Fiber Bragg Grating Sensors for Breaking Tests in Reinforced Concrete Structures Strengthened with Embedded Composite Bars

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Abstract

In this work, the use of fiber optic sensor (FOS) based on fiber Bragg gratings (FBGs) to measure strain in civil structures is examined. In particular, the optical system has been bonded on a carbon fiber bar embedded in a reinforced concrete (RC) beam subjected to bending test. For the interrogation system of these sensors, a robust and costly competitive passive technique is here adopted. Experimental results and comparison with displacement transducers show how FBGs offer an excellent tool for embedded monitoring.

Keywords: fiber optic sensors, Fiber Bragg Gratings, reinforced concrete beam, carbon fiber reinforced plastic materials.

1. Introduction

Aging and extraordinary events like earthquakes or fire cause weakening of concrete and steel structures in the civil engineering field. For this reason strengthening techniques are required. Exploited materials can be represented by fiber reinforced plastic (FRP) materials externally bonded: laminates externally glued or bars put in superficial grooves (near surface mounting FRPs, NSM technique). It is important to underline that reinforced concrete elements strengthened with FRP can have a typical failure due to the detachment of the reinforced element from the concrete [1]. Delamination has to be avoided either because is a very brittle failure mode, either because does not allow using the high strength of fibers. For this reason, the strain distribution monitoring is an important activity, requiring a sensing network able to perform multi-point reliable measurements. Valid candidates for this task are represented by fiber optic sensors (FOSs). They have several advantages for in situ monitoring like a good compatibility with the most part of the materials utilized in this application, low invasivity and the possibility to work in harsh conditions [2]. Among FOSs, fiber Bragg gratings seem to be very attractive. FBGs exhibit good features in terms of high sensitivity, resolution and passing bandwidth [2, 3]. Competitive costs, high multiplexing capability and good structural robustness are typical advantages of this class of devices, too. Fiber Bragg gratings transduce applied strain in wavelength shift, which is an absolute parameter, immune to power drifts along the measurement chain.

Along with this line of argument, in this work, the use of optic sensors based on FBGs to measure strain in civil structures is examined. Within a wide experimental program on reinforced concrete (RC) beams externally strengthened with FRP materials and subjected to bending tests [4], the optical system, previously calibrated, has been bonded on carbon fiber bars embedded in superficial grooves (NSM technique) on the bottom surface of beams. For the interrogation system, a robust technique based on passive optic filtering applied to a ratiometric scheme is here adopted [5]. For this NSM strengthening technique three FBGs have been bonded to the surface of a carbon fiber (CF) bar: one sensor at the center, and two at both sides of the central one. Strain gauges to monitor strain are placed on similar positions in order to check the effectiveness of strain given by FBGs sensors. The aim of this comparison consists into validate the possibility of substituting traditional instrumentations with FBGs strain sensors. For structural applications like strengthening of existing RC elements with composite materials these latter seem to be very promising for their low invasivity and multiplexing measures possibility. Loading pattern is a typical four point bending test, where beam is placed on two supports at the ends and is vertically loaded in two points symmetric respect to the midspan. Loads, measured with a load cell, have been applied by a mechanical system in order to apply tension to the external reinforcement up to the breaking of the beam. Strain values are directly available from FBG sensors responses since a suitable calibration process has been previously performed. In the following, after a description of the used methodology, the experimental set-up and the obtained results are shown confirming a good agreement between FBGS sensors and traditional strain gauges.

2. Methodology

2.1 FBG as strain sensor and interrogation technique

A Fiber Bragg Grating (FBG) is a periodic or semi-periodic permanent perturbation of the fiber core refractive index. So, when FBG is irradiated with a broadband optical source, a narrow band signal is reflected. The central wavelength of this signal, called Bragg wavelength λ_B, is related to the physical parameters of the grating according to the following relationship [6]:

$$\lambda_B = 2 n \Lambda \ . \qquad (1)$$

where: n is the effective refractive index of the fundamental mode propagating inside the fiber and Λ the pitch of FBG. External causes, like strain, able to modify right hand terms of equation (1), cause a shift of the Bragg wavelength.
The axial strain sensitivity of these devices is reported in Eq.2

$$\frac{\Delta\lambda_B}{\lambda_B} = \left(1 - \frac{n^2}{2}\left[p_{12} - \nu\left(p_{11} + p_{12}\right)\right]\right) \cdot \varepsilon = S_\varepsilon \cdot \varepsilon \qquad (2)$$

where ε is the applied strain, p_{11}, p_{12} are two components of the strain optic matrix, ν is the Poisson's ratio. It results by equation (2) that FBGs are linear strain transducers. Since the curvature of the beam is much greater if compared with FBGs lengths, it can be assumed that the applied strain is uniform on the sensors and direct along their length.
The interrogation system used for the proposed magnetic sensor relies on a low cost radiometric technique based on optical filtering combined with broadband interrogation. Using a chirped and strongly apodized FBG can obtain an optic filter with a response linear in wavelength. The block diagram of the interrogation system is reported in figure 1.
An optical broadband source illuminates the FBG trough an Y joint, and the FBG reflected signal goes to the optic filter. The signals at the photodetectors PDT (PhotoDetector Transmitted) and PDR (PhotoDetector Reflected) are related to the convolution between the sensing grating spectrum and the transmission and reflection responses of the optical filter involved in, respectively.

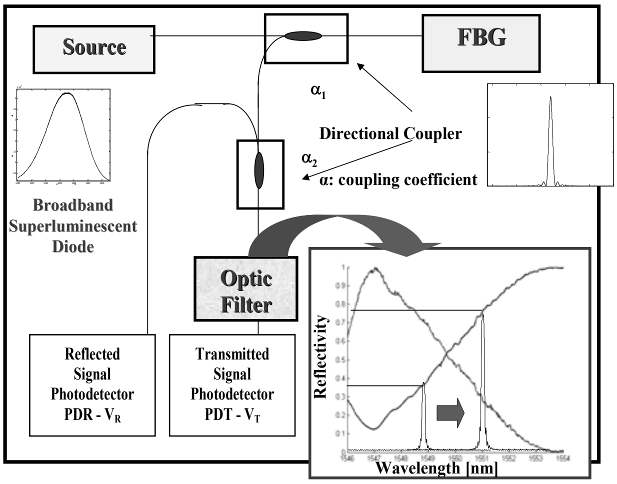


Figure 1: Interrogation sensor system-block diagram

The electronic processing of the two detected signals consisted of taking the ratio of the difference and the sum of the outputs as follows [7] according to:

$$V_n = \frac{V_T - K \cdot V_R}{V_T + K \cdot V_R} \qquad (3)$$

where V_T is the voltage signal of PDT, V_R is the voltage signal of PDR and K is an opportune constant.
The generated normalized signal, V_n, is a good measure of the centre of mass of the sensing grating spectrum, and as a consequence, also of Bragg's wavelength. Furthermore, it is not dependent on the intensity fluctuations but directly related to the Bragg wavelength shift. The additional numeric coefficient K has been introduced in order to compensate the asymmetry in the receiving scheme [6].
In light of the passive nature of the proposed technique, system bandwidth is only limited by the electronic circuitry involved in the receiving unit. Static and dynamic resolutions of 1 pm and $40n\varepsilon/(Hz)^{0.5}$ can be achieved up to 50 KHz.

2.2 FRP materials

Exploited materials for strengthening techniques can be represented by FRP materials: laminates externally bonded or bars embedded in superficial grooves (near surface mounting FRPs, NSM technique [8]). These latter are promising because of simple and rapid application procedures, to their lightness (i.e. for bridge short interruptions of service give low costs), furthermore they are inert to environmental corrosive agents reducing maintenance costs.

3. Experimental

3.1 Instrumentation and loading set- up

For this monotonic test a RC concrete beam with a rectangular section having internal steel reinforcement (A_s=2ϕ10mm, A'_s=2ϕ8mm) has been externally strengthened with 2 carbon bars (diameter ϕ8mm) put in two grooves realized in the bottom part of the beam

(Figg.2-3).

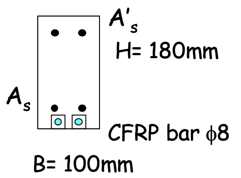


Figure.2: beam cross section

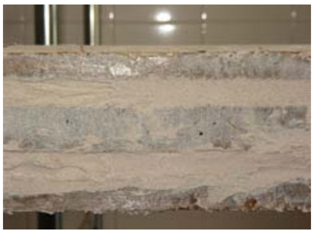


Figure.3: carbon bars at the bottom part of beam

section of the carbon bar.

Loading pattern is a typical four point bending test, where beam is placed on two supports at the ends and is vertically loaded in two points symmetric (300mm) respect to the midspan by a mechanical system (Fig.5).

Due to the loading pattern carbon bars were subjected to tensile stress until failure of beam.

During tests, signals from all the sensors and transducers are synchronously acquired by a commercial HBM Spider 8 digital acquisition board, with its own resolution of 1$\mu\varepsilon$.

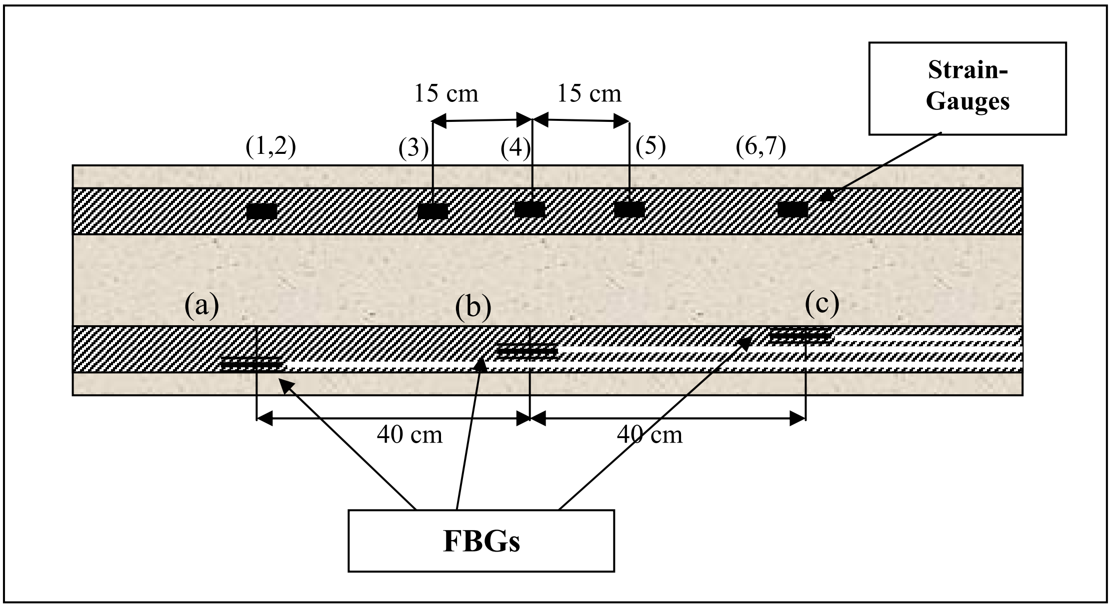


Figure 4. Scheme of a reinforced concrete beam strengthened with carbon fiber beams and sensors locations

Three FBG sensors were bonded on one of the reinforcing carbon fiber bars by using a cyanoacrilate glue, according to the scheme of figure 4. The FBG sensors with a 0.5 FWHM passing bandwidth and different central free wavelengths @ 1548, 1307, 1548 nm were exploited. The first one, @ 1548nm Bragg's wavelength, indicated with 'a' in figure 4, was placed at -40cm respect to the midspan; the second one, 'b', @ 1307nm at the midspan and the third one, 'c', @ 1548nm at the +40cm section. For these sensors three different interrogation systems were used with three superluminescent diodes, two of these with a central wavelength at 1550 nm and one at 1310 nm, all with 40 nm FWHM bandwidth. Successively the carbon fiber bar are embedded and covered with an epoxy mortar.

On the other reinforcing beam, seven strain-gauges were placed. The ones indicated with (1) and (2) in figure 4 were glued at the -40cm section on two diametrically opposite points of the carbon bar. Analogously, (6) and (7) strain-gauges were placed at the +40cm section. Whereas (4) and (5) sensors were placed at -15cm and +15cm sections, respectively. Finally, the strain-gauge (4) was placed at the central

Figure. 5 Experimental set-up

4. Results and discussion

Proper calibration procedures are carried out in order to obtain the FBGs responses expressed as applied strain. A series of steps are devoted to the conversion between the applied strain and the normalized output provided by the interrogation systems.

The beam failure is caused by detachment of concrete cover with carbon bar (see Figure 6) on the right side referring to sensor scheme of figure 4.

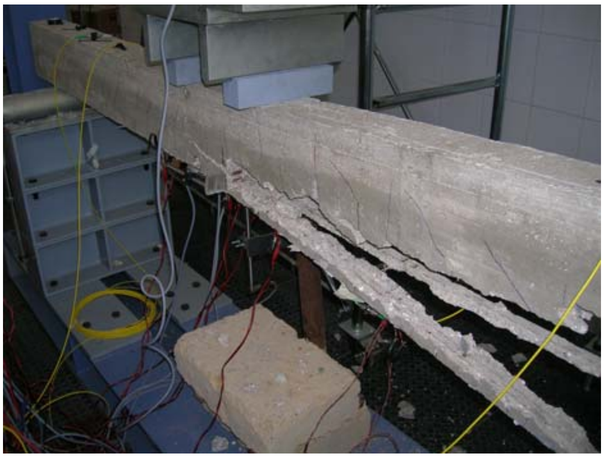
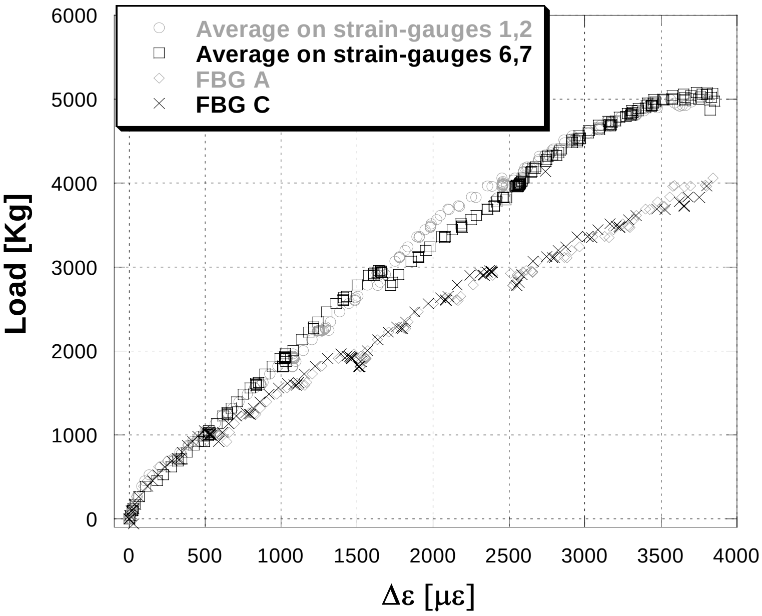


Figure. 6 Failure of beam

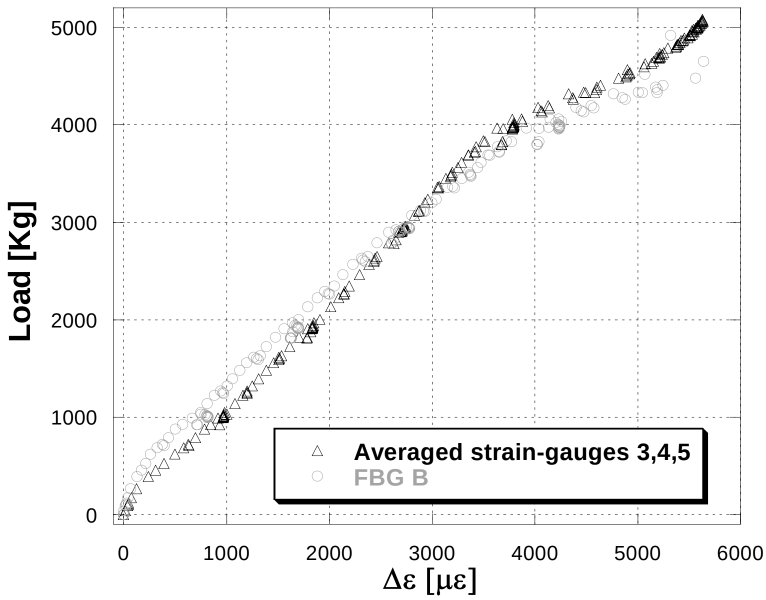
Results for the monotonic tests are reported in figures 7 in terms of applied vertical load (L) versus measured strains ($\Delta\varepsilon$) .
In figure 7.a strain measured by various sensors at the symmetrical sections placed at +40cm and -40cm respect to the midspan are reported: in particular the mean strain given by the couples of strain gauges 1-2 and 6-7 are compared with the values measured by the FBGs sensors 'a' and 'b'.
Therefore in figure 7.b the average strain based on the values measured by the strain gauges 3, 4 and 5, placed in the bending moment constant region, is compared with the strain given by the FBG sensor 'b'.
In general it has to be underlined that strain measured by single strain gauges show a very low scatter respect to the reported average values, confirming the symmetrical behavior of sections placed at ±40cm from midspan and the invariance of strain in the bending moment constant region.
All the sensors show a good fitting with the expected experimental performance of the beam: the load-strain relationship evidence a tri-linear behavior characterized by a progressive decreasing of the slope. The first linear branch is related to an 'uncracked' condition of the entire beam, while at about 1000kg first cracks appear modifying the inertia of the beam that becomes more deformable. In this branch the behavior is linear until about 4000kg corresponding to the yielding of the internal steel bars, after that stiffness decreases more.
For the central section (figure 7.b) there is a good agreement between the average strain measured by strain gauges and FBGs along the entire load history, evidencing that the FBG sensor is able to follow the behavior of the beam also after the steel yielding when deformability increases relevantly.
The same good agreement seems not be replicated for the symmetrical lateral sections (±40cm), where strain measured by both FBGs sensor 'a' and 'c' overestimate values given by strain gauges. This effect could be caused by local phenomena due to a not perfect bond condition between the carbon bar monitored with FBGs and the surrounding mortar in the groove: this can produce a more deformable behavior of the bar. Lost in bond of the carbon bar instrumented with FBG sensor can be caused by a very careful application of the mortar without an effective compacting in the grove in order to avoid accidental breaking of the optical fiber. Furthermore it has to be underlined that FBGs sensor and strain gauges were applied on two different carbon bars.
Central section seem to be less sensible to these phenomena because is generally affected by flexural crack that however reduces the bond effectiveness at the carbon bar-mortar interface.
Further experimental tests are now in progress to confirm the good fitting between measures of strain gauges and FBGs sensors with the aim to focus attention to apply all sensors in the same boundary condition.
However the good results obtained witness the potentialities of these latter devices in this field.

5. Conclusion

Performances of embedded FBG based sensing system for the monitoring of concrete beams reinforced with embedded composite bars have been presented. The sensing system exhibits a good agreement with traditional measurements of strain given by several strain gauges. From these preliminary results, the FBG based sensing systems seem to be good candidates for the monitoring of existing concrete structures with the NSM technique. New tests are in progress to confirm the effectiveness of this agreement.



(a)



(b)

Figure 7. Comparisons between averaged strain gauges and FBGs: (a) at the left (-40cm) and right (+40cm) sections; (b) at the centre.

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