Structural health monitoring method for curved concrete bridge box girders

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ABSTRACT

Curved concrete bridge girders have very complex internal forces, stress and strain distribution. As a consequence of their shape, not only the usual bending moments and shear forces are generated, but also important torsion moments are created. These moments "rotate" the axes of principal tensional stresses increasing the risk of cracking. Post-tensioning can prevent the cracks, but the added compression forces introduced in different directions increase the complexity of stress and strain fields. Therefore, the curved post-tensioned concrete girders must be particularly designed and carefully constructed. However, the real structural behavior should be verified, and risks and uncertainties related to structural design and quality of construction minimized. Structural health monitoring is a natural solution for these issues. Structural health monitoring method, based on the use of fiber optic interferometric technology including long-gage sensors and inclinometers, is presented in this paper. A 36 meters long curved post-tensioned bridge box girder is equipped with so-called parallel and so-called crossed sensor topologies, and inclinometers, in order to monitor axial strain, both horizontal and vertical curvature changes, torsion, average shear strain and rotations in both vertical plans. Important parts of structure life such as construction, post-tensioning and first years of service are registered, analyzed and presented.

Keywords: curved concrete bridge, post-tensioned box girder, fiber optic sensors, fiber optic inclinometer, structural health monitoring

1. INTRODUCTION

The Ricciolo ("curl") viaduct is built in period 2004-2005 at the Lugano North exit of Swiss motorway A2. It consists of five spans with total length of 134 meters. The 35-meters long main span crosses Vedeggio torrential river. It is built in form of curved box girder, post-tensioned in various directions. View to completed main span of the Ricciolo viaduct is given in Figure 1 and the cross-section of box girder in Figure 2.

Fig. 1. View to completed main span of Ricciolo viaduct.

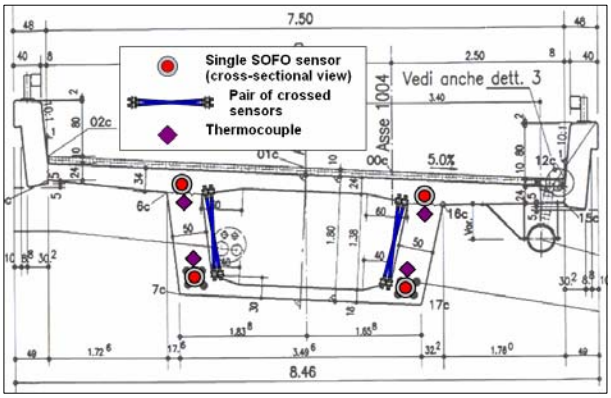

Fig. 2. View to viaduct's cross-section equipped with sensors.

Although the main dead and live loads are vertical, due to curved shape, the girder's cross-sections are subject not only bending moments in vertical plane but also to important torsion moments that changes principal strain and stresses

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directions. Post-tensioning executed in different directions and sections ads to complex strain and stress fields. In order to verify performance and design, to increase safety and enlarge knowledge on real structural behavior of the curved box girder, it was decided to perform long-term monitoring starting with construction.

2. MONITORING STRATEGY

SOFO[1] monitoring system based on low-coherence interferometry[2] in fiber optic sensors is selected for this application. Being proven for more than ten years in domain of structural health monitoring of concrete bridges[3], with long-gage deformation sensors particularly adapted for concrete structures[4] that are easy to embed in concrete or surface mount on structure, complemented with fiber optic inclinometer[5] (tilt meter) and compatible thermocouples, SOFO appeared to be the most suitable choice for this application.

In order to monitor vertical and horizontal curvatures generated by loads and post-tensioning forces, spatial parallel topologies[6] of long-gage sensors were installed in the characteristic cross-sections: at extremities of the span where the maximal negative vertical bending occurs, in the middle of the span where the maximal vertical bending and maximal horizontal bending occur, and in quarter spans in order to "follow" the strain between the most loaded sections. Thermocouples are installed in cross-sections at extremities and in the middle in order to monitor temperature and temperature gradients and make possible estimation of thermally generated strains. The cross-section with spatial parallel topology consisting of four long-gage sensors complemented with thermocouples is presented in Figure 2. The position of equipped cross-sections along the bridge is given in Figure 3.

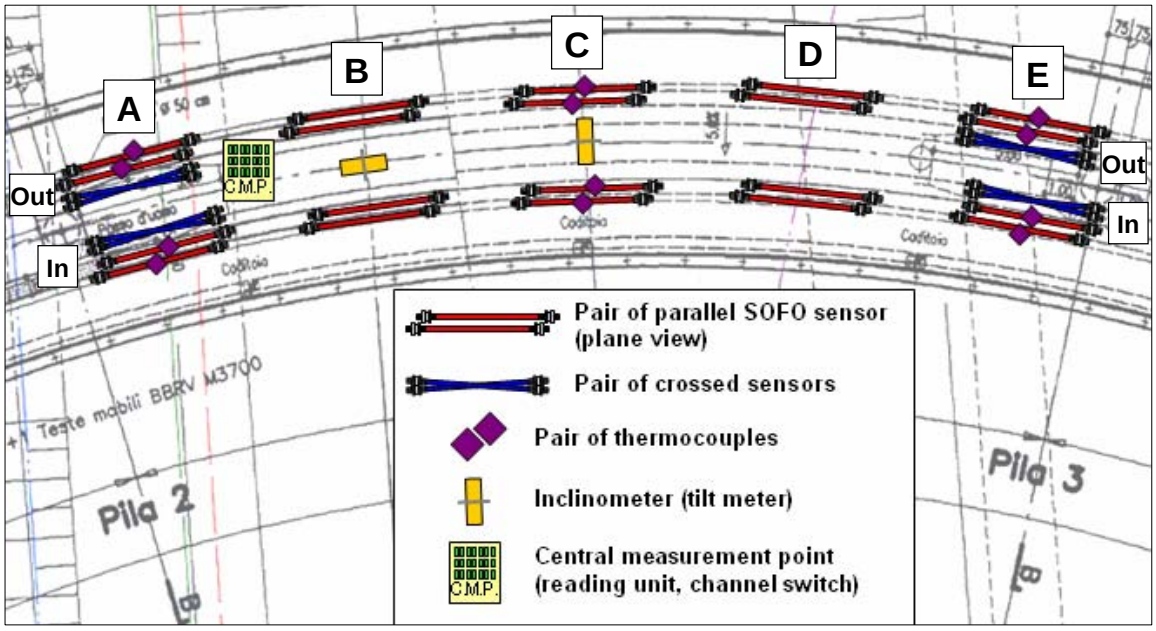

Fig. 3. Schematic representation of sensors' network on Ricciolo viaduct, plane view, sensors not to scale.

In order to evaluate average shear strain generated by vertical forces and torsion, a reduced crossed topologies[6] of sensors were installed at extremities of the span (see Figures 2 and 3). The length of all deformation sensors (parallel and crossed) is 1 m. The angle between crossed sensors is 45°. Finally, single axis inclinometers are installed in quarter span where maximal rotation in longitudinal vertical plane is expected due to vertical deflection, and in the middle of the span where maximal rotation due to torsion is expected in transversal vertical plane. Axis of rotation of each inclinometer is accorded with axis of expected rotation.

Parallel sensors and thermocouples were installed on re-bar cage before pouring of concrete, and embedded in concrete after the pouring. Connectors were protected with embedded boxes that are opened after hardening of concrete and connected with central connection box using extension cables. View to rebar cage with parallel sensors and thermocouples during the installation is given in Figure 4. The sensors' anchoring points are indicted with black arrows, thermocouples are indicated with white arrows and protection box with white circle.

Crossed sensors and inclinometers were surface mounted on hardened concrete. To guarantee vertical orientation of inclinometers, special holders were fabricated and installed. All the cables were guided to the central connection box and protected with ducts. Central measurement point was installed next to central connection box and included portable SOFO reading unit, portable channel switch and modulator for thermocouples (so-called SOFO "Bridge"[1]). Views to crossed sensors and inclinometers after the mounting are given in Figures 5 and 6 respectively, while the view to central connection box and temporarily installed instruments is shown in Figure 7.

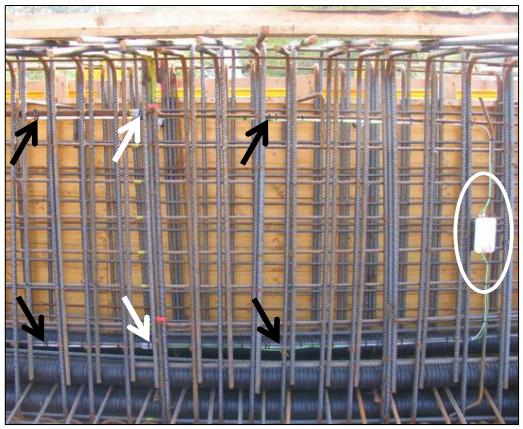

Fig. 4. View to parallel sensors and thermocouples on rebar cage.

Fig. 5. View to surface mounted crossed sensors.

Fig. 6. Inclinometers in quarter- and mid-span.

Fig. 7. View to central connection box and temporarily installed instruments.

3. RESULTS AND ANALYSIS

3.1 One year results

Continuous monitoring started in January 2005, with one measurement session every hour. This schedule was perturbed few times in order to use the instruments in other projects. The average strain measurements registered during more than one year are presented for parallel sensors in Figure 8 and for crossed sensors in Figure 9. Results represent total average strain change including elastic strain, thermal strain and rheologic strain (creep and shrinkage), with respect to reference measurement performed on 11/01/2005 at 17:30. Temperature variations with respect to the same reference are given in Figure 10.

Rotations with respect to reference measurement registered by inclinometers are given in Figure 11. These mesurements includes global rotations of the bridge combined with rotation generated by deformation (elastic, thermal and rheologic).

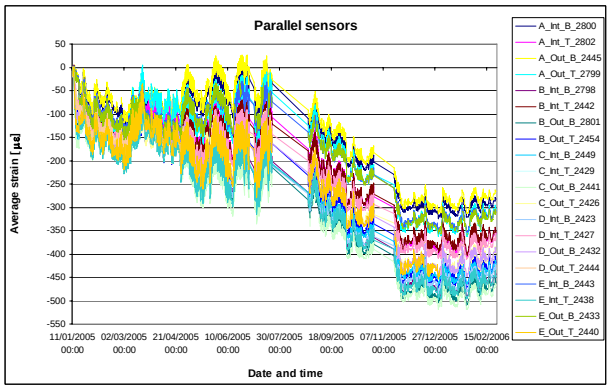

Fig. 8. Average strain measured by parallel sensors.

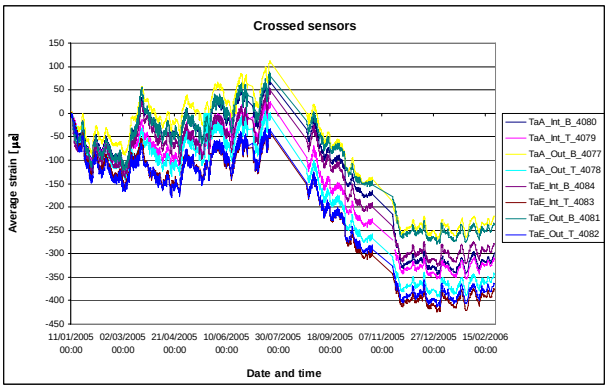

Fig. 9. Average strain measured by crossed sensors.

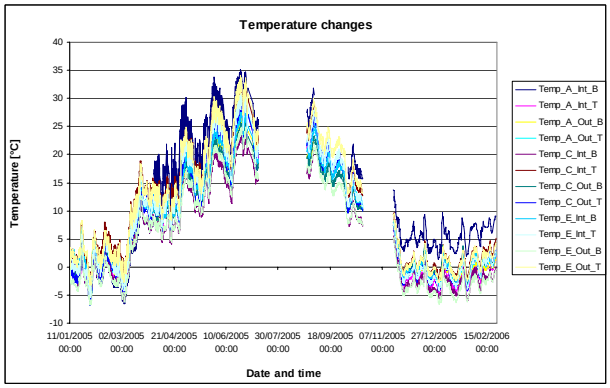

Fig. 10. Temperature changes measured by thermocouples.

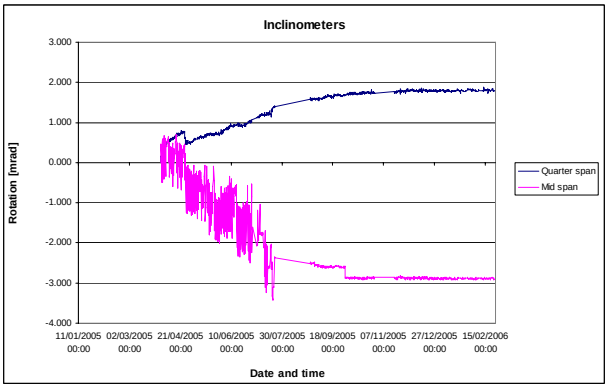

Fig. 11. Rotations measured by inclinometers (tilt meters).

Full presentation of data analysis exceeds the topic of this paper. In order to highlight the power of selected monitoring strategy and employed monitoring system, some examples are extracted and presented in the next subsections.

3.2 Examples of local structural data analysis

In order to simplify the presentation of data analysis, in this subsection only the characteristic cross-sections (cells) were analyzed during the first four months and a half of monitoring. Sections are selected depending on monitored parameter: in case of bending and axial force one section in the middle of the span (C, see Figure 3) and one at extremity (E) are selected. In case of shear forces and torsion both extremities (A and E) were analyzed.

During the first four months and a half, the bridge was still under construction and important works that might influence the stress and strain distribution are given in Table 1. Beside these works, the structure was exposed to the ambient temperature variations and concrete was subject to rheologic strain – creep and shrinkage.

Table 1. Schedule of works.

MAIN SCHEDULE OF WORKS	
Period January 10 – May 26, 2005	
1. Post-tensioning from 30 to 70%	January 12-14
2. Partial lowering formworks	January 17
3. Construction of lateral protection walls	January 17-April 22
4. Post-tensioning from 70 to 100%	April 25-26
5. Cast of left side wing	April 25-27
6. Removal of external formworks	April 25-27

Axial strain and both horizontal and vertical curvatures are calculated for cross-sections (cells) C and E taking into account positions of sensors within the cross-section. Shear strain due to vertical shear forces and torsion moments were calculated for cross-sections (cells) A and E. All the parameters are determined using expressions found in literature[6]. Results are presented in Figures 12-15.

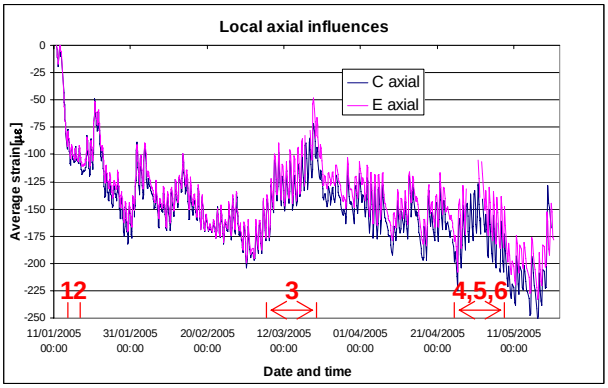

Fig. 12. Axial average strain in cross-sections (cells) C and E.

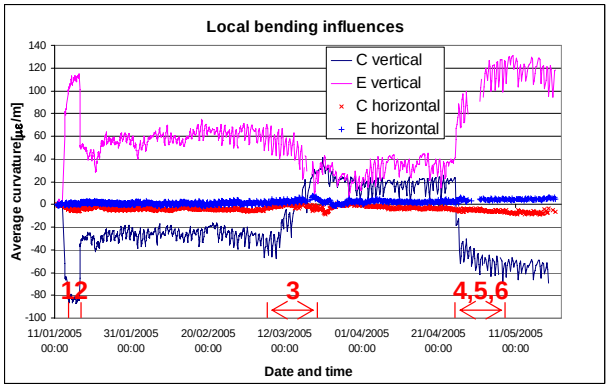

Fig. 13. Average curvatures in cross-sections (cells) C and E.

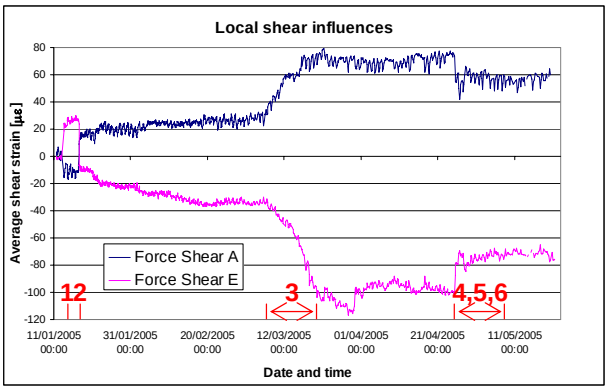

Fig. 14. Average shear strain due to vertical forces in cells A and E.

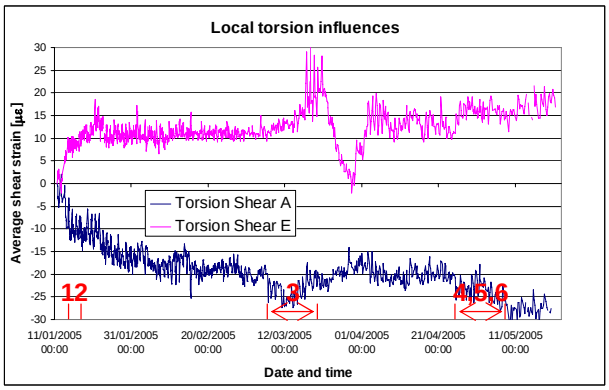

Fig. 15. Average shear strain due to torsion in cells A and E.

The main construction phases presented in Table 1 were detected by the monitoring system. The sensors measured changes that are in accord with expected deformations.

3.3 Example of global structural data analysis

Global bending of the beam was analyzed by observing vertical and horizontal displacement diagrams. These two diagrams were determined from curvatures using double integration algorithm[7], and are presented in Figures 16 and 17. In order to simplify presentation of results only the first 11 days are shown in figures. In addition, the diagrams of vertical and horizontal displacements in the middle of the span, with respect to time, are given in the corresponding figures. Two main works are indicated in diagrams: (1) post-tensioning from 30 to 70% performed on January 12-14, 2005 and (2) partial lowering formworks performed on January 17, 2005.

The global deformations of the girder in vertical plane due to works are observed in diagrams of vertical displacements (Figure 16). The camber (displacement in the middle of the span) due to post-tensioning changed two times, the first to 5 mm approximately and then to 6.5 mm approximately. However, after lowering of formworks the cumber dropped down to 3 mm. The temperature variations in the last third of January 2005 generated camber variations of ± 0.5 mm.

The displacements were rather limited in horizontal plane and neither the post-tensioning nor lowering of formworks generated horizontal bending. This confirms correct execution of post tensioning and formworks lowering. Horizontal bending is only generated by daily temperature variations and ranges between -0.4 mm and +0.1 mm.

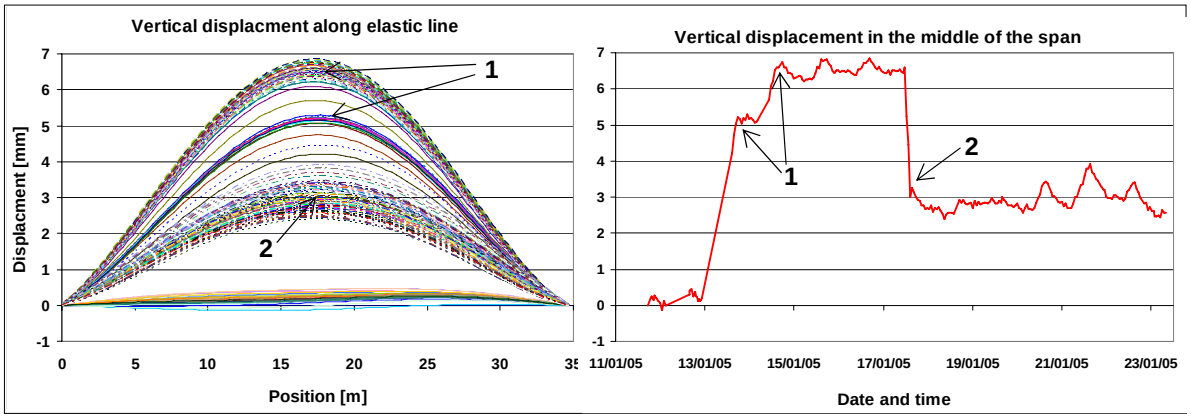

Fig. 16. Distribution of vertical displacements along elastic line (left) and time diagram of vertical displacements in the middle of the span (right).

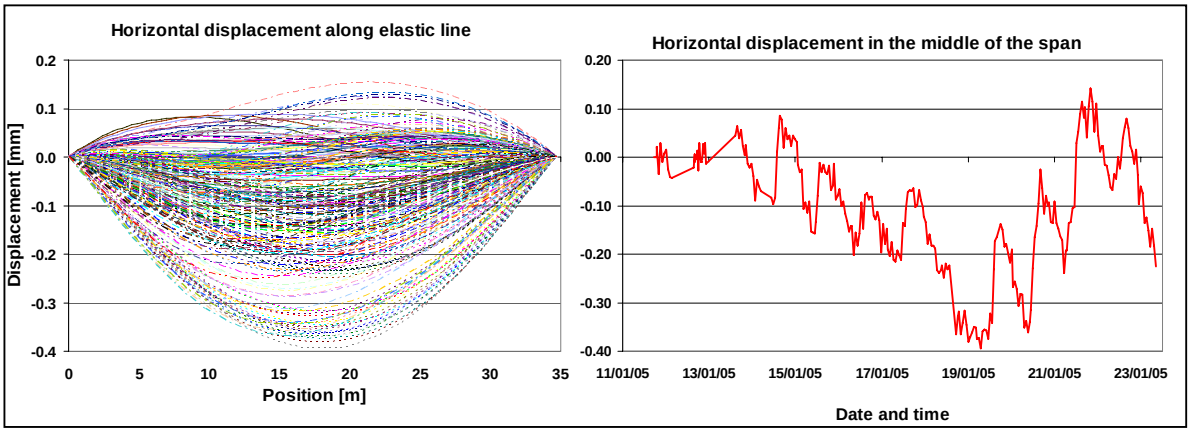

Fig. 17. Distribution of horizontal displacements along elastic line (left) and time diagram of horizontal displacements in the middle of the span (right).

3.4 Example of statistical structural data analysis

The results presented in previous subsections were based on structural analysis approach. In this subsection statistical evaluation of structural behavior based on so-called Moving Principal Components Analysis[8,9,10] (MPCA) is presented.

The MPCA algorithm actually uses a set of data (measurements) collected during the selected period as reference. During the selected period the structure is supposed to be in good health condition. Thus, the algorithm is "learning" data corresponding to sound structural performance.

Once the learning period completed, the algorithm is able to detect unusual behaviors that occur during the structure life, taking into account outliers and missing data periods. The changes in structural behavior due to damage, overloading or unusual loading are detected as a changes in eigenvector values or as a changes in sensors mutual correlation parameters.

In order to make possible the application of MPCA algorithm and to present some examples of results, it was decided to use as a reference the data collected after the works were completed. Since the bridge is good health condition after the completion of works there were no events that could generate unusual behavior. That is why, for the purposes of demonstration, it was decided to invert time scale, so the construction works are placed in "future" and they appears as unusual loadings. The main eigenvectors were calculated and all the works presented in Table 1 were identified as a change in eigenvectors values, as shown in Figure 18.

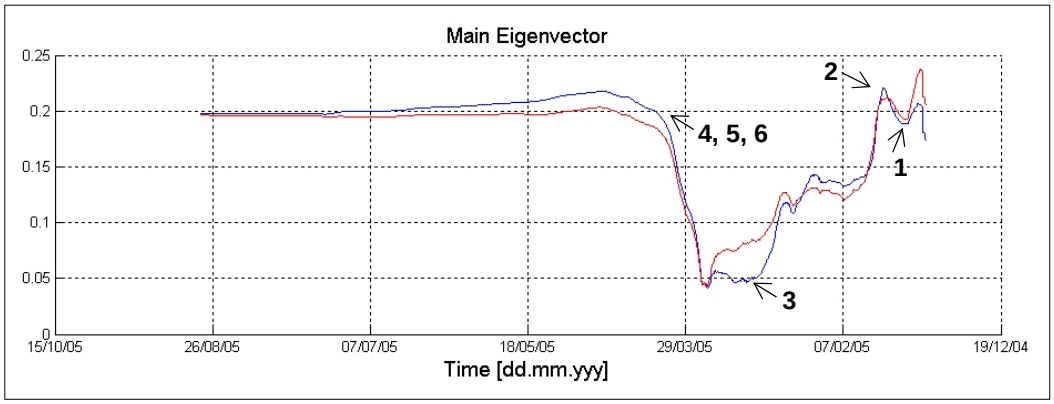

Fig. 18. Detection of construction works as events that create unusual structural behavior (inverted time scale) through the change in eigenvectors values.

In addition, the construction works are identified as generators of unusual structural behaviors since they caused changes of correlation parameter between temperature and deformation sensors (Figure 19) and between different deformation sensors (Figure 20). The construction works change deformed shape or even static system (lowering formworks), thus the regression lines between compared sensors shifts or changes the slope, or the correlation coefficient changes. Examples are shown in Figures 19 and 20. The measurements registered during the works are colored in red (dark color in gray scale, out of the threshold lines) while the measurements registered after the works are colored in blue (light color in gray scale, within the threshold lines).

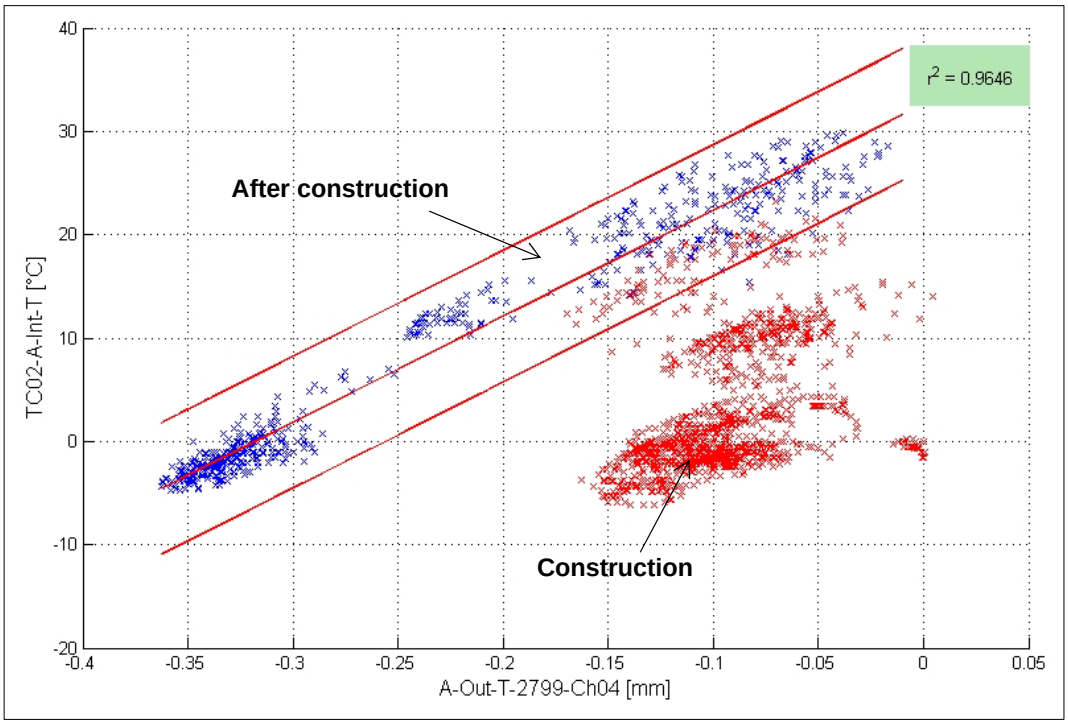

Fig. 19. Detection of construction works as events that create unusual structural behavior through the change in correlation parameters between the temperature and deformation sensors.

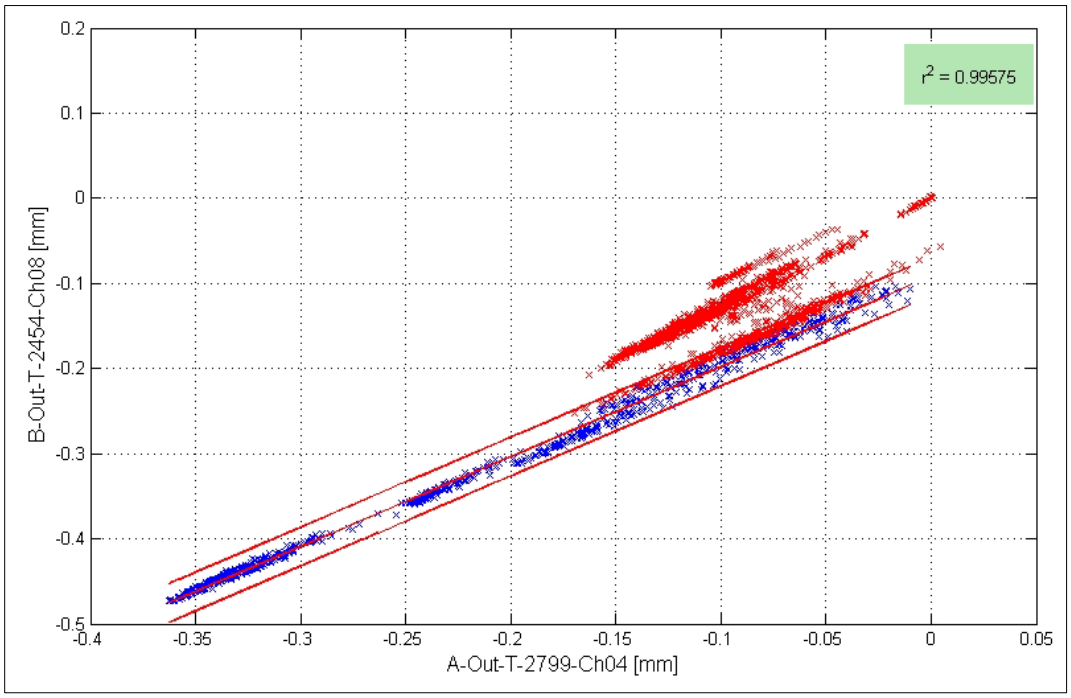

Fig. 20. Detection of construction works as events that create unusual structural behavior through the change in correlation parameters between two deformation sensors.

4. CONCLUSIONS

Monitoring strategy, based on the use of long-gage fiber optic sensor, was developed and applied on curved post-tensioned box girder of Ricciolo Bridge, Manno (Lugano), Switzerland. The bridge was equipped with parallel and crossed topologies of SOFO long-gage sensors at the strategic locations selected in accord with basic principles of structural engineering. The parallel topologies of the sensors were embedded in concrete while the crossed topologies were surface mounted. Fiber optic inclinometers, based on the SOFO technology, and SOFO compatible thermocouples complemented the sensor's network.

The results collected during more than a year are presented in this paper. In order to illustrate assessment of data at local and global structural level the following parameters were determined and presented:

- Time evolution of average strain
- Time evolution of average shear strain due to vertical forces
- Time evolution of average shear strain due to torsion
- Time evolution of average horizontal and vertical curvatures
- Time evolution of rotations
- Time evolution of horizontal and vertical displacement along elastic line
- Time evolution of temperature changes and gradients
- All phases of works were identified and registered directly by measurements

In addition, newly developed MPCA algorithm was successfully applied and proved its performance through identification of deformations generated by works as unusual structural behaviors. The power of this algorithm lays in fact that it is fully model free and it is based on statistical data analysis taking into account missing data periods and outliers.

Monitoring performed in construction phase of the bridge helped verifying correct execution of works, especially post-tensioning of strands and confirmed sound performance of the bridge.

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