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ABSTRACT

Composite materials have been widely used for strengthening weak masonry buildings. Particularly, wrapping with fibre reinforced polymer (FRP) composites has become a common method for strengthening masonry members primarily subjected to compressive static loads or seismic actions. More recently, in an effort to alleviate some drawbacks associated with the use of FRP materials, fibre-reinforced cementitious matrix (FRCM) composites have received a lot of interests for external strengthening of historical masonry structures. It is used as an alternative to FRP in situations where these composites have shown some disadvantages or their use is banned. This paper presents a literature review on the mechanical characterisations of FRCM composites for structural retrofitting. Recent experimental results of tensile and bond tests are discussed, highlighting the roles of the different parameters affecting the mechanical performance, e.g. type of fibre, clamping method. This review aims to form the base for a new experimental investigation on the compressive behaviour of FRCM and FRP wrapped masonry specimens.

INTRODUCTION

A significant part of existing buildings are masonry structures. A large part of this heritage shows damages due to a wide range of events, such as earthquakes, inappropriate construction techniques and materials, environmental deterioration. In response to these problems, the use of different types of composite materials has become a popular solution, for both reinforced concrete (RC) and masonry structures. Most composite materials are a polymeric matrix reinforced with fibres – fibre reinforced polymer (FRP) composites. More recently, in an effort to alleviate some drawbacks associated with the organic character of polymer-based composites, some attention has been paid towards the use of fibre-reinforced cementitious mortar (FRCM) composites, made with inorganic matrices that provide greater environmental sustainability and higher resistance to heat.

FRCM systems can be used for flexural and shear strengthening of concrete and masonry elements, or for confinement of columns. Numerous studies have been conducted on strengthening of masonry panels using tensile reinforced matrix (TRM) composites [1, 2]. Koutas et al. [3] made the first attempt to investigate at large scale the application of textile-based composites with inorganic matrices for retrofitting infill walls in substandard multistory RC buildings. Many researchers have also investigated the effectiveness of confinement of masonry columns using FRCM composites with different types of textile [4, 5, 6, 7].

This paper presents an overview of the state-of-the-art on FRCM composites. The study is preparatory for an experimental study of masonry specimens confined with basalt reinforced FRCM and FRP. In the next sections, a review of the most recent experimental results on FRCM mechanical properties is reported. A final section is devoted to the specimens and the test set-up of the ongoing study.

MECHANICAL CHARACTERISATION OF FRCM COMPOSITES

The FRCM strengthening system is an effective alternative to FRP systems because of factors such as the good compatibility between the mortar matrix and the masonry substrate, its superior performance during fire, its lower environmental impact and less likelihood of debonding. As the development of mortar-based reinforcements is still at an early stage, the mechanical properties of the composites need to be investigated and standardised testing methodologies have to be defined. During the last decades many studies have been carried out with the aim of assessing the mechanical properties of the individual materials making up the FRCM composite (mortar and fibres), the bond behaviour at the fibre/matrix interface and the bond behaviour at the FRCM composite/masonry interface. In the next sections the main results of these experimental studies are reported and discussed.

Tensile Tests

Several factors can influence the tensile behaviour of FRCM composites. The type of fibre, fibre architecture, physical and mechanical properties of fibres and interaction between fibres and matrix material have significant effects on the tensile and flexural behaviour of the FRCM composites. With the aim of investigating the effects of different fabric parameters on the tensile strength of sustainable FRCM, many experimental studies have been carried out during the last decade.

Single Yarn

Codispoti et al. [8] conducted a comprehensive experimental study on the mechanical performance of natural fibres for the strengthening of masonry constructions. Natural fibre-based composite materials present a wide variety of mechanical properties; this is a consequence of the fact that properties of natural materials are strongly influenced by the type of fibre. For this reason, tests performed on the composite materials were preceded by the study of the tensile behaviour of single yarns conducted using tensile tests. Flax, hemp, jute, sisal and coir fibres were investigated both from physical and mechanical points of view, with the aim of producing suitable composite materials particularly for strengthening of historic masonry structures.

Direct tensile tests were performed on single flax yarns [9] in an experimental study aimed at mechanical characterisation of FRCM composites made of flax natural fibres. In [10] and [11], tensile tests of the dry fibres were performed on a single roving in warp and weft directions. De Felice et al. [12] investigated the performance of three reinforcement systems made of steel, carbon and basalt textiles by means of uniaxial tension test of fibres.

Fabrics

There are large differences between the tensile strength and Young's modulus of a single fibre or filament and those of the textile mesh or grid. The main cause of the differences is due to the irregular distribution of stresses in the yarns. Studies have been conducted to determine the mechanical characteristics of the textile reinforcement material through tensile tests of textile specimens. Commonly tabs are used to distribute the stresses in the grids but the irregularities in the load distribution are difficult to avoid. Direct tensile tests of textiles used for the different composites have been performed by many researchers [8,10–17] before testing composite materials, in order to investigate the contribution provided by the matrix in the tensile behaviour.

Composites

Experimental investigations have shown that failure of FRP systems occurs mostly at the composite-substrate interface by debonding. For FRCM strengthening systems, the use of lime or cement-based mortar means that the bond behaviour between the fibres and the matrix is also critical, since sliding phenomena and cohesive failures in the mortar frequently occur. Therefore, for the FRCM materials the knowledge of the bond behaviour at the fibre/matrix is fundamental for evaluating accurately their performance.

Many researchers [8,10,12–15,17–20] have carried out direct tensile tests in order to investigate the behaviour of FRCM composite materials. Direct tensile tests have been conducted for both natural and glass fabric-reinforced composites in [20]. The tensile behaviour of the composite samples and the fabric parameters involved are comprehensively analysed. In particular, considering fabric geometry and physical properties, the flax fabric provided better anchorage development than the sisal and glass fabrics in the cement-based composites. The fabric geometry and the volume fraction of fibres were found to have the greatest effects on the tensile behaviour of these composite systems.

In [8], different production methods (manual wet lay-up technique, vacuum infusion and traditional construction technique using formwork) were used to manufacture Natural Fibre Reinforced Polymer (NFRP) and Natural Fibre Reinforced Cementitious Matrix (NFRCM). Their performance was tested and analysed in detail.

Larrinaga et al. [13] presented an experimental study on 31 Textile Reinforced Mortar (TRM) specimens reinforced with four different reinforcement ratios. The effect of reinforcing ratio was analysed. While specimens reinforced with a single textile fabric fracture smoothly, the increase of the reinforcing ratio transformed the failure mode to a more brittle rupture leading to a sudden loss of bearing capacity. The increase of the reinforcement ratio also affected the development of the crack pattern, which significantly influenced the behaviour of the composite. The number of cracks was larger with more basalt textiles acting as strengthening core, with the crack spacing as well as their width reduced. Other important phenomenon about the failure modes and the crack pattern was observed by De Santis et el. [15]. They demonstrated that as the crack pattern is affected by the layout of the textile, which influences the bond and interlocking between the textile and the matrix, and by the Young's modulus of the mortar, while the failure mode is mainly governed by the reinforcement fabric.

Researchers [10,12,13,16,20] have identified three main stages in the tensile response of FRCM composites: the first stage is characterised by a linear or quasi-linear behaviour. This stage ends with the formation of the first crack in the matrix. In the second stage, the composites show a non-linear behaviour with a sudden reduction in stiffness. During this stage, multiple matrix cracks occur, releasing strain energy and generating an instantaneous decrease of stress in the mortar by the formation of new matrix cracks. In the third stage (post-cracking stage), the reinforcing fabrics govern the tensile behaviour of the composite materials, and the matrix contribution can be neglected. This phase ends when the maximum load is reached. An important phenomenon is the loss of stiffness prior to rupture; this effect could be caused by debonding at the textile-matrix interface and progressive rupture of filaments inside the rovings.

An important aspect regarding the tensile test of FRCM composites is the clamping system, which can strongly influence the measured strength. In [12,15] different options were developed to ensure adequate clamping of the specimen, in order to achieve a uniform load transfer and avoid stress concentration in the gripping area. Carozzi et al. [10] adopted an alternative clamping method to that presented in Annex A of AC 434 [21]. After several tests for comparison, it was concluded that the alternative clamping system was preferable because it gave the possibility to reach the ultimate stress of the textile reinforcement and explore the third phase of the stress-strain plot, limiting the slip of the fibres, while the US Standard produced a bilinear behaviour of the composite limiting the analysis to the first two phases.

Bond Tests

As previously commented, experimental investigations have shown that in the case of FRCM composite strengthening systems debonding is mainly related to the fibre-matrix interface rather than the composite-substrate interface. In particular, three mechanical features are involved in debonding at the fibre–matrix interface: tensile strength of mortar, adhesion between textile and mortar matrix, and frictional adhesion between the threads of a single yarn. The last phenomenon can occur when the internal filaments of each yarn are not sufficiently impregnated with mortar matrix. It has been shown that the fibre–matrix slip is mainly due to the loss of friction between the innermost and outer filaments of the yarn because the innermost fibres were difficult to be fully impregnated [14].

The bond behaviour between different FRCM composites and masonry, and that between textile and cement matrix have been investigated by numerous researchers [10–12,14,17–19, 22] by means of either pull-off shear tests or pull out tests. The design of the set-up test for the FRCM system applied on masonry support is still under experimental investigation; for this reason there is no unique set-up, and various procedures and equipment have been used by different researchers.

In [11] a single yarn embedded into a small block of mortar was tested under an increasing tensile load up to failure to evaluate the bond-slip relationship and interfacial shear stresses.

Olivito et al. [22] investigated experimentally the bond adhesion between sustainable composite material and masonry. Double-lap shear pull-off tests were carried out on masonry clay bricks externally bonded with Flax and PBO-FRCM composites. The results showed a clear difference between the reinforcing system based on natural fibres and those based on synthetic fibres. In the case of the Flax-FRCM, the failure process was slow. It started with cracking in the cementitious matrix, followed by the fracture of individual yarns in the fabric. For the PBO-FRCM reinforcement system, the failure occurred in a brittle manner, typical of FRP composites. The failure occurred either in the composite or debonding of the PBO-FRCM from the brick substrate The current standards [23] classify four failure modes of the composite systems: failure in the composite, cohesive failure (in the substrate and in the matrix) and tensile failure in the un-bonded area. The Flax-FRCM composite system showed a progressive failure which is different from the aforementioned. Another important aspect analysed was the contribution of the different textiles as determined in the experiments. Flax fibres in the composite were made full use of their mechanical properties compared to PBO fibres; indicating the beneficial effects of compatibility of flax fibres with the cement matrix.

Alecci et al. [14] studied the ratio of loading capacity in the double-shear tests to the tensile capacity of the textile obtained from direct tensile tests. It was concluded that glass and PBO-based composites better exploit the tensile strength of fibres compared with carbon-based composites.

The effectiveness of an external reinforcement depends also on the anchorage length. Tests carried out by different researchers [11,12,18,19] with different bond lengths showed that there also exists an effective bond length when the failure is by debonding. The effective bond length is defined as the maximum length beyond which an increase of the bond length does not increase in the force transferred between substrate and reinforcement [24]

EXPERIMENTAL PROGRAM

The aim of the present study is to evaluate the effectiveness of FRCM wraps on the performance of masonry columns, and to compare it with that of FRP wraps. A set of tests are being carried out on brick masonry specimens with a circular cross section, wrapped with either FRP or FRCM material. A similar experimental study has already been carried out on CFRP confined masonry specimens [25].

Description of the Experimental Programme

The experimental programme consists of tests of masonry components (mortar and bricks), the basalt fabric and composite (FRCM), and the masonry bricks confined with either FRCM or FRP. A total of 48 small scale masonry cylindrical specimens will be tested. The specimens are assembled using pressed bricks (215 x 102.5 x 65 mm in dimension), arranged using two different construction schemes (Fig. 1). The specimens were obtained after the bricks were assembled using the two schemes shown in Fig. (1) and using a medium strength binding mortar; a laboratory coring machine was used to extract cylindrical specimens of 100 mm in diameter and 170 mm high, with 2 mm thick joints. The dimension of all constituents, i.e. bricks, mortar joint and composition of mortar sand, were measured.

Thirty specimens were prepared using scheme one: six unconfined clay brick columns were prepared as control specimens; twelve samples were wrapped using one layer of textile, six using FRP composite material and six using FRCM. The remaining twelve specimens were prepared using two textile layers of FRCM or FRP. Twelve specimens were prepared using the second scheme: six control specimens and six samples wrapped using one layer of FRCM.

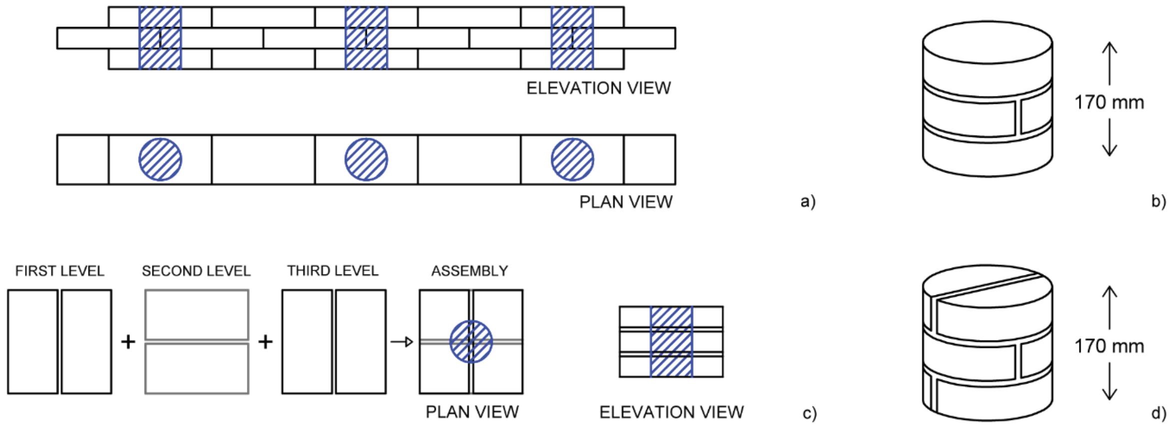

Figure 1. Specimen preparation schemes: (a) scheme one masonry wall; (b) scheme one specimen; (c) scheme two masonry wall; (d) scheme two specimen.

CONCLUSIONS

This paper has presented a review of recent experimental research on FRCM mechanical properties. The following conclusions can been drawn based on this review:

- The properties of composite materials are strongly influenced by the type of fibre, so the determination of single yarn tensile behaviour is important. A significant difference exists between the mechanical properties of a single fibre and those of the textile mesh, due to an irregular distribution of the stress in the yarns during the tests. Direct tensile tests on textile are crucial in order to investigate the actual contribution provided by the matrix and composite mesh;
- One of the most important aspects that affect the tensile behaviour of composite materials is the bond between the fibres and the matrix. Sliding mechanism occurs between the filaments embedded in cementitious matrix, called telescopic failure, caused by the different impregnation of external and inner filaments;
- The clamping method may significantly influence the measured strength. Different procedures have been experimented to identify suitable techniques that avoid local stress concentrations near the clamping wedges. Clamping FRCM composites directly on the mortar, after having applied a reinforcement in the gripping areas to prevent mortar crushing, allows for an appropriate load application to the whole specimen;
- The effectiveness of an external reinforcement depends on the adequacy of the anchorage length. Current Italian standard needs to be revised in terms of calculation of the bond stress and the optimal bond length.

The paper also presented briefly on on-going experimental study aimed at investigating the effectiveness of FRCM wraps on the performance of masonry columns, in comparison with that using FRP wraps. The results of experiment will be presented at the conference.

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