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Investigation on a prototype integrated system for strengthening and monitoring architectural heritage

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***Abstract* – Composite Reinforced Mortar (CRM) is an advantageous system for the upgrade of existing structures and is particularly suitable for architectural heritage. Despite the acknowledged importance of continuous structural health monitoring (SHM), effective technologies have not been developed yet for CRM-strengthened buildings. This paper describes a preliminary investigation on a novel system, which integrates CRM with Fibre Bragg Grating (FBG) sensors. Direct tensile tests were carried out as the first step of a wider prototype development programme. Strains measured by FBG sensors were validated against those provided by Digital Image Correlation, showing the reliability of the proposed CRM-FBG integrated system for combined strengthening and SHM purposes.**

I. INTRODUCTION

A sustainable approach for safeguarding the built heritage requires that the strengthening systems applied for structural upgrade ensure their effectiveness in the long term and that this, or their possible deterioration, is controlled at any time. Among the available technologies for enhancing the capacity of historic structures, innovative mortar-based composites such as Fabric Reinforced Cementitious Matrix (FRCM) [1, 2, 3] and Composite Reinforced Mortar (CRM) [4, 5] are particularly advantageous. They comprise high strength fabrics (FRCM) or Fibre Reinforced Polymer (FRP) meshes, made of carbon, glass, basalt or ultra-high strength steel. Fabrics or meshes are bonded to the outer surface of structural members by means of inorganic matrices, lime, cement or geopolymer mortars. These composites exhibit high strength-to-weight ratio and, when lime-based mortars are used, ensure physical-chemical compatibility with original substrates [6]. The durability of their constituents is verified in the laboratory after accelerated artificial ageing, according to acceptance protocols [7, 8]. Design guidelines have been developed [9, 10]. Their industrial and commercial development has grown exponentially in the last decade, and they have already been widely installed in the field.

Nevertheless, nobody knows whether or not their effectiveness is kept along the service life of the retrofitted structure. Detachments, deterioration mechanisms, possibly associated with their interaction with the substrate, cracking or local strain concentrations, which could even be invisible to the naked eye, may compromise the strengthening effectiveness. Even if it is of the utmost importance that this can be verified (both during installation and at any time afterwards), no investigations have been devoted to this challenging issue so far. Design guidelines do not include clear information on monitoring and control, since the state of knowledge is still too poor to derive recommendations. On the other hand, current practice resorts to routine test methods developed for concrete, or just avoids testing.

A better understanding needs to be gained on the most suitable methodologies to assess the condition of FRCM/CRM systems and the overall behaviour of the strengthened structure. This could possibly be achieved by reliable non-destructive test methods (NDTs), which can be used on any structure (even if it has already been strengthened) for periodic inspection. High-tech smart strengthening systems could be developed for the continuous monitoring of new retrofitting works on particularly important structures. To this aim, the use of optical fibres housing Fibre Bragg Grating (FBG) sensors [11] appears particularly promising, but only few attempts have been made so far combine them with FRCM, whilst nothing has been done on CRM.

In this work, an integrated system is proposed, which combines CRM reinforcements with FBG sensors. This CRM-FBG combined system is ultimately aimed to allow for a continuous condition assessment and dynamic identification to plan/rank rehabilitation works before severe damage or collapse occur. A wide experimental programme is ongoing for prototype development by a research group including Roma Tre University and ENEA, in charge of the scientific development of the technology and its validation in the laboratory, and Ingegneria Integrata srl, an engineering company leading perspective field pilot applications. The preliminary step of this work is presented in this paper, which includes direct tensile tests on Glass Fibre Reinforced Polymer (GFRP) mesh wire specimens, equipped with FBG sensors housed in optical fibres. Strains detected by FBG sensors were validated against those provided by Digital Image Correlation, showing the reliability of the proposed CRM-FBG integrated system for combined strengthening and SHM purposes.

II. STATE OF THE ART

FBG sensors have been used for years in various fields of engineering, such as aerospace, automotive, biomedicine, mechanics, and industry [12]. Applications in civil engineering are recently growing and many studies have demonstrated their effectiveness for Structural Health Monitoring (SHM). The first ones dealt with geotechnics and were devoted to measure accelerations and pressures for oil exploration [13], to record soil deformations and slopes, to control foundation piles [14], and to monitor tunnel structural stability [15]. FBG were used in hydraulic engineering to measure circumferential strains in pipelines [16] and for the SHM of subsea structures [17].

As for structural applications, FBG sensors proved effective for bridge monitoring, and have been applied to measure strains in post-tensioned railway bridges [18] and to monitor vibrations of railway sleepers under rail traffic [19]. Verstrynge and coauthors [20] developed an integrated technique for crack monitoring in masonry structures based on FBGs, Acoustic Emission sensors and Digital Image Correlation.

An integrated reinforcement with a Glass FRCM and FBG sensors was applied by Valvona and co-authors [21] to a masonry vault. FBG sensors were located near expected cracks and debonding. Mechanical and thermic strains were decoupled using an unloaded sensor, allowing detecting strains due to temperature variation and isolating those generated by loads. FBG sensors were applied to an adobe masonry wall to detect crack growing (as displacement transducers) and for dynamic identification (as accelerometers) by Antunes et al. [22].

Shaikh and co-workers [23] tested concrete beams reinforced with different FRCM systems and investigated the possible use of two types of fibre optical sensors, such as FBG (discrete) and Brillouin optical time domain reflectometry (BOTDR, distributed), which were embedded in the RC beams and glued both on steel bars and on FRCM fabric, and whose measurement were compared to those provided by strain gauges.

III. MATERIALS

Direct tensile tests were carried out on a Glass FRP mesh, equipped with an FBG fibre optical sensor (Fig. 1a). More specifically, 50 cm long single wire specimens were extracted from a 50 mm × 50 mm pre-cured FRP mesh made of glass fibres and thermosetting primer, having 335 g/m^2 surface mass density. The mesh is balanced, which means that it has the same fibre amount in longitudinal (warp) and transversal (weft) directions, for each of which the design thickness is 0.044 mm. The cross-sectional area of a wire is 2.19 mm^2.

It is worth mentioning that glass, basalt, carbon and aramid fibres are currently used for the FRP pre-cured meshes of CRM systems [24]. Glass and basalt are considered particularly advantageous for both their mechanical compatibility with masonry substrates and their cost-efficiency (they have a lower tensile modulus of elasticity and are cheaper than carbon and aramid). In this work, a glass-FRP mesh was used because it is the most adopted in the field and due to its compatibility with optical fibre cables, which are also made out of glass fibres.

SMF28 optical fibres with acrylate coating were used, which housed a 10 mm FBG sensor protected by a polyamide coating. According to datasheet, sensor reflectivity is more than 90%, whereas the tolerance on the central wavelength value is +/- 0.15 nm.

First, mesh wires were cleaned with an alcoholic solution and left to dry. Then, FBG sensors were glued using a bicomponent epoxy resin having 30 N/mm^2 tensile strength and 1760 N/mm^2 tensile modulus of elasticity (from technical datasheet).

FBG sensors were installed in the warp direction, either at midspan between two weft wires (“L” location, Fig. 1b) or at the intersection between weft and warp (“X” location, Fig. 1c). Specimens were labelled as DT-G-FBG-L or DT-G-FBG-X, in which DT stands for Direct Tensile, G stands for Glass FRP mesh, FBG denotes the presence of FBG sensors, and, finally, L or X indicates the position of the sensor, as said above.

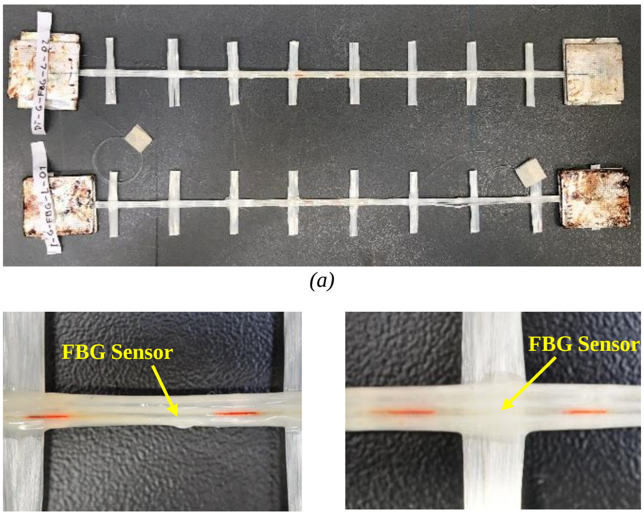
After 7 days of resin curing, 3 mm thick aluminium tabs were glued to the ends of the specimen to ensure proper gripping in the clamping wedges of the testing machine and specimens were ready for testing.

IV. TEST SETUP AND EQUIPMENT

Tensile tests were performed with an MTS Landmark Servohydraulic machine with 100 kN load capacity, were displacement controlled and carried out at 2 mm/s stroke displacement rate. The load was recorded by an integrated load cell at 10Hz sampling frequency. The reflected wavelength shift was recorded by an FS22 Industrial BraggMETER HBM optical interrogator at 1 Hz sampling frequency.

Digital Image Correlation (DIC) strain measurements were carried out by analysing digital photos taken with a Nikon camera at 3 s time interval. Two artificial markers (metal tabs provided with speckle pattern) were glued to the specimen. DIC provided their relative displacement, allowing the monitoring of the central portion of the wire, which included the FBG sensor (Fig. 2). Two LED spotlights ensured stable light conditions. Open source Matlab-based NCorr software [25] was used for DIC analyses.

A slight pre-load was applied before test start to improve alignment. Tests included sets of unloading-reloading cycles as follows: 5 cycles between 0‰ and 1‰ axial strain, 5 cycles between 0‰ and 2‰, 5 cycles between 0‰ and 5‰, and a final ramp from 0‰ to the failure of the FBG sensor.



(a)

(b) *(c)*

Fig. 1 – Single mesh wires with FBG sensors and ready to test (a), and detail of FBG in L (b) and X (c) locations.

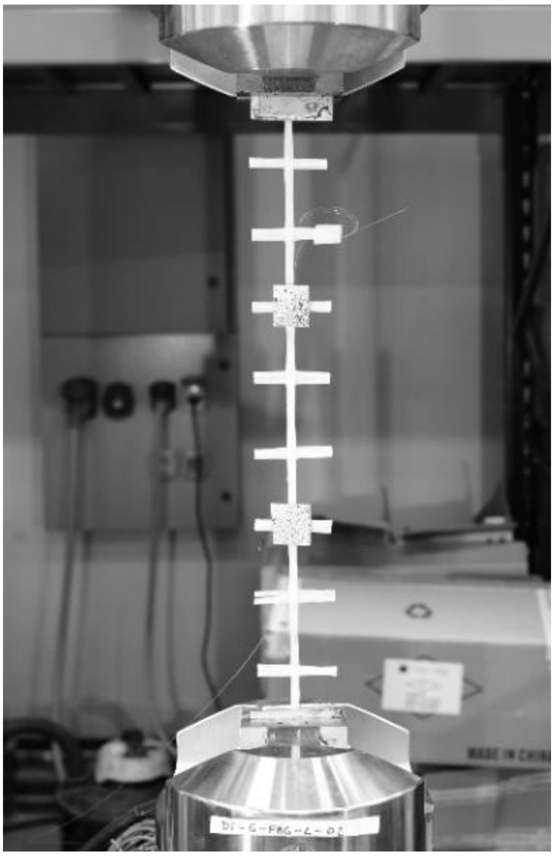


Fig. 2 – Experimental setup.

V. TEST RESULTS

Preliminary characterization tests revealed a linear elastic response of the mesh wires, even in the unloading-reloading phases, up to a purely brittle failure, with 1321 N/mm^2 average tensile strength, 1.50 % ultimate strain, and 100.8 kN/mm^2 modulus of elasticity.

DIC and FBG measurements are shown Fig. 3, in which each subplot refers to a single mesh wire specimen. The former (ε_{DIC}) was calculated as the relative displacement between the two artificial markers divided by their initial distance. The latter (ε_{FBG}) was obtained from the variation of wavelength as follows:

$$\varepsilon_{FBG} = \frac{\Delta\lambda_B}{0.78\lambda_B} \quad (1)$$

where $\Delta\lambda_B$ is the central wavelength change caused by the deformation of the FBG sensor and λ_B is the initial centre wavelength. The error of FBG strain data with respect to DIC ones was calculated through the Root Mean Square Deviation (*RMDS*) as follows:

$$RMSD = \sqrt{\frac{\sum_{i=1}^{T}(\varepsilon_{DIC,i} - \varepsilon_{FBG,i})^2}{T}} \quad (2)$$

where *i* indicates the *i*-th time instant and *T* is the total of time instants considered for the calculation.

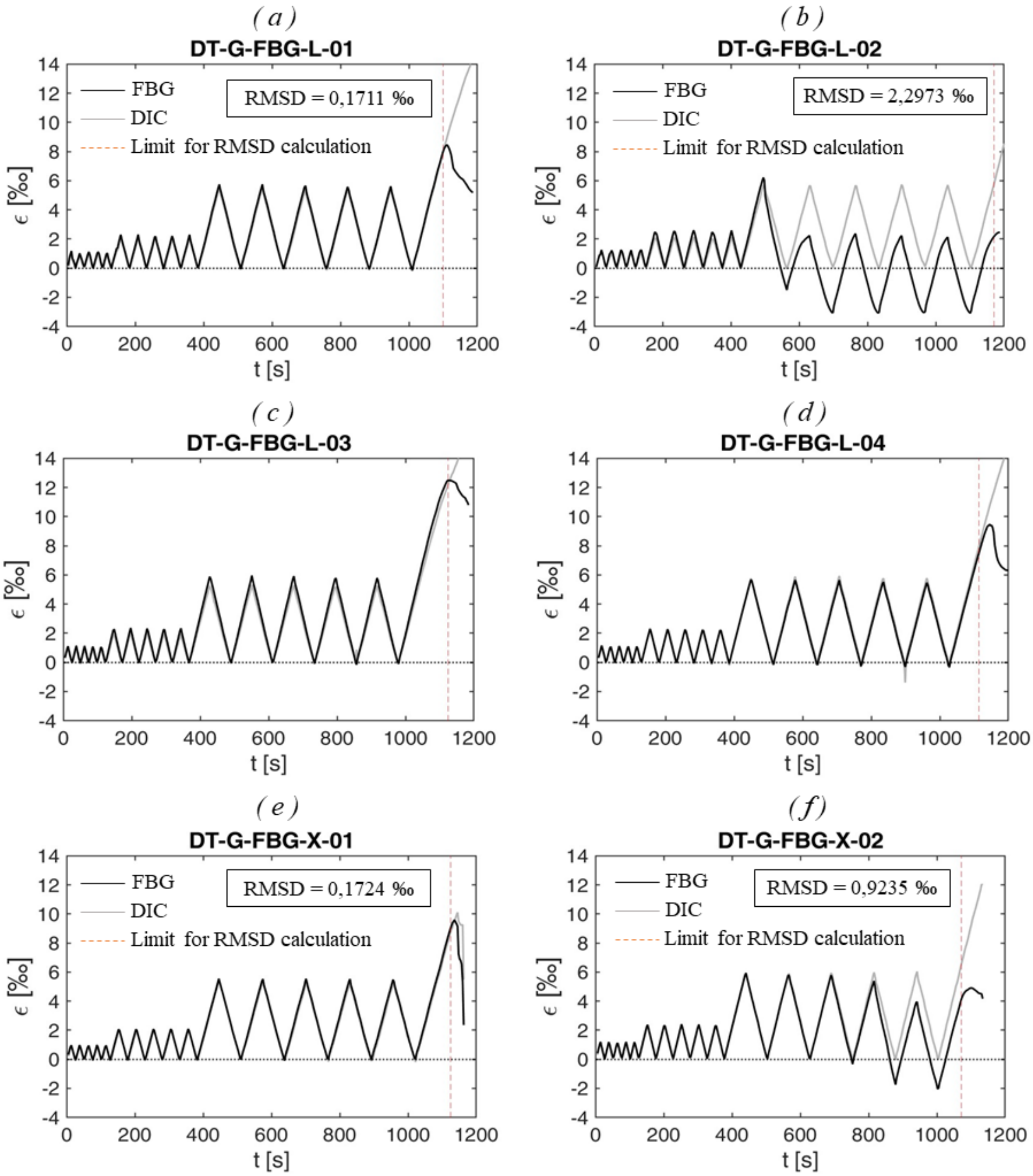


Fig. 3 – Strain vs. time direct tensile test response curves on specimens with different FBG locations: at midspan between two weft wires (L location, a-d) and at the intersection between weft and warp (X location, e-f).

The graphs show that FBG and DIC strains were always in good agreement in the initial phases of the test. Then, at strain values between 5 ‰ and 12 ‰, slippage occurred in the FBG sensor, either between fibre and resin or between core and coating, leading to a non-negligible scatter between the two measurements. Such slippage was clearly detectable during test execution.

RMSD was calculated until slippage activation and varied between 0.05 ‰ and 2.2973 ‰. It is worth noting that these strain values correspond to a Δλ greater than 7 nm, which is the declared polyamide coating limit strain.

In detail, in DT-G-FBG-L-01 specimen, the overlap between the measurements is good until the final ramp, in which slippage took place at 8‰ strain. This specimen showed the minimum RMSD value equal to 0.1711‰. In the DT-G-FBG-L-02, the sensor worked properly until the first cycle at 5‰. The DT-G-FBG-L-03 specimen exhibited a peak at the end of the 4th cycle at 5‰ due to a wire rotation, which was not detected by the FBG sensor. In this case, slippage occurred at 12‰. The DT-G-FBG-L-04 exhibited the same rotation at the same time, but the slippage took place at 10‰. In the DT-G-FBG-X-01 specimen, no slippage occurred before yarn rupture at 10‰. Finally, in the DT-G-FBG-X-02 specimen, slippage started at the top of the third 5‰ cycle and finished at 10‰.

VI. CONCLUSIONS

A prototype Composite Reinforced Mortar and optical Fibre Brag Grating sensors (CRM-FBG) integrated system was proposed, which may provide combined strengthening and monitoring of existing structures, with promising applications to architectural heritage.

Direct tensile tests revealed a good agreement between strain data provided by FBG sensors and Digital Image Correlation, even under unloading-reloading cycles and up to a strain of at least 5‰, which is compatible with structural damage, suggesting that data provided by FBG sensors can help Structural Health Monitoring. At higher strains, the slippage of the FBG sensor or the rupture of the optical fibre made measurements unreliable, or even unavailable, in some tests.

The preliminary outcomes of this work will be complemented by other experimental investigations, which are currently ongoing, to develop an improved understanding of the performances of the proposed CRM-FBG system and its potential use in rehabilitation activities and for the safe and cost-efficient management of architectural heritage.

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