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Experimental study on in-plane cyclic response of partially grouted reinforced concrete masonry shear walls

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ABSTRACT

This article describes the experimental results of ten partially grouted reinforced concrete masonry shear walls (PG-RCMSW) that were subjected to reverse lateral in-plane cyclic loads. The variables analysed in this study were: aspect ratio, shear reinforcement ratio and level of axial pre-compression. The influence of each of these variables on different structural parameters such as degradation of stiffness, shear strength, displacement ductility, dissipation of energy, hysteretic damping and level of drift, was evaluated. In addition, the precision of certain analytical expressions reported in the literature to predict the maximum shear strength of walls was examined and contrasted with the experimental results obtained.

The results showed that the evolution of the damage was propagated in a similar way in all the walls tested until reaching the level of maximum strength. From this point, the evolution and extension of the damage depended on the characteristics and loading conditions particular to each wall. Also, a strong interdependence of the variables studied was identified, which became evident in the evaluation of shear strength, dissipation of energy, hysteretic damping, and level of drift. Using a bilinear idealization, displacement ductility values between 2.85 and 7.94 were found to reflect the presence of a moderate level of ductility in the walls tested. The equivalent viscous damping ratio associated with a non-linear response was found to range from 5% to 11%, indicating a moderate level of energy dissipation before the peak load was reached. Finally, the comparison between the predictions of the analytical expressions from the literature and the experimental results showed that those expressions that incorporated some interdependence in their design variables did not possess an appropriate degree of confidence to be applied in assessing the shear strength of PG-RCMSW, while expressions proposed by some international codes seem to be more reliable and conservative.

1. Introduction

Reinforced masonry is one of the most frequently used structural systems worldwide for the construction of low and medium-height buildings in areas of moderate or high seismic activity. This structural system is mainly comprised of reinforced masonry shear walls, which are arranged in two major axes of a building. Its lateral load-carrying capacity depends on the in-plane resistances of shear walls because the in-plane stiffness of a shear wall is far greater than its out-of-plane stiffness [6]. Because the reinforced masonry shear wall buildings are commonly composed by reinforced concrete slabs that act as rigid diaphragms during a seismic event, horizontal seismic actions are mainly transferred to walls parallel to the load direction [34]. Consequently, frequently observed damage after seismic events is related to in-plane failure modes.

In Chile, reinforced masonry have been used since the mid-seventies in the construction of social housing and residential buildings of up to four storeys [24]. Recent post-earthquake observations have shown that the seismic response of this type of constructions is still deficient [3,4,30,32,37]. In fact, the earthquakes of Tarapacá in 2005 (M_w 7.8), Maule in 2010 (M_w 8.8), and Iquique in 2014 (M_w 8.2) caused severe structural damage in several masonry buildings and even collapse in some cases. During these events, major problems were observed in those buildings that were constructed with partially grouted reinforced concrete masonry shear walls (PG-RCMSW). The failure mechanism observed in the majority of the buildings affected by these seismic events was by shear failure with a pattern of diagonal cracking. As is well known,

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Nomenclature

A_{wh} horizontal gross cross-sectional area of test wall (mm^2)
A_{wv} vertical gross cross-sectional area of test wall (mm^2)
A_w horizontal cross-section area of the wall (mm^2)
A_{nv} net shear area of the wall (mm^2)
A_v area of vertical reinforcement (mm^2)
A_h area of horizontal reinforcement (mm^2)
A_{rh} area of single horizontal reinforcing steel bar (mm^2)
b shear stress distribution factor
C_{rh} horizontal reinforcement capacity reduction factor
d wall length (mm)
d^* effective depth of the wall (mm)
d_{rv} diameter of one vertical reinforcement bar due to dowel action (mm)
d_E elastic idealized displacement (mm)
d_{SL} displacement to elastic limit state (mm)
d_{MR} displacement to maximum resistance limit state (mm)
E_m Young's modulus of masonry, based on net area (MPa)
E_m^* Young's modulus of masonry, based on gross area (MPa)
E_{sh} Young's modulus of shear reinforcement (MPa)
E_{sv} Young's modulus of vertical reinforcement (MPa)
E_T accumulated dissipate energy up to maximum resistance (kN-mm)
E_H energy dissipated for a load cycle (kN-mm)
h_w wall height (mm)
h_{ef} wall effective height (mm)
$K_{s,i}$ secant stiffness of an *i* cycle (kN/mm)
K_o initial stiffness to an imposed lateral displacement of 0.20 mm (kN/mm)
$K_{E,exp}$ experimental elastic stiffness (kN/mm)
$K_{E,theorical}$ theoretical elastic stiffness (kN/mm)
K_R post-cracking stiffness (kN/mm)
k_p coefficient of the effect of flexural reinforcement
k_u reduction factor
α parameter of the stiffness degradation
β parameter of the stiffness degradation
α_t cross area of edge tension bar (mm^2)
δ factor concerning the type of grouting
$\delta_{max,i}$ maximum displacement in the load cycle (mm)
γ factor concerning loading method
γ_g grouted shear wall factor
f'_{bm} cement mortar flexural strength (MPa)
f'_{cu} concrete block compression strength (MPa)
f'_{cm} cement mortar compression strength (MPa)
f'_{cr} grout cylinder compression strength (MPa)
f'_m compressive strength of masonry prism, calculated on net area (MPa)
f'^*_m compressive strength of masonry prism, calculated on gross area (MPa)
f_{yh} yield strength shear reinforcement (MPa)
f_{uh} ultimate strength shear reinforcement (MPa)
f_{yv} yield strength vertical reinforcement (MPa)
f_{uv} ultimate strength vertical reinforcement (MPa)
f_t tensile strength of masonry (MPa)
F_R resistant factor
G_m shear's modulus of masonry, based on net area (MPa)
G_m^* shear's modulus of masonry, based on gross area (MPa)
I_n Moment of inertia of the net section of the uncracked wall (mm^4)
L length of wall (mm)
M maximum moment at the section under consideration (N-mm)
η efficiency factor of reinforcement horizontal
n number of vertical reinforcement bars
ρ_h horizontal reinforcement ratio
ρ_v vertical reinforcement ratio
ρ_{ve} flexural reinforcement ratio due to the cross area of edge tension bar (%)
S_v vertical separation of horizontal reinforcement (mm)
P axial load (N)
R^2 correlation factor
τ_m masonry shear strength, calculated on net area (MPa)
τ_m^* masonry shear strength, calculated on gross area (MPa)
σ_n axial pre-compression stress, calculated on gross area (MPa)
σ_o axial pre-compression stress, calculated on net area (MPa)
σ_a average compression stress due to vertical load (MPa)
v_n tangential stress shear calculated on net area (MPa)
v_m^* diagonal compression resistance calculated on gross area (MPa);
V shear force (N)
V_m nominal shear strength provided by masonry (N)
V_s nominal shear strength provided by shear reinforcement (N)
V_n nominal shear strength (kN)
V_{exp} experimental shear strength (kN)
V_E lateral force to idealized elastic limit state (kN)
V_{SL} lateral force to elastic limit state (kN)
V_{MR} Lateral force to maximum resistance limit state (kN)
ΔV_{max} difference of peak lateral loads of an *i* cycle (kN)
$\Delta\delta_{max}$ difference of displacement corresponding to peak lateral loads of an *i* cycle (mm)
Δ drift *s*
μ_{MR} displacement *t* to maximum resistance limit state;
ξ_{eq} equivalent hysteretic damping (%)
s spacing of shear reinforcement (mm)
t thickness of wall

shear failure in a wall is a mechanism of a brittle nature that is characterised by a low capacity for dissipation of energy and rapid degradation of stiffness and strength after the maximum lateral capacity has been reached.

Given the importance of seismic action, the behaviour of masonry buildings comprised of PG-RCMSW is receiving increasing attention worldwide. Numerous experimental investigations carried out in Chile in recent decades [21,19,20,26,35] as well as in other countries [8,12,22,23,28,39,9,10] have demonstrated that the properties of the constituent materials, the wall aspect ratio, the level of axial load, and the ratio and distribution of vertical and horizontal reinforcements are the principal design parameters that control the response and seismic performance of PG-RCMSW.

From the above-cited experimental results it can be seen that an increase in axial load causes a rise in the shear strength of the walls [22] and additional frictional strength along the diagonal cracks, which favours an increase in hysteretic energy dissipation [23]. However, an increase in axial load also gives rise to the walls developing lower ductility and exhibiting more brittle behaviour than walls without axial load [26]. With regard to the influence of the vertical reinforcement ratio, it can be seen that if this ratio increases, shear strength also increases [8,35,39], and the walls show a greater number of diagonal cracks but where the cracking is less wide. Also, in agreement with Tomazevic [36], the dowel action that develops as a result of vertical reinforcement also contributes to an increase in shear strength. However, a greater