Monitoring System for Long-term evaluation of prestressed railway bridges in the new Lehrter Bahnhof in Berlin

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ABSTRACT

A new central railway station - Lehrter Bahnhof - is being built in Berlin. Because of construction activities in immediate vicinity and because of difficult soil conditions, vertical displacements will be expected. In order to avoid damage to the bridges and to a widely spanned glass roof which will be supported by two concrete bridges these two bridges have to be monitored right from the beginning of construction until commissioning as well as later on for several years. For this purpose, a long-term monitoring concept has been developed. Sensors with excellent long-term stability have been chosen to carry out the concept. This paper describes the measuring concept as well as components of the system. Especially techniques to monitor settlements and heaves (by means of laser-based optics and hydrostatic leveling components) and to measure strain and inclination of the prestressed concrete bridges (by embedded long-gage length fibre-optic strain sensors, resistive strain gages, and inclinometers) are described. All measures are redundantly monitored. Measurements on-site are referenced by measurements on two large-scale beam models well-defined loaded under laboratory and field conditions.

Keywords: monitoring, structure behaviour, fibre-optic sensors, data acquisition

1. INTRODUCTION – MOTIVATION FOR MONITORING

Large structures with a high-level safety standard, e. g. built for large amount of people are increasingly monitored. The new Lehrter Bahnhof in the heart of Berlin - near the Reichstag - is being constructed as one of the largest stations in Europe with a very futuristic design. In its centre there is a large entrance hall at road level. A system of four partly prestressed concrete bridges for east-west railway line on a level of about 10 m above road level crosses the hall. The north-south railway line runs underground at about -15 m. In order to bring sunlight to the underground level the central station area does not have continuous floors but is open. For this reason, the railway bridges in the hall area are supported by 23 m high slender steel columns, which are Y-shaped (fork-shaped) at their tops (see Figure 1). The superstructure of the Lehrter Bahnhof, especially the wide-spanned glass roof consisting of almost 11,000 panes of glass and spanned over the four pre-stressed railway bridges make it particularly sensitive to settlement. Vertical displacements of adjacent piers should not differ by more than 10 mm.

Additionally, construction activities in the immediate vicinity, especially dismantling of the old station building along the new track, cause settlements or heaves at the numerous piers which induce excessive deformations into the building. In this context, the two outer bridges supporting the station's large glass roof with a span of approximately 50 m are of special concern. Because of these activities and the difficult nature of soil in Berlin - mostly sand - the structure has to be monitored during construction, commissioning and for the first few years after loading. Corrective decisions can then be made, i.e. raising or lowering the bridges at the supporting points, depending on measurement results. However, common geodetic measurement of settlement and heave at the piers cannot be repeated at sufficiently short intervals due to time consuming procedures and limited access to measurement points. Therefore geodetic measurement will be backed up by an automatic continuously working monitoring system. This system will record not only settlements and inclinations but also their effects, i.e. stresses at critical points of the building together with environmental parameters which have an influence on the system, e. g. temperature. This is the only way to get reliable and early information about the state of the building and to understand the relation to what happens in the environment of the site.

The following measurements will be carried out: vertical displacement of the bridge at its supports. For this purpose, an arrangement of laser-optical sensors and hydrostatic levelling system (hose scale) is used. On the other hand, strain in the bridge sections in the vicinity of the fork columns are continuously recorded by using electrical and fibre-optic strain gages. All measured data are available by Internet access for authorized persons. Results will be used to assess the state of the bridge and also to verify the mathematical models describing the performance of the railway bridges. For this reason, the monitoring concept includes the instrumentation of two large concrete beam models which will be subjected to defined climate conditions (inside the testing laboratory and outside) as well as to actual loading conditions (pre-stressing, bending, deflection). Long-term tests enable an evaluation of the long-term stability of the sensors applied.

Fig. 1: Two fork columns in the central part of the southern railway bridge

2. MEASUREMENT OF SETTLEMENTS AND HEAVES

2.1 Laser-based measurement

In civil engineering optical non-contacting methods are of growing importance. A laser-based system of BAM has been upgraded with respect to long-term monitoring.[1,2] This system has been installed at the bridges in the central part of the Lehrter Bahnhof. Figure 2 shows two modules of this system: a source (right) and a sensor. The source, installed at mid-span of the bridge field, illuminates two sensors at each side, which are fixed above the piers or near the ends of the span, respectively. The sensors which contain a linear array of photodiodes measure the deviation from a straight reference line given by the laser beam. From these deviations the vertical movements at the piers as well as the sag at mid-span can be calculated. The theory and the performance of these modules had been treated in an earlier publication.[2]

The laser-based system will be installed upon the bridge outside the railing. Characteristic parameters are as follows: measurement range: ±40 mm; uncertainty: ±0.2 mm ±0.1 mm per 10 m beam length; maximum distance: about 50 m. The system is tolerant against extraneous light, protected against dust, insensitive to vibration and effects of the environment, e. g. temperature, harmless for eyes, and compatible to established carrier frequency systems.

Fig. 2: Laser-sensor and photodiode line of the laser based monitoring system; the source has one window at its front side and another one at its (invisible) rear side. In both directions laser beams with flat profile are lanced.

2.2 Hydrostatic levelling

Outside the central region the laser-based system is not applicable since there is not enough free space for a laser beam. In order to enable a continuous measurement of vertical displacements, the well-known and proven hydrostatic levelling system is applied.[3] With regard to the special requirements of long-term monitoring this equipment was upgraded and optimised. Figure 3 shows a sectional view of two modules comprising a buoyancy cylinder hanging on a force sensor. The drift and creep of this can be corrected automatically by cyclic unloading. For this purpose a pump raises all liquid levels until the suspension joints get loose, thus producing zero force at the sensors. The outer cylinders, the tubes and related studs form a coaxial system. The space between the walls serves as a closed path for the backflow of the air. Thus, equalization of pressure is not influenced by local and temporal differences of atmospheric pressure arising from movements of the air inside and outside the building. At its ends, far outside the central area, the levelling system can be traced back to the official benchmark system. Characteristic parameters are: measurement range: ±30 mm; uncertainty: ±0.3 mm; maximum distance: about 500 m. The system is insensitive to temperature and air pressure variations. An automatic modus for correction of drift and creep of the force sensor (zero-point correction) is integrated, and the system is compatible to established devices for reading out resistive strain gages.

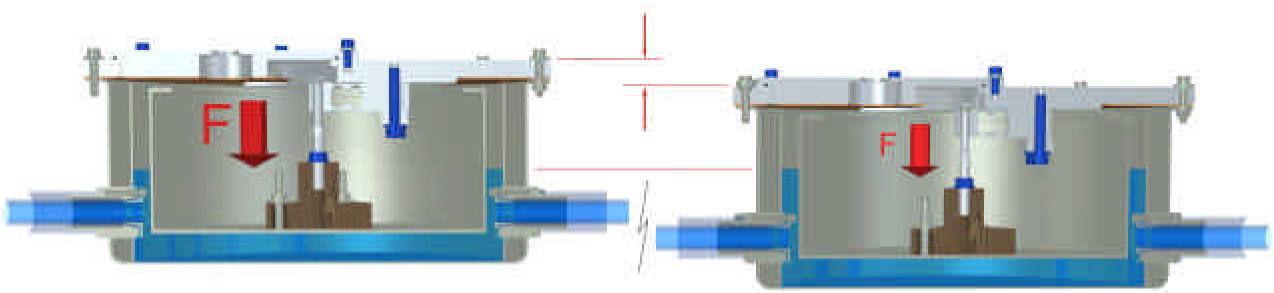

Fig. 3: Hydrostatic levelling modules with force sensors; the higher the measurement point's level at the bridge the lower the liquid in the vessel and following the higher the measured force caused by the byoancy cylinder.

3 INCLINATIONS

Measurement of inclinations helps to evaluate any drilling of the concrete members around the bridge axis. An inclinometer sensor is installed at each third measurement point of the hydrostatic levelling system. The range of the inclination is ± 3°.

4 FORCES AND MOMENTS AT THE FORK COLLUMNS

Resistive strain rosettes have been applied on each of the four steel tubes of each fork column. A white arrow in Figure 1 shows a sensor in the measuring section of a column. By using rosettes, it is possible to measure contraction in vertical direction as well as transverse deformation (for temperature compensation purposes). In order to eliminate bending effects two strain rosettes are installed on opposite sides of the steel tubes. By connecting the strain gages to an multichannel recording device four measuring signals for each steel tube deliver information about acting force and finally about the bending moments of the fork column around the horizontal axes.

5 STRAIN IN THE CONCRETE BRIDGES

The main aim of strain measurements is to get information about stresses in bridge sections. This is known to be difficult because strain does not only arise from stress but also from temperature influences and from processes inside the material, e. g. swelling, shrinkage, creep. On the other hand, such processes may additionally produce real stress, especially if strain is hindered by constraining forces or if locally different influences exist. In order to assess the structure's behaviour, the different causes for strain have to be separated.

Because resistive strain gages are known to have limited long-term stability and because of expected electromagnetic influences fibre-optic strain sensors have been installed at important locations. Both types of sensors are applied in depressions on the concrete surface (see Figure 4). These depressions were closed by a special mortar after completion of the installation. Measurement points are on the upper as well as on the bottom side of the bridge. In Figure 1 such an installation point is marked by a white arrow. Marking points for use of manual strain gages according to Pfender are applied additionally to have a reference method for tracing back all strain measurements. This method is very robust but it cannot be automated. Therefore, the measurement points must be easily accessible at any time. The measurement uncertainty is about 20 µε.

5.1 Strain gages for concrete

To measure strain on the concrete surface strain gages especially designed for concrete are used (length: 6 cm). They are hermetically sealed to protect them from moisture and mechanical deterioration. These gages are prefabricated on a metallic foil and perforated at its edges. After gluing and connecting, an additional layer has been applied to avoid moisture access to the strain gage and the soldered joints (Figure 4, left).

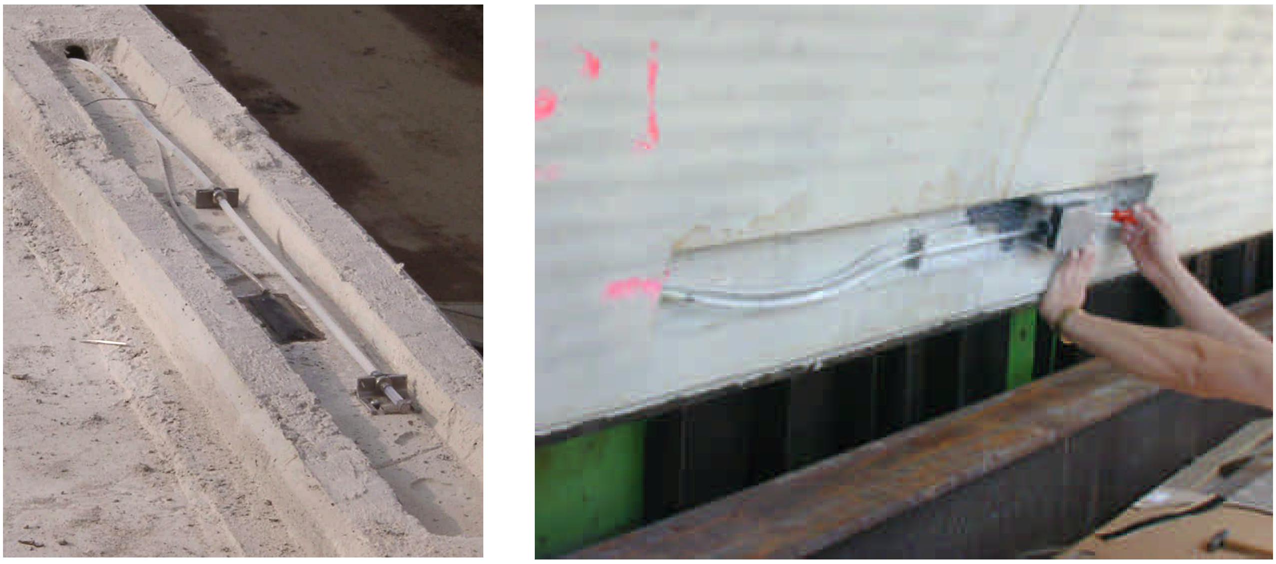

Fig. 4: Resistive and fibre-optic strain gages in a depression on the surface of the concrete bridge before embedding.

5.2 Fibre-optic strain sensors

Before the type of fibre sensors has been chosen for the desired long-term measurements, characteristics of several long-gage length fibre sensor types, e. g. based on Bragg grating sensors, on intensity-modulated principles, on interferometric principle were compared with care. The fibre sensor principle finally used bases on an interferometric one. Inside a plastic tube two standard optical fibres which form the two arms of an Michelson interferometer are positioned: one fibre is fixed at definite points of the tube and tight (sensing fibre), the other one is loosely placed in such a manner that the strain in it stays always at zero (reference fibre). The distance of the fixing points of the sensing fibre defines the measuring length, the loose fibre is required for temperature compensation. Deformation of the bridge causes strain changes in the tight fibre resulting in a change in optical path difference between the two fibres. This sensor principle has the capability of permitting long sensor lengths which are recommended for inhomogeneous materials like concrete. Two different sensor lengths are used: 0.5 m and 3.5 m. Following performance can be reached: resolution about 2 µm; linearity < 0.2 % of measurement range; drift lower than the measurement resolution in the observed time interval.

For reading out the strain information, the sensor must be connected to a demodulator which includes the second couple of interferometer arms. The demodulator is a one-channel device which requires a multiplexer (switching device) for multi-channel operation. In the demodulator, one fibre is terminated at a fixed mirror, the other fibre is terminated in front of a movable mirror controlled by a piezo-actuator. If the sensing fibre in the embedded sensor suffers a length change, this can be measured by moving the mirror in the demodulation unit. When the path difference between the fixed and the movable mirror is identical to that between the tight and loose fibre in the sensor, the length of the sensing fibre can be deduced. Because the mirror in the device has to find the "zero-path-difference" position each measurement takes about 8 s to 10 s. Each of the installed sensors is connected to the optical switching unit. From the economical point of view, several individual sensors will be connected to the switching device by only one multi-fibre cable. It is necessary to mention that this measurement principle is providing an absolute measurement of fibre length, that means concrete strain. Measurement is insensitive to power interruption or disconnecting of leading fibres. Thus, measurements can always be related to primary zero-setting.

6. COMMUNICATION VIA INTERNET

An important aspect is the interpretation and continuous presentation of the actual results. This includes the continuous recording and storage of all data in the measuring centre situated in the railway station itself. The data will be evaluated and presented in a plot. The most important measuring data obtained from the railway bridges ought to be available to the authorized personnel by means of a password. The relevant measurement results can be observed on an interactive diagram presenting the positions of all measurement points. Figure 5 shows one example.

7. LARGE SCALE TESTS - FIRST RESULTS

Tests on concrete beams for several years serve to verify the mathematical models as well as to assess the long-term performance of the sensor techniques used. The concrete beams are 8 m long (300 mm x 400 mm) and pre-stressed. They will be subjected to both bending and torsion which are comparable to those occurring on the bridges. One beam is positioned in the testing hall, the other outside the hall under usual environmental conditions (Figure 5).


Fig. 5: Large scale test in laboratory (left) and under full environmental conditions (right)

Figure 6 shows recordings from fibre-optic sensors installed at one of the concrete bridge. The sensors have additionally been pretensioned by 0.6 % after installation. After curing of the casting material, the sensor lengths were defined to show zero strain (start of data recording).

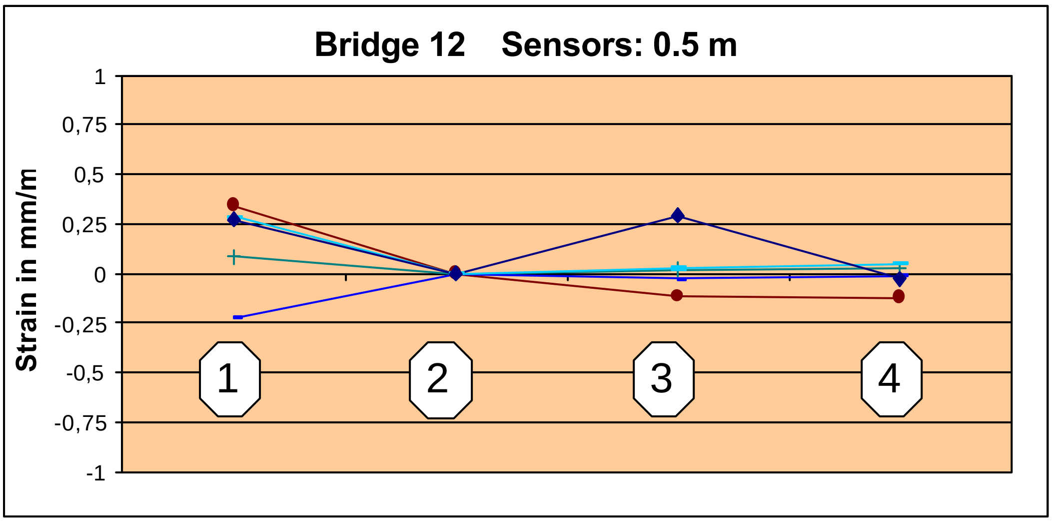

Fig. 6: Strain variations in the prestressed concrete bridge under different loading conditions:
1: Installation of the sensors after prestressing the bridge; 2: Casting of the sensor depression on the bridge surface (start of data recording during construction phase); 3: Measurement on the 24th of January 2002; 4: Measurement on the 12th of March 2002

Figure 7 shows recordings from fibre-optic sensors installed at the beam outside the hall during the winter period. The two strain curves below show the sensors installed at the bottom side of the beam. These two 0.5 m long sensors are installed in depressions on the concrete surface, but the depressions are not closed with mortar. The upper strain curve represents the strain measured by a 2 m long fibre sensor installed on the upper side of the beam. The closing (casting) of the depression is marked in Figure 7. Since closing the depression, the sensor response to temperature variations is reduced because of the increased heat capacity of the surrounding material. Generally, there is a good correlation between temperature changes and temperature-induced strain changes in the concrete beam. All data will continuously be obtained by Internet access.

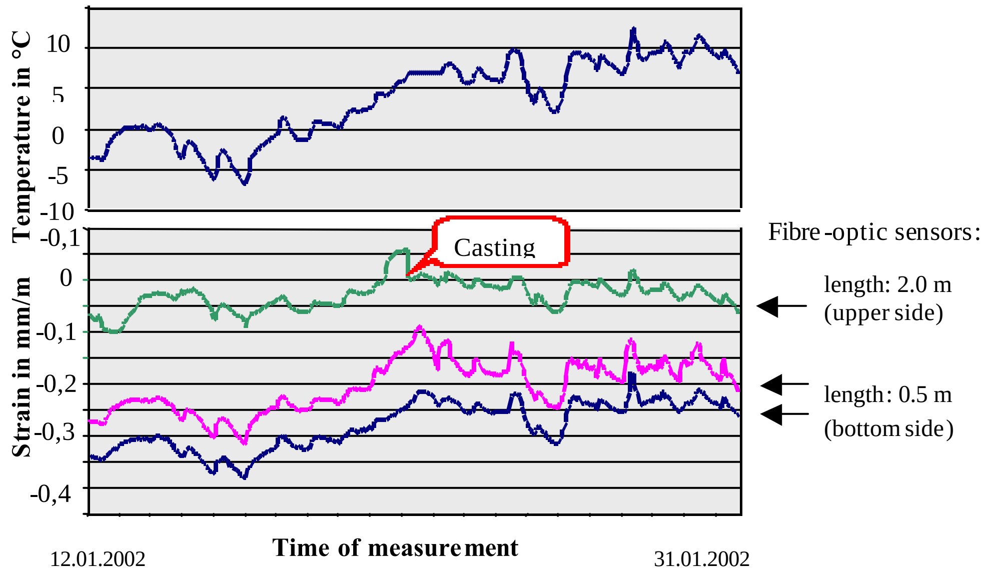

Fig. 7: Temperature-induced strain variations in the concrete beam outside the testing hall under constant loading (the sensor at the upper side is centrally installed, the sensors at the bottom side are symmetrical about the centre)

8. CONCLUSIONS

The monitoring system developed for evaluation of settlements, heaves and deformations of large prestressed concrete bridges have been described. The monitoring concept includes several redundant sensor techniques delivering reliable information for many years. By using continuous monitoring techniques it is possible to discover deviations from the expected structural performance or damage in time. On the other hand, corrections or optimisation of materials used are possible.

Co-operation amongst the experts in the field of sensor technology and structural engineering has been most productive. All co-workers made important contributions to the long-term use and safety of structures in the field of transportation. Especially, parallel long-term tests on large concrete beams are suited to give important information about safety of large structures and reliability of measurement data.

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