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Seismic Performance of a Post-tensioned Concrete Masonry Wall System

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A thesis submitted in partial fulfilment of the requirements
for the Degree of Doctor of Philosophy

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ABSTRACT

This thesis describes the development of a post-tensioned concrete masonry (PCM) wall system designed using generic materials. PCM walls derive their lateral strength and self-centering behaviour from unbonded post-tensioning. During in-plane loading, a horizontal crack forms at the wall base, which minimises masonry tensile strains and associated wall damage.

An extensive literature review identified numerous instances where PCM has been used in projects worldwide, and this is reflected in the growing presence of the technology in international masonry codes. However, the lack of knowledge associated with seismic behaviour has resulted in limited use of this material in seismic zones. Although recent studies have begun to address this through pseudo-static testing, there remained a clear need to investigate the dynamic performance of such walls.

Pseudo-static testing of two partially grouted PCM walls demonstrated the suitability of this system for residential structures in seismic areas. A subsequent shake table test series investigated the response of rectangular walls, walls with openings and a shrinkage control joint. The series concluded with the testing of a simple square structure that investigated multiple openings and wall corners. Rocking was shown to be the predominant deformation component, with minimal residual displacements at the conclusion of testing. Damage was restricted to the lower wall corners and above and below openings.

Equations provided in international masonry codes for estimating the tendon stress at the nominal strength limit state were shown to be inappropriate for in-plane walls. A new expression was developed based on test results and finite element modelling, and was shown to provide improved accuracy, permitting the complete monotonic response of PCM walls to be predicted with excellent accuracy. An investigation into the creep and shrinkage properties of PCM demonstrated that prestress losses can be significant and must be considered in design.

A displacement based design method for post-tensioned masonry walls was developed and demonstrated using a design example. The widely used bracing design method for reinforced masonry structures was adapted for PCM walls and utilised in the design of New Zealand's first post-tensioned concrete masonry house.

DISCLAIMER

This thesis was prepared for the Department of Civil and Environmental Engineering at the University of Auckland, New Zealand, and describes the development of a post-tensioned concrete masonry wall system. The opinions, conclusions and recommendations 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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NOTATION

Roman characters:

a	equivalent rectangular stress block compression zone length
A_{ps}	prestressing tendon area
$A_{ps,i}$	area of i^{th} prestressing tendon
A_s	mild reinforcing steel area
A_{wall}	effective cross-sectional wall area
b_w	wall width
c	distance from the extreme compression masonry fibre to flexural neutral axis
C_1	shear strength coefficient to account for dowel action
C_2	shear strength coefficient to account for aspect ratio
C_c	concrete masonry creep coefficient
$C_h(T)$	spectral shape factor
d	distance between tendon and extreme compression wall fibre
d_{bn}	total lateral displacement beyond d_n
d_c	spectral corner point displacement
d_{cr}	total lateral displacement at h_e due to V_{cr}
$d_{cr,fl}$	lateral flexural displacement at h_e due to V_{cr}
$d_{cr,sh}$	lateral shear displacement at h_e due to V_{cr}
d_e	total lateral displacement at h_e due to V_e
$d_{e,fl}$	lateral flexural displacement at h_e due to V_e
$d_{e,sh}$	lateral shear displacement at h_e due to V_e
d_i	distance between the i^{th} tendon and extreme compression wall fibre
d_n	total lateral displacement at h_e due to V_f
$d_{n,fl}$	lateral flexural displacement at h_e due to V_f
$d_{n,ro}$	lateral rocking displacement at h_e due to V_f
$d_{n,sh}$	lateral shear displacement at h_e due to V_f
d_T	target wall displacement for direct displacement based design
d_{TEST}	maximum wall displacement obtained during testing and used in DDBD validation
d_u	ultimate wall displacement
$d_{v\ max}$	wall displacement at V_{max}
d_y	wall equivalent yield displacement

E_m	masonry elastic modulus
E_{ps}	prestressing steel elastic modulus
f'_m	masonry crushing stress
f_m	axial masonry stress
f_{mi}	masonry stress immediately after prestressing
f_{ps}	prestressing tendon stress at nominal flexural strength
$f_{ps,i}$	stress in i^{th} prestressing tendon at nominal flexural strength
$f_{psbn,i}$	stress in i^{th} prestressing tendon beyond nominal flexural strength
f_{psi}	prestressing tendon stress immediately after anchorage lock-off
f_{pu}	ultimate (rupture) stress of prestressing tendon
f_{py}	yield stress of prestressing tendon
f_{se}	effective prestressing tendon stress after long term losses
f_u	ultimate (rupture) stress of mild reinforcing steel
f_y	yield stress of mild reinforcing steel
g	acceleration due to gravity
h_{cr}	location of first cracking height for applied moment of M_e
h_e	effective wall height
k	defines the maximum permissible extreme masonry strain kf'_m at M_e
k_c	concrete masonry specific creep
K_{eff}	effective stiffness of substitute structure
l_p	unbonded tendon length
l_w	wall length
M	base moment
M_{cr}	first cracking moment
M_e	maximum serviceability moment
m_{eff}	effective mass of substitute structure
M_n	nominal wall strength (moment)
$N(T,D)$	near fault factor
N	axial load due to wall self-weight and dead and live load on supported floors
n_p	number of plastic hinges required to develop failure mechanism
P	prestressing force
r	post-yield stiffness ratio
R	seismic event return period

S_a	spectral acceleration
S_d	spectral displacement
t	time
T	structural period
T_c	spectral corner point period
T_{eff}	effective period of substitute structure
V	applied lateral force at h_e
V_b	design base shear
v_{bm}	basic shear strength of masonry
V_{cr}	wall lateral force at h_e corresponding to M_{cr}
V_f	lateral force applied at h_e corresponding to M_n
V_{max}	maximum lateral force measured during testing
v_n	wall shear stress
V_n	wall shear strength (force)
V_y	yield strength corresponding to d_y
Z	seismic hazard factor

Greek characters:

α	defines equivalent rectangular stress block average stress $\alpha f'_m$
α	angle between the vertical and compression strut when calculating shear strength
β	defines equivalent rectangular stress block length $a = \beta c$
Δf_{cr}	long term prestress loss due to creep
Δf_{pl}	total long term prestress loss
Δf_{pr}	long term prestress loss due to prestressing tendon relaxation
Δf_{ps}	tendon stress increase at nominal wall strength
Δf_{sh}	long term prestress loss due to shrinkage
Δ_i	elongation of i^{th} tendon due to wall rocking
ε_{cr}	long term concrete masonry creep strain
ε_m	masonry strain corresponding to masonry crushing stress f'_m
ε_{mi}	elastic masonry strain immediately after prestressing
ε_{mu}	maximum dependable masonry strain
ε_{pi}	initial effective tendon strain corresponding to f_{se}

ε_{ps}	total tendon strain at a given wall displacement
ε_{pu}	strain corresponding to ultimate tendon stress
ε_{py}	prestressing tendon yield strain corresponding to f_{py}
ε_{rock}	tendon strain increase due to wall rocking
ε_{sh}	long term concrete masonry shrinkage strain
ϕ	strength reduction factor
ϕ_{cr}	curvature at wall section due to M_{cr}
γ_e	non-dimensional crack length at M_e
γ_{max}	wall drift corresponding to $d_{v\ max}$
μ	displacement ductility
μ_s	coefficient of static friction
ν	poisson's ratio
θ	wall rotation due to rocking
ξ	wall axial load ratio
ξ_{eq}	equivalent viscous damping
$\xi_{eq,v}$	modified viscous damping component of ξ_{eq}
ξ_n	wall axial load ratio at M_n
ξ_v	viscous damping