Bridge monitoring by fiber optic deformation sensors: design, emplacement and results

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ABSTRACT

In 1995, our laboratory fitted an highway bridge near Lausanne (Switzerland) with low-coherence fiber optic deformation sensors. The engineers, who had designed the steel-concrete composite bridge were interested in the strain distribution inside the concrete slab and in the effects induced by the concrete shrinkage. More than 30 fiber optic deformation sensors, a few vibrating string deformation sensors, thermoelectric couples as well as resistive strain gages were installed in the concrete deck and on the steel girders of this bridge. Three phases of the bridge life were monitored: concreting and thermal shrinkage, load test with heavy trucks and long term deformations. This contribution presents the fiber optic sensor design, the installation technique and the preliminary results obtained on this bridge.

Keywords: Bridge monitoring, Deformation sensor, Fiber Optic Sensor

1. INTRODUCTION

The civil engineering community is becoming increasingly interested in the monitoring of the structural behavior and in new tools allowing the assessment of structural integrity and performances. Concrete structures are especially interesting because of their prevalence in the ground transportation infrastructure and because of the increasing attention accorded to the behavior of aging structures.
In 1995, our laboratory fitted a highway bridge near Lausanne (Switzerland) with low-coherence fiber optic deformation sensors. The engineers, who had studied the steel concrete composite bridge were interested, besides the long-term monitoring, in the effects of concrete shrinkage during the first few days after concreting. To obtain reliable measurements, special attention was given to the design, the emplacement and the definition of the multiplexing network of the deformation sensors.

2. FIBER OPTIC DEFORMATION SENSOR DESIGN

In order to measure concrete deformations during the first hours after the concreting (i.e. during the thermal expansion phases) it was necessary to rely on internal and temperature insensitive deformation sensors. In fact, during this period, the concrete temperature presents important variations due to the exothermic setting reactions. For this application where the environmental conditions are particularly harsh (mud, water, dust…), a monitoring method including both a reliable reading unit and a stand-alone fiber optic sensor (to be installed in concrete) was necessary. The SOFO system[1] (French short for Monitoring of structures by Optical Fibers) was chosen for this proprieties.

2.1. The SOFO system

The functional principle of the SOFO system is schematized in Figure 1. The sensor consists of a pair of single-mode fibers installed in the structure to be monitored. One of the fibers, called the measurement fiber, is in mechanical contact with the host structure itself, while the other one, 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 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 and eventually compensate for the length difference between the fibers in the structure. Because of the reduced coherence of the source used, interference fringes are detectable in this case only. 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 precision and stability obtained by this setup have been quantified in laboratory and field tests to 10 μm over more than one year. Even a change in the fiber does not affect the precision, since the displacement information is encoded in the coherence properties of the light and not in its intensity. The reading unit is portable, battery powered and waterproof, making it ideal for dusty and humid environments as the ones found in most building sites. Each measurement takes only a few seconds and all the results are automatically analyzed and stored for further interpretation by the external laptop computer. A more detailed description of this measuring technique can be found in the references[1]. The optical fiber sensor used in this experiment give only one elongation at a time. By introducing partial reflector pairs on both the measurement and the reference fiber it is however possible to obtain the deformation relative to different fiber section separately[2].

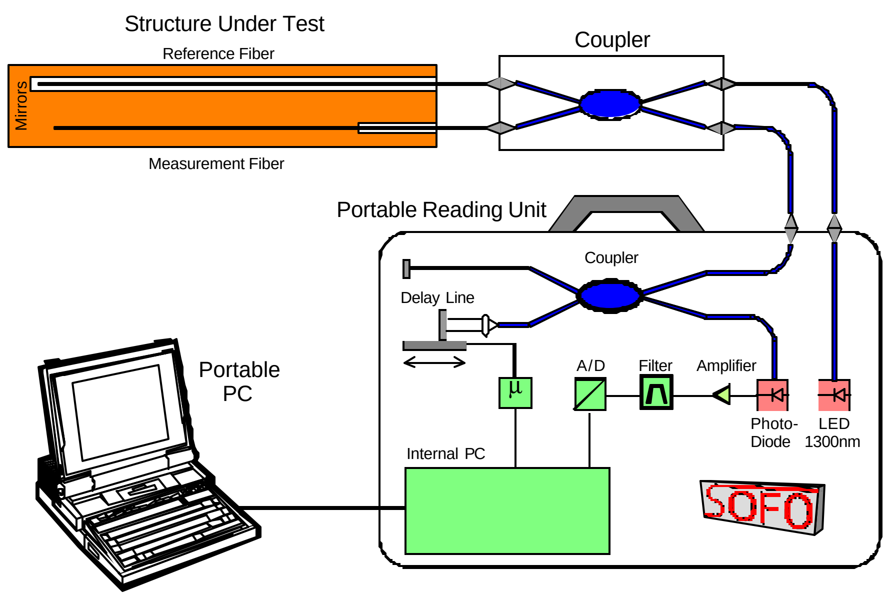

Figure 1. Optical setup of the low-coherence double interferometer. The portable reading unit is waterproof and battery powered. One measurement takes a few seconds. The temperature variation have no effect on the sensor.

2.2. Sensor design

The sensor monitors a displacement between two points. It consists of a pair of single mode fibers with an acrylate coating called respectively the reference and the measurement fiber (see Figure 1.). The measurement fiber is pre-strained between the two anchorage points of the sensor (in order to measure both elongation and shortening) and free elsewhere. These points consist of a mechanical piece transmitting the structure displacements to the fiber. At this points, it was necessary to remove the acrylate coating in order to glue directly the glass fiber on the mechanical piece, and thus avoid creeping problems [3]. The reference fiber is free in the tube and no displacement of the structure should strain it. Both fibers are placed in a 5 mm diameter nylon tube which is joined to the mechanical piece with pneumatic accessories (see Figure 2). Both fiber have a loose-tube jacket protection (near the connector), a silvered end facet (acting as a mirror) and a Diamond E2000 connector (with integrated dust cap). A special piece is integrated at the end of the nylon tube to fix the sensor to the junction box (see Figure 3). This box protects every connectors and enables the connection between a large number of sensors and reading unit.

Sensors were assembled, pre-tensioned at 0,5 % and tested in the laboratory. The pre-tension of the measurement fiber, withstood by the nylon tube, allows to place the sensor in the structure very rapidly.

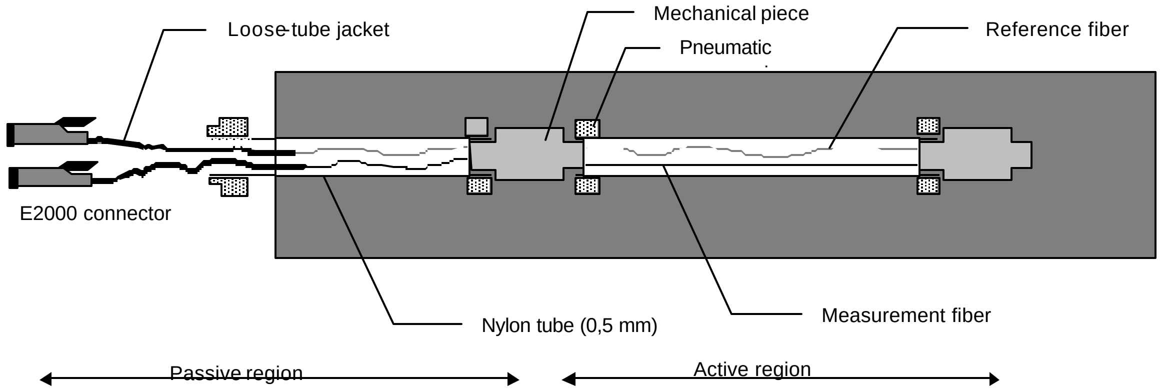

Figure 2. The SOFO sensor: schematic representation

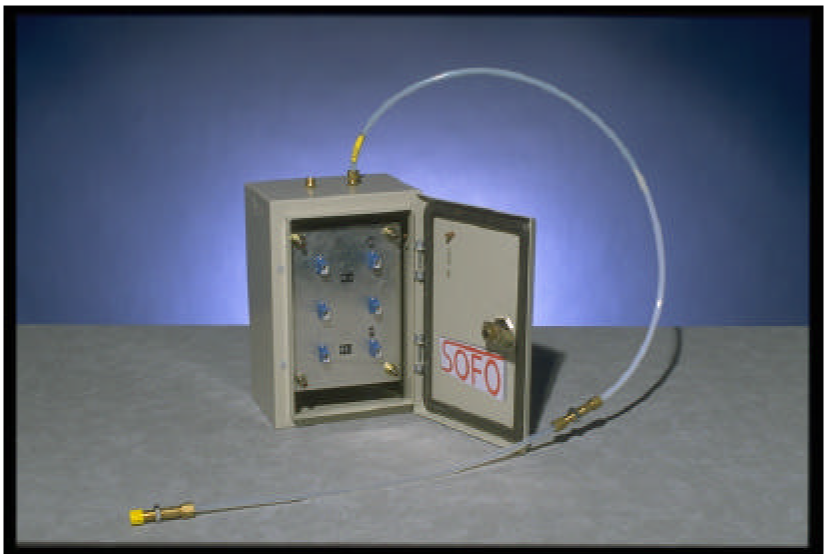

Figure 3. The SOFO sensor and its junction box

3. BRIDGE DESIGN AND EQUIPEMENT

3.1. Design of the bridge

The Venoge highway bridge near Lausanne is a four-spans bridge consisting in two parallel steel girders of 1.0 ÷ 1.9 m in height and supporting a 23 cm thick concrete deck. To widen the bridge in 1995, two identical bridges were built on each side creating a third traffic lane and a new emergence lane in each direction . To increase its knowledge on steel-concrete composite bridges, ICOM concentrates its activities on the behavior and the modeling of real structures. The Venoge bridge widening and the different phases of its construction allowed the observation of different interesting phenomena.
The monitoring of the real behavior of this steel-concrete bridge under direct and indirect action is the general aim of this experiment, which can be divided in 3 main objectives:

- Monitoring of the shrinkage effects, especially during the first hours after concreting. It is very interesting to control the thermal expansion phases[4,6], to understand the real behavior of the steel-concrete interaction.
- Verification of the bridge behavior under static forces.
- Measurement of the bridge behavior under the traffic loads.

More than 30 fiber optic sensors, a few wire strain gauges strings and about 24 thermoelectric couples were installed in the deck and on the steel girders. Forty eight strain gauges where fitted on the steel girders, while four instrumented bearings were installed on the 2 extremities of the first span.

Figure 4. Situation of the fiber optic sensors emplacement

3.2. Fiber optic sensors installation

Three sections have been fitted with 8 fiber optic sensors each. The sensors measure the deformation over 1 m and 2 m long bases. A fourth section has been fitted with 4 sensors (measuring deformation on 1 m and 2 m) near the abutment, monitoring the deck perpendicularly to the axis of the bridge (see Figure 4). Those sensors measure the free shrinkage of the concrete while the other ones measure the shrinkage partially prevented by the steel girders. Two special 1m long sensors with integrated couplers have been added to section 3.
The installation of the sensors was very rapid, half a day was enough to put sensors in sections 1,2 and 4. The sensors were placed in the framework just after its completion and the building yard schedule was not delayed. Sensors were only held with plastic strings (and not fixed) to the re bars (see Figure 5).
To complement and verify the measurements, four vibrating string sensors were installed near the fiber optic sensors in the section 1,2 and 3.

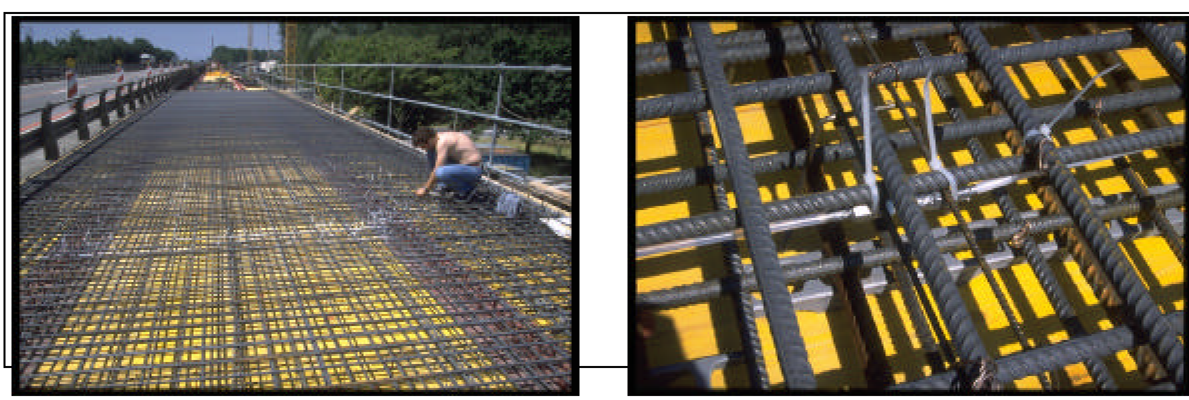

Figure 5 a) General view of the section 1. b) Fixation of the sensor to the framework
Sensors are held but not fixed to the re bars with plastic strings

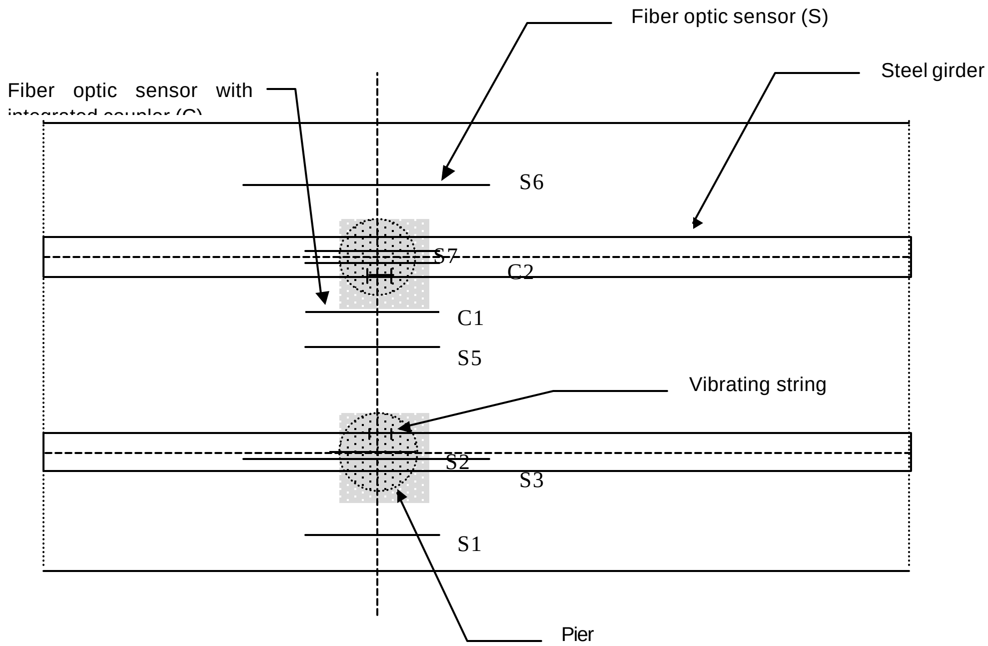

Figure 6. Section 3: Fiber optic sensor and vibrating string sensor emplacement

3.3. Network design

Figure 7. A typical measurement session. The operator connects the coupler to the sensor in the junction boxes and carries out the measurement with a portable PC, the reading unit remains at the bottom of the ladder.

Four metallic boxes with a connection panel gather the sensors of each section and allow the connection to the reading unit. In this way, connectors are protected during the construction phases and the whole life of the bridge. To measure a sensor, the user connects the coupler to the box's panel, and carries out the measurement with a portable PC, the reading unit stays at the bottom of the ladder (see Figure 7). Every measure is saved in a database and analyzed directly at the building site or later back in the office. After the concreting and the removal of the frames, all the sensors operated with a good signal.

4. RESULTS

4.1. Shrinkage measurement

The shrinkage measurements of the concrete deck are divided in two phases:

- the first 14 hours to follow the thermal expansion phase
- the first twenty days to have a global view of the shrinkage

The presented charts show the results obtained by 8 fiber optic deformation sensors in section 3 (see Figure 8), in parallel the results of two vibrating strings on the same section are presented (see Figure 9).

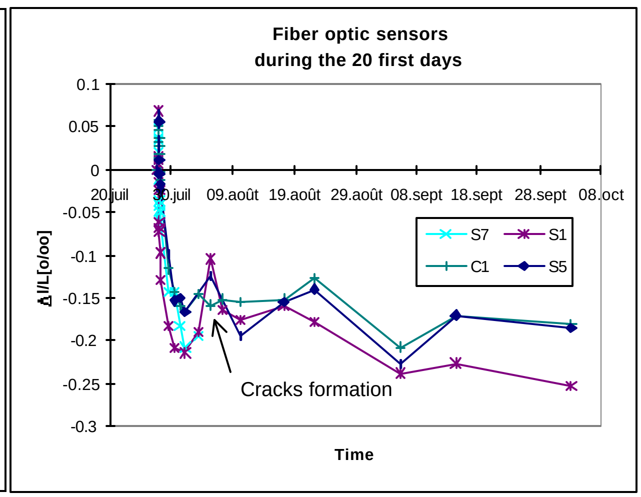

Figure 8 Section 3, fiber optic deformation sensor results during the thermal expansion phase and the shrinkage phase

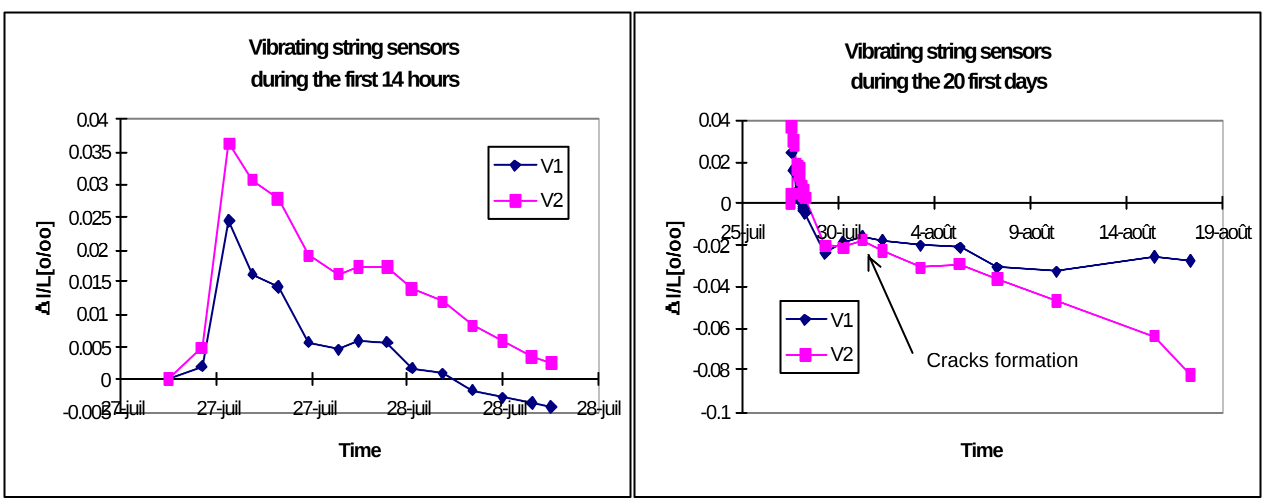

Figure 9 Section 3, vibrating string sensors results during the thermal expansion phase and the shrinkage phase

The thermal expansion phase is perceptible with a elongation value around 0,06 ‰. During the cooling phase, the fiber optic sensors measurements presents a discontinuity pointing to cracks formation, in particular between the 4th and 9th august, eight days after the concreting. A divergence for the vibrating string values after 5 days is also noted.
Observations in the pile zone have indeed shown the apparition of cracks of 0,1 - 0,15 mm width, separated by 2 m, eight days after the concreting. The relative position of the vibrating strings and the crack explains the divergence of those measures. One is placed on a crack and measures its opening while the other is in a crack-free concrete region. A good correlation between the crack width and the reading of the optical fiber sensor shows the interest of placing such sensors in concrete structure.

Unfortunately, two bad points appear in this result: the precision of the measure and the longevity of the sensors.
The precision of the sensors doesn't reach the precision of the reading unit (about 4 μm). A test of repeated connection and re-connection showed a precision of about 25 μm, or 0,025 ‰ for a one meter long sensor. This perturbation is due to an elongation of the fiber between the external coupler and the sensor's connectors. This disturbance did not appear for the sensors with integrated coupler and precision up to a few microns where obtained. The result of a such sensor is showed in the Figure 8 (sensors C1 and C2).
A failure of about 60 % of the sensors after 1 month is the second bad result. The measurement fiber is responsible for this problem, since it breaks at the junction pieces after a few weeks under load. To fix the measurement fiber to the mechanical piece, we had to strip the fiber mechanically in order to glue directly the fiber core, this procedure induces a micro-cracks on the fiber surface and after a few weeks under tension (about 0,5 %), the crack propagates to the fiber core and eventually breaks it. A solution to avoid this problem, is the use of fibers with polyimide coating. In fact, the polyimide coating is very well hang on to the glass fiber and the stripping is not necessary. Sensors with the same setup as the ones used in the Venoge bridge were realized with polyimide coated fibers and installed with much lower failure rates in other concrete structures.

4.2. Load test measurement

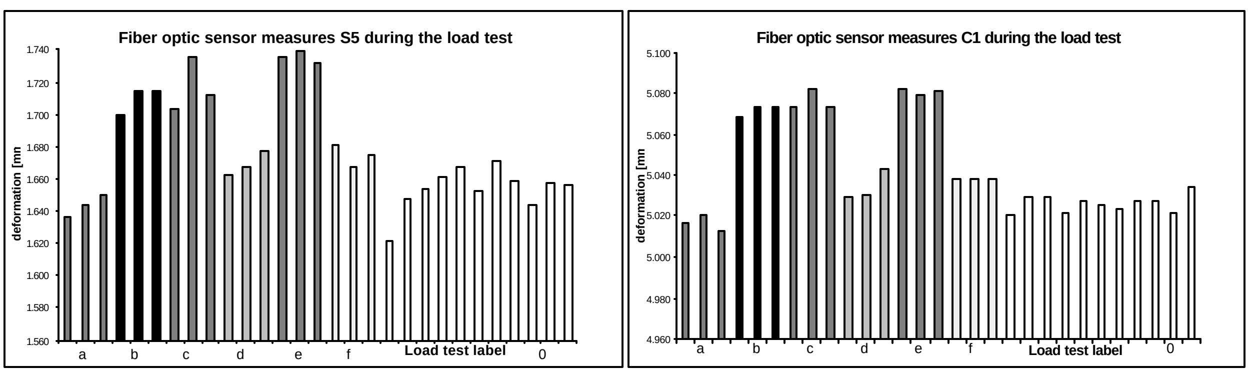

Figure 10 Comparison between a fiber optic sensor without integrated coupler and one with integrated coupler during the load test

The load test, made 4 months after concreting, consisted in placing 25 tons trucks on the bridge. They were placed in accordance with 6 load patterns (a, b, c, d, e, f, o (without trucks)) during 5 minutes each. The load cases were repeated 3 times and separated by a zero load test (load case "o"). During the 5 minutes of loading, the vertical displacements of the bridge were measured at 12 different locations by external dial gauges. The available time allowed to measure only 5 fiber optic sensors on the section 3. The final results, analyzed by IBAP (Laboratory of Pre-stressed concrete), were not available at the time of the writing, so a comparison between the different monitoring method is impossible. Only graphs showing the measured values by two fiber optic sensors in relation with the load case are therefore presented here (see Figure 10). This figure shows a good repeatability for the sensor C1 in comparison with the sensor S5. Sensor C1 includes an integrated coupler and is therefore not disturbed by the connection problems. The error can be evaluated to about 4 μm for C1 and 25 μm for S5. The precision of the sensor S5 is insufficient for a quantitative analysis of the results, while the results of C1 allow and easy differentiation between the different load cases.

5. CONCLUSIONS

The SOFO system, including both a reading unit and a sensor is well adapted for bridge monitoring. A waterproof and battery powered reading unit is necessary to work in the harsh building site conditions. Fiber with polyimide coating appear to be an excellent solution for the deformation sensors, the coating allows the displacement transmission to the core fiber without any creeping and breaking problem. To follow a bridge load test, a precision of 0.004 ‰ is necessary. This can be achieved with the SOFO system, if a coupler is integrated in the sensor. Pre-tensioned deformation sensors (measuring both elongation and shortening) can to be placed very quickly in the framework and do not delay the building yard schedule. A big care has to be given to the connectors. A box protecting them during the concreting and the whole life of the bridge is necessary.
The behaviour of the Venoge steel-concrete composite bridge during the thermal expansion phase can be explained thanks to the results obtained by the fiber optic sensor measurements. Cracks-apparition during the first month after the concreting is found to be the consequence of the interaction between steel and concrete during this phase. This project shows the utility of fiber optic deformation sensors to monitor bridges.
An other bridge, the Versoix bridge near Geneva, will be fitted by IMAC with about hundred low-coherence deformation sensors. The sensors will be placed in order to determine the spatial displacement of two spans from internal horizontal measurements[5]

6. ACKNOWLEDGEMENTS

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For further information on the SOFO project look at the following WWW home page: **http://imacwww.epfl.ch**