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Available measurement methods to evaluate the fiber and matrix bond performance of FRCM composites

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Abstract

Measuring the bond between Fabric-Reinforced Cementitious Matrix (FRCM) composites and the substrate onto which they are applied is crucial for assessing the performance of these materials when used for the strengthening of existing structures. Experimentally, this parameter has been investigated by conducting single/double lap shear tests. However, as the bond failure is usually reached at the fiber-matrix interface, it is hard to obtained reliable date of the local phenomena occurring at such location. This is caused by the impracticality of observing the behavior due to the presence of an exterior matrix layer. In this paper, a detailed review of methods used to measure the bond between the fibres and the matrix is presented. Methods studied include traditional instrumentation such as strain gauges, and more recently developed digital image correlation (DIC). In addition, due to the increase in use of new sensing technologies such as wavelength- or frequency-based fiber optic sensors (FOS), these techniques are also evaluated. The research presented in this paper emphasize the applicability of these techniques and offer a comprehensive analysis of their respective advantages and limitations, ultimately providing valuable insights into their utility for characterizing the bond behavior of FRCM composites.

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Keywords: FRCM; TRM; bond; strain gauge; SG; digital image correlation; DIC; fiber optic sensors; FOS; interface; testing

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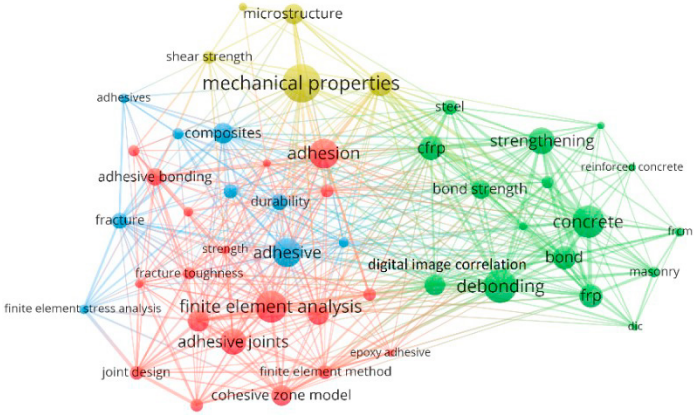
1. Introduction

In the past, when existing masonry or concrete structures needed to be strengthened or rehabilitated, in order to increase or guarantee greater safety performance, one of the methods available was the use of externally bonded composite materials such as fibre-reinforced polymers (FRP). FRP strengthening system made it possible to improve the structural efficiency and durability of the structure at a low cost and with fast intervention (Yang, et al., 2015; De Maio, et al., 2019). However, this method comes with inherent structural limitations, including susceptibility to fire, thermal cycling, and degradation from extended exposure to ultraviolet rays (Zhao, et al., 2017; Cabral-Fonseca, et al., 2018). When FRP composites are deemed unsuitable (Raoof & Bournas, 2017; D'Ambra, et al., 2018; Cerniauskas, et al., 2020), alternative composite materials may be explored, such as textile-reinforced mortars (TRM, that is a textile grid embedded in mortar) or if different combinations of matrix and grid are used it reflects in different TRM composite materials, which may be called: FRM (fabric-reinforced mortar), FRCM (fiber-reinforced cementitious matrix/mortar), TRC (textile-reinforced concrete), IMG (inorganic matrix-grid composites), CRM (composite-reinforced mortar). (FRCM), textile-reinforced mortar (TRM), steel-reinforced grout (SRG), and fiber-reinforced mortar/concrete (FRM/FRC). When implementing these strengthening systems, understanding the behavior of the bond between the composite material and the substrate, as well as among the materials comprising the strengthening system (i.e., fibers and matrix), is crucial. Given the significant variations in mechanical and physical properties inherent in composite strengthening materials, evaluating bond quality becomes a complex goal (Carozzi, et al., 2017; Carozzi, et al., 2017; Barducci, et al., 2020). The heterogeneous nature of constituent materials (i.e., inorganic matrix and fiber textiles) results in various observed failure modes (de Felice, et al., 2018), including: cohesive debonding in the substrate, interface debonding (matrix-to-substrate and/or textile-to-matrix), textile slippage within the matrix, and tensile rupture of textiles. Failure modes such as sliding and matrix-to-textile detachment may indicate poor bonding and suboptimal use of strengthening materials. Thus, improving the bond between textiles and the mortar matrix boosts system performance. This requires a thorough understanding of bond quality between textiles and the mortar matrix, essential for better utilization, improved mathematical models, and robust design guidelines (E. Grande & G. Milani, 2021; Grande & Milani, 2020; Grande, et al., 2020; Bertolesi, et al., 2020; Bertolesi, et al., 2020). Experimental investigations often involve tensile and shear tests on TRM/FRCM materials. Tensile tests reveal the composites' constitutive relationship, while shear tests measure bond capacity. However, the weakest element affecting bond capacity varies and isn't directly identified from shear and tensile tests. Pull-out tests offer useful insights into bond quality but don't fully capture local bonding complexities. Traditional sensors (like SG and DIC) measure global bond strength effectively for FRP but are insufficient for TRM/FRCM materials. This paper presents the most frequently utilized instruments to assess the bond in the composite material as strengthening system (TRM and FRCM), such as: strain gauge (SG) (Zampieri, et al., 2023; Santandrea, et al., 2020; Zou, et al., 2019), digital image correlation (DIC) (Trochoutsou, et al., 2022; Sabau , et al., 2017; De Domenico, et al., 2021) and fiber optic sensors (FOS) (Schranz, et al., 2021; Saidi & Gabor, 2020; Bertolesi, et al., 2022) with their pros and cons. The analyses discussed in this paper highlight the practicality of these methods and provide a thorough examination of all their strengths and weaknesses, finally offering insightful information on how well they may be used to describe the bond behaviour of FRCM composites.

2. Literature review

An analysis of the available literature on the topic was performed by accessing the Scopus database. The search was conducted using the keywords "shear" AND "lap" AND "bond" AND "interface" AND "strain" OR "deformation". These keywords provided 2765 publications between 1972 and 2024 and so the author's keywords co – occurrences was analyzed in the VOSviewer software. As can be seen from Fig. 1a, the network is divided into two major fields: the numerical field (blue and red) and the experimental field (yellow and green).



a)

Keyword	Occurrence
Mechanical properties	101
Debonding	88
Concrete	85
Finite element analysis	84
Adhesion	78
Strengthening	70
Interface	65
Bond	61
Fracture mechanics	56
Digital image correlation	55

b)

Fig. 1 a) Author's keywords in the Scopus database; b) First 10 keywords with the highest co – occurrences number

In the numerical field the primary focus is on providing numerical models to simulate the behavior of materials and interfaces in the stress transfer zone, while the experimental field provides experimental results necessary for calibrating the numerical models. There is particular emphasis on instrumentation in the experimental field, as evidenced by the frequent occurrence of the terms "digital image correlation" or "DIC," which are preferred methods for instrumenting the specimens (as they are non-invasive, as explained later in section 3.2), although they cannot provide the exact type of measurement needed to calibrate the numerical model (Tekieli, et al., 2017).

3. Traditional monitoring methods

3.1. Strain gauges (SG)

Strain Gauges (SG) are sensors used to measure the strain in a material, and consequently, deriving its stress state. They consist of thin metallic wires or strips of conductive material (nickel-chromium or nickel-copper alloy) mounted on a flexible base or adhesive backing. When the material on which they are mounted is subjected to mechanical stress, such as tension, compression, or torsion, the electrical resistance of the gauge changes in proportion to the material's strain. Strain gauges are used in a wide range of strain measurement applications, such as structural testing (to monitor deformation in bridges, buildings, airplane wings, laboratory experimental tests, etc.), pressure measurement (applied to devices like piezoresistive pressure sensors to measure pressure in different environments) and measuring the force applied to various mechanical components or devices, industrial applications (to monitor stress or deformation in machinery, pipelines, etc.). They are generally very versatile instruments as they can assume various sizes and configurations depending on the case at hand (Fig. 2).

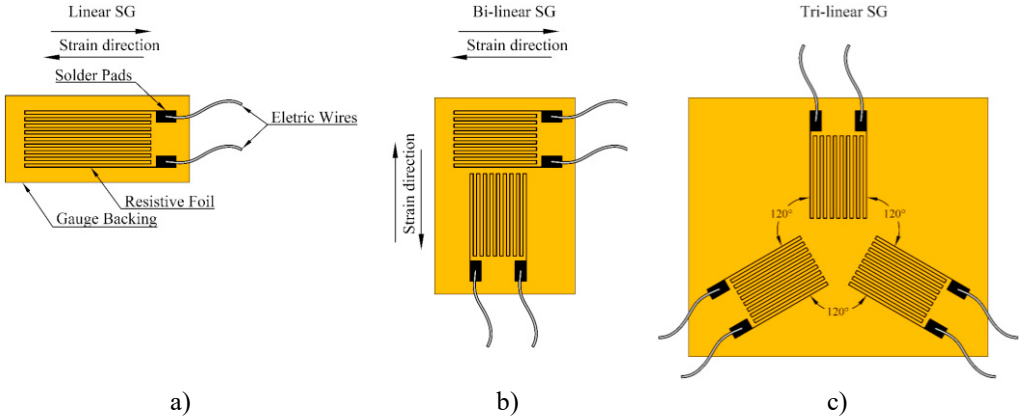


Fig. 2 Some of the possible configurations of strain gauges: a) Linear strain gauge; b) Bilinear strain gauge; c) Trilinear strain gauge

This versatility is dictated by the fact that they possess several advantages, such as: high sensitivity even for small variations in material deformation, a wide measurement range, reliability if installed correctly, and a relatively low cost. However, they also have some drawbacks that may limit their use: installation may not be straightforward (requires proper installation and calibration to ensure accurate measurements) and susceptibility to interference (magnetic fields or vibrations), temperature (affects the expansion coefficient of the substrate and the gauge itself, and the gauge's electrical resistance as a function of temperature) and humidity (deterioration and/or corrosion of the gauge material or changing the properties of the supporting insulating materials with electrical, and so measures, losses). Considering the field of structural reinforcement through FRCM and TRM, strain gauges are installed directly in contact with the fiber at multiple points to have a distribution of the strain state that allows deriving information on the load transfer mechanism between the textile and the matrix, and thus, data to validate numerical models. However, they provide information only at the point where they are installed, also producing a disturbance in the measurements due to the adhesive, and to be installed, a surface preparation of the textile is necessary, which if not adequately performed, can damage the textile itself (Trochoutsou, et al., 2021; Tekieli, et al., 2017). SGs are used in FRCMs and/or TRMs as a consequence of FRPs, the former type of strengthening system. In FRPs, SGs were widely used for the detection of fiber strains (with the exception of fabrics composed of steel cables) because the coating of the fabrics with polymer resins ensured perfect adhesion, and the disturbance on the load transfer mechanism was lower considering the adhesion performance of the resins. SGs can be used for monitoring the FRCM/TRM strengthening system (low maintenance cost), however, they are unsuitable for monitoring over long periods as they cannot be replaced.

3.2. Digital image correlation (DIC)

Digital Image Correlation (DIC) is an experimental technique used to measure the strains and surface movements of objects or structures through the analysis of digital images. DIC involves capturing images of an object or surface before and after the application of a load or stress. These images are processed using specialized software that employs advanced algorithms to compare the pre- and post-deformation images and calculate the strains through point correlation. To implement DIC, a specific setup is required, including an image acquisition system (high-resolution digital cameras mounted on stable supports), adequate lighting, contrast on the object's surface (which can

be achieved through the application of paints with high-contrast patterns), and dedicated analysis software that processes the acquired images and calculates the strains using image correlation algorithms. Fig. 3 shows an example of the setup for a shear lap test of masonry strengthened with FRCM or TRM.

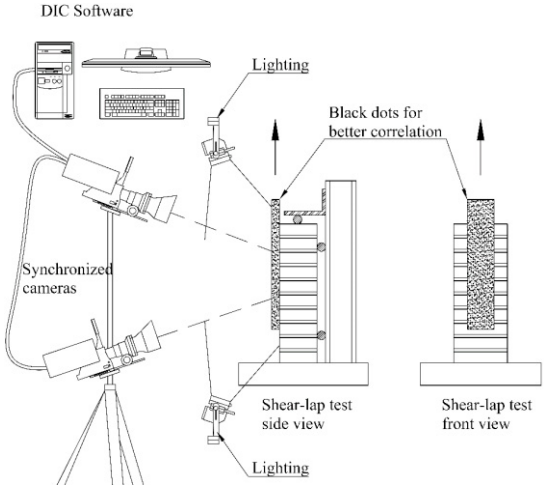


Fig. 3 DIC setup

DIC is used in structural engineering to analyse deformation under various loads, materials science for studying strain under mechanical and thermal loads, biomechanics to assess strain in biological tissues and implants during stress tests, and aerospace and automotive industries to analyse strain in components under aerodynamic loads or vibrations. It offers precise, non-destructive surface strain measurements with high spatial resolution, is versatile across numerous applications, and quickly provides results after installation and calibration.

Some limitations refer to the sensitivity to image quality (extreme temperature values can lead to a change in the focus of the camera and, in the case of long exposures, humidity can also create abnormal condensation, decreasing image quality), complex experimental setup and calibration, data and image analysis requiring specialized skills and dedicated software, and it is primarily a two-dimensional technique and may be limited in measuring three-dimensional strains. One of the first applications of DIC in the field of FRCM and/or TRM date back to 2017 (Bilotta, et al., 2017), this technology has the immediate advantage of being a non-destructive technique and therefore does not alter the behavior of the sample and of the bond at the interfaces. When determining the strain along the bonded area, or the actual bond length, the use of SGs is necessary as DIC only provides the strain of the outer most surface of the matrix, which is a major limitation for this field. However, proper calibration can lead to automatic detection of cracks (even those not visible to the naked eye) and, as nothing is present in the matrix, it does not lead to possible crack formation (Tekieli, et al., 2017) (such as stress concentration points created by the presence of SG leads). In the field of monitoring, a high initial investment is required, but this is balanced by low running costs and long service life.

3.3. Fiber optic sensor (FOS)

Optical fiber sensors (FOS) are devices used to measure various physical quantities, such as strains, temperature, pressure, or force through the interaction of light with an optical fiber. FOS primarily consist of two components:

the optical fiber, which is a flexible waveguide consisting of a glass or plastic core surrounded by a reflective coating, and a sensing element, i.e., a region of the optical fiber modified or treated to be sensitive to the physical quantity being measured (Fig. 4).

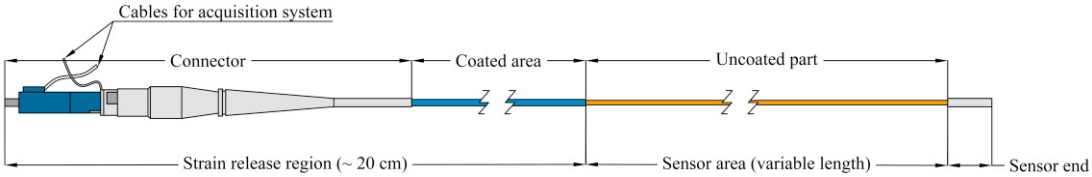


Fig. 4 Generic image of an FOS sensor

FOS are used in various sectors, such as structural engineering for monitoring systems, aerospace industry for measuring strains and loads on aerospace components, wind energy for monitoring blade bending during operation, and in medicine for measuring blood pressure, body temperature, and other physical quantities in medical devices. This technology offers several advantages: using light as the transmission medium makes them immune to electromagnetic interference, they have a wide measurement range, reliability, and durability (excellent resistance to corrosion, moisture, and extreme environmental conditions ensuring long sensor life), and small size and light weight. However, this technology is not without its flaws: complexity in installation and calibration, high cost, sensitivity to excessive bending and handling, limited use at high temperatures (in general a maximum of about 250°C for the optic fiber and 150°C for the connector, for systems based on interferometry or Bragg grids) and humidity (can disturb in case of damage to the connector seals). Considering the field of structural strengthening with FRCM and/or TRM composite materials, the application of FOS is a particularly new methodology, there are very few studies currently available that show applications in terms of deformation measurement or monitoring (Bertolesi, et al., 2020). Their small size allows them to be applied in such a way that the stress perturbation at the load-transmission interface is minimal, so that it is possible to read the strains along the entire length of the application so that the data can be used to validate the numerical methods developed to simulate the behavior of that specific material combination. For monitoring, a high initial investment is required, but FOS have exceptional durability and minimal maintenance.

4. Comparison of the three methods

To observe the main pros and cons of the three monitoring methods exposed in the field of FRCM and TRM composites, the following Table 1 can be consulted.

Table 1 Pros and cons of SG, DIC and FOS

	Pros	Cons
SG	• Cheap and reliability; • Point strain values at the load-transfer interface.	• Difficult to install and they create a disturb of the load transfer mechanism; • Only local values; • Possible incidence of gauges and cables on crack occurrence and bond behaviour;

		• Can't detect crack width and crack opening.
DIC	• Insensitive to setup deflections or misalignments; • Automatic detection of cracks and of their: occurrence, number, width, and distance at any load value.	• Unreliable detection of strain in the textile and at the textile-matrix interface; • High cost set-up with complex software and difficult calibration.
FOS	• Evaluate strain at the textile–matrix interface; • Can provide data along all the bonded length; • Can be used as monitoring.	• High cost.

5. Conclusions

All the described methods are functional in determining the main characteristics of FRCM and TRM composite systems; however, some critical aspects must be considered when choosing one system over another:

- SGs can provide only punctual strain information. They require installation space in the fiber (so they can't be used with steel fiber), and additionally, the glue and the cable can cause interference with measurements or create cracks;
- FOS are able to provide a continuous strain reading and with a small size their impact on the load transfer mechanism is minimal;
- DICs are not capable of providing strain readings at the fibre-matrix interface. However, they are insensitive to misplaced or misaligned specimens and can also determine cracks not visible to the naked eye.

These aspects are based on the most used materials, so if a new fabric is produced (e.g. in the latest fabrics of natural origin) these considerations may change. It is therefore essential to be able to develop research that identifies key factors and differences between one technology and another, also to determine a correlation between results for the same application. In this way, it is possible to create scientific criteria and turn them into useful guidelines for future experimentation and monitoring of FRCM/TRM- strengthened structures.

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