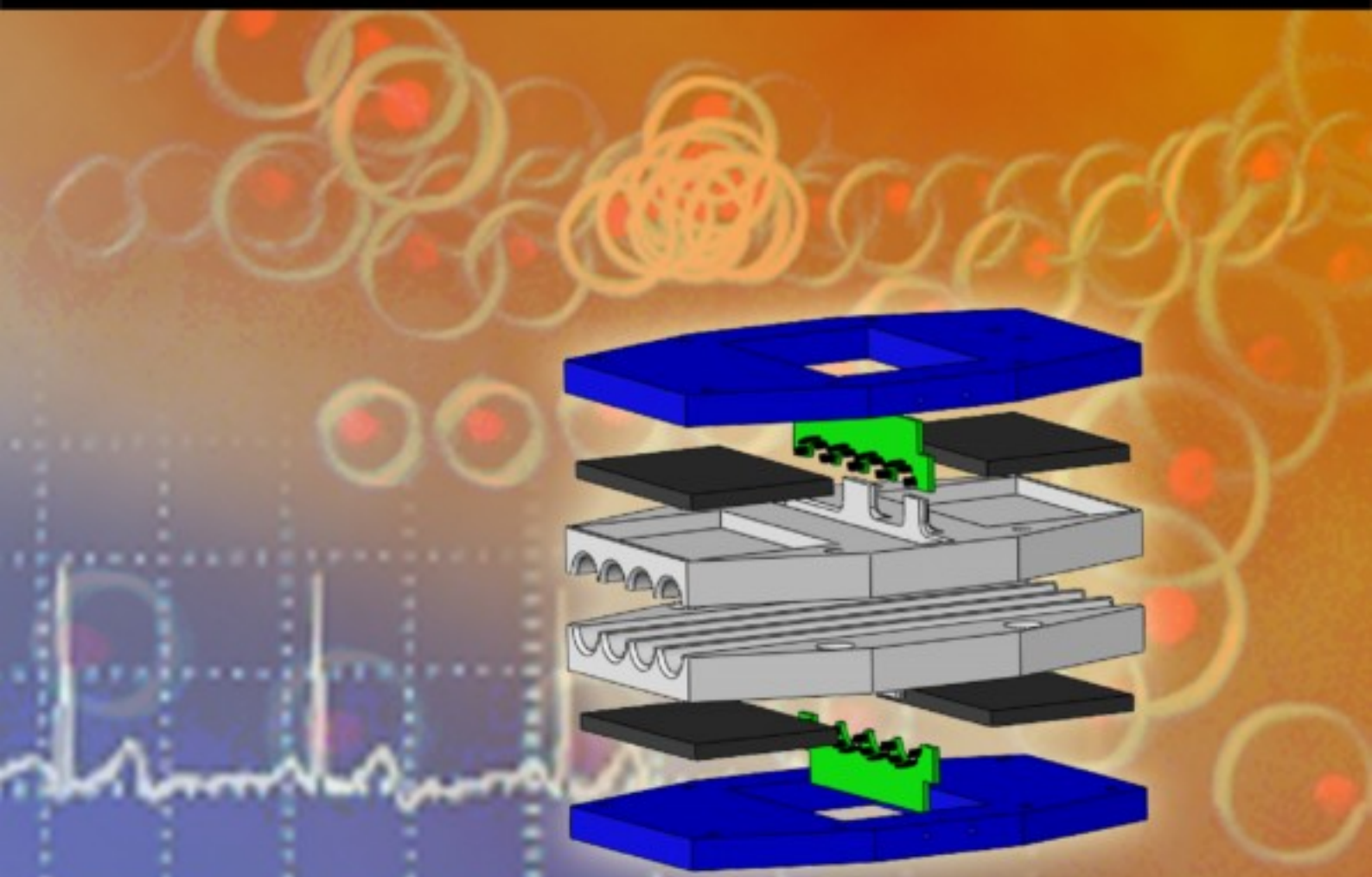


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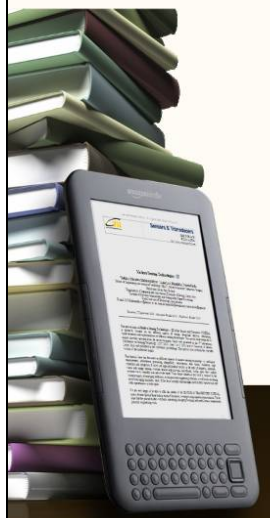
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- Biomanufacturing

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Submission (full paper)	January 10, 2011
Notification	February 20, 2011
Registration	March 5, 2011
Camera ready	March 20, 2011

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ICNS 2011

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Important deadlines:

Submission (full paper)	January 10, 2011
Notification	February 20, 2011
Registration	March 5, 2011
Camera ready	March 20, 2011

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Tracks:

- ENCOT: Emerging Network Communications and Technologies
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- GRIDNS: Grid Networks and Services
- EDNA: Emergency Services and Disaster Recovery of Networks and Applications
- IPv6DFI: Deploying the Future Infrastructure
- IPDy: Internet Packet Dynamics
- GOBS: GRID over Optical Burst Switching Networks



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Production and Characterization of Multifunctional Textile for Masonry Retrofitting and Health Monitoring

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Abstract: Composite materials are recently used in civil applications, in strengthening of masonry and concrete structures. They offer many advantages, in comparison with traditional techniques, mainly related to the favourable strength to weight ratio. Besides, monitoring the structure during its lifetime is very important, in order to detect possible anomalous situations. The innovative and original multifunctional textile, described in this work, is conceived to perform both these functions: thanks to a tube woven inside the fabric during manufacturing process, a fibre optical sensor can be inserted successively inside this tube, directly on the reinforced structure, allowing the structural health monitoring. Tensile tests on composite material performed with the textile allowed the mechanical characterization and the identification of the gage factor of the embedded sensor. Moreover, flexural tests, carried out on small scale samples reinforced with the textile, allowed to test the measuring performance of the textile in possible real applications. *Copyright © 2010 IFSA.*

Keywords: Masonry, Smart textile, Reinforcement, FBG, Monitoring.

1. Introduction

The use of composite materials (FRPs – Fibre Reinforced Polymers) in civil applications during last years is increasing more and more, thanks to their many advantages, such as low weight, high strength-to-weight ratio, ease of handling, drapability, speed of installation, low thickness and visual impact, reversibility, in comparison with traditional retrofitting techniques. Besides, thanks to their low weight, once applied on the external surface of the structural elements, FRPs do not cause an increase of weight of the whole structure. This last aspect is very important for the seismic reinforcement of existing buildings, often designed in the past to resist mainly to vertical loads. At the same time, monitoring the structure during its lifetime (strain, cracks, temperature, etc.) revealed to be very important, in order to predict possible anomalous situations, such as diffused cracking caused by additional unexpected loads or seismic events, soil subsiding, etc. In this way, the real-time monitoring of the structure allows the repairing of the structure in the early stage, avoiding possible successive retrofitting and reducing maintenance costs.

Multifunctional textiles can allow both structural reinforcing and monitoring, thanks to the presence of an optical sensor embedded inside the textile during the weaving process or by coating fibre with nanocrystalline piezoceramic materials. At present, sensorised textiles have been studied only in laboratory, without any solution for industrial production and applications in real conditions. Nevertheless, in technical literature, there are some studies made on multifunctional textiles.

Zangani [1] describes the development of technologies for manufacturing textiles with integrated sensor fibre, designing both the best configuration of the textile, in terms of mechanical and physical performances after the application in situ and the type of the optical sensor to be inserted inside the fabric. Besides, the application of sensorised textile on masonry structure is studied varying the constituent materials and performing mechanical tests, in order to find the best configuration for real applications. Liehr [2] studied the performance of a multifunctional grid-like textile of different mesh size and reinforcement properties, inside which a distributed Polymer Optical Fibre (POF) strain sensor, based on the Optical Time Domain Reflectometry (OTDR), is inserted in order to reinforce and retrofit masonry structures. Several small-scale tests were made on structural elements reinforced by this multifunctional textile applied with a cementitious matrix, in order to verify the suitability of the POF strain sensor for crack detection, recording the crack opening both with POF sensor and with displacement transducers. The smallest crack size measured was equal to 1 mm and its position can be determined with an accuracy of 10 cm.

The work described in the present paper was conducted within POLYTECT project (Polyfunctional Technical Textiles against Natural Hazards), whose main aim is to develop new multifunctional textile structures to retrofit masonry structures and earthworks, in civil applications. Particularly, in the present work, a multifunctional textile, inside which a PA6 (Polyamide 6) tube was inserted during the weaving process, has been studied. The innovation of this textile is that the optical fibre sensor can be inserted inside the tube, even after the application of the composite material on masonry structures, in the points of major interest for the structural analyzer.

The first aim of the tensile tests done on the multifunctional textile was to characterize its mechanical properties, evaluating their possible reduction, caused by the presence of the internal tube. Besides, linearity of the measuring response was checked and the gage factor was identified, taking into account that embedding the sensor in a different structure could, in principle, alter its measuring behaviour. Finally, flexural tests were performed on small scale masonry samples reinforced with the textile, in order to test the measuring performance of the multifunctional textile in possible real applications.

2. Materials and Methods

2.1. Design of the Textile

In the first stage of this work the design of the textile was performed. Taking into account the way of application of composite materials in real structures (by hand-lay up technology, mainly using an epoxy resin), the fabric was chosen with a unidirectional textile architecture with a low surface density, allowing a good impregnation by the polymeric matrix and making the fabric application more versatile, once varying the necessity of reinforcing design. Particularly, preliminary tests were done in order to evaluate the wettability of the fabric by the polymeric resin and in order to choose the best surface density. Besides, considering both the good mechanical properties and the suitable cost in comparison with other types of fibres, E-glass fibres were chosen for the production of the textile.

Successively, the tube to be inserted inside the fabric was chosen in terms both of material type and of dimensions. In fact, tube material has to create a good chemical link with the resin of the laminate, in order to follow the deformation of the composite material during service conditions. At the same time, considering dimensions, tube has to be neither too big, in order not to create large defect inside the laminates with consequent considerable reduction of the mechanical properties, nor too small, in order to permit FOS to be inserted inside. First of all a preliminary research was made about the material of the different types of flexible tubes commercially available. Successively, their physical properties (polarity, free surface energy, friction coefficient) were studied and compared. Besides, preliminary tests were carried out, unthreading the tube outside a laminate, produced using a unidirectional E-glass fabric with a woven tube and commercial epoxy resin through hand lay-up, after resin cure. The tubes used in this preliminary tests were made by PTFE (Teflon), PA6 (Polyamide 6) and PA11 (Polyamide 11). While PTFE tube was easily unthread from the laminate with a simple and low hand force, PA6 and PA11 were not able to coming out from the laminate: the tube broke at its end part (outside the laminate) showing a greater deformation before rupture. In fact, PA has higher free surface energy, in comparison with PTFE. Besides, PA6 has higher polarity [3] and a lower value of contact angle [4], that are higher adhesion bond properties, and a lower cost in comparison with PA11. Consequently, the material chosen was PA6 and the tube had an external diameter equal to 2 mm and an internal one equal to 1 mm. Particularly, the tube was chosen with this small value of the internal diameter because it could be flattened by the machine during the weaving process. At last, tests of inserting an optical fibre (without any sensor) inside the tube were performed, in order to make the insertion easier and faster. After several and different attempts, the best way seemed to be applying a PTFE lubricating spray at the end point of the optical fibre.

In conclusion, the designed multifunctional textile was a unidirectional E-glass fabric (410 g/m^2), with PA6 tube (external and internal diameters equal to 2 mm and 1 mm respectively), inserted directly during the weaving process, along the 0° fibres direction of the fabric itself (Fig. 1).

This fabric was made by SELCOM that is one of the industrial partners of POLYTECT project.

2.2. Main Characteristics of FBG (Fibre Bragg Grating) Sensors

FBG (Fibre Bragg Grating) sensors have attracted considerable attention since their development as strain and temperature sensors in the late 1980s. The use of FBGs as embedded sensors in fibre composite materials to provide in situ measurements of strain, temperature, corrosion, vibration and state of cure has been reported by a number of researchers. The advantages associated with the use of optical fibre sensors range from immunity to electromagnetic interference to signal stability and suitability for long-term monitoring and wavelength multiplexing.



Fig. 1. Multifunctional textile.

The last is particularly useful in practical sensing applications, where large number of sensor may be required to properly monitor various aspects of a structure. The preferred approach is serial multiplexing where several sensors are connected along a single line providing quasi-distributed sensing capability.

Typically, an FBG sensor consists of a single mode fibre with a short length grating written within the core. The grating is photo-induced by exposing the appropriate section of fibre to an interference pattern produced by either the intersection of two ultra-violet laser beams or a phase mask. The light and dark fringes of the interference pattern induce a permanent modulation of the refractive index with a period Λ in the core. Hence, if a broadband light signal is travelling into the fibre, the grating acts as a filter, reflecting only the light component at a specific wavelength λ_{Bragg} that is related to Λ by the Bragg equation:

$$\lambda_{Bragg} = 2n_{eff}\Lambda, \quad (1)$$

where n_{eff} is the effective refractive index.

The remaining optical spectrum is unaffected. When the FBG is strained, changes in Λ and n_{eff} lead to changes in the Bragg condition, resulting in a shift of the reflection spectrum. The theoretical wavelength shift for isothermal conditions is given by:

$$\frac{\Delta\lambda_{Bragg}}{\lambda_{Bragg}} = (1 - p_e)\varepsilon, \quad (2)$$

where the strain over the length of the sensor is $\varepsilon = \frac{\Delta L}{L}$ and p_e is the strain-optic coefficient for the fibre.

With regards to embedding of FBG sensors in FRPs, a major attention must be paid to sensor placement, as an improper alignment along the loading direction can result in coarse measurements errors. Moreover, improper embedding of FBG sensors in FRPs can result in non-uniformly strain of the grating, leading to a distortion of the reflection spectrum. Finally, both distortion of the FBG spectrum and birefringence inducing additional Bragg reflection may occur as a result of non-uniform longitudinal or transverse residual stresses generated during the manufacturing process.

2.3. Production of Specimens for Mechanical Tests

The mechanical tests performed were tensile tests on composite material (ASTM D 3039/D 3039M) and flexural tests on small-scale masonry beams. For comparison purposes, strains were recorded both with optical fibre sensor and with surface-bonded electrical strain gages.

2.3.1. Specimens for Tensile Tests on Composite Material

Laminates for tensile specimens were made through hand lay-up technology, in order to characterize the textile in the same condition of application used in real applications. Laminates were produced using one ply of fabric and a commercial epoxy resin (MapeWrap 31 by MAPEI). Particularly, laminates were made putting the fabric between two layers of resin and removing air bubbles using a roller. Specimens were produced both without (Reference – EPA series – 8 repetitions) and with (Sensorised – EPAS series – 6 repetitions) the tube inside, in order both to characterize the fabric and to evaluate the possible reduction of mechanical properties. Specimens, produced from these laminates, were 350 mm long and 40 mm wide. Sensorised specimens had the tube positioned in the middle of its width and along its length (tube was fixed inside the laminate only for 140 mm), as shown in Fig. 2.



Fig. 2. Sensorised tensile specimen.

Particularly, before inserting FBG sensor inside the tube, two little holes were made near the two end points where tube was well linked with the composite material. After this, the sensor was inserted inside the tube, aligned with a slight pre-stretching and fixed to the composite material with glue.

2.3.2. Specimens for Flexural Tests on Small-scale Masonry Beams

Flexural tests (four point bending – 3 repetitions) were performed on small-scale masonry beams, in order to verify the smooth functioning of the FBG sensor when the multifunctional textile is applied in real applications. The masonry used in these tests was “Pietra Leccese” stone, a calcareous sedimentary rock, typical of a part of the South-East of Italy. Beams were of length, width and height equal to 1200 mm, 70 mm and 150 mm respectively. They were reinforced with one ply of multifunctional textile applied on the tension side and using also two U shear reinforcements (one ply) to be applied in the parts in contact with the two support noses. The fabric applied was 1400 mm long and 60 mm wide. On the contrary, U shear reinforcements were 270 mm long and 80 mm wide. Before the application of the multifunctional textile with a commercial epoxy resin (MapeWrap 31), the surface was pre-treated with a preliminary sandpapering and cleaning, followed by the application of an epoxy primer (MapeWrap Primer 1 by MAPEI) and an epoxy putty (MapeWrap 11 by MAPEI). The specimens are shown in Fig. 3:

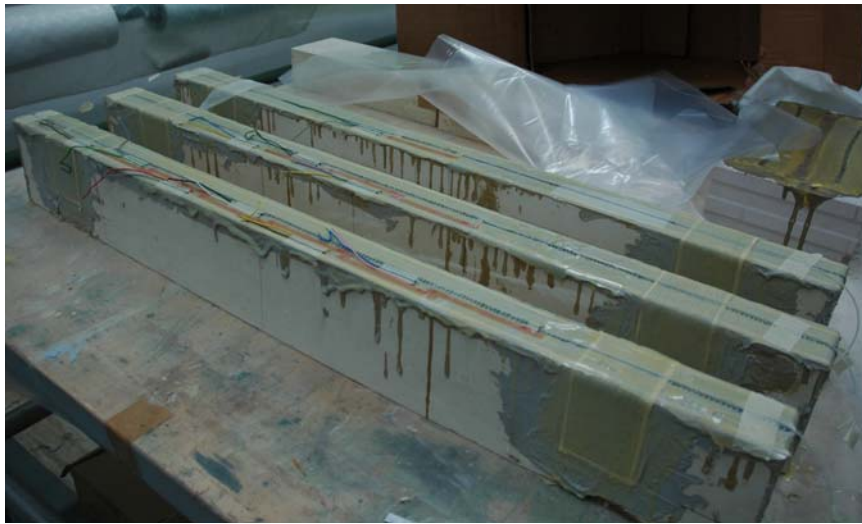


Fig. 3. Sensorised flexural specimens.

3. Experimental Results

3.1. Mechanical Properties

Tensile tests were performed following the technical procedure describe in ASTM D 3039/D 3039M. The universal testing machine (MTS Insight 100) used for these tests was equipped with mechanical grips and a 100 kN load cell. Particularly, a 2 mm/min displacement speed was used. Strain measurements were made with strain gages (PFL-30-11, produced by Tokyo Sokki Kenkyujo Co., Ltd and with a gage length equal to 30 mm), with extensometer (gage length equal to 50 mm) and with FBG sensors (produced by Broptics, model OS1500, with a nominal strain sensitivity equal to 1.20 pm/ μ strain, with three different values of λ_{Bragg} equal to 1541 nm, 1549 nm, 1557 nm and with a fixed gage length equal to 140 mm). Besides, a strain gage was positioned on the surface of the composite material, near the tube and along the longitudinal axis of the specimen. The main results, both for Reference (series EPA) and Sensorised (series EPAS) specimens are shown in Table 1 and Table 2, respectively, where P_{max} is the Maximum Load, R_u the Tensile Strength, ϵ_u the Ultimate Tensile Strain and E the Elastic Young's Modulus. In addition to the single values for each specimen, also the mean value (Mean) and the coefficient of variation (CV) are reported.

Table 1. Reference specimens (EPA series).

P_{max} [N]	R_u [MPa]	ϵ_u [%]	E [GPa]
13310	2144	2.4	103
11485	1844	1.9	103
11961	1916	1.8	115
12756	2061	2.2	103
12712	2062	2.3	98
12679	2054	2.1	109
11462	1885	2.1	101
10915	1751	1.7	120
Mean: 12160	Mean: 1964	Mean: 2.1	Mean: 106
CV: 6.8 %	CV: 6.9 %	CV: 9.5 %	CV: 7.5 %

Table 2. Sensorised specimens (EPAS series).

P_{max} [N]	R_u [MPa]	ϵ_u [%]	E [GPa]
13167	2114	2.0	114
13233	2126	1.9	127
13836	2232	2.0	117
12300	1979	2.1	106
11180	1788	1.7	113
13142	2094	2.0	115
Mean: 12810	Mean: 2056	Mean: 2.0	Mean: 115
CV: 7.3 %	CV: 7.5 %	CV: 6.8 %	CV: 5.9 %

The variation of these mechanical properties, comparing results of both Reference and Sensorised specimens, is reported in Table 3:

Table 3. Variation of mechanical properties.

P_{max}	R_u	ϵ_u	E
+ 5.3 %	+ 4.6 %	- 5.8 %	+ 8.3 %

Statistical tests, made on all these specimens, show that these variations are not statistically significant, except for Young's Modulus. This is probably due to the fact that, during laminates production, there is an accumulation of resin near the tube, which just causes a noticeable local increase of the stiffness of the laminates themselves.

Consequently, we could conclude that the presence of the tube inside the multifunctional textile does not affect the mechanical properties of the fabric.

3.2. Sensor Strain Sensitivity

Making a long gauge strain sensor by fixing a FBG sensor in two points of the tube inside the composite material, the strain sensitivity expected for the so made long gauge sensor could be altered with respect to the nominal strain sensitivity of the "bare" FBG sensor; consequently, its check is required. At this aim, tensile tests were carried out, in which strains were recorded using both strain gages and FBG sensor. Since all tests were carried out in temperature controlled environment, the thermal effect could be neglected in the study.

Linearity of the λ - ϵ relationship is evaluated verifying that the ratio between the Bragg wavelength λ of the FBG sensor and the strain ϵ , measured by the strain gages, is constant during the test. The curve shown in Fig. 4 was used for the evaluation of the strain sensitivity of the sensor, after its application (the optical fiber sensor is inserted inside the tube and, successively, fixed with glue at the end points of the chosen gauge length) inside the multifunctional textile; the curve shown in Fig. 4 is fully representative of the linearity of the curve obtained for all used FBG sensors:

According to Fig. 4, the linearity of the curve was verified during the entire test for each specimen. The strain sensitivity α of the developed sensor, defined as:

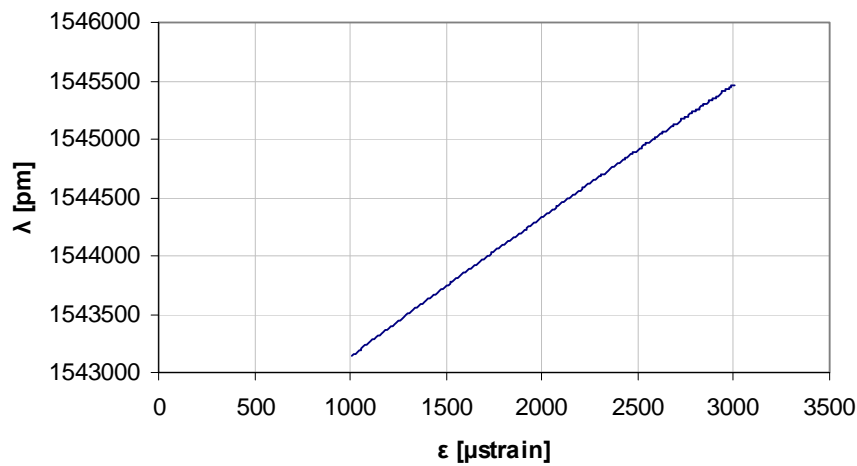


Fig. 4. Evaluation of the strain sensitivity of the embedded sensor (EPAS02).

$$\lambda = \alpha \cdot \varepsilon, \quad (3)$$

and calculated as the slope of the curve of Fig. 4, is shown for each specimen, in Table 4. We can notice that these values are repeatable and comparable. Besides, they are not so far from the expected value of strain sensitivity, given in the technical data sheet, equal to 1.2 pm/ $\mu\varepsilon$.

Table 4. Values of sensor strain sensitivity α .

Specimen	α [pm/ $\mu\varepsilon$]
EPAS01	1.19
EPAS02	1.16
EPAS03	1.13
EPAS04	1.10
EPAS05	1.11
EPAS06	1.23
Mean value	1.15
C.V. [%]	4.41

3.3. Flexural Tests Results

Flexural tests (four points bending) were carried out in order to verify the smooth measuring functioning of multifunctional textile, when applied in real applications. Test set-up is shown in Fig. 5.

The span was chosen equal to 900 mm while the distance between the loading noses equal to 200 mm. The speed of test was 2 mm/min. The gage length of FBG sensors was different for the three different beams: 120 mm for specimen PL F120, 360 mm for specimen PL F360, 720 mm for specimen PL F720. Sensors were fixed to the reinforcement, applied on the tension side, in the same way described for tensile specimens. Besides, long uniaxial (PL-120-11, produced by Tokyo Sokki Kenkyujo Co., Ltd. and with a gage length equal to 120 mm) strain gage were fixed near the tube, in order to compare both the strain measurements. The comparison between the strain obtained with FBG sensors (according to equation (3), where the wavelength was zeroed respect to Bragg wavelength, and using the mean value of the sensor strain sensitivity of the Table 4) and with strain gages (evaluated as mean value of the readings of the reference strain gages) is shown in Fig. 6-8, for PL F120, PL F360 and PL F720 specimen respectively.

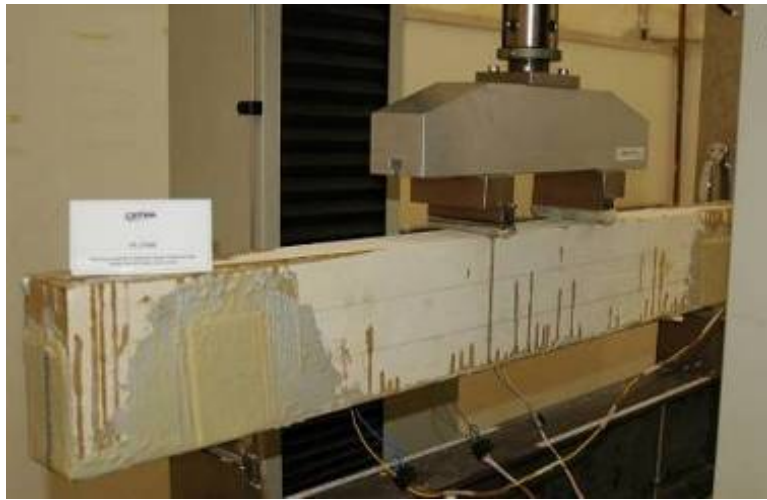


Fig. 5. Set-up of flexural tests.

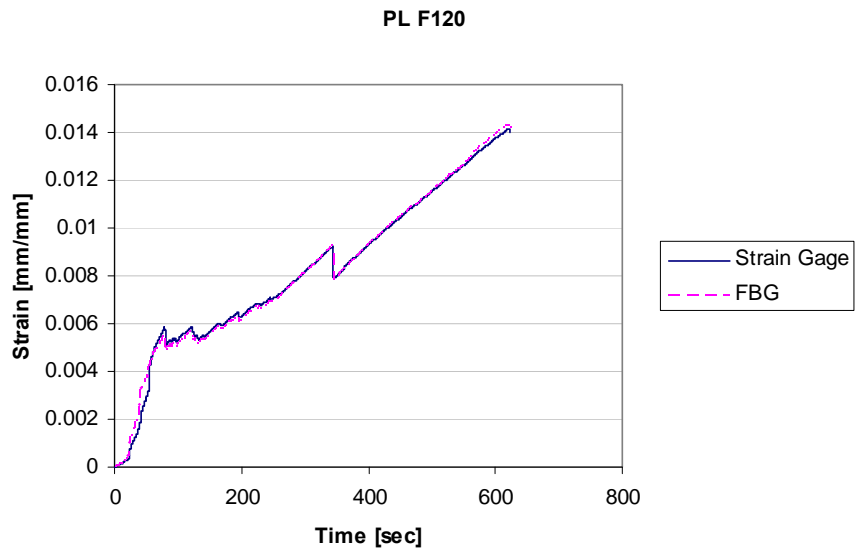


Fig. 6. PL F120 specimen.

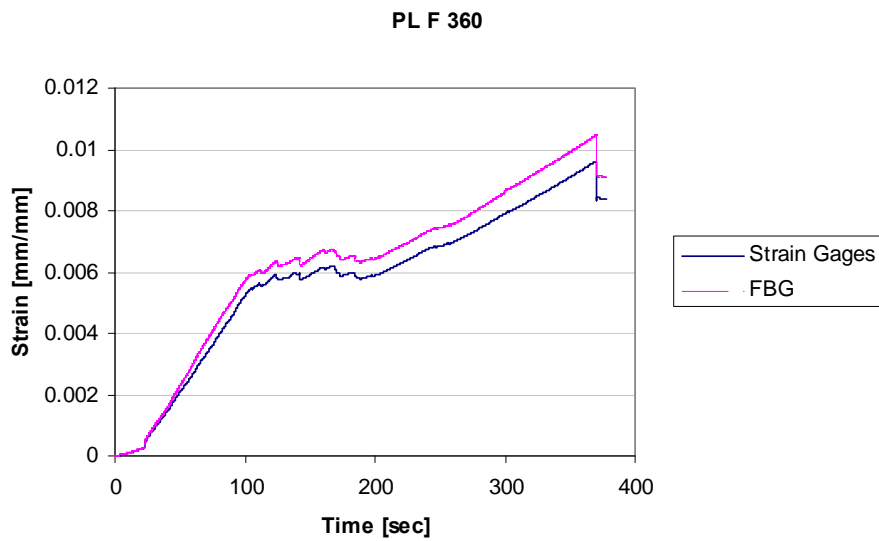


Fig. 7. PL F360 specimen.

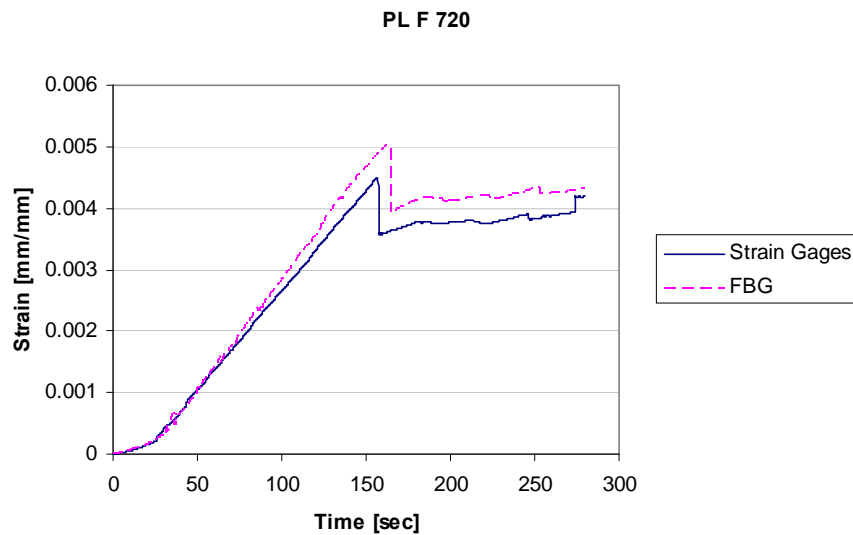


Fig. 8. PL F720 specimen.

From the figures, we can notice that the strain measured with both sensors was almost the same for all the specimens, thus assessing the effectiveness of the multifunctional textile for structure retrofitting and health monitoring purposes. The slight differences can be attributable to the fact that FBG sensor and strain gages are positioned in non perfectly coincident points and to the fact that FBG and strain gage have different geometry and, consequently, different gage lengths. The latter explanation found confirm in the optimum agreement obtained with PLF120 that have the same gauge length of the resistive strain gauge. For each specimen, the trend of the two curves is the same until the end of the test, pointing out that the embedded FBG sensors are able to follow very well the extension of the beam.

4. Conclusions

In this work, an experimental study was performed on a multifunctional textile that is a textile for civil applications, able, at the same time, to reinforce structures and to monitor their strain. This is achieved through the presence of an FBG sensor inserted inside a tube, woven in the fabric during the manufacturing process. After the design of the textile architecture, the fabric was characterized, verifying that the presence of the tube does not affect mechanical properties of the fabric. Besides, a check of the sensor strain sensitivity was carried out after the fixing of the sensor in two points of the tube. Successively, the smooth functioning of the multifunctional textile was checked in flexural tests on small-scale masonry beams reinforced with such textile, verifying that the sensorised textile is able to correctly measure the strain of the structural elements.

At last, once verified the effectiveness and the smooth functioning of this new fabric, we can conclude that the innovative and original aspect of this work is the design and the production of a new multifunctional textile which can both reinforce and monitor the structure where it is applied. Particularly, the innovation is that the sensor can be inserted inside the fabric (particularly, in the tube woven inside), also after the reinforcing intervention, permitting a better installation of the sensor and avoiding, in this way, problems which could appear during fabric installation (use of rollers and trowels which could damage sensor, for example). At last, points to be monitored can be chosen also after the fabric installation: in this way reinforcing and monitoring phase can be separated.

Further studies will be focused on the development and the characterization of other multifunctional fabric with different textile architecture and different types of sensor inserted inside (distributed

sensors, etc.), in order to make the project of the reinforcement more versatile and to increase the number of the monitored points. At the same time, new techniques for a faster, easy, cost-effective and reliable installation in real structures will be studied and tested.

Acknowledgements

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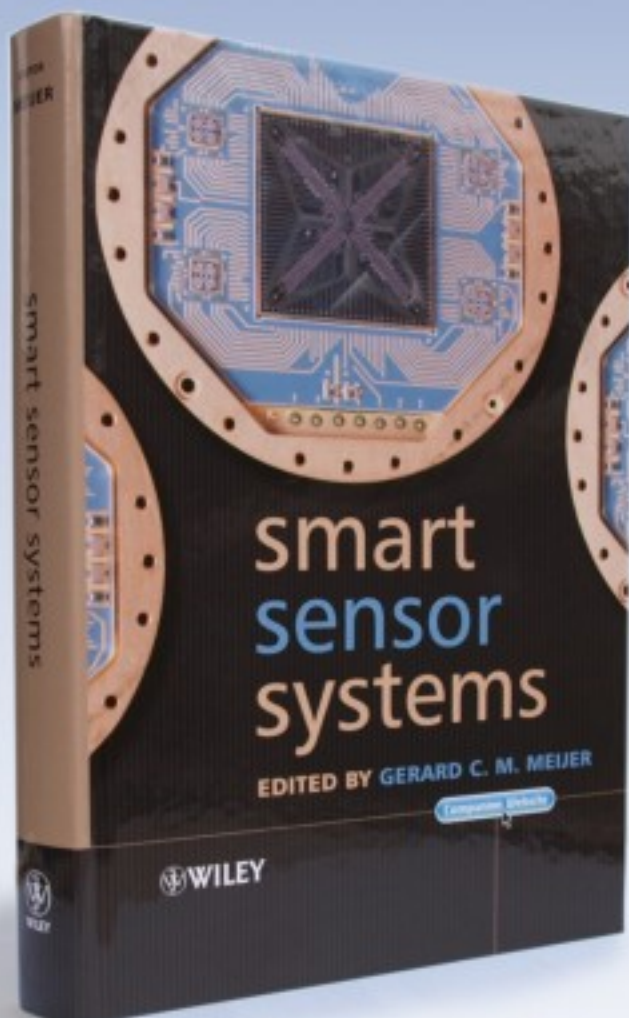
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