Bridge Spatial Displacement Monitoring with Fiber Optic Deformations Sensors

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ABSTRACT

Our laboratory fitted an highway bridge near Geneva (Switzerland) 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 behaviour between the old and the new concrete, low-coherence fiber optic sensors was chosen in order to measure the displacements of the fresh concrete during the setting phase and to monitor its long term deformations. The aim is to retrieve the spatial displacements of the bridge in an earth-bound coordinate system by monitoring its internal deformations. The curvature of the bridge is measured locally at multiple locations along the bridge span by installing sensors at different distances from the neutral axis. By taking the double integral of the curvature and respecting the boundary conditions, it is than possible to retrieve the deformation of the bridge. The choice of the optimal emplacement of the sensors and the mathematical model required to interpreter the results are also presented.

Keywords: Bridge monitoring, Deformation sensor, Fiber Optic Sensor.

1. INTRODUCTION:

The civil engineering community is becoming increasingly interested in the monitoring of the structural behaviour 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 behaviour of aging structures. This last ten years, a considerable number of bridge hint their theoretical “end of life” or are repaired and transformed. In order to better know their condition to know the best solution of the rehabilitation possibility, it is necessary to survey their behaviour. Bridge spatial displacement is actually the best factor given an indication of the condition of a bridge. This factor is a good symptom of disaster (even little) in a bridge. In 1996, our laboratory fitted a highway bridge near Geneva (Switzerland) with low-coherence fiber optic deformation sensors. The engineers, who had studied the enlarging of this concrete bridge were interested, besides the long-term monitoring, by the spatial displacement of the bridge and the effects of concrete shrinkage between the old part and the new part of the bridge. To obtain reliable measurements, special attention was given to the design, the emplacement and the definition of the multiplexing network of the deformation sensors.

Figure 1: The north Versoix bridge during its widening

2. WHY PERMANENT MONITORING IS NECESSARY ?

Bridge spatial displacement is a factor relatively facile to measure for short term condition but difficult for long term monitoring. In fact, it is generally not possible to put mechanical gauges in permanence under a bridge or place a geometer measuring every hours by optical levelling process. Permanent monitoring is necessary to compare the spatial displacement due to non-temperature effect. In fact, effect on bridge are due to 5 causes:

- permanent load (for example the weight)
- static and variable load (traffic load, wind load…)
- thermal effect
- evolution of the material proprieties (shrinkage, creep…)
- disaster in the bridge (crack, support settlement…)

Security and serviceability of bridge is only change by the two last effect so it is necessary to measure them alone. To not take in consideration the first effect, it is just necessary to remove measure to a initial measure considering all the permanent load. The second effect can be cancelled by eliminate all the variable load (by

stop the traffic on the bridge for example). Finally the elimination of thermal effect have to be done by a monitoring of the structure undergone a same temperature field. This last point is difficult to obtain without automatic monitoring of bridge. Measuring bridge at a same moment in the year is not sufficient because daily temperature effect in the bridge is very important compare to other effect. Figure 2 shows us the scale of daily thermal effect on the Lutrive bridge [5].
Solution consist to put automatic deformation and thermal monitoring in a bridge, to monitor and compare spatial displacement between two measures done in the same temperature field.

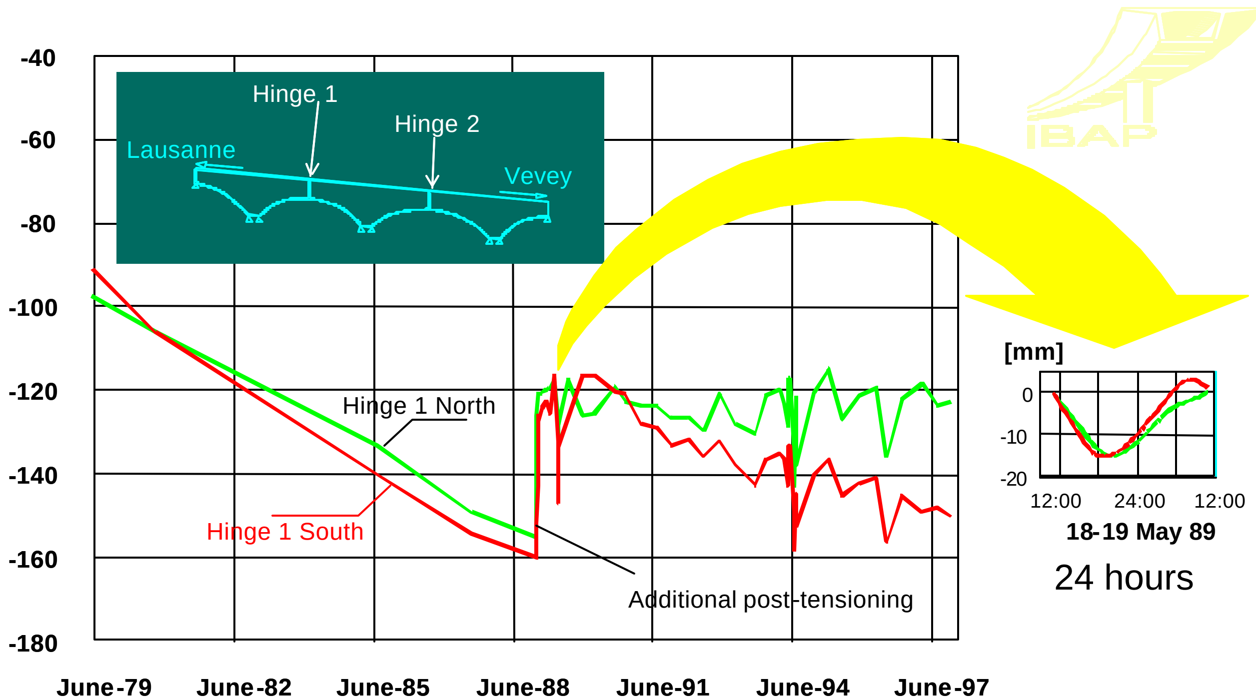


Figure 2: Vertical displacement of the Lutrive Bridge since July 79. The Daily temperature effect in the bridge vertical deflection is showed at right.

3. INTERNAL MEASUREMENT : A DIAGNOSTIC OF THE ALL THE BRIDGE

Direct spatial measurement of the displacement is a good symptom to indicate an bridge abnormal behaviour but do not precise what and where are problems. A solution to obtain these information is to measure internal deformation in the bridge and to calculate bridge spatial displacement from these measures. Appropriate monitoring method have to satisfy at least two points in order to retrieve spatial displacement. First, measure have to be effect on a representative base of measure of the structure to not be too disrupt by local effect. Secondly, the monitoring method have not to be perturb by thermal effect. Low coherence fiber optic concept satisfy generally this two conditions and this is the reason the SOFO monitoring was choose for these type of application.

3.1 Choice of the monitoring method

To measure representative measure of bridge, good accuracy independent thermal effect and an easy employment in civil structure, a monitoring method including both a reading unit and a stand-alone sensor (to be installed in the concrete) is advised. The SOFO (French short for Monitoring of Structures by Optical Fibers) system purpose all this characteristic, it is a long base displacement sensor system designed for long term monitoring. This system is robust, usable in the harsh building site conditions, quick to install and very accurate (about 2 µm). It was already used with success on more than five bridges[1]. It is base on low coherence interferometry and the reading unit measures the difference of length between two fibers, one is called the measurement fiber and follows the displacement of the structure while the other one (the reference fiber) is free (see figure 3). The system is compose by a portable, waterproof and battery powered reading unit and a sensor. The resolution of this monitoring method is about 2 µm (independent of the measurement length) with a linearity of 1% and a dynamic range of 50 mm. The sensor were pre-tensioned at 0,5 % allowing to place it in the structure very rapidly. All these component were furnished by the SMARTEC SA company.

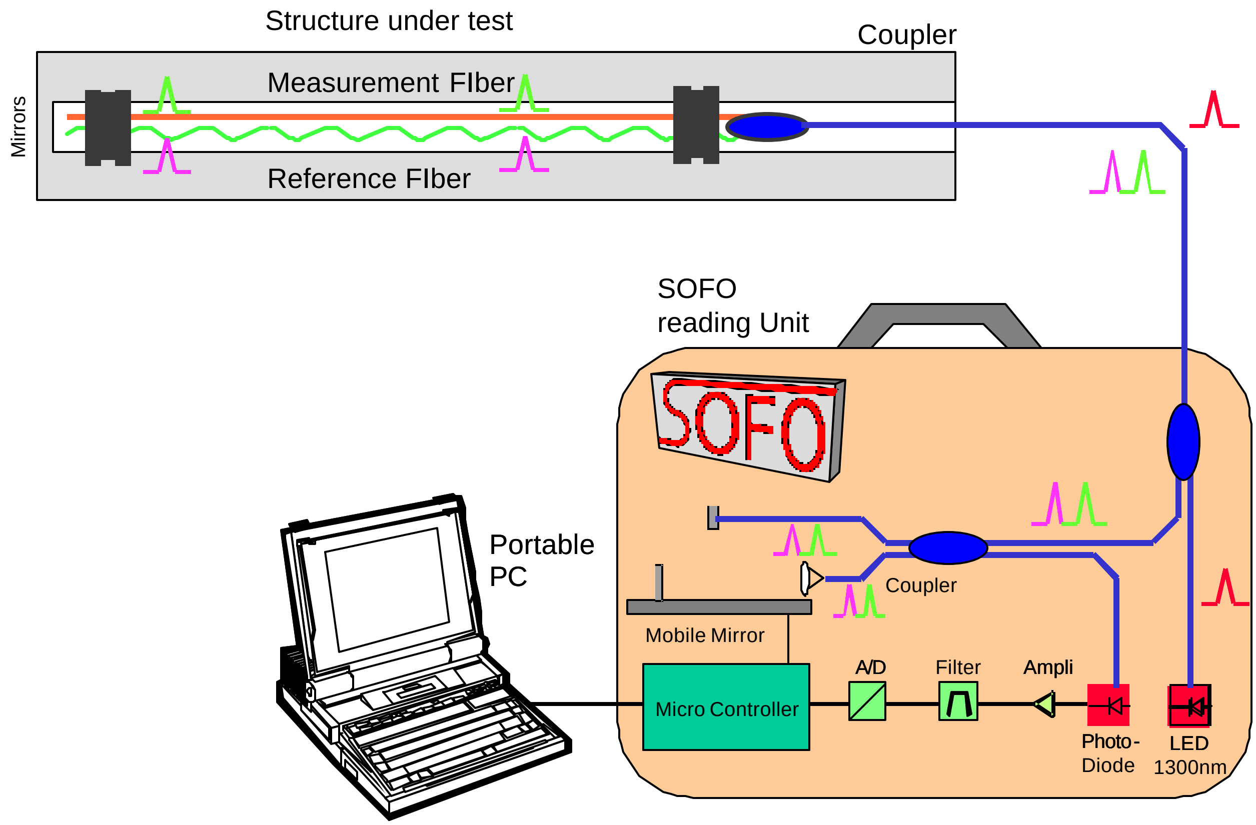


Figure 3: Optical setup of the SOFO system. The portable reading unit is waterproof and battery powered. The Sensor is made up of a reference fiber which is free and a measurement fiber which is attached to the structure.

3.2 From local measure to global behaviour

Bridge automatic measurement require intern sensor measuring local effect in the bridge. Global behaviour (spatial displacement for example) obtained from these measures needs appropriate mathematic algorithm [2]. This one uses the determination of mean curvature obtained placing sensor parallel to the neutral axis [3].
Considering the plane section conservation law of Bernoulli, the vertical displacements of an uniformly loaded beam on n spans is expressed as a sequence of n fourth degrees polynomial with a C_1 continuity at their border. Each polynomial $P_i^4(x)$ domain includes a section of beam which has a constant inertia, a constant uniform load and end forces and moments. The second derivative of the vertical displacement gives n second degree polynomials. To determine the exact displacement functions, it is therefore necessary to retrieve the curvature functions $P_i^2(x)$ on the beam sections and to integrate them twice guaranteeing the C_1 continuity on the boundaries.

In the case of combined bending and axial load and temperature variations, it can be shown that a pair of relative displacement gauges, placed at different distances parallel to the neutral axis are required to measure the mean curvature of a beam element.

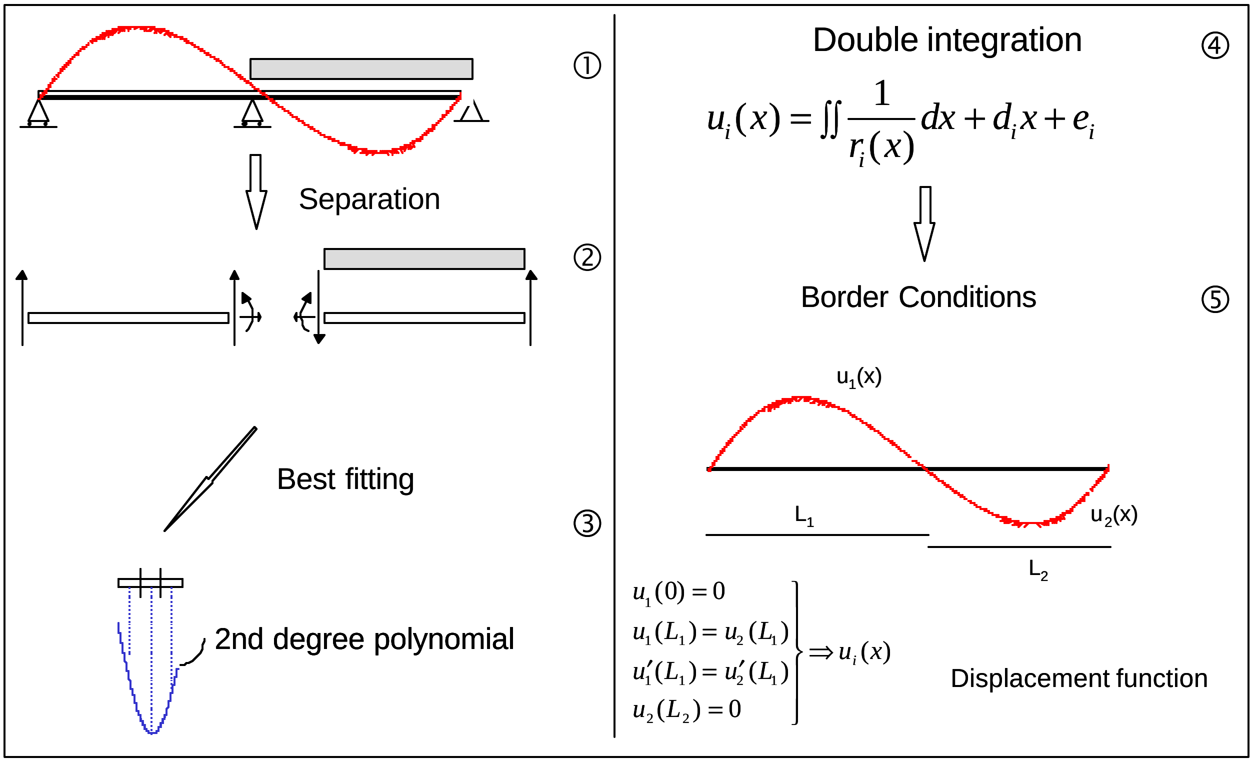


Figure 4: General description of the algorithm. Vertical shape is retrieved by a double integration of the measured curvature function.

4. APPLICATION ON THE VERSOIX BRIDGE: DESIGN AND WIDENING

The North and South Versoix bridge are two parallel twin bridges (see figure 1). Each one supported two lanes of the Swiss national highway A9 between Geneva and Lausanne. The bridges are classical bridges 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 emergence lane, the exterior beams were widened and the overhangs extended (see figure 5). The construction progressed in two phases: the interior and the exterior overhang extension. The first one began by the demolition of the existing overhang followed by the reconstruction of a larger one. The second phase consisted to demolish the old overhang, to widen the exterior web and to rebuild a larger overhang supported by metallic beams. Both phases were built by 14 m stages. The differential shrinkage between the old and the new concrete influences the bridge security. In order to increase the knowledge on the bridge behaviour, the engineer choose to monitor the long term deformation of the north bridge.

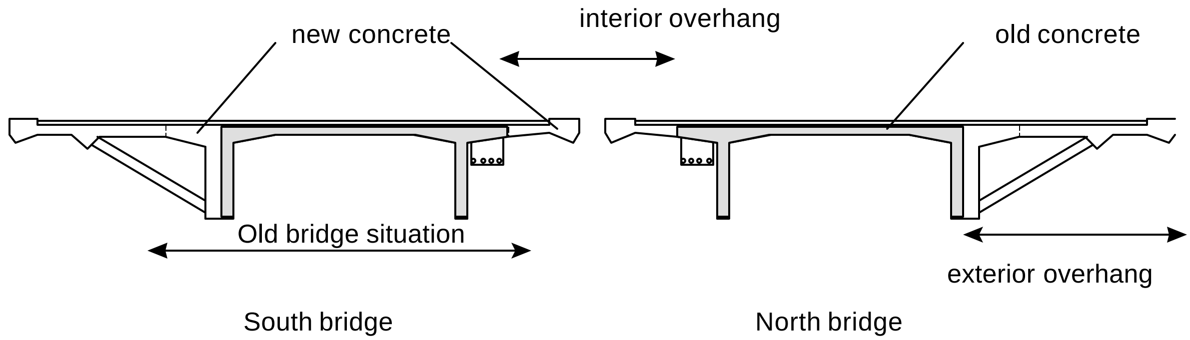


Figure 5: The north and south Versoix bridge: widening principle

5. THE MONITORING SETUP

5.1 Number and emplacement of the sensors

To measure the spatial displacements of the bridge, we apply the algorithm [2,3] briefly exposed in paragraph 3.2. In order to obtain good precision and to follow the building stage of 14 m, 1 section fitted by optical fiber sensors has been placed each 7 m on 2 spans. A preliminary study by finite element showed that the deformations of the two spans could be approached by two 5th degree polynomial functions. Five sensors (Sensor 1, Sensor 2, Sensor 3, Sensor 4, Sensor 6) have been placed inside the new concrete and to give a good representation of the curvature section. One additional sensor (Sensor 8) has been installed on the surface of the old concrete (see figure 6). To obtain a good representation of the mean curvature, sensors with four meter active length have been chosen. Two additional sensors were been installed (Sensor 3 and Sensor 5) to give information about the differential shrinkage between the old and the new concrete. Curvature measurement will be retrieved by 8 sensors for each section and the spatial displacement will be calculated by 5 and 7 sections on the first and the second span (see figure 7).

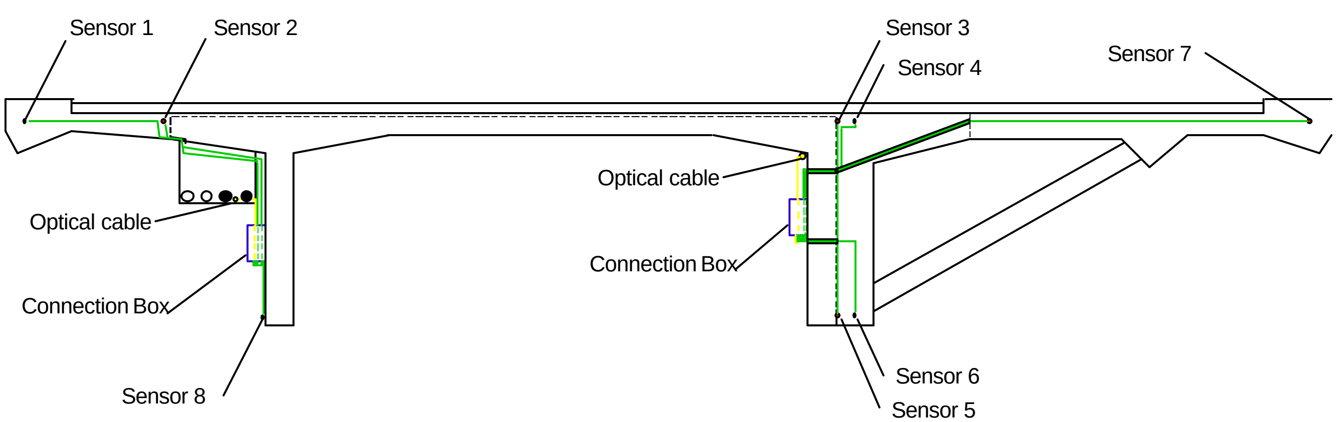


Figure 6: Sensor situation.

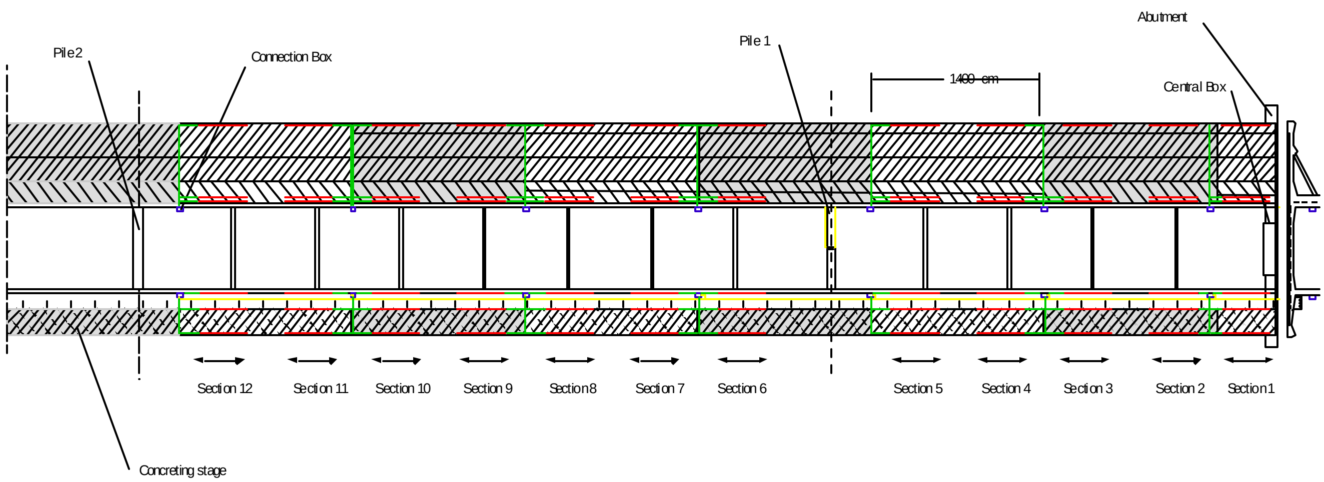


Figure 7: Top view of the Sections situation.

5.2 Sensor network

To facilitate the future implantation of automatic and remote surveillance, the sensor network has to be measured in one single and easily accessible location: the abutment. To rapidly install the sensors in the structure, their size has been optimized and each one reaches a connection box linked by an optical cable to the central box. The network is composed by 104 fibers optics deformations sensors of 4 m active length and 2-10 m passive length, 14 optical cables 10-100 m length, 14 connections boxes (see figure 7) and one central box. The central box will allow to place the reading unit, optical switches, portable PC and mobile phone to measure the bridge through the Internet.

6. RESULTS

6.1 Determination of the spatial displacement during the construction

During all the construction, especially from the 8th april 1997 to 21 may 1997, the 104 sensors was regularly measured in order to obtain information concerning shrinkage of the different concrete and global displacement evolution. The brut presentation of all the sensors (See Figure 8) bring only an information of a normal shrinkage behaviour and thermal effect on the bridge.

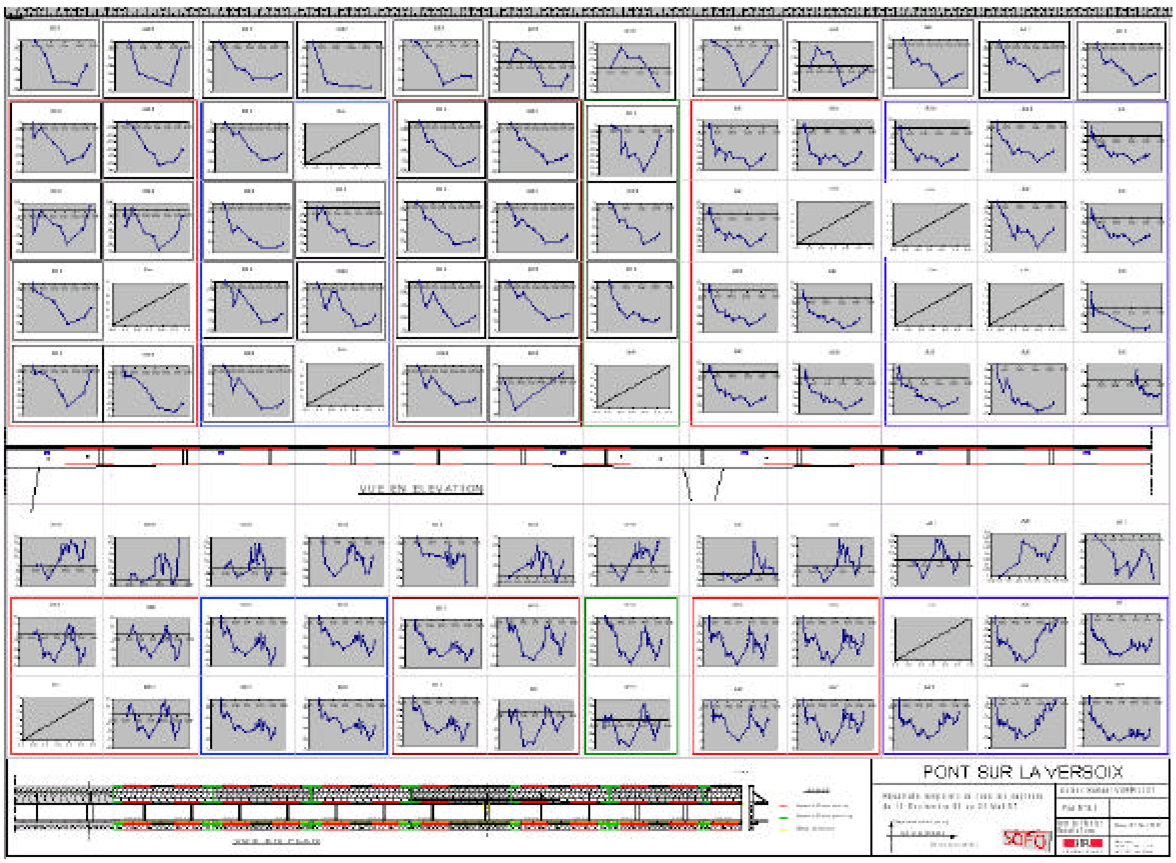


Figure 8 : Brut Measures of all the sensors concerning 9 month of measurement

Spatial global displacement of these two spans was calculated for the period of time between the 8th april 1997 and the 21 May 1997. The 8th of may correspond to the instant where all the fiber optic sensor was installed whether before the concreting of the third span. Result showing the vertical displacement is on the Figure 9.

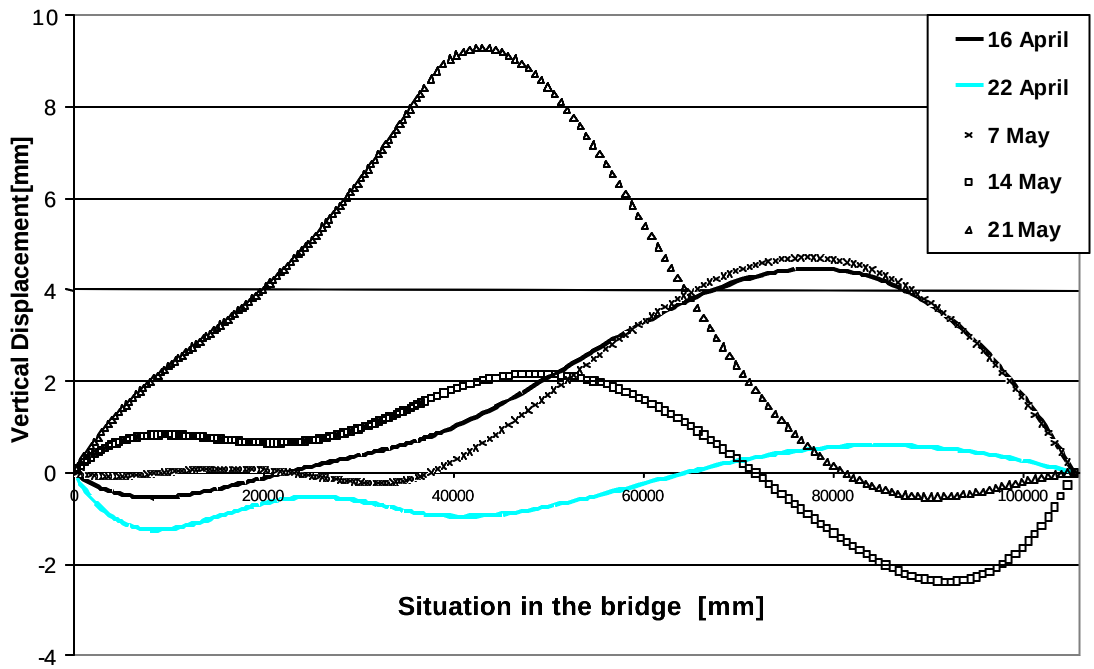


Figure 9 : Evolution of the vertical displacement of the two spans

Results seems not very accurate but coherent. Un rising of 4 mm on the second span is calculated. This effect is normal because at this instant, the third span was just concreted and by its weight rise the second span. Complexity of the load cases (the bridge is in construction, it is cut, loaded, a lot of punctual load are mobile, a thermal load case (bridge is heated during the cure of concrete) is applied on the bridge and fitting of ptop) can explain this accuracy.

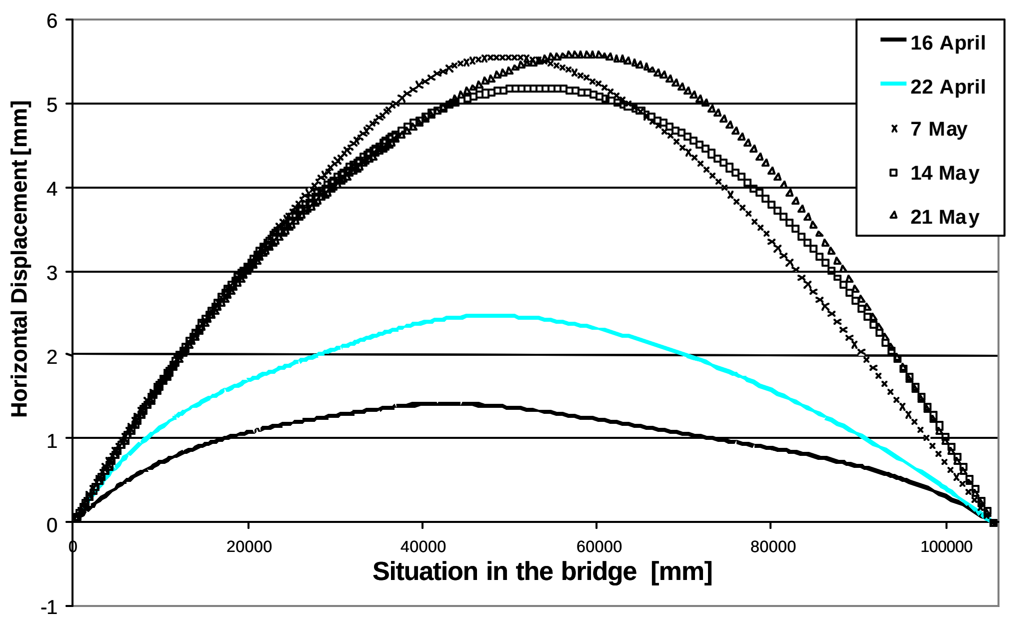


Figure 10 : Horizontal displacement evolution. The free point is at pile 1

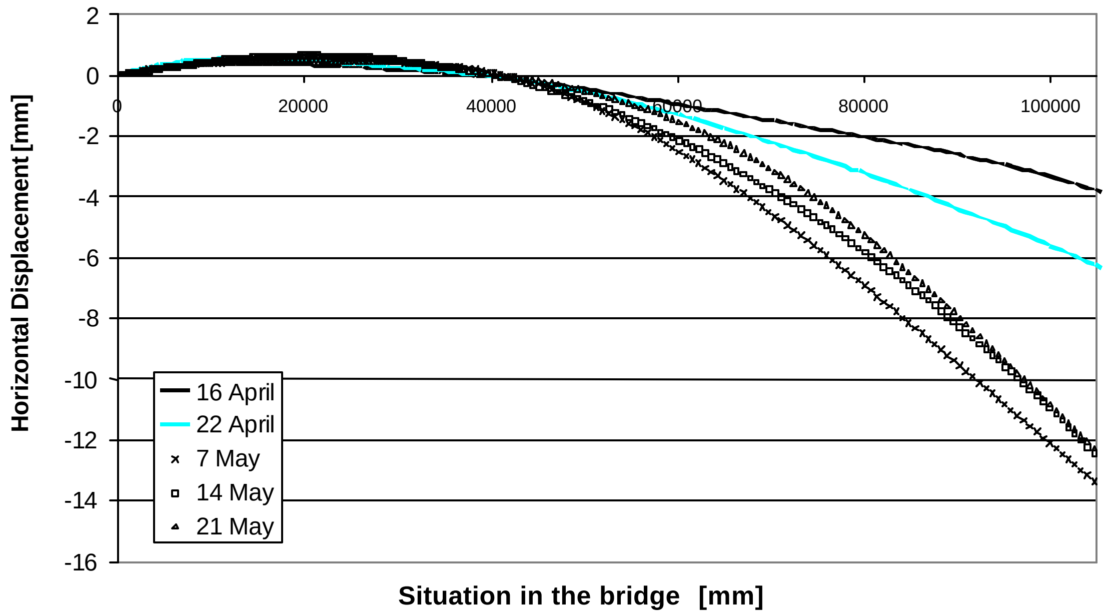
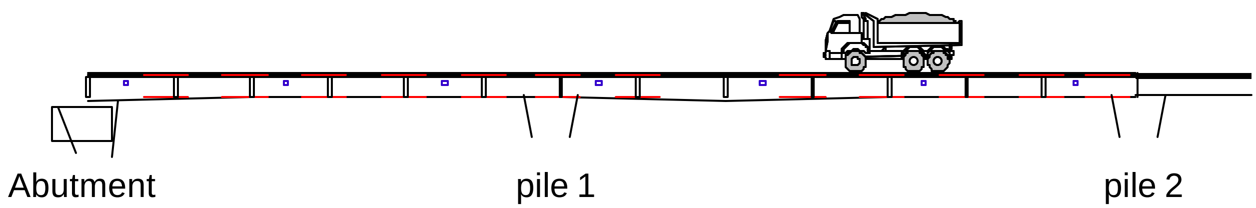


Figure 11 : Horizontal displacement evolution. The free point is at pile2

The two representations (see figure 10 and 11) show the same horizontal displacement. The unique difference concern the limit condition. First is calculated with a null displacement at the abutment and pile 2 whereas the second consider a null displacement at the abutment and the pile 1. This two representations show that the algorithm determine always the displacement relatively at a relative axis composed by two limits conditions (for more ample discussion concerning limit condition of the algorithm, see [4]). The real absolute displacement are surely located between this two cases showing displacement of the pile 1 and 2. Displacements and their evolution are more harmonious that in the precedent case. The bridge is less perturbed in the horizontal plane. The take is a "banana" form to the opposite side of the new concrete because this one wants to contract itself, bended the beam. This global behaviour, retrieved from the locals measures, shows us also a stabilisation of the shrinkage effect in the bridge after one month, confirming the engineer hypothesis.

6.2 Determination of the spatial displacement during the load test of the bridge

The bridge fitted with fiber optic sensor was tested by the IBAP (Laboratory of Pre-stressed concrete at EPFL). This occasion was grasp to compare our algorithm with standard measure executed with mechanical gauges placed under the bridge.



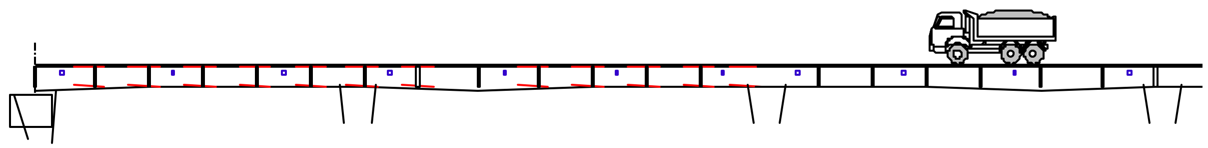


Figure 12 : Load test A and B

These load tests were performed on spans 2 and 3. 6 trucks with 3 axles loaded at 185 kN, which is 74% of the nominal load, were placed in the middle of the span 2 for the load case A and the middle of the span 3 for the load case B. The vertical displacement of the span 1 and 2 were determined with mechanic comparator measuring the absolute displacement from the soil with a precision of 1/10 millimetre. The limits conditions of the algorithm for the load cases are constituted by null displacement at the abutment and the pile 2. The vertical displacement concerning the load test A is represented at figure 14. The incertitude was calculated with:

- a standard deviation for the sensor measurement of 2 µm
- a variance calculated concerning the plane section conservation for the curvature calculation and the polynomial for the curvature function on the beam.

The algorithm gives an excellent concordance with the mechanic comparator placed under the bridge. A null displacement at pile 1 is retrieved. The incertitude concerning the error propagation through the calculation explains the difference between the two systems.

The other load case measured during these tests is showed at the Figure 15. The vertical displacement is retrieved with a good precision. The incertitude of the algorithm is more little than the precedent case (incertitude max of 0,023 mm vs. 0,61 mm). This decreasing is due to the more little value of the vertical displacement for the load case B than in the case A (2,29 mm vs. 7,56 mm). This lower level of load respect better the hypotheses of degree of polynomial function of curvature and the Bernoulli law are confirmed (the torsion effect are really limited with lower load).

7. CONCLUSION

Comparison between calculated displacement compare to those measured by mechanic comparator where the base hypotheses are not respected (especially the load), permit with these load test to give a judgement on the value of the algorithm. Even when the hypotheses are not respected (load cases, variable inertia, 2 concrete of different age and characteristic, rebar and pretensionning in all the direction…), the principle of the double integration brings satisfaction and a good idea concerning the tendency of the displacement. Moreover, curvature measurement allows not only the determination of the overall displacement profile, but also the source and importance of detected problem. Fiber optic sensors based on low-coherence interferometry proved ideal to implement this concept in the case of concrete structures. The presented application shows the power of the method, the great amount of information and the precision that can be obtained.

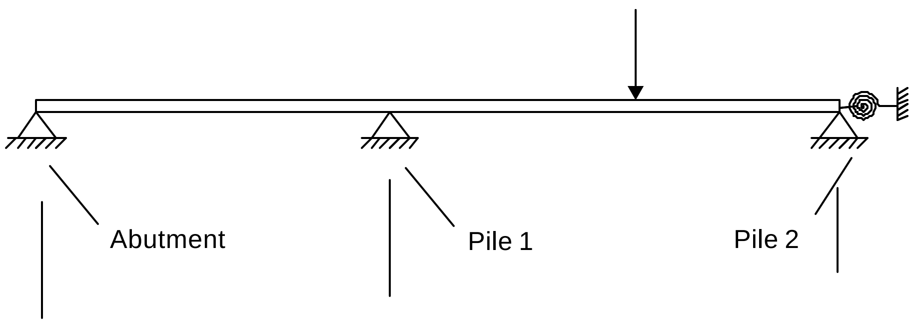


Figure 13 : Static modelisation of the 2 spans analysed on the load case A

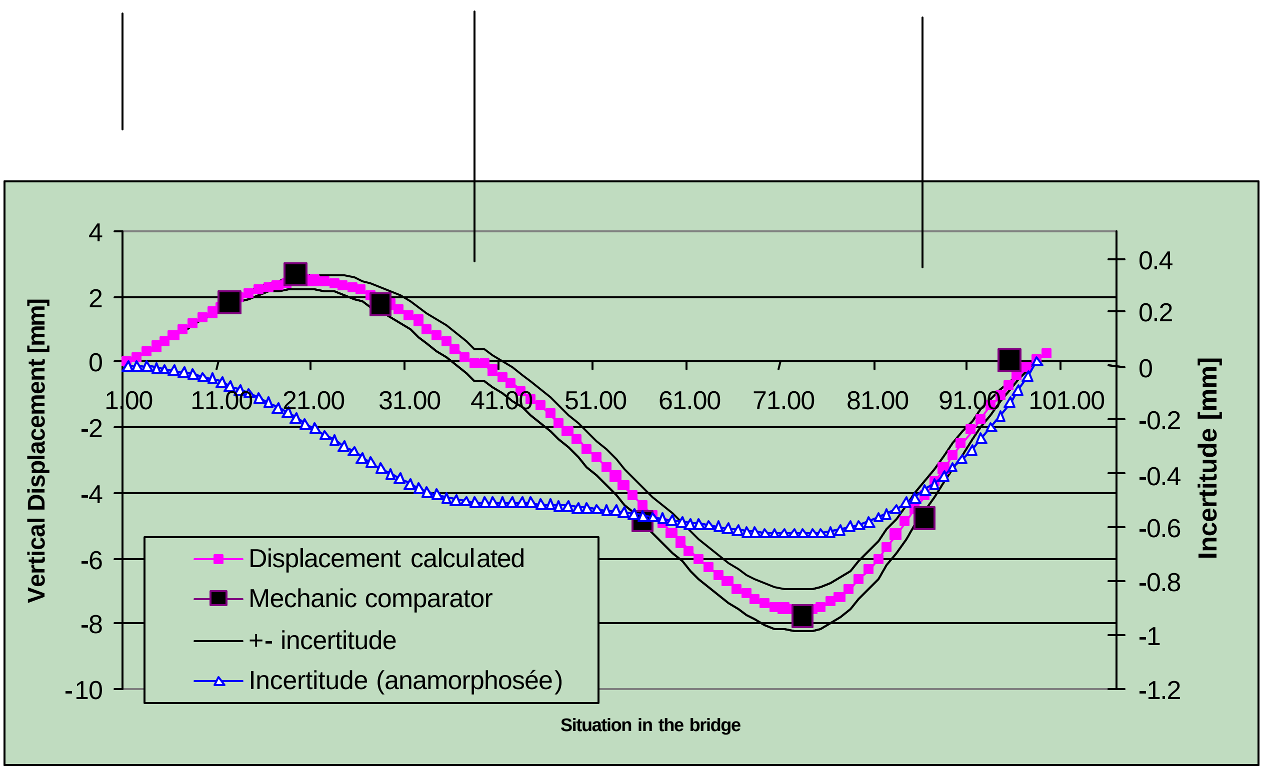


Figure 14 : Comparison of the vertical displacement calculated and the incertitude for the load case A.

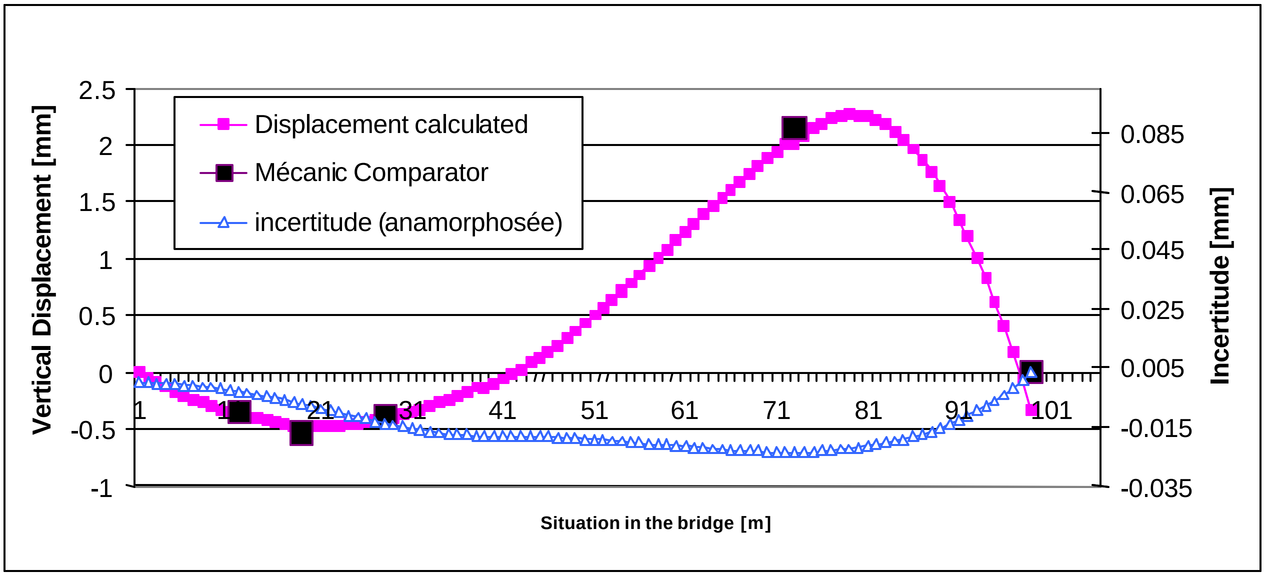


Figure15 : Comparison between the algorithm and the mechanical comparator for the load case B

8. ACKNOWLEDGEMENTS

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9. REFERENCES

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

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Samuel Vurpillot earns a degree in Civil Engineering from the Swiss Federal Institute of Technology in Lausanne (EPFL). He is active as researcher at the Laboratory of Stress Analysis (IMAC-EPFL) where he received, in 1999 his phD degree. He works on the application of fiber optic sensors in the field of civil engineering smart structures, and his area of interest is the automatic analysis of deformation measurements. Since 1999, he works as project manager in the SMARTEC company and teachs static to the Engineer School of Vaud (Lausanne).

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Daniele Inaudi received a degree in physics at the Swiss Federal Institute of Technology in Zurich. His graduation work was centered on the theoretical and experimental study of the polarization state of the emission of external grating diode lasers and was prized with the ETHZ medal. Since 1992 he is active as researcher at the Laboratory of Stress Analysis (IMAC) of the Swiss Federal Institute of Technology in Lausanne where he received, in 1997 his phD degree. He is manager of the SOFO project, a multidisciplinary research program including optics, civil engineering and computer science aiming to the application of fiber optic smart sensing to civil structural monitoring. Daniele Inaudi is co-founder and director of SMARTEC (Grancia, Switzerland), a company active in the domain of fiber optic smart sensing.