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SURVEILLANCE PAR CAPTEURS À FIBRE OPTIQUE D'UN PONT À ARC EN BÉTON PENDANT LA CONSTRUCTION

MONITORING A CONCRETE ARCH BRIDGE DURING CONSTRUCTION USING FIBER OPTIC SENSORS

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RESUME : Le pont de Siggenthal, construit sur la rivière Limmat à Baden, Suisse, est un pont-arc avec une travée principale de l'arc de 117 m.

Le pont a été équipé avec 58 capteurs à fibres optiques de long base de mesure, 2 inclinomètres et 8 capteurs à température destinés à ausculter sa déformation pendant la construction ainsi qu'à long-terme. Les capteurs installés dans le pont sont du type SOFO avec une base de mesure entre 3m et 5m. Ils ont été noyés dans le béton pendant la construction et configurés en paires contenant deux capteurs identiques. Ces derniers sont parallèles à l'axe du pont, placés, l'un dans le niveau supérieur et l'autre dans le niveau inférieur de la section de l'arc. Les mesures effectuées sur chaque paire permettent de déterminer la courbure moyenne du segment correspondant du pont. La double intégration des ces courbures permet de calculer les déplacements hors du plan de l'arc.

Les capteurs ont été installés avec le succès et l'arc a été ausculté pendant le décoffrage et l'enlèvement des appuis. Ainsi, les déformations dues au poids propre de l'arc et aux fluctuations journalières de la température ont été enregistrées. Les mesures ont montré que les fluctuations de température excitent les déformations du même ordre de grandeur que celle de la charge due au poids propre. Les déplacements calculés par double intégration des courbures mesurées se sont montrés en bon accord avec ceux mesurés par triangulation.

Dans la phase qui suit, l'auscultation sera pointée à la construction de la superstructure associée avec la redistribution des efforts dans le corps de l'arc.

Cet article comprend une introduction abrégée de principe de fonctionnement des capteurs à long base de mesure SOFO utilisés dans cette application, la présentation de leur installation ainsi que l'analyse des résultats obtenus pendant la construction.

ABSTRACT: The Siggenthal Bridge is a concrete arch bridge with an arch span of 117 m, being built over the Limmat River in Baden, Switzerland.

This bridge has been instrumented with 58 long-gauge fiber optic deformation sensors, 2 inclinometers and 8 temperature sensors to monitor its deformations during construction and in the long-term. The installed SOFO fiber optic sensors have a measurement basis between 3m and 5m and were installed in pairs in the concrete arch. Each pair consists of two identical sensors embedded in the concrete during construction. They are installed parallel to the arch length, one near the top face and one near the bottom face of the slab. Measuring the deformations of these pairs of sensors it is possible to determine the curvature change in each of the instrumented arch segments. By a double-integration of the obtained curvature function it becomes possible to calculate the out-of-plane displacements of the arch.

The sensors have been installed successfully and the arch was monitored during the removal of the formwork and supports. It was therefore possible to observe the deformation of the arch when being loaded by its dead load and by the daily temperature fluctuations. The measurements have shown that the temperature changes produce deformations of the same order of magnitude

as the dead loads. The out-of-plain displacements obtained by double-integration of the measured curvatures are in good agreement with the direct triangulation measurements.

Monitoring will now concentrate on the construction of the superstructure, with the associated change of the load distribution in the arch.

This paper will briefly introduce the functional principle of the long-gage sensors used in this application, illustrate their installation and discuss the measurement results obtained during construction.

1. BRIDGE MONITORING

The security and management of bridges, tunnels, dams and other important structures require periodic monitoring, maintenance and restoration. Excessive and non-stabilized deformations are often observed in concrete bridges and although they rarely affect the global structural security, they can lead to serviceability deficiencies.

Furthermore, accurate knowledge of the behavior of the structures is becoming more important as new structures become lighter, new building techniques are introduced and an increasing number of existing bridges are required to remain in service beyond their theoretical service life. Monitoring, both in the short and long term, helps to increase the knowledge of the real behavior of the structure and in the planning of maintenance intervention.

In the long term, static monitoring requires an accurate and very stable system, able to relate deformation measurements often spaced over years.

The monitoring of a new or existing bridge can be approached either from the material or from the structural point of view. In the first case, monitoring will concentrate on the local properties of the materials used (e.g., concrete, steel, timber, composite materials…) and observe their behavior under load, temperature variations or aging. Short base length strain sensors are the ideal transducers for this type of monitoring approach. If a very large number of these sensors are installed at different points, it is possible to extrapolate information about the behavior of the whole structure from these local measurements.

In the structural approach, the structure is observed from a geometrical point of view. By using long gage length deformation sensors with measurement bases much larger than the characteristic dimensions of the materials (for example a few meters for a concrete bridge), it is possible to gain information about the deformations of the whole structure and extrapolate on the global behavior of the construction materials. The structural monitoring approach will detect material degradation like cracking or flow only if they have an impact on the shape of the structure. This approach usually requires a reduced number of sensors when compared to the material monitoring approach.

The availability of reliable strain sensors like resistance strain gages or, more recently, fiber Bragg gratings [1, 2] have historically concentrated most research efforts in the direction of material monitoring rather than structural monitoring. This latter has usually been realized using external measuring methods like triangulation, dial gages and invar wires. Interferometric fiber optic sensors systems like the SOFO system now offer an interesting means of implementing structural monitoring with internal or embedded sensors.

2. THE SOFO FIBER OPTIC MONITORING SYSTEM

In recent past years, fiber optic sensors have gained in importance in the field of structural monitoring. They are the ideal choice for many applications, being easy to handle, dielectric, immune to EM disturbances and able to accommodate deformations up to a few percents.

The IMAC laboratory at EPFL has developed a non-incremental, long-term monitoring system based on low-coherence interferometry, which has successfully been used in several bridges [3], tunnels [4], dams [5] and other civil engineering structures. This system is named SOFO® (the French acronym of "Surveillance d'Ouvrages par Fibres Optiques" or structural monitoring by optical fibers). A detailed description of the functional principle of this system can be found in the cited literature [6, 7]. In this contribution we will concentrate on static measurements, however the

SOFO system is being extended to dynamic measurements. In the near future it will therefore be possible to perform on the same network of sensors both dynamic and long-term measurements.

The following table resumes the performance of the SOFO system:

Parameter	
Gage length	20cm to 10m for standard sensors Up to 50m with special (long) sensors
Cable length	Up to 5 km
Resolution	2µm, independently from gage length
Dynamic range of the sensors	1% elongation, 0.5% shortening
Precision	Better than 0.2% of the measured deformation
Measurement speed	Less than 10 seconds per measurement
Stability	Drift not observable over at least four years

3. THE SIGGENTHAL BRIDGE

The "Siggenthal" bridge (see Figure 1 and Figure 2) is a concrete arch bridge with an arch span of 117 m, being built over the Limmat River in Baden, Switzerland. The bridge also included two approaches with one span on one side and three spans on the other (see Figure 3). The total length of the bridge is of 217 m.

Figure 1 Artist rendering of the finished Bridge

Figure 2 Finished arch.

The arch has a variable width from 10 m at the ends, where it doubles in two parallel and distinct arc segments, and 8 m at the top. Its thickness is 0.8 m at the top and 1.4 m at the feet.

The arch curve is made of 7 segments with inflexion points under the columns supporting the deck and slightly curved in-between.

The deck is a longitudinally- and transversally-prestressed box girder with constant height. On the arch it is supported by two pair of columns on each side. In the central section, the arch and the deck fuse into a single structure.

The arch construction proceeded in five successive concrete pouring phases, executed symmetrically and starting from the feet. After lowering of the scaffolding the arch was left free to stand unsupported (see Figure 3). During the construction of the vertical columns and of the deck, the arch is stabilized by two temporary towers under the first columns (see Figure 4).

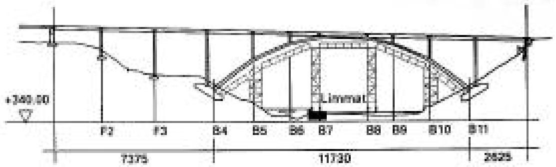

Figure 3 scaffolding during arch construction

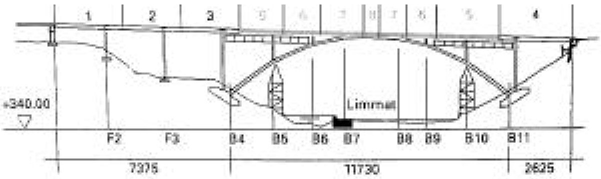

Figure 4 Temporary supports during deck construction

4. INSTRUMENTATION

The aims of the installed monitoring system were the following:

- Monitoring of the local concrete deformations
- Measurement of local curvatures in the vertical plane
- Reconstruction of the perpendicular displacements of the whole arch

These measurements were to be carried out during the whole life span to the bridge, but with particular interest during the following phases: concreting of the different arch sections, removal of the scaffolding, free standing phase of the arch, installation of the temporary towers, construction of the supporting columns and of the deck, bridge testing, long-term, in-service monitoring.

At the time of writing the arch and the supporting columns have been built, but the deck is still to be added.

In order to allow the mentioned measurements, we have decided to install pairs of long-gage fiber optic sensors in the arch. Each pair is constituted by a sensor placed near to bottom of the arch thickness and one near the top. The two sensors are parallel to each other and to the arch axis (see Figure 5). The instruments are installed near one of the abutments (see Figure 6). The local concrete deformations are directly observable from the sensors readings. The curvature measurements are obtained by looking at the difference between the parallel sensors. Finally the perpendicular displacements are calculated by an appropriate algorithm based on the double-integration of the measured curvatures and taking the boundary conditions into account [8].

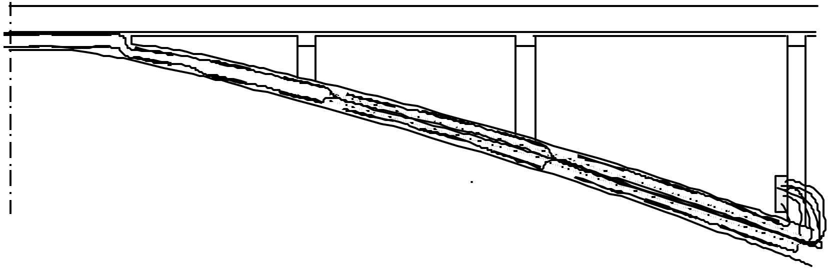

Figure 5 Sensor positions in the cross-section

5. MEASUREMENT RESULTS

We will now briefly present a few examples of measurements obtained with the described monitoring system.

5.1 Concrete deformations

Figure 7 shows the deformations measured by three pairs of sensors installed in one of the arch feet. In the first phase (before 10.7.2000) all sensor measure a similar shrinkage. On 10.7.2000 the second section was concreted on top of the one under consideration. Because of the slight curvature of the arch, this additional load induces a bending in the section. This is clearly observed, since the three top sensors show an elongation and the three bottom sensors a shortening. After this event the curves continue to show a parallel shrinkage behavior.

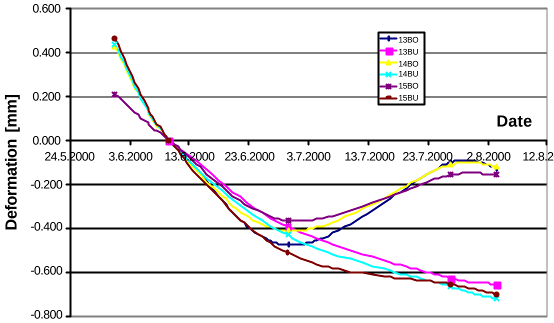

Figure 7 Concrete deformations in the feet during construction

5.2 Curvature measurements

Figure 8 shows the curvatures measured in section of the arch during scaffold removal and free standing of the arch. The Measurements done before 13.8.2000 show an irregular behavior corresponding to the different phases of the scaffolding removal. As soon as the arch is completely free, a periodic behavior with circadian period is observed. It is interesting to notice that the curvatures induced by the dead-load activation are of the same order of magnitude as the ones induced by the daily temperature variations and sun irradiation (on a late summer day).

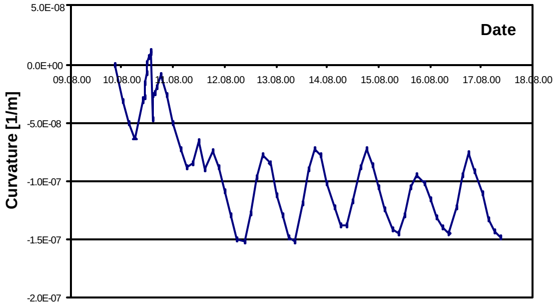

Figure 8 Curvature readings during scaffold removal and free standing of the arch

5.3 Displacement Measurements

The displacement measurements are calculated from the local curvatures by double integration. As boundary conditions we used a fixed position of the abutments. The bridge was divided in 7 sections and the measured curvatures were fitted to a polynomial function for each of these sections. After integrating the polynomial functions the different sections were reconnected under the assumption of identical radial displacement and rotation at the interfaces. The pure longitudinal displacements were not taken into account since they do not introduce bending moments in the arch.

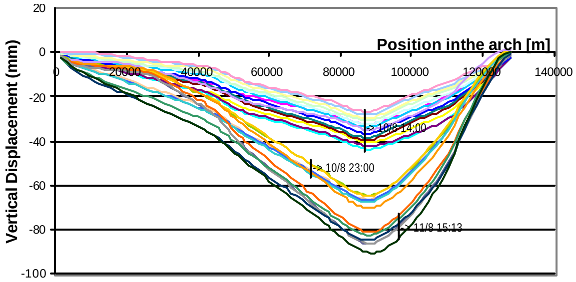

Figure 9 Radial displacement in mm as a function of the curvilinear abscissa during scaffolding removal

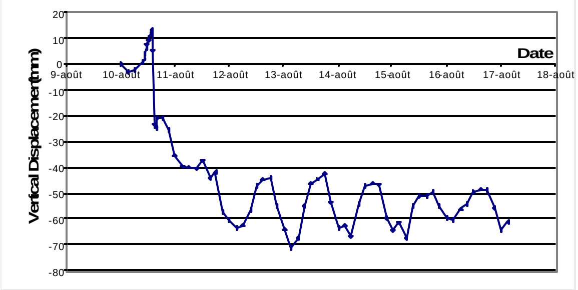

Figure 10 Vertical displacement in mm at mid-span during scaffolding removal and while free standing

Figure 9 shows the calculated radial displacement as a function of the curvilinear abscissa along the arch. Each curve was taken at 30 minutes interval during the lowering of scaffolding. As expected the arch moves inwards when the scaffolding is removed. Three distinct phases can be observed: the scaffolding is first lowered on the left side, than at the right. These operations were performed stepwise, which is also observable from the measurements. It can be noticed that the deformation is not completely symmetrical. Figure 10 shows the calculated vertical displacement near mid-span during scaffolding removal and during the arch freestanding phase. Again, it is possible to observe the different lowering phases and the periodic movement due to daily temperature variations. The vertical displacement of about 10 cm corresponds to direct measurements done through triangulation. It is once more interesting to notice that the vertical displacements due to the activation of the dead load are of the same order of magnitude as the daily movements due to sunshine. This makes it difficult to directly compare triangulation measurements (that are performed on a period of many hours during daytime) with SOFO measurement.

In the future it will be important to measure the concrete temperatures along with the deformations to allow a better analysis of the measured data. To this purpose, 8 thermocouples have been installed at different location in the concrete arch.

6. CONCLUSIONS

The benefits of structural monitoring are manifold. A continuous or at least regular monitoring of a structure increases the knowledge on its behavior and helps to guarantee its safety and to plan for maintenance interventions.

Besides short-gage strain sensors that measure directly the local properties of the construction materials, long-gage length deformation sensors can give additional and complementary information on the global behavior of the structure.

The SOFO monitoring system is composed of a portable reading unit (adapted to field conditions), of series of sensors (that can be either embedded into concrete or surface mounted on metallic and other existing structures) and of a software package (allowing the treatment of the large data-flow resulting from these measurements). This system has been applied to the monitoring of the Siggenthal arch bridge during construction. It was possible to measure the local deformations of concrete and reconstruct the radial displacements during scaffolding removal and during the freestanding period of the Arch. It was found that during summer the daily temperature influence on the arch is particularly large and should be taken into account when performing point-measurements like triangulation. An automatic and permanent monitoring system can follow the deformations during many days and provide a more reliable assessment of the “real” deformation of such a bridge. The measurements will now continue during the deck construction and in the long tem.

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