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Effect of test setup on the fiber-to-mortar pull-out response in TRM composites: Experimental and analytical modeling

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ABSTRACT

Textile-reinforced mortars (TRM) have recently received significant attention for the externally bonded reinforcement (EBR) of masonry and reinforced concrete structures. The fiber-to-mortar bond, the TRM-to-substrate bond, and the mechanical properties of the TRM constituents have a fundamental role in the performance of this strengthening technique and therefore require special attention. Despite this importance, only few investigations are devoted to characterization of the single fiber-to-mortar bond response in these systems.

This paper, as an step towards addressing the fiber-to-mortar bond, presents a combined experimental and analytical investigation on the effect of test setup on the pull-out response and bond-slip laws in TRM composites. Three different pull-out test setups, consisting of one pull-pull and two pull-push configurations, are developed and investigated for characterization of the single fiber-to-mortar bond behavior. The experimental and analytical results are critically discussed and presented and bond-slip laws are extracted for each test setup.

1. Introduction

Textile reinforced mortars (TRMs) have recently received an extensive attention for externally bonded reinforcement (EBR) of masonry and historical structures. In comparison to fiber reinforced polymer composites (FRPs), TRMs exhibit several advantages such as fire resistance, vapor permeability, removability, and compatibility with the substrate [1–6]. TRMs are composed of continuous fiber grids embedded in an inorganic matrix that is applied to the surface of the structure on site. The available textile fibers are diverse and consist of steel, glass and basalt fibers, to name a few. As for the matrix, cementitious or lime-based mortars are usually used. Lime-based mortars are preferred for application to masonry and historical structures due to their compatibility, sustainability, breathability and capability to accommodate structural movements [7–9].

TRMs, also referred as FRCM or TRC in the literature, have been investigated as a strengthening system for both reinforced concrete and masonry structures. These include flexural strengthening of RC beams and slabs [10], shear upgrading of elements [11], confinement of column [12], or strengthening of masonry walls [13], and arches [14]. The experimental results have clearly shown that the mechanical properties of TRM composites and their effectiveness in improving the performance of masonry or concrete structures are strongly dependent on the mortar and fiber properties, the bond at the fiber-to-mortar interface and the bond at the TRM-to-masonry interface [15]. While several studies can be found in the literature devoted to characterization of mechanical properties of TRMs, e.g. Refs. [16–18], or to the characterization of TRM-to-masonry bond behavior, e.g. Refs. [3,19], the fiber-to-mortar bond response in these systems has only received a limited attention [15]. This mechanism is however critical for fully utilization of this strengthening system and, without any doubt, requires special attention [15].

Although there is a gap in literature on fiber-to-mortar bond response in TRM composites (made of lime-based mortars), several information can be found regarding this mechanism in textile reinforced concrete (TRC), where cementitious mortars are utilized [20]. The available results show that the mechanical properties of the textile and the mortar, the chemical interaction between them [20–24] as well as the fiber embedded length [25,26] and orientation with respect to the crack surface [27–29] are among the main parameters that can affect the fiber-to-mortar bond response. A variety of pull-out test setups have been used in literature for the characterization of the fiber-to-mortar (or concrete) bond behavior. These can generally be categorized into pull-push (or single-sided) [30–32] and pull-pull (or double-sided) [33,34] tests. However, the differences between the experimental results obtained from different test setups are poorly addressed.

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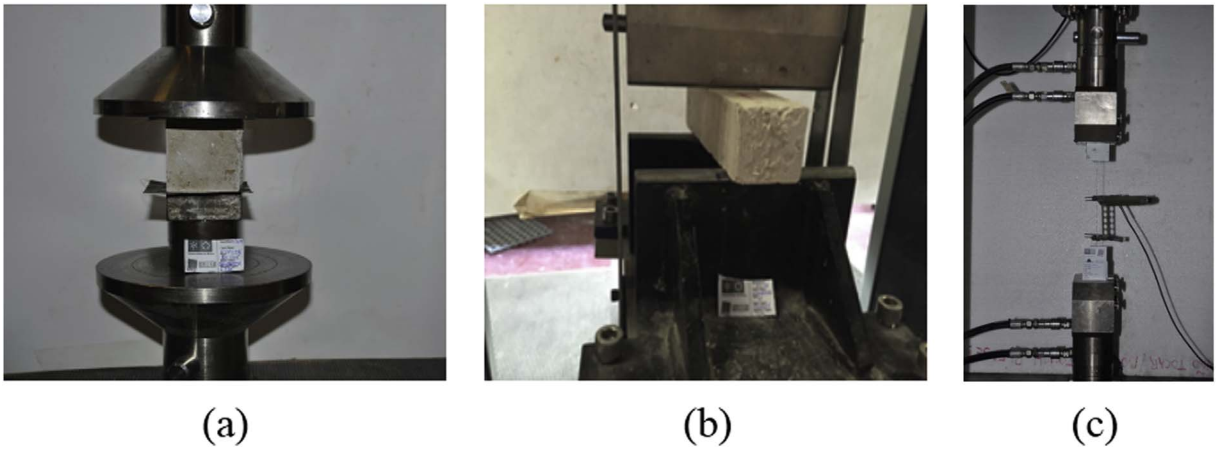

Fig. 1. Mechanical characterization tests: (a) mortar compressive test; (b) mortar flexural test; (c) fiber direct tensile test.

Among the few available studies on the characterization of fiber-to-mortar bond behavior of TRM-strengthened masonry, Ghiassi et al. [15] used a single-sided pull-out test configuration on fibers embedded in cylindrical specimens. They, however, reported difficulties in preparation of the specimens (vertical alignment of the fibers) and in measurement of the slip during the tests due to the flexibility of the fibers. Additionally, due to the geometrical limitations of the test setup, the LVDTs used for slip measurements were attached at a certain distance from the mortar edge. The elastic deformation of the fibers therefore had to be reduced from the recorded values with the LVDTs that could lead to additional uncertainty in the slip measurements.

The present study, as an attempt for development of an optimized test setup for performing the pull-out tests, presents a combined experimental, analytical and numerical investigation on the effect of test setup and configuration on the pullout respose of TRM composites. Three test setups consisting of two pull-push and one pull-pull configurations are developed to perform the pull-out tests. Steel fiber embedded in a pozzolanic lime-based mortar (also referred as SRG in the literature) is used as a conventional composite material for strengthening of masonry structures. The experimental results are compared and critically discussed in terms of force-slip response, stiffness, toughness and peak load. With the aim of analytical and numerical modeling, bond-slip laws are also extracted from the experimental results obtained from each test setup and the results are compared.

2. Experimental program

The experimental program consists of a series of pull-out tests on the specimens tested in three different test setups. The detailed procedure followed for preparation of the specimens and performing the tests are given in this section.

2.1. Materials

Materials consist of a commercially available hydraulic lime-based mortar as the matrix and a commercially available steel fiber as the reinforcing material. Based on the technical sheets provided by the manufacturer, elastic modulus of the mortar after 28 days is 9.23 GPa. The mortar is prepared according to the manufacturer's technical sheets by mixing 0.204 L of water with 1 kg of powder. A low-speed mechanical mixer is used to mix the paste for 7 min until the blend is completely homogeneous and no powder is remained in the container. The reinforcing material is a unidirectional ultra-high tensile strength steel fiber, with a density of 670 g/m^2, an effective area and equivalent diameter of one cord (five filaments) equal to 0.538 mm^2 and 0.827 mm, respectively, a tensile strength of 2820 MPa, and an elastic modulus of 190 GPa according to the technical datasheets provided by the manufacturer.

2.2. Material characterization tests

For mechanical characterization of the mortar, compressive and flexural tests are performed according to ASTM C109 [35] and EN 1015-11 [36] at different ages. Five cubic (50 × 50 × 50 mm^3) and five prismatic (40 × 40 × 160 mm^3) specimens are prepared for compressive and flexural tests at each age, respectively. The tests are carried out with a Lloyd testing machine under force-controlled conditions at a rate of 2.5 N/s (for the compressive tests) and 10 N/s (for the flexural tests), as shown in Fig. 1. In the compressive tests, for reducing the friction at the specimens' boundaries and ensuring a uniform distribution of stresses at the center of the specimens, a pair of friction-reducing Teflon sheets with a layer of oil in between is placed between the specimens and the compression plates (Fig. 1a). The flexural tests are performed according to the three-point bending test scheme with a 100 mm distance between the supports (Fig. 1b).

As for the steel fibers, direct tensile tests are conducted [3,15] to obtain their tensile strength and elastic modulus. A universal testing machine with a maximum load capacity of 10 kN is used for these tests. The tests are performed under displacement-controlled conditions at the rate of 0.3 mm/min (Fig. 1c). The free length of specimens is 300 mm. A 100 mm clip gauge is attached to the center of the specimens to measure the fiber strain during the tests.

2.3. Bond characterization tests

In the pull-push tests (Fig. 2a and b), the mortar is fixed from the top and the fiber is pulled out from the same direction. Compressive stresses are therefore generated in the mortar near the loaded end in this test configuration. In the pull-pull tests (Fig. 2c), on the other hand, the mortar is fixed from the bottom and the fiber is pulled out from the top (or vice versa) simulating direct tensile tests. Tensile stresses are therefore developed in the mortar in this test setup. Due to the different stress conditions imposed on the specimens in these test configurations, different pull-out responses are therefore expected.

Two pull-push and one pull-pull test setups are used in this study for performing the pull-out tests. Five specimens are prepared and tested for each test setup (see Table 1 for information). Based on the previous studies performed by the authors, the bonded length is selected as 150 mm to be larger than the effective bond length.

The first pull-push test setup (pull-push I) is the one used by Ghiassi et al. [15]. In these tests, the specimens are made of fibers embedded in mortar cylinders with a 150 mm-bonded length and a 150 mm free