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STRUCTURAL HEALTH MONITORING OF THE LINGOTTO CABLE-STAYED PEDESTRIAN BRIDGE WITH OPTICAL FIBER SENSORS

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Abstract

A cable supported pedestrian bridge was constructed in Turin, Italy for the 2006 Olympic Winter Games. The bridge was constructed to link the athlete village with the rest of the city. The bridge construction consisted of a steel framed superstructure. One half of the steel beam superstructure is supported by steel columns. The other half of the bridge is supported by cables attached to a large arch. The bridge geometry is quite complex. For example, the bridge deck is constructed on a radius, has a vertical rise and fall slope, and the elliptical arch is set on a diagonal with cables at various levels.

As a result of the complex bridge geometry, it was decided to monitor the performance of the bridge cables. The bridge cables were outfitted with long gauge fiber optic deformation sensors. The fiber optic sensors possess the capability for making dynamic real-time measurements. This article describes the structural health monitoring (SHM) of the bridge by using the optical fiber sensors. A synopsis of SHM involving dynamic modeling of the entire structure, the design and placement of the sensors and the analysis schemes for assessment of damage are discussed in this article.

INTRODUCTION

Cable-stayed bridges with modern unique styles are increasing in number worldwide. These bridges are now built in more unusual styles for structural and artistic reasons. Condition evaluation of civil structures which is largely based on visual observations and described by subjective indices does not allow precise assessment of serviceability and safety of these complicated bridges. This makes an urgent need and essential motivation to develop quantitative methodologies to continuously monitor the health of these bridges. Dynamic-based methods have become of increasing interest as an assessment tool to evaluate these infrastructures due to their efficiency. The most common dynamic parameters used in damage detection are eigenfrequencies and mode shapes. Although it is hard to obtain

spatial information of the structural damage from changes in only the eigenfrequencies, it is relatively easy to estimate the cable forces using the fundamental dynamics of elements pertaining to natural frequency, material and geometry properties of cables.

The Lingotto Footbridge was constructed in Turin, Italy as part of the 2006 Olympic Winter Games (Figure 1). The bridge construction was completed in late 2005. The bridge was designed to link pedestrian traffic from the Winter Olympic Village to the Lingotto Commercial Center by spanning over railroad tracks separating the two. The bridge was designed with a complex geometry. For example, the bridge deck is constructed on a radius, has a vertical rise and fall slope, and the elliptical arch is set on a diagonal with cables at various levels. Due to the unusual design of the bridge, it was decided that sensors should be installed to monitor the structural health of the bridge. The objective of the monitoring was to record the cable forces to evaluate the condition of the bridge.

Bridge Geometry

The main structural component of the bridge is a large parabolic steel arch. The cross section of the arch is triangular and constructed of 15 mm thick steel plates. The triangular cross section had 3m sides at the base and rotates toward the top. The arch has a 55m footprint and stands up to a height of 70m. The main bridge superstructure consisted of two steel edge beams. Additional steel framing spans between the two steel beams. The deck is reinforced concrete. The total length of the bridge is 368m and the main span is 150m. Eight pairs of cable stays support the main span of the bridge from the arch. There are eight pairs of cable stays on each side of the arch. The cables on opposing sides of the arch work together to anchor the arch and support the bridge span. The cables are spaced approximately 18.5m along the span of the bridge. The cables consist of twisted steel wires. The steel cables consisted of three diameters; 55mm, 60mm, and 75mm. Figure 2 is a three-dimensional drawing of the bridge and Figure 3 is a plan view of the bridge deck.

Figure 1. Lingotto Footbridge.

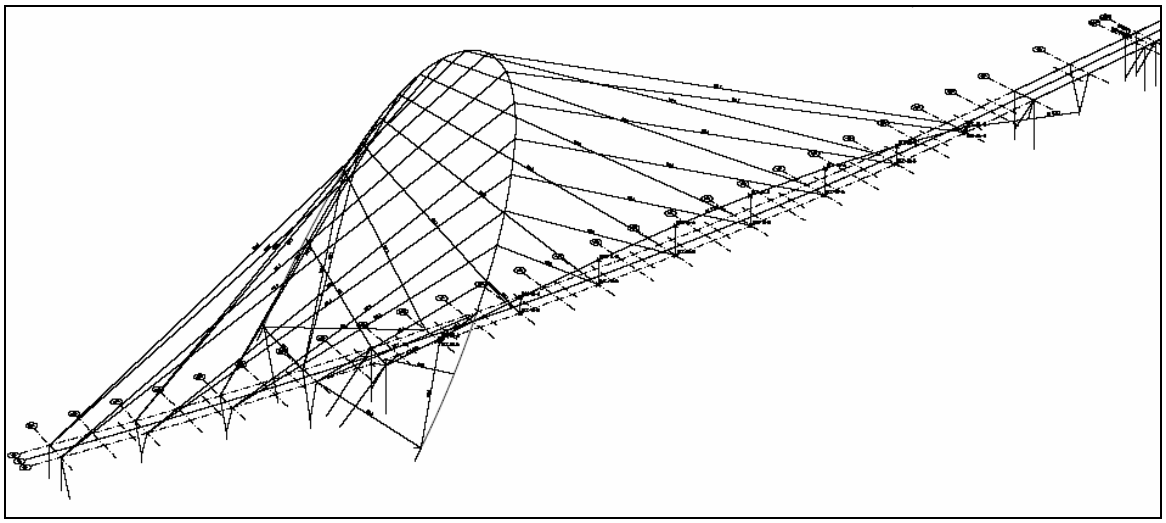


Figure 2. Arch and the cable stays of the Lingotto Footbridge.

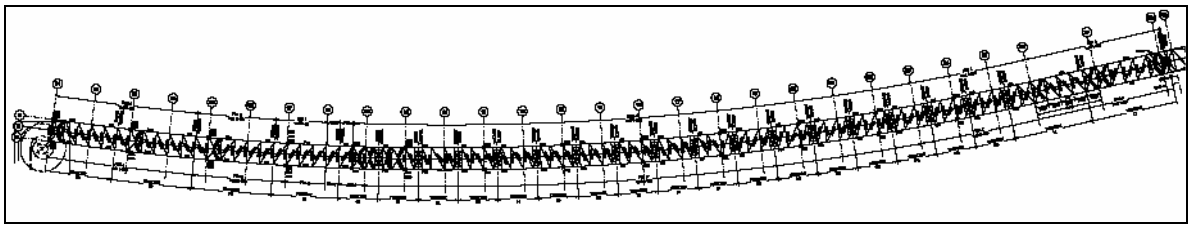


Figure 3. Plan view of the bridge deck.

STRUCTURAL HEALTH MONITORING APPROACH

The main sensors used for the structural health monitoring of the bridge consisted of specially designed Fiber Optic Bragg gratings (FBG). The FBG sensors were designed to measure dynamic deformations over a long gauge. Conventional sensors and accelerometers were also employed for monitoring of the deck.

Cable Fiber Optic Sensors: Design and Calibration

The basic working principle of FBGs lies in the monitoring of the wavelength shift of the returned Bragg-signal as a function of the measurand (e.g. strain, temperature, etc.). Sensor systems involving such gratings work by injecting light from a spectrally broadband source into the fiber. The propagating lightwave is modulated by changes in length and the refractive index of the core with the result that the grating reflects a narrow spectral component at the Bragg wavelength, or in transmission this component is eliminated from the observed spectrum. The modulated lightwave is then transmitted to an interrogation system for detection and demodulation. Calibration is required to convert the optical change into the measurand of interest, i.e. strain or temperature. In a manner similar to strain gages, calibration of optical fibers is related to the strain and temperature sensitivities of the fiber by appropriate gage factors. A complete review of theoretical basis for the establishment of strain and temperature sensitivities is given by Measures, 2001. The fiber optic cable sensor used on the bridge is shown in Figure 4. It includes a pre-tensioned FBG and protective wire glued to angled steel supports at each end. The FBG is protected by a PVDF (polyvinylidene difluoride**)** tube. After manufacturing, each sensor is installed on a cable to be tested and calibrated. The calibration process for these sensors involved cyclic loading to assess the sensor sensitivity, resolution, repeatability, and hysteresis. The induced changes in the wavelength of the sensor were calibrated against a high precision standard extensometer. The gauge factor for these sensors varied between 2.1 to 2.32 (based on displacement) or 1.05 to 1.16 (based on strain). Figure 5 shows a typical plot of the calibration test data including the scatter in repeated loads. These sensors are capable of measuring strain and dynamic properties such as vibration frequency and damping ratios. The resolution of these sensors is typically rated at 1.2 ms (micro strain).

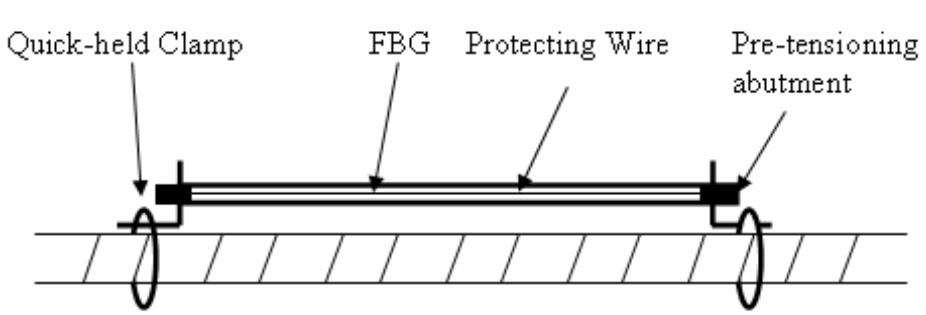


Figure 4. Fiber optic sensor.

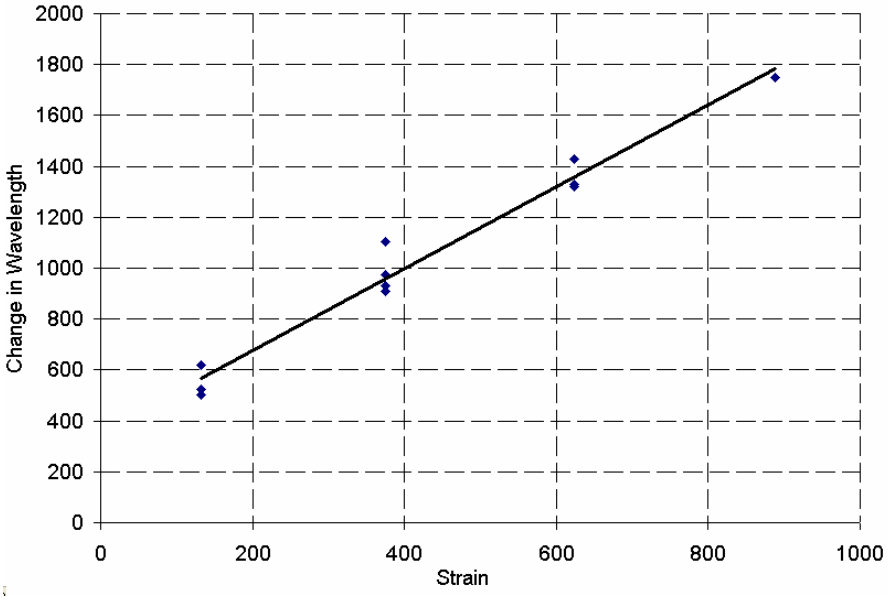


Figure 5. Calibration Data.

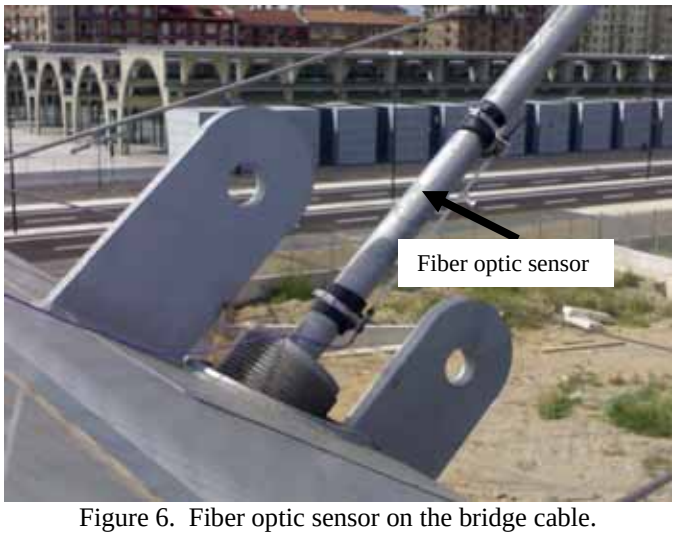


Figure 6. Fiber optic sensor on the bridge cable.

Twenty sensors were installed on the cables of the Lingotto Bridge to continuously monitor the deformation and dynamic response of the cables. These sensors were installed on the cables near the end closest to the bridge deck. Figure 6 shows a sensor mounted on one of the bridge cables. Data acquisition was accomplished by an interrogator capable of acquiring the sensor data at a sampling frequency rate of 250 Hz for both on and off site remote monitoring.

FIELD TESTS

In addition to monitoring the cable stays under ambient load conditions, static and dynamic load tests were conducted and the performance of the cables was monitored.

Static Tests

Static load tests were completed by loading the bridge deck. Boxes were placed on the bridge deck and they were filled with water in sequence starting from the north side. Each of the 138 boxes was filled with 600L of water. The static load tests took place from August 29 through 31 in 2006. The boxes were filled in sequence starting at the north side from one end of the span to the other. Then the boxes were filled on the south side. After the tests, the boxes were emptied in the same manner. Figure 7 shows the area of the span which was loaded. The strain in the FBG sensors was used to calculate the force in the cables and this was compared to the estimated design forces.

Dynamic Tests

Various test setups were used to test the bridge dynamically. First, a 500 kg concrete mass was hung as a pendulum from a steel frame. The mass was hung at three different heights to excite the bridge at different natural frequencies. Figure 8 is a schematic drawing of the pendulum setup and an actual photograph of the test setup. The three positions of the hanging mass are shown in Table 1. The mass position is the length of the pendulum. By swinging the pendulum mass, the bridge superstructure was excited. The pendulum setup was tested at three different locations along the span of the bridge. The next series of tests involved subjecting the bridge to impact by individuals jumping on the bridge. The dynamic load tests were performed from September 14 through 20 in 2006. The cables on the bridge were outfitted with tuned mass dampers. The dynamic tests were completed both with and without the dampers activated.

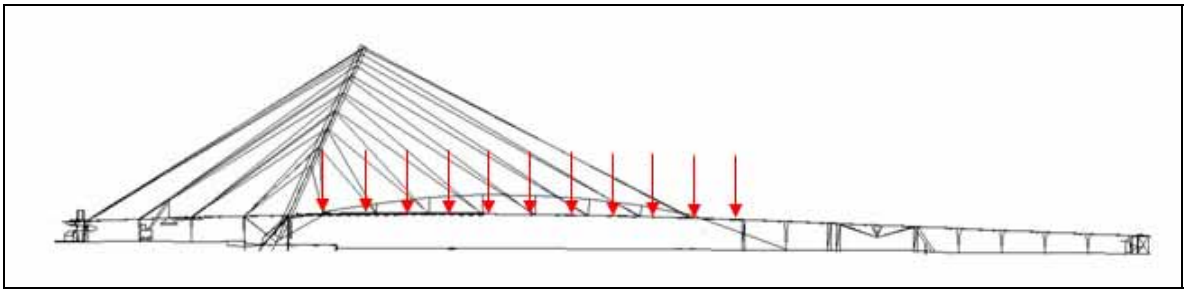


Figure 7. Area of the span loaded during static test.

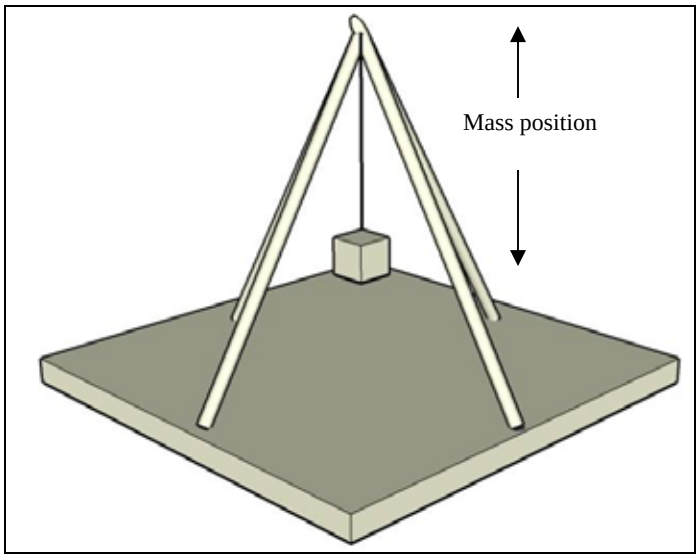


Figure 8. Schematic of the pendulum test setup.

Table 1: Position of the pendulum for dynamic tests (length of pendulum from top)

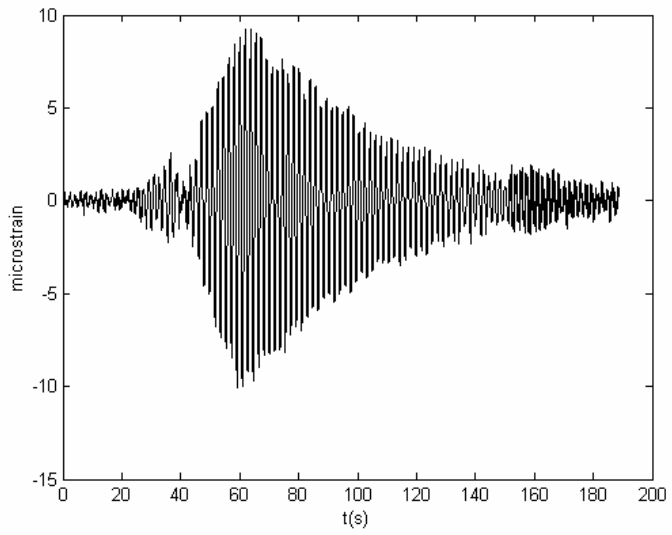
Oscillations	**Mass Position (cm)**
I	74
II	98
III	123

TEST RESULTS

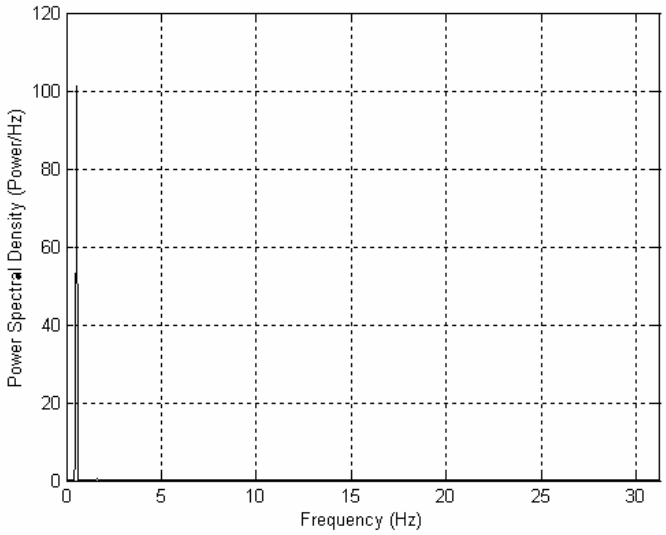
Tests involved application of low amplitude dynamic loads and therefore, the induced strains and deformations were extremely small (1.5-10 micro strain at times). The raw data obtained from fiber optic sensors were filtered to omit the unwanted parts of the input signal. A Butterworth low pass filter was designed based on the sampling rate and cutoff frequency. To extract the frequencies of the filtered data, power spectral density (PSD) of the data was estimated using the Welch method of spectral estimation. Figures 9 and 10 are examples of the filtered data in both time and frequency domains for two of the fiber optic sensors.

DISCUSSION OF RESULTS

Previously, analytical computer models of the bridge had been studied. The first three natural frequencies of the bridge were determined by these models to be 0.454, 0.489, and 0.592 Hz, respectively. Because of the complex geometry of the bridge, almost all of the mode shapes composed of a combination of the lateral, bending and torsional deformations of the bridge. The first mode shape was lateral-torsional. In the second mode shape, the first bending mode shape was dominant. The third mode shape is the combination of lateral, bending and torsional deformation with more emphasis on the lateral movement.

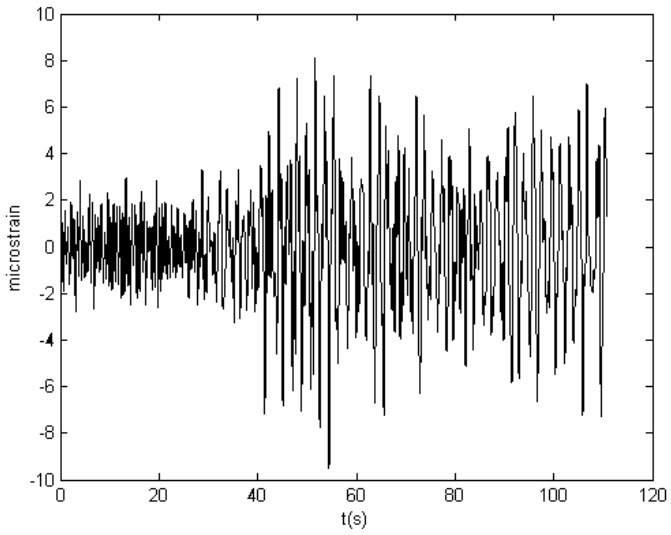


(a)



(b)

Figure 9. Fiber optic sensor data (a) time domain (b) in frequency domain.



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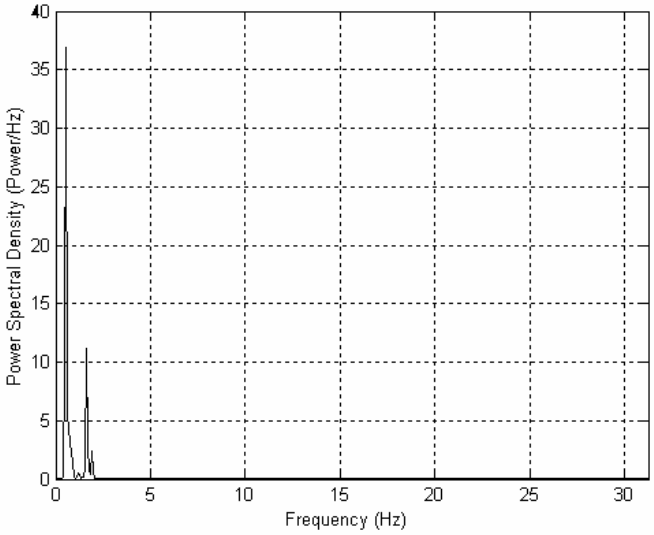

(b)

Figure 10. Fiber optic sensor data (a) time domain (b) in frequency domain.

Comparison with Analytical Results

Dynamic tests were done in both the longitudinal and transverse directions with different pendulum lengths. For the tests which were performed with pendulum oscillating in the transverse direction, nearly all of the sensors recorded a frequency of 0.54 Hz. Considering that the pendulum was swinging in the transverse direction, mode shapes which were dominated by the lateral deformation were more likely to be excited. So, it is evident that the third natural frequency of the bridge was captured precisely with the fiber optic sensors. The same results were obtained from the impact test done using individuals jumping on the bridge.

CONCLUSIONS AND FUTURE WORK

The recently constructed Lingotto Pedestrian Bridge is an example of an aesthetically pleasing and yet a geometrically complex structure. In order to monitor and understand the performance of this bridge, it was decided to perform structural health monitoring using various types of sensors including optical fibers. This article

concentrated on the structural health monitoring of the Lingotto Bridge using specially designed optical fiber sensors. The requirements for the sensors were high resolution in order to measure minute dynamic perturbations due to ambient conditions and load tests; robustness for long-term monitoring; and easy installation on the existing cable stays. The sensors were employed during the static and dynamic load tests of the bridge and a brief summary of the results were presented here. The sensors were capable of measuring axial deformations during the load tests in order to determine the cable deformations as well as the dynamic properties of both the cables and the bridge. The natural frequencies of the bridge were then compared to the original design analysis and the numerically acquired response of the bridge.

The bridge is currently being monitored in real time, and a finite element model of the bridge is being completed to further investigate the dynamic characteristics of the cable sensors and study various methods to detect any possible future damage to the bridge. Structural health monitoring of the bridge with fiber optic sensors will continue for the bridge during its service life.

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