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Calibration of analytical formulations predicting compressive strength in consolidated three-leaf masonry walls

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HIGHLIGHTS

- Calibration of analytical models for the prediction of the compressive strength of consolidated three-leaf stone masonry.
- Construction of 3 series of stone masonry walls (16 panels in total) for testing under compression.
- In grouts with $f_{gr}/f_{wc,0}$ ratio higher than 5, grout strength does not contribute to the increase of the wall resistance.
- The effect that the reduced scale has on the compressive strength is taken into account in the presented formulations.

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ABSTRACT

This paper presents calibration of analytical models to predict the compressive strength of three-leaf stone masonry before and after consolidation with grout injection. Experimental results from previous campaigns were used, both published (Vintzileou and Tassios, 1995; Valluzzi et al., 2004; Vintzileou and Miltiadou-Fezans, 2008; Mazzon, 2010) [1–4] and from recent laboratory experiments at the University of Padova. As part of the present research work, three-leaf stone masonry panels in 1:1 and 2:3 scales, both in their original condition and consolidated with natural hydraulic lime-grout injections, were tested under monotonic and cyclic simple compression (Silva, 2012; Silva et al., 2014a,b) [5–7].

This work focuses on providing a data-enriched formula based on previous proposals by (Vintzileou and Tassios, 1995; Valluzzi et al., 2004; Vintzileou, 2007) [1, 2, 8] and also compiled in (Vintzileou, 2011) [9] to predict the compressive strength of three-leaf stone masonry before and after consolidation, together with analyses of the exploitation ranges of the formulations and grout compatibility. The effects of the reduced scale were also taken into account in the updated formulations.

1. Introduction

Stone masonry is one of the oldest known "structural materials". It has been extensively used throughout time for a large variety of constructions, both common and monumental. It is by nature a heterogeneous composite material made up of stones and mortar, very often with infill material, and with complex links and interactions between the components. In most cases, masonry components have unknown geometry and highly variable mechanical properties, which makes the definition of realistic behaviour laws very challenging.

Observation of damage after seismic events has highlighted how the type of construction, quality and state of preservation of masonry is essential to proper understanding of the seismic behaviour of existing buildings. Brittle failure is frequently observed in stone masonry walls characterised by two or three leaves without effective transversal connections, demonstrating that the resistance of masonry to various actions depends not only on the mechanical properties of its constituent materials, but also on geometric and physical characteristics which allow monolithic behaviour [10].

Recent seismic events have also shown the ineffectiveness of some past interventions applied to stone masonry structures and, consequently, of the approaches, methodologies and tools used in their conception. In this type of structure, solutions to problems must be adapted to each case, which implies a validation process

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Nomenclature

E	elastic modulus of materials
E_{cyl}	elastic modulus of cylinders
$E_{wc,0}$	elastic modulus of non-injected wall
$E_{wc,s}$	elastic modulus of injected wall
f_{ext}	compressive strength of external layers
$f_{cyl,s}/f_{cyl}$	compressive strength of injected cylinders
f_{gr}	compressive strength of grout
$f_{gr,t}$	tensile strength of grout due to bending
$f_{inf,0}$	compressive strength of non-injected infill
$f_{inf,s}$	compressive strength of injected infill
f_t	tensile strength of materials
f_{wc}	experimental compressive strength of walls
$f_{wc,0}$	experimental compressive strength of non-injected wall
$f_{wc,0\ (1:1)}$	predicted compressive strength of non-injected walls (1:1)
$f_{wc,0\ (2:3)}$	predicted compressive strength of non-injected walls (2:3)
$f_{wc,s}/f_{wc,s\ exp}$	experimental compressive strength of injected wall
$f_{wc,s\ (1:1)}$	predicted compressive strength of injected walls (1:1)
$f_{wc,s\ (2:3)}$	predicted compressive strength of injected walls (2:3)
$f_{wc,s\ av}$	average experimental compressive strength of the injected wall
$f_{wc,s\ pred}$	predicted compressive strength of injected wall
$f^{*}_{inf,s}$	percentage of infill strength which actually contributes to panel strength
V_{inf}	volume of internal layer
V_{ext}	volume of external layer
V_w	total volume of walls
γ_{rd}	safety factor
η	injection effectiveness – ratio between strength effectively implemented by the panel and whole infill strength
θ_{ext}	empirical corrective factor to take into account influence of external layers in overall behaviour of wall
θ_{inf}	empirical corrective factors to take into account influence of internal core in overall behaviour of wall
σ_{max}	maximum compressive of materials
ν	poisson ratio of materials

based on real application conditions, to guarantee optimal compatibility, low intrusiveness, and removability/reversibility with a minimum intervention approach. Experimental studies are an important source of information regarding this validation process, particularly in what regards the development and calibration of analytical and numerical tools capable of predicting the behaviour of these structures.

An extensive experimental campaign on multi-leaf stone masonry panels, in their original condition and consolidated with natural lime-based grout, was performed at the Laboratory of Construction Materials of the Department of Civil, Environmental and Architectural Engineering (University of Padova, Italy). This campaign, on which this research work is based, is described in detail in [5–7]. Its main aims were to assess the effectiveness of grout injection as a strengthening technique and to extend knowledge of its influence on the static and dynamic behaviour of stone masonry and stone masonry elements.

This work focuses on the use of data from the experimental campaign, together with already published reports, to provide a data-enriched formula based on previous proposals by [1,2,8] to predict the compressive strength of three-leaf stone masonry before and after consolidation, with analysis of the limitations of the formulations and grout compatibility.

1.1. Existing models for predicting compressive strength of three-leaf masonry

1.1.1. Non-injected models

Egermann [11] proposed an analytical model to predict the compressive strength of three-leaf masonry before grouting, calculated as the weighted sum of the compressive strength of the external and internal leaves (Eq. (1)). In the present work, the hypotheses of: (i) the elastic behaviour of the layers; (ii) plane connections among them, and (iii) negligible transverse strains, were all considered.

$$f_{wc,0} = \left(\frac{V_{ext}}{V_w}\right) \cdot \theta_{ext} \cdot f_{ext} + \left(\frac{V_{inf}}{V_w}\right) \cdot \theta_{inf} \cdot f_{inf,0} \tag{1}$$

Vintzileou and Tassios [1] derived a formula to estimate the compressive strength of non-injected masonry, based on [11], assuming that the compressive strength of the original wall (before intervention) was mainly due to the external layers, so that the influence of the internal core could be considered negligible. The following Eq. (2) was thus derived:

$$f_{wc,0} = \left(\frac{V_{ext}}{V_w}\right) \cdot f_{ext} \tag{2}$$

Tassios [12] used this equation to predict the compressive strength measured in [1,13,14] in a satisfactory way. In view of the available experimental data, a partial safety factor γ_{rd} of 1.5 was used to calculate compressive strength values suitable for design.

1.1.2. Grout-injected models

A simple formula was developed in [1], based on the assumption that: (i) grouting does not significantly affect the mechanical properties of external leaves; (ii) it substantially improves the mechanical properties of the infill. Therefore, strength enhancement by the infill was taken as proportional to the square root of the compressive strength of the grout, as an indicator of its tensile strength. The contribution of the reinforced infill material to the compressive strength of the masonry is thus proportional to the ratio V_{inf}/V_w:

$$f_{wc,s} = f_{wc,0} \cdot \left(1 + 1.25 \cdot \frac{V_{inf}}{V_w} \cdot \frac{\sqrt{f_{gr}}}{f_{wc,0}}\right) \tag{3}$$

Valluzzi et al. [2] recalibrated Eq. (3) on the basis of results from the literature and systematic testing of cylinders made of filling material injected with hydraulic lime-based grouts, using empirical formulation (Eq. (4)) to obtain Eq. (5). Eq. (4) is based on the results by Valluzzi et al. [2] and Vintzileou and Tassios [1], to predict the compressive strength of the grouted infill material.

$$f_{inf,s} = f_{cyl,s} = 0.31 \cdot f_{gr}^{1.18} \tag{4}$$

$$f_{wc,s} = f_{wc,0} \cdot \left(1 + \frac{V_{inf}}{V_w} \cdot \frac{f_{inf,s}}{f_{wc,0}}\right) \tag{5}$$

Eq. (3) showed a very good match when applied to walls injected with low-strength grouts ($f_{gr} \leqslant$ 4–5 MPa), but led to more approximate estimations than Eq. (5) in the case of high-strength grouts ($f_{gr} \geqslant$ 14–15 MPa). Eq. (5) seems to overestimate the compressive