NHRP

Natural Hazards Research Platform

Contest 2012

Title: Reinforced concrete walls

Leader: Dr Richard Henry
Organisation: University of Auckland
Total funding (GST ex): $230,000

Natural Hazards Research Platform

Contest 2012 – Final Report
2012-UOA-03-NHRP

Title: Improving the seismic performance of reinforced concrete walls

Programme Leader: Dr Richard Henry

Affiliation: University of Auckland

Key message for media: Why are these findings important?

Reinforced concrete (RC) walls are one of the most common lateral load resisting systems in buildings and despite several instances of poor behaviour of RC walls during the Canterbury Earthquakes they remain a popular rebuild option. The lack of distributed cracking in RC walls was a major concern following the earthquakes with the Canterbury Earthquakes Royal Commission recommended that research was required to address this issue. Large-scale tests and detailed numerical models were used to verify appropriate minimum vertical reinforcement limits in RC walls to ensure that distributed cracking occurred, and these recommendations have led to recent amendments to the New Zealand Concrete Structures Standard (NZS 3101).

Abstract:

In light of the poor performance of some modern reinforced concrete (RC) wall buildings during the 2010/2011 Canterbury earthquakes, research was undertaken to clarify the observed performance of these buildings and to address recommendations from the Canterbury Earthquakes Royal Commission (CERC). A combination of physical testing and numerical modelling was used to investigate several priority topics, including lightly reinforced walls, precast wall connections, coupled wall systems, wall axial elongation, and wall-to-floor interaction. As a result of the research findings, proposed amendments to the New Zealand Concrete Structures Standard (NZS 3101) have been adopted related to minimum vertical reinforcement, anti-buckling ties, coupling beam overstrength, and wall axial loads. Furthermore, the outcomes of this research have resulted in improved design requirements for RC walls, a better understanding of interactions between wall and floor elements and the loads generated on RC walls during earthquakes, and the development of innovative solutions to reduced he damage to concrete buildings during major earthquakes.

Keywords: Seismic design, concrete structures standard, reinforced concrete wall, minimum reinforcement, precast concrete wall, coupled walls, building interaction.

Introduction / Background

The performance of reinforced concrete (RC) wall buildings during the Canterbury earthquakes raised a number of concerns with respect to current design practice. Despite some examples of well designed RC walls with good performance, a significant number of modern RC walls were severely damaged and exhibited unexpected failure modes. The poor performance of these modern RC walls led to several recommendations from the Canterbury Earthquakes Royal Commission (CERC), including research to refine crack control provisions in design standards (recommendation #42), the development of greater awareness to interactions between structural elements due to elongation (recommendation #47), and axial load limits in RC walls (recommendation #44). Additional interim design guidance by the Structural Engineering Society (SESOC) following the Canterbury earthquakes further highlighted the need for research to improve the design of RC walls.

This project was funded from the NHRP 2012 contestable round "Lessons learned from Christchurch" portfolio to address these recommendations from CERC and SESOC. The overall goal was to understand the performance of RC walls during the Canterbury Earthquakes, and to use a combination of experimental testing and numerical modelling to develop improved design procedures that could be implemented into the NZ Concrete Structures Standard (NZS 3101). The project focused on several main topics: lightly reinforced walls, precast wall connections, coupled wall systems, wall axial elongation, and wall-to-floor interaction. The outcomes of the research that addressed the NRHP project objectives are presented. However, it should be noted that research into the seismic behaviour of RC walls is on-going and has extended many of the original objectives and focus areas.

Objectives or Research Aims

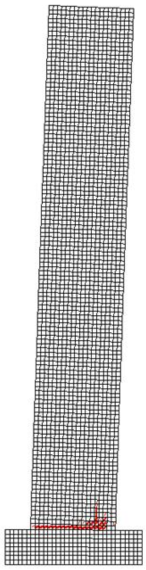
Objective No. 1
Objective Title: Evaluation of the performance of RC walls during the Canterbury Earthquakes
Budget: $90,197.50
Objective Achieved? Yes

The reports of numerous reconnaissance activities following the Canterbury Earthquakes were used to develop a database of RC wall buildings in Christchurch that included 50 damaged multi-storey buildings. Six modern buildings that had been well documented with publically accessible detailed engineering reports were used as case-study buildings to evaluate the performance of modern RC walls during the Canterbury earthquakes. These case-study buildings, along with findings from the Canterbury Earthquakes Royal Commission (CERC), Structural Engineering Society (SESOC), and MBIE Engineering Advisory Group (EAG), were used to determine the priority research areas that this project focused on. A summary of the performance of RC walls during the Canterbury Earthquakes and analysis of key design issues was published in collaboration with international experts (Sritharan et al. 2014 – Earthquake Spectra).

The distribution of cracking in lightly reinforced walls was identified as one of the key priority areas by both CERC, SESOC, and EAG. The Gallery Apartments building was used as a case-study due to the extremely poor performance during the 22 Feb 2011 Christchurch

earthquake. Moment-curvature analysis was conducted to assess the likely cracking, yield, and ultimate strength of the critical grid-F wall in the Gallery Apt. building (Henry 2013 – NZSEE Bulletin). The moment-curvature analysis highlighted the possible non-ductile sectional response of the grid-F wall as a result of the low vertical reinforcement content and high concrete strength. Additional detailed finite element analysis was conducted to investigate the expected lateral load behaviour of the grid-F wall. As shown in Figure 1, the finite element results confirmed that only a single flexural crack was expected to form at the wall base, and that the concentration of inelastic strain at the crack lead to premature fracture in the vertical reinforcement (Sritharan et al. 2014 – Earthquake Spectra).

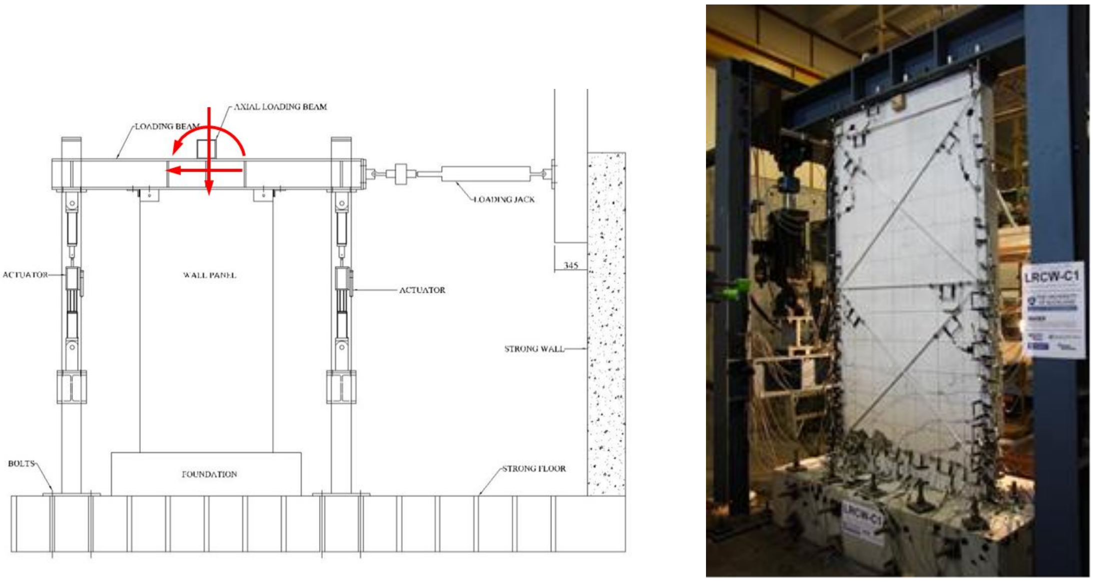
(a) Gallery Apt. building



(b) Finite element model of grid-F wall

Figure 1 – Assessment of RC walls in the Gallery Apt. building

A series of large-scale laboratory tests were conducted on lightly reinforced concrete walls. The Gallery Apt. building was not compliant with current concrete design standards, and the poor behaviour was confirmed by the numerical analysis. For these reasons, it was advised that the test walls should focus on RC walls compliant with current design standards, so that the minimum vertical reinforcement limits in NZS 3101:2006 could be investigated. A series of 6 walls were tested to investigate design variables set out by a group of industry representatives (Lu et al. – Journal of structural Engineering). A test setup was used that involved testing the lower portion of a prototype multi-storey wall and using three actuators to apply complex boundary conditions at the top of the test wall, as shown in Figure 2. The test results highlighted that RC walls designed to current minimum reinforcement limits did not exhibited a sudden non-ductile failure, but lacked the crack distribution and drift capacity required in a multi-storey building designed for a ductile response. Additional modelling of the test walls discovered that the performance of these lightly reinforced walls deteriorated as the size of the wall increased, concrete strength increased, and reinforcement ductility and strain hardening was reduced (Lu and Henry – Engineering Structures).



(a) Test setup (b) Wall at end of test

Figure 2 – Testing lightly reinforced RC walls

An investigation as also conducted into the detailing and seismic behaviour of precast wall panel connections. An extensive database of precast panel connections was collected that lead to two streams of experimental tests. The first involved in-plane tests of panels with grouted connections (Seifi et al. 2015 – NZSEE conference), and the second involved out-of-plane tests of panels with shallow embedded inserts (Burley et al. 2014 – NZCIC conference). The results of these tests have confirmed some of the suspected vulnerabilities of current precast panel connections and research is ongoing to understand and improve the design of precast panel buildings.

List of key outputs

- Sritharan, S., Beyer, K., Henry, R. S., Chai, Y. H. Kowalsky, M., Bull, D. (2014). ‘Understanding poor seismic performance of concrete walls and design implications’, *Earthquake Spectra*, 30(1), 307-334.
- Henry, R. S. (2013). ‘Assessment of minimum vertical reinforcement limits for RC walls’. *Bulletin of the New Zealand Society for Earthquake Engineering*, 46(2), 88-96.
- Lu, Y., Henry, R. S., Gultom, R., Ma, Q. T. ‘Cyclic testing of reinforced concrete walls with distributed minimum vertical reinforcement’, *Journal of structural engineering*, (submitted Mar 2015).
- Lu, Y., Henry, R. S., ‘Numerical modelling of reinforced concrete walls with minimum vertical reinforcement’, *Engineering Structures*, (to be submitted July 2015).
- Burley, J., Faitotoa, T., Seifi, P., Henry, R. S., & Ingham, J. M. (2014) ‘Out-of-plane behaviour of connections between precast concrete panels and their foundations’. *Proceedings of the New Zealand Concrete Industry Conference 2014*, (265-271). Wairakei, New Zealand.
- Seifi. P., Henry, R. S., Ingham, J. M. (2015) ‘Preliminary test results of precast concrete panels with grouted connections’, *Proceedings of the 2015 NZSEE Annual Conference*, Rotorua, April 10-12.
- Several workshops and invited presentations by Dr. Henry.

List of end-users

- Structural engineering consultants

- Concrete Structures Standard committee (NZS 3101)
- Cement and Concrete Association of New Zealand (CCANZ)
- New Zealand Concrete Society (NZCS)
- Structural Engineering Society of New Zealand (SESOC)
- New Zealand Society for Earthquake Engineering (NZSEE)

Objective No. 2

Objective Title: Quantify the design loads on RC walls

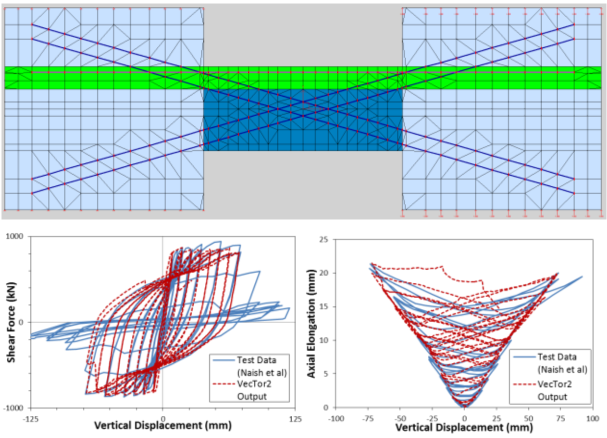
Budget: $49,605.00

Objective Achieved? Yes

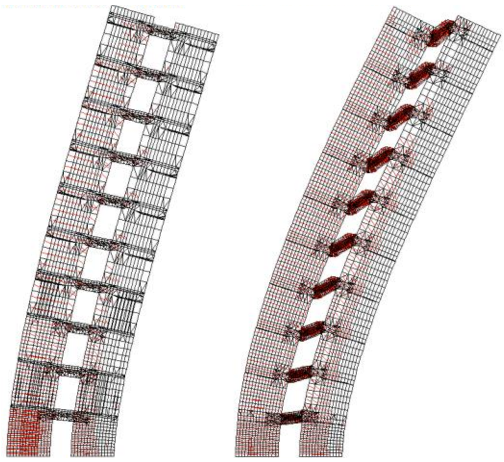
An initial literature review of current design standards and research revealed that seismic design loads on RC walls could be incorrectly estimated when the wall was analysed in isolation. Interactions between the wall and surrounding structure could alter the loads imparted to the wall during an earthquake and violate the capacity design strength hierarchy. Evidence of these interactions was raised as a contributing factor in the poor performance of several RC walls during the Canterbury Earthquakes, and was highlighted in CERC reports. Three mechanisms were identified for further investigation, including wall axial elongation, axial restraint to coupling beams by floor diaphragms, and out-of-plane bending of floor diaphragms creating an outrigger effect between wall and frame elements.

Despite being well understood in RC beams, axial elongation of RC walls had previously received little attention. As flexure dominant RC walls elongate, restraint provide by the floor diaphragms increases the axial loads in the wall. Results from recent tests were used to investigate the magnitude of axial elongation in RC walls and the effect of axial load in restraining this elongation (Encina et al. – NZSEE Bulletin). Additionally, both fibre-based and shell element numerical models were developed for RC walls and their accuracy in capturing the axial elongation was verified by comparing against available test data (Encina et al. – NZSEE Bulletin). Preliminary results of this research were used to advise the NZS 3101 committee on axial load limits for RC walls, and commentary was added to NZS 3101 to highlight the potential increase in axial loads that may occur due to wall elongation.

A series of numerical models were used to investigate the axial restraint of coupling beams (Malcolm 2015 – ME thesis). A finite element model developed for the coupling beams was verified against existing test data and able to capture the axial elongation with good accuracy, as shown in Figure 3a. A series of models were then developed to capture the axial restraint forces generated by the adjacent floor diaphragm, with consideration to the type and configuration of the floor system. When the floor restraint was incorporated into models of coupled wall systems, the strength hierarchy changed with inelastic deformations no longer concentrated in the coupling beams, as shown in Figure 3a, and increased shear and axial demands were observed on the wall piers. Parametric analyses were used to investigate the accuracy of overstrength calculations for coupling beams proposed in the NZS 3101 amendments, as well as to develop additional recommendations to improve the design procedures of such systems.



(a) Coupling beam model



(b) Coupled wall with and without floor restraint

Figure 3 – Modelling of coupled wall systems

The effect of wall-to-floor interaction on the overall building response during an earthquake was further examined. A series of building typologies was developed from existing RC wall buildings in New Zealand to characterise the potential wall-to-floor interaction mechanisms. These typologies were then examined using a series of case-study buildings in Christchurch. The IRD building was modelled to understand the effect of an RC core wall with coupling beams interacting with a perimeter RC frame (Ahn 2015 – ME thesis). It was discovered that the lateral load behaviour of the building was significantly altered when the out-of-plane stiffness of the floor diaphragm was included in the model. The coupling beams did not yield as intended, resulting in an increased the lateral strength of the RC core wall. Additionally, the outrigger framing action between the core and the perimeter frame further increased the building lateral strength and wall shear demand.

This initial research into the effect of wall-to-floor interaction on RC wall design loads has highlighted a number of issues that are not currently considered during the design of RC buildings. As a result, a working group is being established with funding from MBIE to further guide this ongoing research and assist in converting the research findings to design guidance and standards.

List of key outputs

- Encina, E., Lu, Y., Henry, R. S. 'Axial elongation in RC walls', *Bulletin of the New Zealand Society for Earthquake Engineering,* (to be submitted July 2015).
- Advice to NZS 3101 committee regarding potential increase in axial loads due to wall elongation.
- Malcolm, R. C. (2015) Seismic performance of reinforced concrete coupled walls, ME thesis, Dept. Civil and Environmental Engineering, University of Auckland.
- Verification of proposed NZS 3101 amendments to estimate axial restraint of coupling beams by floor diaphragms.
- Ahn, A. (2015) Effect of out-of-plane floor stiffness on the seismic performance of a reinforced concrete core wall building, ME thesis, Dept. Civil and Environmental Engineering, University of Auckland.
- MBIE funded working group to be established to interpret and guide the research into wall-to-floor interaction.

List of end-users

- Structural engineering consultants
- Concrete Structures Standard committee (NZS 3101)
- Cement and Concrete Association of New Zealand (CCANZ)
- New Zealand Concrete Society (NZCS)
- Structural Engineering Society of New Zealand (SESOC)
- New Zealand Society for Earthquake Engineering (NZSEE)

Objective No. 3

Objective Title: Development of improved design procedures for RC walls

Budget: $90,197.50

Objective Achieved? Yes

Analysis of the experimental tests (Lu et al. – Journal of structural Engineering) and numerical models (Lu and Henry – Engineering Structures) resulted in the development of improved design procedures for lightly reinforced concrete walls. The current minimum vertical reinforcement limits in NZS 3101:2006 were deemed suitable for walls designed for a nominally ductile response, but not a limited ductile or ductile response. Numerical models were used to confirm that adding additional vertical reinforcement to the ends of RC walls was a cost effective way to improve the crack distribution and wall ductility. Additionally, the tests showed that lightly reinforced concrete walls are highly susceptible to vertical bar buckling, and that current exclusions for restraining ties for this type of wall in NZS 3101:2006 were inappropriate. There two findings were presented to the NZS 3101 committee and subsequently adopted into the proposed amendments (A3). A discussion article was also published to highlight some of the challenges and appropriate procedures to analyse existing lightly reinforced concrete walls (Wibowo et al. 2014 – Magazine of Concrete Research).

A series of tests were conducted on RC prisms to investigate the influence on reinforcement deformation patterns on the crack development and ductility (Patel et al. – Construction and Building Materials). The use of a bar with lower bond strength, achieved by reducing the size of the rib deformations, resulted in increased debonding and yield penetration at cracks. However, in lightly reinforced concrete prisms the standard bar allowed the tensile stresses to be transferred back into the concrete section, resulting in the initiation of secondary cracks. While the reduced bond bars may offer a solution where debonding is advantageous, it was concluded that for RC walls it was better to encourage the development of well distributed secondary cracks through the use of conventional reinforcement and appropriate vertical reinforcement contents.

Low-damage wall systems that offer an alternative to traditional RC wall and precast wall construction were further developed in collaboration with US researchers. Seismic resilient post-tensioned rocking wall systems were tested with both cyclic and dynamic loading, including shake-table tests (Twigden et al. – Engineering Structures). These tests have been used to refine the design procedures for such wall systems. A further series of tests was conducted to address the wall-to-floor interaction in post-tensioned rocking wall systems. As with RC walls, wall-to-floor interaction can result in undesirable behaviour of low-damage precast concrete buildings, and so an innovative connector was tested that isolated the floor from the vertical uplift of the wall by using a slotted mechanism (Watkins et al. – PCI Journal).

List of key outputs

- Recommendations related to minimum vertical reinforcement adopted by NZS 3101:2006 (A3) committee.
- Recommendations related to bar buckling triggers adopted by NZS 3101:2006 (A3) committee.
- Lu, Y., Henry, R. S., Gultom, R., Ma, Q. T. 'Cyclic testing of reinforced concrete walls with distributed minimum vertical reinforcement', *Journal of structural engineering*, (submitted Mar 2015).
- Lu, Y., Henry, R. S., 'Numerical modelling of reinforced concrete walls with minimum vertical reinforcement', *Engineering Structures*, (to be submitted July 2015).
- Wibowo, A., Wilson, J. L., Lam, N. T. K., Gad, E. F., Lu, Y., Henry, R. S. (2014). 'Discussion: Seismic performance of lightly reinforced structural walls for design purposes'. *Magazine of Concrete Research*, 66 (20), 1073-1074.
- Patel, V. J., Van, B. C., Henry, R. S., Clifton, G. C. 'Effect of reinforcing steel bond on the cracking behaviour of lightly reinforced concrete members', *Construction and Building Materials*, (submitted Mar 2015).
- Twigden, K. M., Henry, R. S., Sritharan, S. 'Cyclic testing of unbonded post-tensioned concrete wall systems with and without supplemental damping', *Engineering Structures*, (submitted Sept 2014).
- Watkins, J., Sritharan, S., Henry, R. S. 'Experimental investigation of a wall-to-floor connector for seismic Application', *PCI Journal*, (to be submitted July 2015).

List of end-users

- Structural engineering consultants
- Concrete Structures Standard committee (NZS 3101)
- Cement and Concrete Association of New Zealand (CCANZ)
- New Zealand Concrete Society (NZCS)
- Structural Engineering Society of New Zealand (SESOC)
- New Zealand Society for Earthquake Engineering (NZSEE)

Conclusions & Recommendations:

The following significant conclusions and recommendations were made as a result of this research project:

- The poor performance of the RC walls in the Gallery Apt. building during the 22 Feb 2011 Christchurch earthquake was attributed to a combination of low vertical reinforcement contents and high concrete strengths.
- The seismic behaviour of lightly reinforced concrete walls designed to current design standards would be significantly better than the behaviour observed in the Gallery Apt. building.
- It is recommended that the current minimum vertical reinforcement requirements for RC walls in NZS 3101 are suitable for walls designed for a nominally ductile response, but that additional reinforcement is required at the wall ends to achieve a limited ductile or ductile wall response.
- Wall axial elongation can result in significant increases in axial load and a limit on allowable design axial loads should be included in NZS 3101.

- The axial restraint of coupling beams must be considered when assessing the overstrength actions to ensure the desired inelastic mechanism forms in coupled walls.
- Low-damage post-tensioned rocking walls can be used to improve the seismic behaviour of concrete wall buildings and can be detailed to accommodate displacement incompatibilities at the wall-to-floor connection.

Acknowledgements:

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References (all published outputs):

Published journal articles:

Wibowo, A., Wilson, J. L., Lam, N. T. K., Gad, E. F., Lu, Y., Henry, R. S. (2014). 'Discussion: Seismic performance of lightly reinforced structural walls for design purposes'. *Magazine of Concrete Research*, 66 (20), 1073-1074.

Sritharan, S., Beyer, K., Henry, R. S., Chai, Y. H. Kowalsky, M., Bull, D. (2014). 'Understanding poor seismic performance of concrete walls and design implications', *Earthquake Spectra*, 30(1), 307-334.

Henry, R. S. (2013). 'Assessment of minimum vertical reinforcement limits for RC walls'. *Bulletin of the New Zealand Society for Earthquake Engineering*, 46(2), 88-96.

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Twigden, K. M., Henry, R. S. 'Experimental response and bilinear approximation of steel plate O-connector dissipaters', *Structures*, (In-press).

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Lu, Y., Henry, R. S., Gultom, R., Ma, Q. T. 'Cyclic testing of reinforced concrete walls with distributed minimum vertical reinforcement', *Journal of structural engineering*, (submitted Mar 2015).

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Watkins, J., Sritharan, S., Henry, R. S. 'Experimental investigation of a wall-to-floor connector for seismic Application', *PCI Journal*, (to be submitted July 2015).

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Encina, E., Henry, R. S. (2015) 'Preliminary analysis of RC wall elongation', *Proceedings of the fib Symposium*, Copenhagen, Denmark, May 18-20.

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Henry, R. S. (2013). Assessment of the minimum vertical reinforcement limits for RC walls. *Proc., New Zealand Society for Earthquake Engineering Conference*, Wellington, New Zealand.

<u>ME theses</u>

Ahn, A. (2015) Effect of out-of-plane floor stiffness on the seismic performance of a reinforced concrete core wall building, ME thesis, Dept. Civil and Environmental Engineering, University of Auckland.

Malcolm, R. C. (2015) Seismic performance of reinforced concrete coupled walls, ME thesis, Dept. Civil and Environmental Engineering, University of Auckland.

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Haysom, M. (2012). Investigation of minimum reinforcement in concrete shear walls, Undergraduate research project report, Dept. Civil and Environmental Engineering, University of Auckland.

Appendices: Copies of all manuscripts available on request.