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Design, Manufacturing and Experimental Validation of Optical Fiber Sensors Based Devices for Structural Health Monitoring

Angela CORICCIATI
Consorzio CETMA, S.S. 7 Appia km 706+030, 72100, Brindisi, Italy
Tel.: ++39-0831-449111, fax: ++39-0831-449120
E-mail: angela.coricciati@cetma.it

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Abstract: The use of optical fiber sensors is a promising and rising technique used for Structural Health Monitoring (SHM), because permit to monitor continuously the strain and the temperature of the structure where they are applied. In the present paper three different types of smart devices, that are composite materials with an optical fiber sensor embedded inside them during the manufacturing process, are described: Smart Patch, Smart Rebar and Smart Textile, which are respectively a plate for local exterior intervention, a rod for shear and flexural interior reinforcement and a textile for an external whole application. In addition to the monitoring aim, the possible additional function of these devices could be the reinforcement of the structures where they are applied. In the present work, after technology manufacturing description, the experimental laboratory characterization of each device is discussed. At last, smart devices application on medium scale masonry walls and their validation by mechanical tests is described. *Copyright © 2016 IFSA Publishing, S. L.*

Keywords: Structural health monitoring, Optical fiber sensors, FBG sensor, Distributed sensing, Smart composite devices, Civil application.

1. Introduction

Optical fiber sensors are recently used in many fields for Structural Health Monitoring (SHM). Particularly, they could be mainly used for strain and temperature monitoring: an external stimulus causes a shift in optical fiber sensor spectrum, which is tightly correlated to the mechanical and/or thermal applied stress. Besides their many advantages, such as for example immunity to electromagnetic fields and high time-durability, optical fiber sensors are very fragile and, consequently, difficult to be applied on some structures and in harsh environments. In this sense, embedding optical fiber sensors in composite structures before in-field installation could be interesting because sensors application results easier and more successful, avoiding unexpected ruptures.

In scientific literature there are some examples of optical fiber sensors, embedded inside composite structures. The author has already designed and tested a Smart Textile [1] where a PA6 little tube has been inserted inside the textile during the weaving process. The point (a FBG – Fiber Bragg Grating - one) optical fiber sensor has been inserted inside this tube successively, after fabric application on the structures. Mechanical and calibration tests have been performed on the smart device and, successively, four point flexural tests on masonry beams reinforced with the Smart Textile have been performed: the presence of the tube does not affect textile mechanical properties and strain values, measured by FBG sensor, are in accordance with the strain measured by the corresponding control strain gages positioned beside the sensor. In another paper [2] the functionality of a FBG sensor, inserted inside a PVC sheet for strain and temperature monitoring and manufactured by spread-coating technique, is described: the advantage of this solution is sheet flexibility, handling easiness and sensor protection in harsh environments. In another paper [3] the effect of different textile structures, manufactured by a semi-automatic loom, on the embedded optical fiber sensor has been described: the denser textile stitch causes a higher loss in light transmission properties. Concerning Smart Patches, the author has already designed and tested a uniaxial Smart Patch, as described in a paper [4] where the manufacturing technology (resin infusion technology) is described as well as device mechanical and metrological characterization. The presence of the embedded optical fiber sensor does not influence composite material mechanical properties as well as composite material manufacturing process and accelerated aging tests in a climate chamber do not influence sensor calibration constant. In another paper [5] the methodology used to insert a FBG sensor at different laminate thickness depths and its successive mechanical characterization are described: laminate strength is lower when the sensor is positioned far from section neutral axis. Regarding pultruded sensorized profiles, in a first paper [6, 7] there is the description of the combined manufacturing process (pultrusion and filament winding) and the applicative methodology adopted for a smart rebar, designed with an improved ductility and to be is used for SHM. Besides, the optical fiber sensor is inserted and glued inside a groove, manufactured in the rebar after its consolidation. In another paper [7] the embedding, during the pultrusion process, of a Fabry-Perot optical fiber sensor, previously inserted inside a protective capillary glass tube, is described.

Aim of the present study is the design and the experimental validation of three different smart devices, sensorized with optical fiber sensors and to be used for civil structures SHM.

2. Optical Fiber Sensor Characteristics

2.1. FBG Sensors

FBG sensors give information about strain and temperature, which are tightly correlated to periodical alterations, caused by thermal and mechanical stresses, of their grating refractive index. FBG sensor works as a filter: in fact, once the light goes across it, only the wavelength (Bragg wavelength) which corresponds to the grating grid is reflected. Strain and temperature changes are directly correlated to Bragg wavelength shift as shown in the following formula:

$$\Delta\lambda_{Bragg} = \alpha \cdot \varepsilon + \beta \cdot \Delta T \, , \tag{1}$$

where $\Delta\lambda_{Bragg}$ is the Bragg wavelength shift, α [pm/με] and β [pm/°C] are the Strain and Temperature Sensitivities respectively, ε is the strain and ΔT is the temperature variation.

2.2. Distributed Sensors

The herein used distributed optical fiber sensors are telecommunication glass fibers which are able to measure strain and temperature variation by estimating Rayleigh backscatter as a function of length in optical fiber with high spatial resolution. Rayleigh backscatter in optical fiber is caused by random fluctuations in the index profile along fiber length, whose index of refraction is sensitive to environmental parameters (strain, temperature, pressure, etc.) in terms of shifts of the reflected spectrum. Strain changes are directly correlated to spectral shift as shown in the following:

$$\Delta\varepsilon = -\frac{\lambda}{c \cdot k_{\varepsilon}} \Delta\nu \, , \tag{2}$$

where $\Delta\varepsilon$ is the strain variation, λ (equals to 1550 nm) is sensor central wavelength, c is the light speed, k_{ε} is sensor calibration constant (equal to 0.78 for bare acrylate sensor) and $\Delta\nu$ [GHz] is optical fiber sensor spectral shift.

3. Smart Devices Design

Embedding optical fiber sensor inside a host structure is very important in order to protect it and to make handling and installation easier. Three types of smart devices have been design, manufactured and experimentally tested: Smart Patch, Smart Rebar and Smart Textile.

3.1. Smart Patch

Smart Patch (Fig. 1) is a composite plate with an optical fiber sensor embedded during the manufacturing process and whose main aims are local monitoring (strain, temperature and crack opening) and reinforcement. It is generally applied on structures surfaces by an epoxy fast-hardening glue and its dimensions and plies lay-up could be designed each time, according to project specific requirements. The herein described Smart Patch has been conceived using a vinylester resin and two plies of a unidirectional glass fabric and manufactured by resin infusion technology, whose whole description is reported in a previous author's paper [4].

Besides uniaxial Smart Patch, a 250 mm * 250 mm biaxial Smart Patch (two plies of a plain glass fabric and an epoxy resin) has been designed and manufactured, with a combined process (hand lay-up and vacuum bagging), in order to monitor two different types of strain, in two perpendicular positions, contemporaneously. At this aim, two FBG sensors have been positioned inside, perpendicularly each other and in correspondence of medians directions. At last, in this experimental activity, both for uniaxial and for biaxial Smart Patches, polyimide coated FBG optical fiber sensors, produced by Alxenses, have been used.

Fig. 1. Smart Patch application on masonry wall.

3.2. Smart Rebar

Smart Rebar is a composite material pultruded rod, with an optical fiber sensor (a polyimide coated FBG sensor, produced by Alxenses) embedded inside the device during pultrusion manufacturing process, less modified in comparison with the traditional one. It is worth to underline that Smart Rebars, herein manufactured with glass fibers and vinylester resin, could have different cross sections, such as circular and rectangular ones (Fig. 2), even if also other different pultruded profiles could be sensorized, like C-shaped beams. Smart Rebar is generally used as shear and flexural reinforcement of masonry wall and concrete structural elements (beams and/or pillars) and it is applied on these structures by using NSM (Near Surface Mounted) technique, which consists of inserting the Smart Rebar inside a groove previously manufactured in the structure to be reinforced and monitored.

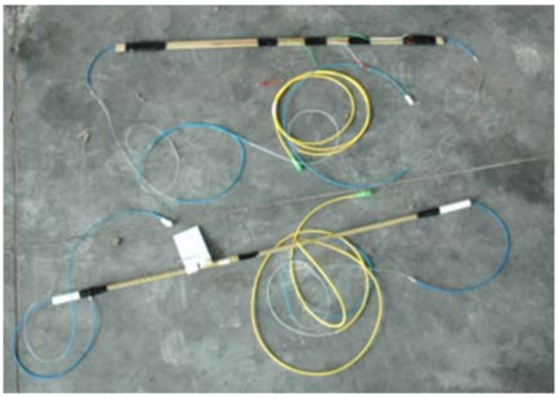

Fig. 2. Smart Rebars.

3.3. Smart Textile

The herein described Smart Textile (Fig. 3) is a reinforcing unidirectional glass textile, sensorized with a distributed optical fiber sensor inserted inside during the weaving process. Nevertheless, the fabric could be designed with different textile structures, according to design requirements and its final application. It could be applied, as distributed reinforcement, both on masonry and on concrete structures, using both polymeric or inorganic matrixes and by hand lay-up technology: after applying a first layer of resin, a ply of fabric will be positioned and fixed on the substratum by a roller. In this experimental activity two different types of distributed optical fiber sensors have been used: a bare polyimide coated one (250 μm diameter) and an acrylate sheathed one (900 μm diameter).

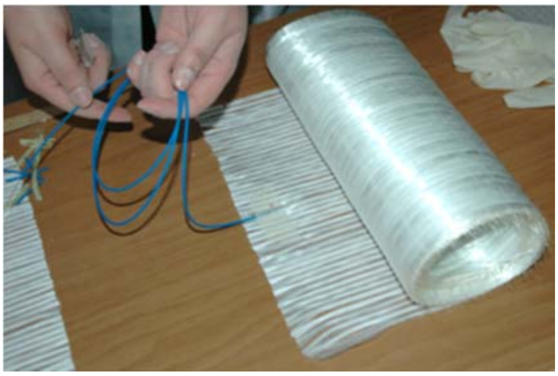

Fig. 3. Smart Textile.

4. Smart Devices Experimental Validation

4.1. Calibration Tests

Once inserted inside FRPs structure, optical fiber sensor could suffer unexpected effects, such as birefringence phenomenon or additional stress/strain, caused both by manufacturing technology and by materials processing, which lead to a distortion of the reflection spectrum. Besides, an improper positioning of the optical fiber sensor along the loading direction could cause coarse measurements errors. At this aim calibration tests have to be performed in order to calculate sensor calibration constant after embedding. These tests consist of applying a tensile stress (according to the standard "ASTM D 3039/D 3039M – 00") on the sensorized specimens, up to a strain equal to 5000 με and to measure it both by optical fiber sensor and by an electrical strain gage (PL-60-11 by Tokyo Sokki Kenkyujo Co., Ltd., 120 Ω and 60 mm gage length), positioned outside the laminate and in correspondence of the embedded sensor. Strain Sensitivity has to be evaluated using Equation 1 for FBG sensor (for Smart Patch and Smart Rebar and not considering the second term of the equation because of laboratory isothermal conditions during test) and using Equation 2 for distributed sensor (Smart Textile). In both equations ε is the strain measured by electrical strain gage. Strain Sensitivity α and calibration constant k_ε are estimated in 0.1 % ÷ 0.3 % strain range. Strain Sensitivity values for uniaxial Smart Patch and for Smart Rebar are reported in Table 1 and in Table 2. Besides, in each test and for both devices $\Delta\lambda$-ε trend is linear in the strain range between 0.1 % and 0.3 %.

Table 1. Smart Patch Strain Sensitivity α.

Specimen	α [pm/με]
1.	1.22
2.	1.45
3.	1.28
4.	1.13
5.	1.12
Mean	***1.24***
St. Dev.	***0.13***
C.V.	***10.80%***

Table 2. Smart Rebar Strain Sensitivity α.

Specimen	α [pm/με]
1.	1.29
2.	1.18
3.	1.40
Mean	***1.29***
St. Dev.	***0.11***
C.V.	***8.39%***

The calculated mean value of Strain Sensitivity (respectively 1.24 pm/με and 1.29 pm/με), to be used for further tests on small scale elements, are not largely different from the theoretical one, equal to 1.18 pm/με, as declared by the supplier.

Smart Textile Calibration Constant k_ε value both for bare and for sheathed sensors are reported in Table 3 and in Table 4. Besides, in each test and for both sensors the Δv-ε trend is linear in the strain range between 0.1 % and 0.3 %.

Table 3. Smart Textile calibration constant k_ε for bare polyimide coated sensor.

Specimen	k_ε
1.	0.78
2.	0.76
3.	0.80
4.	0.82
5.	0.82
Mean	***0.80***
St. Dev.	***0.03***
C.V.	***3.21%***

Bare and sheated sensor Strain Sensitivity mean values are respectively equal to 0.80 and 0.69, while the theoretical value, for a bare sensor, is 0.78 as declared by the supplier. The best match between the calculated value and the supplier's one is for bare sensor. For the sheathed one, instead, the higher difference in value is due to a slipping between the sensor and its sheath. Consequently, for further tests on medium scale elements, only Smart Textile with bare sensor is used.

Table 4. Smart Textile calibration constant k_ε for sheated sensor.

Specimen	k_ε
1.	0.70
2.	0.73
3.	0.61
4.	0.73
Mean	***0.69***
St. Dev.	***0.06***
C.V.	***8.12%***

At last, both for Smart Patch and for Smart Textile, tensile tests have been performed both on sensorized and on unsensorized specimens in order to evaluate if the presence of the sensor causes a reduction in laminate mechanical properties and, in particular, on tensile strength and on ultimate strain. The strength has been reduced of about 11 % in case of FBG (Patch) and of bare sensor (Textile) and of about 24 % in case of sheathed sensor. Similarly, in the first case the ultimate strain has been reduced of about 10 % while in the second case of about 20 %. We can conclude that the presence of the sensor causes a slight reduction in laminate mechanical properties, to be taken into account in devices design, when they have to be used with the additional aim of structural reinforcing.

4.2. Biaxial Smart Patch validation

The designed bi-axial Smart Patch has been experimentally tested through "Picture Frame test", which consists of applying a tensile force to a square symmetric and balanced carbon-epoxy composite panel (500 mm × 500mm; 3mm thick) along one of its diagonals: all panel sides are fixed to rigid plates by bolts, while in correspondence of the vertexes there are four hinges. Two bi-axial Smart Patches have been applied centrally on both panel sides by a fast-hardening epoxy glue, as shown in Fig. 4, with sensors positioned on panel diagonals direction, which are stressed respectively in tension and in compression. At last, for comparison purpose, electrical strain gages have been applied both above the panel and above FBG gratings embedded inside the Smart Patches. Particularly, FBG1, SG1, SG1 PT, SG1 PB are positioned on panel tension stressed vertical diagonal, where FBG1 is Bragg sensor, SG1 the electrical strain gage positioned above FBG1, SG1 PT (on the top) and SG1 PB (on the bottom) are the strain gages positioned on the panel. Similarly, FBG2, SG2, SG2 PR (on the right), SG2 PL (on the left) are positioned on panel compression stressed horizontal diagonal. Smart Patch strain trends are shown in Fig. 5 and in Fig. 6.

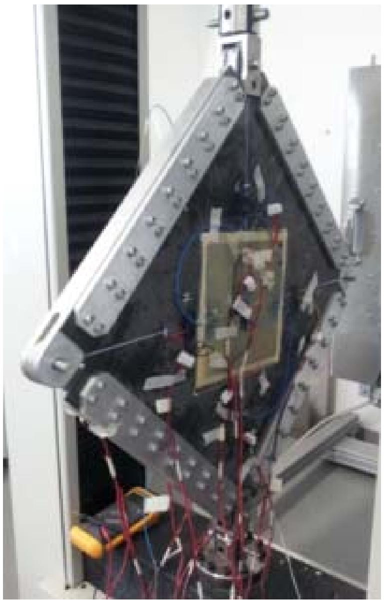

Fig. 4. Picture Frame Test

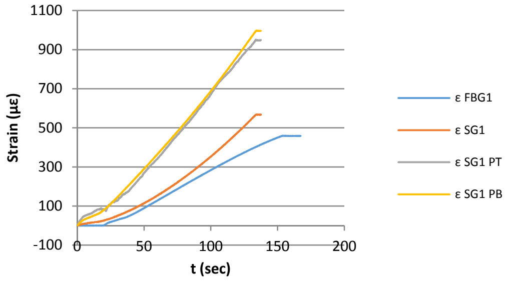

Fig. 5. Smart Patch strain trend on tension side.

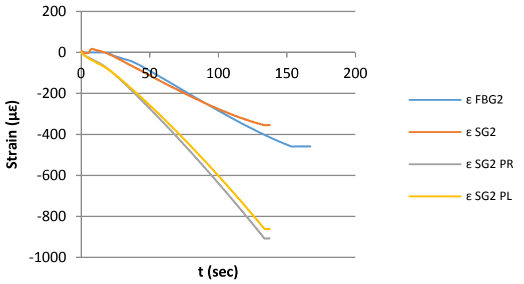

Fig. 6. Smart Patch strain trend on compression side.

Both on tension (Fig. 5) and on compression (Fig. 6) side, FBG sensors and the strain gages positioned on them measure the same value of strain which is, in both cases, in accordance with the expected trend. Besides, in both cases the strain measured by strain gages positioned on the panel is higher than that one measured both by FBG sensor and by the strain gage positioned on it, according to the fact that the part of the panel where the bi-axial Smart Patch has been glued is stiffer (and consequently less deformable) than the other parts of the panel.

4.3. Out-of-plane Flexural Tests on Medium Scale Masonry Walls

Out-of-plane four points bending tests have been performed, according to the standard UNI EN 1052-2, on two medium-scale masonry walls (1200 mm × 800 mm), whose bricks have been manufactured using a natural calcareous stone (“Pietra Leccese” stone, typical of the South-East of Italy) and reinforced with all the herein designed smart devices. Uniaxial Smart Patches, with FBG sensor, have been applied as local reinforcement and for mortar joints crack opening monitoring; Smart Rebars, with FBG sensor, has been applied by NSM technique (ACI 440.7R-10) as wall flexural reinforcement; Smart Textile, with distributed bare sensor, has been applied by hand lay-up as flexural reinforcement. Two different masonry configurations has been used, according to the standard: bricks disposition with the rupture plane parallel to horizontal joints (“Wall 1”) and bricks disposition with the rupture plane perpendicular to horizontal joints (“Wall 2”): in both cases the span and the distance between the loading noses are respectively equal to 100 cm and to 50 cm. Three uniaxial Smart Patches (300 mm × 130 mm) have been applied on “Wall 1” (one on the intradoss and two on the extradoss). Three Smart Patches (300mm*80mm) and two Smart Rebars (a 4mm*20mm square one and a Φ10 circular one) have been applied on the extradoss of “Wall 2”. At last, Smart Textile was applied and wrapped both on tension and on compression sides of both walls, by a MAPEI epoxy system, according to the standard CNR-DT 200 R1/2013. For comparison purpose strain values were measured also by electrical strain gages. Smart devices application scheme, for both walls, is shown in Fig. 7 (Patch in green and Rebar in pink) while test set-up is shown in Fig. 8.

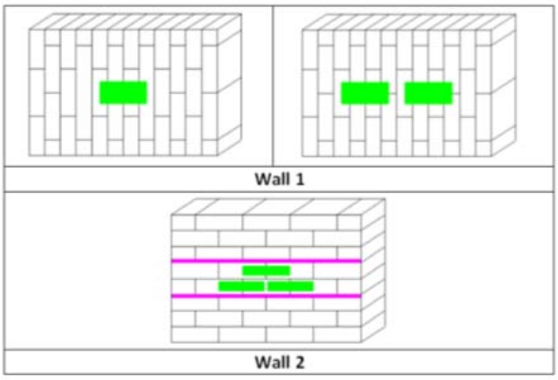

Fig. 7. Smart devices application scheme on masonry walls.

In Fig. 9 strain trend measured by two Smart Patches (SP1 on compression side and SP3 on tension one) and by their respective strain gages (SG1 and SG3) applied on Wall 1 is shown. Strain trend is similar to the expected one and in accordance with that one measured by electrical Strain Gages. Strain trend is step shaped because the load has been applied by step using an hydraulic jack. In Fig. 10 the strain trend, at different load levels, measured by the bare sensor embedded inside the Smart Textile applied on Wall 1 tension side is shown: the trend is not linear but it decreases in correspondence of mortar joints and of support and loading noses. At last, in Fig. 11 there is strain trend measured by the circular Smart Rebar (Bar) and by the corresponding Strain Gage (SGBar), applied on Wall 2: trends are similar to the expected ones and similar between them. Also in this case, strain trend is step shaped because the load has been applied by step.

Fig. 8. Out-of-plane flexural test set-up on masonry walls.

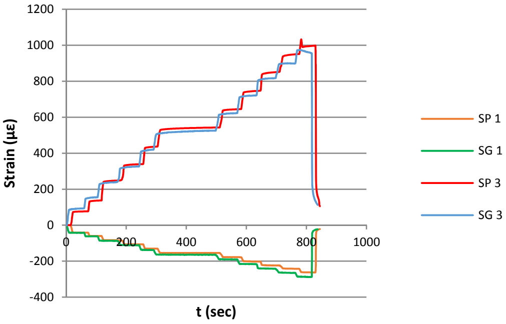

Fig. 9. Smart Patches strain trend (Wall 1).

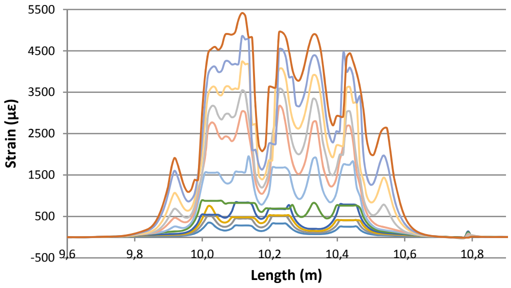

Fig. 10. Smart Textile strain trend on tension side (Wall 1).

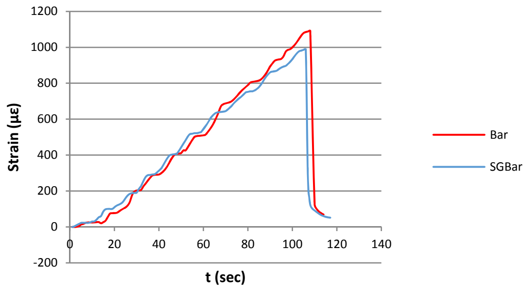

Fig. 11. Smart Rebar strain trend (Wall 2).

5. Conclusions

In the present paper a study has been performed on three different types of smart devices (Smart Patch, Smart Rebar and Smart Textile), which are composite material structures inside which optical fiber sensors have been embedded during the manufacturing process and whose aim is the structural health monitoring. Particularly, smart devices design, mechanical and metrological characterization and mechanical validation on medium size masonry walls have been described.

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