Use of FBG sensors for monitoring cracks of the equestrian statue of Bartolomeo Colleoni in Venice

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ABSTRACT. The Bartolomeo Colleoni monument suffered for years damage from the local climate. The process of restoring the Colleoni equestrian statue, started in 2003, allowed to understand how the bronze statue was originally cast and manufactured and the techniques used in its construction. During this process a relevant crack on the right foreleg was investigated in correspondence of the cast-on joining the right foreleg to the front portion of the horse body. The crack was investigated experimentally by Fiber Bragg Grating (FBG) sensors, avoiding any modelling because of the very complex structure of the statue. An array of FBG sensors connected in series was glued on the crack with the aim of capturing live information about the effect of applying stress on the crack opening. The monitoring system was successfully tested during repositioning of the RIDER on the horse and is available for long term inspection of the crack opening evolution.

KEYWORDS. FBG sensors; Health monitoring; Crack monitoring; Restoration; Colleoni equestrian statue.

INTRODUCTION

The Bartolomeo Colleoni equestrian statue, located beside the Scuola Grande di San Marco in the Campo SS Giovanni e Paolo, was erected in fulfillment of a request made by the mercenary captain before his death in 1475. After switching allegiances several times, in 1457 he was endowed with supreme command of the Venetian army by the doge of Venice. Shortly before his death, Colleoni bequeathed a sizable portion of his estate to the Republic of Venice, with the stipulation that a bronze equestrian monument should be erected in the Piazza San Marco to perpetuate his memory. The Venetian Senate honored his request but placed the statue near the Scuola Grande di San Marco rather than in Piazza San Marco. Andrea del Verrocchio won the commission for the Colleoni statue in a competition. Contests for public art commissions were frequent in fifteenth-century Italy. In fact, sponsors hoped to obtain not only the best, but also the most efficient designs. The Bartolomeo Colleoni Monument is among the best-known works of Verrocchio, that was a teacher of Leonardo da Vinci. Verrocchio died in 1488, before finishing the work, and the statue was finished by Alessandro Leopardi in 1495.

The Bartolomeo Colleoni monument suffered from years of neglect and damage from the local climate. In 2003 the World Monument Fund began the cleaning and restoring of the equestrian statue that was subjected to the last major conservation work in 1919 [1].
The process of restoring the Colleoni Monument allowed to understand how the bronze statue was originally cast and manufactured and the techniques used in its construction. These studies give a historical insight into the practice of skilled foundrymen and the technologies used for manufacturing big statues.
Considering the impressive size of the statue, Verrocchio decided to use the lost-wax casting method for manufacturing different parts of the monument that would be subsequently joined by means of the cast-on method [2] used by the fifteenth century foundrymen to join two different castings. Therefore the equestrian monument of Bartolomeo Colleoni, that weighs about 6000 Kg, is composed of 14 different castings (8 for the horse and 6 for the rider). As far as the horse is concerned the single cast parts were: 1) right foreleg, 2) left foreleg; 3) right hind leg, 4) left hind leg, 5) front portion of the body; 6) rear portion of the body, 7) head, 8)tail.
The cast-on method has to join the different parts in such a way that they fit closely and that joints are strong enough to support the monument weight. In fact the huge weight of the statue stands on a pedestal where three horse's hoofs are placed at the vertexes of a slender triangle.
During the restoration work of the Colleoni equestrian statue a system of FBG sensors has been applied for long-term structural health monitoring of a crack in the right foreleg [3-5]. The system allowed to verify the structural stress during sensor calibration performed by applying a mechanical stress on the riderless horse and during the rider repositioning [6,7].
FBGs are basically optical strain gages but offer several advantages over the conventional ones. The most interesting characteristics for the applications under concern are the possibility to multiplex dozens of them within the same fiber and the long term stability. One of the processes commonly used for the production of FBG is that one of using coherent UV light illuminating transversally the fiber. The interference pattern can be produced with a phase mask positioned just above the optical fiber. The result of the irradiation is the production of a periodic fluctuation of the index of refraction (called Bragg Grating) in the longitudinal direction of the fiber core. The property of the FBG is to reflect a specific wavelength called Bragg wavelength λ_B if some broad-band light propagates along the optical fiber. Since the value of λ_B is affected by strain according to a predictable relationships, measuring λ_B allows measuring the strain of a structure to which the FBG has been attached with adequate structural contact [8,9].

CRACK MONITORING BY MEANS OF FBG SENSORS

On the right foreleg in correspondence of the welding seam an extended crack affects almost the whole section of the thigh (Fig. 1). In some places the crack branches into two or more paths.
This crack was probably formed already during the welding seam cooling, in fact it is possible to find in it shrinkage cavities. The reinforcement of the right foreleg with an internal iron bar (Fig. 2) suggests that Leopardi had already identified this crack.

Figure 1: Macrograph showing the crack in the right foreleg of the horse.

Figure 2: Detail of the internal part of the horse right foreleg showing the iron bar used as a reinforcement.

The monument repair by means of welding was not recommended considering that welding could have a negative impact on the monument with unforeseeable consequences. For that reason the crack has been monitored by means of FBG sensors that should allow to evaluate the crack criticality and to check the crack propagation over the years. Obviously this methodology can be used only if sensors are left on the statue and appropriately hidden.
The measurements were performed using four FBG sensors, in particular three were used for structural monitoring and one was used for compensating the effect of temperature. The measurement method set up has been done in several stages.
In a first stage needed to evaluate the method reliability, three sensors were glued in correspondence to the crack. One of them was used for compensating the effect of temperature.
The sensor system has been tested and calibrated via measurement campaigns carried out by applying controlled thermal and mechanical stresses. In a second stage four FBG sensors arranged in series were glued in correspondence to the crack on the right foreleg by means of M-BOND AE10. The array of sensors has been realised and positioned as shown in Fig. 3.

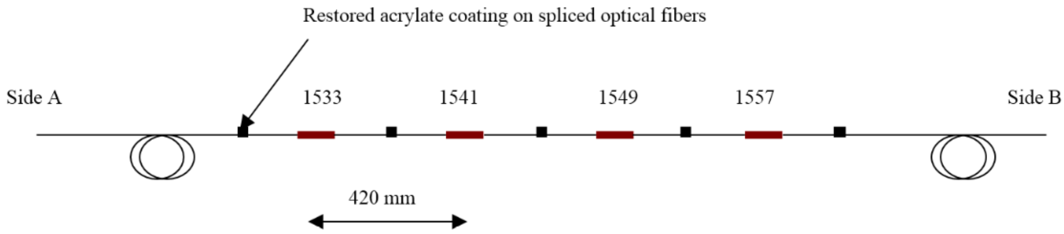

Figure 3: FBG sensor system.

Fig. 4 shows the sensor array and highlights that the sensor with a wavelength centered at 1533 nm is about 20 cm away from the crack. Two sensors were glued in correspondence of the same areas selected for the previous ones.
The sensors' system has been realized as shown in Fig. 3 and glued on the horse right side as highlighted in Fig. 4.

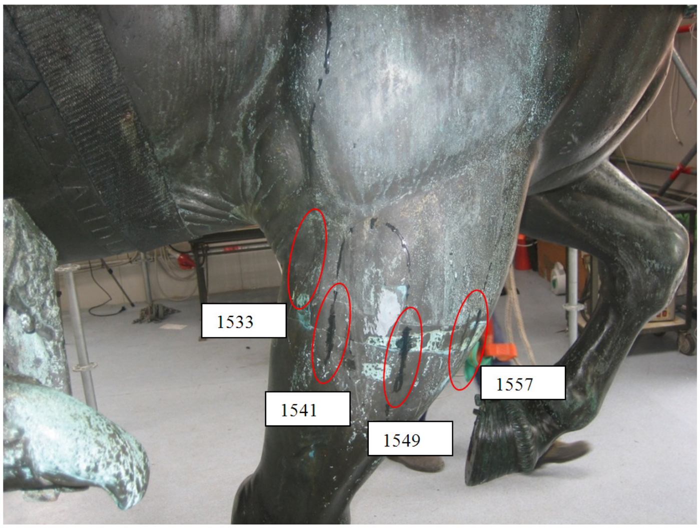

Figure 4: FBG sensor positions.

MEASUREMENTS MADE BY APPLYING FORCES MEASURED BY A DYNAMOMETER

In order to carry out tests, load was applied by a dynamometer. Fig. 5 shows the points where the load was applied and measured by a dynamometer. On the right side of the horse, the load was applied in correspondence of points A, B, C, D and L while on the left side it was applied in correspondence of points H, G, F, E and I that are arranged symmetrically with respect to the previous ones.
The last measurements were made while repositioning the rider on the horse (Fig. 6).

RESULTS AND DISCUSSION

Graphs of the tests performed with the dynamometer are reported below. Fig. 7 shows the graphs, in arbitrary units, of the deformations detected by the sensors as a function of the time of application of a load of about 500 N (green line). These graphs were obtained in preliminary tests performed by using the first array of sensors and by applying loads only in the points A, B and D.

Graphs show concavities which arise as load is first applied and then removed: when load is applied, the signal either increases if the crack opens (positive deformation) or decreases if the crack closes (negative deformation); when the load is removed, the crack goes back to its initial configuration (no deformation) and the signal goes back to zero.

Tests highlighted the good response of the sensors showing that when load is applied on the points A and B the crack closes (compression) while the application of a load on the point D produces an area subjected to compression and an area subjected to tension. Fig. 8 shows the graphs of the second array of sensors, always in arbitrary units. They highlight again the deformations detected by the sensors but in this case, as indicated in the figures, the load trend is represented by the blue curve.

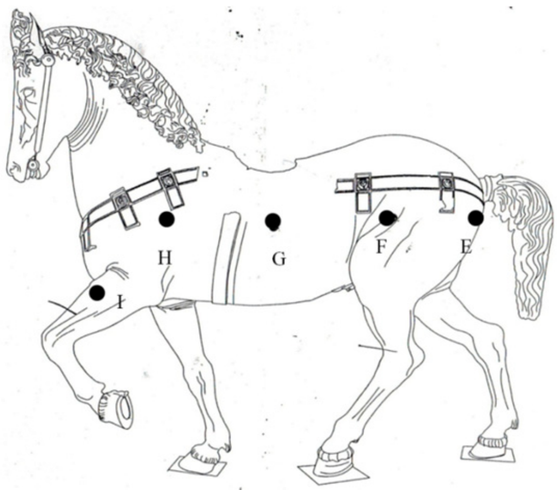

Figure 5: Points of load application.

Figure 6: Repositioning of the rider on the horse.

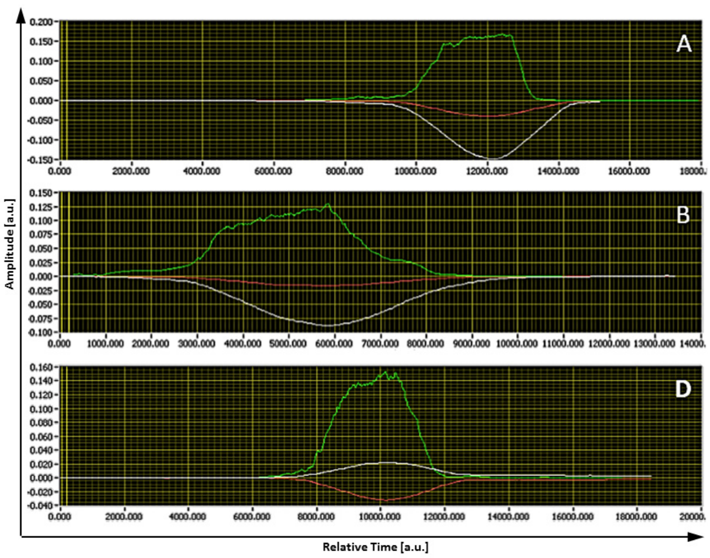

Figure 7: Deformation detected by sensor 1541 (white line) and by sensor 1545 (red line) when load (green line) is applied in correspondence of points A, B and D.

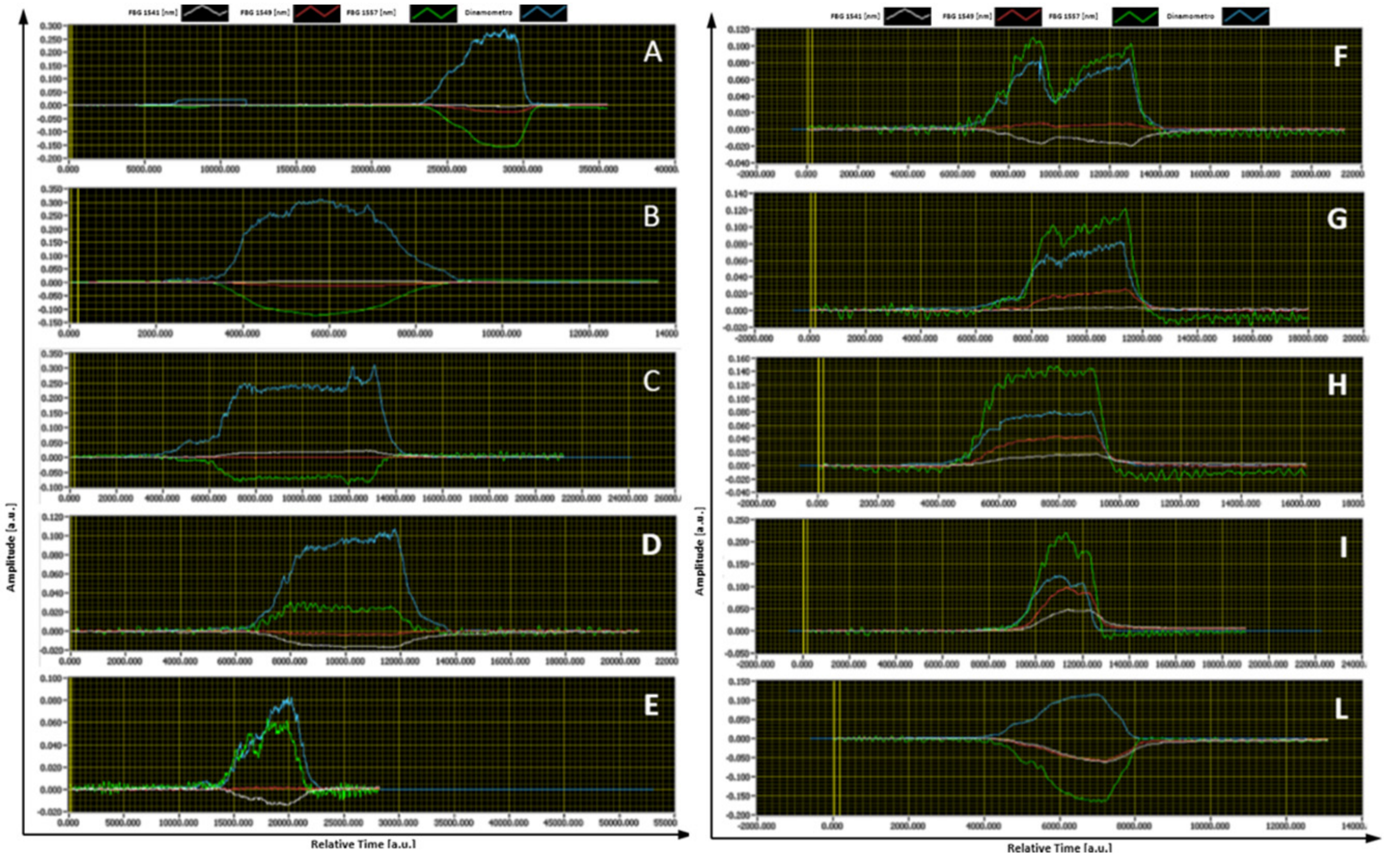

Figure 8: Deformation detected by sensor 1541 (white line), sensor 1549 (red line) and sensor 1557 (green line) when load is applied in correspondence of points A, B, C, D, E, F, G, H, I and L. The load trend, measured by a 500 N dynamometer, is described by the light blue line.

It should be immediately pointed out that the most stressed crack area was on the front of the horse where the sensor 1557 is located. By moving towards the rear of the foreleg deformations are significantly reduced (sensor 1541). A further important information can be gathered considering the points of load application and distinguishing those on the right (L, A, B, C, D) from those on the left (I, H, G, F, E) of the horse. The points are taken from the front to the rear of the horse. When loads are applied on the right side the crack always closes. The only exception is the position D, at the extreme rear of the horse, where the load application determines the crack front opening. When loads are applied on the left side of the horse the crack opens predominantly on the front (sensor 1557). Even in this case by applying the loads in the posterior areas of the horse (F and E) the rear part of the crack behaves differently and closes (sensor 1541).
In conclusion measurements have shown good sensitivity and good reproducibility as revealed by the good comparability between measurements performed with the first and the second array of sensors.
The sensors for the temperature measurements followed the daily temperature. The temperature range was not wide because the measurements were performed during the restoration when the horse was inside a special encasement built around it. For that reason the horse was not exposed to direct sunlight or to the night rigour. In any case, during the tests the temperature was almost constant.
The plot in Fig. 9 shows the trend of the crack deformation during the repositioning of the rider. It highlights an important opening of the crack always in the front area where the sensor 1557 is located. The crack does not deform in his central area (sensor 1549), while it closes in the posterior part of the foreleg (sensor 1541).
In 2006 the monument restoration was completed but the crack monitoring over time was not possible because of logistical and bureaucratic problems. For this reason the results of this research have been published after several years. In any case a photographic reconnaissance carried out after 4 years in the area in which the sensors were positioned showed that the sensors detached from the metallic surface (Fig. 10). This suggests that more efforts must be devoted to the study of sensors' bonding and coating in order to ensure long lasting bond [8, 9].

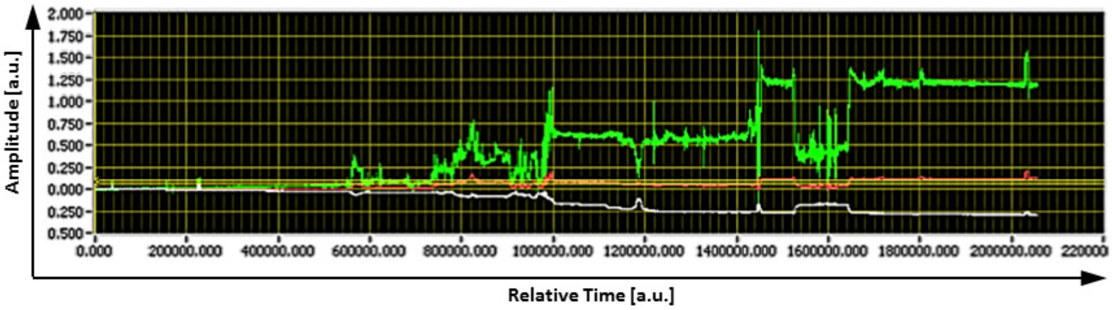

Figure 9: Data acquired during the rider repositioning by means of sensor 1541 (white line), sensor 1549 (red line) and sensor 1557 (green line).

Figure 10: Macrograph showing the sensor detached from the metallic surface.

CONCLUSIONS

An important crack was present in the weld area of the right foreleg of the horse of the equestrian statue of Bartolomeo Colleoni in Venice. This crack was monitored during the monument restoration with an innovative technique based on FBG sensors.

This technique has proved to be reliable and repetitive and showed very well crack opening or closure according to the stresses applied in different areas of the horse.

It was possible to measure in real time the crack deformation while repositioning the rider on the horse. The obtained data highlighted that the crack was not critical.

As far as the continuous monument monitoring is concerned some bureaucratic, technical and logistical difficulties arose. Especially the sensors' gluing and coating durability over time is a considerable problem. In future research efforts should be made to increase their durability with the aim of making the proposed technique reliable over time.

ACKNOWLEDGMENTS

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