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To cite this article: C. Mazzotta *et al* 2025 *JINST* **20** C05003

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7th INTERNATIONAL CONFERENCE FRONTIERS IN DIAGNOSTIC TECHNOLOGIES
INFN RESEARCH CENTER OF FRASCATI, ITALY
21–23 OCTOBER 2024

Prototype tests of integrated systems CRM-FBG sensors for civil structural health monitoring

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ABSTRACT: CRM (Composite Reinforced Mortar) with embedded FBG (Fibre Bragg Grating) sensors were tested in order to guarantee long-term effectiveness end of reinforcement as well as continuous monitoring, indeed, to measure mechanical parameters for Structural Health Monitoring (SHM) of civil engineering structures, fiber optic sensors based on FBG technology are not infrequently used. FBG sensors are particularly suitable for permanent monitoring applications in civil structures, being able to specifically exploit some unique characteristics: resistance to atmospheric agents, low invasiveness of both the sensors and the wiring.

The tests presented in this study highlight the reliability of the proposed CRM-FBG integrated system for both structural reinforcement and long-term health monitoring.

KEYWORDS: Overall mechanics design (support structures and materials, vibration analysis etc); Detection of defects; Instruments for environmental monitoring, food control and medical use; Real-time monitoring

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1 Introduction

Preserving the integrity of the built heritage by detecting degradation, as well as monitoring the behaviour of civil structures in response to vibrations or seismic phenomena is a challenge that is addressed by proposing different approaches and lines of research. A secure strategy is ensuring that strengthening systems used for structural upgrades remain effective over time, while their condition and any potential degradation are consistently monitored.

Among the modern technologies to improve the robustness of historical structures, innovative mortar-based composites like Fabric Reinforced Cementitious Matrix (FRCM) and Composite Reinforced Mortar (CRM) [1–4] offer notable benefits. These systems utilize high-strength fabrics (FRCM) or Fiber Reinforced Polymer (FRP) meshes made from materials such as carbon, glass, basalt, or ultra-high-strength steel. The fabrics or meshes are affixed to the exterior surfaces of structural components using inorganic matrices, including lime, cement, or geopolymer mortars.

This study exposes some tests on CRM with embedded FBG sensors to guarantee both long-term effectiveness end of reinforcement and continuous monitoring. Indeed, the integration of FBG sensors into technical textiles, widely applied in the structural retrofit and seismic upgrade of earthen-work and masonry structures, emerges as a promising solution and it is furtherly confirmed by these tests.

2 FBG technology

FBG sensors are produced in the core of the fiber, as a short length (a few mm) diffraction grating. The principle of operation of the FBG sensors is based on the diffraction occurring at the grating: if broadband light is launched in the fiber, a quasi-monochromatic counter propagating light originates (figure 1).

The wavelength of the diffracted light depends on the thermoelastic parameters of the core at the grating so that, by performing spectral analysis of the counter propagating light, information about the strain and the temperature variation can be obtained. Indeed, the refractive index and pitch of the grating are affected by the axial strain and the temperature variation experienced by the grating itself.

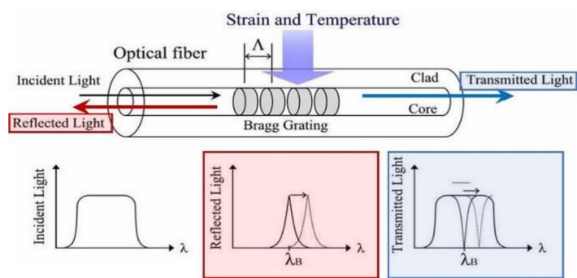


Figure 1. Scheme of the FBG sensors principle of operation, the reflected light moved proportionally to the elongation of the grating (change in the refractive index) due to the support deformation.

This is how the peculiarities of FBG-based fiber optic sensors are found suitable and widely used to produce monitoring systems for measuring mechanical parameters for SHM of civil engineering structures [5–9]. Since many FBG sensors can be connected in series along an optical fiber and operated in Wavelength Division Multiplexing mode, a dense pattern of sensing points closely positioned along the routing of the optical fibre can be easily installed. That installation pattern is usually referred to as a quasi-distributed (or quasi-continuum), as it can provide a very high sampling of the measurement over a full surface or length.

3 CRM technique and experimental set up

The FRP is a reinforcement technique through the application of fabrics and sheets of glass, carbon and aramid fibers through thermosetting resins; as well as the FRCM, which involves the use of fabrics in various types of fibers applied through inorganic matrices (mortars); and the CRM, an intervention technique through preformed fibrous-based reinforcements and inorganic mortars. The Composite Reinforced Mortar technique can be traced back to that of traditional reinforced plaster on existing walls, which involves the use of a reinforcement armor made up of preformed meshes and angles in glass fibers (GFRP Glass Fiber Reinforced Polymer) or carbon (CFRP) embedded in a structural mortar based on lime or cement [10].

With the scope to demonstrate efficacy of seismic retrofitting and monitoring integrated systems (i.e. equipped with sensors) to monitor strengthened masonry structures combining Glass Composite Reinforced Mortar (GCRM) composites by embedding FBG sensors, some tests were performed.

The project involves an experimental working group formed by DICITA (Department of Civil, Computer and Aeronautical Engineering) of the University of Roma Tre, they created the structural reinforcement prototypes, and by the FOS (Fiber Optic Sensors) laboratory of ENEA, which carried out the sensorization of the samples. This work presents a scientific validation, through laboratory tests consisting of: direct tensile tests on the single yarn and

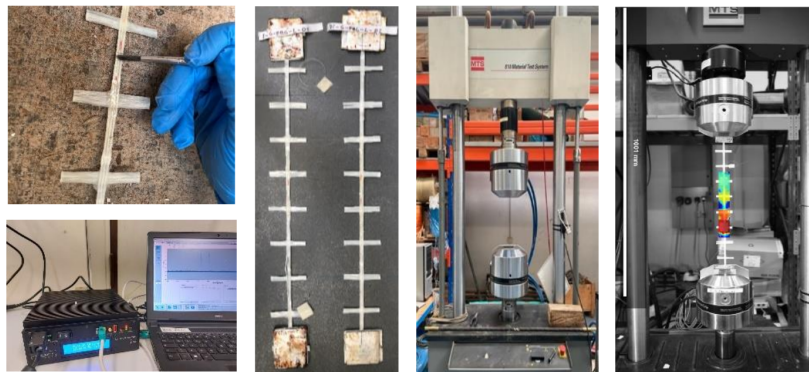


Figure 2. Experimental set up, from left to right: application of FBG sensor into a single yarn specimen; (bottom) the optical interrogator of the FBGs; single yarn specimens; MTS (Module Test System) tensile test machine in Roma Tre University laboratory; the colors target for the Digital Image Correlation technology.

on the coupon, i.e. sample embedded in a GCRM, and bond tests on GCRM applied on masonry support, all equipped by FBG sensors. Once the fabric samples were prepared with sensors embedded, they were subjected to a tensile machine test. The measurements were performed simultaneously, both by collecting the tension data from the tensile machine and with a digital camera, but especially by taking data from the FBG sensors that have a greater sensitivity to deformation, in figure 2 the experimental procedure is exposed.

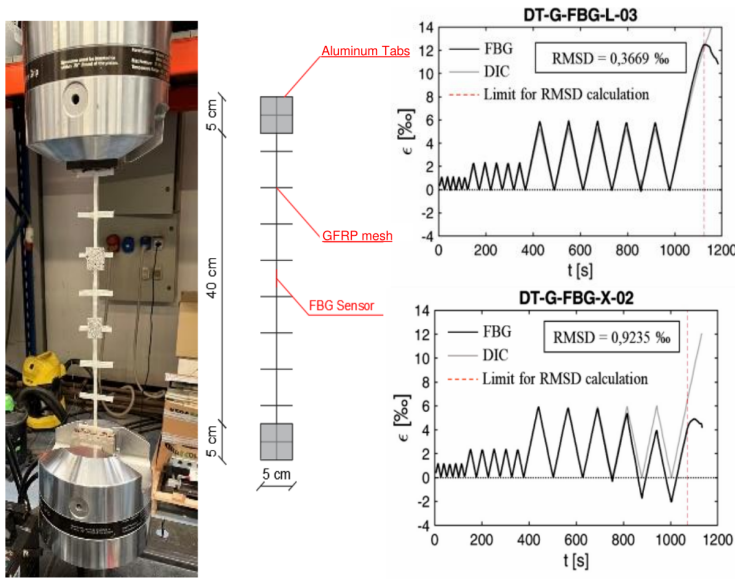


Figure 3. Test on single yarn, from left to right: tensile tests machine; scheme of the specimen and sensors; plots of the cycles as comparison of strain values obtained from FBG sensors with those from DIC for two samples.

to a strain of at least 5 ‰. The measurements of the coupon named DT-G-FBG-X-02 are recorded in the lower plot, at the time of 0.8 s start to show a discrepancy, which can be considered indicative of an internal structural damage, not yet detected by DIC.

FBG sensors have been found to be very promising for this specific SHM application, as they can measure fabric deformation and thus detect a change in the state of stress and a possible initiation of a failure mechanism

4 Tensile tests on coupon

Tensile tests on mesh are the first step to evaluate the elastic behavior and the deformation revealed by the FBG sensors. The second step is to embed the FBG-equipped fabric into a composite material, trying to detect the state of deformation within the composite until failure. The set up and results are shown in figure 4.

FBG signals record the deformation of the mesh at the points where they are applied, measuring the different deformation states on the mesh. The graphs in the figure show how the embedded sensors can detect the slip failure between the glass fabric and the cement matrix, while the other measuring instruments: LVDT (linear variable differential transformer of the testing machine, named MTS in the trace of the graphs) and DIC, can only measure what happens on the outer surface of the composite. This can be seen by the fact that the strain revealed by the three FBG sensors follows the stress trend recorded by the testing machine, where the stress value reaches a maximum value around 200 seconds, and then gradually decreases during the slip phase, while the deformation obtained by the other measuring instruments continues to increase.

Third type of tests regards the single-lap shear bond tests on the CRM reinforcement, with FBGs embedded, applied on a masonry substrate [14, 15]. The FBG sensors can help to interpret the type of displacement and/or breaks occur during the traction. In figure 5, the first drawing illustrates the types of sliding; a cycle test is traced in the plots. The sensor positioned on the horizontal yarn reports that it is substantially not involved during the tests (CH3 cyan trace). It can be observed that during the final tensions the break of the left and right side can be distinguished thanks to the FBG sensors. The digital camera can observe the crack externally (photos before and after the crack), it is marginally useful for interpreting the sliding (pink trace). It can be concluded that it is a case of slip and breakage of both yarn (D and E1 types of the upper drawing).

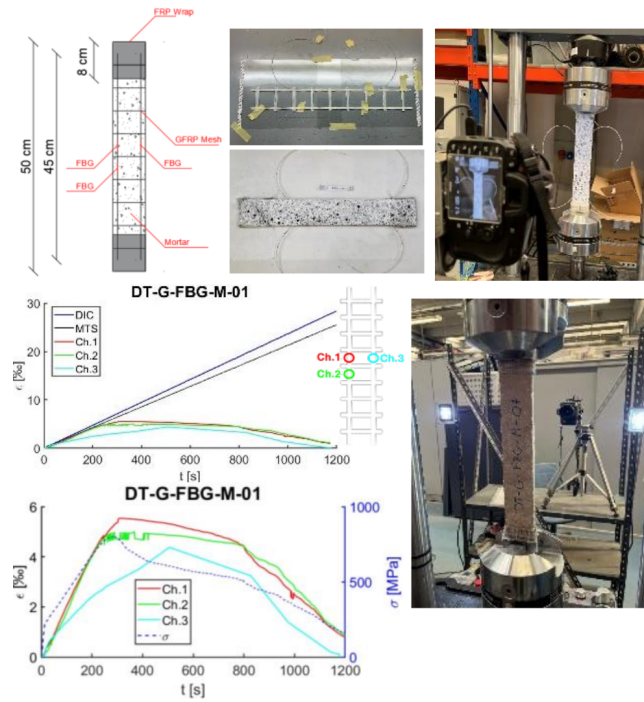


Figure 4. Experimental set up of direct tensile test on composite: scheme and photos of the compound and set up. In the upper plot a linear tension test up to break is shown, the second plot is a zoom: the y axis reports the FBG strain (left), and the tension applied (right axes).

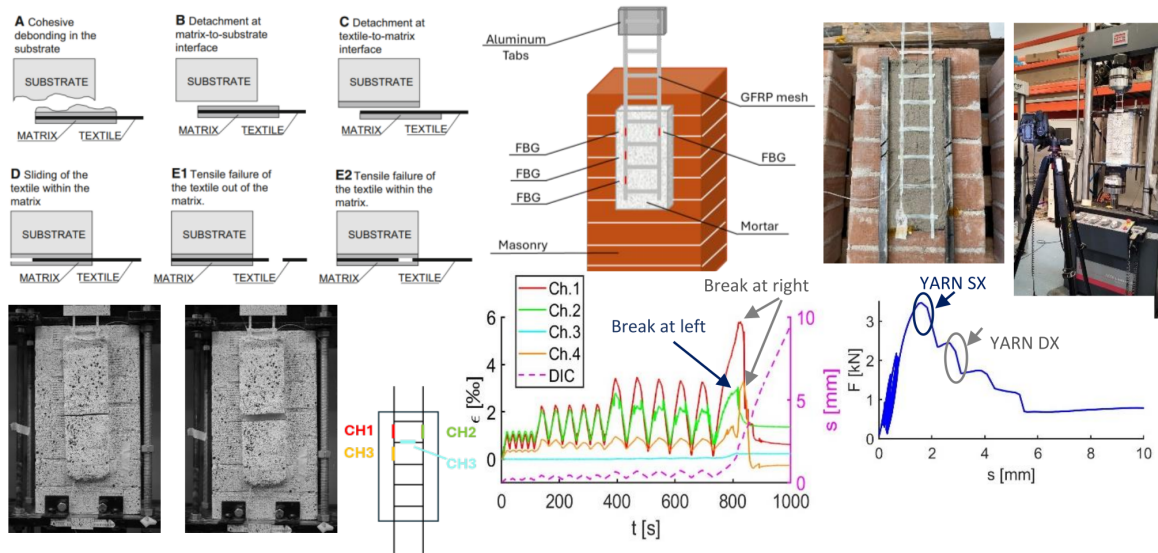


Figure 5. Bond test of the mortar on the masonry substrate, the FBG sensors identify the type of sliding. Upper left drawing, types of breakage [16]; in the middle, scheme and picture of the sample; at right, photos during the test. At the bottom, from the left to right: digital images during the strain until breakage and the plots of the measurements. Reproduced from [16], with permission from Springer Nature.

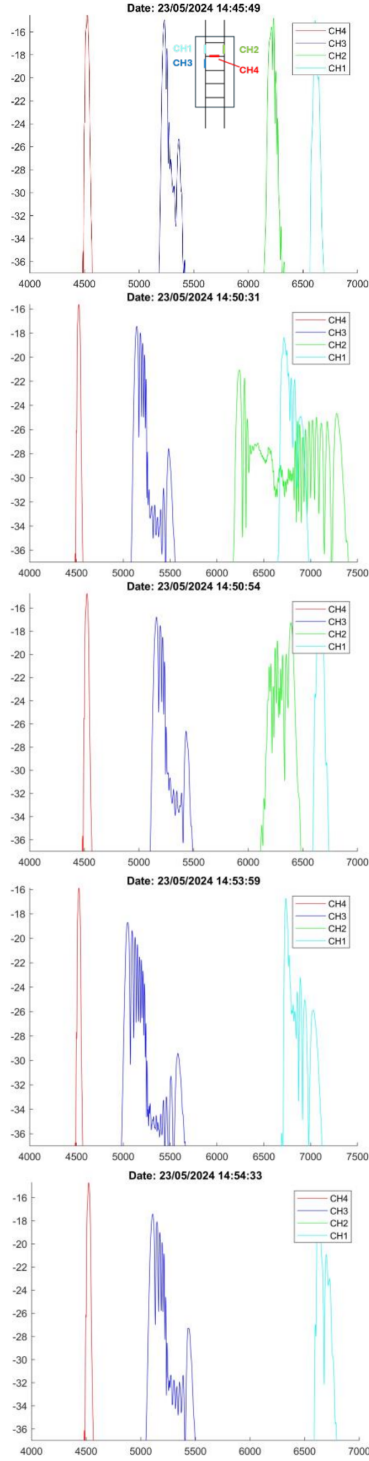


Figure 6. Spectra of four sensors during a bond test of the mortar on the masonry substrate. Top frame: spectra before the test and FBGs scheme, second and third plots during the stress, bottom plots: relaxing and end of the test.

The figure 6 shows the spectra of four sensors at different times during another tension test, before (top graphs), during and at final phase of it. The spectra before the test will obviously be approximately like the nominal ones reported by the manufacturer, however the blue trace (CH3) already shows a hint of a typical double peak (behavior that will be analyzed shortly). In the subsequent moments, during the stress phase, while channel 4 (red peaks, in this sample is placed horizontally) is not at all sensitive to vertical tension as expected, the channels 3, 2 and 1 show extremely distorted spectra. In the final phase of the test (bottom frames) the signal of channel 2 (green trace) is no longer reported, because the fiber breaks due to the tear resulting from the applied tension. It's interesting to note that the spectrum of channel 1 returns to being coincident with the shape it had before tensioning. Indeed, this sensor suffered a wide distortion, but at the end of the test it slipped, that is, it was detached with respect to the mortar or the fabric and therefore returned to its relaxed state.

As regards the blue spectra of channel 3, it is interesting to investigate this phenomenon further. During the phase of extreme stress that precedes the breakage of the sample, it may happen that the Bragg grating deforms to the point that the spectrum appears noisy or with multiple peaks. In this case, if it was necessary to follow the breakage phase until the last instant, an algorithm that follows the main peak must be provided. The explanation of the physical phenomenon that causes the presence of multiple peaks is related to the deformation of the grating due to compressions on directions transversal to the main axis (which is the one for which the variation of the nominal wavelength is expected and measured). The case of two peaks can be interpreted as a model of a birefringent crystal, where the asymmetry of the crystal determines the emission of two close wavelengths.

5 Conclusion

In this paper, experimental measurements of integrated systems CRM-FBG by embedding fiber optic sensors into innovative reinforced mortar-based composites are presented. The solutions developed by DICITA department of Roma Tre University within the project can be applied for specific reinforcement and monitoring purposes in the field of civil engineering. The sensors were prepared and tested in the FOS laboratory of the ENEA Research Centre in Frascati. The developed solutions proved to be extremely promising. In fact, the measurements demonstrate one of the most peculiar characteristics of FBG sensors, namely the ability

to measure, with great sensitivity, microdisplacements inside concrete structures, such as to identify the type of damage occurred inside the composite.

Indeed, it has been highlighted as through a detailed analysis of both the temporal trends and the spectra, it is possible to provide precise information useful for creating a behavioural model during an effort. The long-term stability for quasi-static measurements as well as those of rapid response to transient events, allow to implement long-distance structural monitoring procedures without the local power supply, it is for this reason that large developments of these techniques are expected.

References

- [1] S. Babaeidarabad, F. De Caso and A. Nanni, *Out-of- Plane Behavior of URM Walls Strengthened with Fabric-Reinforced Cementitious Matrix Composite*, *J. Compos. Constr.* **4** (2013) 04013057.
- [2] S. De Santis et al., *Out-of-plane seismic retrofitting of masonry walls with Textile Reinforced Mortar composites*, *Bull. Earthquake Eng.* **17** (2019) 6265.
- [3] S. De Santis and G. de Felice, *Shake table tests on a tuff masonry structure strengthened with composite reinforced mortar*, *Compos. Struct.* **275** (2021) 114508.
- [4] P. Meriggi, S. De Santis, S. Fares and G. de Felice, *Design of the shear strengthening of masonry walls with fabric reinforced cementitious matrix*, *Constr. Build. Mater.* **279** (2021) 122452.
- [5] K.O. Hill and G. Meltz, *Fiber Bragg grating technology fundamentals and overview*, *J. Lightw. Technol.* **15** (1997) 1263.
- [6] M.A. Caponero, *Fiber Optic Sensors for Structural and Geotechnical Monitoring*, MDPI (2020) [DOI:10.3390/books978-3-03936-033-8].
- [7] C. Mazzotta et al., *The PREFOS project: fiber optic monitoring system for prefabricated buildings*, Volume ENEA (2024), p. 105 [ISBN digital: 978-88-8286-476-7; ISBN printed: 978-88-8286-477-4].
- [8] A. Castaldo et al., *Strain and vibration measurements by FBG sensors for engineering applications*, **2023 JINST 18 C06030**.
- [9] M.A. Caponero, *Use of FBG sensors in advanced civil engineering applications*, **2023 JINST 18 C07020**.
- [10] L.A.S. Kouris and T.C. Triantafillou, *State-of-the-art on strengthening of masonry structures with textile reinforced mortar (TRM)*, *Constr. Build. Mater.* **188** (2018) 1221.
- [11] G. Montesano et al., *Sviluppo e Testing di u sistema WIM con sensori in fibra ottica FBG*, RT/2024/8/ENEA, paragraph 2.3.
- [12] S. De Santis et al., *Investigation on a prototype integrated system for strengthening and monitoring architectural heritage*, in the proceedings of the 2022 IMEKO TC4 International Conference on Metrology for Archaeology and Cultural Heritage, Rome, Italy, 19–21 October 2023 [DOI:10.21014/tc4-arc-2023.149].
- [13] S. De Santis et al., *Experimental characterization of a novel combined composite reinforced mortar — fibre Bragg grating technology for the retrofit and control of existing structures*, *Acta IMEKO* **13** (2024) 1.
- [14] S. De Santis et al., *Direct Tensile Tests on a CRM-FBG Integrated System for the Reinforcement and the Structural Health Monitoring of Masonry Structures*, in *18th International Brick and Block Masonry Conference*, Springer Nature Switzerland (2025), p. 611–621 [DOI:10.1007/978-3-031-73310-9_43].
- [15] G. Moretti et al., *Shear bond tests on a novel integrated reinforcement-monitoring system for architectural heritage*, in the proceedings of the *IEEE International Conference on Metrology for Archaeology and Cultural Heritage*, Valletta, Malta, 7–9 October 2024.
- [16] G. Felice et al., *Recommendation of RILEM Technical Committee 250-CSM: Test method for Textile Reinforced Mortar to substrate bond characterization*, *Mater. Struct.* **51** (2018) 95.