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Irregular stone masonries: Analysis and strengthening with glass fibre reinforced composites

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ABSTRACT

Two masonry types with irregular texture are analysed to evaluate mechanical properties, sources of vulnerability and to design proper strengthening interventions.

Direct surveying, laboratory and in situ tests were performed to evaluate morphological characteristics and mechanical properties. Experimental values were compared with results obtained from analytical and FEM homogenizations, which exploited automated image segmentation process to determine volume fractions and description of the Reference Volume Element.

Strips of Glass Fabric-Reinforced Cementitious Matrix and transversal bars were considered and tested as strengthening solutions to overcome irregular masonries limits derived from multi-leaf structure highlighting levels of capacity improvement.

1. Introduction

The main issues in conservation of built heritage are the understanding of mechanical features and the identification of the sources of vulnerability in order to calibrate appropriate strengthening interventions.

Sustainable solutions for structural strengthening of historical buildings must improve mechanical properties without changing neither the architectonical value nor applied loads. To this aim, effective intervention techniques are those that exploit composite materials.

Cultural heritage of historical city centres is characterised by monumental masonry buildings, but also by ordinary dwelling constructions, often realised with irregular stone masonries. Among irregular masonries, block dimension and shape can vary remarkably, either stone chips, brick pieces or roof tiles can be found as blocks, and mortar quality is generally low. In order to perform global analyses and calibrate specifically designed strengthening strategies for these structures, a crucial issue is the characterization of actual mechanical properties of masonry constituents and of masonry walls.

Actual mechanical properties of masonry walls can be accurately achieved only through in situ tests [1–3]. These tests are typically destructive or semi-destructive, and, most important, are demanding in terms of financial and human resources. When laboratory or in situ tests are not feasible on each part of the building to investigate on, reliable models through which characterizing mechanical behaviour become indispensable for assessment or design purposes.

In the framework of micromechanics theory, masonry is a composite medium constituted by a mortar matrix with block inclusions and homogenization techniques permit to define an equivalent homogeneous material [4].

For masonries with periodic microstructure, homogenization techniques enable a reliable assessment of mechanical properties through two classes of parameters, i.e. geometry of the microstructure and mechanical characteristics of constituents, namely blocks and mortar. To evaluate constitutive parameters of periodic masonry, in Refs. [5,6] authors make use of the Mori Tanaka method [7] and lamination theory [8] in a two-steps procedure (i.e. firstly defining a transition material for which the presence of mortar bed joints is neglected and, secondly, completing homogenization applying lamination theory). Such a procedure is adopted also in Refs. [9–11] to evaluate damage process of masonry. Dry blocks masonry is considered in Ref. [12].

Making use of homogenization techniques in association with the finite element method, in Ref. [13], assuming micro periodicity

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and perfect interfaces, the overall elastic properties of an in-plane loaded masonry are derived from brick and mortar characteristics. Successive studies focus on damage models, ultimate strength and assumption of rigid or flexible blocks [14–17].

As for assessment of non-linear behaviour of masonry, finite element methods are usually employed. Indeed, increased computational capability of personal computers have allowed to mesh precisely the Unit Cell or the whole micro-structure to be analysed and to determine, thanks to non-linear constitutive relation of phases or to interfacial laws between phases, a macroscopic non-linear behaviour model, in a so-called multi-level or multi-scale approach [18–23].

For an extensive review on recent advances in homogenization techniques for regular masonry, see Ref. [24].

Nonetheless, for most of the masonries that characterise historical city centres worldwide, the assumption of regular micro-structure could be inappropriate. Thus, an approach that considers the statistical distribution of the phases becomes indispensable. In Ref. [25], the authors define a statistically equivalent periodic unit cell in a purely geometrical context making use of two-point correlation functions. In Refs. [26,27], distribution of masonry phases is described through random fields and the application of the Hashin-Strikman Variational principles, as was previously proposed by Luciano and Willis in Refs. [28–33], allows numerical analyses on a finite-sized body. In Refs. [34,35] an operative procedure to define a proper dimension of the Representative Volume Element (RVE) is considered through a double convergence criteria on the finite size window test. The operational value of these studies can be reached only through experimental validation, still unavailable in the literature.

This contribution proposes a direct comparison between the results of an experimental campaign carried out on two irregular masonry typologies, and the estimations of mechanical properties of the analysed masonries with different homogenization techniques. In particular, masonry walls were tested with the double flat-jack technique, while mortar and block quality were investigated through both in situ and laboratory tests. Complementary, segmented digital images of the tested masonries was used to define adequately the RVE. Three different Unit Cells were assumed for a description of the masonry with increasing morphological precision based on image segmentation results.

Once the masonries have been characterised, highlighting capacities and vulnerabilities, the most appropriate strengthening intervention can be designed.

Effective solutions for structural strengthening of historical structures exploit composite material technologies because they increase mechanical properties without increasing dead loads through the application of external FRP strips as shown in Refs. [36–47]. Remarkable capacity improvements are obtained also with cementitious matrix composites system [48–53], which exhibit more compatibility with historic masonries. Irregular masonries show a poor transverse response due to the multiple leaf structure [54,55], thus the insertion of horizontal ties allow an out-of-plane capacity and an increase in load carrying capacity and ductility [56–59]. Combined transverse tying and external textile reinforcement maximise the efficacy of interventions, experimental tests on reinforced columns or walls are reported in Refs. [60–63].

To assess the increase in bearing capacities of a wall pier made of one the analysed masonries, horizontal tying bars of different materials (i.e. glass fibre, carbon fibre and steel), and Glass Fabric Reinforced Cementitious Matrix (GFRCM) applied on external surfaces were considered as strengthening systems. Mechanical parameters related to the GFRCM strengthening systems were deduced from a dedicated experimental campaign.

The rest of the article is organised in four sections. In Section 2, the experimental campaign on two irregular masonries is illustrated. Section 3 presents methods to assess mechanical properties of the considered masonries. Fibre reinforced strengthening solutions most suitable for irregular masonries are analysed in Section 4. Comments of results obtained and conclusions are reported in Section 5.

2. Experimental evaluation of mechanical properties

The experimental campaign involved the analysis of two masonry types, labelled Mu1 and Mu4 (Figs. 1 and 2), belonging to the constructive culture of the nearby of L'Aquila (Italy). Mu1 and Mu4 masonries exhibit features similar to masonries of many historical centres of the Mediterranean basin, constituting a widespread heritage that must be preserved [64–66].

The masonries were surveyed through visual inspections, and analysed through experimental testing. In particular, elastic properties of walls were investigated through double flat-jack tests, and compressive strength of mortar was estimated through the in situ PNT-G Drilling test. Mortar specimens were subjected to mineralogical analyses and study of thin sections. Stone blocks were collected on site and subjected to compression tests to determine strength and elastic modulus.

In situ investigations allowed a morphological description of both the façade and cross section of masonries (Fig. 1). The hard limestone blocks are roughly hewn with very irregular shape. Limestone taken from quarry and calcareous pebbles of the river were also employed in the construction of walls. The little dimension of blocks and the masonry texture cause inefficient internal connections between leaves. Therefore masonries are substantially made by two separate leaves, held together only by mortar layers and low interlocking forces (Fig. 1).

Masonry Mu1 is characterized by partially irregular stone pieces and by accurate execution that tends to bed joints horizontality. The masonry arrangement appears enough effective since medium

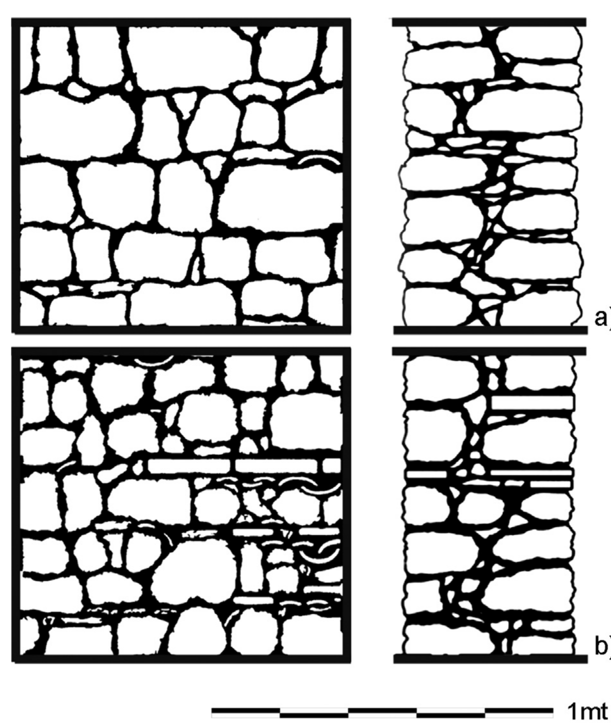

Fig. 1. Façade and cross-section of masonry types: a) Mu1; b) Mu4.