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Experimental and numerical study on the shear behavior of stone masonry walls strengthened with GFRP reinforced mortar coating and steel-cord reinforced repointing

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ABSTRACT

The research work herein presented is aimed at investigating the structural behavior of stone masonry walls reinforced through different strengthening techniques. In particular, the difference between them is given by (i) application on both faces of a mortar coating reinforced with a GFRP (*Glass Fiber Reinforced Polymers*) mesh; (ii) application of the GFRP jacketing on one side only and (iii) application of a hybrid technique, obtained by the combination of a GFRP jacketing, on one side, and a reinforced repointing with steel-strands, on the other. Shear-compression (SC) and diagonal compression (DC) experiments were carried out on full-scale masonry walls both reinforced (RM) and unreinforced (URM), as reference. The structural effectiveness of the various reinforcing techniques is highlighted. Further assessment of test predictions was then performed by means of well-calibrated finite-element (FE) numerical models able to properly take into account the effective contribution of each specimen component. Interesting correlations were generally found between test predictions and corresponding numerical models. The experiments, as shown, generally evidenced a good effectiveness of the strengthening techniques proposed, with particular concern to that with the reinforced coating on both sides, and highlighted also the importance of the transversal connectors to prevent in plane cracks in the masonry and the detachment of the reinforced coating.

1. Introduction

The assessment of the structural behavior of masonry structures under seismic excitation represents a topic of interest for researchers, due to the very low tensile strength of masonry and to the large number of existing seismically inadequate masonry structures. For this reason, various reinforcement techniques have been proposed over the last decades and investigated through experiments and numerical analyses [1].

Lin et al. [2], for example, tested 25 masonry wallettes, in order to assess the strengthening capabilities of sprayed ECC (Engineered Cementitious Composite) shotcrete. In their work, the authors highlighted how the used fiber reinforced concrete can increase the ductility (up to 220%) and in-plane strength of unreinforced clay wallettes, hence resulting extremely advantageous for the seismic retrofitting of masonry structures.

Kadam et al. [3] experimentally investigated the structural behavior of reinforced masonry walls under in-plane diagonal compressive loads. In that case, the strengthening technique consisted of a Ferro-cement welded wire mesh (WWM) and micro-concrete coating. In [4], the structural efficiency of surface mounted fiber reinforced polymer strips has been investigated. In that case, two-leaf and three-leaf walls were retrofitted by means of CFRP (Carbon Fiber Reinforced Polymers) strips. Further extended experimental investigations on clay brick masonry walls retrofitted by means of CFRP strips with various applications have been discussed also in [5,6], where results of shake table tests have been compared for reinforced masonry specimens in terms of measured lateral strength, drift, maximum strain in composites. Quasi-static cyclic experiments on brick walls retrofitted with CFRP strips have been presented also in [7], where the effects of various anchorage systems have been emphasized. In [8], the cyclic shear-compression response of brick masonry walls with window openings, strengthened with various GFRP patterns, has been experimentally and numerically investigated. FRP retrofitted masonry walls have been tested also in [9].

Borri et al. [10] proposed a "Reticolatus" technique, consisting in small diameter, high strength stainless steel cords embedded in the repointing mortar and connected to the masonry panels by

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means of stainless steel connectors passing through the wall. The main advantage of this technique is that it can be applied also to masonry walls with uneven surfaces and composed of irregular components, such as historic masonry walls obtained by assembling together rubble stone elements.

In [11], the structural behavior of multi-leaf stone masonry panels strengthened with grout injections have been investigated by means of experiments performed on 1:1 and 2:3 scaled specimens under in-plane cyclic lateral loads and simultaneous vertical compressive loads. In that experimental campaign, the effects of different levels of compression have also been investigated. Milosevic et al. [12] assessed the in-plane shear strength of rubble stone masonry walls through diagonal compression experiments. The authors did not investigate the structural behavior of reinforced specimens, mainly focusing on the behavior of unreinforced masonry walls in order to provide useful mechanical correlations with existing works of literature. Gattesco et al. [13,14] carried out numerous diagonal compression tests on different types of masonry walls strengthened by applying on both the surfaces a mortar coating reinforced with a GFRP (Glass Fiber Reinforced Polymer) mesh. The role of the materials' mechanical properties was also investigated, and the obtained test results evidenced good effectiveness of the investigated technique. In it, the interaction between the GFRM (*Glass Fiber Reinforced Mortar*) jacketing and the masonry walls is provided by appropriate GFRP connectors. Borri et al. [15] recently performed a wide series of cyclic diagonal compression experiments on masonry specimens reinforced by means of various strengthening techniques: GFRM jacketing on both the faces, "Reticolatus" system on both the faces and a combined system with GFRM jacketing on one side and "Reticolatus" on the other. All these techniques evidenced interesting effectiveness in terms of increase of shear resistance for masonry.

In this paper, the structural efficiency of GFRM jacketing and hybrid (GFRM jacketing + "Reticolatus") strengthening techniques, applied on stone masonry walls, are assessed through shear-compression (SC) cyclic experiments and diagonal compression (DC) tests. Full-scale experiments are performed on a total number of seven specimens. Further assessment and validation of experiments is then performed by means of well-calibrated, geometrically simplified but computational efficient finite-element (FE) numerical models (ABAQUS/Standard [16]). A general good agreement is found between test predictions and the corresponding numerical simulations. Although the discussed findings should be further validated by an extended experimental campaign, in conclusion, the high potentiality of the proposed techniques – as well as the effects of their main influencing parameters – are emphasized throughout the paper.

2. Experimental investigation

Two series of shear-compression (SC) experiments and diagonal compression (DC) tests were carried out on masonry specimens characterized by different strengthening approaches.

Careful attention was paid, during the experimental campaign, for the assessment of the structural effectiveness and potentiality of various solutions.

2.1. Strengthening techniques

2.1.1. GFRM jacketing technique

Experiments were firstly performed on stone masonry specimens strengthened with a special coating, composed of mortar reinforced with a GFRP mesh. The reinforced mortar coating is 30 mm thick and is applied to the interested masonry surfaces as a plaster.

The main properties of the GFRM jacketing technique is that the conventional mortar reinforcement composed of steel bars is replaced by a reinforcing mesh made with GFRP wires. In this experimental campaign, specifically, the GFRP mesh consisted of AR (Alkali-Resistant)-glass fibers and epoxy vinyl ester resin (Fig. 1a). Compared to traditional steel reinforcements and metal meshes, the main advantages of GFRP strengthening systems are given by their low weight, easiness of application, lack of corrosion phenomena and high electromagnetic transparency. GFRP nets have a typical square shaped mesh, as also discussed in [14,15]. A 66×66 mm^2 regular pattern was used in this work, with a cross section of the single wire equal to $A_{net} = 10$ mm^2, obtained by assembling a set of fibers with a nominal dimension of 19–24 µm. The adopted GFRP mesh (mesh density 500 g/m^2), in accordance with the technical data provided by the producer and preliminary tensile tests performed on ten small GFRP mesh specimens, can offer an average Young's modulus close to $E_{bar} = 27$ GPa, a characteristic ultimate tensile resistance $F_{ub,bar} = 5.7$ kN and an ultimate tensile strain $\varepsilon_{u,bar} = 3\%$.

The structural interaction between the masonry wall and the GFRM jacketing is then guaranteed by appropriate connectors, having a typical "L" shape, composed of GFRP (Fig. 1b) and generally used in a number of 6 elements per m^2. The cross section of these connectors – obtained by assembling together a set of glass fibers (60% minimum percentage, compared to the total cross-section area of the connector) with size 19–24 µm – has a rectangular shape of nominal dimensions $s_1 = 12$ mm $\times$ $s_2 = 8$ mm. The L_1, L_2 dimensions of the L-shaped connectors used in this experimental campaign were 300 mm and 100 mm, respectively. Based on recommendations of the producer and three tensile tests carried out on L-shaped specimens, the adopted connectors can offer an ultimate tensile characteristic strength $F_{ub,conn}$ up to 39 kN, corresponding to a tensile characteristic stress $\sigma_{ub,conn} = 455$ MPa (standard deviation ±11 MPa), and an average Young's modulus $E_{conn} = 20.5$ GPa. The L-shaped connectors are generally located in the masonry wall through $\phi = 25$ mm diameter passing-through holes and are superposed at least 210 mm to lap splice. The structural interaction between the connectors and the masonry wall is then offered by injection of thixotropic resins. At the interception between each L-connector and the GFRP mesh, being the nodal connection of crucial importance for the effectiveness of the strengthening technique, a further 33×33 mm^2 piece of GFRP mesh is then applied (Fig. 1c), in order to offer a proper distribution to possible peaks of stress.

The GFRM jacketing has to be applied on both faces of the interested masonry wall. In some cases, the application of the mortar coating is possible only on one side of the masonry, because on the other side frescos or fair-face are present. In this paper, the structural efficiency of both solutions is properly assessed.

2.1.2. Hybrid "Reticolatus" technique

A hybrid solution was also investigated during the same investigative campaign. In this case, the technique consists in strengthening the masonry walls by means of a combined "Reticolatus" system and a GFRM jacketing. The "Reticolatus" technique is described in [15], where it has been applied to a large number of stone and brick masonry specimens.

The technique consists of inserting in the mortar of the repointing (generally every three joints) a continuous mesh made of AISI 316 stainless steel cords (3 mm diameter). The cords are arranged in the vertical and horizontal directions, to form a net whose size typically depends on the dimensions of the stone elements. The intercepting nodes of these cords are then rigidly connected to the opposite face of the masonry wall by means of transverse stainless steel bars (typically in a number of 5 elements per m^2), able to provide a full interaction between the cords and the specimen