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Experimental investigation on out-of-plane behavior of masonry panels strengthened with CFRP sheets

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A B S T R A C T

The use of composite materials, in particular Carbon Fibre Composite Materials (CFRP), as reinforcement of both concrete and masonry structures is more and more widespread in the structural rehabilitation and retrofitting of existing buildings, thanks to their excellent mechanical performance combined with lightness and simplicity of application. Since the bond capacity of CFRP-to-masonry bonded joints, with respect to in-plane loads, is generally lower than the composite tensile strength, several methods have been proposed in the literature to increase their structural performance. Among these, CFRP spike anchors showed to be able to effectively increase strength and dissipative capability of CFRP reinforcement sheets. Nevertheless, their use in technical practice is discouraged by the lack of specific rules that adequately support designers. The development of predictive formulas, appearing necessary to bridge this gap, requires an extensive experimental database that highlights the peculiar characteristics of these reinforcements. As a contribution in this field, this paper presents an experimental program concerning the analysis of the mechanical behavior of this type of reinforcements applied to masonry structural elements loaded by out-of-plane actions. The experimental results showed that the effectiveness of such anchors strongly depends on the shape ratio of the specimens.

1. Introduction

As it is well known, a significant part of the existing buildings belonging to the World cultural and historical heritage (particularly European and Italian) has masonry structure. The peculiar characteristics of such structures (e.g. the presence of thrusting elements, quality of the constituent materials and of continuity between different structural elements, brickwork, etc.) and in particular the very low tensile strength of masonry, contribute to their seismic vulnerability. Different failure mechanisms can be activated by seismic actions: for example, both in-plane and out-of-plane mechanisms can be induced in masonry walls. As it is well known, the in-plane behavior of masonry walls (mainly defined by initial stiffness, strength and post crack characteristics) mostly contribute in the global structural response of masonry buildings. Nevertheless, out-of-plane failure mechanisms represent a serious life-safety hazard for this type of buildings, since they involve an almost instantaneous loss of the wall load bearing capacity for vertical loads.

Several strengthening and consolidation techniques have been proposed in the scientific and technical literature to mitigate the seismic vulnerability of masonry structures. Among these, bonding Carbon Fiber Reinforced Polymer (CFRP) sheet demonstrated to effectively improve the mechanical behavior of masonry walls, subjected to both in-plane and out-of-plane actions [1–12], as well as of curved masonry structural elements [13–23]. Thanks to the wide experience gained in research activities concerning masonry structural elements reinforced by CFRP sheets subjected to in-plane loads [24–30], the main features of the mechanical behavior of such reinforcements are known and quite shared among specialists: tensile (in plane) force on the reinforcement sheet is transferred to the substrate mainly via shear stresses mostly concentrated in a limited portion of the bonded surface, which length is called “effective bond length”. Increasing the bond length more than the effective length do not produce a significantly increase in the (in plane) load bearing capacity of the reinforcement. Failure of such reinforcements, subjected to in-plane actions, generally occurs in the substrate, a few millimeters below the bonding surface. For this reason, the load bearing capacity strongly depends on the mechanical properties of the substrate [31], as well as other parameters like the brickwork and the sheet geometric characteristics [27].

Since the shear capacity of CFRP reinforcement sheets is generally lower than the composite tensile strength, several methods have been proposed in the literature to increase it [32,33]. Among these, CFRP spike anchors [31,34–42] proved to effectively increase strength and

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ductility of CFRP reinforcement sheets: this "fiber-anchors", made rolling a carbon fiber fabric sheet, are inserted into a hole drilled in the reinforced structural element and glued upward, in a "fan" shape, to the reinforcement strip, fixing the reinforcement to the substrate. Such anchors can effectively improve the CFRP-to-masonry joint and can be efficiently used in structural rehabilitation or retrofitting interventions needed, for example, after seismic events, or due to other factors such as environmental degradation, changes in usage resulting in heavier loading conditions. It is of course noteworthy that spike anchors bring some drawbacks since, for example, they require onerous preliminary preparation (surface preparation, drilling of masonry, inclusion of CFRP anchors, etc.) and longer installation time with respect to plane reinforcements. Moreover, such reinforcements are clearly irreversible so that their use in buildings belonging to the historical and cultural heritage must be carefully evaluated. Nevertheless, the pool of existing buildings in which anchored reinforcements can be effectively used is still very large. However, the use of mechanical anchors in technical practice is discouraged by the lack of specific rules adequately supporting design choices and sizing. In this regard, existing guidelines [27,43] state that the practical use of mechanical anchors must be substantiated by representative experimental testing. Of course, predictive formulas to be inserted in appropriate regulations, needed to bridge this gap, can be defined only after collection of an extensive experimental database that highlights the peculiar characteristics of these reinforcements also with reference to the substrate material. Most of the literature devoted to anchored CFRP-to-masonry reinforcements refer to in-plane actions. Therefore, given the lack of information in this respect, the experimental research described in this paper is devoted to the analysis of the effectiveness of spike anchors in CFRP reinforcements bonded to masonry structural elements loaded by out-of-plane actions. The experimental results showed that the effectiveness of such anchors strongly depends on the shape ratio of the specimens.

The paper layout is the following: the experimental program is globally described in the next paragraph; the mechanical properties of the used materials are reported in section 3 and the specimens preparation is described in section 4; the test setup is described in section 5; the test results are reported an described respectively in section 6 and 7; final remarks conclude the paper.

2. Overall description of the experimental program

The experimental program described in this paper aims at the analysis of the mechanical behavior of masonry specimens reinforced with CFRP sheets, subjected to out of plane actions. Particular attention is paid to the evaluation of the increase in load bearing capacity and dissipation capability due to CFRP spike anchors applied to the reinforcements, also with respect to the shape ratio of the specimens.

In the experimental campaign described in Ref. [41] it has been observed that masonry panels, reinforced with CFRP sheets (with and without spike anchors) having fiber direction parallel to the bed joints, subjected to out-of-plane loads, substantially behaved, after the occurrence of the first cracks, as separate (reinforced) masonry beams. Therefore, in the experimental program here described we considered masonry beams, instead of panels, reinforced by CFRP sheets, loaded out of plane using a four point bending test scheme, made with bricks assembled as in masonry panels reinforced with horizontal strips. In view of the results described in Ref. [41], such beams can be intended as representative of the effective part of a reinforced masonry panel subjected to the considered type of loads. A four point bending test scheme was preferred to a three point (used in Ref. [41]) because in so doing the maximum tensile normal force in the reinforcement can be easily estimated using the measurements of a strain gauge bonded to the reinforcement sheet in the constant bending moment region of the beam, having length equal to 118 mm (see Fig. 1). In order to analyze the effectiveness of the reinforcement system with respect to the shape ratio of the specimen, both half brick and one brick thickness masonry beams have been considered. These were made using 1:2 scale bricks.

In the scheme reported in Fig. 1, L represents the length of the specimens and is equal to 935 mm and 928 mm respectively for single leaf and double leaf specimens (see section 4 for the specimen's characteristics).

Two different brickwork (single leaf and double leaf masonry) and two strengthening systems (without and with spike anchors) were considered in the experimental campaign; three specimens for each series were tested, so that the experimental program involved twelve specimens, all of them manufactured at the "Laboratorio Ufficiale Prove Materiali e Strutture" of the University of Florence, where the tests were carried out.

3. Material properties

The materials employed in the experimental program described in this paper are analogous to those used in Refs. [31,34,35,41]. The reader can refer to these papers for a comprehensive description of the tests performed to characterize the mechanical properties of the materials. Here, just the main mechanical parameters are summarized for completeness sake.

Soft mud bricks, also called solid pressed bricks, have been used to manufacture the specimens. These were preferred to drawn bricks because their material structure resembles the one of traditional soft pressed bricks, that are used in most existing buildings [44]. In order to determine the compressive strength and elastic modulus of the bricks, six of them were randomly chosen from the brick supply and cut to obtain cubic ($50 \times 50 \times 50$ mm) and prismatic specimens ($50 \times 50 \times 150$ mm) as schematized in Fig. 2. Moreover, prismatic specimens ($40 \times 40 \times 200$ mm) were obtained from other six randomly chosen bricks and tested using a three-point bending test scheme. Then, from one of the two halves of the specimen resulting from the bending test, a specimen was obtained for a tensile test. The mechanical parameters so determined for the bricks are summarized in Table 1.

Ready mixed mortar, made with lime and cement as binder, was employed in manufacturing the specimens: the compressive and tensile strength, obtained according to [45] are reported in Table 2.

A composite material, made of a unidirectional carbon fiber fabric and epoxy resin, was used to realize both the reinforcements and the spike anchors. The reinforcement sheets were applied to the substrate using a wet lay-up process (with a single layer of carbon fiber fabric), after surface preparation and primer application, according to the producer's guideline. The main characteristics of the constituent materials, declared by the producer, are summarized in Table 3.

4. Specimens

As previously said, two brickworks, having different shape ratio, were considered in the experimental campaign. In particular, half brick (single leaf) and one brick (double leaf) thickness specimens (see Fig. 3) were manufactured using 1:2 scale bricks (dimensions $28 \times 53 \times 113$ mm) obtained cutting solid pressed bricks, having initial dimensions of $65 \times 120 \times 250$ mm, in eight equal portions. Ready mixed mortar (see Table 2) was used to make the joints: all of them had thickness equal to 5 mm, except the vertical longitudinal joints of double leaf specimens, having thickness equal to 7 mm (see Figs. 3 and 12b) in order to respect the length of the 1:2 scale bricks.

Four different specimens type were considered in the experimental campaign, namely:

- 1T.0.M series, single leaf specimens strengthened with not anchored CFRP sheets;
- 2T.0.M series, double leaf specimens strengthened with not anchored CFRP sheets
- 1T.A.M series, single leaf specimens strengthened with anchored CFRP sheets;