Monitoring Bridges of the New Lehrter Bahnhof in Berlin by Means of Long-term Stable Sensors

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Abstract

Two concrete bridges of the new Lehrter Bahnhof in Berlin have to be monitored with regard to their deformation performance during construction and later over several years. For this purpose sensors with excellent long-term stability are needed. The paper describes a new system for the measurement of settlements and elevations by means of laser-based optics and hydrostatic levelling, the application of fibre-optic strain sensors and conventional strain gauges, inclinometers and temperature sensors as well as model tests on pre-stressed concrete beams inside and outside the laboratory.

1. Why monitoring ?

Two concrete bridges of the new Lehrter Bahnhof in Berlin have to be monitored with regard to their deformation performance during construction and later over several years. Various construction activities in the vicinity can cause settlements or elevations at the numerous piers inducing excessive deformations into the bridges.

Figure 1 shows a part of the central region of the station, where the bridges for the west-east-route cross the underground north-south rails. The photo was taken at the end of 2001.

In June 02 the glass roof of the large hall has just been completed as seen in Figure 2.

The outer two of the four bridges are of major concern, because they are additionally loaded by the large glass roof.

Therefore it was recommended to monitor the vertical movements and their effects continuously in order to avoid possible damages by preventive measures. For this purpose sensors with excellent long-term stability are needed.

2. Harsh environment: Innovative technologies versus proven conventional methods

For selecting suitable sensing methods and equipment for long-term monitoring a number of problems had be solved with regard to the harsh environmental conditions during construction of the bridges and afterwards during operation.

Sensors and related equipment have to be long-term stable for at least 5 years, partly under open-air conditions.

Sensors have to work in the immediate vicinity of electrically powered railway trains. Furthermore, low-level measurement cables are running over a distance of more than 100 m in the same channel near high-voltage and high-power cables. This requires an equipment with excellent immunity against electromagnetic interference.

There are only limited possibilities for maintenance and repair in case of degradation or failure. Most of the sensors and related cables are absolutely inaccessible after installation.

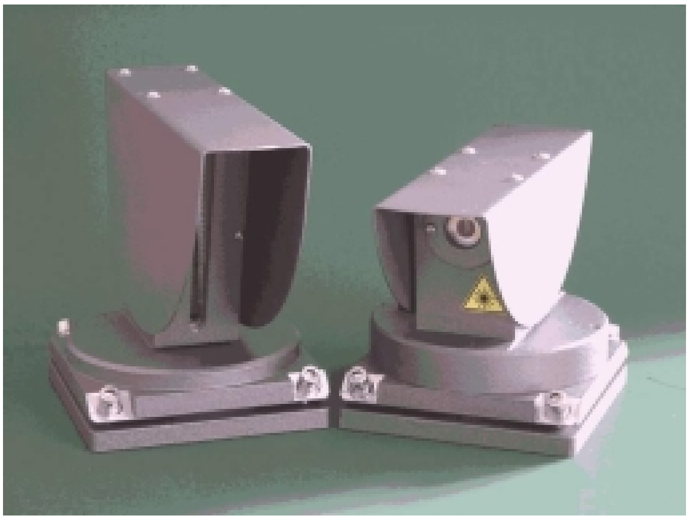
All systems must be robust. A sufficient protection of sensors and cables against damages during the various construction activities had to be provided.

In order to meet all these requirements and to allow a certain failure rate without loss of information, a sufficient degree of redundancy is necessary. This concerns the number of measurement points as well as different principles of measurement. At the very beginning of the project only new promising and innovative principles such as fibre-optic sensors (FOS) and laser-based deformation measurement were favoured. The final approach is now a combination of both, new technologies and conventional techniques, e.g. strain gauges and hydrostatic levelling.

3. Measurement of settlement and elevation: laser-based measurement versus hydrostatic levelling

3.1 Laser-based measurement

In civil engineering optical non-contacting methods are of growing importance. A laser-based system of BAM was upgraded with respect to long-term monitoring [2,3]. This system has been installed at the bridges in the central part of the Lehrter Bahnhof. Figure 3 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 and near the ends of the span. 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 has been treated in an earlier publication [3]. The laser-based system has been installed upon the bridges in the central region 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.

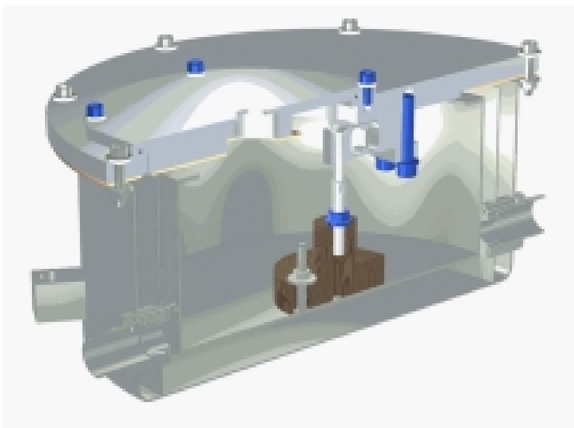


Problems can arise from obstacles in the optical path, turbulent air especially during hot and sunny periods, horizontally incident light from the rising or falling sun, deposition of dust and dew on the optical surfaces, especially on the output windows of the laser source. Therefore it is useful, to take measurements preferably at night and to clean the optical windows in intervals of several months.

3.2 Hydrostatic levelling system

Outside the central region the laser-based system is not applicable, since there is not enough free space for a laser beam. Here the optical system is replaced by the well-known and proven hydrostatic levelling system (HLS) [4].

Figure 5 shows a sectional view of an HLS module comprising a buoyancy cylinder hanging on a load cell. The drift and creep of the sensor 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, equalisation 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: ±0.5 mm; maximum distance: about 500 m.

4. Strain and stress: fibre-optics versus strain gauges

4 .1 The general problem

In Figure 1 two points of measurement – one at the concrete body and the other at a steel column - are marked by white arrows.

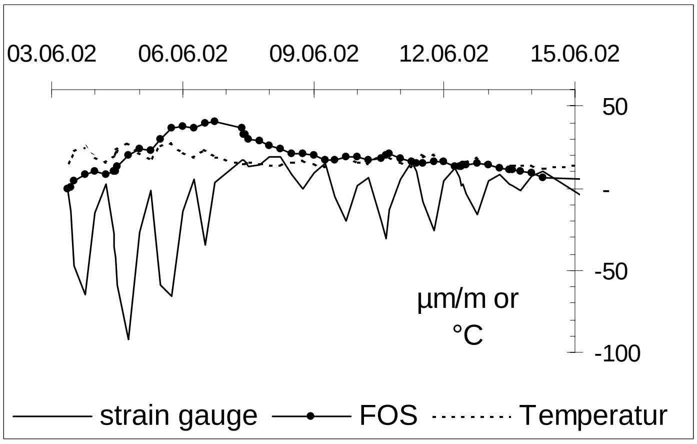
The main aim of strain measurements is to get information about stresses in selected sections. This is known to be difficult since strain does not only arise from stress but also from influences of temperature and from processes inside the material, e. g. swelling, shrinkage and creep. On the other hand, such processes may additionally produce real stress, especially if strain is hindered by constraining forces or if locally different influences exist. Therefore, in order to assess the structure's behaviour, all different influences, which may cause strain, have to be separated neatly. This should be done preferably by direct measurement of disturbing quantities, e.g. temperature, or – if this method is not applicable – by material investigations or by accompanying model tests. The latter will be shortly described in paragraph 6.

4.2 Strain measurement in concrete by means of fibre-optics and strain gauges

Figure 6 shows a cavity (100 mm wide, 30 mm deep) in the surface of the concrete, where two types of strain sensors (Sofo/Smartec, gage length 500 mm and TML/WFLM-60-11-2LT, gauge length 60 mm) had been installed together with a resistive temperature sensor (Measurement Group, WTG-50B) before closing the cavity with mortar.

The fibre-optic strain sensors are based on an interferometric principle. In the centre of a plastic tube there are two optical fibres: a pre-stressed sensing fibre and an unstressed reference fibre for temperature compensation. The gauge length is defined as the distance between two clamps which hold the fibre and serve as a fixture before filling the sensor cavity with mortar. This type of strain sensor can be produced with large gauge lengths, which is advantageous for concrete as an inhomogeneous material. We used gauge lengths of 0.5 m and 3.5 m. For data transmission each sensor requires two-fibres.

Besides, we applied encapsulated strain gauges especially designed for application on concrete. These gauges are built up on a metallic carrier which is perforated at its edges and covered with an elastic humidity



protection coating. A further humidity protection coating enclosing also the temperature sensor and the cable connections was applied after gluing and soldering.

In a test series at the unloaded model beam under outdoor conditions we found, that the fibre-optic stain sensor has a temperature coefficient of about +13.5 µm/m per Kelvin, which is nearly equal to the expansion coefficient of the concrete, i.e. this type of sensor is not designed as a self-compensating gauge. The corresponding figure of the electrical strain gauge was only +4,6 µm/m per Kelvin. In the ideal case this factor should be zero, i.e. self-compensation is imperfect.

The temperature of the small-scale model beams follows the ambient temperature in a few hours, whereas the much larger, massive structures of the bridges have time lags in terms of days or weeks instead of hours.

Figure 7 is the result of strain measurement at the same place by means of a FOS and a strain gauge. The dashed line represents the temperature at the point of measurement. The two different strain sensors produce quite different output signals: an extremely smooth signal on the one hand and on the other hand a curve with strong waves of opposite phase with regard to temperature. This seems to be contradictory at first glance, but both sensors “tell the truth”.

The fibre-optic signal represents the total strain which is dominated by the mean temperature of the massive concrete body, whereas the strain gauge, due to its self-compensation is very sensitive to quick changes of temperature at the surface of the concrete. The strain gauge signal essentially represents the stress at the outer layer of concrete caused by hindered strain.

The example given above underlines the necessity for an individual treatment of each sensor type concerning the influence of temperature. The influence of temperature is of major importance for an exact analysis of the structure. In the first loading test of the bridges in June 02 it turned out, that stresses and deformations caused by traffic load are almost one order of magnitude lower than those caused by changes in temperature.

4.3 Strain in the forked columns

All four tubes of each forked column are equipped with strain gauges. For this purpose we use so called T-Rosettes (HBM 1-XY11-6/120), which measure the strain not only in vertical but also in horizontal direction. The latter is used only for temperature compensation. This method is applicable under two conditions: the stress state must be uniaxial and Poissons ratio has to be known. Both conditions are sufficiently fulfilled. The instrumented cross section has been chosen far enough from the cross-links which join the four tubes. Two T-rosettes are glued at opposite positions of each tube in order to eliminate bending strain. The four grids of these two rosettes are connected as a half-bridge. The half-bridge output signal represents the vertical force in the tube. The sum of all four signals corresponds to the total vertical load of the column.

Taking into account the geometry of the four-tube-column it is also possible to estimate the bending moments from the vertical loads in the different tubes.

5. Inclination

Inclinometers measure the tilt of the bridges with regard to their longitudinal axis. Every third module of the hydrostatic levelling system is equipped with an inclinometer type AMOS/AIM70, range +/-3°.

6. Model tests

Accompanying tests on pre-stressed concrete beams have two aims: verification of mathematical models and suitability testing of sensors. Two equal beams of 8 m length have been definitely loaded with regard to longitudinal compression, bending and torsion. One of these beams is placed inside, the other one outside a testing hall. These tests had been started earlier than the construction of bridges on site in order to prove the suitability of selected sensor equipment.

7. Communication via internet

Compiled and interpreted results of measurements are made available in real time for all concerned persons, accessible by password via internet. The presentation of data is organised hierarchically with regard to the different importance of measured data. An interactive map of points of measurement helps to find easily the relevant data as well as their time history.

8. Conclusion

Monitoring in civil engineering is an often used term nowadays which stands for a multitude of different methods aiming at extending the life of existing structures, especially bridges. In complex cases monitoring should begin already during construction in order to avoid early damage and costly repair. In this context the presented concept can be a helpful contribution.

Acknowledgement

The fruitful cooperation with DB Projekt Verkehrsbau, in particular with Dipl.-Ing. H. Hänichen, is gratefully acknowledged.

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