Bridge Deformation Monitoring During Enlargement and Refurbishment Works Under Traffic Conditions



Daniele INAUDI

SMARTEC
Grancia, Switzerland

Daniele Inaudi holds a degree in physics and a Ph.D. from the Swiss Federal Institute of Technology in Zurich and Lausanne, respectively. He is co-founder and R&D director of SMARTEC SA, a company active in the domain of civil structural monitoring.

Nicoletta CASANOVA

SMARTEC / IMM
Grancia, Switzerland

Nicoletta Casanova received her civil engineering degree from the Swiss Federal Institute of Technology in Zurich. She is co-founder and director of SMARTEC SA. She is also technical director of the Institute of Material Mechanics IMM.

Samuel VURPILLOT
Branko GLISIC
Pascal KRONENBERG
Sandra LLORET

SMARTEC / IMAC-EPFL
Lausanne, Switzerland

Samuel Vurpillot holds a degree in civil engineering and a Ph.D. from the Swiss Federal Institute of Technology Lausanne. He is project manager at SMARTEC SA and specialist for the automatic analysis of monitoring data from bridges.

1. Summary

Refurbishing bridges in urban environments presents the challenge of performing the repair with the smallest possible perturbation to the traffic. For concrete bridges, an additional challenge comes from the necessity to insure a perfect connection between the old and the added concrete. The setting reaction can be disturbed by the vibrations generated by the heavy traffic. Long-gage deformation sensors can help in the solution of these problems providing information on the static and dynamic deformations of the structure before during and after the refurbishment works. This contribution presents three examples of application of the SOFO® system to the monitoring of refurbished concrete bridges.

Keywords: bridge refurbishing, monitoring, fiber optic sensors, deformation sensor, concrete setting, composite action.

2. Introduction

Maintaining the existing infrastructure network and adapting it to new capacity requirements has become one of the most challenging tasks for today's structural engineers. Bridges designed and built only a few tens of years ago are now asked to carry traffic loads well above the design ones. At the same time, it has become evident that the durability of concrete bridges is not always guaranteed, even for relatively recent constructions. In this context, the engineer is often asked to design refurbishments, enlargements and repairs on structures that are under heavy usage. This presents challenges that are even greater than the ones required to design and build a new bridge.

For bridges in urban areas the space concern are predominant and building a new bridge alongside an existing one is not a viable option. It is therefore necessary to intervene on the structure while preserving, at least partially, its traffic bearing capacity.

Monitoring the real bridge behavior in these conditions is both a necessity and an opportunity. On one hand the knowledge of the initial state of the structure is often insufficient. In this case, monitoring can be used to refine the numerical modeling of the structure and tailor the interventions accordingly. On the other hand, a system installed to monitor the structure before and during a refurbishment work remains in place to evaluate the bridge evolution in the long term.

There are a great variety of parameters that can be measured to evaluate a bridge performance before, during and after refurbishment. In this paper we will concentrate on deformation measurements because they are among the most important indicators of the structural behavior and they can be directly related to the data generated by modeling software.

In the case of refurbished concrete structures the most interesting deformation measurements can be classified as follow:

- *Static deformations of the structure before refurbishment*. This is used to evaluate the stiffness and other global mechanical parameters and to update the finite element simulation accordingly [1, 2].
- *Evaluation of the deformations under traffic loads*. This is useful to determine the dynamic properties of the structure. It is also interesting to evaluate the traffic-induced deformations to determine if a good adherence between old and new concrete can be attained under these conditions [3].
- *Evaluation of the deformations inside the concrete during setting*. These measurements can be used to limit the heavy traffic on a bridge during the first critical hours of concrete setting.
- Meas*urement of the relative deformation between old and new concrete*. The aim of a refurbishment is to create a composite structure that acts monolithically. Installing sensors on the old concrete and in the fresh concrete it is possible to detect relative movements resulting from a delamination.
- *Static deformations of the structure after refurbishment*. Comparing these measurements to the one performed on the bridge before refurbishment can give an indication on the effectiveness of the repair.

In our work we have developed a monitoring strategy that is based on geometrical measurements. We are convinced that the *global behavior* of a bridge or any other large structure is best evaluated using *"global sensors"*, i.e. sensor with long gage-length. A deformation sensor network should be able to give information on the local material properties as well as on the global three-dimensional deformations of the bridge. It is obviously interesting to perform both tasks with the same sensors as shown in the application examples described below. In this case we speak of Global Lifecycle Structural Monitoring. "Global" refers to the spatial extension of the monitoring network that should cover the whole structure, "Lifecycle" refers to the time extension that should include all phases of a structure's life (construction, operation, refurbishment, …).

An interesting way to install long sensors to perform both local and global measurements consists in dividing the bridge into sections and in measuring the mean curvature in each of these zones (see Figure 2). The vertical displacement of the bridge can be calculated by integrating the curvature measurements twice and applying the appropriate border conditions [1].

To obtain a precision of the order of 0.1 mm in the vertical displacement of the bridge it is necessary to measure the elongations with a resolution of the order of a few microns. The SOFO® sensors (see below) allow to obtain these precisions over a gage-length of up to a few tens of meters and over measurement periods of years. The sensors can be surface mounted or embedded into fresh concrete and therefore allow the monitoring of new and existing parts of the same structure with the same type of sensor. The next section describes the performance of this system.

3. 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, 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 for standard sensors up to 3% for membrane sensors
Precision	Better than 0.2% of the measured deformation
Temperature sensitivity	< 0.5 μm /°C/m
Measurement speed	Less than 10 seconds per measurement
Stability	Drift not observable over at least four years

4. Application examples

To exemplify the monitoring concepts described above we have selected three application examples. In all cases the described application is only a part of the whole monitoring concept but it is useful to see how the SOFO® system performs in field conditions and to point in the direction of a G*lobal Lifecycle Structural Monitoring*.

4.1 Lutrive bridge: Monitoring under traffic conditions

The current SOFO system is capable of measuring deformations with a precision of 2 microns over measurement bases between 20 cm and 10 m. The reading unit delivers a deformation reading each 10 s. If the measurement is performed on a structure undergoing dynamic deformations, the reading unit will record a snapshot of its instantaneous deformations each 10 s. If the deformations of the structure are

statistically repeatable, as in the case of periodic loading or traffic loading, it is possible to gain interesting information about the structural dynamics by statistically analyzing a large number of these snapshots.
If the structure undergoes a time-dependent deformation $\Delta L(t)$ it is possible to associate a probability function $P(\Delta L)$ describing the relative probability of finding the structure in a state of deformation ΔL at any given time.
In this application example we will show how it is possible to obtain the $P(\Delta L)$ function by analysis of the static SOFO measurements.

The Lutrive (Switzerland) North and South bridges are two parallel twin bridges. Each one supports two lanes of the Swiss national highway between Lausanne and Vevey. Built in 1972 by the corbelling method with central articulations, the two bridges are gently curved (r = 1000 m) and each bridge is approximately 395 m long on four spans. The two bridges have the same cross-section. It consists of a box girder of variable height (from 2.5m to 8.5m) and two slightly asymmetric cantilevers meant to reduce the effect of torsion in the curved bridges.

Figure 1 The Lutrive bridge

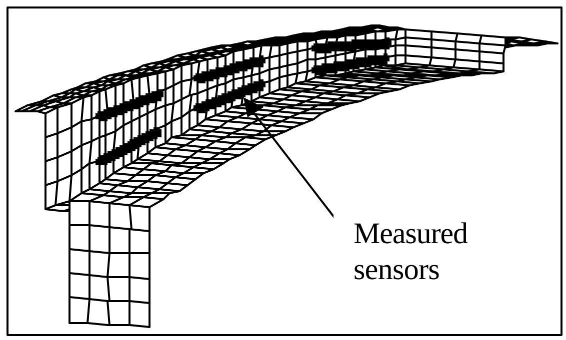

Figure 2 Sensor placement for monitoring the Lutrive bridge. The setup is repeated on the other side of the bridge

The fourth span of the South bridge, was instrumented with 30 6m long SOFO sensors. To measure the curvature variations, the sensors are installed in pairs at the interior of the box girder. Curvatures are measured with sensors placed near the top and the bottom of bridge web and the vertical displacements can be retrieved by double integration of the curvatures. The sensors were used mainly for quasi-static testing under thermal loading and under a static load-charging test.
In order to test the statistical analysis algorithm, two sensors placed at quarter-span (see Figure 2) where measured during 24 hours under traffic loading. Both sensors were measured with a single scan of the SOFO system by coherence multiplexing them with an external coupler. The data from the two sensors is therefore correlated since the two readings are obtained in less than 0.1 s.

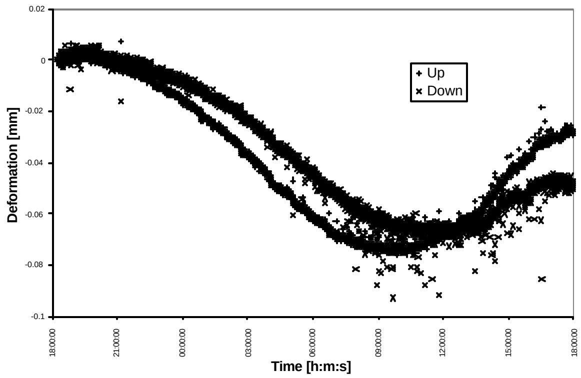

Figure 3 Deformation data obtained on two parallel sensors placed at quarter-span in the Lutrive bridge.

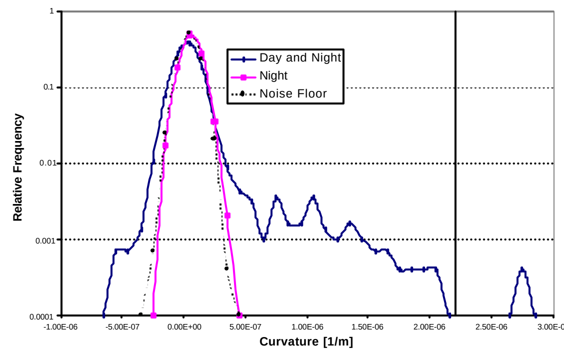

Figure 4 Relative curvature probability

Figure 3 shows the results obtained by the two sensors. The drift in the measurements on both sensors is due to the bridge's temperature variations that were however very small in this cold winter day. The total drift is of only about 80 microns over a sensor length of 6 m. This corresponds to a temperature variation of the order of 1°C. By subtracting the two deformation values and dividing by their length and distance it is possible to obtain the curvature variations of the bridge.

The bridge's temperature drift is removed with a polynomial fit on the initial data. As expected most data points lie around a zero curvature corresponding to the mean static state of the bridge. High curvature values indicate a deformation induced by the passage of a truck and are concentrated during the day when truck circulation is allowed. Except for one reading around 21:00 no trucks were registered during the night. Most curvatures are positive and indicate a downward bending of the bridge under the quasi-static loading of the truck. A few points lie outside the noise floor curve for negative curvatures. These ere either rebounds of the bridge after a truck leaves the instrumented span or deformations induced by trucks on neighboring spans.

Figure 4 shows the statistical analysis on the whole set of data (Day and Night, 3269 data points), the night data only (Night, 996 points) and of a Monte-Carlo simulation based on simulated deformation measurements with a standard deviation of one micron (noise Floor, 3267 points). The good agreement between these two latter curves indicates that the noise floor of the SOFO system limited the measurements during the night. During the day the higher deformations due to the passage of the trucks are clearly visible. The vertical line indicates the curvature that was obtained during the static loading test with a truck of 28 t placed at center span. Since the load limit on the Swiss highway network is 28 t, Figure 4 indicates that the dynamic effects on the bridge are very limited. A rebound of a passing truck could for example induce higher curvatures than this same truck statically placed on the bridge. The isolated event at $2.7\ 10^{-6}$ 1/m either indicates an overweight truck (some 40 t trucks are also circulating) or two trucks on the bridge at the same time.

This same figure can be used to quantify the probability of having a truck on the bridge at any given time. This is given by the ratio of the number of points of the Day and Night curve inside, respectively outside the Noise Floor curve. This ratio gives 90% and indicates the probability of obtaining a reliable static deformation value when the measurements are performed under traffic conditions. This shows that it is possible to obtain reliable static deformation measurement even without stopping the traffic on the bridge. It is sufficient to perform three or more measurements on each sensor and discard any statistically aberrant value to obtain a reliable value. A theoretical analysis considering the truck traffic density, the mean truck speed, the mean transit time gives a slightly lower value of 80%.

This type of analysis will be soon carried out in fresh concrete setting in high vibration environments as the ones typically found during refurbishments under traffic conditions.

4.2 Bissone Bridge: Old-new concrete interaction

The Bissone-Lugano bridge is a road viaduct of the 60's along the lake Ceresio in southern Switzerland. Due to the critical concrete condition caused by mechanical and chemical ageing, refurbishing measures were necessary. Part of the structure was hydro-demolished and rebuilt with new concrete [4]. The healing concrete had to respect certain mechanical and chemical characteristics. In particular, the shrinkage of the healing coat had to be limited in such a way to prevent tension cracks.
Two fiber optic SOFO sensors (see Figure 5) with an active length of 1.50 m were installed on the lake side of the bridge. Shrinkage deformation was measured regularly with the fiber optic sensors during concrete setting (several hours), then with regular intervals of 1 day, 1 week, and so on.
For the sake of comparison, surface deformations were monitored by conventional mechanical gages over a distance equivalent to the active length of the internal fiber optic sensor (1500 mm). Shrinkage measurements were also made on two concrete prisms held in laboratory at a constant temperature of 20°C and relative humid ity of 60%.

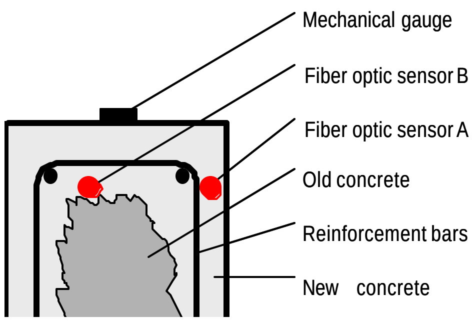

Figure 5 Cross-section of the refurbished beam and placement of the sensors

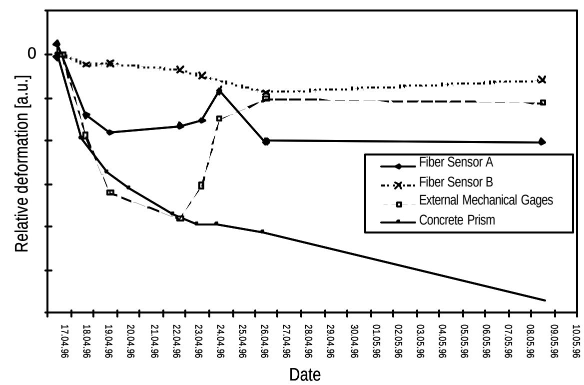

Figure 6 Measurements on the SOFO® sensors, on the mechanical extensometer and on the concrete prisms

The results beginning 24 hours after concrete pouring are shown in Figure 6. The chart shows different behaviors between the two fiber optic sensors that are placed in two different positions. The first one (Sensor B) is located entirely inside the new healing concrete, while the second one (Sensor A) lies along the interface between old and new concrete and therefore measures partially hindered shrinkage.
It is easily to see the influence on the repaired beam of environmental factors like temperature and humidity variations (high gradients during the day, rain) as well as of hydration process of the fresh concrete. The concrete behavior shows an interesting gradient due to the location of the measurement instruments : along the interface between old and new concrete the shrinkage value in the first week is ca. 1/3 of the shrinkage measured in the new concrete and ca. 1/7 of the of the shrinkage measured on the surface. That can be explained with the partially hindered shrinkage along the interface and with the hydration process of the concrete that also depends on the environmental humidity. The good adhesion of the new concrete to the old one can therefore be verified.
The time of the form removal and the contemporary wet weather can also be easily identified (23.4), because the concrete shows then an elongation. Measurements during more that one year confirmed the

good adhesion between the two materials. The same shrinkage was measured on the two sensors and the total value is about 1/2 of the free shrinkage measured on prisms.

4.3 Versoix Bridge: Old-new concrete interaction

The North and South Versoix bridges are two parallel twin bridges. Each one supported two lanes of the Swiss national highway A9 between Geneva and Lausanne. The bridges are classical ones consisting in two parallel pre-stressed concrete beams supporting a 30 cm concrete deck and two overhangs. In order to support a third traffic lane and a new emergency lane, the exterior beams were widened and the overhangs extended (see Figure 7). The construction progressed in two phases: the interior and the exterior overhang extension. The first one began by the demolition of the existing internal overhang followed by the reconstruction of a larger one. The second phase consisted in demolishing the old external overhang, to widen the exterior web and to rebuild a larger overhang supported by metallic beams. Both phases were built by 14 m stages.

Because of the added weight and pre-stressing, as well as the differential shrinkage between new and old concrete, the bridge bends (both horizontally and vertically) and twists during the construction phases. In order to increase the knowledge on the bridge behavior and performance and to optimize the concrete mix, the engineer choose low-coherence SOFO sensors to measure the displacements of the fresh concrete during the setting phase and to monitor the long term deformations of the bridge. The bridge was instrumented with more than hundred of these sensors.

Two additional sensors were installed to give information about the differential shrinkage between the old and the new concrete. These sensors are rigidly connected to the existing concrete and their measurements can be compared with parallel sensors placed in the newly added concrete. This installation scheme is repeated 12 times, 5 times in the first span and 8 in the second one.

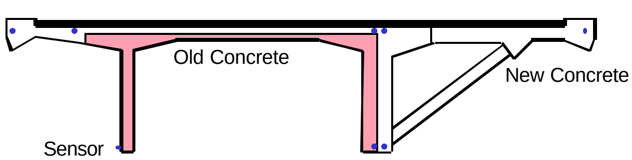

Figure 7 Sensor placement in the bridge cross-section. The red part represents the old concrete. Notice the sensor pairs in the right beam.

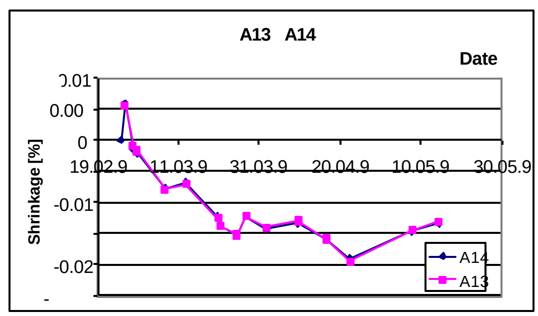

Figure 8 Differential shrinkage between old and new concrete. No relative movement is visible indicating that the bridge is acting monolithically

Figure 8 shows an example of the measurement of shrinkage for two parallel sensors, A14 (new concrete) and A13 (old concrete). The two curves overlap almost perfectly, indicating an overall differential shrinkage close to zero, an index of a good cohesion between the two concretes.

5. Conclusions

The presented application example show how it is possible to instrument a bridge to obtain information on the static and dynamic deformations before during and after refurbishment works. These measurement are useful to evaluate the state of the bridge, to refine its computer modeling and to prevent problems due for example to insufficient adherence between old and new concrete or to excessive vibrations during setting.

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7. Bibliography

For further information on the SOFO® system consult the following homepages:
http:/www.smartec.ch and http://imacwww.epfl.ch/

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