Textile reinforced concrete composites for existing structures: performance optimization via mechanical characterization

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Abstract

Textile Reinforced Concrete (TRC), also known in Italy as Fabric-Reinforced Cementitious Matrix (FRCM) composite, represents a promising reinforcement solution for the upgrading and the restoring of the load carrying capacity of structural elements unable to meet the requirements imposed by recent technical regulations with respect to seismic actions. The research is focused on the investigation of the mechanical properties of FRCM composites at different scales of analysis; both mechanical characterization of the composite systems (fabric, matrix and dispersed short fibers) and meso-scale tests focussing on the interface bond-slip behaviour are presented in this paper.

1 Introduction

In Italy, recent seismic events have shown the vulnerability of a large part of existing buildings historically designed according to standards not oriented towards seismic safety. The updating of technical regulations in this field entails the upgrading and the restoring of the load carrying capacity of inadequate structural elements. As shown in literature [1], Fabric-Reinforced Cementitious Matrix (FRCM) composites, appear to be an effective reinforcement solution. The research is focused on the investigation of the mechanical properties of FRCM composites and aims at evaluating and assessing the potential of this kind of reinforcement technology by means of a combination of mechanical testing and numerical modelling. Three scale levels of analysis are considered in the experimental campaign: mechanical characterization of the composite materials, meso-scale tests focussing on the interface bond-slip behaviour and full-scale tests on different reinforced elements. The main advantages of this solution with respect to other reinforcement technologies, like FRP, are the better compatibility with irregular surfaces and substrate materials as concrete and masonry, the easier workability, the greater resistance to fire, the greater vapour permeability. Moreover, the cost of installation and materials is smaller. In this work, the results of the first part of the experimental campaign that involves Politecnico di Milano in the framework of the Italian ReLUIS interuniversity consortium are presented. Regarding the material scale, a wide series of uniaxial tensile tests was performed in order to optimize all the components of the FRCM system (different Alkali-Resistant glass fabrics, matrices and dispersed short micro-fibers were used) and define parameters able to better describe the response of different composite systems. Moreover, a set of preliminary Double Edge Wedge Splitting (DEWS) and single lap shear tests on concrete and masonry substrates devoted to characterize the interface properties was carried out. At the end, the procedure proposed by recent Italian guidelines to conventionally qualify the composite system applied on a selected substrate is presented and discussed.

2 Materials

A group of four AR-glass fabrics was selected out of the whole set, following a preliminary experimental campaign aimed at optimizing the behaviour of FRCM composites. The main properties of these fabrics are summarized in Table 1, and they are sorted by an increasing load capacity. Three different kinds of coatings were used: one made by epoxy resin and the other two by Styrene-Butadiene resin (SBR). With respect to SBR1, SBR2 is characterized by the increasing of the hardening additive (from 10% to 25%), the reduction of the quantity of coating distributed on the fabric to reduce tangential slippage and the increasing of the curing temperature (up to 250° C). In this paper only the weft fabric direction will be considered in the mechanical characterization.

Table 1 Alkali-resistant glass fabric characteristics (weft direction).

Characteristics	F1	F2	F3	F4
Fabrication technique	Leno weave	Double Leno weave	Double Leno weave	Leno weave
Wire grid (warp × weft) [mm]	18 × 18	38 × 38	38 × 38	5 × 12
Uncoated grammage [g/m^2]	134	127	255	480
Equivalent reinforcement thickness [mm]	0.049	0.046	0.093	0.179
Equivalent cross sectional area on 70 mm [mm^2]	3.43	3.22	6.51	12.53
Coating	SBR2	Epoxy	Epoxy	SBR1
Average tensile load on 70 mm [kN]*	5.71	6.31	13.03	15.98

(*Average value of 5 nominally identical direct tensile tests)

In this work, three matrices are considered. Matrix M1 consists of a self-compacting Hig-Performance Concrete (HPC) [2] characterized by a cubic compressive strength f_{cc} > 90 MPa and a flexural tensile strength f_{ctf} > 14 MPa (note that this solution can be used only if temporary form-works are employed), while M2 and M3 are commercial shrinkage-compensated thixotropic repair mortars, respectively suitable for retrofitting applications on concrete and masonry substrates. The mechanical properties declared by the manufacturer are f_{cc} > 45 MPa and f_{ctf} > 8 MPa, for matrix M2, and f_{cc} > 15 MPa for the M3 one. Moreover, M3, which is a lime based mortar, is specifically designed for masonry structures, since the absence of cement increases its vapour permeability, hence the durability of the reinforcement application.

Straight high-carbon steel microfibers (diameter 0.21 mm, length 13 mm, aspect ratio 62, tensile strength 2750 MPa) and High alkali resistance PVA fibers (equivalent diameter 0.16÷0.24 mm, length 18 mm, aspect ratio 90, yield strength 790÷1160 MPa) were added to the mixture to an extent of 1% volume fraction. After preliminary experimental tests, it was observed that the addition of steel fibers to thixotropic matrices can increase the quantity of material defects reducing the effectiveness of the fabric reinforcement. For this reason, PVA fibers were preferred in composites based on matrix M2.

3 Experimental tests

In this paper, the results of direct uniaxial tensile tests on FRCM composites and single lap shear tests considering different substrates are presented. The experiments were performed using an electro-mechanical press with maximum load capacity equal to 30 kN, displacement-controlled at a costant stroke rate (0.02 mm/s for tensile tests and 0.01 mm/s for shear ones). At the end, the results of preliminary Double Edge Wedge Splitting tests (DEWS) performed using a 100 kN load capacity hydraulic press are shown.

3.1 Direct uniaxial tensile tests

The curves introduced in the following represent the average uniaxial tensile behaviour of 3 nominally identical (400 × 70 × 9 mm) FRCM specimens. The results are presented in terms of average nominal stress on the cross section of the specimen vs. normalized displacement (stroke divided by the free specimen length, approximately equal to 300 mm). Each specimen was clamped through 2 mm thick steel plates and instrumented with a Linear Variable Differential Transformer (LVDT) per side, operating on a gauge length equal to 200 mm. A simplified scheme of the setup is shown in Fig.1 (right).

3.1.1 Effect of the fabric coating

The choice between different kinds of coatings affects both the ultimate load capacity of the fabric and the effectiveness of the reinforcement embedded within the composite system. In Fig. 1 (left) it is possible to observe that, to obtain the typical tensile trilinear behaviour [3] considering a composite reinforced by a wide-spaced fabric (i.e. F2), it is necessary to use an epoxy coating instead of an SBR one, while in Fig.1 (right) it is depicted that a composite system reinforced with a narrow-spaced fabric (i.e. F4) clearly exhibits a trilinear tensile response. In the latter case a greater bearing capacity is achieved thanks to the reduction of the grid spacing that increases the mechanical anchoring, but no direct proportionality between the uncoated grammage of AR-glass and the ultimate load was observed (despite the amount of glass is about twiced from F3 to F4, the ultimate load is substantially the same).

This might be explained by the capability of the epoxy resin to better impregnate all the filaments of a yarn with respect to the SBR coating, giving them the possibility to work in parallel, avoiding a telescopic failure mode [4].

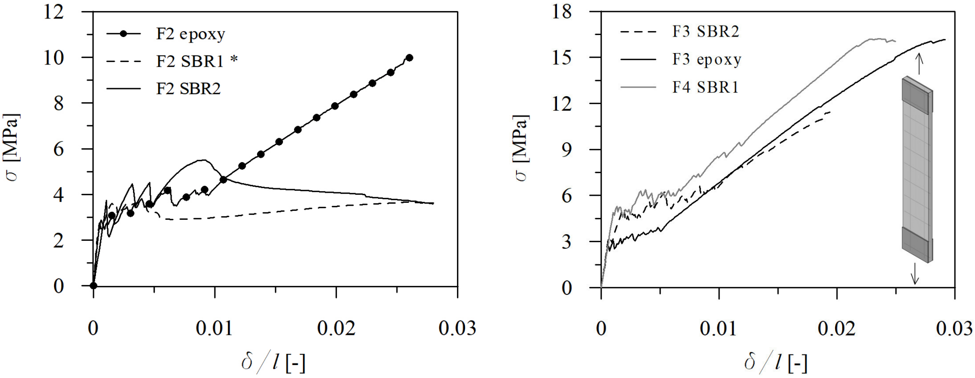

Fig. 1 Effect of different coatings on the uniaxial tensile response of F2-M1 composites (left) (*6 mm thick instead of 9 mm) and on F3-M1, F4-M1 ones (right).

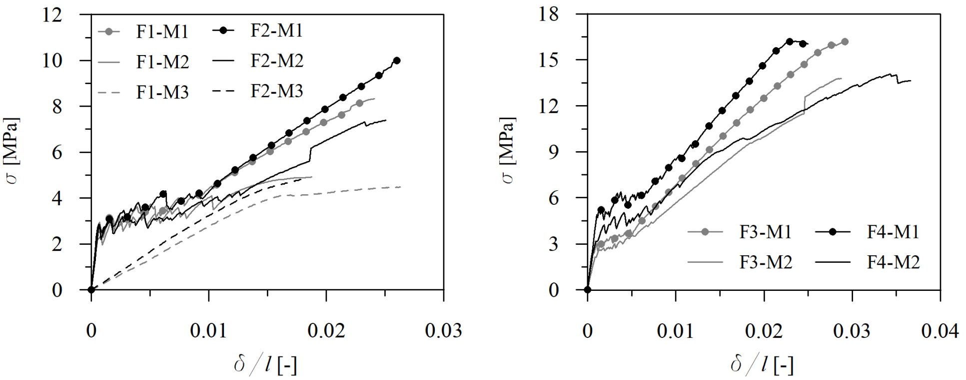

Fig. 2 Average uniaxial tensile response of each fabric combined with different matrices.

3.1.2 Effect of different matrices

Fig. 2 (left) and 2 (right) show that the uniaxial tensile response of an FRCM composite system is significantly influenced by the employed matrix. The greater porosity and the reduced mechanical properties of the M2 matrix with respect to the M1 are responsible of the reduction of the peak load because of the weakeaned adhesion and the consequent non-uniform distribution of stresses on the fabric. Moreover, it is possible to observe that the matrix M2 responses tend to loose the linearity also in the third branch (fabric response) because of the slippage of the fabric within the matrix.

Regarding matrix M3 systems, it is necessary to underline that all the specimens underwent significant shrinkage and demolding cracking connected to unsatisfactory mechanical performances. In this regard, further research will focus on the reduction of the water content, so as to simulate the amount retained by the porous masonry substrate, as observed in preliminary meso-scale applications.

3.1.3 Effect of dispersed short fibers and ductility parameters definition

The effects of the addition of dispersed short fibers to the matrix on the mechanical performance of TRC composites noted by Barhum et al. [5] are: the increase of the first cracking stress, the formation of a denser cracking pattern and an increasing of the nominal values of stresses in the second branch of the trilinear response due to the improvement of the bond between the textile and the matrix (microscopic investigations of fracture surfaces showed that short fibers are frequently linked to the yarns).

In Fig. 3 (left) and 3 (right) it is possible to notice the overall increase of the mechanical response of FRCM composites due to the presence of added short fibers (except for the case F4-M2, because of the narrow-spaced mesh combined with the weakness of the matrix). Morover, the comparison between the cracking patterns at the end of the tests with or without the addition of short fibers in Fig. 4 (left) confirms the increasing number of micro-cracks providing a better behaviour in terms of durability.

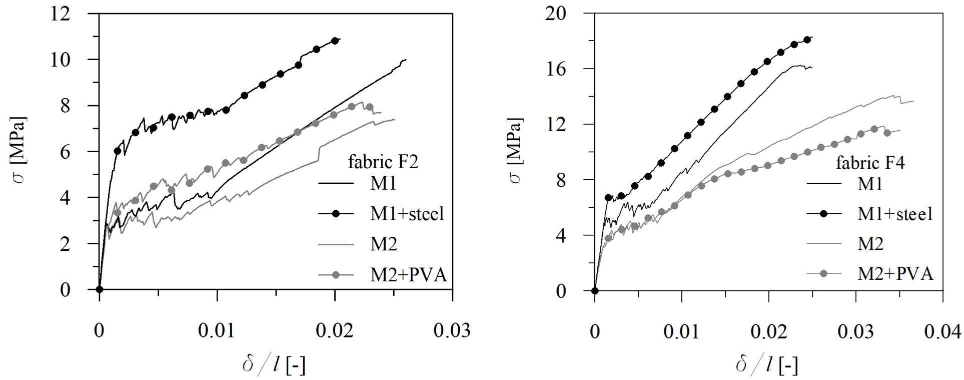

Fig. 3 Uniaxial tensile test responses with or without the addition of short dispersed fibers: fabric F2 (left) and F4 (right).

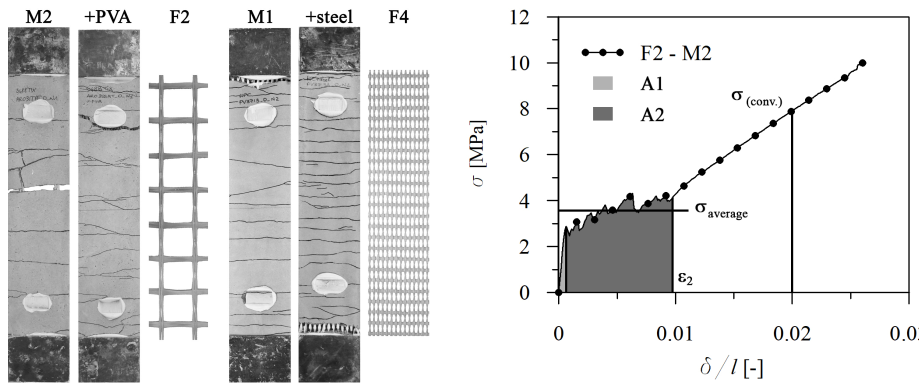

Fig. 4 Cracking patterns with and without short fibers addition (left) and ductility parameters definition (right).

To better quantify the effect of fibers addition, ductility parameters are defined in Fig. 4 (right): i) the total area under the first two branches of the stress-normalized displacement uniaxial tensile response (A1+A2), ii) the value of the normalized displacement at the end of the multi-cracking phase (ε_2) and iii) the average stress value obtained imposing an equivalence of toughness at the end of the second branch ($\sigma_{average}$). A conventional stress value ($\sigma_{(conv.)}$) at strain equal to 2% is also considered.

For the composites produced with matrix M1, Fig. 5 (left) displays the comparison between the ductility parameters of specimens additionally reinforced with mico-fibers, normalized with respect to the ones without fibers. It can be noticed that the consequences of fiber addition in F1 and F2 fabric composites are a remarkable increase of the average stress ($\sigma_{average}$) and of the toughness at the end of multi-cracking phase, and a feeble growth of the strain ε_2. Conversely, in the F3 and F4 cases the responses become stiffer (smaller ε_2 and A1+A2) and the increasing of the overall mechanical behaviour is visible only considering the global curve (Fig. 3 (right)). This is probably due to the greater fabric reinforcement ratio of composites produced with textiles F3 and F4.

3.1.4 Efficiency factors

The meaning of the efficiency factors is to describe the behaviour of TRC composites in terms of ultimate load capacity. In addition to the standard efficiency factor that refers the maximum load of the composite under uniaxial tensile test divided by the one of the plain fabric ($EF_{frcm}=P_{frcm}/P_{fabric}$), a new factor was defined as the ratio between the ultimate stress of the FRCM composite referred to the fabric equivalent cross sectional area ($\sigma_{dry,textile}=P_{frcm}/A_{fabric}$) and the characteristic value of the ultimate stress of an AR-glass filament, approximatively equal to 2000 MPa ($EF_{glass}= \sigma_{dry,textile} / \sigma_{glass}$).

According to Fig. 5 (right) is it possible to introduce some observations valid for both M1 and M2 matrix composites: i) the use of fibers increases the efficiency of each system (except for the case F4-M2, as already noticed in Fig. 3 (right)), ii) higher fabric grammage (F3 and F4) entails a general reduction of efficiency factors and iii) the use of an epoxy coating (F2 and F3) shows two close values of the efficiency parameters, providing a good exploitation of the quantity of glass introduced as reinforcement.

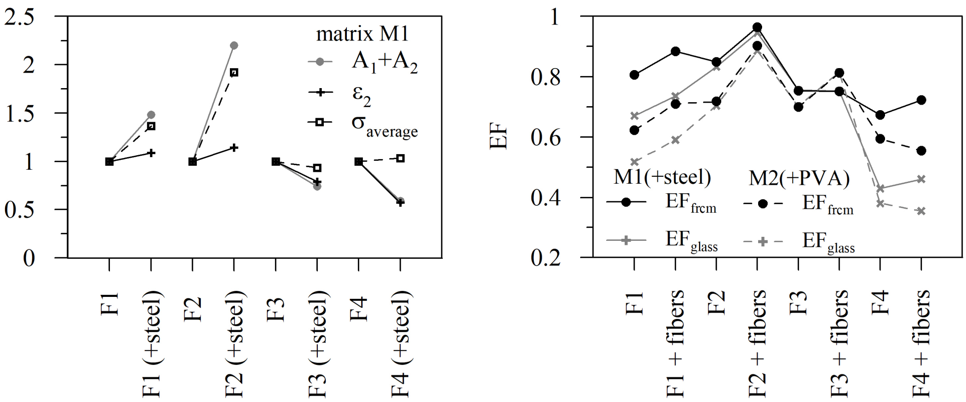

Fig. 5 Ductility parameters variation due to the addition of steel micro-fibers in matrix M1 composites (left) and Efficiency Factors values for matrix M1 and M2 composite systems (right).

3.2 Single lap shear tests and preliminary double edge wedge splitting tests

Bond-slip properties at the FRCM-substrate interface were investigated by means of 2 nominally identical single lap shear tests considering different types of substrate: sandblasted concrete supporting M2(+PVA) matrix composites and masonries made by bricks characterized by different roughnesses (B1 smooth, B2 rough) supporting M3 matrix systems. In addition to the stroke output, 2 LVDT transducers were positioned so as to measure the relative displacement between the support and the head of the reinforcement. The experimental setup and the specimen sizes of the single lap shear test are depicted in Fig. 6 (left), while DEWS tests are described in Fig. 9 (left). Please note that all the curves presented in the following are referred only to a single test response and not to an average behaviour.

3.2.1 Single lap shear tests results

In Fig. 7 (left) the comparison between the single-lap shear responses to a single lap shear test of two different composites applied on sandblasted concrete substrate is shown. It is possible to notice that two failure modes documented in the literature [6] were observed. The F2 fabric composite response exhibited a monotonic load-stroke curve up to failure, with a slip value constantly close to zero; this means that the end of the test was due to the rupture of the AR-glass fabric (Fig. 6 (center)), while in the case of F4 fabric the failure was triggered by the delamination of the reinforcement from the support, at a value of nominal shear stress equal to 0.54 MPa.

In the case of single lap shear tests on masonry substrates, all the specimens failed due to the rupture of the AR-glass fabric, except for the F1-B1 system that manifested a delamination from the support (Fig. 6 (right)) at a value of nominal shear stress equal to 0.30 MPa. In Fig. 7 (right), it is possible to appreciate the different bond-slip behaviour on masonry substrates due to the brick finishing; as expected, roughness played a significant role in the overall response, improving the mechanical adhesion at the interface.

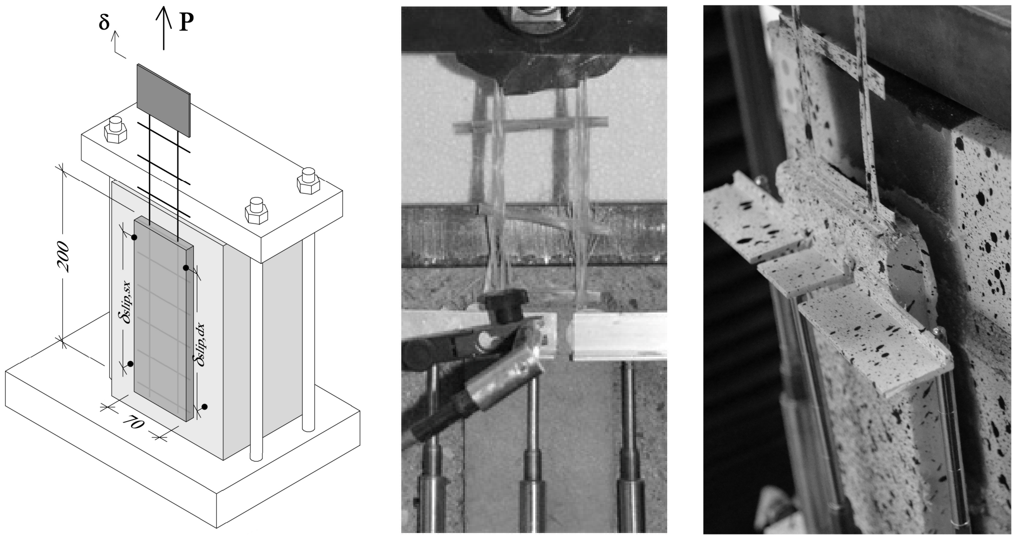

Fig. 6 Single lap shear test setup (left) and examples of different failure modes: fabric rupture (center) and delamination at the reinforcement/substrate interface (right).

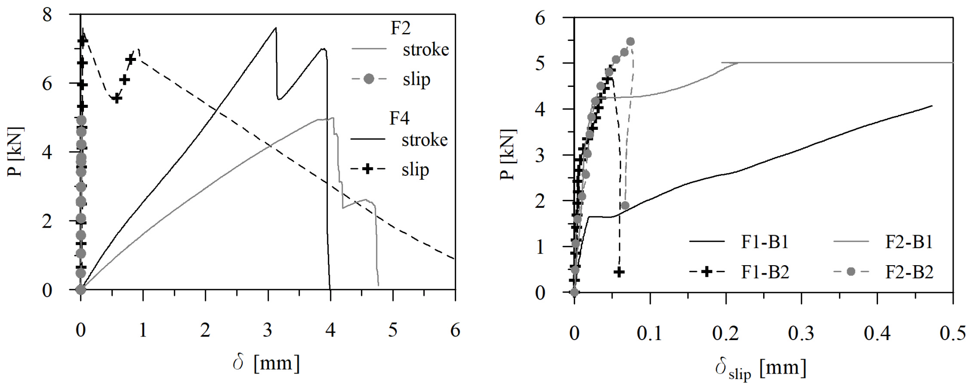

Fig. 7 Comparison between single lap shear test responses for different FRCM systems applied on a sandblasted concrete substrate (left) and on masonry substrates with different roughnesses (right).

3.2.2 Procedure for the identification of design parameters

According to the new Italian guidelines for FRCM applications, wich are now approaching their final approval, structural design parameters can be obtained by simply cutting the uniaxial tensile response at the average load value obtained from the shear tests, as shown in Fig. 8. In this way, the mean peak stress and strain (σ_u, ε_u) and the secant tensile modulus of elasticity $E_{sec} = \sigma_u/\varepsilon_u$ can be easily obtained. This procedure qualifies the composite system on the basis of the weakest failure mechanism exhibited in the shear test (stresses in the textile are imposed to be lower than both its tensile strength and the stress that induces delamination [6]) and can be extended to FRCM systems composed of different materials, simply taking into account the characteristics of the substrate. Furthermore, it is also important to define which kind of debonding failure occours; as a matter of fact, proper debonding mechanism are the ones localized at the reinforcement/substrate interface or connected to the tensile rupture of the fabric. On the contrary, telescopic failure and sliding of the textile whithin the reinforcement thickness indicates that the mechanical properties of textile are not fully exploited.

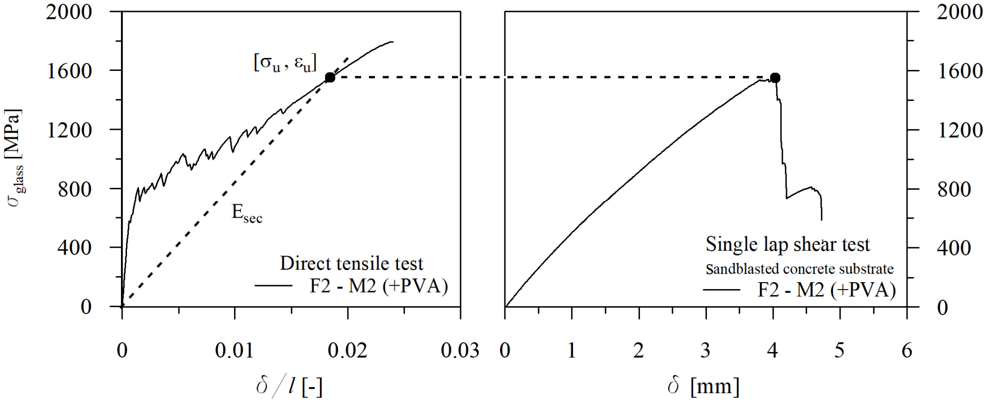

Fig. 8 Identification procedure of FRCM design parameters: combination of direct uniaxial tensile test (left) and single lap shear test (right).

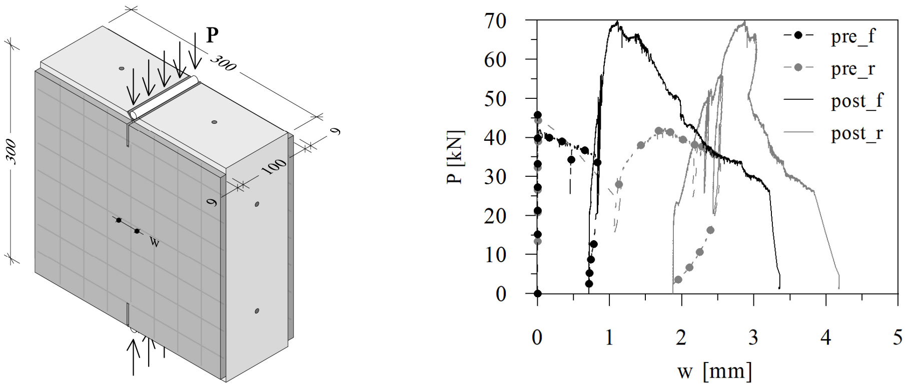

Fig. 9 Double Edge Wedge Splitting test setup (left) and example of vertical load vs. crack opening curves (front and rear) in the pre-cracking phase (pre) and after the application of the FRCM system (post) (right).

3.2.3 Preliminary double edge wedge splitting (DEWS) tests results

A set of 8 preliminary Double Edge Wedge Splitting tests [7] was performed, applying an F2-M2(+PVA) composite on both sides of a sandblasted concrete specimen. The advantages of this test is the possibility to transfer the stresses of a pre-damaged substrate block directly to the reinforcement layers by means of chemical and mechanical adhesion [8] and to verify the capability of the reinforcement to restore or upgrade the capacity of the integer support. The results show that it is necessary to increase the roughness of the interface, for instance using alternative surface machining options (i.e. hydro-scarification); infact, only one specimens shown a satisfactory response, with an increase of total vertical load and the absence of early delamination phenomena Fig. 9 (right)).

4 Conclusions and further developments

Based on the presented results of the experimental campaign, it is possibile to draw the following conclusions: 1) Fabric-Reinforced Cementitious Matrix composites represent a promising solution for both restoring and upgrading of load-bearing capacity of existing structural elements; 2) the mechanical behaviour of different composite systems can be effectively compared by using the efficiency and ductility parameters presented in this work; 3) the interpretation of the results of direct tensile tests oriented towards the effect of each component (fabric, coating, matrix, dispersed short fibers) helps to better understand the complexity of the involved phenomena and to optimize the FRCM solution for each kind of application; 4) single lap shear tests and preliminary double edge wedge splitting tests show the importance of the substrate machining in ensuring a better interaction at the interface level and a greater effectiveness of the reinforcement application.

The next phase of the research will comprise: 1) uniaxial and biaxial tensile tests on FRCM composites considering different widths, numbers of fabric layers, thicknesses and materials; 2) the calibration of the ACK-model (originally developed for Textile Reinforced Concrete [9]) to build a design tool for the prediction of the mechanical behaviour of the composites; 3) additional meso-scale tests (DEWS tests on concrete substrates and diagonal shear tests on masonries) considering different machining options to improve the effect of direct mechanical anchoring; 4) full-scale tests on different structural elements (reinforced concrete slabs, coupling beams, masonry walls etc.) to verify the effectiveness of the FRCM reinforcement in retrofitting (on pre-damaged elements) and upgrading of the load bearing capacity; 5) validation of the simplified design tools by means of advanced numerical analyses.

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