



<http://researchspace.auckland.ac.nz>

ResearchSpace@Auckland

Copyright Statement

The digital copy of this thesis is protected by the Copyright Act 1994 (New Zealand).

This thesis may be consulted by you, provided you comply with the provisions of the Act and the following conditions of use:

- Any use you make of these documents or images must be for research or private study purposes only, and you may not make them available to any other person.
- Authors control the copyright of their thesis. You will recognise the author's right to be identified as the author of this thesis, and due acknowledgement will be made to the author where appropriate.
- You will obtain the author's permission before publishing any material from their thesis.

To request permissions please use the Feedback form on our webpage.

<http://researchspace.auckland.ac.nz/feedback>

General copyright and disclaimer

In addition to the above conditions, authors give their consent for the digital copy of their work to be used subject to the conditions specified on the Library Thesis Consent Form.

Seismic Analysis and Design of Post-tensioned Concrete Masonry Walls

By Peter T. Laursen

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

Supervised by Dr. Jason M. Ingham

University of Auckland

Department of Civil and Environmental Engineering

New Zealand

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 its 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.

ADVISORY COMMITTEE

Dr. J.M. Ingham, Senior Lecturer (principal advisor)

Dr. B.J. Davidson, Senior Lecturer

Assistant Professor R. C. Fenwick

Professor B. Melville

Mr. E. Lapish, Consultant Engineer

EXAMINATION COMMITTEE

Assistant Professor C.E. Ventura, Department of Civil Engineering, University of British Columbia, Canada (chair)

Dr. J.M. Ingham, Senior Lecturer, University of Auckland

Dr. H.R. Ganz, VSL (Switzerland) Ltd.

Professor M.J.N. Priestley, University of California, San Diego, USA

LIST OF PUBLICATIONS

Journal articles:

Laursen, P.T. and Ingham, J.M. (2001), *Structural Testing of Single-Storey Post-Tensioned Concrete Masonry Walls*, TMS Journal, Vol. 19, No. 1, The Masonry Society, Boulder, Colorado, Sept. 2001.

Ingham, J.M., Laursen, P.T. and Voon, K.C. (2001), *Appropriate Material Values for Use in Concrete Masonry Design*, Journal of the Structural Engineering Society, Vol. 14, No. 1, Auckland, New Zealand, April 2001.

Laursen, P. and Ingham, J. M. (1999), *Design of prestressed concrete masonry walls*, Journal of the Structural Engineering Society, Vol. 12, No. 2, Auckland, New Zealand, October 1999.

Conference papers:

Laursen, P.T., Davidson, B.J. and Ingham, J.M. (2002), *Seismic analysis of prestressed concrete masonry shear walls*, Proceedings of the 12th European Earthquake Conference, London, England, September 2002, paper reference 247.

Laursen, P.T. and Ingham, J.M. (2001), *Research on multi-storey post-tensioned concrete masonry walls*, Proceedings of the NZCS Combined Concrete Industry Conference, Taupo, New Zealand, October 2001.

Laursen, P.T. and Ingham, J.M. (2001), *Material properties for New Zealand concrete masonry*, Proceedings of the 6th Australasian Masonry Conference, Adelaide, Australia, July 2001.

Laursen, P. and Ingham, J. M. (2001), *Seismic Resistance of Prestressed Concrete Masonry Shear Walls*, Proceedings of the Structural Engineering Institute Congress & Exposition 2001, American Society of Civil Engineers, Washington DC, May 2001.

Laursen, P. and Ingham, J. M. (2000), *In-plane Response of Post-tensioned Concrete Masonry*, Proceedings of 12th International Brick/Block Masonry Conference, p. 905, Madrid, Spain, October 2000. (Alan H. Yorkdale, FASTM Memorial Award winning paper 2000)

Laursen, P., Ingham, J. M. and Voon, K.C. (2000), *Material Testing Supporting a Study of Post-tensioned Concrete Masonry*, Proceedings of 12th International Brick/Block Masonry Conference, p. 937, Madrid, Spain, October 2000.

Laursen, P. and Ingham, J. M. (2000), *Current Research on Post-tensioned Concrete Masonry Walls*, Proceedings of the New Zealand Concrete Society Conference, p. 56, Taupo, New Zealand, October 2000.

Laursen, P. and Ingham, J. M. (1999), *Ductile response of post-tensioned concrete masonry walls*, Proceedings of the IPENZ Technical Conference, Auckland, New Zealand, July 1999.

Laursen, P.T., Seible, F. and Hegemeir, G.A. (1995), *Seismic retrofit and repair of masonry walls with carbon overlays*, Non-Metallic (FRP) Reinforcement for Concrete Structures. Proceedings of the Second international RILEM Symposium (FRPRCS-2), pp. 616-623., Gent, Belgium, July 1995.

Technical reports:

Laursen, P.T. and Ingham J.M. (2000), *Cyclic In-plane Structural Testing of Prestressed Concrete Masonry Walls, Phase 1: Simple Wall Configurations*, School of Engineering Research Report #599, Dept. of Civil and Resource Engn., University of Auckland, New Zealand, September 2000.

Laursen, P.T. and Ingham J.M. (1999), *Material Testing of Dricon Superset Mortar*, Auckland Uniservices Research Report 7796.00, University of Auckland, New Zealand, July 2000.

Laursen, P.T. (1999) *Progress Report and Feasibility Study into Prestressed Concrete Masonry in New Zealand*, Report prepared for the New Zealand Concrete Masonry Association, Auckland, April 1999.

Laursen, P.T., Seible, F. and Hegemeir, G.A. (1995) *Seismic repair and retrofit of masonry walls with carbon overlays*, Structural Systems Research Project, Report No. SSRP-95/01, University of California, San Diego, USA, June 1995.

TABLE OF CONTENTS

ABSTRACT	i
DISCLAIMER	ii
ACKNOWLEDGEMENTS	ii
ADVISORY COMMITTEE	iii
EXAMINATION COMMITTEE	iii
LIST OF PUBLICATIONS	v
TABLE OF CONTENTS	vii
LIST OF FIGURES	xiii
LIST OF TABLES	xvii
NOTATION	xix
INTRODUCTION	
1. PRINCIPLE OF UNBONDED POST-TENSIONED WALLS.....	1
1.1 MOTIVATION FOR PCM RESEARCH	2
1.2 SCOPE AND ORGANISATION OF THESIS.....	3
LITERATURE REVIEW	
2. OVERVIEW	7
2.1 CODIFICATION OF PRESTRESSED MASONRY	8
2.2 CURRENT STATE OF RESEARCH.....	9
2.2.1 Materials	10
2.2.1.1 Concrete masonry.....	10
2.2.1.2 Prestressing steel	10
2.2.2 Structural behaviour.....	10
2.2.2.1 Out-of-plane response	10
2.2.2.2 In-plane response	11
2.2.2.3 Joints	14
2.2.2.4 Prestress loss	14
2.3 CONCLUSIONS.....	14
2.4 REFERENCES.....	16
MATERIAL PROPERTIES	
3. OVERVIEW	19
3.1 STRESS-STRAIN CHARACTERISTICS.....	20
3.2 CRUSHING STRENGTH.....	21
3.2.1 Grade dependent strength	22
3.2.2 Characteristic strength	23
3.2.3 Experimental data	24
3.2.4 Australian approach	27
3.2.5 USA approach.....	28
3.3 ELASTIC MODULUS.....	28
3.3.1 Current New Zealand codification.....	28
3.3.2 Literature and other codes.....	29
3.3.3 Experimental data	29
3.4 MASONRY STRAIN CAPACITY	30

3.4.1	Code rules and recommendations.....	30
3.4.2	PCM testing results	31
3.5	FLEXURAL STRESS DISTRIBUTION	32
3.6	THEORETICAL STRESS-STRAIN RELATIONSHIP.....	33
3.6.1	Unconfined concrete masonry	34
3.6.1.1	Failure mode	34
3.6.1.2	Theoretical stress-strain curve	35
3.6.2	Confined concrete masonry	36
3.6.2.1	Failure mode	37
3.6.2.2	Theoretical stress-strain curve	37
3.6.3	Evaluation of stress-strain relationship	38
3.6.3.1	U200, Unconfined prisms.....	40
3.6.3.2	CP200, Confined prisms.....	41
3.6.3.3	CP100, Confined prisms.....	43
3.6.4	Effect of strain rate	44
3.6.5	Tensile strength.....	45
3.6.6	Unloading properties	45
3.7	PRESTRESSING STEEL.....	45
3.7.1	Types of high strength prestressing steel.....	46
3.7.2	Material properties	46
3.8	CONCLUSIONS	47
3.9	REFERENCES	49

TIME DEPENDENT EFFECTS

4.	ASSESSMENT OF PRESTRESSING LOSSES.....	51
4.1	THEORETICAL CONSIDERATIONS.....	52
4.1.1	Creep and shrinkage of concrete	52
4.1.2	Creep and shrinkage of concrete masonry	55
4.1.3	Mathematical expressions	56
4.1.3.1	Creep strain.....	57
4.1.3.2	Shrinkage strain.....	58
4.1.3.3	Relaxation of prestressing steel	58
4.1.3.4	Total Prestress Loss	59
4.2	CREEP AND SHRINKAGE EXPERIMENT	60
4.2.1	Design of the experiments.....	60
4.2.2	Test setup and instrumentation	62
4.2.3	Series 1 experimental results.....	65
4.2.4	Series 2 experimental results.....	67
4.2.5	Discussion of experiments.....	71
4.3	EXPERIMENTAL VS. CODE VALUES.....	74
4.3.1	Other experimental work.....	74
4.3.2	Code values for creep and shrinkage.....	75
4.3.3	Comparison	76
4.4	RECOMMENDATIONS FOR CREEP AND SHRINKAGE	76
4.4.1	Creep	76
4.4.2	Shrinkage.....	77
4.4.3	Comments.....	77
4.5	TYPICAL PRESTRESS LOSS	77

4.5.1	Typical losses - additive approach	78
4.5.2	Incremental approach.....	80
4.6	REFERENCES.....	85

STRUCTURAL TESTING - SERIES 1

5.	SINGLE-STOREY PCM WALLS	87
5.1	INTRODUCTION.....	87
5.2	CONSTRUCTION DETAILS.....	88
5.2.1	Wall specifications	88
5.2.2	Wall construction	89
5.2.3	Material properties.....	89
5.3	TESTING DETAILS.....	89
5.3.1	Test setup	89
5.3.2	Testing procedure.....	90
5.3.3	Predicted nominal flexural strength.....	90
5.3.4	Predicted masonry shear strength	91
5.4	TEST RESULTS	92
5.4.1	Fully grouted walls	92
5.4.1.1	Force-displacement response	92
5.4.1.2	Damage pattern and failure mode	94
5.4.1.3	Sliding	95
5.4.1.4	Prestressing force	95
5.4.2	Partially and ungrouted walls.....	96
5.4.2.1	Force-displacement response	97
5.4.2.2	Damage pattern and failure mode	97
5.4.2.3	Sliding	98
5.4.2.4	Prestressing force	98
5.4.3	Vertical masonry strain	98
5.5	DISCUSSION	99
5.5.1	Fully grouted walls	99
5.5.1.1	Flexural strength.....	99
5.5.1.2	Ultimate drift capacity.....	100
5.5.1.3	Tendon yielding.....	101
5.5.1.4	Vertical masonry strain.....	102
5.5.1.5	Masonry shear strength	103
5.5.1.6	Sliding propensity	104
5.5.1.7	Axial load ratio.....	104
5.5.2	Partially and ungrouted walls.....	105
5.5.2.1	Masonry shear strength	105
5.5.2.2	Flexural strength.....	106
5.5.2.3	Vertical strain	106
5.5.2.4	Axial load ratio.....	106
5.6	CONCLUSIONS AND FUTURE RESEARCH.....	107
5.6.1	Fully grouted walls	107
5.6.2	Partially and ungrouted walls.....	108
5.7	REFERENCES.....	109

STRUCTURAL TESTING - SERIES 2

6.	ENHANCED SINGLE-STOREY PCM WALLS.....	111
6.1	INTRODUCTION	111
6.2	CONSTRUCTION DETAILS	112
6.2.1	Wall specifications.....	112
6.2.2	Wall construction.....	116
6.2.3	Material properties	116
6.3	TESTING DETAILS	117
6.3.1	Test setup	117
6.3.2	Testing procedure	119
6.3.3	Predicted nominal flexural strength	119
6.3.4	Predicted masonry shear strength.....	120
6.4	TEST RESULTS.....	120
6.4.1	Force-displacement response	121
6.4.2	Damage pattern and failure mode	123
6.4.3	Sliding	125
6.4.4	Prestressing force	126
6.4.5	Vertical masonry strain.....	128
6.5	DISCUSSION.....	135
6.5.1	Flexural response.....	135
6.5.2	Tendon yielding.....	137
6.5.3	Vertical masonry strain.....	137
6.5.4	Hysteretic energy dissipation	138
6.5.5	Sliding propensity.....	139
6.5.6	Initial stiffness	139
6.5.7	Comparison with Series 1 wall tests.....	140
6.6	CONCLUSIONS	142
6.7	REFERENCES	144

STRUCTURAL TESTING - SERIES 3

7.	3-STOREY PCM WALLS.....	145
7.1	INTRODUCTION	145
7.2	CONSTRUCTION DETAILS	146
7.2.1	Wall specifications.....	146
7.2.2	Wall construction.....	149
7.2.3	Material properties	151
7.3	TESTING DETAILS	152
7.3.1	Test setup	152
7.3.2	Instrumentation.....	153
7.3.3	Testing procedure	154
7.3.4	Flexural strength prediction.....	156
7.3.5	Predicted masonry shear strength.....	157
7.4	TEST RESULTS.....	158
7.4.1	Force-displacement response	159
7.4.2	Damage pattern and failure mode	162
7.4.3	Sliding	162
7.4.4	Prestressing force	162

7.4.5	External axial force	167
7.4.6	Vertical masonry strain	167
7.4.7	Lateral wall displacement profile.....	174
7.5	DISCUSSION	174
7.5.1	Flexural response	174
7.5.2	Tendon behaviour.....	178
7.5.3	Vertical masonry strain	178
7.5.4	Hysteretic energy dissipation.....	179
7.5.5	Sliding propensity	181
7.5.6	Initial stiffness.....	181
7.6	COMPARISON WITH RCM WALL TESTING	182
7.6.1	Priestley and Elder walls.....	182
7.6.2	Strategy for comparison of results	183
7.6.3	Comparison of results	186
7.6.4	Conclusions from comparison of PCM with RCM testing.....	188
7.7	CONCLUSIONS.....	188
7.8	REFERENCES.....	190

ANALYSIS AND DESIGN

8.	PREDICTION OF WALL IN-PLANE BEHAVIOUR.....	191
8.1	FLEXURAL RESPONSE OF CANTILEVER WALLS.....	192
8.1.1	Limit states.....	192
8.1.2	First cracking	194
8.1.3	Maximum serviceability moment	195
8.1.4	Nominal flexural strength	198
8.1.5	Yield strength.....	202
8.1.6	Flexural overstrength	204
8.1.7	Ultimate displacement capacity	205
8.1.8	Calculation example.....	209
8.2	DESIGN CONSIDERATIONS.....	211
8.2.1	Required prestressing force and area	211
8.2.2	Un-cracked section analysis.....	213
8.2.3	Cracked section analysis	213
8.2.4	Ultimate limit state.....	214
8.2.4.1	Strength design.....	214
8.2.4.2	Capacity design	214
8.2.4.3	Displacement capacity	215
8.2.5	Base sliding.....	215
8.3	VERIFICATION OF PREDICTION METHOD	218
8.4	REFERENCES.....	219

DYNAMIC ANALYSIS

9.	INTRODUCTION.....	221
9.1	MULTI-DEGREE OF FREEDOM STRUCTURE.....	221
9.1.1	Prototype structures	221
9.1.2	Finite element modelling	223
9.1.3	Push-over analysis.....	224

9.2	EQUIVALENT SINGLE-DEGREE OF FREEDOM STRUCTURE	226
9.2.1	Transformation	226
9.2.2	Definition of SDOF structure	227
9.3	DYNAMIC ANALYSIS	229
9.3.1	Earthquake records	231
9.3.2	Time-History response: MDOF vs. SDOF	233
9.3.2.1	Displacement response	235
9.3.2.2	Drift demand.....	237
9.3.2.3	Base moment response	238
9.3.2.4	Base shear response	238
9.4	SPECTRAL ANALYSIS.....	240
9.4.1	Elastic response	241
9.4.2	Ductile response	241
9.4.3	Spectral displacement.....	241
9.4.4	Displacement ductility demand.....	245
9.5	USE OF DISPLACEMENT SPECTRA.....	246
9.6	NOTES	247
9.7	CONCLUSIONS	247
9.8	REFERENCES	248

SUMMARY OF CONCLUSIONS

10.	CONCLUSIONS AND FUTURE RESEARCH	249
10.1	MATERIAL PROPERTIES - CHAPTER 3.....	250
10.2	TIME DEPENDENT EFFECTS - CHAPTER 4	250
10.3	STRUCTURAL TESTING - CHAPTERS 5, 6, AND 7	251
10.4	ANALYSIS AND DESIGN - CHAPTER 8.....	253
10.5	DYNAMIC ANALYSIS - CHAPTER 9:.....	253
10.6	FUTURE RESEARCH.....	254

APPENDIX A

A.	DEFORMATION AT NOMINAL FLEXURAL STRENGTH.....	257
----	---	-----

APPENDIX B

B.	FORCE-DISPLACEMENT PREDICTION - CALCULATION EXAMPLE.....	265
----	--	-----

APPENDIX C

C.	COMPARISON OF PREDICTED VS. EXPERIMENTAL BEHAVIOUR ..	269
C.1	FLEXURE/ROCKING PREDICTION METHOD	269
C.1.1	Assumptions	269
C.1.2	Comparison	269
C.1.2.1	Series 1 walls	270
C.1.2.2	Series 2 walls	276
C.1.2.3	Series 3 walls	276
C.1.3	Conclusion.....	280

LIST OF FIGURES

Fig. 1.1—Post-tensioned concrete masonry wall2

Fig. 2.1—Schematic of PRESSS wall test [2-17]13

Fig. 3.1—Typical stress-strain relationship for grouted concrete masonry.....20

Fig. 3.2—Typical PCM cantilever wall force-displacement characteristics.....21

Fig. 3.3—Statistical compressive strength distribution, 20 series concrete masonry.....24

Fig. 3.4—Prism and confining plate dimensions and specification26

Fig. 3.5—Flexural stress block.....32

Fig. 3.6—Priestley-Elder compression stress-strain curves [3-2]34

Fig. 3.7—Theoretical stress-strain relationships, definition of symbols.....36

Fig. 3.8—Typical failure modes for prisms.....39

Fig. 3.9—U200, Unconfined masonry stress-strain curve40

Fig. 3.10—Variation of masonry strain ϵ_{mp} with masonry strength42

Fig. 3.11—CP200, Confined masonry stress-strain curve42

Fig. 3.12—CP100, Confined masonry stress-strain curve44

Fig. 3.13—Prestressing steel stress-strain relationship47

Fig. 4.1—Change of strain in axially loaded and drying concrete masonry53

Fig. 4.2—Walette dimensions and test setup.....61

Fig. 4.3—Walette test setup and instrumentation.....64

Fig. 4.4—Series 1, creep + shrinkage strain.....65

Fig. 4.5—Series 1, creep strain66

Fig. 4.6—Series 1, ambient air temperature variation.....67

Fig. 4.7—Series 2, creep + shrinkage strain.....69

Fig. 4.8—Series 2, creep strain70

Fig. 4.9—Series 2, ambient air temperature and humidity variations71

Fig. 4.10—Experimental Creep coefficient C_c 73

Fig. 4.11—Experimental Specific Creep k_c 74

Fig. 4.12—Expected prestress loss in fully grouted concrete masonry79

Fig. 4.13—Expected prestress loss in ungrouted concrete masonry79

Fig. 4.14—Time variation $F_n(t)$ for creep, shrinkage and relaxation.....81

Fig. 4.15—Comparison of prestress loss, incremental vs. additive approaches.....83

Fig. 5.1—Test setup and instrumentation90

Fig. 5.2—Fully grouted walls; Force-displacement histories.....93

Fig. 5.3—Fully grouted walls; Extent of wall damage at failure94

Fig. 5.4—Fully grouted walls; Tendon force histories (all tendons).....96

Fig. 5.5—Partially and ungrouted walls; Force-displacement histories.....97

Fig. 5.6—Partially and ungrouted walls; Extent of damage at failure98

Fig. 5.7—Fully grouted walls; F-D envelopes99

Fig. 5.8—Fully grouted walls; F-D envelopes, normalised with V_f 100

Fig. 5.9—PG and UG Walls, F-D envelopes, normalised with V_f 106

Fig. 6.1—Wall geometry for CP walls (number 1 - 4)113

Fig. 6.2—Wall geometry for HB wall (number 5)114

Fig. 6.3—Wall CP-CA-ED energy dissipation bars115

Fig. 6.4—Typical instrumentation	118
Fig. 6.5—Force-displacement histories	122
Fig. 6.6—Damage accumulation at failure	124
Fig. 6.7—Relative sliding between wall and base	125
Fig. 6.8—Prestressing force histories	127
Fig. 6.9—FG:L3.0-W15-P1-CP, Horizontal strain profiles, pull direction only.....	129
Fig. 6.10—FG:L3.0-W15-P2-CP, Horizontal strain profiles	130
Fig. 6.11—FG:L3.0-W15-P2-CP-CA, Horizontal strain profiles.....	131
Fig. 6.12—FG:L3.0-W15-P2-CP-CA-ED, Horizontal strain profiles	132
Fig. 6.13—FG:L3.0-W15-P2-HB, Horizontal strain profiles.....	133
Fig. 6.14—F-D envelopes, P2-CP, P2-CP-CA and P2-HB	135
Fig. 6.15—F-D envelopes, P2-CP-CA and P2-CP-CA-ED	136
Fig. 6.16—Cumulated hysteretic energy dissipation	138
Fig. 6.17—Initial wall stiffness.....	140
Fig. 6.18—F-D envelopes, P2-CP, P2-HB, P2C and P2E.....	141
Fig. 7.1—Wall geometry for Series 3 walls.....	147
Fig. 7.2—Dimensions and location of confining plates.....	148
Fig. 7.3—(a) Prestressing ducting and shear reinforcing and (b) confining plate	150
Fig. 7.4—Reinforcing layout for RC elements.....	151
Fig. 7.5—Testing setup	153
Fig. 7.6—External axial load system.....	154
Fig. 7.7—Photograph of S3-1 in the testing setup ready to be tested.....	155
Fig. 7.8—Instrumentation, (a) in-plane lateral displacement and (b) load cells.....	156
Fig. 7.8—Instrumentation (Cont.), (c) vertical deformation and (d) sliding displ.	157
Fig. 7.9—Force-displacement histories	160
Fig. 7.10—Cyclic loading histories	161
Fig. 7.11—(a) and (b), S3-1 Damage accumulation at failure.....	163
Fig. 7.11—(c) and (d), S3-2 Damage accumulation at failure.....	164
Fig. 7.12—Sliding displacement.....	165
Fig. 7.13—Prestressing force histories	166
Fig. 7.14—External axial load histories	168
Fig. 7.15—S3-1, Horizontal strain profiles, levels 0-200 mm and 200-400 mm.....	169
Fig. 7.15—(Cont.) S3-1, Horiz. strain profiles, levels 400-600 mm and 600-800 mm..	170
Fig. 7.16—S3-2, Horizontal strain profiles, levels 0-200 mm and 200-400 mm.....	171
Fig. 7.16—(Cont.) S3-2, Horiz. strain profiles, levels 400-600 mm and 600-800 mm..	172
Fig. 7.17—S3-1, Lateral displacement profile.....	175
Fig. 7.18—S3-2, Lateral displacement profile.....	176
Fig. 7.19—Force-displacement envelopes	177
Fig. 7.20—Cumulated hysteretic energy dissipation	180
Fig. 7.21—Initial wall stiffness.....	181
Fig. 7.22—Priestley/Elder wall specification, from [7-5].....	183
Fig. 7.23—PE1 experimental result and PCM-1 prediction envelope.....	185
Fig. 7.24—PE2 experimental result and PCM-1 prediction envelope.....	185
Fig. 7.25—PE3 experimental result and PCM-2 prediction envelope.....	186

Fig. 8.1—Definition of cantilever wall dimensions, forces and deformations.....	194
Fig. 8.2—First cracking.....	195
Fig. 8.3—Maximum serviceability moment	196
Fig. 8.4—Curvature distribution at maximum serviceability moment.....	197
Fig. 8.5—Wall equilibrium at nominal flexural strength	199
Fig. 8.6—Wall deformation at nominal flexural strength.....	200
Fig. 8.7—Wall rocking response	203
Fig. 8.8—Vertical strain evaluation at ultimate displacement capacity.....	206
Fig. 8.9—Post-tensioned concrete masonry cantilever wall	210
Fig. 8.10—Predicted in-plane wall response.....	211
Fig. 8.11—Cracked section analysis	213
Fig. 9.1—5-Storey PCM wall prototype and modelling	222
Fig. 9.2—Masonry constitutive relationships.....	224
Fig. 9.3—Cyclic push-over response.....	225
Fig. 9.4—Force-displacement relationships.....	225
Fig. 9.5—5-storey wall, Analytical prediction model based on Chapter 8	229
Fig. 9.6—Bi-linear elastic model	229
Fig. 9.7—Uniform Earthquake Hazard Spectra	230
Fig. 9.8—Normalised earthquake records N1:N4.....	232
Fig. 9.9—Spectral response of N1:N4, 3% and 5% damping.....	233
Fig. 9.10—5-storey, Displacement response MDOF vs. SDOF, N1:N4	234
Fig. 9.11—8-Storey, Displacement response MDOF vs. SDOF, N1:N4.....	236
Fig. 9.12—5-storey wall, storey shear.....	239
Fig. 9.13—8-storey wall, storey shear.....	239
Fig. 9.14—Displacement spectra, $\alpha = 0.01$	242
Fig. 9.15—Displacement spectra, $\alpha = 0.02$	243
Fig. 9.16—Design displacement Spectra, $\alpha = 0.01$	244
Fig. 9.17—Displacement ductility demand μ_d	245
Fig. A.1—Definition of cantilever wall dimensions, forces and deformations.....	257
Fig. A.2—Flexure / rocking cracking patterns	258
Fig. A.3—Wall deformation at nominal flexural strength.....	259
Fig. A.4—Moment-curvature relationships.....	260
Fig. A.5—Wall deformation at M_n for unconfined concrete masonry	262
Fig. A.6—Wall deformation at M_n for confined concrete masonry	263
Fig. C.1—Series 1 FG-L3.0-W20-P3: Prediction vs. experimental behaviour	271
Fig. C.2—Series 1 FG-L3.0-W15-P3: Prediction vs. experimental behaviour	272
Fig. C.3—Series 1 FG-L3.0-W15-P2C: Prediction vs. experimental behaviour	273
Fig. C.4—Series 1 FG-L3.0-W15-P2E: Prediction vs. experimental behaviour.....	274
Fig. C.5—Series 1 FG-L1.8-W15-P2: Prediction vs. experimental behaviour	275
Fig. C.6—Series 2 FG-L3.0-W15-P2-CP: Prediction vs. experimental behaviour.....	277
Fig. C.7—Series 2 FG-L3.0-W15-P2-CP-CA: Prediction vs. experimental behav.....	278
Fig. C.8—Series 2 FG-L3.0-W15-P2-HB: Prediction vs. experimental behaviour	279
Fig. C.9—Series 3 S3-1: Prediction vs. experimental behaviour	281
Fig. C.10—Series 3 S3-2: Prediction vs. experimental behaviour	282

LIST OF TABLES

TABLE 3.1—NZS 4230:1990 Masonry grades	22
TABLE 3.2—Measured crushing strength	25
TABLE 3.3—Confined prism testing	26
TABLE 3.4—Ultimate compression strain.....	31
TABLE 3.5—Vertical masonry strain, test results.....	31
TABLE 3.6—Material properties of prestressing steel	47
TABLE 4.1—Relaxation of prestressing steel (20°C).....	58
TABLE 4.2—Specifications for series 1	62
TABLE 4.3—Specifications for series 2	63
TABLE 4.4—Creep and shrinkage testing, schedule of events.....	63
TABLE 4.5—Series 1, summary of results	68
TABLE 4.6—Series 2, summary of results	70
TABLE 4.7—Experimental maximum values of C_c , k_c , ϵ_{sh}	74
TABLE 4.8—Experimental values of k_c , normal weight concrete masonry	75
TABLE 4.9—Experimental values of k_c , light weight concrete masonry	75
TABLE 4.10—Code defined creep and shrinkage coefficients	75
TABLE 4.11—Recommended values of C_c , k_c , ϵ_{sh}	77
TABLE 5.1—Wall specifications	88
TABLE 5.2—Predictions and results	91
TABLE 5.3—Measured masonry vertical strain	99
TABLE 5.4—Masonry shear strength	103
TABLE 6.1—Wall specifications	112
TABLE 6.2—Material properties	116
TABLE 6.3—Predictions and results	120
TABLE 6.4—Measured masonry vertical strain	134
TABLE 7.1—Wall specifications	146
TABLE 7.2—Material properties	152
TABLE 7.3—Strength predictions	158
TABLE 7.4—Predictions and results	158
TABLE 7.5—Vertical strain	173
TABLE 7.6—Theoretical and experimental results for PE and S3 walls.....	184
TABLE 7.7—Theoretical performance of PCM walls for comparison.....	184
TABLE 8.1—Basic plastic deformation zone parameters.....	207
TABLE 8.2—Predicted force and displacement	210
TABLE 9.1—Equivalent SDOF properties, m at each floor and roof.....	228
TABLE 9.2—Equivalent SDOF properties, m at each floor, m/2 at roof.....	228
TABLE 9.3—Analysis results for 5-storey wall models, maximum values.....	235
TABLE 9.4—Analysis results for 8-storey wall models, maximum values.....	235

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_{cfl}	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
\bar{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
F_n	generic symbol for 'function of'
F_n^{cr}	time development function for creep
F_n^{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 $a = \beta c$
$\Delta \epsilon_{py}$	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 at 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
$\gamma_{v,max}$	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 n^{th} mode