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In-plane Seismic Design of Concrete Masonry Structures

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Doctor of Philosophy (PhD) in Civil and Environmental Engineering.
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Abstract

The research presented in this thesis consists of two parts. The first part involved the investigation of concrete masonry shear strength and the second part reports an investigation of the lateral strength of partially grout-filled nominally reinforced perforated concrete masonry walls.

Valuable information about masonry shear strength is reported following the testing of ten full scale concrete masonry walls. It was verified that horizontal shear reinforcement and axial compression load provided additional shear resistance to masonry walls. Consequently, the nominal shear strength of reinforced masonry walls could be evaluated as a sum of contributions from masonry, shear reinforcement and applied axial load. It was also established that masonry shear strength decreases inversely in relation to an increase of the wall aspect ratio.

Criteria relating to codification of the in-plane shear strength of concrete masonry walls when subjected to seismic loading are presented. Particular emphasis is placed on a computational model that is capable of representing the interaction between flexural ductility and masonry shear strength to account for the reduction in shear strength as ductility level increases. The simple method proposed here allows the strength enhancement provided by axial compression load to be separated from the masonry component of shear strength and is considered to result from strut action. In addition, minor modifications are made to facilitate adoption of the method in the updated version of the New Zealand masonry design standard, NZS 4230:2004.

Prediction of shear strength from NZS 4230:2004 and using alternative methods are compared with results from a wide range of test of masonry walls failing in shear. It was established that the shear equation in the former version of the New Zealand masonry standard (NZS 4230:1990) was overly conservative in its prediction of masonry shear strength. The current NEHRP shear expression was found to be commendable, but it does not address masonry shear strength within plastic hinge regions, therefore limiting its use when designing masonry structures in seismic regions. Finally, the new shear equation adopted by NZS 4230:2004 was found to provide significantly improved shear strength prediction with respect to its predecessor, with accuracy close to that resulted from NEHRP.

Test results obtained in the second part of this research indicated that the size of openings and the length of trimming reinforcement significantly affected the lateral strength of perforated masonry walls. The observation of diagonal cracking patterns that aligned well with the load paths by which shear force was assumed to be transferred to the foundation in the strut mechanism supported the use of strut-and-tie analysis as a viable tool to evaluate the flexural strength of walls of this type. Strength prediction using the improved strut-and-tie method and the modified plastic collapse analysis were found to closely match the experimental results of the perforated walls tested in this study. Strength prediction by the simplified strut-and-tie method was found to closely match the test results of masonry walls with a single opening, but significant underestimation of strength by this method was found for walls with double openings. Full plastic collapse analysis was found to significantly over-predict the strength of all perforated walls included in this study.

Finally, the NZS 4229:1999 detail for shrinkage control joints was shown to result in adequate structural performance. In addition, shrinkage control joints constructed in accordance with the NZS 4229:1999 prescription resulted in masonry bracing capacity substantially in excess of the tabulated values in the standard, with gradual strength and stiffness degradation. This increase in strength is due to pier double bending that is not considered by the standard.

Disclaimer

The opinions and conclusions presented herein are those of the author, and do not necessarily reflect those of the University of Auckland or any of the sponsoring parties to this project.

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List of Symbols

A = depth of compression
A_h = area of single horizontal reinforcing steel
A_n = net cross-sectional area
A_r = wall aspect ratio
A_s = area of vertical reinforcing steel
b = width of compressive stress block
a = compression block depth
b_f = maximum width of ungrouted flue
b_w = effective wed width
C_m = compression force in masonry
C_1 = shear strength coefficient in 4.3.1
C_2 = shear strength coefficient in 4.3.1
C_3 = shear strength coefficient in 4.3.3
C_d = nominal shear strength coefficient
D_{eff} = effective depth of section
c = neutral axis depth
d = distance from end of wall to the extreme wall vertical reinforcement
d' = distance between wall edge and outermost wall vertical reinforcing steel
F_{code} = code specified wall nominal strength
E = elastic modulus of reinforcement
$F_{code,amd}$ = wall bracing capacity according to proposed amended procedure
$F_{code,no\text{-}op}$ = code specified nominal strength for wall without opening
F_n = nominal flexural strength
F_{max} = maximum strength recorded during testing
$F_{n,fr1}$ = nominal wall strength according to modified plastic hinge model
$F_{n,fr0}$ = nominal wall strength according to full plastic hinge model
$F_{n,no\text{-}op}$ = nominal strength of wall without opening
$F_{n,st1}$ = nominal wall strength according to improved strut-and-tie model
$F_{n,st0}$ = nominal wall strength according to simplified strut-and-tie model
F_v = shear force applied to masonry wall
f'_m = masonry compressive strength
f_v = masonry shear stress
f_{vr} = masonry shear stress

f_{yh} = yield strength of horizontal reinforcing steel

f_{yv} = yield strength of vertical reinforcing steel

h = wall height

h_e = effective height

h_e/L_w = shear span ratio

jd = lever arm

k = ductility reduction factor

k_p = coefficient of the effect of flexural reinforcement

k_u = reduction factor

L_w = length of masonry wall

M_{bc} = flexural strength for the coupling element section at compression pier end

M_{bt} = flexural strength for the coupling element section at tension pier end

M_c = flexural strength for the compression pier end sections

M_n = nominal bending moment

M_t = flexural strength for the tension pier end sections

N = axial compressive load

P_{ovt} = axial force due to overturning

p_w = $A_s/b_w d$

s_h = spacing of horizontal reinforcement

T = tension force in reinforcing steel

t = thickness of masonry wall

U_b = flexure displacement

U_r = rocking displacement

U_s = shear displacement

V_c = ultimate lateral load capacity of compression pier

V_m = shear strength provided by masonry

V_{max} = maximum lateral strength recorded during testing in positive direction

V_{min} = maximum lateral strength recorded during testing in negative direction

V_n = nominal shear strength

V_p = shear strength provided by axial compressive load

V_s = shear strength provided by shear reinforcement

V_t = ultimate lateral load capacity of tension pier

v_{bm} = basic type-dependent shear strength of masonry

v_m = maximum permitted type-dependent shear stress provided by masonry

v_n = total shear stress corresponding to V_n

W_t = wall self weight

x = depth of masonry block unit

y = width of masonry block unit

Δ_y = nominal yield displacement

α = parameter for compressive stress block

β = parameter for compressive stress block

δ = factor concerning loading method

ϵ_s = reinforcing steel strain

φ = wall section curvature

ϕ = strength reduction factor

μ = ductility level

μ_{av} = available ductility

μ_f = coefficient of internal friction

μ^* = reduced coefficient of friction

ρ_h = horizontal reinforcement ratio

ℓ_{dh} = development length of reinforcement

ρ_v = vertical reinforcement ratio

σ_n = axial compressive stress

τ_m = shear stress

τ_o = shear bond strength

τ_o^* = reduced cohesion

τ'_{tb} = masonry tensile strength

θ = wall section rotation