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Failure modes in FRCM systems with dry and pre-impregnated carbon yarns: Experiments and modeling

Jacopo Donnini[a], Giovanni Lancioni[b,*], Valeria Corinaldesi[a]

[a] Dipartimento di Scienze e Ingegneria della Materia, dell'Ambiente ed Urbanistica, Università Politecnica delle Marche, Ancona, Italy

[b] Dipartimento di Ingegneria Civile, Edile e Architettura, Università Politecnica delle Marche, Ancona, Italy

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ABSTRACT

Fiber Reinforced Cementitious Matrix (FRCM) systems have emerged in recent years as an effective tool for strengthening and retrofitting of the existing built heritage.

The effectiveness of FRCM systems is strongly related to the bond developed at the interface between inorganic matrix and fabric reinforcement and between the inorganic matrix and the substrate. However, since the major weakness is often located at the matrix-to-fiber interface, the study of stress-transfer mechanisms between fibers and matrix, and a better understanding of the failure processes become of fundamental importance.

In this paper, interface bond-slip relations are derived from pull out tests on multifilament carbon yarns embedded in a cementitious matrix. Two different types of yarns are investigated, dry and pre-impregnated with epoxy resin. A variational model able to reproduce the mechanisms of interface debonding and frictional slippage observed in experiments is developed, where the constitutive parameters are calibrated on the base of the experimental data available from pull out tests. The model is implemented in a finite elements code, and pull out and double shear bond tests on masonry substrates are simulated. Finally, numerical results are compared with experimental evidences.

1. Introduction

In the last few years, the growing need to recover, reinforce and strengthen existing masonry or concrete buildings led to the development of innovative materials and new repair techniques with low environmental impact and high efficacy. Fiber Reinforced Cementitious Matrix (FRCM), also called Textile Reinforced Mortar (TRM), applied as external reinforcement and acting as an additional tensile-resistant element, proved to be very effective in increasing both mechanical strength and ductility of masonry and concrete structures.

FRCM are generally constituted by uni-directional or bi-directional fabrics, consisting of multifilament yarns made of carbon, glass, basalt or PBO fibers, disposed along two orthogonal directions. If compared to organic matrix systems (e.g. FRP, SRP) the use of a cementitious or lime-based matrix guarantees better compatibility with concrete or masonry substrates, higher breathability and vapor permeability, high temperature resistance, applicability on wet and irregular surfaces, more security for operators during installation [1–4].

FRP and FRCM are similar in the way they are designed as external reinforcement for structures or elements that need to be strengthened. However, while the performances of FRP are strongly influenced by the effectiveness of the stress transfer mechanisms from the substrate to the composite, since the failure often occurs before the ultimate tensile strength of the composite is reached [5,6], FRCM performances are more affected by the stress transfer mechanisms at the interface between fabric reinforcement and inorganic matrix, since the failure is often expected at this interface.

The FRCM mechanical behavior and failure mode are strongly dependent on the type of fabric reinforcement used. Fabrics are usually constituted by yarns made of dry filaments but often they are coated or pre-impregnated with organic compounds in order to improve the adherence with the inorganic matrix. In this context, the term coating is intended for a superficial impregnation of the yarn fibers, with the inner filaments of the bundle left dry, while pre-impregnation indicates a complete impregnation of the yarn with organic resins.

In case of fabric reinforcement made of multifilament dry yarns, FRCM properties are influenced by the ability of the inorganic matrix to penetrate within the filaments. Since the matrix is able to engage only the external fibers of the yarns, the so called 'telescopic' behavior, due to slippage of the internal filaments of the yarn, is activated [7].

In case of coated or pre-impregnated yarns, the penetration of the mortar within the filaments is prevented by the presence of the organic

* Corresponding author.
E-mail addresses: j.donnini@univpm.it (J. Donnini), g.lancioni@univpm.it (G. Lancioni), v.corinaldesi@univpm.it (V. Corinaldesi).

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resin. As a consequence, the bond between yarn and matrix is no longer dependent on the ability of the mortar to penetrate within the filaments but rather from the bond at the interface between coating and matrix [8,9]. In this case it is possible to precisely identify a contact surface between yarn and matrix, while in case of dry yarns it is not easy to establish how many filaments are engaged in the stress transfer mechanisms. In fact, the ability of the mortar to penetrate between the filaments depends on many factors, such as mortar viscosity, size of the aggregates or fillers that constitute the mortar, space between filaments and also by the technique used to apply the FRCM to the substrate (trowel, plastering machine). Thus two different types of bond are distinguished in multifilament dry yarns: bond between filaments and matrix and bond between filaments. In case of pre-impregnated yarns the slippage between filaments is prevented by the resin and only the bond between yarn and cementitious matrix is considered.

In this scenario, the definition of an appropriate bond-slip law (BSL) for a given FRCM system is fundamental to allow the development of analytical or numerical models able to simulate the FRCM mechanical behavior and failure modes.

The bond between multifilament yarns and cementitious matrix has been studied by several authors by using different methodologies. Banholzer and coworkers proposed two different methods: the so called 'direct method', which requires the knowledge of an idealized BSL or the measurement of the longitudinal strain along the interface between yarn and matrix [10] and the 'indirect method', that is able to predict a BSL based on experimental parameters obtained by means of pull out, single or double shear bond tests on FRCM systems [11].

An indirect method to calibrate the cohesive material law of FRCM-concrete joints was proposed by Focacci and coworkers [12]. The method is based on single-lap shear bond tests on FRCM-concrete joints with different bonded lengths, using the peak load versus bonded length to calibrate the BSL. Other models based on the analysis of the shear stress at the interface yarn-matrix in pull out [13,14] or single shear tests [15–19] have been proposed in the literature.

However, all these studies have shown that measuring the fiber strain in FRCM composites is a difficult task, due to the presence of the matrix embedding the fabric yarns, while using idealized BSL is not always able to accurately describe the FRCM mechanical behavior.

In this work a different approach has been proposed, by using simple pull out tests on single yarns to calibrate the BSL, for different FRCM systems.

During pull out test on a single yarn embedded in a cement matrix, force and slip at the loaded end can be easily measured. As a result, the relationship between the shear stress and the slip along the interface (BSL) can be derived by considering the shear stress to be constant along the interface with no need to apply strain sensors on the yarn surface. This assumption is acceptable for short embedded lengths (equal to 20 mm), as confirmed by experimental and numerical results, while it is no longer reliable for higher lengths.

Two types of carbon yarns, dry and fully pre-impregnated with an organic resin, have been used, these two representing the antipodes of what is currently on the market of FRCM systems. As a consequence, two different BSL have been obtained from pull out tests.

A variational model has been developed and implemented in a finite element code to simulate the possible failure mechanisms of FRCM systems reinforced with these two types of carbon fabrics.

Following a phase-field approach [20], the proposed model is based on an energy functional which depends on a damage parameter α ranging from 0 to 1 ($\alpha = 0$ means sound material, and $\alpha = 1$ means totally damaged material), which accounts for possible fracture of the constituents (cementitious matrix and carbon reinforcement), or debonding and slippage at the yarn-to-matrix interface. Different energies have been assigned to the system constituents and to the interface. Regarding matrix and yarn, the energy proposed in Refs. [21,22] has been considered. It incorporates a linear local damage term and a non-local damage contribution in order to describe the behavior of brittle materials. The energy assigned to the yarn-to-matrix interface is constituted by three terms: (1) an elastic contribution, which accounts for a distribution of elastic springs whose elastic stiffness degrades when damage increases, (2) a local damage term, accounting for debonding, and (3) a frictional energy, expended in the phase of slippage that follows the detachment. This third term is similar to that proposed in Refs. [23,24] to model plastic slip flow, and it only depends on one parameter, τ_0, which represents the frictional shear stress. The corresponding parameter in Ref. [23] represented the plastic yielding stress.

It follows that the three energy terms are directly related to the three basic phases of the failure process at the yarn-to-matrix interface observed in experiments, i.e., the initial elastic shear, the debonding in a regime of stress-softening, and the slippage occurring at constant frictional shear stress. This strict correlation is a distinguishing feature of the proposed formulation, with respect to the model proposed in Ref. [25], where a unique damage energy was considered to describe the post-elastic evolution.

Two different failure modes, brittle and ductile with a softening phase, have been observed for dry and pre-impregnated carbon yarns, respectively. To account for these differences, two expressions of the damage energy have been considered: a concave function of α, to capture brittle damaging, and a linear function to describe the softening phase.

Evolution of strain and damage, as the external load increases, is determined by solving a constrained incremental minimization problem, that has been implemented in a sequential quadratic programming algorithm. Incremental minimization was used to determine local minima in many different evolution problems concerning fracture [26], plasticity [27,28] or crystal plasticity [29].

Experimental data have been used to calibrate the constitutive parameters that characterize the interface, such as the shear elastic stiffness k, the peak shear stress τ_e and the frictional shear stress τ_0. They have been easily derived from the experimental force-displacement curves of pull out tests. Once the model has been calibrated, numerical simulations have been carried out. Both pull out and double shear bond tests have been reproduced by considering different bond lengths. Interface debonding and slippage have been investigated in the two cases of dry and pre-impregnated yarns, and comparisons with experimental results have been carried out.

The paper is organized as follows:

Experimental results of pull out tests on specimens made of dry or pre-impregnated carbon yarns embedded in a cementitious matrix are presented in Section 2. The effect of varying the bond length is also discussed.

In Section 3 a phase-field model has been developed in order to reproduce the FRCM mechanical behavior, taking into account the possible failure of the constituent materials, the slippage at the yarn to the matrix interface and the frictional stress in the post-elastic phase. The bond parameters have been calibrated, based on experimental results, and implemented within the model.

Pull out tests and double shear bond test have been simulated in Section 4. The effect of varying the bond length of the carbon yarn or fabric within the inorganic matrix and the use of dry or pre-impregnated carbon yarns was also considered. Finally, numerical results have been compared with experimental outcomes in terms of load-displacements curves.

2. Experiments

2.1. Pull out test

A commercially available cementitious mortar with a maximum aggregates size of 0.5 mm has been used as FRCM matrix. Mechanical properties were investigated by means of three-point bending tests on standard prisms (40x40 × 160 mm) and compressive tests on the two remaining broken parts. Tests were performed after 28 days of casting