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Shear capacity of masonry walls externally strengthened by a cement-based composite material: An experimental campaign

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ABSTRACT

Composite materials are getting more and more common for strengthening existing members and structures; fiber-reinforced polymers (FRP) are widely used, while carbon-fiber-reinforced cement matrix (CFRCM) materials have been more recently proposed especially for strengthening masonry members. In the present paper, the results of an experimental campaign carried out on tuff-masonry walls strengthened in shear by a cement-based composite are reported and commented. The reinforced masonry walls failed after loss of adhesion between the strengthening layer and the masonry substrate. Comparisons between the experimental results and some analytical formulations available in the scientific literature for determining shear resistance of strengthened masonry walls are finally proposed. Huge variability can be observed by applying those alternative formulations which are not able to reproduce the premature nature of the observed failure mode. Consequently, the present study is a thorough experimental report which can be useful for developing and validating more refined theoretical models for describing the ultimate behaviour of masonry walls externally strengthened by FRP.

1. Introduction

Masonry buildings are rather common in Italy as well as in Southern Europe and around the Mediterranean basin. Although those regions are all characterized by medium-to-high levels of seismic hazard, masonry structures, as well as a wide class of existing buildings, have been only designed against gravitational loads, provided that often they have not been designed at all, but simply realized according to well-established rules of common practice. Consequently, the significant levels of both vulnerability of those structures and hazard of the regions in which they lie, result in even significant seismic risk levels as sadly pointed out by the huge loss of human lives caused by the recent earthquakes in Italy, Greece, Turkey, and Iran.

Seismic performance of existing masonry buildings is significantly affected by various failure mechanisms dealing with either out-of-plane or in-plane behaviour of walls. As far as the in-plane behaviour is concerned, failure can generally be controlled by shear or bending with axial force: the present paper will focus on the former one.

Different theoretical models are currently available for quantifying shear strength of walls. One of the most well-established models is the so-called "shear–tension" mechanism whose strength has been firstly determined by Turnsek and Cacovic [1]. Shear–tension failure is basically achieved as a diagonal crack completely develops throughout the wall. A different shear-induced mechanism can be also observed in masonry structures during seismic shakings: it consists in a roughly horizontal crack developing throughout the mortar layer and is named "sliding-shear" mechanism. Eurocode 8 – Part 3 [2] as well as the Italian Seismic Code on existing structures [3] define shear strength of masonry walls looking after both the mentioned failure mechanisms.

Seismic behaviour of masonry walls can be experimentally simulated by two kinds of tests. On one hand it can be reproduced by the so-called diagonal-compression test, ruled by the ASTM 519 [4], and, on the other hand, it can be simulated by shear compression test.

Corradi et al. [5] carried out a wide number of "in situ" tests on various kinds of natural masonry walls they found on the structures struck by the Umbria-Marche earthquake occurred in 1997 in Central Italy. Besides the other conclusions provided by the above research, the mentioned authors observed that strength values obtained by diagonal-compression tests are generally more conservative than those given by shear–compression tests. Nevertheless, both methods pointed out the general lack in shear strength of those masonry walls that can be generally extended to a wide class of similar existing structures. Consequently, masonry structures are generally in need for strengthening in shear and various techniques can be adopted with that aim. Besides

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the traditional techniques based on materials like steel and concrete, often resulting in heavy and hardly reversible solutions, composite materials are frequently utilized in enhancing shear strength of masonry.

The results of diagonal-compression tests carried out on clay-brick masonry walls, strengthened in shear by diverse kinds of FRPs (either carbon, glass or polyvinylalcohol-based) applied in different ways, can be also found in the scientific literature [6]. No significant improvements in shear strength have been usually observed for single sided strengthening and, even for double-sided ones, debonding failure is as premature as the composite is stiff (and resistant). Since adhesion between the composite layer and the masonry substrate usually controls shear resistance of strengthened walls, pull-out tests have been carried out upon composites glued on masonry specimens for determining the key properties of the adhesion between the strengthening material and masonry substrate which is usually the weakest link in the ideal chain of the resisting elements [7]. Consequently, with the aim of looking after the possible premature failure due to debonding, a suitable coefficient can be introduced for reducing the ultimate strength of composite for evaluating its contribution to the shear resistance of the wall as a result of its possible premature failure due to debonding. In particular, Triantafillou [8] proposed for concrete a reduction factor depending on the axial stiffness of the composite layer.

A brand new type of composite material, commonly known as fiber-reinforced cement matrix (FRCM) material, featuring a cement matrix instead of the more usual epoxy one, is nowadays available for strengthening RC and masonry members in civil structures. Pull-out tests carried out on these materials applied on clay-brick masonry samples showed that debonding failure usually does not involve masonry substrate, but develops throughout the matrix itself which cannot effectively adhere to the fiber net [7].

This failure mode has been also observed by Di Tommaso et al. [9] in some experimental tests carried out on RC beams strengthened in bending by either FRP or FRCM materials; a progressive loss of composite action has been observed in those tests for the FRCM materials without debonding between the composite layer and the concrete substrate. That work, as well as the other mentioned one, pointed out that loss of composite action within the FRCM material and debonding from the concrete or masonry substrate are two concurrent failure modes, the former one being more likely to occur as the mechanical properties controlling adhesion between the two adherents increase.

The present paper reports the main results obtained by an experimental campaign carried out at the Laboratory of Structures of the University of Salerno (Italy) on yellow-tuff-masonry walls, which are rather common in the South of Italy as well as in the Mediterranean basin. In particular, three unreinforced masonry walls and six ones externally strengthened on both sides by one layer of FRCM material have been tested under diagonal compression with the main aim of quantifying their shear strength.

After a detailed experimental report, a final comparison between the key experimental results and some simplified formulae available in the scientific literature for evaluating externally strengthened shear strength of masonry walls are also proposed with the aim of pointing out the huge variability of the results deriving by those models which are not generally capable of reproducing the premature failure of externally strengthened masonry walls due to loss of adhesion between the reinforcing layer and the masonry substrate. Consequently, in the authors' opinion the present work describes, first of all, a thorough experimental report which can be utilized by the same authors in their future research as well as by any other researcher interested in developing and calibrating analytical or numerical models for externally strengthened masonry walls; indeed, a complete description of the mechanical properties of the component materials can be derived on the basis of experimental results presented in the paper. Secondly, it finally presents a short overview of the state-of-the-art about the present proposals available in the scientific literature on the same topic pointing out their general lack of accuracy in reproducing the debonding phenomenon.

2. Description of specimens and testing procedure

Nine yellow-tuff-masonry walls have been tested. Their dimensions (chosen according to the mentioned ASTM code $120 \times 120 \times 40\ \text{cm}^3$), and textures are schematically represented in Fig. 1. The composite material utilized for strengthening is made out of a carbon fiber mesh placed within two layers of mortar, according to the usual procedure currently carried out for spreading a plaster layer upon the wall faces: in particular, two mortar layers have to be placed for embedding carbon fibers and developing composite interaction between fibers and matrix (Fig. 2).

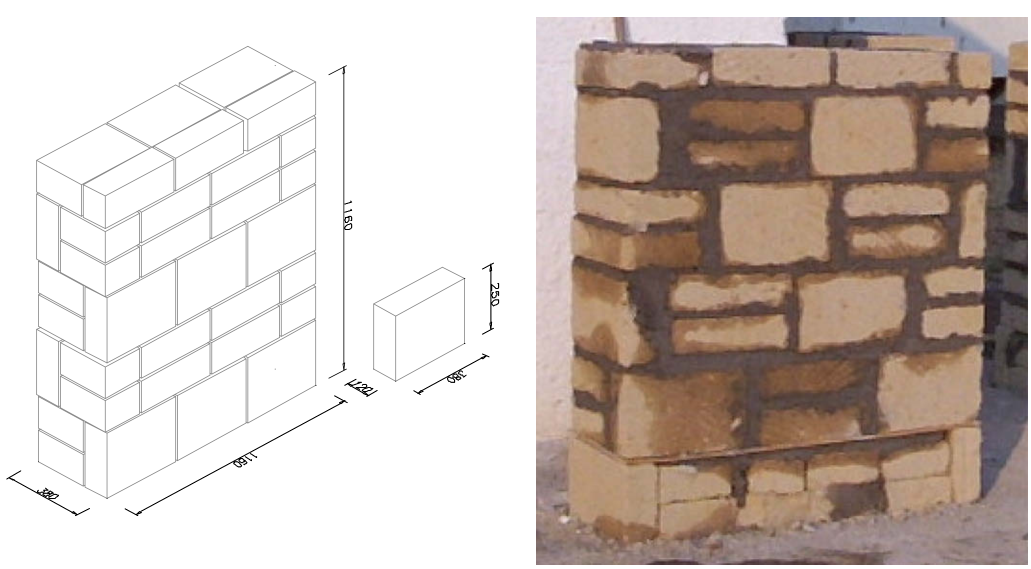

Fig. 1. Texture of the masonry panel.