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Fibre reinforced mortar application for out-of-plane strengthening of schist walls

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HIGHLIGHTS

- Investigation of physical-mechanical properties of a new strengthening material (FRM).
- Characterization of an innovative strengthening technique for the rehabilitation of existing masonry.
- Out-of-plane test on real scale schist walls prototypes (reinforced and unreinforced).
- Numerical simulations to estimate the properties of the adopted materials.
- Parametric study to explore the potentialities of the proposed strengthening technique.

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ABSTRACT

The aim of the present work is to assess the effectiveness of an innovative strengthening technique for the rehabilitation of masonry buildings deficiently prepared to resist to loading conditions typical of seismic events. This technique is based on the application of outer layers of fibre reinforced mortar (FRM) by spray technology and it is used for increasing the load carrying capacity and deformation ability of masonry elements. For this purpose three almost real scale schist walls prototypes were strengthened and tested. The experimental program is described and the relevant results are presented and discussed. For estimating the properties of the schist walls and FRM taking into account the application conditions, the tested prototypes were simulated with a FEM-based computer program that has constitutive models for the simulation of the nonlinear behaviour of these materials. By using the derived properties, a parametric study was conducted to identify the influence of the FRM properties on the performance of the proposed strengthening system.

1. Introduction

Schist constructions represent a very important reality within the cultural, historical and architectural European heritage that need to be preserved. Different construction methodologies, building typologies and adopted materials have been used in schist masonry constructions [1,2]. For this heterogeneity it contributes the region where schist is extracted, leading to materials with different physical and mechanical characteristics, and also the conomic, cultural and social characteristics of the region [3,4].

Like other natural materials, schist masonry inevitably loose material performances due to ageing effects, mainly the low strength mortar used to bond the schist units, and the external micro-structure of the schist units. Therefore, in certain circumstances the overall behaviour of the building can be deficient, and its structural safety can be considerably compromised [5–7]. In addition, masonry buildings are the most vulnerable structures to earthquakes, mainly those made by schist units due to the deficient bond between the constituent materials. For this reason, the rehabilitation and strengthening of masonry walls is a demanding task, especially after the recent earthquakes that demonstrated the vulnerabilities of this type of constructions (e.g. L'Aquila, Italy in 2009; Christchurch, New Zealand in 2010; Lorca, Spain in 2011).

Furthermore, the upgrade of these constructions, promoting the living quality for their users, can contribute for attracting tourism

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for the interior regions of the countries, decreasing the huge depopulation of the regions occurred in the last decades.

Several kinds of materials have been used for the strengthening of masonry walls, like reinforced concrete, iron or steel, in an attempt of overcoming its brittle nature. However, these conventional retrofitting techniques demonstrate several disadvantages such as the reduction of available space, architectural impact, heavy mass addition, potential corrosion etc. [8,9]. Recently, advanced materials, like Fibre Reinforced Polymers (FRPs), have been also explored for the retrofitting of masonry structures since they have high strength to weight ratio, are ease of applying, and are immune to corrosion [10–13]. However, FRP's have low bond performance to these types of substrate, mainly when submitted to wet-dry cycles [14].

Considering the seismic response of stone masonry walls, the deficient out-of-plane load capacity is the main reason of vulnerability observed in the post-earthquake damage surveys. Despite that, relatively few experimental research was carried out for the characterization of the out-of-plane behaviour of stone masonry walls [15–19].

This research aims to contribute for the mitigation of masonry elements vulnerability, by characterizing the out-of-plane behaviour of unreinforced schist masonry walls, and exploring the potentialities of an innovative strengthening technique to increase the out-of-plane load carrying capacity and deflection performance of this type of constructions. In particular, this research provides a practical methodology for the application of a non-conventional strengthening system, and proposes a reliable methodology for the assessment of the relevant characteristics of the applied materials. The proposed strengthening technique is based in spraying thin outer layers of fibre reinforced mortar (FRM).

For the assessment of the effectiveness of this technique, an experimental program was carried out with almost real scale schist walls subjected to out-of-plane three points bending test setup. The load-deflection relationships, the crack patterns and the failure modes of strengthened and unstrengthened prototypes were obtained and discussed.

For assessing the relevant properties of the constituents that form this complex constructive system, the tested prototypes were simulated by using the FEMIX 4.0, a computer program based on the finite element method (FEM) that includes constitutive models capable of simulating the nonlinear behaviour of several types of materials. By using this software, a parametric study was conducted to estimate the potentialities of this proposed strengthening technique, by investigating the influence of variables like: thickness of FRM and post-cracking performance of FRM.

2. Experimental program

2.1. Properties of the constituent materials

The materials adopted in the present experimental research can be classified into two main categories: materials belonging to the schist masonry of the north-western regions of Portugal, namely stones and mortar, and fibre reinforced mortar (FRM) with engineered properties in order to have fresh requisites for being applied with spray-up technique, and with hardened properties for being effective for the structural strengthening of this type of masonry walls.

The schist stones for building the masonry wall prototypes of the tests program had irregular size and shape and were collected from a demolished house in the Portuguese Ovar costal city. Due to their geological formation, their physical and mechanical properties, such as Young's modulus, strength and permeability, are strongly dependent of the direction they are evaluated, due to the pronounced material orthotropy, as demonstrated elsewhere [20].

To bond the schist units, a Hydraulic Lime based Mortar (HLM) was used, which was prepared by a worker specialized in the reconstruction of this type of buildings. For this purpose it was used constituents similar, as much as possible, to those used in the original schist based housing, namely a type of clay that incorporates sand, with size grains ranging from 0.01 mm to 10 mm, hydraulic lime (HL5 according to the BS EN 459-1 [21]) and water. A binder/clay ratio of 1:7, and a water/binder ratio of 0.6 (all ratios in weight) were used. The HLM mechanical properties were assessed according to the EN 1015-11 [22] on three sets of three prismatic samples ($160 \times 40 \times 40\ mm^3$), casted on metal moulds during the schist walls construction, and then stored in a humidity chamber. To evaluate the development of the HLM strength over the time, the three aforementioned sets were tested in bending and in compression at three different ages: 28, 60 and 127 days after casting. The average flexural strength obtained for the aforementioned ages was 0.24, 0.29 and 0.33 N/mm^2, respectively, whereas the compressive strength was 1.1, 1.2 and 2.3 N/mm^2, respectively.

The FRM was made up by mixing the following constituents (in weight): cement 42.5R (25.13%), fly ash (30.75%), fine sand (20.1%), water (17.93%), superplasticizer (0.97%), viscosity controller (0.16%), glass (4.41%) and polypropylene fibres (0.55%). Both types of fibres have 12 mm of length, while the diameter is and 0.2 mm and 0.7 mm, respectively, for the glass and polypropylene fibres. By executing flow table tests according to EN 1015-3 [22], a flow value of 185 mm was measured in the developed FRM [23]. Additionally, a total air content of 6.5% was measured in the tests executed according to the recommendations EN 1015-7 [24].

The FRM strength was evaluated by executing flexural and compressive tests according to the recommendations of EN 1015-11 [25]. Three sets of three prismatic samples of FRM ($160 \times 40 \times 40\ mm^3$), casted on metal moulds and cured in a humidity chamber, were tested at 28, 48 and 104 days. The samples exhibited an average flexural strength of 11.8 (9.4%), 16.1 (6%) and 15.9 (7.9%) N/mm^2 at, respectively, 28, 48 and 104 days, while the average compressive strength was 25.7 (5.4%), 30.5 (4.3%) and 29.9 (10%) N/mm^2, respectively, where the values into round brackets are the corresponding coefficient of variation.

Since the FRM was designed to be applied to the outer surfaces of schist wall prototypes by spray-up technology, the adhesion between the FRM and the schist substrate was investigated by means of pull-off tests (Fig. 1), executed according to EN 1015-12 [26] recommendations.

This test consisted in the application of a tensile load to the FRM-schist stone system by means of a standard pull-head circular steel plate (ϕ 50 mm) glued with epoxy resin to the test area of the FRM surface. Seven pull-off test specimens were executed, and the pull-off strength was calculated as the quotient between the maximum load and the test area (1963.5 mm^2). A predominant adhesion type fracture failure mode occurred, and the average value of adhesive strength was 0.64 N/mm^2, with CoV of 28.2%, which is similar to the results obtained by other researchers for this type of substrate but using different mortars [27].

2.2. Influence of the FRM application in its flexural behaviour

The strengthening technique consists of spraying onto the outer surfaces of the schist masonry walls three consecutive FRM layers, of a thickness of about 10 mm per layer, up to its final thickness (Fig. 2a). Each layer is compacted with a roller/spatula applied in vertical direction (Fig. 2b). The walls were maintained in vertical position in order the application procedure be identical to the real strengthening conditions.

Once the spraying pressure, FRM rheology and distance between the operator and the sprayed surface were established, a FRM panel (see Fig. 2a and b) of 30 mm thickness was prepared