Application of Natural FRCM Composites in Structural Strengthening/Rehabilitation: State-of-the-Art Analysis

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Abstract. In recent decades, the vulnerability of structures in the building sector has led to the need to improve the structural performance of existing and new structures. Composite materials referred to as textile-reinforced mortars (TRM) and known in the literature as textile-reinforced concrete (TRC) or fabric-reinforced cementitious matrix (FRCM), have been extensively investigated as a promising alternative to fibre-reinforced polymers (FRP) for strengthening concrete or masonry elements.

These cementitious matrix composites offer substrate compatibility, lower cost, and better performance at high temperatures compared to FRP. In addition, the use of natural fibres in FRCM has increased significantly due to their good mechanical properties and lower the environmental impact of construction materials.

This paper presents a brief overview of the work on strengthening structural elements with natural FRCM. It gives an overview of the different parameters affecting the effectiveness of natural FRCM, the different strengthening techniques and some applications to improve mechanical performance.

Keywords: Fabric-reinforced cementitious matrix (FRCM) · Strengthening · Natural fibres · Masonry · Mechanical properties

1 Introduction

The ageing and vulnerability of civil engineering structures have been of particular concern to engineers and those involved in construction for several decades. In earthquake-prone areas, masonry buildings have suffered significant damage in previous earthquakes [1–3]. The issue of rehabilitation and strengthening of existing structures is of great importance due to their deterioration, lack of maintenance, or the need to meet current modernization requirements. Developing composite materials or designing effective strengthening systems [4–6] to solve current problems and improve the structural behaviour of structures has attracted increasing interest and triggered important research programs. Fibre-reinforced polymers (FRP) have long been used as the primary external strengthening application for existing structural elements. Studies [84–87] have shown

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that FRP have advantageous properties such as good tensile behaviour (high strength), corrosion resistance, ease and speed of application. However, some disadvantages of strengthening technique using FRP have also been found: use of epoxy resins (high cost, carbon impact, hearth risk), poor compatibility with the substrate (concrete or masonry), poor adhesion to wet surfaces, lack of vapour permeability, and poor performance at high temperatures [83].

To overcome the above-mentioned shortcomings of using FRP, some authors [7–9] suggested using mortar (inorganic matrix), which promotes effective bonding between the reinforcing fibres and the matrix, as well as between the composite and the substrate, instead of epoxy resin (organic matrix). However, the problem of adhesion between the fibres and the cementitious matrix has existed for a long time, regardless of the grain size of the mortar. Thus, the solution to the problem of impregnation of the mortar into the fibres has been to replace the fibres with textiles. As a result, new textile-based materials are being developed around the world. These new textile-based composites have been given various names, such as textile-reinforced concrete (TRC), textile-reinforced mortar (TRM), or fabric-reinforced cementitious matrix (FRCM), etc. The increasing use of FRCM composites is due to their good fire resistance compared to FRP, good mechanical properties, permeability, reversibility of the intervention, etc. Other studies have also shown that FRCM composites are more compatible with masonry and concrete substrates than FRP composites [7], 8, 9]. It should also be noted that the mechanical behaviour of FRCM composites is significantly different from that of FRP composites due to the nature of the matrix. Several authors have studied the mechanical behaviour of FRCM composites, including the tensile properties of FRCM and the adhesion of textiles to the cementitious matrix, identifying several failure modes [10, 11, 16–23].

As for the application of FRCM in strengthening systems, the longest used high strength textiles are polybenzoxazole (PBO), carbon, steel, glass, basalt, aramid, etc. [10–15]. However, in recent decades, sustainable development goals have led to an interest in using natural fibres to develop innovative materials and technological solutions in the construction sector. The choice of natural fibres is justified by their good mechanical properties, their answers to the questions of durability and limiting the environmental impact of building materials. Moreover, the use of natural fibres (such as hemp, flax, jute, sisal, miscanthus, etc.) reduces or eliminates some of the problems associated with the low recyclability and energy consumption associated with the production of glass and carbon fibres in conventional composites [25–27]. The use of natural fibres as strengthening in FRCM composites has shown that there is a good bond between the fibres and the mortar matrix [19, 24]. However, variability in the results was observed, which was explained by the type of fibres and the low stiffness values.

In order to verify the structural effectiveness of FRCM composites based on natural textiles, several studies have addressed their application in the reinforcement of structural elements such as masonry (brick, stone, etc.) and concrete (beams, columns, concrete walls, etc.). It should also be noted that the vulnerability of masonry structures is increased when they are subjected to eccentric, seismic and out-of-centre loads. Experimental campaigns have also been carried out to study the structural behaviour of masonry elements [28–33, 33–35]. Regarding the shear behaviour, several studies have been carried out on masonry structures subjected to diagonal compression tests [30, 31, 34, 35]. For example, Olivito et al. [35] investigated the strengthening of brick slabs under eccentric loading using natural textile FRCM composites. The results of these different experimental campaigns showed the high efficiency of FRCM composite systems in improving the shear behaviour of masonry units. Moreover, an increase in the ductility of reinforced structures under in-plane loading was also demonstrated [29]. In addition to the numerous improvements observed, the durability of these natural textile-based reinforced composites remains a concern in recent studies. These strengthening materials may be exposed to different environmental conditions, which may lead to the deterioration of their mechanical properties.

The durability of these strengthening materials is currently under investigation, as they may tend to deteriorate their mechanical properties under certain environmental conditions [36, 37]. The procedure for the strengthening of structural elements by FRCM composites made of natural textiles can be summarised as follows: 1°) preparation of the substrate surface; 2°) application of a first layer of the matrix on the wetted substrate surface; 3°) application of the textile (this process is repeated until all textile layers are well impregnated with the matrix); and 4°) application of a final layer of the matrix on the last textile layer.

This paper reviews the state of the art of various works on the strengthening of structural elements by FRCM composites made of natural textiles based on concrete applications. It also provides a critical review of previous studies to identify deficiencies and gaps in the literature that could be the subject of future studies. This introductory section is followed by a description of the mechanical behaviour (tensile and matrix-textile adhesion) of natural textile FRCM composites. An overview of the different applications (shear, flexural or confinement) is given, followed by the different failure modes.

2 Natural FRCM Composites

2.1 Materials

Today, the growing interest in the use of natural textile FRCM composites as reinforcement and restoration materials for masonry structures is mainly due to their high strength-to-weight ratio, minimal invasiveness, good resistance to high temperatures, the possibility of application on irregular surfaces or in high humidity, vapour permeability, easy and safe application for workers, chemical and mechanical compatibility with various masonry substrates, and reversibility of the intervention, etc. [43, 47, 48].

Natural FRCM composites consist of textiles of plant fibres (flax fibres, hemp fibres, sisal fibres, jute fibres, etc.) embedded in an inorganic matrix, e.g., a cement-based matrix or hydraulic lime [41], etc. Studies [17, 37] have shown that the cementitious matrix does not have the same adhesive properties as an organic matrix (epoxy resin), resulting in a different bonding mechanism between the textile and the matrix than is the case with FRP [7]. The mortar does not allow good penetration and impregnation of the yarn filaments due to the large size of the granules in the matrix. Bonding at the interface between textile and matrix determines the mechanical behaviour of the composite, as it is responsible for load transfer between filaments within a yarn and between the yarn and the matrix. The impregnation of fabrics with polymeric matrices (resin) or mineral fillers has been proposed to improve the bonding properties and thus enhance the mechanical performance of natural FRCM composites [10, 44].

2.2 Mechanical Behaviour of Natural FRCM

The tensile behaviour of FRCM composites has been studied in detail by several authors. FRCM composites are usually used to reinforce masonry components with low tensile strength, so the tensile behaviour of FRCM systems has been studied by several authors [17, 37–40, 45, 46]. Tensile tests on FRCM specimens allowed the determination of the mechanical properties, in particular the ultimate stress and strain and the modulus of elasticity. The typical response describing the mechanical tensile behaviour of FRCM composites is represented by the idealised trilinear shape in Fig. 1, where E1, E2, and E3 are the elastic moduli of phases I, IIa, and IIb, respectively [17, 18, 69]. The uncracked phase I, characterised by a linear behaviour, determines the mechanical properties of the matrix. The appearance of the first crack in the matrix from the first stress drop, followed by several cracks, represents phase II. The opening, number and spacing of the cracks depend mainly on parameters such as the geometry of the textile (mesh size, weave properties), the matrix and the curing conditions. The adhesion between the fabric and the matrix and the number of fibres also determine the extent of phase IIa [70]. Other studies on FRCM made of flax have shown that increasing the number of layers in the fabric reduces the maximum crack widths [28, 46]. The stress-strain curve's third phase (phase IIb) is nearly linear and has a lower slope (modulus of elasticity) than phase I. The composite is completely cracked, and its behaviour is determined by the mechanical properties of the textile. The stiffness of this phase is like that of the textile. The critical cracks propagate to failure, followed by abrupt failure due to the rupture of the textile fibres. Several failure modes can be observed: (i) fibre breakage near the clamps, (ii) fibre breakage at the free part (the unclamped part at the corners), and (iii) fibre slip without breakage [70, 71]. The mechanical performance of the natural FRCM composite is strongly influenced by the reinforcement ratio, textile properties, and adhesion performance at the fibre/mortar interface [45, 46, 71].

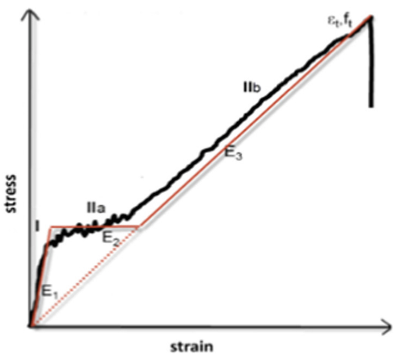

Fig. 1. Tensile behaviour of an FRCM composite [82]

2.3 Adhesion Between Natural FRCM Composite and Substrate

In a reinforcement system, the bond between the different elements plays an indispensable role to achieve the set objectives. In fact, the adhesion between the matrix and the textile, on one hand, and the natural FRCM composite and the substrate, on the other hand, is of great importance, allowing to realise of the effectiveness of the reinforcement. The adhesion between the textile matrix and the FRCM composite and the substrate has been studied in detail by the authors using shear tests (pull-out test, pull-in test…) [21, 46]. It is necessary that poor adhesion leads to detachment, which in turn leads to failure. These failures limit the loading of the natural FRCM composites, especially the activation of the natural textile [46]. Therefore, when there is good adhesion between the natural FRCM composite and the substrate, the following failure modes can be observed: Slippage or breakage of the textile through the matrix and detachment of part of the substrate or matrix from the natural FRCM composite [28, 29]. In addition, six failure modes can be identified (see Fig. 2) [21, 28, 46]. These failure modes are observed in most studies by examining parameters such as the effect of bond length, the effect of bond width, and the effect of substrate surface preparation [11, 14, 15, 19, 21, 22, 24, 28–32, 35].

Trichoutsou et al. (2021) [46] studied the effect of the number of plies for two different geometries of linen fabric. The results showed that increasing the number of plies may or may not change the failure mode. Insufficient impregnation of the yarns may prevent the effective transfer of forces from the yarns to the matrix. As a result, significant deformation/slippage of the textile occurs, possibly due to pronounced telescoping behaviour, followed by failure of individual filaments or yarns (failure modes D, E1, and E2). However, the increase in the number of plies resulted in a non-proportional increase in the maximum load. This non-proportional increase in load capacity is due to the better stress distribution within the composite due to the more uniform distribution of the wires in the matrix. In addition, a change in the failure mode of fibre slip through the matrix was observed upon the detachment of the natural FRCM layers with a portion of the substrate. The same observations were made in the studies of [72], and [73] where synthetic fibres were used.

Bond length was a parameter investigated in most studies. It should be noted that it is important to determine the sufficient bond length of the sheathing for better transfer of tensile loads from the masonry substrate or concrete to the natural FRCM to avoid the different types of premature failure [21, 28, 46, 72, 73, 75]. The capacity of the bond is related to the length of the bond between the substrate and the natural FRCM composite. The results of these studies have shown that the bonding capacity increases nonlinearly with increasing bond length and tends to stabilise at a certain length, called the "effective bond length" (see Fig. 3). In a recent study by [46], the results showed that the effective bond length of the tested flax/substrate FRCM systems ranged from 150 to 210 mm and the observed failure was dominated by fibre breakage.

The effects of bond width have also been studied in the literature [28, 46, 74–76]. This work has shown that an increase in bond width results in a linear increase in axial load capacity but has no effect on the change in failure mode.

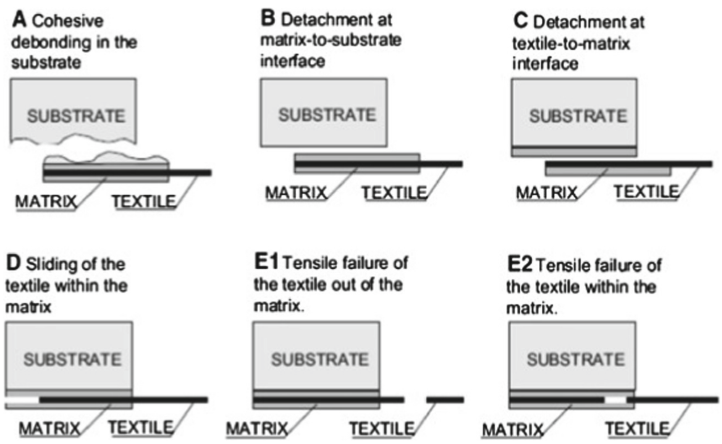

Fig. 2. Different failure modes of FRCM-substrate [21]

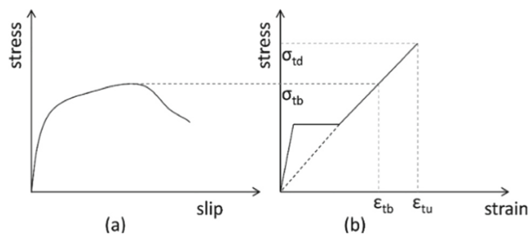

Fig. 3. Definition of the maximum bond a) stress and b) strain of the FRCM [82]

3 Strengthening of Structural/Masonry Elements by Natural FRCM Composites

The use of FRCM composites has been shown to be effective in strengthening masonry structures such as.: vertically loaded columns [49–52], in-plane loaded walls [53–57], out-of-plane loaded walls [58–61], vaults and arches [62–68], sandwich panels [77].

3.1 Compression Strengthening of Masonry Structures

The load-bearing walls of masonry are designed to support both vertical and lateral loads. It should be noted that masonry has complex behaviour and is influenced by various parameters such as the mechanical and geometric properties of the components and the connection between the components and the mortar. Nowadays, the strengthening of these building elements (masonry/concrete) with natural FRCM composites is an innovative topic. Studies have shown that the enclosure of columns with FRCM composites has a double effect: (1) an increase in axial load-bearing capacity and (2) an improvement in axial deformation capacity (ultimate strength) [49–52]. KHALEEL et al. (2021) [78] used a jute textile FRCM composite to reinforce a brick masonry prism in the following manner (see Fig. 4): A 2 mm mortar layer was applied to the four sides of the prism, then the jute textile was applied so that the mortar passes through the meshes of the textile, once the textile is properly wound, another mortar layer of about 2 mm is applied to the surface of the fibre to cover it completely. The results show that the compressive strength increases. Different failure modes were observed such as longitudinal cracking of the masonry or detachment of the outer layer of the FRCM matrix (see Fig. 5).

Fig. 4. Application of FRCM in confinement [78]

Fig. 5. Modes of rupture [78]

3.2 Shear Strengthening

Masonry units generally have a low shear capacity caused by seismic actions parallel to the walls or by sliding. These actions make the masonry vulnerable. The importance of strengthening these walls with FRCM composites based on plant fibres fits well with the goals of sustainable development and the promotion of eco-materials. Strengthening can be accomplished by placing FRCM layers on one or both sides of the wall, depending on the load on the wall or the possibility of intervention. Diagonal compression tests (see Fig. 7) have long been used to assess the shear strength of walls [75, 78, 79]. Ferrara et al. (2020) [28] proposed an experimental study on the shear strength of masonry walls externally reinforced with flax-FRCM composite systems. The results show that the application of the flax-FRCM system significantly improves the mechanical response of brick masonry (see Fig. 6) tested under diagonal compression, increasing the shear capacity by 118% in the case of the system with one layer of flax fabric (SW -1L) and by 136% in the case of the system with two superimposed layers of flax fabric (SW -2L). The increase in shearing capacity is not linear with the increase in the number of layers of the textile, as other authors have found [46, 72, 73].

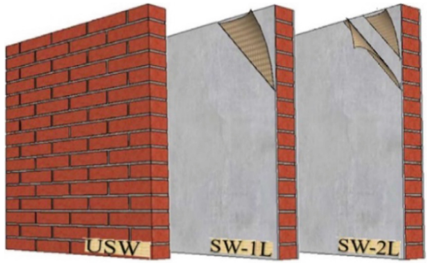

Fig. 6. Walls reinforced with flax-FRCM [28]

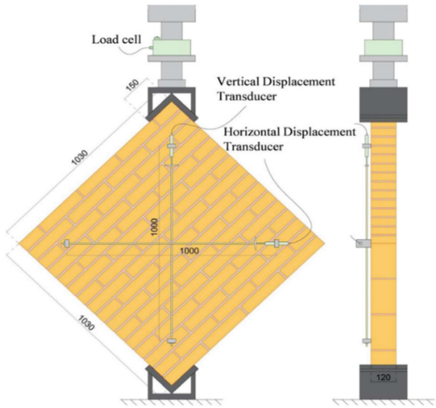

Fig. 7. Diagonal compression test [28]

3.3 Flexural Strengthening of Sandwich Panels

Sandwich panels are a lightweight solution with additional insulating properties compared to conventional solutions used for building envelopes. These panels are used as facade elements, and interior or exterior walls. They can also be used as structural or non-structural elements. In recent decades, the use of FRCM composites as reinforcement systems has increased to achieve better effectiveness against tensile and shear stresses and to expand the use of these panels in the construction sector [77, 80, 81]. Mercedes et al. (2022) [77] recently conducted a study on the reinforcement of sandwich panels (see Fig. 10) using FRCM composites made of different plant fabrics (hemp and sisal) as sandwich skin and an extruded polystyrene core. The two composite skins were joined with different types of connectors, including plant-based ones (see Fig. 8). The results of their work showed that the sandwich panel with hemp-FRCM composite had higher flexural strength without causing fabric cracking, while the panels with sisal and glass fibre FRCM had fabric cracking. A better distribution of cracks was observed with hemp-FRCM compared to sisal-FRCM. This failure is related to the properties of the textile as shown by other authors [28, 46]. Shear failure was also observed despite the use of connectors (Fig. 9).

Fig. 8. Connectors [77]

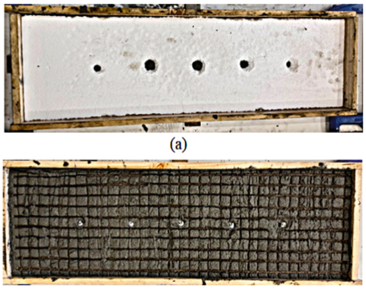

Fig. 9. Sandwich panels with connector system [77]

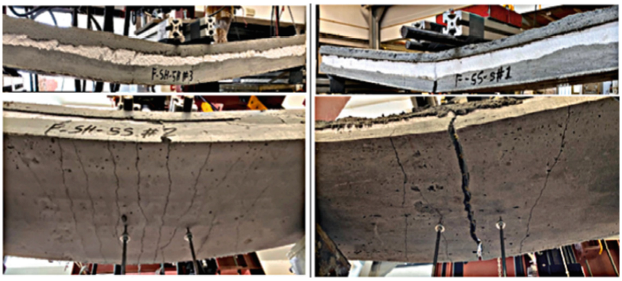

Fig. 10. Failure modes of sandwich panels [77]

4 Conclusion

The application of natural FRCM composites in the field of reinforcement and rehabilitation of existing and new structures is briefly presented in this paper. The focus is on the mechanical behaviour of natural FRCM composites, the adhesion phenomenon of FRCM and its bond to the substrate, and some of the different reinforcement modes (bending, shear, column confinement). The key parameters affecting the effectiveness of the reinforcement systems have been described for better optimization in future works.

In all the studies reviewed in this manuscript, the strengthening of structural elements, masonry or sandwich elements by natural FRCM composites was found to be successful. This strengthening technique was found to be effective in increasing the mechanical capacity (flexural, shear or compressive strength) and stiffness of existing or new structures (concrete or masonry, etc.) and consequently their performance under service loads. On the other hand, several rather complex failure modes have been identified, mainly related to the adhesion of the natural FRCM and to the properties of the matrix and the textile (plant fibres). Although several works have already addressed this issue, the topics of durability and the effect of high temperatures certainly deserve further research.

It is important to note that the studies conducted to date on the practical applications of natural FRCM (plant fibres) provide only sufficient data to allow the development of a design guideline and recommendations for standardising their use in construction.

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