Seismic Analysis and Design of Post-tensioned Concrete Masonry Walls

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

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December 2002

ABSTRACT

This thesis explores the seismic analysis and design of post-tensioning concrete masonry (PCM) walls. Using unbonded post-tensioning, walls are vertically prestressed by means of strands or bars which are passed through vertical ducts inside the walls. As the walls are subjected to lateral displacements (in-plane loading), gaps form at the horizontal joints, reducing the system stiffness. As long as the prestressing strands are kept within the elastic limit, or at least maintain a considerable amount of the initial prestressing force, they can provide a restoring force, which will return the walls to their original alignment upon unloading. The key feature in this behaviour is attributable to the tendons being unbonded over the entire wall height, allowing for distribution of tendon strain over the entire length of the tendon.

An extensive literature review found that post-tensioning of masonry has had limited application in seismic areas and that there currently are no specific code requirements for it's use for ductile seismic design, largely as a consequence of little knowledge about the ductility capacity and energy dissipation characteristics. It was concluded that structural testing of PCM walls and concrete masonry creep and shrinkage testing were essential to advance the understanding of this construction type.

Creep and shrinkage experiments confirmed that long term prestress losses are considerable in both grouted and ungrouted concrete masonry, and must be taken into account in design. It was concluded that it is essential to use high strength steel for prestressing of PCM in order to reduce long term losses.

Structural testing confirmed that fully grouted unbonded post-tensioned concrete masonry is a competent material combination for ductile structural wall systems. In particular, PCM walls strengthened in the flexural compression zones with confining plates are expected to successfully withstand severe ground shaking from an earthquake. It was suggested that partially and ungrouted PCM walls may suitably be used in strength design (non-ductile).

The proposed prediction method for wall in-plane behaviour was validated by experimental results. Good correlation between predictions and results was found. Displacement spectra were developed for ductile seismic design of PCM walls. These can be used to accurately estimate the displacement demand imposed on multi-storey PCM cantilever walls.

DISCLAIMER

This thesis was prepared for the Department of Civil and Environmental Engineering at the University of Auckland, New Zealand, and describes analysis and design of post-tensioned concrete masonry walls. 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.

ACKNOWLEDGEMENTS

This research was funded by direct industry sponsors W. Stevenson and Sons Ltd., Firth Industries Ltd., Ready Mix Concrete Ltd., and by the industry organisations New Zealand Concrete Masonry Association (NZCMA) and the Cement and Concrete Association of New Zealand (CCANZ). VSL (Aust.) Pty. Ltd., Construction Techniques Group Ltd., Fletcher Steel Ltd., Alan H. Reid Engineering Ltd. and SIKA (NZ) Ltd. generously provided their products free of charge. Their contributions are gratefully acknowledged.

The author also wishes to acknowledge the contributions by Hank Mooy, Tony Daligan and Mark Byrami who were responsible for the practical aspects in relation to construction and testing of the walls in the Civil Test Hall. Furthermore, the important contributions made by final-year undergraduate students in designing and constructing the Series 1 testing setup, and in testing of two walls reported herein are acknowledged.

Special thanks are given to those who found time to comment on this thesis. This includes Assistant Professor R.C. Fenwick and Dr. B.J. Davidson of the University of Auckland, E. Lapish of Auckland, and particularly my primary supervisor and friend Dr. J.M. Ingham.

Finally, a very special thanks to my wife, Jill, for her lasting love and support, particularly throughout the period of research and preparation for this thesis.

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NOTATION

Roman characters:

a	equivalent rectangular stress block compression zone length
a_g	seismic ground acceleration
A_g	gross area of wall cross section
a_o	flexural compression zone length at M_o
A_p	confining plate area for Priestley-Elder stress-strain curve
A_{ps}	total prestressing steel area in wall cross section
A_{psj}	prestressing tendon area of tendon ‘j’
A_r	wall aspect ratio
A_v	shear (horizontal) reinforcing steel area
a_y	flexural compression zone length at M_y
b_w	wall thickness
c	distance from extreme masonry fibre in compression to flexural neutral axis
C_c	concrete masonry creep coefficient
c_e	distance from extreme masonry fibre in compression to flexural neutral axis at M_e
d	effective wall length for calculation of V_{st}
d	lateral displacement at h_e
D	displacement level
d_{cr}	total lateral displacement at h_e due to V_{cr}
d_{crfl}	lateral flexural displacement at h_e due to V_{cr}
d_{crsh}	lateral shear displacement at h_e due to V_{cr}
d_e	total lateral displacement at h_e due to V_e
d_{efl}	lateral flexural displacement at h_e due to V_e
d_{esh}	lateral shear displacement at h_e due to V_e
d_h*	lateral displacement demand at the equivalent SDOF structure height
d_j	lateral displacement of floor ‘j’
d_n	total lateral displacement at h_e due to V_f
d_{nfl}	lateral flexural displacement at h_e due to V_f
d_{nsh}	lateral shear displacement at h_e due to V_f
d_o	lateral displacement increment at flexural overstrength
d_r	roof lateral displacement demand
d_{tg}	target displacement demand
d_{ty}	lateral displacement increment at first tendon yield
d_y	lateral displacement at first tendon yield

d_u	ultimate wall displacement capacity
d_{vmax}	measured wall displacement at V_{max}
EI	elastic stiffness of wall cross section
E_m	masonry elastic modulus
$\overline{E}_m$	average masonry elastic modulus related to Priestley-Elder stress-strain curve
E_{ps}	prestressing steel elastic modulus
e_t	total tendon force eccentricity with respect to wall centre line
e_{tc}	shortest horizontal distance between any tendon and compression end of wall
e_{te}	horizontal distance between extreme tendon in tension and compression end of wall
e_{tj}	horizontal distance between tendon ‘j’ and compression end of wall
f'_{cb}	concrete masonry unit crushing strength
f'_{cg}	grout cylinder crushing strength, specific to AS 3700
f'_g	grout cylinder crushing strength
f'_j	mortar cylinder crushing strength
f'_m	masonry crushing strength
f'_{uc}	unconfined masonry unit crushing strength, specific to AS 3700
f_m	axial masonry stress
f_{mf}	final prestress at termination of creep and shrinkage experiment
f_{mi}	masonry stress immediately after prestressing
Fn	generic symbol for ‘function of’
Fn^{cr}	time development function for creep
Fn^{sh}	time development function for shrinkage
f_{ps}	instantaneous prestressing steel stress
f_{psi}	prestressing steel stress immediately after anchorage lock-off
f_{pu}	ultimate (rupture) strength of prestressing steel
f_{py}	yield strength of prestressing steel
f_{se}	average tendon stress at V_f for wall in unloaded state
f_{vy}	nominal yield strength of shear reinforcing steel
f_y	nominal yield strength of reinforcing steel
f_{yh}	nominal yield strength of confining steel
h^*	equivalent height of SDOF structure
h''	horizontal confined dimension
h_{cr}	location of first cracking height for applied moment of M_e
h_e	wall equivalent height
h_n^*	equivalent height of modal mass of n^{th} mode
h_p	vertical extent of plastic deformation zone at wall ultimate displacement

h_s	vertical distance between floors n and n-1
h_w	wall height
k	defining the maximum permissible extreme masonry strain kf'_m at M_e
K	prism strength and strain enhancement factor for Priestley-Elder stress-strain curve
K_1	initial stiffness of bilinear elastic SDOF
K_2	post-yield stiffness of bilinear elastic SDOF
k_c	concrete masonry specific creep
K_d	similar to K but related to high strain rate
k_r	prestressing steel relaxation parameter
l_j	length of tendon 'j'
l_w	wall length
M	base moment
M*	applied factored moment
M*	equivalent mass of SDOF structure
M_{cr}	first cracking moment
M_e	maximum serviceability moment
M_{max}	maximum developed base moment from time-history analysis
M_n	nominal strength of wall (moment)
M_n*	modal mass of n^{th} mode
M_o	wall base moment overstrength
M_t	total seismic horizontal mass
M_{ty}	wall base moment increase at first tendon yield
M_y	wall base moment at first tendon yield
M_y	required yield moment strength of nominally elastic SDOF structure
M_y'	provided yield moment strength for SDOF structure
N	axial load due to wall self-weight, and live and dead load from suspended floors
N*	applied factored axial force
N_e	externally applied axial load in Series 3 experiments
N_w	wall self-weight in Series 3 experiments
P	prestress force in wall
P*	applied factored prestress force
P_i	prestressing force immediately after anchorage lock-off
P_j	prestressing force in tendon 'j' (unloaded state)
P_l	prestressing force after all loss has occurred
P_y	total tendon force when stress in all tendons is f_{py}

R	force reduction factor associated with ductile seismic design
r_a	concrete roughness amplitude of construction joint (shear friction calculation)
s	vertical spacing of shear reinforcing steel
S_{ae}	elastic spectral acceleration
S_d	spectral displacement
S_h	vertical confined dimension (confining plate spacing)
T	fundamental structural period
T_1	first mode natural period
t	time
t_0	time of application of prestress to masonry
t_l	time at which all time dependent prestress loss has occurred
t_n	time at time step n
u_e	vertical extension of 'tension' end of wall at V_f
u_j	vertical displacement of top anchorage point of tendon 'j' at V_f
u_s	vertical shortening of 'compression' end of wall at V_f
V	applied lateral force at h_e
V^*	applied factored shear force
V_{base}	base shear due to lateral forces
V_{cr}	wall lateral force at h_e corresponding to M_{cr}
V_e	wall lateral force at h_e corresponding to M_e
V_f	lateral force applied at h_e corresponding to M_n
v_m	masonry shear strength (stress)
V_m	wall shear strength (force) due to masonry
v_{max}	maximum measured wall shear stress
V_{max}	maximum experimental lateral force
V_{max}	estimated maximum base shear at wall overstrength (shear friction calculation)
V_{max}	maximum developed base shear from time-history analysis
v_{nehrp}	shear strength (stress) predicted by NEHRP provisions
v_{nzs}	shear strength (stress) predicted by NZS 4230:1990 provisions
V_o	wall lateral force at h_e corresponding to M_o
v_{pp}	shear strength (stress) predicted by Paulay and Priestley provisions
V_s	wall shear strength (force) due to contribution from V_m and V_{st}
V_{st}	wall shear strength (force) due to horizontal reinforcing steel
V_{ty}	wall lateral force at h_e at first tendon yield
V_y	wall lateral force at h_e corresponding to M_y

V_y	required yield strength of nominally elastic SDOF structure
V_y'	provided yield strength for SDOF structure
y_j	horizontal location of tendon 'j' with respect to wall centre line
Z	seismic zone factor (NZS 4203:1992)
Z_m	slope of descending branch of Priestley-Elder stress-strain curve
Z_{md}	similar to Z_m but related to high strain rate
$\{h\}$	vector indicating location (height) of masses given by $\{m\}$
$\{m\}$	mass vector of MDOF structure

Greek characters:

α	defines equivalent rectangular stress block average stress $\alpha f'_m$
α	strain hardening ratio for bilinear SDOF structure
β	defines equivalent rectangular stress block length $a = \beta c$
$\Delta\varepsilon_{py}$	strain increase in extreme tendon at first tendon yield
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 steel relaxation
Δf_{sh}	long term prestress loss due to shrinkage
ΔP	total tendon force increase at M_n
ΔP_j	tendon force increase of tendon 'j' at V_f
ΔP_{ty}	total tendon force increase a first tendon yield
ΔP_{tyj}	force increase in tendon 'j' at first tendon yield
Δt_n	length of time step n
ε	masonry axial strain
ε_{cr}	long term concrete masonry creep strain
ε_m	masonry strain at maximum prism strength f'_m
ε_{me}	extreme fibre strain in wall section due to M_e
ε_{mi}	elastic masonry strain immediately after prestressing
ε_{mp}	masonry axial strain at initiation of post-peak strength plateau for Priestley-Elder stress-strain curve
ε_{mu}	maximum dependable masonry strain
ε_{pu}	ultimate elongation strain of prestressing steel
ε_{sh}	concrete masonry final shrinkage strain
ϕ	curvature at wall section due to applied moment M
ϕ	wall average curvature in the plastic deformation zone at ultimate displacement capacity

ϕ	strength reduction factor
ϕ_{cr}	curvature at wall section due to M_{cr}
ϕ_e	curvature at wall section due to M_e
ϕ_f	flexural strength reduction factor
γ_e	non dimensional crack length at M_e
γ_{h*}	drift demand at equivalent SDOF structure height
γ_i	interstorey drift demand
$\gamma_{i,max}$	interstorey drift limitation
γ_u	wall ultimate drift capacity
γ_{vmax}	wall drift corresponding to d_{max}
γ_w	roof drift demand
Λ	Loss ratio between prestress loss calculated with additive and incremental methods
μ_d	displacement ductility demand
ν	poisson's ratio
θ	wall rocking rotation
ρ_a	transverse confining ratio for Priestley-Elder stress-strain curve
ρ_s	volumetric confining ratio for Priestley-Elder stress-strain curve
ω_v	seismic dynamic base shear amplification factor
x	ratio of net concrete masonry unit area to total area of masonry unit and void
ξ	wall axial load ratio
ξ	viscous damping ratio
ξ_n	wall axial load ratio at M_n
ξ_u	wall axial load ratio at wall ultimate displacement capacity
$\{\phi_n\}$	mode shape vector for nth mode