Long-term monitoring of a concrete bridge with 100+ fiberoptic long-gage sensors

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ABSTRACT

In 1996, a concrete highway bridge near Geneva (Switzerland) was instrumented with more than 100 low-coherence fiber optic deformation sensors. The Versoix Bridge is a classical concrete bridge consisting in two parallel pre-stressed concrete beams supporting a 30-cm concrete deck and two overhangs. To enlarge the bridge, the beams were widened and the overhang extended. In order to increase the knowledge on the interaction between the old and the new concrete, we choose low-coherence fiber optic sensors to measure the displacements of the fresh concrete during the setting phase and to monitor the long term deformations of the bridge. The aim is to retrieve the spatial displacements of the bridge in an earth-bound coordinate system by monitoring its internal deformations. The vertical and horizontal curvatures of the bridge are measured locally at multiple locations along the bridge span by installing sensors at different positions in the girder cross-section. By taking the double integral of the curvature and respecting the boundary conditions, it is then possible to retrieve the deformations of the bridge.
This paper presents the sensor network design and the measurements that were performed during the construction phases, during the bridge operation since it was reopened and under a recent static-loading test.

Keywords: Deformation sensor, Bridge, Structural monitoring, Fiber optic sensors.

1. INTRODUCTION

The security of bridges requires periodic monitoring, maintenance and restoration. Excessive and non-stabilized deformations are often observed and although they rarely affect the global structural security, they can lead to serviceability deficiencies. Furthermore, accurate knowledge of the behavior of bridges is becoming more important as new structures become lighter and as an increasing number of existing bridges is required to remain in service beyond their theoretical service life. Monitoring, both in the long and short term, helps to increase the knowledge of the real behavior of the bridge and in the planning of the maintenance interventions. In the long term, static monitoring requires an accurate and very stable system, able to relate deformation measurements often spaced over long periods of time.
The monitoring of a new or existing structure 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 in the construction (e.g. concrete, steel, and timber) and observe their behavior under load 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 in the structure, 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 of the order of one to a few meters, it is possible to gain information about the deformations of the structure as a whole 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 a direct impact on the form 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 has historically concentrated most research efforts in the direction of material monitoring rather than structural monitoring. This latter has usually been applied using external means like triangulation, dial gages and invar wires. Interferometric fiber optic sensors offer an interesting means of implementing structural monitoring with internal or embedded sensors.

2. THE SOFO SYSTEM

The functional principle of the SOFO system (Short for "Surveillance d'Ouvrages per Fibers Optiques") is schematized in Figure 1. The sensor consists of a pair of single-mode fibers installed in the structure to be monitored and having a length between 0.2m and 10 m. One of the fibers, called measurement fiber, is in mechanical contact with the host structure itself, while the other, the reference fiber, is placed loose in a neighboring pipe. All deformations of the structure will then result in a change of the length difference between these two fibers.

To make an absolute measurement of this path unbalance, a low-coherence double Michelson interferometer in tandem configuration is used. The first interferometer is made of the measurement and reference fibers, while the second is contained in the portable reading unit. This second interferometer can introduce, by means of a scanning mirror, a well-known path unbalance between its two arms.

Because of the reduced coherence of the source used (the 1.3 micron radiation of an LED), interference fringes are detectable only when the reading interferometer compensates the length difference between the fibers in the structure.

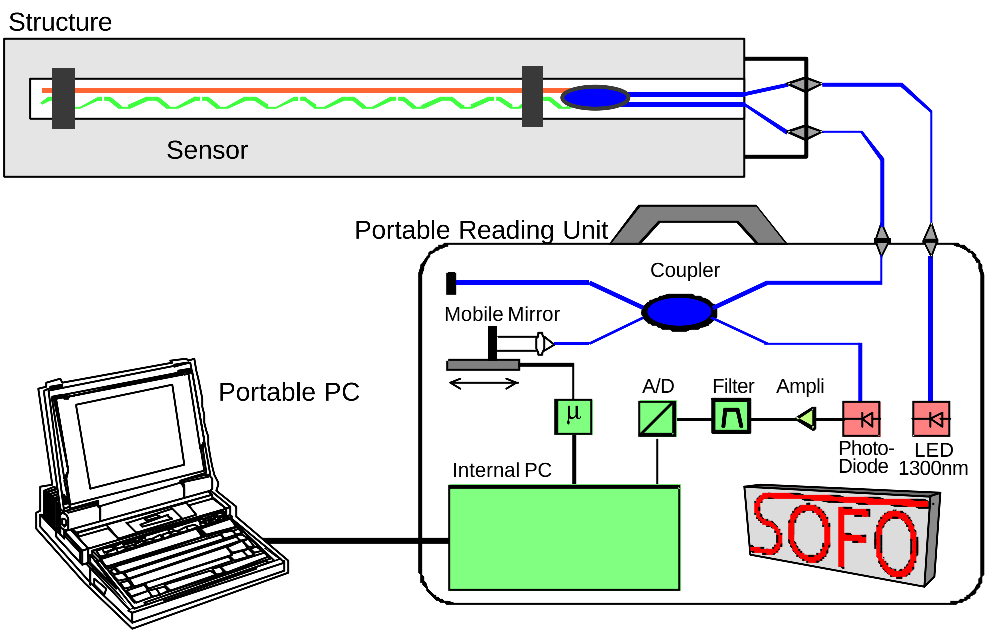

Figure 1: Setup of the SOFO system

If this measurement is repeated at successive times, the evolution of the deformations in the structure can be followed without the need of a continuous monitoring. This means that a single reading unit can be used to monitor several fiber pairs in multiple structures.

The signal detected by the photodiode is pre-amplified and demodulated by a band-pass filter and a digital envelope filter.

The precision and stability obtained by this setup have been quantified in laboratory and field tests to 2 micron, independently from the sensor length over more than four year. Even a change in the fiber transmission properties does not affect the precision, since the displacement information is encoded in the coherence of the light and not in its intensity.

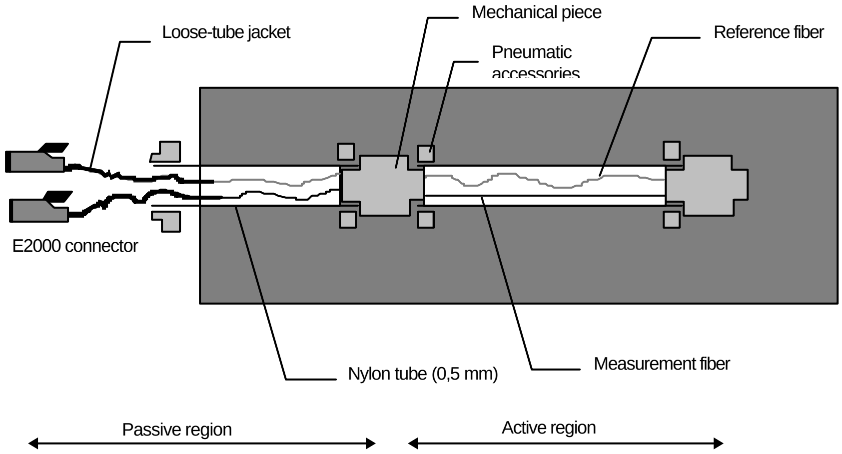

Figure 2: Setup of the SOFO sensors

Figure 2 shows a typical sensor for length up to 10 m. This sensor is adapted to direct concrete embedding or surface mounting on existing structures. The passive region of the sensor is used to connect the sensor to the reading unit and can be up to a few kilometers long.

The reading unit is portable, waterproof and battery powered, making it ideal for dusty and humid environments as the ones found in most building sites. Each measurement takes about 10 seconds and all the results are automatically analyzed and stored for further interpretation by the external laptop computer.

The measurements can either be performed manually, by connecting the different sensors one after the other, or automatically by means of an optical switch. Since the measurement of the length difference between the fibers is absolute, there is no need to maintain a permanent connection between the reading unit and the sensors. A single unit can therefore be used to monitor multiple sensors and structures with the desired frequency.

3. DATA ANALYSIS ALGORITHMS

The data analysis packages interpret the data stored by the acquisition software in the database. Some of these packages are general and can be used with each type of structure, while others are aimed to a precise structure or structure type. Examples of such tools are:

- *Displacement evolution analysis:* This general-purpose package extracts the results concerning a single sensor and displays them as a function of time or load. The data can than be exported to other software packages, like spreadsheets or other graphical tools for adequate representation.
- *Curvature:* In beams, slabs, vaults and domes, it is possible to measure the local curvature and the position of the neutral axis by measuring the deformations on the tensile and compressive sides of a given element. In many cases, the evolution of the curvature can give interesting indication on the state of the structure. For example, a beam, which is locally cracked, will tend to concentrate its curvature at the location of the cracks. Furthermore, by double integration of the curvature function, it is possible to retrieve the displacements perpendicular to the sensor direction. This is particularly interesting since in many cases the engineers are interested in deformation that are at a right angle to the natural direction in which the fiber sensors are installed. For example: in a bridge fibers are installed horizontally, but vertical displacement are more interesting. In a tunnel the fibers are placed tangentially to the vault, but measurement of radial deformation is required. In a dam the fibers are installed in the plane of the wall but displacements perpendicular to it have to be measured.

4. THE VERSOIX BRIDGE

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. 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 to demolish 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.

Figure 3: The Versoix Bridge during the rehabilitation works

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.

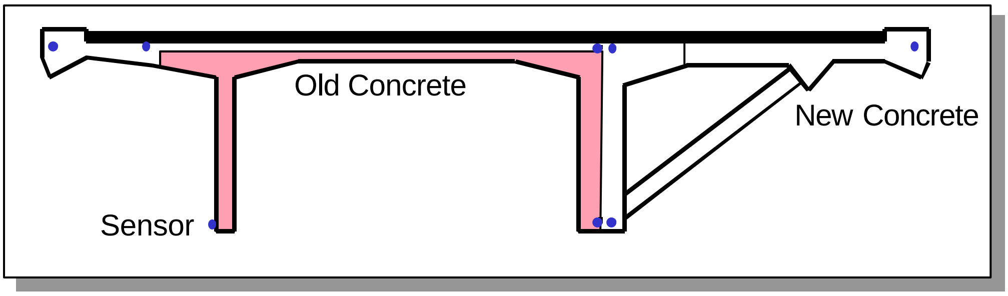

Figure 4: The Versoix Bridge cross-section and placement of the sensors

4.1 Fiber Optic Instrumentation

To obtain a good representation of the bridge deformations, it was necessary to find a mean to measure the horizontal, vertical and torsion displacements of the bridge during the different construction phases and in the long term. To measure them, we decided to use an algorithm retrieving the displacements from curvature measurements. In order to guarantee a sufficient redundancy and to follow the concrete pouring stages of 14 m, 1 section of sensors was placed each 7 m. Because of budget limitations, only 2 of the 6 spans were instrumented. A preliminary study by finite element simulation showed that the deformations of the two spans could be approximated by two 5th degree polynomial functions. At least 4 curvatures measurements for each span are therefore necessary to obtain the bridge spatial displacements. In each section, five sensors have been embedded in the new concrete and one sensor has been installed on the surface of the old concrete (see Figure 4). To obtain a good representation of the mean curvature, sensors with four-meter active length were chosen. 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.
The horizontal and vertical curvature is calculated separately for each of the 12 sections usin g all the 8 sensors. The spatial displacements are then calculated by integrating the mean curvature of the 12 sections.

4.2 Sensor network installation

To facilitate the implantation of automatic and remote monitoring, the whole sensor network had to be measured from one single and easily accessible location: the abutment. The main sensor network is composed by 96 fibers optics deformations sensors with a 4 m active length and 2-10 m passive length, 14 optical cables with 10-100 m length, 14 local connections boxes (see Figure 5) and one central box. The central box (see Figure 6) also allows the installation of a reading unit, optical switches, portable PC and modem to measure the bridge remotely.

Figure 5: Local connection box

Figure 6: Central connection box

The sensor installation followed the bridge widening schedule. The installation was very rapid; 2 hours were sufficient to place 4 sensors in each concrete pouring stage (for the interior overhang widening). Sensors were placed in the framework just after its completion and the building yard schedule was not delayed. Sensors were only held with plastic rings (and not fixed) to the re-bars (see Figure 7). Connection boxes were placed at the same time as the sensors in order to protect the optical connector, to check each one during the installation and to measure the bridge during construction. Finally, before the catwalks allowing the access to the local boxes were removed, all boxes were linked to the central one. The exterior sensors were attached to the surface of the old interior web using L-shaped metallic adapters (see Figure 8).
During concreting, the workers were not aware that sensors were present in the framework and worked like every day, pouring the concrete directly on the sensors and vibrating as usual.

Figure 7: Sensor installation in concrete

Figure 8: Surface sensor installation

All but nine of the sensors are working properly two years after the end of the installation. Two sensors were lost during installation (one of them cut with an acetylene torch!); three during concreting and other two were damaged in the passive region. The death of the other two still waits for an explanation. Thanks to the redundancy built in the curvature analysis algorithms, these losses do not affect the performance of the sensor network as a whole.

5. MEASUREMENTS

5.1 Measurements on single sensors

Figure 9 shows the typical concrete deformations measured in one sensor during the first 8 months. All the optical fiber sensors of a same concrete pouring stage indicate about the same behavior. On the graph, four phases are distinguishable: the first is the drying shrinkage (phase 1), followed by a stabilization phase (phase 2) and finally there is a zone of variation (phase 3) corresponding to the thermal elongation of the bridge. Phase 4 is due to the decrease of the bridge temperature during the month of November 1996. These variations are consistent with a temperature variation of about 10°C that was actually observed.

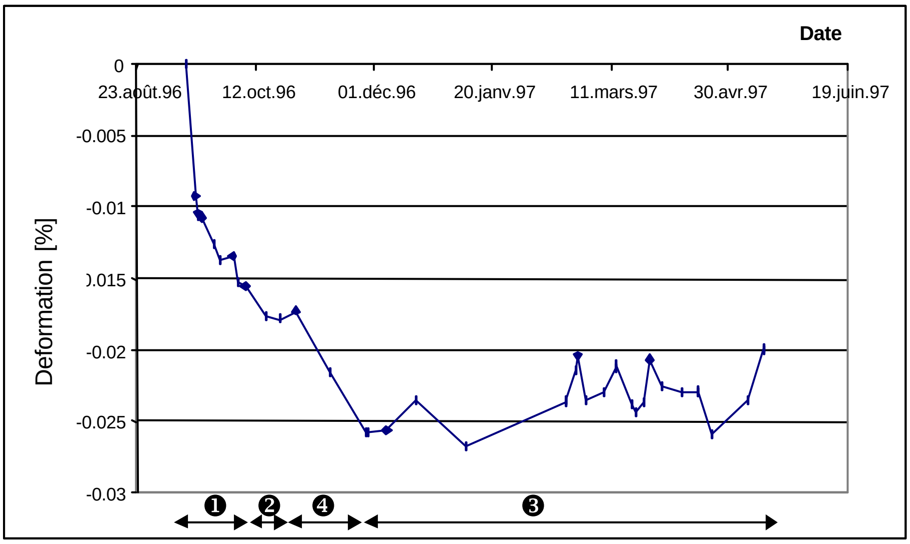

Figure 9: Typical deformation measurement over 8 months

Figure 10 show measurement performed on two successive concrete pouring stages. The sensors in the same stage give similar results, but the two groups show a different behavior. Stage A has a shrinkage of about 0.02 % while the other one has an apparent shrinkage of only about 0.005%. This difference is explained by the use of a different concrete mix between the 2 stages and the different climatic conditions. Stage B showed cracking while stage A did not. In the case of a cracked region, the 4m long sensor will typically bridge several cracks and the overall shrinkage of concrete is almost entirely compensated by the crack openings. This explains the lower values and allows an easy and early detection of the crack onset.

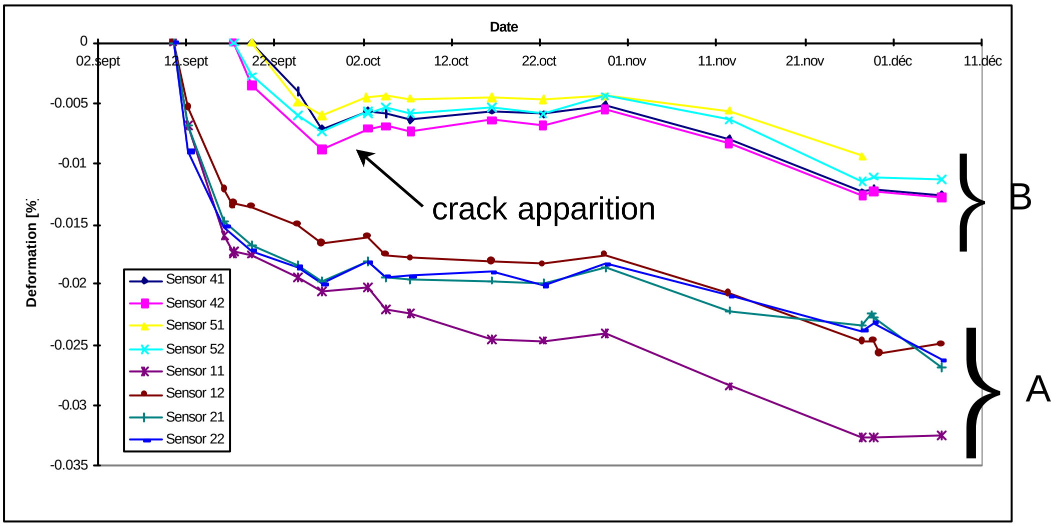

Figure 10: Comparison between cracked and un-cracked sections

5.2 Differential shrinkage measurements

Figure 11 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.

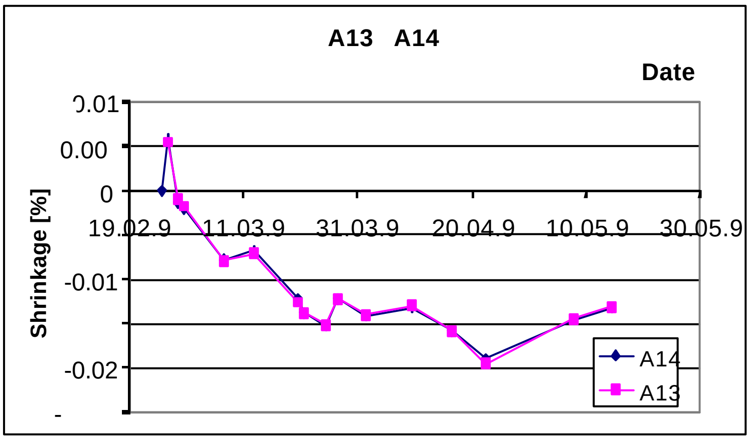

Figure 11: Differential shrinkage between the old and new concrete

5.3 Global displacement measurements

The horizontal and vertical displacements of the first two spans of the bridge were calculated using the double-integration algorithm previously described.

Figure 12 shows the horizontal displacement of the two spans of the bridge as calculated by algorithm, for different times and relatively to the line Abutment-Pile 2. The observed 'banana' effect is due to the shrinkage of the concrete of the new exterior overhang. This effect stabilizes to a value of 5 mm of horizontal lateral displacement after one month.

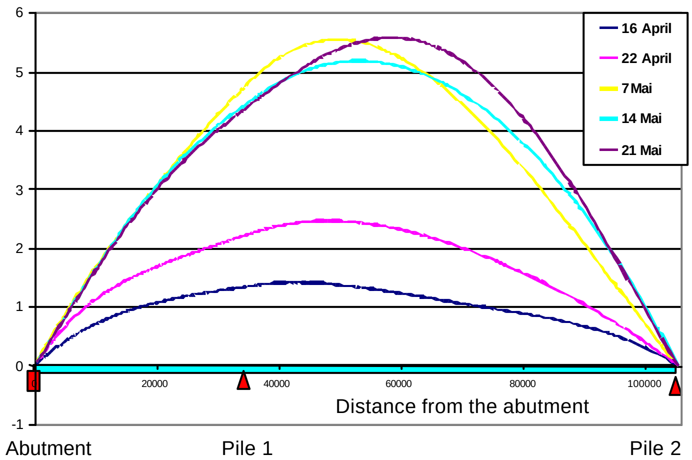

Figure 12: Horizontal displacement of the bridge

During a load test, performed in Mai 1998 after the end of construction works, the vertical displacement of the bridge was also monitored using the fiber optic sensors.

Error! Reference source not found. shows the measurement with SOFO sensors (Vertical Displacement Calculated) compared to those obtained with dial gages (invar wires under the bridge). This load pattern (Case A) consists in 6 trucks placed on the second span of the bridge (position 73 in the graph). The error of the algo rithm is estimated from the deviation from a flat surface of the section deformations (the algorithm is based on the assumption that plan sections remain plain under load). The algorithm (Vertical Displacement Calculated) retrieves within in the error interval the position of the first pile (not entered as a boundary condition for the integration) and matches the vertical displacement measured with the dial gages.

Error! Reference source not found. shows the measurements during the load test for the case B. The case B consists in 6 trucks on the third span of the bridge (position right, out of the graph).

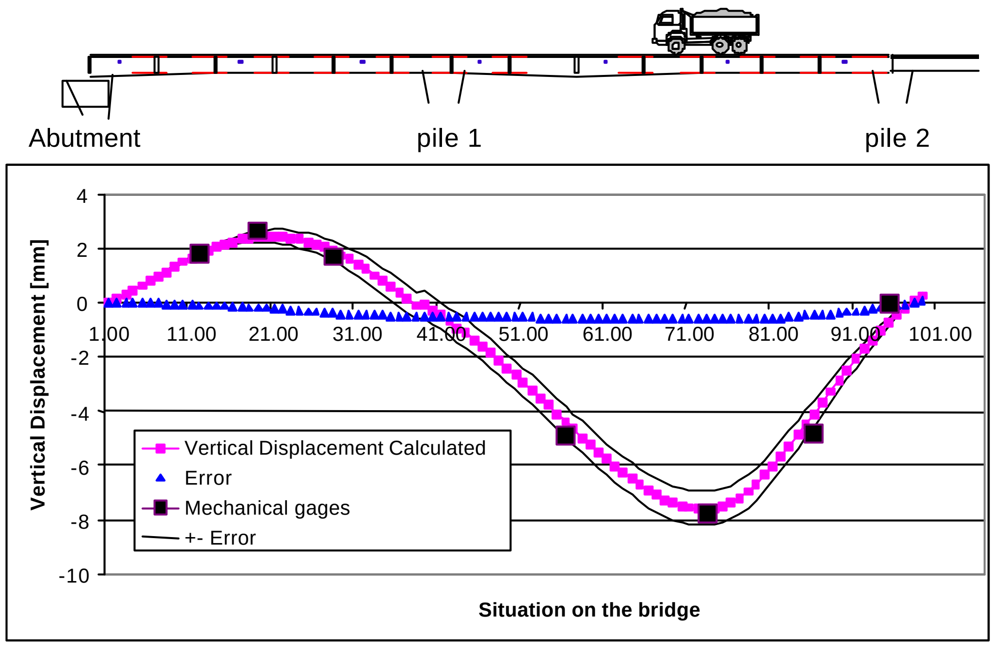

Figure 13: Vertical displacement, load case A

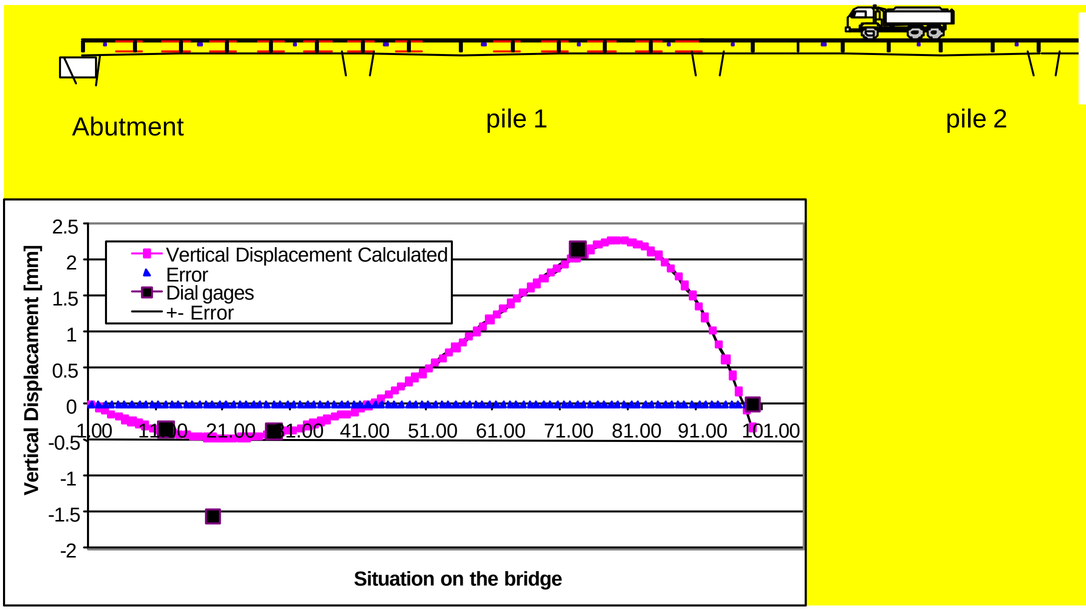

Figure 14: Vertical displacement, load case B

In this case the error is very small because the torsion is not significant, the deformations are small and the condition "the plain sections remain plain" for the algorithm is better respected. Only the position 19 of the mechanical gages doesn't correspond well: this because this particular mechanical gage is placed on the overhang of the bridge where torsion is more important instead than on the beams.

The overall precision in the horizontal and vertical displacements of the two spans can be evaluated to 0.2 mm, a remarkable figure for a total integration length of over 100m. This shows that it is indeed possible to retrieve the global deformations of a bridge using internal horizontal measurements. If the deformatio ns have to be known in an absolute referential and since the internal sensor can non give information on the rigid-body motion of the structure, it is necessary to complement the sensor network with at least two absolute measurements systems, for example inclinometers or GPS systems.

6. CONCLUSIONS

The measurement allowed gathering precious information about the behavior of the bridge. In particular, it was possible to observe the effect of different concrete types on the hindered shrinkage and to anticipate and observe the apparition of cracks in some of the sections. The curvature measurements showed that it is indeed possible to retrieve the spatial displacement in both the horizontal and vertical planes. The horizontal measurements clearly show a bending induced by the differential shrinkage produced by the asymmetric distribution of the added concrete. The vertical displacements were more difficult to interpreter during construction, because of the continuous changes in the live loads (crane, trucks, temporary structural elements) and support conditions (temporary scaffolding and shoring). On the other hand, the vertical displacement during the load test were in excellent agreement this those obtained with dial gages.
The treatment of the data resulting from the 100+ sensors proved to be very time consuming and dedicated software was created in order to represent and analyze the data. The efficient handling of such huge and complex data flows certainly represents a challenge that must not be underestimated. At IMAC-EPFL, two Ph.D. theses are currently in preparation on this topic.

7. ACKNOWLEDGEMENTS

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For further information on the SOFO project look at the following WWW home pages: \\www.smartec.ch and \\imacwww.epfl.ch.