Monitoring with Fiber Optic Sensors of a Cable-Stayed Bridge in the Port of Venice

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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 long-term and periodic 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 structural characteristics. The first analyses of the data collected during the final stages of the construction and just after construction completion are presented. The characteristics of the algorithms that have been selected to interpret the monitoring data are also 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.

Because 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 et al. 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.

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 monitoring system, the processing of the readings obtained during the phases of the construction and the finite-element model carried out in order to compare the data with the theoretical behaviour of the structure.

2 MONITORING SYSTEM DESCRIPTION

The SOFO System is one of the most diffused fiber 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 fiber” is fixed, optically coupled at one end with a "reference fiber" of equal length, left free inside the plastic protection that also covers the active fiber. By means of an interrogation fiber, the light reaches the other end of the two sensing fibers and is reflected back, thus causing interference if the active fiber is stretched and varies its length. The principles of Michelson interferometry are used to measure the difference in the length between the two fibers caused by the relative movements of the two extremes of the base. The reference fiber 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.

The detailed description of monitoring system has been already the subject of a companion paper (Del Grosso & al. 2005). In this paragraph, the description will just be briefly summarized.

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 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. 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 fiber 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 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 described 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.

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

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 stays*

The stays, 9 for each span, are constituted by galvanized strands variable in number from 31 to 85, in function of their design load. They are connected to the axis of the deck and to the pylon by means of anchorage systems, where the prestressing force, variable from stay to stay, is to be applied.

In order to measure the deformations in the stay cables, every one of the 18 stays has been instrumented with a SOFO deformation sensor 250 mm in length, connected to one of their strands.

3 STATIC DATA ANALYSIS ALGORITHMS

The main principle of this method consists in subdividing the structure into a number of macro-elements that undergo relatively simple deformations (Inaudi & Vurpillot 1999). These sections are further segmented into cells containing only a few sensors or even a single one.

The first step requires the structure to be subdivided into sections. Each section is supposed to have a constant or continuously varying inertia, a constant load across its length and introduction of local forces and supports only at its ends. If the behavior of the materials in a section can be considered as homogeneous, the polynomial degree that best approximate its deformation is determined either analytically or using finite-element programs. If a degree N+2 is found to approximate satisfactory the deformation of the section, this will be subdivided into N cells.

For a beam with constant inertia the deformation is a polynomial of fifth degree and three cells are therefore necessary. For sections with variable inertia, it is sometimes useful to use cells with variable size. If local variations of the material behavior are expected, more cells are needed. In this case the number N and the size of the cells will be determined in such a way that the material properties inside each single cell can be considered reasonably constant. The deformation of the section will in this case be approximated by a polynomial of at most degree N+2.

3.1 *Cell analysis*

The sensor inside a single cell will be used to determine the local behavior of the materials and the global behavior of the cell itself. The sensors will generally be positioned parallel to the beam axis at different heights. The base-length of the sensors can be shorter that the cell length, but the best precision is usually obtained with sensors having the same length of the cells.

The most relevant parameter that can be analyzed is the mean curvature. The radius of curvature of the cells gives an indication of its bending. To obtain this value it is necessary to install one or more sensors at different distance from the neutral axis. Considering the Bernoulli's law on an element dx of the beam, for the simple flexion, the equation of curvature is expressed as:

$$1/r(x) = -\varepsilon(x)/y \tag{1}$$

Where: r is the curvature radius, x the curvilinear abscissa, ε the strain in the x direction and y the distance from the neutral axis.

A displacement gauge, installed parallel to the neutral axis, measures the deformation over a gage length L. In the case of composed flexion and temperature variations a pair of displacement gauges, placed at different distances to the neutral axis, is necessary to measure the mean curvature of a cell. In this case the mean curvature will be given by the integration of Equation (1):

$$1/r_m = (\Delta L_1 - \Delta L_2)/[(y_1 - y_2)\, L] \qquad (2)$$

Where: r_m is the mean curvature radius and ΔL_1 e ΔL_2 are the deformations measured by the two sensors, L their length and $y_{1,2}$ their vertical position inside the cell, all relative to a common arbitrary origin. This calculation can be generalized for two-dimensional cases using matrix calculus.

3.2 *Section analysis*

After analyzing each cell separately one obtains an estimation of the curvature as a function of the curvilinear abscissa along the beam length. From the local curvatures it is possible to obtain the section's curvature function by fitting the cell's curvature values to a polynomial of appropriate degree. For a polynomial with N unknowns, only N cells are necessary to be retrieved for a single beam section. If the number of cells exceeds the polynomial degree chosen for the curvature function, the system should be solved by the least squares method.

3.3 *Structure analysis*

By combining the curvature function of each section one can now calculate the curvature of the whole structure and obtain its deformed shape by double integration. Having the curvature functions of adjacent sections, one retrieves the displacement functions by integrating them. Furthermore, the continuity of the displacement function and its derivate has to be guaranteed by imposing the same displacement and rotation at the adjacent borders of the adjacent sections.

4 STATIC MONITORING DURING THE CONSTRUCTION PHASES

The monitoring system has stored the deformation data during the second phase of tensioning of the cables. The first tensioning of the stays has been carried out during their installation by load steps and continuous tension adjustments, until the project configuration was reached.

The second phase has been carried out for braces of stays, following a procedure that involve pouring of the slab into portions of 10.50 m length, symmetrically with respect to the pylon and subsequently increasing the tension of the two stays interested by the poured slab portion.

4.1 *Data processing*

The possibility of obtaining the curvature from the measurement of the axial deformation of the sensors in more points of the section is valid if one admits that the section shows a smooth pattern of deformations: in the reality this hypothesis cannot be accepted in presence of high concentrated loads, like those of the stays.

For this reason, a pre-processing of the deformation data in every section has been carried out: such analysis has shown that, especially in the sections near the stays, the sensors installed in the central beam were measuring anomalous deformations with respect to the sensors installed on the lateral beams. This observation has induced to discard, in the first data processing stage, the data of the central sensors, retaining only the data relative to the lateral sensors; in a subsequent phase, once the final configuration has been determined, the data of the sensors discarded could be used again.

4.1.1 *Data processing for the beam*

The beam has been subdivided in two macro-elements, corresponding to the two main spans, everyone composed by 4 cells. Once the mean curvatures in every section has been obtained, these values have been interpolated by means of a polynomial of degree n-1 (n = number of cells) in every macro-element, imposing the continuity of the curvature at the boundary.

The presence of a concentrated load inside the macro-elements, does not allow applying completely the algorithm previously described: therefore, for this phase it has been necessary to get the deformed shape of the beam by means of a finite-difference method, imposing zero displacements at the extremes and an additional continuity condition on the central support.

For the evaluation of the deformed shape in the final phase, the rotation data of the inclinometers will be used; moreover, the concentrated loads of the stays could be approximated with a uniformly distributed load, for which the previously described algorithm could be employed.

The use of this modified algorithm, therefore, has allowed obtaining the vertical deformed shape of the beam during the main prestressing phases: data comparison with topographic measures has shown satisfactory results, as illustrated in Figure 2.

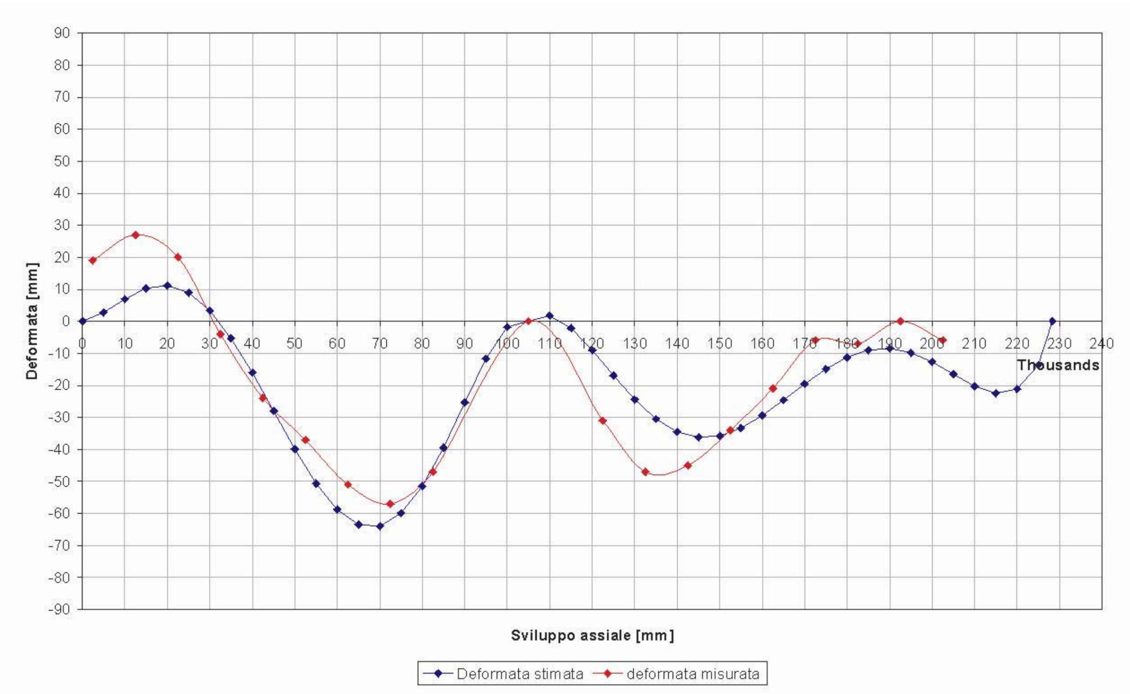

Figure 2. Comparison between the evaluated deformed shape and topographic measures

4.1.2 *Data processing for the pylon*

The pylon can be assimilated to a cantilever subject to a concentrated load on the top and to its weight; therefore it has been subdivided into a single macro-element constituted from 4 cells. Also in this case the deformed shape has been obtained by means of the finite-difference method: the boundary conditions are null rotation at the base and null curvature at the top.

The obtained deformed shape, shown in Figure 3, is also comparable with the direct topographic measures.

4.2 *Finite-element model of the bridge*

The theoretical deformation of the structure during the tensioning phases has been obtained by realizing, with the Ansys 9.0 + Civil Fem 9.0 code, the three-dimensional finite-element model shown in Figure 4. The deck is composed of steel beam elements; the pylon is constituted by concrete solid elements, accurately reproducing the real geometry of the structure. Finally the stays are constituted by appropriate “link” elements: these elements have only tensional stiffness and can be assigned an initial strain.

In order to correctly simulate the second stressing phase of the stays, a “birth and death” analysis has been carried out, consisting in activating and deactivating portions of the slab, in such a way to simulate the phases.

The obtained deformed shapes have been referred to the data of the first tensioning phase and have been used to compare the real behaviour of the structure with that given by the model, with the aim of updating the parameters of the model.

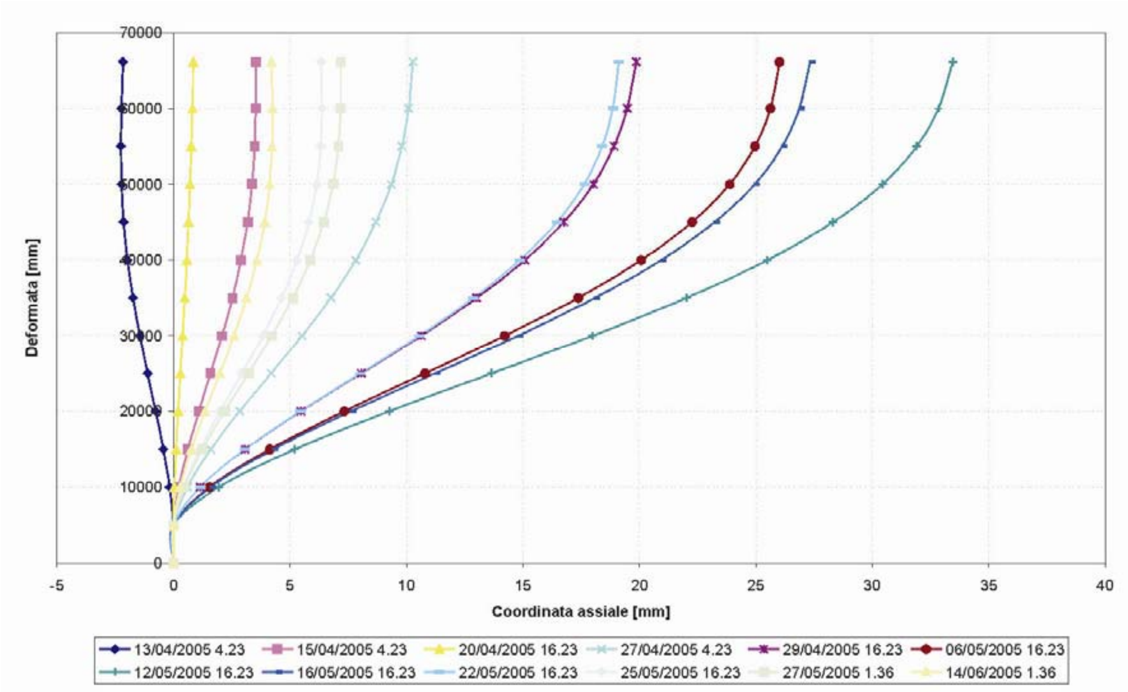

Figure 3. Deformed shapes of the pylon

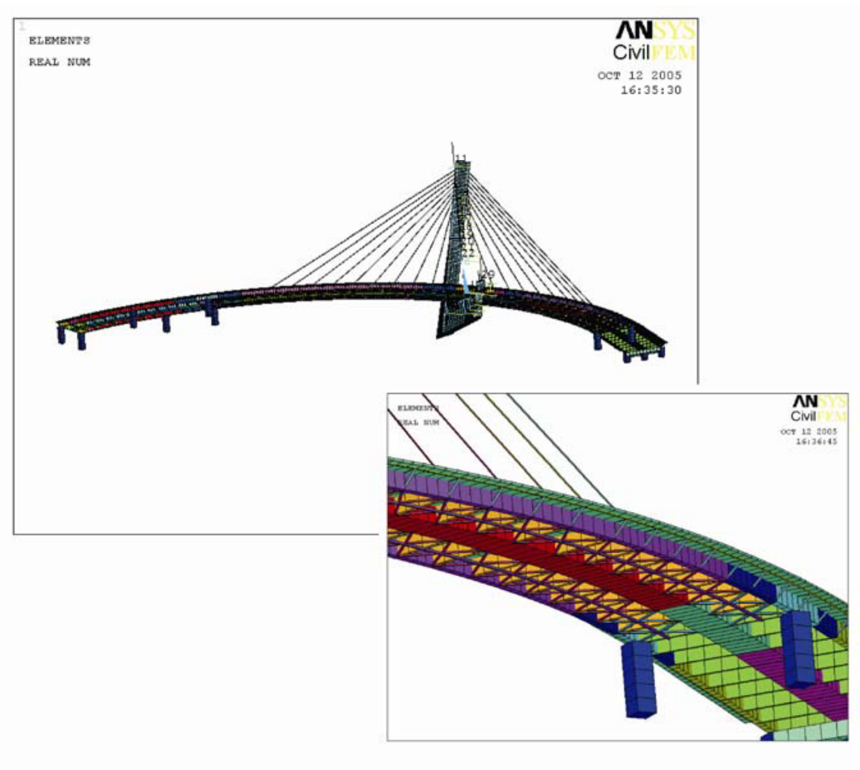

Figure 4. Finite-element model of the bridge

5 CONCLUSIONS

The monitoring system installed on the West Industrial Channel Bridge in the Port of Venice has been described. Through this system an interpretation of the behaviour of the structure during the main phases of construction has been carried out and the comparison with the direct measurements has shown the effectiveness of the data processing algorithms.

A finite-element model of the bridge has been carried out, in order to compare the real behaviour of the structure with that given by the model, with the aim of updating the parameters of the model.

The updated model will be used to verify the proof-load test on the structure that will be run shortly and to interpret the results of the subsequent in-service monitoring phase. During the proof-load test, measurements under dynamic excitation will also be performed.

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