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Experimental assessment of in-plane behaviour of three-leaf stone masonry walls

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HIGHLIGHTS

- We carried out shear compression tests on 16 three-leaf stone masonry panels, before and after injecting NHL grout.
- Non-injected panels underwent external leaf separation at lower displacement levels.
- Injected walls presented enhanced behaviour and increased mechanical parameters.
- The use of scaled specimens may be considered representative of the tested masonry.

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ABSTRACT

This paper presents an experimental campaign on multi-leaf stone masonry panels, scales 1:1 and 2:3, in both original conditions and strengthened with grout injections. The panels were subjected to horizontal in-plane cyclic loading combined with vertical loading for different pre-compression levels, and provided important information on failure mechanisms, maximum displacement capacity, shear strength and other mechanical parameters, such as shear modulus and tensile strength. Further analysis provided results on other parameters which mainly characterise the behaviour of three-leaf masonry under seismic loads, i.e., stiffness degradation, energy dissipation, and viscous damping.

The main aim of this study was to gather information on the static and dynamic behaviour of three-leaf stone masonry structures in non-injected and injected conditions, in order to accurately characterise their mechanical behaviour. In particular, the effectiveness of injections of hydraulic lime-based grout as a reinforcement technique was assessed and validated.

1. Introduction

During an earthquake, a resistant masonry wall is subjected to both vertical loads (due to gravity and the vertical component of the seismic action) and horizontal loads as a consequence of inertia-restoring forces. Multi-leaf stone masonry is particularly susceptible to in-plane shear actions, due to its low tensile strength. In addition, if the quality of the inner leaf with respect to the external leaves is poor, and if there are no transversal elements connecting the leaves, detachment and out-of-plane collapse of external leaves very often occurs, as shown in Fig. 1.

In order to predict the seismic resistance of masonry, study of its shear capacity is therefore necessary, as well as evaluation of the effectiveness of grout injections, to prevent out-of-plane and in-plane collapse mechanisms.

Grout injections have proved effective in improving the in- and out-of-plane behaviour of multi-leaf stone masonry. Shaking table tests on storey-high walls have recently also demonstrated the effectiveness of injections in delaying leaf detachment under seismic loads, significantly improving wall behaviour [1].

As regards behaviour under horizontal in-plane loads, Shear Compression (SC) tests are typically used, to determine shear and tensile strength, including shear modulus. Parameters such as ductility, energy dissipation and stiffness degradation can also be evaluated by testing specimens under cyclic loading, in conditions which buildings actually undergo during an earthquake. In this technique, specimens are subjected to a constant vertical (axial) load, simulating the pre-compression level acting on the building. Cyclic lateral displacements are then applied at increasing

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Nomenclature

A	cross-sectional area of wall
b	shear stress distribution factor
E	Young's modulus
E_{hys}	dissipated energy
E_{inp}	input energy
$E_{wc,0}$	elastic modulus of non-injected walls
$E_{wc,s}$	elastic modulus of injected walls
f_{gr}	compressive strength of grout
f_t	tensile strength
$f_{wt,0}$	experimental tensile strength of non-injected walls
$f_{wt,s}$	experimental tensile strength of injected walls
G	shear modulus
G_{exp}	shear modulus corresponding to cracking limit state
$G_{exp\ 30–60\%}$	experimentally obtained shear modulus, resulting from average of values ranging from 30% to 60% of maximum shear resistance
G_k	theoretical shear modulus
$G_{w,0}$	shear modulus of non-injected walls
$G_{w,s}$	shear modulus of injected walls
h	height of stone masonry panels
H	horizontal resistance
H_{cr}	horizontal resistance corresponding to cracking limit state
$H_{\delta u}$	horizontal resistance corresponding to ultimate displacement limit state
H_f	horizontal resistance corresponding to flexural cracking limit state
H_{max}	horizontal resistance corresponding to maximum resistance limit state
K	secant stiffness
K_{cr}	secant stiffness at cracking limit state
l	length of masonry panel
p_0	open porosity
p	total porosity
t	thickness of stone masonry panels
V	vertical load
w	width of stone masonry panels
α	boundary condition parameter
δ	horizontal displacement measured at top of panels
δ_u	ultimate displacement
δ_{cr}	displacement corresponding to cracking limit state
δ_f	displacement corresponding to flexural cracking limit state
δ_{Hmax}	displacement corresponding to maximum resistance limit state
Δ	imposed displacement at top of wall
γ_i	shear strain evaluated on masonry panel
ρ_b	apparent density
ρ_r	real density
σ'_0	vertical pre-compression
σ_{max}	compressive strength of panels
τ	average nominal shear strength evaluated on panels
τ_{Hmax}	average nominal shear strength evaluated on panels at maximum resistance
$\tau_{u,0}$	shear strength of non-injected walls
$\tau_{u,s}$	shear strength of injected walls
μ	ductility
μ_0	ductility of non-injected walls
μ_s	ductility of injected walls
v	Poisson ratio
ξ	equivalent viscous damping
ξ_{cr}	equivalent viscous damping corresponding to cracking limit state
$\xi_{\delta u}$	equivalent viscous damping corresponding to ultimate displacement limit state
ξ_f	equivalent viscous damping corresponding to flexural cracking limit state
ξ_{Hmax}	equivalent viscous damping corresponding to maximum resistance limit state

amplitudes step-wise. Walls can be tested as cantilevers with central vertical loading or as double fixed-end walls [2].

Since the early 1960s, several authors have carried out shear compression tests on multi-leaf stone masonry, both in the laboratory and on-site, before and after grout injection. The main results of such experimental results are listed in Table 1. The geometry, mechanical properties of the studied materials, and the mechanical properties of the masonry before and after grouting are shown.

Shear compression tests on injected and non-injected multi-leaf stone masonry specimens show that diagonal cracks generally develop in mortar joints, in some cases also passing through the stone, particularly at higher pre-compression levels. With repeated imposed lateral displacement, cracking becomes more extensive and, at maximum lateral resistance, vertical cracks appear as an effect of compression [1,3]. Cracking also occurs in the transversal sides, due to increased out-of-plane deformation of the external leaves, reducing the resistant section of the compressed walls. Experimental tests also show that the failure mechanisms of injected masonry walls submitted to in-plane cyclic loading are mainly governed by the slenderness ratio, pre-compression level, and masonry bond.

As observed from the failure modes of masonry walls, separation of external and internal leaves is due to shear failure planes generated in the infill material, causing high horizontal pressure on the external leaves [4]. The main cause of the im-

Fig. 1. Out-of-plane failure of stone masonry walls without transversal connections due to horizontal seismic actions, L'Aquila, Abruzzo, Italy.