# Monitoring system for a cable-stayed bridge using static and dynamic fiber optic sensors

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ABSTRACT: The paper describes the characteristics of a monitoring system installed on a cable-stayed bridge recently constructed in the Port of Venice. The system is based on the use of the SOFO™ fiber optic sensor family and it has been conceived for both static and dynamic monitoring. The monitoring system has been installed during construction, in order to acquire control over the most significant construction phases, and for permanent static monitoring. Linear deformation sensors and their locations have however been selected in order to allow the execution of periodic dynamic measurements and identification of the dynamic characteristics of the structure. The characteristics of the algorithms that have been selected to interpret the monitoring data will also be briefly discussed.

## 1 INTRODUCTION

The Port Authority of Venice, in the framework of the development of the container and multipurpose terminals of the Marghera basin, situated at the inner edge of the Venice Lagoon, have decided the construction of a new road link between the national highway system and the port areas. The road link is crossing the "West Industrial Channel" and the railways serving the terminals, thus requiring the construction of a long-span bridge.

An international competition has been launched for the design of the bridge and related access viaducts. The preferred design was including a cable-stayed bridge formed by a composite steel and reinforced concrete beam, continuous over two spans of 105 m and 126 m in length, respectively. The bridge axis is a circular segment of 175 m radius. The deck on each of the two spans is supported by 9 cables, composed by 31 to 85 strands, attached to a reinforced concrete pylon nearly 80 m high. A realistic rendering of the bridge is reported in Figure 1.

The beams are composed by two I-shaped longitudinal steel girders connected by means of transverse diaphragms to a central box girder, in order to provide torsional stiffness (Figure 2). The concrete deck is made of precast slabs integrated by an in-situ layer.

Beacause of the characteristics of the bridge structure, namely its curvature, leading to a complex behavioral scheme, it has been decided to design and install a permanent monitoring system able to verify the design assumptions and to provide information on the response of the structure during its service life.

For the realization of the monitoring system, the choice has been made to use the SOFO™ fibre optics sensor family (Inaudi 1994), recently extended to cover both static and dynamic responses (Lloret et al. 2003).

Figure 1 – Aerial view of the Bridge (rendering)

The monitoring system has been installed during construction, in order to acquire control over the most significant construction phases. The system has been mainly designed for permanent static monitoring but linear deformation sensors and their locations have however been selected in order to allow the execution of periodic dynamic measurements and identification of the structural characteristics.

Figure 2 – View of the steel deck during transport

The system comprises 48 linear SOFO deformation sensors, 4 SOFO compatible fiber optic inclinometers and 24 temperature sensors placed on the two spans. In addition, each cable is equipped with a specially packaged SOFO sensor while 12 SOFO sensors and 6 thermocouples have been embedded in the structure of the pylon. An anemometer has also been placed on the top of the mast.

All the signals are routed to a control room placed in the basement of the mast, where the permanent static data acquisition hardware is located. When needed, the signal lines may be manually switched to the dynamic data acquisition hardware, temporarily attached. The permanent acquisition system is linked to a standard telephone line for remote operation and control.

This paper is aimed at presenting the main features of the design process for the monitoring system and the physical arrangements utilized for the placement of the sensors on the structures. Processing of the readings obtained during the phases of the construction is presently under way.

## 2 MONITORING SYSTEM DESIGN

The SOFO System is one of the most diffused fibre optic sensory systems for the monitoring of civil structures, and therefore its characteristics will be only briefly summarized here.

The SOFO linear deformation sensors are classified as “long base” deformation sensors as they can be manufactured with base lengths from 20 cm to several meters. The extremes of the base are fixed to the structure surfaces or to the reinforcing bars (before pouring of concrete) by means of mechanical clamps. Between the extremes, an “active fibre” is fixed, optically coupled at one end with a “reference fibre”of equal length, left free inside the plastic protection that also covers the active fibre. By means of an interrogation fibre, the light reaches the other end of the two fibers and is reflected back, thus causing interference if the active fibre is stretched and varies its length. The principles of Michelson interferometry are used to measure the difference in the length of the two fibres caused by the relative movements of the two extremes of the base. The reference fibre also provides self-compensation for the temperature variations.

A high-precision optomechanical device is used in the static reading unit, while a full software processing is used in the dynamic reading unit. A precision of the order of 2 microns and a very high stability is reached, thus rendering the system very suitable for long term static monitoring, eventually integrated by short-term dynamic measurements.

SOFO compatible fiber optic inclinometers have also been developed.

The only drawback of the system, that sometimes induces high installation costs, is that every sensor must be connected to a single interrogation fiber. Nowadays, developments of the SOFO sensor technology integrating Bragg Gratings, allows multiple sensors to be placed on a single interrogation fiber, but this technology has become available only very recently.

The SOFO reading unit is able to connect, by means of an extension called “ADAM bridge”, conventional sensors networked through ADAM modules. By this extension, it is then possible to realize and manage large sensory systems utilizing different sensor technologies.

The first problem to be solved in designing a monitoring system, after individuating the scope of monitoring and the characteristics of the responses to be studied, is the selection of the base length of the linear deformation sensors, their position, type and location of the other sensors.

### 2.1 *Monitoring system for the beam*

The base length of the deformation sensors has been determined in function of the type and size of the structural members, as the local deformation phenomena are averaged over the base. In this case, it has been selected to attach the sensors on the steel girders in couples, one at the top and the other one at the bottom of the web. This disposition allows curvature determination, as explained later. The length of the sensors has been selected to be 1.5 m, i.e. of the same order of magnitude than the height the same order of magnitude than the height of the girder (1.90 m).

To select the sections to be monitored, a finite element model has been prepared in order to study the static and dynamic deformations of the beam. Figure 3 depicts the general features of the model, while Figure 4 represents the first mode of vibration.

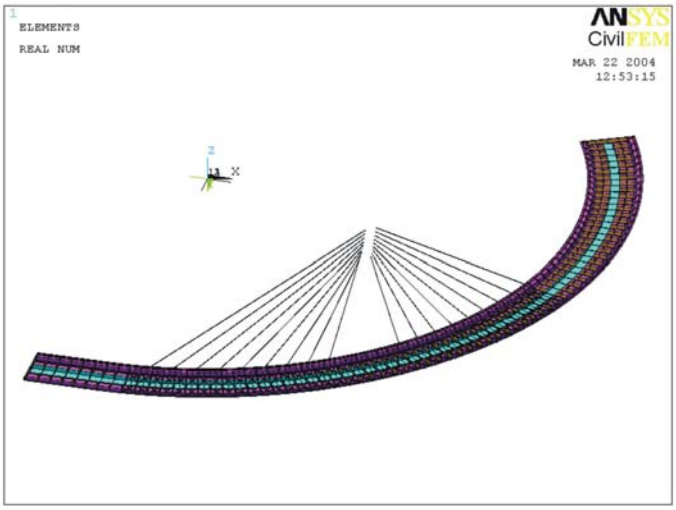

Figure 3 – The ANSYS finite element model

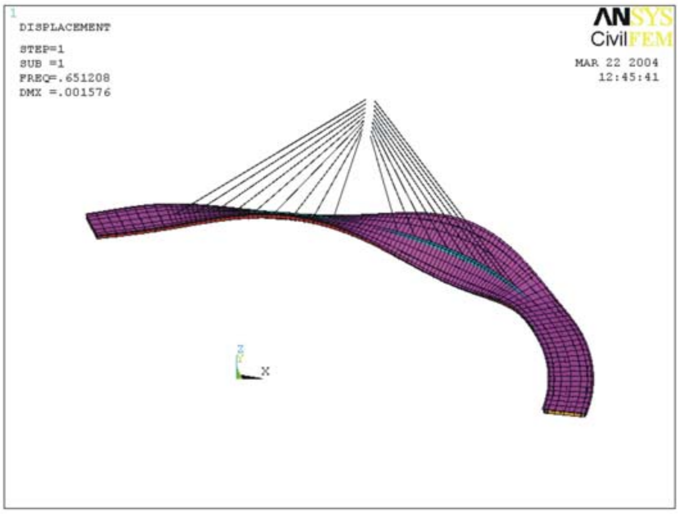

Figure 4 – The first mode of vibration

On the basis of the analyses, consisting in the application of various load configurations to the model, including temperature variations, it has been recognized that instrumenting four sections for each of the two spans would be sufficient in order to reconstruct the main static and dynamic deformation modes.

In each section, three webs (two of the lateral girders and the outer web of the central box) have been indicated for the placement of the sensor couples. In addition, two fibre optics inclinometers have been installed at the ends of the cable-supported spans, measuring the rotations in the longitudinal plane.

To measure the temperature fields, standard technology thermocouples have been placed at the sensor locations at the two intermediate sections of each span.

The conventional and fibre optics cabling has been optimized by creating a network of junction boxes connected by multifibre cables.

The system defined on the beam permits the definition of the global strain characteristics over four “cells” on each of the two spans.

## 2.2 *Monitoring system for the pylon*

The monitoring system for the pylon has different characteristics than the one describe above. The pylon is a reinforced concrete structure, partially prestressed, inclined on the vertical with the same angle as the resultant of the forces in the cables. By this way, the pylon is mainly compressed, being subjected to flexure only by wind and temperature effects and by the self-weight, this latter compensated by the post-tensioning of the prestressing cables.

The section of the pylon is a cave triangle and the cross sectional sizes are decreasing towards the top (Figure 5).

In order to study the strain characteristics of the structure, four monitoring sections have been selected over the height, starting from a few metres over the bridge deck. In each section, three SOFO linear deformation sensors, each having a base length of 7.5 m, where attached to the reinforcing bars at the corners of the triangle.

Figure 5 – View of the pylon during construction

At the top of the pylon, two fiber optics inclinometers, measuring the rotations in two orthogonal planes, and an anemometer have been installed.

On each of the three faces of the pylon in correspondence of the top two monitored sections, conventional thermocouples have also been installed.

### 2.3 *Monitoring system for the cables*

Monitoring of the phenomena that may affect integrity and efficiency of the cables is one of the major problems in the management of suspension and cable-stayed bridges.

Detection of slackened or broken strands in cables has been the subject of many researches in Structural Health Monitoring of bridges, but no simple procedures are available as of today. One of the methods that have been proven effective in detecting the presence and location of damaged strands in cables is an extension to large-diameter cables of the MFL (Magnetic Flux Leakage) Method (Bergamini 2001).

According to this method, the test consists in creating a traveling saturated magnetic field in the strands by moving a coil along the cable. The presence of a defect in a strand creates a discontinuity in the magnetic permeability of the cable that can be detected by measuring the intensity in the magnetic field. Processing of the measuring data provides the means for detecting and locating the damaged strand.

This method, however, is suitable to be used for periodic inspection but it is not suitable for a permanent installation.

In the case at hand, it has been decided to install on one of the strands of each cable, a SOFO linear deformation sensor of a base length of 25 cm. The scope of these sensors is to monitor the strain variation of each cable and eventually detect anomalies that may indicate malfunctioning of the cables. A full MFL inspection may be decided, based on the responses of the static monitoring.

Dynamic monitoring of the strain in the strands for some limited periods is also programmed. In conjunction with such periods, the possibility of temporarily installing conventional accelerometers is also under study.

## 3 SENSOR INSTALLATION

The installation of the monitoring system on the bridge has been recently completed.

Figure 6 shows the installation of a SOFO sensor in the pylon. This operation revealed some difficulties because the length of the sensors was greater than the length of the pouring courses. Density of re-bars also complicated the installation. One of the sensors went accidentally damaged.

Figure 6 – Positioning of a SOFO sensor inside the pylon

Installation of the sensors on the steel girders took place after the complete mounting of the steel part of the deck and in parallel with the spinning of the stay cables. A typical installation set up of the sensors on a lateral girder is shown in Figure 7.

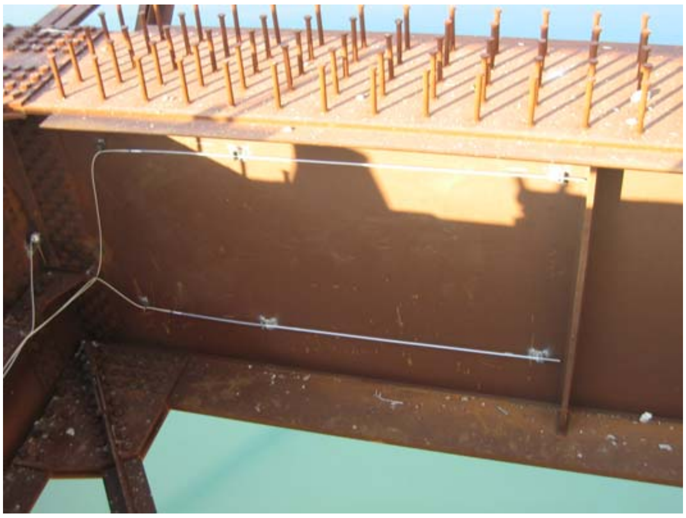

Figure 7 – SOFO sensors and thermocouples installed on the girder web

For clamping the sensors on the surface, steel reference plates have been previously welded on the girder web. Hooks were also welded on the surface in order to facilitate routing and fixing of cables.

After spinning and tensioning of the stay cables was performed, the sensors were installed on one strand per cable. This operation required a complex procedure because of the need of cutting and restoring the protection coatings. Figure 8 and Figure 9 show the arrangement of the sensor on the cables; in the figures, the interaction of the sensors with the protective covers is clearly visible.

Figure 8 – Attachment of a SOFO sensor on the stay cable

Figure 9 – Attachment detail

After sensor installation, final tensioning and injection of the cables have been performed.

The total cost of the monitoring system, including installation, has been of the order of 1.75 % of the construction cost of the bridge.

## 4 DATA PROCESSING SYSTEMS

Data storage for static continuous monitoring is performed in the SOFO reading unit by means of the SOFODB data base. A connection with a private telephone line makes the data available for processing at a remote station, where the data base software and data interpretation modules are installed.

Various levels of processing have been designed by means of both existing SOFO data processing software modules and special purpose procedures. Software personalization and development are presently under way.

In the following, a brief description of the various processes that are being used is given. It should be pointed out that, before interpretation, the measurements will be checked against incompleteness of the time-series. Time-series containing missing data will be integrated by means of the procedure described by Lanata (Lanata 2004).

### 4.1 *Curvature analysis*

The first level of data processing consists in calculating the curvatures of the various “cells” (beam sections) were the sensors have been installed and in the reconstruction of the deformed shape of the beams at each time the measurement campaigns are performed.

To perform this task, the SOFO data processing module named SPADS (Inaudi et al. 1997) will be used. The algorithm implemented in this module performs the calculation of the curvatures in each section from the linear deformation sensors at the top and bottom of the girder webs. Subsequently, a statistical best-fitting is performed, in order to derive the curvature distribution over a “macro-element” of the structure, containing more cells. Finally, the curvature law for all the macro-elements in which the structure has been subdivided is double-integrated with the appropriate boundary conditions to find the displacement distribution over the entire structure.

In this case, the geometry of the bridge implies torsional deformation as well as flexural and, consequently, the reconstruction of the deformed shape requires the generalization of the algorithm to cope with spatial states of displacements.

The procedure will be applied with some modifications to reconstruct the deformed shape of the pylon.

### 4.2 *Correlation analysis*

After reconstruction of the deformation modes of the beams and of the pylon, a correlation analysis must be performed between the two, with the data coming from the sensors attached to the stay cables and with temperature data.

In the analysis, both data fitting and interpolation tools, as permitted by the SOFO PRO standard data management module and model-based interpretation will be used. In this process, the finite element model generated for the design of the monitoring system will be used, after having been updated during static and dynamic proof-load tests.

The analysis of the data acquired during construction is also being correlated with the data of the placement and concreting of the slabs and with the data on the tensioning of the stay cables.

During in-service monitoring, correlation will be performed only with ambient conditions (temperature and wind), while traffic loadings will be treated as disturbances and filtered out by a preprocessing of the raw measurements.

However, the installation of weight-in-motion sensors is being considered for a future extension of the monitoring system.

### 4.3 *Structural Integrity Assessment*

The use of higher-level algorithms for structural integrity assessment using static long-term monitoring data is presently under study.

Based on the results of the processing of the data obtained during construction and from the proof-load testing the response of the structure will be characterized.

The best suited classes of algorithms as described in a different paper presented in this Conference (Del Grosso and Lanata 2005) will be implemented to provide detection of behavioral anomalies and localization of possible structural malfunctions.

Model-based integrity assessment procedures will also be used.

### 4.4 *Dynamic Measurements*

During proof-load testing of the bridge, the most significant sensors will be temporarily attached to a dynamic SOFO reading unit in order to acquire data on the vibrational characteristics of the structure. It is emphasized that the dynamic response will be recorded in terms of time-histories of strains.

These data will be processed by means of commercially available dynamic system identification software and the finite element model of the bridge will be updated accordingly.

Periodically, dynamic measurements will be repeated to detect variations in the dynamic characteristics of the structure.

Short-term dynamic monitoring will also be performed.

## 5 CONCLUSIONS

The monitoring system installed on the West Industrial Channel Bridge in the Port of Venice has been described.

The system has been based on the use of the SOFO fiber optic sensory system for both long-term static and short-term dynamic monitoring.

Only the static SOFO reading unit is permanently attached to the system, while the dynamic reading unit can be temporarily attached.

The sensors have been attached to the steel girders of the deck, to the re-bars of the concrete pylon and to one strand in each of the stay cables. Compatible fiber optic inclinometers have also been used, together with conventional thermocouples. An anemometer has been installed on the top of the pylon.

The characteristics of the data processing and interpretation software have also been described.

Smartec SA, Switzerland, provided the system and Tecniter s.r.l, Italy, performed sensor installation and system start-up. D’Appolonia S.p.A., Italy, is acting as construction supervisor and is responsible for the design of the monitoring system, including software personalization for data analysis and interpretation. The Department of Structural and Geotechnical Engineering of the University of Genoa, Italy, is consulting on the scientific aspect of Structural Health Monitoring procedures.

The system has been recently put into operation and the analysis of the data recorded during the final phases of construction is presently under way. Proof-load testing on the bridge is scheduled in the very next future.

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