Measurement of Forces in the Cable Stays of the Apollo Bridge

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INTRODUCTION

The contribution deals mainly with the measurement of forces in the cable stays in the Apollo arch bridge. In parallel with the construction of the Apollo bridge, the Projstar PK s.r.o. company developed, manufactured and installed on the bridge a unique monitoring system for the measuring of the forces in the cable stays. From a total number of 66 stays, in 62 of them were embedded a magneto-elastic monitoring system for the measurement of the individual forces in each strand of the stay. The system allows the long-term continuity, or time defined measurement of the forces, and is part of the greater monitoring whole of the bridge.
The non-standard resolution of the construction of the bridge, the activation of the stays and their rectification led the projector and the investor to the establishment of very strict conditions for the dispersion of the tension in the individual strands of the stays. From the monitoring system which was constructed for this purpose in the end became an active element of the construction by which was performed not only an inspection activity for the investor but also served as calibration technological equipment for the firm, which implemented the assembly of the DYNA Grip 12 cable stays. Since part of the installed system is also very precise sensors of temperatures, it was possible for the first time purposefully and in great detail to track the influences of climate temperature changes in the stress of the stays. The limited range of this contribution allows the description of only the torso of the measuring issue, more on the measuring can be found in [1] and [2].

Keywords: cable stays, stress measurement, bridge monitoring system

DESCRIPTION OF THE MEASURING SYSTEM

Basic elements of the monitoring system are PSS22 elastomagnetic force sensors. The sensors were developed for very precise measurements of the force in seven wire strand of dia 0,6" encased in plastic from HDPE of 22mm diameter. The minimal available outside diameter of the sensor is 36mm. The length of a sensor is 75mm. These dimensions allow the using of the sensor also in the very narrow transitional area of the anchoring of the prestressing tendon or cable stay. The sensor, calibrated for the samples of the used cables, guarantees an uncertainty of measurement of +/-1,0 MPa. With the usage of average calibration curves for the given type of strand, the uncertainty of measurement is higher, and moves around +/- 50 MPa. The sensor may be equipped with an identifier which has a non volative memory preserving the data necessary in measurement, and a precise sensor of temperature, which serves also for the heat correction of the measured values. The placement of the PSS22 sensors in the lower anchoring of the cable stay is shown in Fig.1. The sensors were installed on each strand during the stay assembly and remained in a horizontal position at the top of the deck.

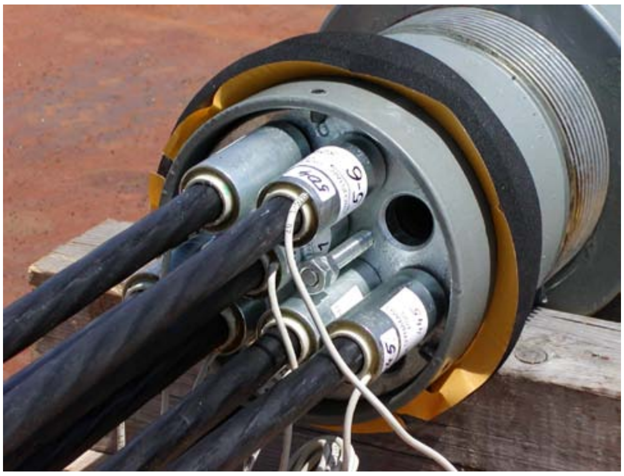

Fig. 1. Assembly of PSS22 sensors

Fig. 2. Connection of sensors on multiplexer

After the installation of the stays, the sensor outputs were carried through a outlet to the bridge box and connected to the multiplexer inputs (Fig.2), by means of which the ongoing measurement of the forces in the strands is carried out. In the lower anchor of the stay is placed an external identifier and precise temperature sensor. After connection of the measuring apparatus, the stay is unambiguously identifiable, so it is not possible to confuse the measured data. By connecting the multiplexer to a portable measuring apparatus, it is possible to carry out individual measuring of the forces in the stay. For the automatic measuring of all the stays are used eight eight-cable measuring apparatuses, to which are connected eight multiplexers. All of the measuring apparatuses are connected through an RS485 interface to an Advantech technological computer, which manages the measuring and archives the measured data.

A schema of the entire monitoring system of the bridge is found in Fig.3. In conclusion, a few data on the capabilities of the system:

- duration of force measurement in 12 strands - max. 40 seconds
- duration of force measurement in all 62 of the monitored stays (total of 704 sensors) along with simultaneous measurement by all measuring apparatuses – max. 450seconds
- minimal period of measurement of one sensor (dynamic effects) – max. 5 seconds

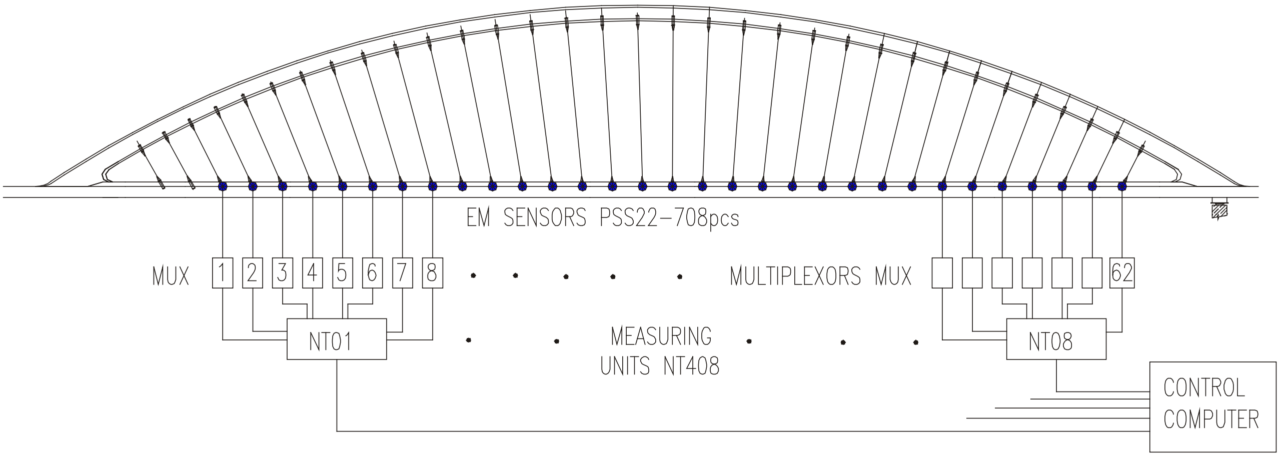

Fig. 3. Schema of the monitoring system of the Apollo bridge.

CONSTRUCTION OF THE BRIDGE AND CONSTRUCTION TECHNOLOGY

As an introduction, some technical data on the Apollo bridge [4]. Total length of the bridging is 854,00m (Fig.4). From this, the main steel bridge structure has a length of 517,50m. The approaching flyovers on both sides of the Danube have lengths of 141,50m and 195,00m, and are made from pre-stressed concrete. The route of the bridging is for almost the entire length curved, while only the section above the floating gabarit is

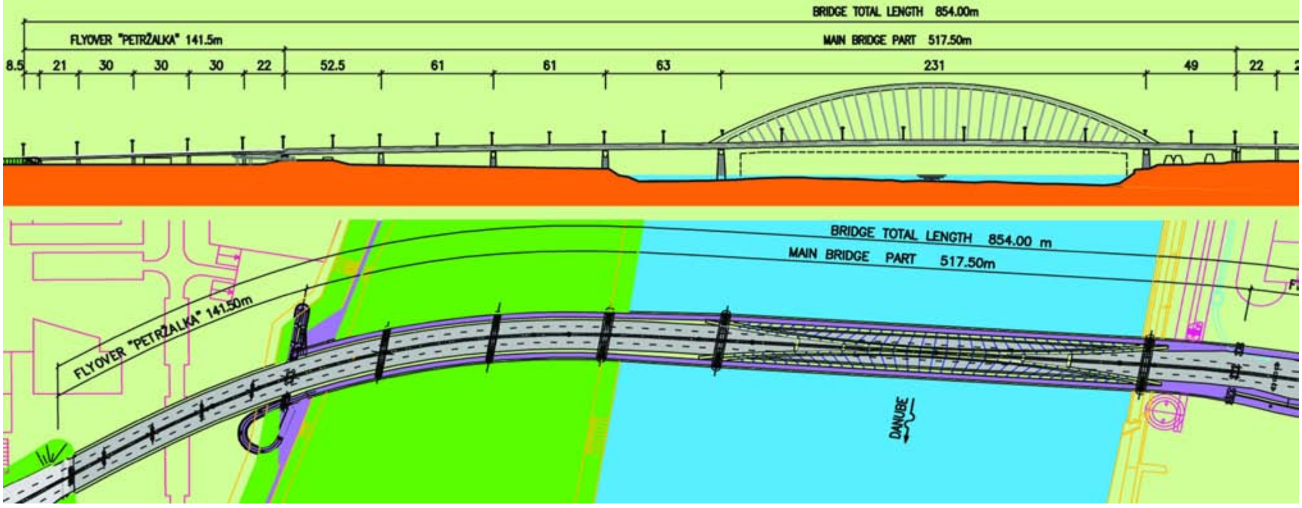

Fig. 4. Longitudinal bridge profile

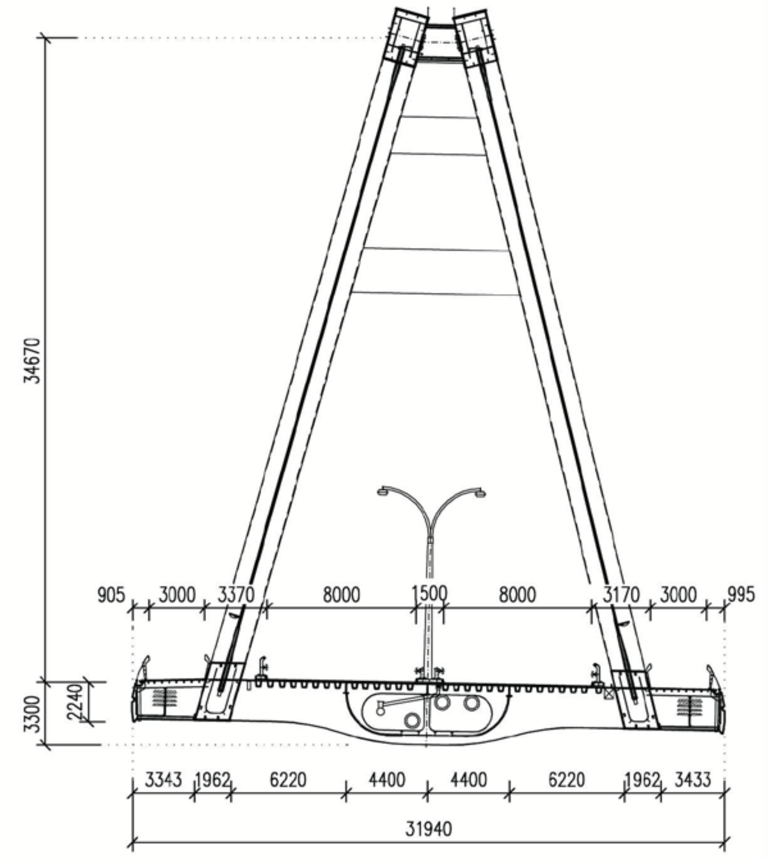

Fig. 5. Transversal bridge profile

straight. For the bridging of the gabarit is used a steel arch bridge construction with an arch of length 231,00m and height of 34,67m (pic.5). The hanging of the main girders for the arches is executed by a radial cable -stayed system.

From a number of alternatives of technological resolutions of the construction of the bridge was used the technically demanding and unorthodox method of rotating the completed main bridge construction.

This technology allowed the construction of the almost complete main bridge construction directly on the bank of the river with the use of temporary support systems. The construction process included these stages:

a. the main girders and the deck were constructed on the temporary supports. The only definitive support point was the calotte bearing on the “Bratislava” bank, around which the later rotating of the bridge was executed

b. the bridge arch was constructed on the temporary supports placed on the deck
c. the temporary arch supports were removed
d. the cable stays were installed and activated
e. the temporary girder supports were removed and the bridge remained supported only on the four bearings
f. the movement of the end of the bridge on pontoon followed, then its rotation towards the “Petrzalka” pier.

A closer and more detailed description of the entire rotation operation can be found in the literature [2].

SOME RESULTS OF THE FORCE MEASUREMENT IN THE CABLE STAYS

The basic monitoring of the force in the stays covers the period from the emplacement of the first sensors up to the final measuring carried out during the bridge loading test. The data from the more than 10 months of the construction of the bridge provide many valuable concepts which deepen our knowledge of the actual activity of multi-strands cable stays. Due to the limited range of this contribution, it is possible to discuss only part of the results.

Activation of Stays – Introductory Prestressing of Stays

The first measurements of the force in the strands were carried out during the installation and activation of the stays. The stays were assembled onto the deck in a horizontal position. During the assembling of the stays, PSS22 sensors were embedded onto each strand of the stays no.5-66 (Fig.1). After the installation of the stays, when there was zero stress on all the strands, null reading of the sensors was executed. EM sensors PSS22 allow very precise measuring of the differences of force as against the reference value, most often zero, and therefore the null reading is very important.

Against the original goal of actively inputting force into the stays and thus lifting the girders over the temporary supports, the forces were input into the stays passively by raising the end of the bridge in its provisional place through hydraulic cylinders, and then removing the temporary supports.

The first operation after the installation of the stays was the tensing of the whole stay to approximately10 kN, and the balancing of the forces in the strands to the level of 1 kN. For balancing of the forces was used a mechanism manufactured for this purpose which enabled the manual stressing of the strand to the precise force, as well as the manual pressing of the anchoring wedges into the anchor head. It was shown that balancing the force between the individual strands of the inclined short stays to such a low level of tension is practically impossible.

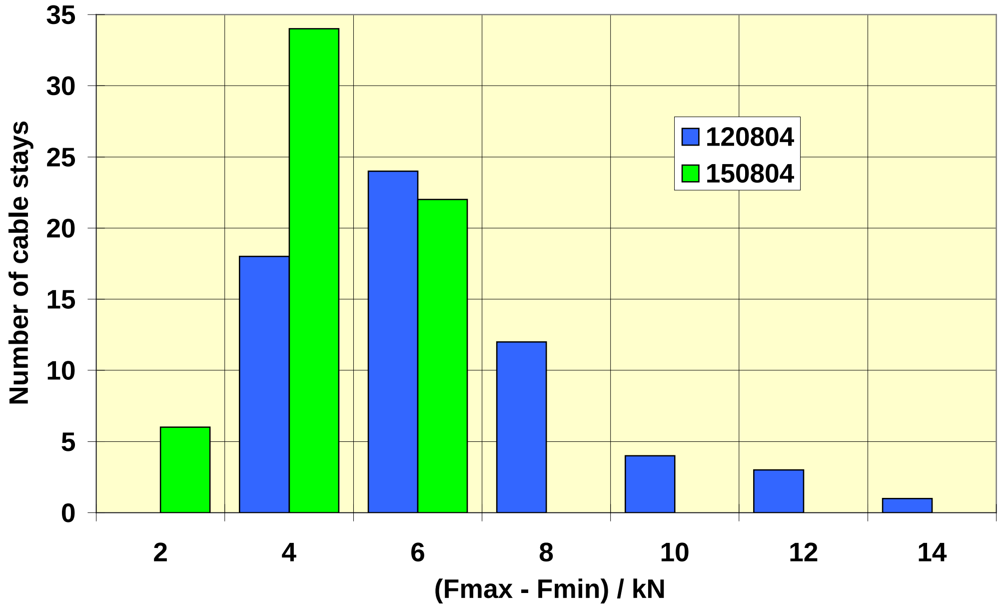

Fig. 6. Maximum difference of forces among the strands in a stay after stressing to 40 kN (12.8.2004) and after rectification, 15.8.2004

Therefore the stays were activated by higher stress of about 40 kN, therefore they were tightened as a group from the bridge arch. Even with this process, the differences in force between the individual strands were unacceptably large. Accordingly, rectification of the forces was carried out on the critical stays by the manual mechanism. In Fig.6 are given the results of the measurement of the forces before and after the rectification of the stays.

During the rectification of the force in the strands, the possibility of determining the force in the strands by a manual mechanism from the data of a dynamometer at the moment of realising wedges was inspected.
In Fig. 7 the time history of the force in the strands of stay no. 50 during such measuring on 13.8.2004 is shown. For clarity, only the changes in force as against the original state are illustrated. As is seen, at the moment of realising wedges the force in the strand is already 1 – 2 kN greater than the actual value. This is due to the short stays, where even tenths of a millimeter are decisive. For illustration: length of stay is 10m, an ellogation of 1mm means a change in stress of 19,5MPa and a change of force, 2,93 kN. In the first strands checked, after repeated anchoring of the strand the force returned to its original value, and for the other strands there occurred a mutual influence of the strands and the anchoring at a different force value.

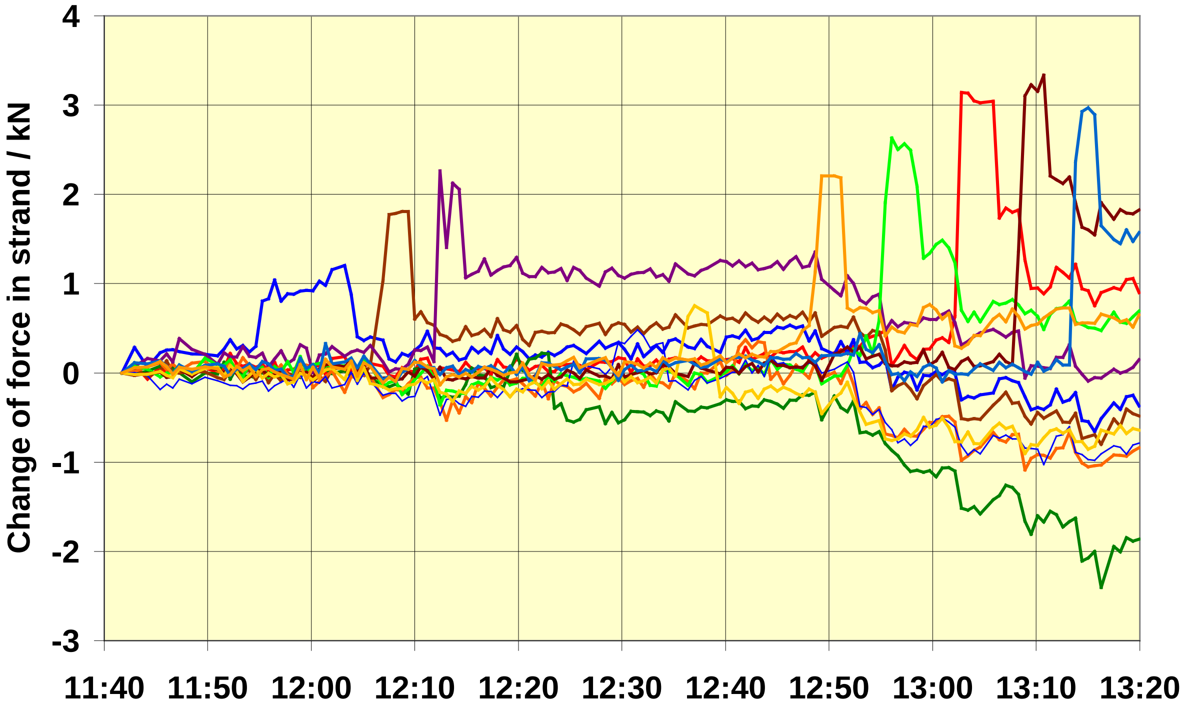

Fig. 7. Time change of force in the individual strands of stay no. 50 during the checking of force by dynamometer

Second Activation of Cable Stays – Removing of Girders from Temporary Supports

After the rectification of the force in the individual strands of the stays, the bridge construction was lifted at one end, thus freeing the temporary supports, and the weight of the girders was distributed among the stays. During this operation the force in stays no. 14 and 50 was continually monitored. In Fig. 5 is illustrated the time history of the force in the individual strands of stay no. 50 during the raising of the bridge construction.

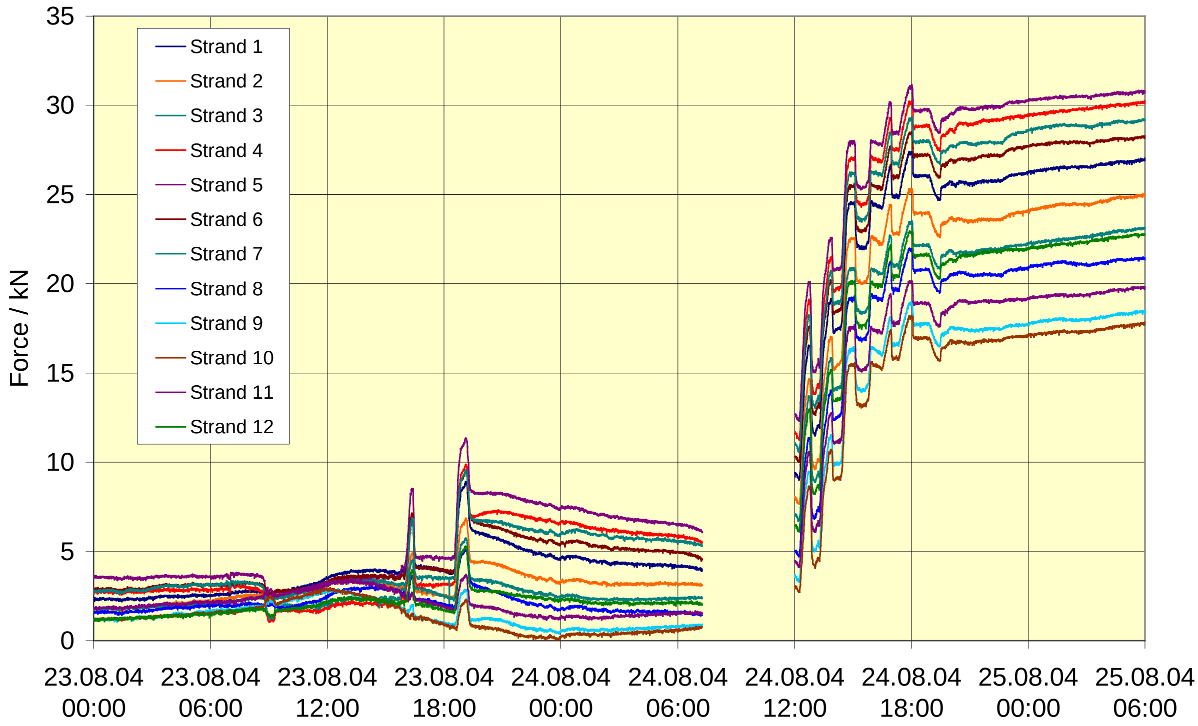

Fig. 8. Time course of force in individual strands of stay no. 50 during bridge lifting.

Time history of the force in Fig. 8 are visible not only the problems during the bridge lifting (problem with hydraulic cylinders), but also a more unfavourable fact – despite the detailed rectification of the stays, which lasted three days, the first raising of the bridge construction meant a significant redistribution of the force between the individual strands. The difference of Fmax – Fmin, which was 2,4 kN at the beginning, increased to 13,1 kN after the lifting of the bridge construction, exceeding the tender requirements. The second monitored stay, no. 14, behaved similarly.

After the shift of the bridge construction onto the pontoons, the bridge was floated to pillar in the Danube river. During the rotation, which lasted 9 days, the longest stay, no. 34, was continually monitored. Figures 9a, b show the time course of the overall force in the stay and the temperature development in the lower anchoring of the stay.

As can be seen from the force development, temperature has a significant influence on the force, especially the slope of temperature drop and growth. Positioning of the bridge construction on pillar on September 24 did not significantly change the force in the stay.

Fig. 10 shows the time course of the maximum force difference between the strands of the stay no. 34 during the bridge rotation. As is seen, as a result of the unequal heating of the individual strands of the stay, the force difference between the individual strands is also changing (max. 1,7 kN), which represents 5,5% of the average force values in the strands of the stay. Therefore e.g. the original tender requirement that the force difference between the individual strands is smaller than 2% of the immediate value of the force was from the outset unrealizable.

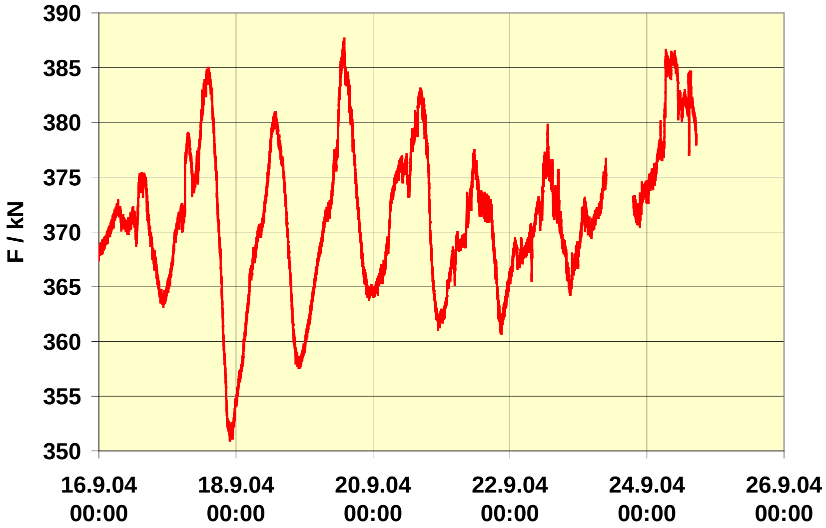

Fig. 9a. Time course of the overall force in stay no. 34 during the bridge rotation.

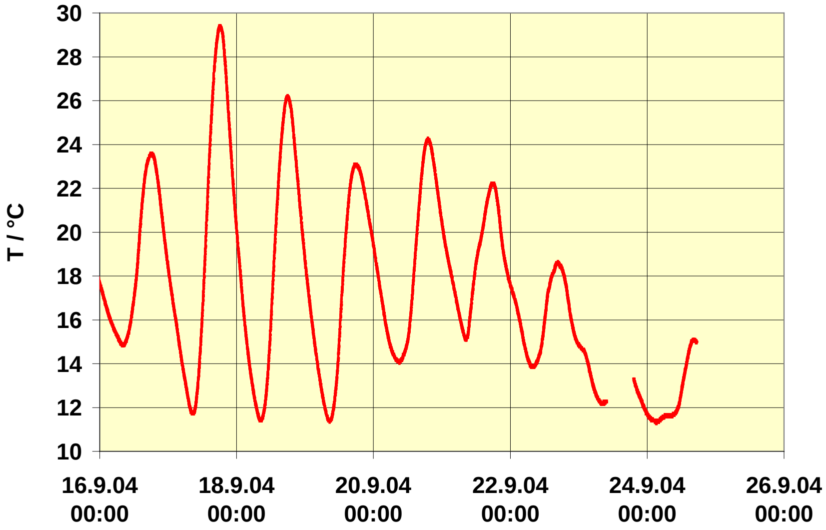

Fig. 9b. Temperature development in the lower anchor of stay no. 34 during the bridge rotation.

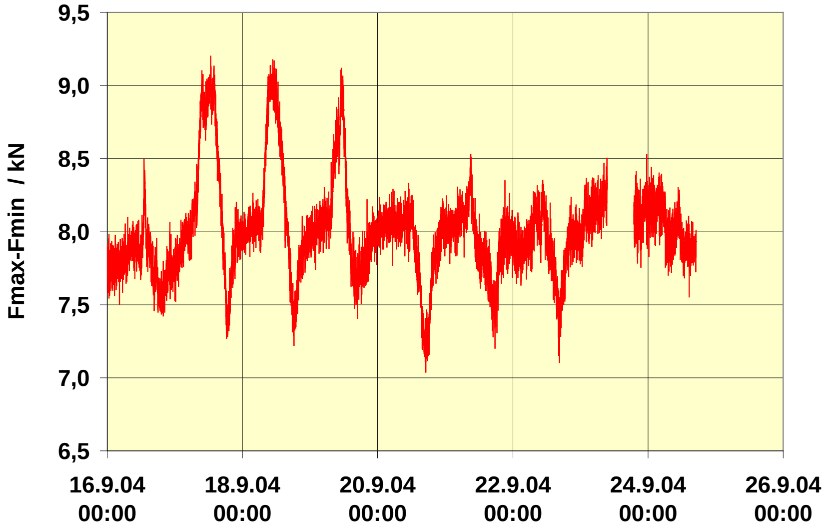

Fig. 10. The development of maximum force difference between the strands of stay no. 34 during the bridge rotation.

Final Rectification of the Cable Stays

After the connection of the outer steel beams to the main arch bridge, rectification of the stays was executed in three phases to achieve the projected shape of the construction. The forces in all monitored stays, including the force divergence in the strand from the average value, were measured before the rectification. The result of the measurement is displayed in Fig. 11.

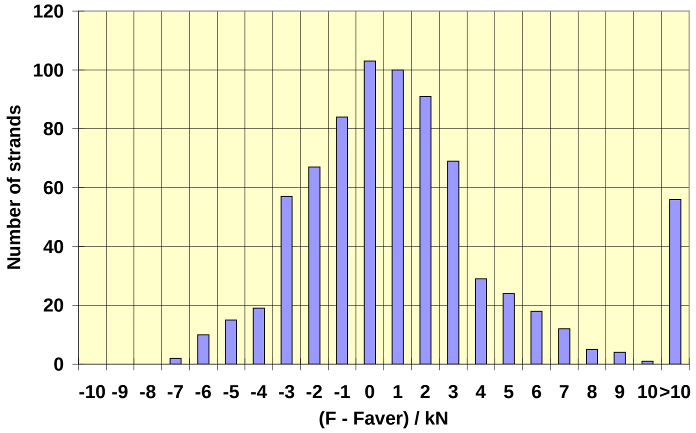

Fig. 11. Histogram of the force divergence in individual strands from the average force value before rectification of the stays.

According to the FIB recommendation [3], the force divergence in individual strands from the average force value should not exceed ±2% GUTS, which in the given case represents the force value 5,58 kN. As is seen in Fig.11, this requirement is not achieved by 108 of the total number of 704 measured strands.

The measured force values in the stays were used by the designer to calculate the progress of rectification, while the limit force values in the stay and the allowable divergence in the measured and calculated value were determined. During the rectification the force in any stay must not exceed 185 kN for an individual strand, the minimum force in the stay, depending on the position of the stay, ranged from 23,4 kN to 101,5 kN and the difference between the measured and calculated force value in the stay had not to exceed 5% of the maximum allowed force.

Force rectification in the stays was executed in three rounds, and the input value for the rectification was the overall shortening of the stay. Because it referred to values ranging from 18 to 35 mm, the short stays (up to no.10 and from no.58) were rectified in groups through so-called gradient press, other stays were rectified with a single strand prestressing jack, one strand after another. According to the results of the force measurement in individual strands of the stays, a procedure of stressing of individual strands was determined so as to minimize the force difference between the individual strands of the stay. This procedure has proved to be very effective, as shown by the final histogram of force divergences from the average force values of the individual strands displayed in Fig. 12.

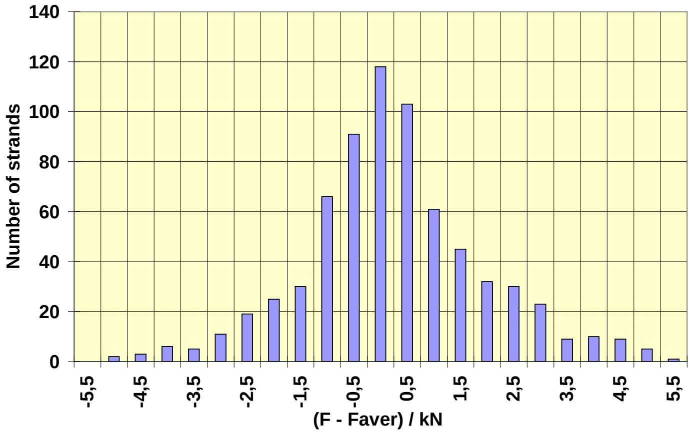

Fig. 12. Histogram of the force divergence in individual strands from the average force value after rectification of the stays

During the rectification of stay couples, the forces were continually monitored in all strands of both stays, and possible divergences were corrected immediately. After finishing the rectification of the stay couples, the force in the five neighbouring stays were re-measured from both sides and the results were compared with the designer's data. The problem with the correction of force differences between individual strands of the stay originated in the short stays, where even tenth of a millimetre is important. Even though anchoring wedges with small slip were used, it was almost impossible to predict the force loss after pressing the anchoring wedges. Moreover, there is a force loss in the previously stressed strands. An example of rectification of a short stay, no. 65, is displayed in Fig. 13.

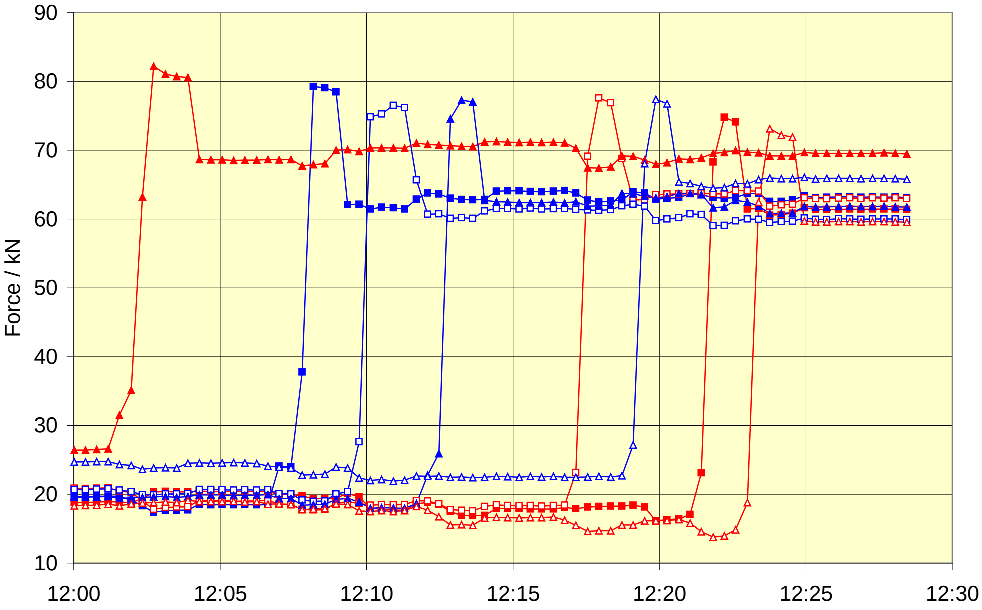

Fig. 13. The force course in individual strands of stay no. 65 during rectification.

Especially figure no. 13 documents the need for monitoring of the actual force in every strand of the stay. Even though we very precisely measured the value of input force (for example with a precise dynamometer on a prestress press), the force values after the anchoring may only be roughly estimated. For stay no. 65, the average force loss during anchoring was equal to 13.5 kN, with the maximum loss of 16,3 kN and minimum loss of 11,4 kN.

CONCLUSIONS

As is proved in Fig. 12, the rectification of the Apollo bridge cable stays fulfils the requirements of the tender. We assume that without the use of EM sensors and extensive measuring, it would be impossible to verify the final force state in the bridge cable stays and the force distribution for individual strands of the stay.
It was shown that the generally declared method of force distribution in the strands of the stay with various preparations, or with a couple of single-strand jacks, does not have to lead to the desired result and to the fulfilment of the requirement of max. stress divergence of the strands of the cable stay according to [3].

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