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The role of mortar joints in FRP debonding from masonry

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A R T I C L E I N F O

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A B S T R A C T

The present paper aims at investigating the influence of the mortar joints on the FRP-masonry debonding process and providing some insights on the reliability of experimental tests carried out on single bricks and theoretical formulas available to predict the debonding force. Masonry panels were constructed using two types of bricks and two types of mortars with significantly different properties. The masonry specimens were strengthened using glass fiber reinforced polymers and the debonding force was evaluated by a single-lap push-pull set-up. The obtained debonding forces were compared to those obtained by applying the same reinforcements to single bricks and calculated by applying theoretical formulas. The results of the study point out that neglecting the presence of the mortar joints and taking into account only brick mechanical properties, thus neglecting their surface and microstructural properties, may lead to significant inaccuracies in the estimation of the debonding force.

1. Introduction

Masonry buildings represent the largest part of the European cultural heritage, which has to be preserved and protected. The vulnerability of these structures is increased by several factors, such as seismic events and materials deterioration, often leading to serious consequences and threatening the buildings structural safety. As a result, strengthening interventions are often required [1–3]. One of the key aspects to be taken into account, when dealing with cultural heritage, is the adoption of strengthening solutions with low invasiveness and high efficiency. Interventions based on the application of fiber reinforced polymers (FRP) to masonry constructions ensure the respect of the above mentioned requirements, thus representing a very attractive strengthening solution [4–6]. To further improve the compatibility with the substrate, the durability and the reversibility of the strengthening composites, the use of matrices alternative to polymers, such as cement and geopolymers, is receiving increasing attention [7–10].

Contrary to the case of concrete, the FRP-masonry bond mechanisms have started to be systematically investigated only recently [11,12]. Even if the number of experimental studies carried out on masonry specimens is increasing [13–20], still the largest part of experimental results available in the literature actually concerns bond tests carried out on single bricks as substrate. Studies aimed at comparing the debonding force measured on single bricks and corresponding masonry panels have highlighted that significant differences may be found, amounting to up to 20% as a function of the brick type [13] and up to 18% as a function of the reinforcement type [20]. The possibility to extend results obtained on single bricks to masonry presents two main limitations: (i) the presence of the discontinuity represented by the mortar joints is neglected; (ii) the surface to which the reinforcement is applied when considering single brick tests may differ from that used to the same purpose when the whole masonry is considered, which may lead to significantly different results. This latter aspect is fundamental, because, as first pointed out in Ref. [16] and then systematically investigated in Ref. [21], in the case of bricks exhibiting a strong anisotropy, bond tests carried out applying the FRP to the "*bed*" surface (where FRP are usually applied in laboratory tests for simplicity's sake) may lead to a significant overestimation of the debonding force measured on the "*face*" surface (where FRP is actually applied in real structures).

Similar concerns arise also when the debonding force of FRP applied to masonry structures is predicted by theoretical calculations. The Italian reference Guidelines CNR-DT 200 R1/2013 [22] are currently one of the most reliable tools (at a design level) providing theoretical formulas for calculating the FRP-masonry debonding force, based on the FRP and the substrate characteristics. However, as far as the masonry substrate is concerned, only brick mechanical properties are taken into account, while two important factors are neglected: (i) the presence of the mortar joints; (ii) the surface and microstructural characteristics of the bricks. As pointed out by the Authors in a previous

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Table 1
Labeling and description of the specimens.

Label	Type	Number of specimens	Bond width [mm]
B1	Brick	6	30
B2	Brick	6	30
M1	Mortar	8	–
M2	Mortar	8	–
B1-M1	Masonry	4	30
B1-M2	Masonry	4	30
B2-M1	Masonry	4	30
B2-M2	Masonry	4	30
B2-M1-50	Masonry	4	50

study [21], brick surface roughness and the depth of resin penetration into the brick may play a very important role.

Therefore, in the present paper the influence of the mortar joints on the FRP debonding mechanism was investigated, by measuring the debonding force of the same type of FRP applied to masonry specimens constructed using two types of bricks and two types of mortars with significantly different properties. The obtained debonding force values were then compared to values measured on single bricks, strengthened using the same FRP applied to the same type of brick surface, so that an evaluation of the influence of the mortar joint presence could be derived. The accuracy of the theoretical formulas provided in the CNR Guidelines was also evaluated and discussed.

2. Materials and methods

The names and characteristics of the brick, mortar and masonry specimens are summarized in Table 1 and described in detail in the following.

2.1. Bricks

Two types of solid fired clay bricks were used for the tests. The bricks (labeled "B1" and "B2") were characterized in a previous experimental campaign [21]. As reported in Table 2, the bricks exhibit significantly different mechanical properties (measured perpendicular to the brick "*face*" surface): B1 has higher compressive strength than B2 (32.3 MPa *vs* 6.7 MPa) and higher flexural strength (6.0 MPa *vs* 2.7 MPa). Accordingly, B2 has higher open porosity than B1 (44.7% *vs* 33.8%) and higher water absorption (30.5 wt% *vs* 17.5 wt%) (Table 2). Notably, B1 is characterized by a strong anisotropy (properties measured perpendicular to the "*bed*" surface resulting ~25% higher than those measured perpendicular to the "*face*" surface), while almost no anisotropy is present in B2. This is a consequence of the different manufacturing technology of the two bricks: B1 is produced by extrusion, while B2 is obtained by compaction in molds. A further consequence of the different production technique is the different surface roughness: B1 exhibits a very smooth surface, while B2 has a quite rough surface and is covered with sand (used to facilitate brick demolding) [21].

Table 2
Brick compressive ($f_{b,c}$) and flexural ($f_{b,f}$) strength, measured perpendicular to the brick's "*face*" surface (values are averages for 6 samples, standard deviation in brackets), water absorption (*WA*) and open porosity (*OP*) [21].

	B1	B2
$f_{b,c}$ [MPa]	32.3 (± 2.8)	6.7 (± 1.1)
$f_{b,f}$ [MPa]	6.0 (± 2.1)	2.7 (± 0.7)
WA [wt %]	17.5	30.5
OP [%]	33.8	44.7

2.2. Mortars

Two types of mortars were used for the tests. The mortars (labeled "M1" and "M2") were selected to have significantly different mechanical properties: M1, the strongest mortar, is based on natural hydraulic lime (NHL), while M2, the weakest mortar, is a mixed NHL-cement mortar.

Mortar flexural strength ($f_{m,f}$) and compressive strength ($f_{m,c}$) were determined on standard prisms (40 × 40 × 160 mm^3), prepared and tested according to the European standards EN 196–1:2005 [23] and EN 1015–11:2007 [24].

Since previous studies by the Authors pointed out that mortar mechanical and microstructural properties tested on standard prisms are not necessarily representative of properties of mortar joints, because of the different curing conditions [25], the compressive strength of the two mortars was also determined by double punch tests (DPT) on samples obtained from the mortar joints of the masonry panels used for the bond tests (cf. § 2.3) [25–27]. The DPT was carried out on prismatic samples (40 × 40 × 10 mm^3) obtained by chisel from the masonry joints after the bond test and then regularized by sawing and lapping. For comparison's sake, the DPT was also carried out on 40 × 40 × 10 mm^3 samples obtained by slicing a standard prism after the same curing time as the masonry joints. The DPT was carried out by loading the specimens by two circular steel platens (20 mm diameter) and calculating the resulting mortar compressive strength ($f_{m,DPT}$) by dividing the maximum failure load by the area of the circular platens [26,27].

Mortar pore size distribution and total open porosity (*OP*) were determined by mercury intrusion porosimetry (MIP) on samples obtained from the masonry joints and from the standard prisms after the compressive test. A Porosimeter 2000 Carlo Erba with a Fisons Macropore Unit 120 was used.

2.3. Masonry panels

For each brick and each mortar type, four masonry panels were constructed. Each type of masonry panel is labeled by the combination of the brick and mortar types used for its construction: for instance, the 4 panels constructed using brick B1 and mortar M1 are identified as panels "B1-M1".

Each panel was constructed using 6 half bricks, separated by 5 mortar joints, as illustrated in Fig. 1. The bricks were cut in halves to use a smaller number of elements, thus reducing the samples variability. Before constructing the specimens, the half bricks were saturated with water for 24 h, to prevent them from absorbing water from the mortar joints while curing. During the masonry panels construction, excess water on brick surface was prevented by extracting bricks from water 15 min before their use. The thickness of the mortar joints was 10 ± 1 mm for all the specimens. The masonry panels were left to cure in laboratory conditions (T = 20 ± 2 °C, RH = 50 ± 5%) for 28 days. Before reinforcement with the FRP, specimens B1-M1 and B1-M2 were dried in an oven at 50 °C for 1 week, to remove moisture. As described in § 3.4, the presence of residual moisture (not evaporated yet after curing for 28 days) had been found to significantly alter the adhesion between FRP and the masonry substrate.

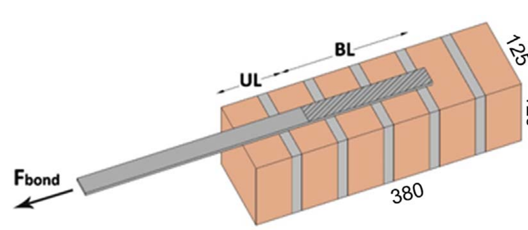

Fig. 1. Scheme illustrating a masonry panel reinforced with a GFRP strip (BL = bonded length, UL = unbonded length).