MONITORING MARBLE CRACKING IN THE DAVID BY MICHELANGELO

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Abstract

A monitoring system has been installed on the David by Michelangelo at the Galleria dell'Accademia in Florence, in order to monitor the possible evolution of the cracking pattern present in the tree trunk lying flat to the right leg and in the left ankle of the famous statue. Other parameters as vibrations and inclinations are monitored too. The system is based on a innovative device and on minimally invasive sensors as fiber optic Bragg gratings. The monitoring activity is ongoing. The first results, even in the absence of seismic events, have shown high sensitivity to vibrations and temperature variations.

Introduction

The David by Michelangelo (Figure 1) is located inside the Galleria dell'Accademia since 1873, after lying for more than three centuries in the Piazza della Signoria in Florence. The white Carrara marble with which the statue is made presents a surface degradation, which has been observed by many scientists and researchers which have been working in the last decades to analyze from several points of view the conservation state of the precious work of art.

A lot of work has been done to improve the knowledge of the conservation state of the material from the physical and chemical points of view (MIBAC, 2004).

From the structural point of view it has to be pointed out that in large marble statues, the weight and the shape sometimes thin and articulated give rise to complex stress states, which can become particularly severe in case of vibrations due to earthquakes or other causes. Such a severe stress state, in conjunction with the brittleness of the marble, can originate cracks. Many scientists have been working to assess the safety of the David. In particular, the attention has been concentrated on the evaluation of the risk induced by both static and dynamic loads, taking into account the cracking pattern (Borri 2005, Borri et al. 2006).

Before to take actions to protect the artwork, the authorities have decided to implement a monitoring program to get a complete information of the situation and its evolution over time. With this aim, some smart technologies recently developed and used for monitoring structures have been applied. These technologies are based on new monitoring devices (Bastianini et al. 2011), wireless networks (Grosse et al. 2008), and innovative sensors (Falciai et al. 2004).

Figure 1 – The David by Michelangelo

A system based on Bragg Grating fiber optic sensors was chosen to monitor the crack width evolution considering the minimally invasive size of the sensors installed on the artwork. The fiber optic sensor system cooperates with one "Smartbrick®" device, an autonomous and self-sufficient monitoring unit that has been configured to track temperature, inclination and vibrations to trigger data frame acquisitions of both acceleration and fiber optic data in case of vibration events exceeding a peak-to-peak acceleration of few mg, such as events induced by even minor earthquakes. The logged information is remotely stored and processed (Lolli 2010).

At the same time an experimental program is being carried out in the laboratory for the mechanical characterization of white Carrara marble, in order to collect information useful for the future non-destructive ultrasonic investigations to be carried out on the statue.

Monitoring system

The installed equipment consists of the following components:

1) integrated monitoring unit for vibrations, rotations, and environmental parameters;

2) reading unit for fiber optic sensors;

3) fiber optic sensors;

4) hardware and software for acquisition and transmission of fiber optic data.

Integrated monitoring unit

One “Smartbrick®” self-contained WSHM (Wireless Structural Health Monitoring) device was adopted to monitor the stability of the basement of the statue the envirnmental conditions and notable vibration events eventually present.

The chosen “Smartbrick®” is a completely autonomous SHM unit featuring a seismic trigger for dynamic frame capture, self-contained battery supply, embedded sensors and pre-conditioned inputs, data log memory, data processing capability and automatic data broadcast through an embedded internet cell-phone connection.

Referring to the specific application, the “Smartbrick®” device has been configured to:

- acquire data every 2 hours from the embedded sensors for: air temperature, basement temperature, basement roll inclination, basement pitch inclination;
- trigger dynamic frame capture from both the internal accelerometers and from the fiber optic sensors when a vibration event is detected with a peak-topeak acceleration level above the preset threshold.
- In absence of notable dynamic events, broadcast the acquired data every 3 days trough email and upload to FTP web server.

The following table resumes the performances for the “Smartbrick®” embedded sensors and the data acquisition options configured.

Embedded sensor	**Performances**
Environmental temperature	0.1°C Resolution, ±1.5°C Absolute accuracy
Marble basement temperature	0.1°C Resolution, ±1.5°C Absolute accuracy
2-axis basement inclinometer (roll & pitch)	0.001° Resolution
3-axis accelerometer	0.1mg Resolution, 3.5 mg/√Hz Noise performance
Dynamic frame capture	
Sampling speed	200 Samples/second (each channel)
Sampling frame length	20.5 seconds (4095 samples per each channel)

In order to maximize battery life, the Smartbrick remains in sleep mode whenever possible, periodically switching to active mode for a brief time in order to read the signals monitoring slowly-changing phenomena and to send data. Such time-driven operation cannot capture structural vibrations induced by random environmental excitation. Hence, an event-driven operational mode and trigger system have been added to enable detection of acceleration peaks within the 2÷25 Hz frequency region. The trigger system developed has power consumption of less than 66 μW and has a negligible effect on the Smartbrick’s battery life. Depending upon the options configured, data can be simultaneously acquired from up to eight different channels, with a total maximum sampling rate of 4100 S/s and memory depth of 64 k samples. The -3dB bandwidth of the sensor input is 0.1÷110 Hz for the embedded accelerometers and 2000 Hz for other channels.

The bench test confirmed that the sensitivity of the trigger system could reach and even exceed the design specification of 0.49 m/s^2 (50 mg) peak acceleration threshold in the 2÷25 Hz frequency band. The isotropy of the trigger with respect to the three coordinate directions is to be considered acceptable at the highest limit of sensitivity adjustment.

The Smartbrick device was installed on the back of David, resting on the basement, in order to place the instrument on a fairly large area and a flat surface (Figure 2).

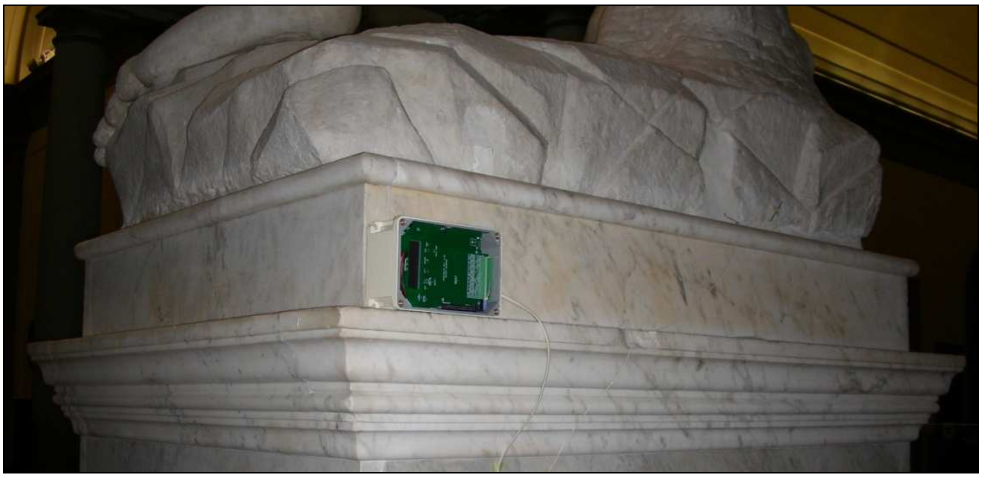

Figure 2 – The basement of David and the device Smartbrick

Fiber Optic Sensors

Fiber optic Bragg gratings (figure 3) are made by producing permanent periodic index variation along a short section in the core of a optical fiber. First introduced in later 1970s, fiber optic Bragg grating development increased steady and attracted widely attention since high reflectivity FBGs were manufactured by a transverse holographic method, which permits the use of FBGs in any wavelength attainable by the writing process. The FBG is a good sensing element for strain and temperature because it linearly responses to the measured magnitude (strain or temperature). Because the FBG sensors are based on the wavelength encoding of the signal information, multi-point sensing using wavelength multiplexing is possible. The wavelength of a FBG spectrum is related to the effective index refraction and the periodicity of the index variation in the fiber core. So small perturbations on FBGs cause wavelength shifts, which can be used to measure any physical magnitude, as strain or temperature. The wavelength-encoded signal is finally converted into electrical signal for easy and real-time reading.

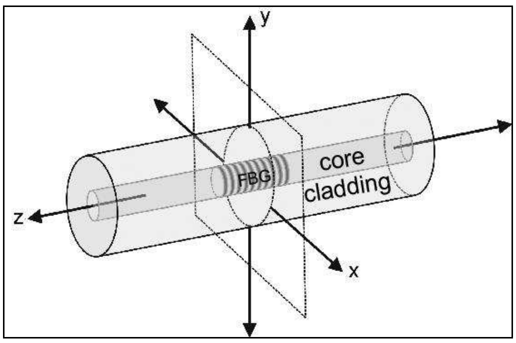

Figure 3 - Fiber optic Bragg grating

Figure 4 - Instrumental setup with FBG interrogation unit

Interrogation system

The detection of Bragg wavelengths is performed using a commercial interrogation unit Micron Optics® FBG-IS. An optical coupler split the radiation generated by a 1550 nm LED. One arm of the coupler ends in a standard connector (FC), to which the FBG is connected. A fiber Fabry-Pérot tunable filter scans the back-reflected signals in a 40 nm wavelength range. The system is connected to a PC and is entirely controlled by a LabVIEW® program. The best resolution is 1 pm, and several gratings can be interrogated at the same time, with a sampling frequency of 50 Hz.

In order to allow the remote acquisition, the UltraVNC software was used.

Figure 4 shows the cabinet were the interrogation unit was located together with a computer and a uninterruptible power supply.

The interrogation can be carried out in two different operating modes: static and dynamic.

The static mode is always active an is aimed to give a continuous monitoring. The acquisition interval for this mode was set initially at 20 min and then at 1 hour.

The dynamic mode is aimed at giving information on the crack opening during seismic events. It is activated when the Smartbrick device detects acceleration peaks within the 2÷25 Hz frequency interval, as can be expected in case of earthquake.

System installation

A visual inspection showed that the most significant cracks are on the tree trunk. In a first step, it was decided to apply there two sensors.

Any sensor was pre-strained before applying it, then it was glued to the marble in two points, at a distance of about 20 mm. A cyanoacrylate M-Bond 200 was used as adhesive, which is characterized by good transparency, ease of removal, good adhesion, no creep and stability over time.

The two sensors were placed as shown in Figure 5:

- the sensor named FBGC across one of the more severe cracks, to measure the opening changes;
- the sensor named FBGM on the marble in a position not cracked and not subjected to mechanical stress, with only the function to measure the deformation of the marble due to changes in temperature.

A third sensor was used as a dummy sensor, not glued to the marble, positioned near the top of the tree trunk; the use of this sensor is necessary because, as the wavelength shift is caused by both strain and temperature variations, the shift due to temperature variations has to be subtracted by the total shift, in order to obtain only a strain measure.

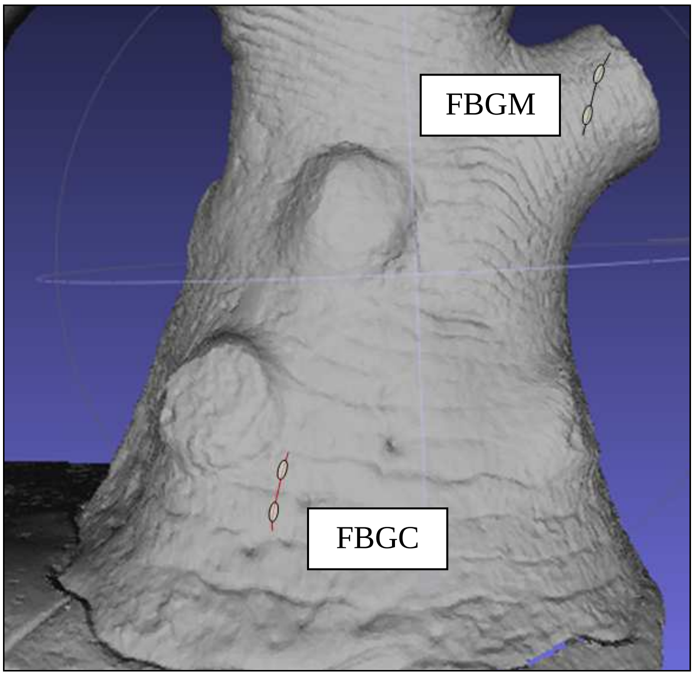

Figure 5 – Locations of FBG on the tree trunk

Results and discussion

Monitoring is ongoing. The first results are presented here.

The graph of Figure 6 shows the results in terms of strain measured by the two FBG's, compared with the temperature, for the period from day 0 (may 31, 2010) to day 84 (august 24, 2010) from the beginning of monitoring. Moving average lines have been superimposed to the graphs, in order to make them easier to interpreting.

As it can be noted, the marble strain (FBGM) is strictly related to temperature variations. This does not occur for the strain across the crack (FBGC).

Figure 7 shows a window of the previous graph, for the period from day 60 to day 70.

We can observe that the variations of the strain measured by the two sensors are in opposite directions. Maximum values given by FBGC correspond to minimum values given by FBGM.

Across the crack, in fact, an increase in temperature causes an expansion of the marble in the vicinity of the crack itself, which causes a decrease of the crack opening. The order of magnitude of the variations of crack opening is about 0.10 μm.

This behavior is not constant over time. This problem must be studied more thoroughly. A numerical analysis is ongoing, with the aim of evaluating the influence of both temperature variations over time and temperature gradient inside the material.

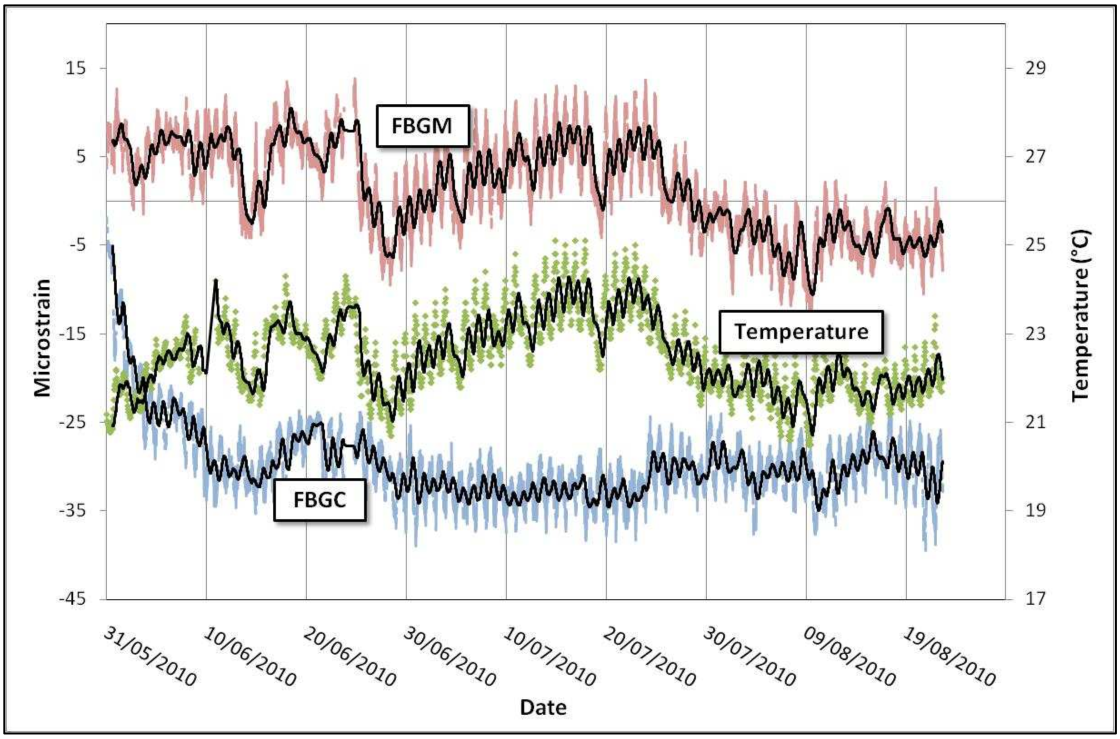

Figure 6 - strain measured by the two FBG's, compared with the temperature, for the period from day 0 (may 31, 2010) to day 84 (august 24, 2010) from the beginning of monitoring

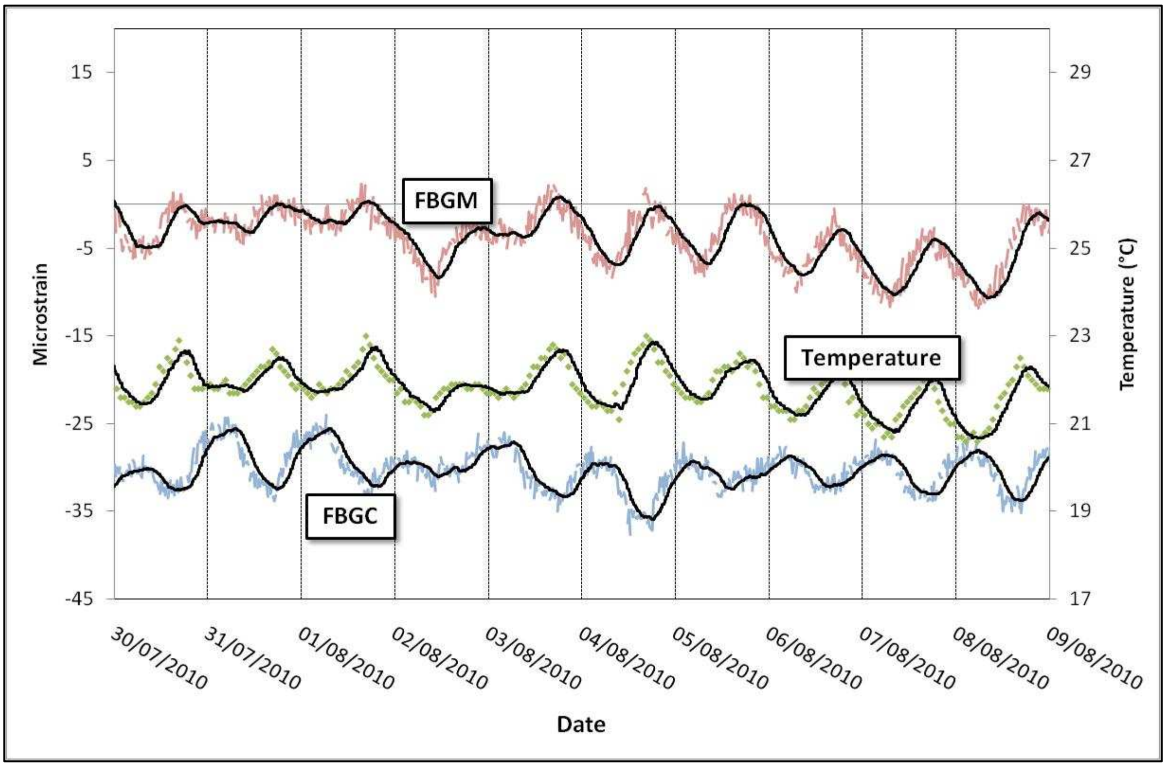

Figure 7 - strain measured by the two FBG's, compared with the temperature, for the period from day 60 to day 70 from the beginning of monitoring.

Conclusion and future developments

During the period of observation fortunately there were no earthquakes. However, even the limited temperature fluctuations have shown the high sensitivity of the sensors and the good behavior of the whole system.

For what concerns the future monitoring activity, it is expected to increase the number of sensors.

In addition an experimental program has also started with the use of ultrasound analyses to define maps of marble homogeneity and to estimate the depth of the more important cracks.

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Bibliography

MIBAC (2004), "Exploring David", Giunti, ISBN 88-09-03325-6.

Borri A. (2005), "La stabilità delle grandi statue: il David di Michelangelo", DEI, Roma.

Borri A., Grazini A. (2006), "Diagnostic analysis of the lesions and stability of Michelangelo's David", Journal of Cultural Heritage, 7 (2006) 273-285.

Bastianini F., Sedigh S., Pascale G., Perri G. (2011), "Cost-Effective Dynamic Structural Health Monitoring with a Compact and Autonomous Wireless Sensor System", International Symposium on Nondestructive Testing of Materials and Structures, May 15-18, 2011, Istanbul, Turkey.

Grosse C.U., Pascale G., Simon S., Krüger M., Troi A., Colla C., Rajčić V., Lukomski M. (2008), "Smart monitoring of historic structures - overview about a medium-scale research project in the eu 7th research framework programme", International Workshop - SMW08, In Situ Monitoring of Monumental Surfaces, Florence, 27-29 October 2008, ISBN 978-88-7970-390-1.

Falciai R., Trono C., Pascale G. and Bonfiglioli B. (2004), "Some aspects of FRP monitoring with fiber Bragg grating sensors", ESHM, 2nd European Workshop Structural Health Monitoring, Munich (Germany), July 2004, pp. 877-882, (C. Boller, W. J. Staszeski Edd., DEStech Pub.).

Lolli A. (2010), "Monitoraggio per la diagnostica strutturale del David di Michelangelo", graduation tesi, University of Bologna, Italy.