Application of Externally Bonded Inorganic-Matrix Composites to Existing Masonry Structures

Angelo S. Calabrese, Tommaso D'Antino, Carlo Poggi, Pierluigi Colombi, Giulia Fava and Marco A. Pisani

Abstract Fabric-reinforced cementitious matrix (FRCM) and composite-reinforced mortar (CRM) are recently introduced inorganic-matrix composites that have shown promising results as externally bonded reinforcement (EBR) of existing masonry structures. FRCM and CRM comprised high-strength fiber textiles embedded within inorganic matrices. Different fibers and matrices can be used, which lead to a large number of systems characterized by different properties. In this paper, different techniques employed to strengthen the existing masonry structures with EBR. FRCM and CRM composites are presented and discussed.

Keywords Fabric-reinforced cementitious matrix · Mechanical characterization · Flexural strengthening · Shear strengthening

1 Introduction

The numerous seismic events that have struck the Italian territory emphasized the great vulnerability of its built heritage. In the event of an earthquake, strategic constructions such as schools and hospitals have often shown vulnerabilities associated with certain local and global collapse mechanisms.

Over the last decades, the need for improving the behavior of these strategic structures with respect to seismic events led the construction engineering community toward the development of new and innovative strengthening solutions. Among them, composite materials have shown to be an excellent solution for strengthening and retrofitting the existing structures due to their high-strength-to-weight ratio, corrosion resistance, and ease and speed of application. Within this category of materials, those comprised high-strength textiles embedded within cement-based matrices (usually referred to as fabric-reinforced cementitious matrix, FRCM) and those comprising a composite grid embedded within an inorganic-matrix (referred to as composite-reinforced mortar, CRM) represent one of the most recent and promising innovations

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(Carloni et al. 2016). FRCM has good resistance to high temperatures and excellent compatibility with masonry structures (De Felice et al. 2014). Because of this last feature, as well as the partial reversibility of the strengthening interventions, the use of FRCM reinforcements may be considered a good solution for the strengthening and retrofitting of the existing masonry members (walls, arches, vaults, etc.), which are largely diffused in education buildings in Italy (De Santis 2017).

FRCM composites comprise one or more layers of a high-strength fiber, open-mesh textile embedded within an inorganic mortar. The dimensions of the granules in the inorganic mortar do not allow for a good impregnation of the fiber filaments as is the case for organic resin impregnation. Therefore, to create a mechanical interlock between matrix and textile, the textile bundles/yarns are spaced in such a way as to allow for the penetration of the mortar into the grid spacing. Different types of fiber and inorganic matrices can be paired to achieve different composite properties, suitable for a wide range of applications. Figure 1 shows a selection of textiles commonly used in FRCM composites, even though some hybrid textiles have recently been introduced (Carozzi et al. 2015).

When dealing with seismic retrofitting of existing buildings, one of the key issues is the speed and ease of the execution. This is particularly appealing for educational buildings in order to avoid long interruption of the educational activities. The application of FRCM strengthening is a very effective solution in this regard. Indeed, the application requires a limited number of steps (see Fig. 2): (i) preliminary preparation of the surface that can be mechanically roughened to enhance adhesion, (ii) application of a first layer of mortar, followed by the positioning of the textile by means of a common trowel, and (iii) application of the final layer of mortar on top of it. The impregnation of the fiber textile is of crucial importance for the effectiveness of the application. Thus, the textile shall be gently pressed within the mortar to guarantee its complete impregnation and the absence of voids in the matrix. The curing time is usually of 28 days.

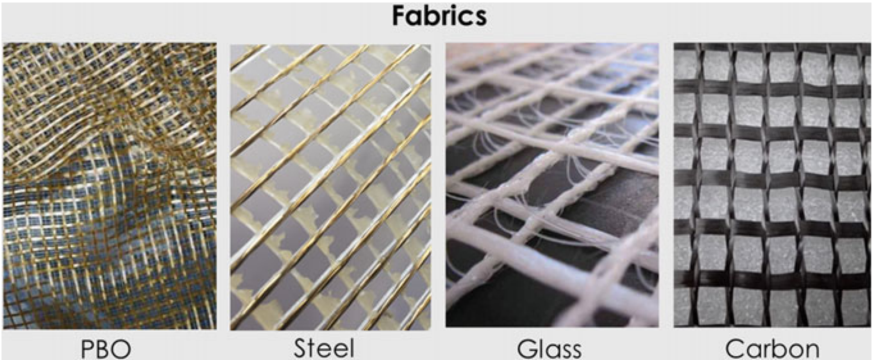

Fig. 1 Main typologies of fiber used in FRCM composites

Fig. 2 Application of a PBO-FRCM strengthening to a masonry substrate

This paper describes the fundamental mechanical properties of FRCM composites, including their tensile and bond behavior. Furthermore, a number of strengthening applications with inorganic-matrix composites, namely the out-of-plane and in-plane strengthening of masonry walls, are described and discussed. The results show that the use of FRCM composites is a valid tool to improve the structural behavior of the existing educational buildings.

2 Constitutive Behavior of FRCM Composites

Several studies have been recently presented regarding the characterization of FRCM composites, aimed at investigating their main mechanical properties, for example, ultimate tensile stress, ultimate strain, and elastic moduli (Carloni et al. 2016). These parameters can be obtained by experimental testing of FRCM coupons in tension using different methodologies.

Tensile coupons can have a rectangular or dumbbell shape and are made by successive layers of inorganic mortar, poured into molds (see Fig. 3) to correctly control the specimen shape. The coupon thickness usually ranges between 10 and 20 mm, depending on the number of fiber (and matrix) layers employed (D'Antino and Papanicolaou 2018).

According to the so-called clamping-grip method (Arboleda et al. 2015), the FRCM coupon ends are gripped directly by the testing machine, which applied the tensile load, under displacement control, up to failure. The specimen ends should be reinforced by applying FRP tabs to promote a more uniform distribution of the clamping pressure and avoid cracking of the matrix at the specimen ends. The load applied to the specimen is measured by a load cell, whereas axial strains may be measured by means of different technologies: extensometers, linear variable displacement transducers, strain gauges, and digital image correlation (DIC) (D'Antino and Papanicolaou 2018). The gripping method has a significant influence on the behavior and failure mode of the FRCM. With the clamping-grip method, possible

Fig. 3 Casting of a rectangular PBO-FRCM tensile coupon using flat molds

debonding of the textile within the matrix is prevented by the pressure applied by the machine grips (Arboleda et al. 2015).

The typical stress–strain curve of a tensile clamping-grip test has a tri-linear behavior (Carozzi and Poggi 2015), as shown in Fig. 4. The first branch is associated with the uncracked state and ends when the mortar attains its tensile strength. At the end of the first branch, cracks occur in the matrix in a number of locations depending on the grid spacing and matrix-fiber bond properties. Owing to matrix cracking (second branch), stresses are transferred from the matrix to the textile and vice versa and the stiffness of the stress–strain curve decreases. When the matrix is fully cracked, a third linear branch develops. This branch is characterized by a slope lower than or equal to that of the stress–strain curve of the dry textile. Finally, sudden failure occurs once the textile tensile strength is reached.

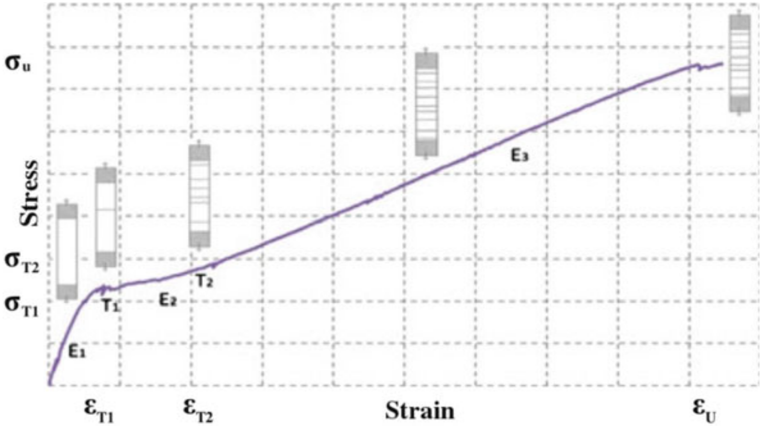

Fig. 4 Typical stress–strain curve (Carloni et al. 2016)

3 Bond Properties of FRCM Composites

The bond between composite and substrate, which is responsible for the stress-transfer mechanism between the composite and the existing substrate, is of fundamental importance in externally bonded strengthening applications.

For FRCM strengthening comprised of only one layer of textile, debonding generally occurs at the matrix-to-fiber interface, with significant slippage of the fiber bundles with respect to the embedding matrix. This phenomenon is in part attributed to the poor impregnation ability of the inorganic mortar, which cannot penetrate within the fiber bundles leading to core filaments slippage with respect to the sleeve filaments (see Fig. 5).

The stress-transfer, from fiber bundles to cement matrix and vice versa, occurs mainly due to shear stress at the fiber-to-matrix interface. The relationship between the interface shear stress and the corresponding slip can be described by a bond slip law (BSL) (Colombi and D'Antino 2019). After the shear stress reaches a limit value (referred to as shear strength), it decreases according to the BSL until attaining a residual shear stress provided by friction/interlocking between the matrix and fiber. When the shear stress attains the residual values, which may be equal to 0 for certain composites, debonding occurs. With a further increase of the slip after the onset of debonding, the load carried by the composites may increase further, provided there is a sufficient bonded length, due to the contribution of matrix-fiber friction. When debonding involves the entire bonded length, the composite becomes completely detached.

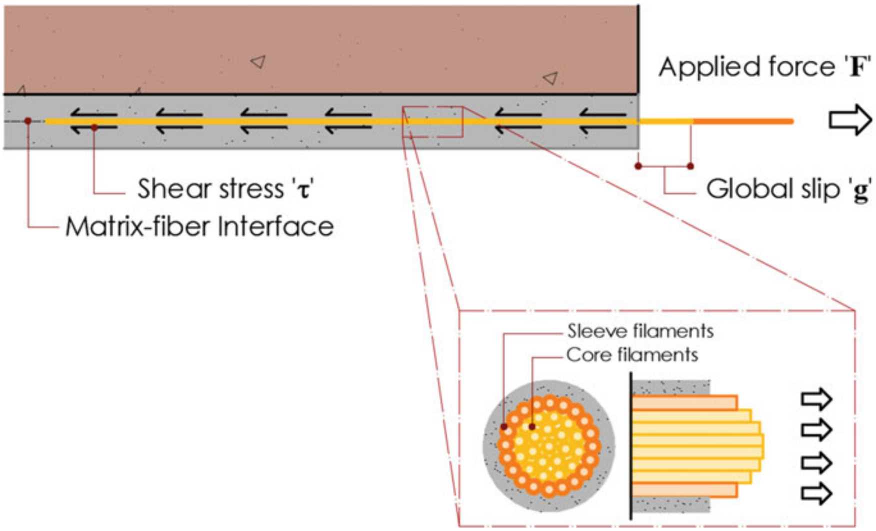

Fig. 5 Debonding at matrix–fiber interface

Several parameters affect the bond behavior of FRCM composites, such as the spacing of the textile, properties of the inorganic matrix, substrate preparation, and level of impregnation of the fibers. In addition, the test set-up may influence the results. Different set-ups are indeed employed to study the debonding process of FRCM composites. The most commonly used are single-lap and double-lap direct-shear tests, where a tensile force is directly applied to the composite. Other set-ups have recently been proposed, such as the hinged and notched beam tests, which indirectly induce a tensile force in the composite as an effect of the presence of a bending moment (Calabrese et al. 2019).

4 Out-of-Plane Strengthening of Masonry Structures

A consistent part of educational building heritage is characterized by a large use of structural and non-structural masonry elements, for example, piers, infill walls, ceilings, and partitions. These elements are extremely vulnerable in the case of seismic events, because the resistance of unreinforced masonry structures to out-of-plane external forces is mainly dependent on its geometry, connection to the adjacent structural elements and on the interlocking between bricks and mortar and on the mortar properties. For instance, the overturning of infill walls in the case of an earthquake is one of the most dangerous events for the safety of the building occupants.

FRCM composites represent an effective solution against these vulnerabilities. They can increase the flexural capacity of bearing walls and prevent the overturning of partition and infill walls. In this section, a study of the efficiency of an FRCM strengthening system, conducted at the Politecnico di Milano, is presented and discussed (Carozzi et al. 2015).

A series of 16 three-point bending tests was performed on masonry elements composed of solid and hollow clay bricks, reinforced with two different PBO-FRCM composites. Certain specimens (specimens' dimensions and test set-up are depicted in Fig. 6) were left unreinforced and tested as control specimens. The load was applied across the entire width of the walls, perpendicular to the mortar bed joints.

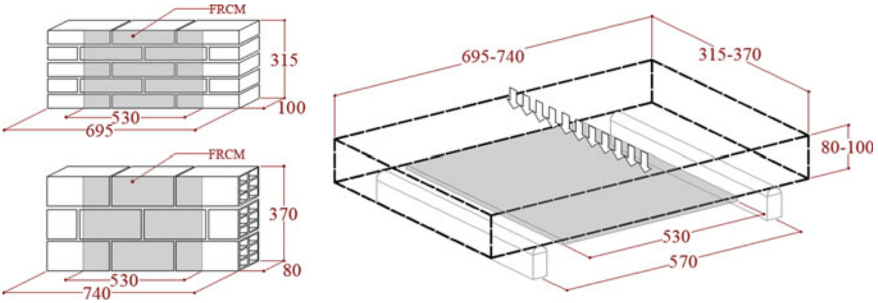

Fig. 6 Specimens' dimensions and test set-up (dimensions in mm)

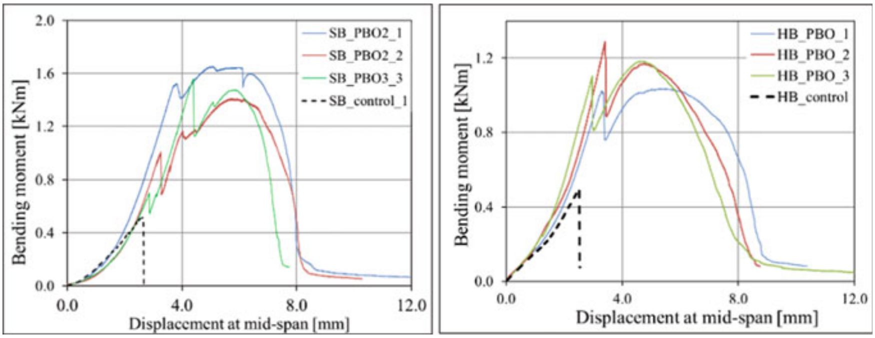

Fig. 7 Flexural responses of solid (left) and hollow (right) brick specimens

The mid-span deflection and the opening of the crack below the point of application of the load were recorded by means of linear variable displacement transducers.

The bending moment versus-mid-span displacement curves are reported in Fig. 7. Each graph in this figure provides the results of solid brick (SB) and hollow brick (HB) specimens strengthened with a specific PBO-FRCM composite analyzed, together with the control specimens.

Five phases could be identified in the strengthened specimen responses. An initial elastic branch, representative of the uncracked state, extended up to the opening of a major crack in the substrate. At this point, the curve shows a vertical drop and a macro-crack appears in the cementitious matrix. After the crack opening, the response may increase (with a low stiffness) due to the presence of friction between the slipping fibers and the embedding matrix. When the mid-span deflection further increases, the propagation of the main crack and the matrix-fiber debonding along the FRCM reinforcement induce a progressive loss of flexural capacity, represented by a descending branch. Finally, the applied load levels off at a low constant value provided by the residual friction between textile and matrix.

Comparing the results of control and strengthened specimens, it is possible to notice a bending moment capacity increase of approximately 170 and 180% for solid brick and hollow brick walls, respectively. Furthermore, a significant increment of the mid-span deflection is observed, equal to 660 and 926% for SB and HB specimens, respectively. This last aspect is of crucial importance because it shows that this reinforcement technique can significantly increase the displacement capacity of the masonry before collapse and guarantee occupants' safety in case of seismic events.

5 In-Plane Strengthening of Masonry Structures

Inorganic-matrix composites may be designed to best fit the substrate characteristics/properties. Recently, new types of inorganic-matrix composites, comprising lime-based and cement-based matrices and high-strength composite grids, were proposed. These composites, which are usually referred to as composite reinforced mortar (CRM), are characterized by the use of reinforcing grids with a yarn spacing higher than 30 mm and by a thickness of the composite higher than 20 mm. In this section, two experimental campaigns involving in-plane strengthening of masonry walls with FRCM and CRM composites are described and discussed.

In both campaigns, historical solid brick masonry walls were strengthened on both sides with FRCM and CRM composites and subjected to diagonal compression up to failure. The comparison between the results obtained from the strengthened members and the control specimens allows for the investigation of the contribution provided by the externally bonded composite systems to the masonry walls' shear strength.

In D'Antino et al. (2019), three historical brick masonry walls (see Fig. 8) of dimension 830 × 830 × 270 mm were strengthened with a CRM system, including a glass composite grid and a lime-based mortar. To anchor the composite grid, four helical inox steel bars were inserted at the corners through the entire thickness and bent against the wall faces. The diagonal compression was applied to the specimens in displacement control, by means of a hydraulic jack with capacity of 1000 kN. Two LVDTs on each side of the specimens were used to measure the vertical and horizontal displacement of the walls.

In Carozzi et al. (2018), two masonry panels (see Fig. 9) measuring 1000 × 1000 × 300 mm, cut from an ancient masonry structure, were strengthened with an FRCM composite comprising a glass fiber textile and a lime-based mortar, anchored with helical steel bars bent against the wall faces. The specimens were tested in situ using two parallel manual jacks equipped with load cells, one on each side of the wall. As in the previous described study, the wall displacement was recorded by means of LVDTs placed diagonally along both specimens' faces.

The typical load response of the tests of both CRM (Fig. 8) and FRCM (Fig. 9) strengthened walls described is characterized by an initial linear ascending branch up to the opening of diffused micro-cracks in the specimens. After the occurrence of micro-cracks, the applied load remains approximately constant with the increasing

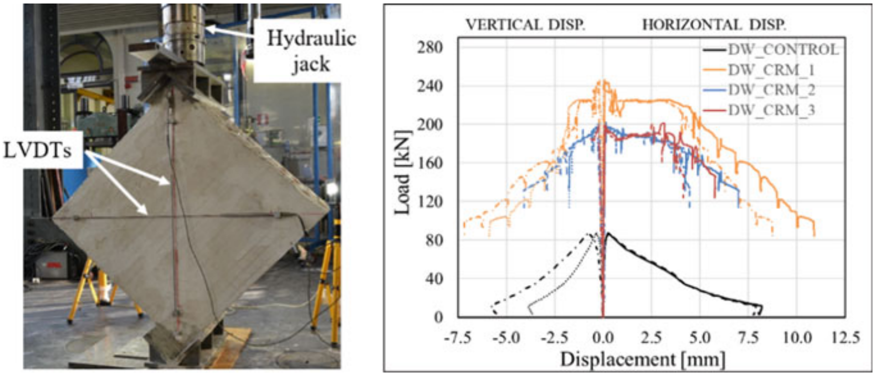

Fig. 8 Specimen set-up and load responses

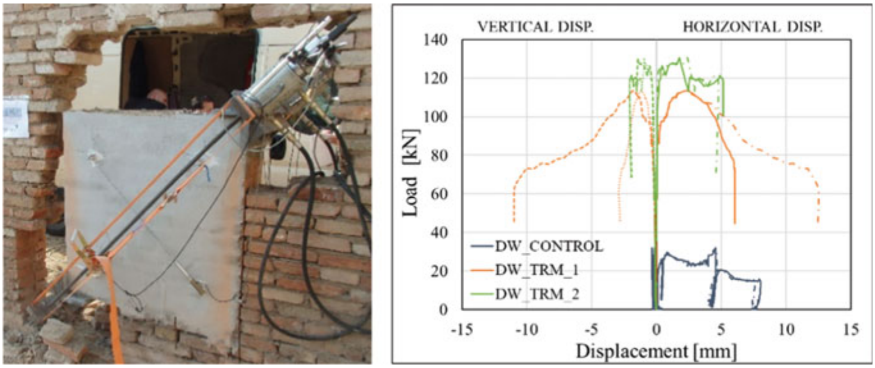

Fig. 9 Specimens set-up and load responses

displacement of the walls, due to the stress redistribution in the bonded composite. This load stage may be considered as a pseudo-ductility stage, which was associated with a slight increase of applied load for certain specimens. When the applied displacement further increased and the stress could no longer be redistributed in the reinforcement, the applied load started decreasing until the specimen eventually collapsed due to the spalling of the external matrix layer, whereas the grid remained anchored to the wall due to the helical bars' presence.

The results of both experimental campaigns show a significant increase in the applied load of the reinforced masonry walls with respect to that of the control specimens. Furthermore, the stress redistribution phenomenon allowed for a relevant pseudo-ductility, which could guarantee the displacement capacity of the masonry with an (approximately) constant load applied.

6 Conclusions

In this paper, some promising applications of fiber-reinforced cementitious matrix composites (FRCM) such as the strengthening of existing masonry structures were discussed. The main mechanical properties of the composite were discussed, with particular attention given to the tensile and bond behavior. An experimental campaign conducted at the Politecnico di Milano, which proved the effectiveness of different PBO FRCM composites for the out-of-plane strengthening of masonry walls, was illustrated. In addition, two experimental campaigns aimed at investigating the contribution of FRCM and CRM materials for the in-plane shear strengthening of masonry walls were described. The results obtained show the effectiveness of the inorganic-matrix composites for strengthening masonry structures. These techniques represent valuable tools to improve the behavior of Italian educational buildings with respect to seismic events in an easy, fast and effective way.

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