appearing in the prestressing process wasn't conducted. On the basis of the experiences of authors it can claim that acoustic wave generated in the prestressing structure are good information carriers.

Experienced operator of system can detect the acoustic effects and he can diagnose the problem. It is subjective assessment, which has had to be confirm by the application objective research methods (diagnostic instruments).

3. Conception of monitoring system of the prestressing process

3.1. Post-tensioned post-tensioning system

The applied in post-tensioned technology hydraulic devices are controlled by throttling with the application of the standard control elements. This devices consist of two hydraulic unit which are connected by flexible hydraulic conduits: tensioning and transporting unit as well as drive and control unit. The work of the tensioning and transporting unit supplied by drive and control unit is cyclic. The normal cycle contains following stages:

- tensioning: strings gripped by internal wedges is stressed up design force value with the measurement of the piston motion,
- bracing, tensioned strings are gripped by external wedges and next tensioning chambers are discharged,
- back, every work of press and hydraulic supplier come back to the initial state.

Both of this unit have the simple and compact building resulting the application of high pressure hydraulic elements. The low efficiency and the heating of work fluid causing the discontinues work are the defects of this units.

Modern ASIN hydraulic drive and control unit have the frequency inverter and microprocessor system (Fig. 6). The structure of this unit consists of standard hydraulic elements. This unit is general-purpose resulting from the connection of the characteristics of the standard hydraulic devices with the modern digital technology. Hence, the unit can be used to different applications and the requirements. Applied digital technology enables software realization (not only hardware) of the algorithms of unit work. These algorithms can be modified without changes of the elements creating system. The harmful dynamic states are decreased by the using of feedback from work pressure during the work cycle. The innovative connection of the inverter drive and microprocessor technique enables the elaboration of the simple and reliable hydraulic structure of the drive and control unit. The control of the supplied flow parameters have the every advantage of the hydraulic proportional control like:

- control of the hydraulic quantities,
- accurate courses of the motions control,
- decrease of the number of the hydraulic elements in unit,
- major durability of mechanical and hydraulic elements,

Additional advantage of this unit solution is the elimination of power losses appearing with the fluid flow changes by elimination of the throttling of the fluid flow. Due to it the work fluid isn't overheated and can be exploited longer.

The elaborated unit have the lower sensitive on the impurity of work fluid in comparison with unit using proportional techni-

que of control. The requirements of the filtration of work fluid are the same like in other standard hydraulic units.

Applied nowadays prestressing systems work according to the described above rules despite of the systems differ in the structure of devices. The view of the prestressing devices during prestressing process is presented in Fig 7.
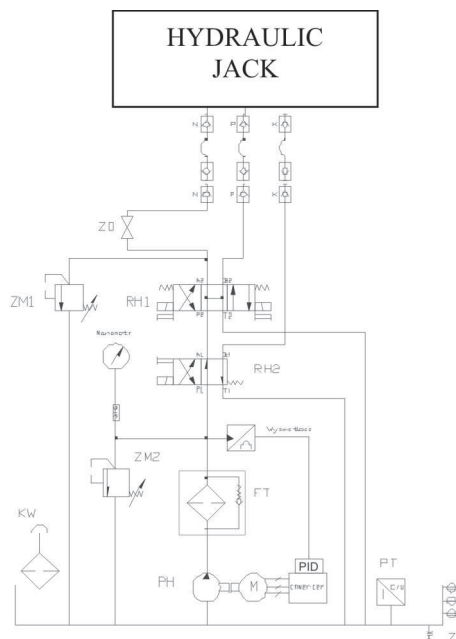

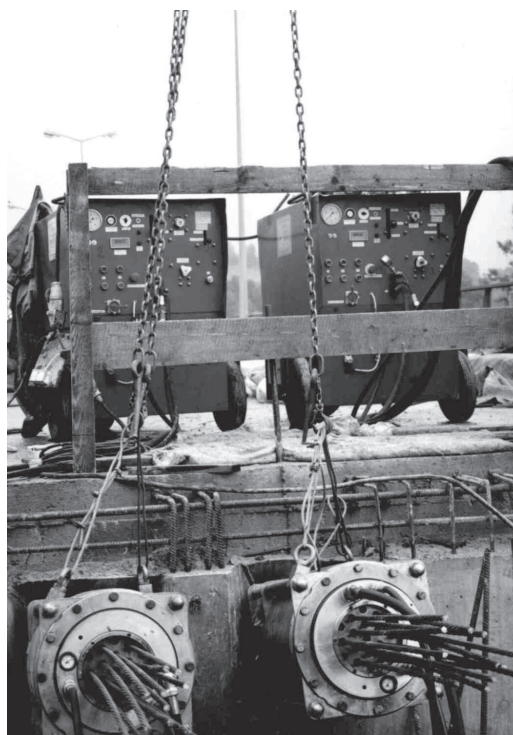*Fig. 6. The schema of drive and control unit for ASIN system*

Fig. 7. The view of the prestressing devices during prestressing process (Chabówka viaduct)

3.2. Monitoring system

The following assumption was established to the elaboration of the conception of monitoring system:

1. The system should enable the registration:
   - Courses of the prestressing forces,
   - Courses of the cable aberrations,
   - vibration of the cable string and prestressing press,
   - acoustic waves generated in prestressed structure.

2. Monitoring system don't effect on prestressing process and the work of the prestressing devices.

3. Monitoring system should have the possibility of connection to the every prestressing system without the change of its structure.

Such elaborated monitoring system enables the full diagnostic of prestressing process and it can be used to all of used prestressing system.

The elaboration of independent system equipped with microprocessor, measurement systems as well as the memory for registration of the courses of measured qualities enables meet described above assumptions. The schema of the monitoring system is presented in Fig 8.

4. Conclusions

The elaboration and application of the described above conception is possible for the present technical state. The acquisition of data from the post-tensioning of concrete isn't enough to the quality assurance of this process. Hence, the elaboration of the analysis methods of the measurement results is needed in order to the detection of the damages of the hydraulic jacks, anchorages, tendons as well as stressed structure. The knowledge base about the diagnosis methods of post-tensioning process isn't enough. Hence, the works connected with the elaboration of this methods should be conduct. One of the difficulties which can make difficult the diagnosis is the big complexity of phenomena appearing in the object during the post-tensioning process. Hence, The laboratory research and its verification on real object is needed to the elaboration of this methods. The definition of the connection between the chosen parameters of the acoustic signal and kind of the damages with taking into consideration the anisotropic, nonlinear and no continues characteristics of concrete enables the assessment of quality of post-tensioning process. The possibility of detection of states like the tensile element crack or the slip in the wedge-tensile element system will effect on the increase of post-tensioning structure safety at the manufacturing stage.

The introduction of monitoring system enables the simplification of the supervision work because supervision workers will have the objective dates from the process course. The date from monitoring system will effect on work of stressing company, which workers don't have often knowledge about the responsibility their work.

The choice of the parameters and control of post-tensioning process is other but very important factor. The introduction of potential energy at the level of $5*10^8$J to the post-tensioned object is the very complex process taking into consideration of the friction phenomena, contraction of post-tensioned object as well as shape interactions of the tensile elements in the tendon. This process is no continues and the concrete get energy batch wise which causes vibroacoustic phenomena with big dynamic.
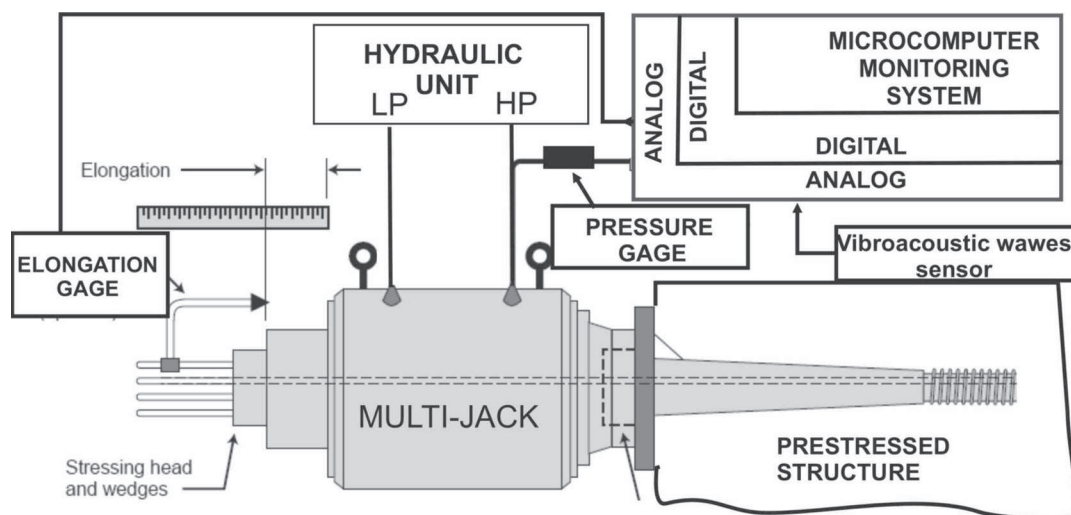

Fig. 8. Scheme of monitoring system [7]

5. References

[1] Aparicio, A. C.; Casas, J. R.; Ramos, G.: *Computer aided design of prestressed concrete highway bridges*. Computers & Structures Volume: 60, Issue: 6, July 24, 1996, pp. 957-969.

[2] Jurkiewicz A. Apostoł M.: *Laboratory stand for ASIM type anchor blocks research for prestressed post-tensioned concrete technology, legal with eurocodes and euronorm*. Inernational Carpatian Control Conference ICCC 2001, Krynica, pp. 519-524.

[3] Jurkiewicz A., Apostoł M., Cygankiewicz T.: *Technology of individual tensioning of strings in pre-stressed constructions - development and the implementation work*, Acta Montanistica Slovaka, 1/1998, s. 37-42.

[4] Jurkiewicz A., Kowal J., Micek P., Grzybek D.: *Testing of elements of ASIN system*. COST ACTION. New Materials and systems for Prestressed Concrete Structures 2005, pp. 231-240.

[5] Jurkiewicz A., Micek P., Apostoł M., Mularz S. 2004: *Controlling a set of hydraulic pumping engines In 3-D prestressing*. International Carpathian Control Conference ICCC/2004, Zakopane Poland. pp.445-450 ISBN 83-89772-00-0.

[6] Micek P., Pluta J., Podsiadło A., Sibielak M. 1996: *Control and monitoring system of hydraulic testing machine*, Proceedings of the 12th International Conference on Process Control and Simulation ASRTP'96, Kosice, Slovak Republic.

[7] *Post-Tensioning Tendon Installation and Grouting Manual*, Technical Report, U.S. Department of Transportation, May 2004.

[8] Radkowski S., Szczurkowski K.: *The influence of stress in reinforced and pre-stressed beam on the natural frequency.* COST ACTION. New Materials and systems for Prestressed Concrete Structures 2005, pp.160-170.

[9] Robertson I. N.: *Prediction of vertical deflections for a long-span prestressed concrete bridge structure.* Engineering Structures Volume: 27, Issue: 12, October, 2005, pp. 1820-1827.

Dr inż. Andrzej JURKIEWICZ
Dr inż. Piotr MICEK
Mgr inż. Marcin APOSTOŁ
Mgr inż. Dariusz GRZYBEK

Akademia Górniczo Hutnicza
Katedra Automatyzacji Procesów
A. Mickiewicza 30, 30-059 Kraków, Poland
fax 012 6173080
micek_pt@agh.edu.pl