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CHARACTERIZATION OF FRCM- AND FRP-MASONRY BOND BEHAVIOR

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Abstract. *Composites made of fibers embedded in organic or inorganic matrices are efficient systems for reinforcing historical masonry structures to provide strength and ductility with a negligible mass increment. As it is well known, the structural performance of the composites mainly relies on their adhesion to the substrate. There are different methods to test the adhesion of the composite to the substrate: in laboratory direct shear test is the most commonly employed, while on-site the bond between the reinforcement and the substrate is checked by the pull-off test. In this paper, the adhesion of different composites to the same substrate made of fired-clay bricks is investigated by both the shear test and the pull-off test to qualitatively assess the difference in the two methods. Additionally, to investigate whether the bond is affected by the presence of water in the pores, half of the specimens were tested in water saturated conditions. Three different types of matrix (based on epoxy resin, natural hydraulic lime and Portland cement) were used for the composite matrix, without changing the geometry, the type of masonry substrate and the fibers (galvanized steel cords).*

1 INTRODUCTION

The effectiveness of externally bonded (EB) composites, both fiber-reinforced polymer (FRP) and fiber-reinforced cementitious matrix (FRCM) composites, applied to masonry structures is governed by the adhesion between the reinforcement and the substrate. The bond behaviour between composites and masonry can be experimentally assessed by means of single-lap shear, double-lap shear, and beam tests [1-3]. The majority of the studies available in literature deals with the direct shear test (and in particular single-lap type), which is extensively used in laboratory testing. Information on the adhesion between the reinforcement and the substrate and the presence of defects in the application of the composite can be potentially obtained by means of pull-off tests, which are easily performed on site without the burden of building a test fixture necessary to conduct direct shear tests [4]. Although the Mode-II bond behaviour should be studied by performing direct shear tests, the outcomes of pull-off tests could be still valuable in practice. A relationship between the results obtained from the single-lap shear test and those obtained from the pull-off test has not been established, especially for FRCM composites.

In this paper, a comparison between two experimental campaigns is presented. In one experimental program, three groups of masonry blocks made of fired-clay bricks and mortar joints, reinforced by a unidirectional steel fabric embedded in an epoxy resin, in a hydraulic lime-based mortar matrix and in a cement-based mortar matrix were subjected to single-lap shear tests [5-7]. In the other experimental campaign, pull-off tests were conducted on the same type of composites (same fibers and matrices) applied to fired-clay bricks belonging to same batch of bricks employed to manufacture the specimens tested in the first campaign [8]. Results of the single-lap shear test are compared with those obtained in the pull-off test to determine if a relationship exists and whether pull-off test could be a suitable way to obtain information on bond in field applications. This comparison is usually hindered by the fact that composite is applied on the side surface of the bricks for the shear test (the same surface that is actually reinforced on-site), while it is applied in the bed surface for the pull-off test. However, the bricks employed in this study were manufactured by a process similar to that used for historic bricks, namely by pressing, hence the characteristics of the side and one bed surface are very similar. This would be not the case of bricks manufactured by extrusion, for this brick type, the bed and side surfaces are completely different in terms of roughness and characteristics. Additionally, in order to check if the presence of water in the pores may affect the adhesion, half of the specimens were tested in water saturated conditions.

2 MATERIALS AND METHODS

The material used as a substrate in this study is a fired-clay brick of nominal dimensions 250 mm × 120 mm × 55 mm. Three types of composites were considered:

- SRP composite: constituted by steel fibers embedded in an organic matrix, namely a bi-component epoxy resin. The fibers employed are arranged as a unidirectional sheet made of ultra-high strength galvanized steel cords, fixed to a secondary 6 mm-spaced fiberglass micromesh. The cross-sectional area and equivalent thickness of the cord are 0.538 mm^2 and 0.084 mm, respectively. The tensile strength, ultimate strain, and Young's modulus of the steel fibers are 3000 MPa, 2%, and 190 GPa, respectively.
- S-FRLM composite: constituted by the same steel fibers as before embedded in an inorganic matrix [9]. The matrix was a commercially available dry-mix mortar made of natural hydraulic lime (NHL 3.5) and quartz sand, and belongs to the strength class M15 according to EN 998-2 [10].
- S-FRCM composite: constituted by the same steel fibers as before embedded in an inorganic matrix [11]. The matrix was a commercially available dry-mix mortar made of Portland cement binder and quartz sand, with a limited amount of

polymeric admixtures, and compressive strength > 45 MPa according to EN 12190 [12].

2.1 Pull-off specimens

Twenty-four fired-clay bricks were reinforced with composites applied to the 250 mm × 120 mm brick surface. The bricks were cleaned before the application of the composite. A first layer of matrix (2 mm-thick for resin and 4 mm-thick for lime and cementitious mortars) were applied on the surface for S-FRLM and S-FRCM specimens, respectively. After that, sheets of fabric were slightly pressed on them, and a second layer of matrix (having the same thickness of the first one) was applied on the S-FRLM and S-FRCM specimens. The total thickness of the composite was equal to 4 mm (±1mm) for SRP samples and 8 mm (±1mm) for S-FRLM and S-FRCM samples. After curing (1 week for SRP and 1 month for S-FRLM and S-FRCM specimens), two shallow cores perpendicular to the composite surface were drilled in each specimen, leaving the core attached to the brick. The core driller had a diameter equal to 53 mm. In accordance to EN 1542 [13], the cut depth should penetrate 10 mm in the substrate. Steel disks were attached to the external surface of the cores using epoxy adhesive. To investigate if the presence of water in the pores of the substrate may affect the pull-off strength, half of the reinforced bricks were tested after water saturation (suffix 'SATUR' in the label), while the remaining ones were tested in dry conditions (suffix 'DRY' in the label), for comparison purposes. For each type of condition, three tests were carried out.

2.2 Shear test specimens

The performance of the inorganic based composite was determined in terms of adhesion capacity of composite strips applied to a fired-clay brick masonry block. The masonry blocks were constructed with 6 half solid fired-clay bricks (55 × 120 × 125 mm^3) and 5 mortar joints (10 mm thick). The mortar used for the joints was a commercially available dry-mix product made of natural hydraulic lime (compressive strength class NHL 3.5 according to EN 459-1 [14]). Twenty-four 120 × 125 × 380 mm^3 masonry blocks were constructed and left to cure for 1 month at room temperature and humidity. After 1 month, the composite strips were applied to one of the faces of the blocks. The total thickness of the composites was the same as the one for the pull-off specimens. The three groups of reinforced masonry specimens (the group with SRP, the group with FRLM and the group with FRCM) were left to cure for 28 days in laboratory. Twelve composite-masonry joints (4 for each matrix) labeled "DRY" and used as control specimens were tested in dry conditions. Twelve composite-masonry joints (4 for each matrix) were immersed in deionized water for 2 days and then tested in saturated conditions. These specimens were labelled "SATUR".

2.3 Pull-off test setup

The pull-off test was performed in accordance with EN 1542 [13]. A uniaxial direct tensile load was applied perpendicular to the surface of both dry and wet specimens using the pull-off testing device up to failure.

2.4 Shear test setup

Direct shear tests were performed to assess the bond quality between the SRP/S-FRLM/S-FRCM composites and the masonry blocks. Details of the set-up of the single-lap shear tests are reported in [15]. During the tests, the masonry specimens were restrained between two steel plates, while the composite strip was pulled. The load *P* was applied to the end of the bare fibers where an epoxy tab was realized. Two linear variable displacement transformers (LVDTs) were mounted on the face where the composite was applied to measure the displacement of the composite with respect to the masonry surface at the beginning of the bonded area. All tests were conducted in LVDT displacement control at a constant global slip rate equal to 0.84 μm/s until failure.

3 RESULTS AND DISCUSSION

3.1. Mechanical properties of the matrices

The average compressive strength of the cement-based matrix and the natural hydraulic lime-based matrix resulted equal to 46.9 MPa (CV=8.5%) and 13.5 MPa (CV=6.5%), respectively. CEM matrix exhibited a compressive strength more than three times higher compared with the natural lime-based matrix [7, 15]. Epoxy resin had a tensile strength equal to 14 N/mm^2 as reported in the manufacturer data sheet [16].

3.2. Pull-off and shear test results

In general, with the pull-off and shear tests four possible failure modes may occur:

(1) Cohesive failure in the substrate (hereinafter denoted as F1);

(2) Bond failure at the composite/substrate interface (hereinafter denoted as F2);

(3) Interlaminar failure in the composite between the inner layer of matrix and the fabric (hereinafter denoted as F3);

(4) Bond failure at the steel disk/composite interface (hereinafter denoted as F4, this type of failure may occur only in pull-off tests).

Results for the pull-off tests are listed in Table 1 in terms of average strength (calculated as the peak force divided by the area of the disk) and failure modes. As expected, all the SRP specimens failed in the substrate (F1 type) and the decrease in bond strength between a dry and a water saturated substrate was 7.4%. Even if the substrate was involved in the failure surface, its saturated condition led to negligible difference in bond capacity: this is due to the fact that the presence of water in the pores of the brick did not influence significantly its tensile strength, and the substrate in the case of pull-off tests is mainly subjected to a direct traction. In the case of specimens reinforced with lime-based composites (S-FRLM), the failure mode mainly was interlaminar at the interface between the steel sheet and the inner layer of matrix, that remained attached to the substrate. In general, the bond strength was lower with respect to SRP, as usually occurs for these composites (lower than 1 MPa in the case of dry specimens, and lower than 0.8 MPa in the case of water saturated specimens). For this group, the decrease in bond strength between dry and wet specimens is remarkable: around 30%. In Fig. 1, typical failure modes occurred during the pull-off tests for SRP and S-FRLM samples are reported. It should be noted that S-FRCM specimens in this study showed a brittle behavior and most of the samples failed before pull-off testing during curing and/or during the operation of core cutting. This aspect should be better investigated, however it points out the compatibility issues between such a high strength and stiff matrix and a porous substrate such as fired-clay bricks. Usually, this kind of high strength matrices is employed to strengthen concrete structures, however in certain particular cases, for example in presence of harsh environments these high strength mortars can be employed also for strengthening of masonry structures, leading to compatibility problems with low strength substrates.

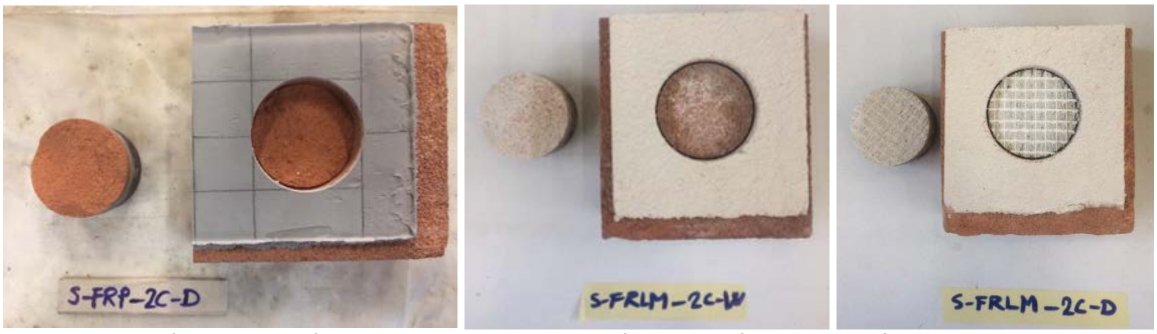

Figure 1. Type F1 failure mode for a SRP specimen on the left, type F2 failure mode for a S-FRLM specimen at the center and type F3 failure mode for a S-FRLM specimen on the right.

Table 1: Results of the mechanical tests: pull-off and shear tests. In parentheses, the coefficient of variation is reported.

Test type	Matrix type	Specimen	Adhesion strength or force	Δ^* [%]	FAILURE MODE
Pull-off test	Epoxy resin	SRP-DRY	1.12 MPa (13.4)	-	F1
		SRP-SATUR	1.04 MPa (12.9)	-7.4	F1
	Natural hydraulic lime based	S-FRLM-DRY	0.99 MPa (14.7)	-	F3
		S-FRLM-SATUR	0.76 MPa (13.4)	-30.1	F3 (in one case F2)
Shear test	Epoxy resin	SRP-DRY	10.72 kN (0.1)	-	F1
		SRP-SATUR	10.16 kN (7.0)	-5.2	F1
	Natural hydraulic lime based	S-FRLM-DRY	6.7 kN (14.9)	-	F3
		S-FRLM-SATUR	5.1 kN (18.0)	-23.5	F3
	Cement based	S-FRCM-DRY	7.5 kN (14.6)	-	F1
		S-FRCM-SATUR	8.6 kN (17.0)	12.8	F1

Results for the shear test in terms of average maximum load for each group of specimens and failure modes are reported in Table 1. All SRP specimens showed a failure mode characterized by debonding with cohesive fracture of the support (F1 type). After cycles in deionized water, SRP specimens exhibited a negligible decrease in bond capacity (-5.2% compared to REF), as appeared from the pull-off tests.

Failure mode of S-FRLM-DRY specimens was interlaminar failure at the matrix-fibers interface (F3 type). As expected, cement-based specimens reached an average peak load that is higher than the lime-based specimens: due to the different mechanical performance of the two mortars. The failure mode that characterized S-FRCM-DRY specimens was debonding at the matrix-substrate interface (F1 type), with a thin layer of masonry that remained attached to the composite strip, typical failure mode of FRP-masonry joints showing that this mortar is more similar to an organic matrix rather than a mortar. The FRLM specimens tested in water saturated conditions showed a decrease in peak load of about 23%, which is comparable to the one found in the pull-off tests (-30%). It should be noted that the two results in terms of values cannot be compared since one is the average bond strength obtained from a pull-off test and the other is a bond force as obtained in the direct shear test. However, the decrease in terms of adhesion between dry and water saturated conditions is qualitatively similar. Interestingly, the specimens reinforced with cement-based composites show a small increment in the bond force (+12.8%) passing from DRY to SATUR specimens. This increment cannot be compared to the results of the pull-off tests, since as stated before, results for the cement-based specimens are not available.

4 CONCLUSIONS

This work investigated the effects of water presence in the pores of the substrate materials on the bond behavior between composites and fired-clay brick masonry blocks. Both composites applied with organic and inorganic matrices were considered, employing the same type of fibers (galvanized steel cords). Both pull-off tests and shear tests were conducted to compare qualitatively the main results. The following conclusions can be drawn:

- All the specimens reinforced with steel reinforced polymer composites are characterized by a failure mode that involved the substrate (cohesive failure) both tested in dry and in water saturated conditions.
- All the SRP specimens (both pull-off and shear tested) showed adhesion values (strengths and forces) that are higher with respect to specimens reinforced with composites applied with inorganic matrices.
- The decrease in bond strength between dry and water saturated specimens is negligible in the case of SRP (around -6% for both pull-off and shear tests).
- All the specimens reinforced with lime-based composites and steel fibers showed an interlaminar failure mode, i.e. failure plane involved the interface between the inner layer of matrix and the steel sheet.
- All the specimens reinforced with lime-based composites showed a decrease in bond strength (both measured with pull-off and shear tests) between dry and wet conditions (on average around 25%).
- All the specimens reinforced with cement-based composites and steel fibers showed a cohesive failure mode, i.e. failure plane involved the substrate as in the SRP reinforced specimens. In case of shear test, the bonding capacity for saturated specimens showed a small increment with respect to the dry specimens (around 12%). However, this trend cannot be confirmed with the results of the pull-off tests, since all the specimens failed during curing or cutting operations. This last aspect pointed out the compatibility issues between composites having an extremely high rigidity and strength and porous and weaker substrate (the employed cement-based matrix has a compressive strength > 45 MPa, while this value for brick is 17 MPa).

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