THE UNIVERSITY OF AUCKLAND
NEW ZEALAND

Resilient Infrastructures and Communities (RIC)

Terminating Contracts (2009) Review – Evidence Portfolio

UOAX0411 Retrofit Solutions for NZ

Portfolio: Resilient Infrastructures and Communities

Programme Leader: Associate Professor Jason Ingham

Funding: $3,750,000 incl GST
Start date: 1 July 2004

End date: 30 September 2010

Key Personnel

Key researchers
Assoc Prof Jason Ingham (UOA, structural engineer – Science Leader)
Adj Prof Desmond Bull (UOC, structural engineer – Objective Leader 1)
Assoc Prof Stefano Pampanin (UOC, structural engineer – Objective Leader 2 and Associate Science Leader)
Prof Michael Pender (UOA, geotechnical engineer)
Assoc Prof Suzanne Wilkinson (UOA, construction management)

NZ collaborators
Assoc Prof John Butterworth (UOA, structural engineer)
Prof Athol Carr (UOC, structural engineer)
Assoc Prof Nawawi Chouw (UOA, structural engineer)
Assoc Prof Charles Clifton (UOA, structural engineer)
Assoc Prof Greg Macrae (UOC, structural engineer)
Dr Graeme McVerry (GNS, seismologist)
Prof Pierre Quenneville (UOA, structural engineer)
Dr Gerald Weber (UOA, software engineer)

Doctoral Researchers

- Umut Akquzel (UOC)
- Tom Algie (UOA)
- Razak Abdul Karim (UOA)
- Gabriele Attanasi (UOC exchange researcher – U. of Pavia, Italy)
- Anna Brignola (UOC exchange researcher – U. of Genova, Italy)
- Hossein Derakhshan (UOA)
- Dmytro Dizhur (UOA)
- Temitope Egbalakin (UOA)
- Debra Gardiner (UOC)
- Adane Gebreyohaness (UOA)
- Giovacchino Genesio (UOC exchange researcher – U. of Stuttgart, Germany)
- Anas Ibrahim (UOA)
- Najif Ismail (UOA)
- Reza Jafarzadeh (UOA)
- Charlotte Knox (UOA)
- Ronald Lumantarna (UOA)
- Hamid Mahmood (UOA)
- Dion Marriott (UOC)
- Majid Naderi (UOA)
- Claudio Oyarzo Vera (UOA)
- Patricio Quintana Gallo (UOC)
- Alistair Russell (UOA)
- Lina Sa'Don (UOA)
- Weng Yuen Kam (UOC)
- Aaron Wilson (UOA)
- Fei Ying (UOA)
- Mohammed Reza Zare (UOA)

Introductory Remarks

Programme overview

The 'Retrofit Solutions' research programme is the largest structural engineering research programme to have ever been undertaken in New Zealand. The primary goal is to develop a body of knowledge and expertise associated with targeted seismic retrofit techniques that specifically addresses the unique characteristics of New Zealand's earthquake risk building stock, to be disseminated to New Zealand's professional earthquake engineers, enabling implementation to create more earthquake resilient buildings. A further goal is to better understand the decision making process used by building owners when considering 'earthquake strengthening' decisions, and to address impediments to the implementation of seismic retrofits. The project has an Industry Advisory Board (IAB) selected by the Structural Engineering Society of New Zealand in consultation with the New Zealand Society for Earthquake Engineering. The research team presents updated findings to the IAB approximately every 6 months, with individual members of the IAB also acting as advisors on specific research tasks.

The research programme is a 50/50 collaboration between the Universities of Auckland (UOA) and Canterbury (UOC). The two universities have collectively hosted 26 PhD and 11 Masters researchers associated with the research programme. The majority of these students are financially supported by over $1.5M of co-funding secured from both New Zealand sources and from foreign governments. Staff researchers Ingham (Science Leader), Pampanin (Obj. 2 leader and Associate Science Leader), Butterworth and Wilkinson have been promoted to Associate Professor since research programme commencement. UOC is responsible for both pre- and post-1970 concrete buildings, and for masonry infilled frames and UOA is responsible for studies on steel and unreinforced masonry buildings, and on aspects of retrofit implementation. The research programme has a broader scope than contracted, with Initial Evaluation Procedure (IEP) software, retrofit of building foundations, and multi-criteria seismic risk analyses for application at territorial scale added to the research programme scope.

Research outputs

Whilst the research programme goal is to develop targeted cost-effective seismic retrofit solutions, early consultation with the IAB led to the realisation that a primary factor in order to achieve this goal was to deploy substantially greater resources to the development of superior seismic assessment procedures than had originally been anticipated. This greater emphasis on detailed seismic assessment is reflected in many of the research programme outputs.

The inherent seismic vulnerability of existing RC buildings, designed prior to the introduction of more adequate seismic code provisions in the early 1970s, has been dramatically highlighted by earthquake events in the recent past. The New Zealand building stock has proven to be based on similar structural deficiencies (poor reinforcement detailing, lack of transverse reinforcement in the joint panel zone region, absence of capacity design principles, brittle failure mechanisms expected at either local or global level) as those encountered overseas. The programme's research has resulted in a better understanding of the vulnerability of as-built solutions, while proposing simple and cost-effective retrofit solutions according to a performance-based retrofit approach. These results were achieved via 1) a comprehensive experimental campaign on frame and wall subassemblies (before and after retrofit) using design details typical of NZ older code provisions and subjected to more refined testing protocol (including pseudo dynamic, real-time dynamic [shake-table] testing and quasi-static cyclic loading under uni or bi-directional loading), and 2) analytical modelling and numerical investigations.

Post-1970 buildings cannot be assumed to be exempt from seismic risk. Knowledge of seismic risk and its mitigation have advanced significantly since the 1970s, as confirmed by the implementation of significantly improved seismic design provisions in NZ in the mid-1980s, mid-1990s and mid 2000s. Concerns were, in particular, related to a) the

seismic performance of, and possible remedies to, precast/prestressed flooring systems (hollowcore in particular), widely adopted in the NZ's construction practice and b) the displacement capacity of older columns. Experimental testing on floor-to-beam seating connections were carried out using refined testing protocols (e.g. simulating beam elongation effects during the lateral sway of frame) to derive specific assessment and retrofit guidelines, recently adopted within Department of Building and Housing guidelines. Bilateral cyclic seismic loading regime were used to assess the behaviour of older (1980s) columns (or part of a gravity-only frame) and proposed efficient retrofitting solutions.

Steel was the preferred ferrous material in New Zealand from 1880 onwards, with most New Zealand steel framed buildings being comprised of one-way acting moment-resisting frames (MRFs) in conjunction with transverse walls with columns typically encased in lightly reinforced concrete. Early beam-column connections typically comprised semi-rigid riveted (pre-1950) or bolted connections having good rotation capacity but limited moment capacity. Retrofit solutions involve modifying connection behaviour to ensure joint integrity, with a symmetrical distribution of inelastic response in beam plastic hinges. In buildings with a reinforced concrete slab, the slab can be utilised to increase the moment capacity of the semi-rigid connections.

For many decades unreinforced masonry (URM) has been recognised as New Zealand's most earthquake-vulnerable building form. However, prior to this contract there had been little research attention in New Zealand directed to this class of buildings. Consequently the research programme has been addressing: characteristic building typologies; prevalence and distribution of URM building stock; URM material properties; in-plane and out-of-plane wall response; assessment and retrofit solutions for flexible timber diaphragms and wall-diaphragm connections; wall retrofit solutions; and numerical modelling of as-built and retrofitted URM buildings. Significant (uncontracted) research effort has been directed to the testing and/or extraction of representative URM buildings scheduled for demolition.

Special topics associated with the retrofit of building foundations include: computer modelling of soil-foundation-structure interaction; measurement of pile foundation cyclic loading response; field measurement of dynamic response of shallow foundations for shear walls; in situ measurement of dynamic soil properties; and laboratory measurement of soil properties.

The factors that affect the decision of the building owner on whether or not to retrofit a building are complex and inter-related. For instance, cost, heritage value, building use and strengthening level are all part of the decision. The research programme is assisting building owners to make more informed decisions by providing a decision analysis framework. Motivational factors and incentive schemes used to promote beyond compliance retrofitting of buildings are also being examined. A cost model aimed at enabling building owners to fully assess the costs of retrofitting their buildings is being constructed. Ultimately, this component of the research programme will lead to building owners in New Zealand having a better appreciation of, and tools to assist, the retrofit decisions they need to make.

Dissemination of results

It was originally anticipated that research programme outputs would be compiled into a single retrofit manual to be disseminated to professional engineers via a nationwide seminar series. Instead, it is now planned that results will be disseminated via a suite of material-focused manuals in order to facilitate rapid dissemination as findings become available. The research programme has a dedicated website at www.retrofitsolutions.org.nz. This research programme website provides details of the staff and student researchers, and contains an archive of research programme outputs. In 2008 the website had 100,844 hits by 7,403 unique visitors. The website also contains details of the research programme Industry Advisory Board.

(A) Research Outputs – 1. Key Outputs

Key Output 1: Retrofit solutions for post-1970 reinforced concrete buildings

Description: Some design practices thought to be appropriate in the early part of the post-1970s have been shown to be inadequate. These research programmes have focused on producing better methods (filling the gaps in knowledge) of analysing and retrofitting constructed details/connections within buildings with particular attention to poorly transversely reinforced columns (examples date from the 1960s) and precast concrete floors, principally hollowcore floors (the dominant form from the late 1970s). The interior columns of most pre- and post-1970 RC buildings (until 1995) are inadequately detailed to withstand earthquakes.

Evidence: Department of Building and Housing, 2009, 'Seismic Performance of Hollowcore Floor Systems - Guidelines for Design Assessment and Retrofit', NZSEE, SESOC, NZCS, *Prelim. Draft*, April 2009; SESOC Journal, 2009, 'Precast Double Tee Support Systems', (in print). Woods, L., Fenwick, R. & Bull, D.K., 'Seismic Performance of Hollow-core Flooring: the Significance of Negative Bending Moments', in *Proceedings, New Zealand Society for Earthquake Engineering Conference*, Wairakei, New Zealand, 2008. Plus papers by Jensen, Woods, Gardiner and Boys – journals and conferences.

Significance: This programme practically completes the understanding of how concrete topped precast floor units are subjected to forces and to local deformations in buildings. A suite of retrofit solutions was also developed. A refined method for assessment of capacity was developed. The assessment methods aids in determining the best retrofit option for such columns. This methodology can be used in high-end computer analysis as well as desk-top studies.

Transfer to end users: The analysis and technical resolutions from this programme have made significant contributions to two major documents. The DBH 'Seismic Performance of Hollow Core Floor Systems' will be out for full public use in the next 3 months. The SESOC report (on www.sesoc.org.nz) on flange-hung Double Tees is about be produced in the national Journal. Recommendations from this programme on assessing the performance of precast concrete floors in a building undergoing lateral movement have been incorporated in the Concrete Structures Standard NZS 3101:2006 and a subsequent amendment. Information produced from this programme has appeared and is about to appear in the Journals of the NZ Society for Earthquake Engineering and NZ Structural engineering Society. Further, papers have been presented at the conferences of NZSEE, NZ Concrete Society and the 14th World Conference for Earthquake Engineering.

Benefit to NZ: The development of a complete suite of analysis methods for the interaction of floor units within the building, in terms of 9 localised damage modes, can now be used for both assessing existing buildings and designing new structures. The refined assessment of strength and ductility (failure hierarchy) of RC columns now covers all the load cases required by the NZ Loadings Standard. The proposed safety assessment methodology and associated retrofit solutions will lead to improvements in buildings' seismic resistance.

Contribution of research contract team and reasons for choice: The UoC Obj. Leaders Prof D. Bull and Associate Prof. S. Pampanin have directed a number of research students. Two staff members, Prof. A. Carr and Prof Richard Fenwick, world experts in computer analysis and concrete structural mechanics, made significant contributions through their technical input and mentoring of students. This output will provide practical and cost-effective solutions to real design and construction issues facing architects, structural engineers and contractors today.

Key Output 2: Seismic Vulnerability Assessment and Retrofit Solutions for NZ Pre-1970 Reinforced Concrete (RC) Buildings

Description: The project has developed an improved understanding of the damage and collapse mechanisms for pre-1970s RC buildings, while developing alternative and novel performance-based retrofit strategies and technical solutions for practical implementation at a relatively low cost and invasiveness (e.g. reduced downtime & business interruption and potential reversibility). Two major outcomes were achieved:
1) Refinements of current **seismic vulnerability assessment techniqu**es and methodology to be included within an updated version of the NZSEE Guidelines. These refinements were based on a comprehensive analytical and experimental campaign on RC Building beam-column joints (2D and 3D) and wall systems. The structural characteristics of NZ pre-1970s RC building stock were derived from case studies provided by the Industry Advisory Board and primary sources. Emphasis was given to: use of plain round bars, joint shear damage mechanism under unidirectional and (less frequently used) bidirectional loading, assessment of the hierarchy of strength and sequence of events when accounting for the axial load variation (typically neglected).
2) Development of **a set of retrofit solutions** for different levels of seismic protection (from collapse prevention to damage control): a) low-invasive and low-cost diagonal metallic haunch solution for easy and broad implementation at territorial scales; b) Fibre Reinforced Polymers, with substantial improvements to design and practical implementation (i.e. external side of the building); c) post-tensioned wall systems to control behaviour and damage of soft-storey-prone older frames, using a wide range of energy dissipation devices (e.g. standard yielding mild steel, viscous dampers, or a combination); d) selective weakening (instead of strengthening), based on local disconnections to modify the load path, enhancing the inelastic mechanism and overall performance of the building after an earthquake.

Evidence: Pampanin, 2007, 'Alternative Performance-Based Retrofit Strategies and Solutions for Existing R.C. Buildings', Chapter in *'Seismic Risk Assessment and Retrofitting - with special emphasis on existing low rise structures'* (A. Ilki, F. Karadogan, S. Pala and E. Yuksel, eds), Springer; Pampanin, S., Christopoulos, Chen, T-H., 2006 'Development and Validation of a Metallic Haunch Seismic Retrofit Solution for Existing Under-Designed RC Frame Buildings' *EESD; 35:1739–1766.*
Significance: The refined and/or newly proposed solutions (in some cases counter-intuitively based on "weakening") can be effective in meeting structural performance requirements at low cost, invasiveness and simple implementation.

Transfer to end users: Several publications/presentations at national/international conferences. Graduate course on Seismic Assess. and Retrofit of RC structures introduced at UoC. Feasibility study and/or practical implementation on real buildings.

Benefit to NZ: (A) A new set of alternative retrofit solutions in NZ are now available. These solutions are more technically sound and quality-controlled, and are simpler to design and implement for NZ's building stock. (B) The programme is already increasing NZ's platform of knowledge in assessment and retrofit, by training younger engineers and exposing senior engineers/ contractor to the use of new technology and materials.

Contribution of research contract team and reasons for choice: The UoC PI and Objective Leader Associate Professor Stefano Pampanin has coordinated a wide research team of several staff and students researchers from both NZ and overseas, in collaboration with Prof. Des Bull (practical implementation and case studies) and Prof. Athol Carr (numerical modelling), Prof. Eligehausen (University of Stuttgart, FEM modelling, bond issues and anchorage to concrete), Prof. Constantin Christopoulos (University of Toronto, haunch system) and several Ph.D., ME students, Research Assistants and Exchange students. The selection of this output is due to the demonstrated high potential and interest on the developed methodology and solutions from both the scientific community and the industry both in NZ and overseas.

Key Output 3: Seismic Zonation and Default Suite of Ground Motion Records for Time-History Analysis in New Zealand

Description: This study integrated the specialist knowledge of seismologists and engineers to develop a suite of recommended earthquake ground motions for use in seismic time-history analysis to perform superior analytical modeling of seismic retrofit implementation. The New Zealand Standard for Structural Design Actions, NZS 1170.5:2004, defines a criterion for selecting ground motion records for time-history analysis based on similarity between the seismological signature of earthquakes used for seismic structural analysis and those that are expected to be encountered at a given location. However, as most structural designers are not familiar with the specific details of the probabilistic seismic hazard model used to determine the design spectra, further information regarding critical earthquake characteristics is currently required before designers can readily select appropriate earthquake records.

Evidence: Oyarzo-Vera, C., McVerry, G. H., Fleming, R., Ingham, J. M. 'Seismic Zonation and Default Suite of Ground Motion Records for Time-History Analysis in New Zealand', *Bulletin of the New Zealand National Society for Earthquake Engineering (submitted April 2009);* Oyarzo-Vera, C., McVerry, G. H., Ingham, J. M. 'Seismic Hazard Zonation and Ground Motion Records for Time-History Analysis in the North Island of New Zealand', *ASCE Journal of Structural Engineering* special issue dedicated to *Earthquake Ground Motion Selection and Modification for Nonlinear Dynamic Analysis of Structures (submitted May 2008).*

Significance: Time-history analysis is rapidly becoming a widely employed tool used by many consulting engineering firms for both seismic analysis and design of new structures, and for seismic assessment of existing buildings. The development of a standard suite of earthquake ground motions for New Zealand will accelerate the accurate implementation of this powerful analysis technique, and will minimise the potential for misuse of inappropriate earthquake ground records to justify unsound seismic retrofits.

Contribution to Intermediate Outcome: This output is a key contribution to intermediate outcomes No. 3, 7, 11, 13 and 14 associated with the development of appropriate analytical modelling techniques for seismic retrofit implementation.

Transfer to end users: Publication of the suite of earthquake ground motions in the NZSEE Bulletin will ensure that the information has wide exposure amongst the intended end users, being New Zealand's structural seismic engineers. All earthquake records are available from internet based free-access databases and following publication of the NZSEE article, will be reproduced on the NZSEE web site. An article will also appear in the Journal of the Structural Engineering Society of New Zealand, to maximise transfer of this information to end users.

Benefit to NZ: This output will ensure that structural engineers responsible for retrofit implementation will be able to employ accurate earthquake time history records to ensure that their designs are neither under-strength, and therefore a danger to the New Zealand public in the event of an earthquake, nor conservatively over-strength and therefore expensive, which leads to a financial burden on building owners and generates an impediment to retrofit implementation.

Contribution of research contract team and reasons for choice: The Principal Investigator (Ingham) and his doctoral student (Oyarzo-Vera), assisted by a final year undergraduate student (Fleming), have collaborated with McVerry of GNS to form a highly successful partnership combining the expertise of structural engineers and seismologists. We consider the development of a default suite of earthquake ground records that are consistent with the fault mechanisms used to derive the criteria for NZ earthquake design loads to be an important output, both for seismic retrofit implementation and for the design of new structures. We expect this output to become the default New Zealand standard practice used by the majority of New Zealand's seismic structural engineers.

Key Output 4: Detailed seismic assessment of unreinforced masonry buildings

Description: The New Zealand Society for Earthquake Engineering has developed a rapid screening process to determine building earthquake strength, referred to as the 'Initial Evaluation Procedure' (IEP). When a building is identified to have insufficient strength using the IEP, it is necessary to perform a detailed seismic assessment in order to determine the appropriate level of seismic retrofit intervention that is necessary. The current NZSEE detailed seismic assessment technique for URM buildings has been found to be difficult to use, which has resulted in the document having little uptake by end users. Early consultation with the research programme Industry Advisory Board led to the determination that one of the most crucial aspects associated with the development of cost effective seismic retrofit solutions for New Zealand was to develop a superior detailed seismic assessment technique for unreinforced masonry (URM) buildings. Whilst the final assessment manual is not scheduled to be completed until late 2009, important findings have already been published regarding characteristic building forms, building prevalence and aggregated earthquake risk using the IEP process, and in particular the seismic assessment of URM walls subjected to earthquake face loads. An error has been identified in the existing NZSEE assessment technique, with this research presented at the 2009 NZSEE conference. A superior displacement-based procedure using the earthquake ground records detailed in Key Output 3 is currently being developed.

Evidence: Russell, A. P., Ingham, J. M., 'Architectural characterisation of New Zealand's unreinforced masonry building stock', *ASCE Journal of Architectural Engineering (submitted March 2009)*; Russell, A. P., Ingham, J. M., 'Prevalence and distribution of New Zealand's unreinforced masonry building stock', *Bulletin of the New Zealand National Society for Earthquake Engineering (submitted April 2009);* Derakhshan, H., Ingham, J. M., Griffith, M. C., 'Out-of-plane assessment of an unreinforced masonry wall: Comparison with NZSEE recommendations', 2009 NZSEE Conference, Christchurch, April 3-5.

Significance: Qualitative and quantitative studies have led to the determination that there are approximately 3,600 unreinforced masonry buildings in New Zealand, having a commercial value of approximately $1.5 billion. Many of these buildings have earthquake strength less than that stipulated for an equivalent new building, and depending on building location within New Zealand and building importance, many of these buildings will require a detailed seismic assessment as the precursor to seismic retrofit.

Contribution to Intermediate Outcome: This output is a key contribution to intermediate outcomes No. 11, 13 and 14 associated with the development of appropriate analytical modelling techniques for seismic retrofit implementation.

Transfer to end users: Currently information has been transferred via articles in the NZSEE Bulletin and at the NZSEE conference, augmented by articles in leading international earthquake and masonry conferences. Once the 'Detailed Seismic Assessment of URM Building' manual is complete in draft form, a nationwide seminar series is scheduled in conjunction with NZSEE and SESOC.

Benefit to NZ: The development of a superior detailed seismic assessment technique for URM buildings will save millions of dollars for building owners tasked with elevating their building strength to prescribed levels. Having a technique that is both accurate and comparatively straightforward to use will facilitate better, cheaper assessments by seismic structural engineers.

Contribution of research contract team and reasons for choice: The Principal Investigator (Ingham) and his doctoral students (Russell and Derakhshan), in collaboration with Assoc Prof Griffith from the University of Adelaide, have developed a framework for the detailed seismic assessment of URM buildings that sample end users have found to be uncomplicated and a notable improvement over the existing NZSEE technique. We consider the identification of an error in the existing NZSEE assessment technique for URM walls to be a significant contribution.

(A) Research Outputs - 2. Other Outputs

	Output type	Description
1	*Tools and Processes* Software	Gerald, W. et al. (2008): Open source software to conduct the NZSEE 'Initial Evaluation Procedure' utilising searchable web-based technology has been written by a team of final year undergraduate software engineers. The software has been demonstrated to the Department of Building and Housing, and to a number of Territorial Authorities. During 2009 a new team of students is further developing the software.
2	*Tools and Processes* Software	A web-based cost modelling system, developed by PhD student R. Jafarzadeh, can be found at www.retrofitcost.net. This is being populated with data from NZ buildings after extensive consultation with NZ businesses and government organisations (eg EQC and DBH). The cost modelling software will be completed in 2010, and will allow building owners to obtain a thorough idea of the costs involved in retrofitting their buildings.
3	*End user interaction* Peer reviewed publication	Pender, M. J. (2007). 'Seismic design and performance of surface foundations', Chapter 10, *Earthquake Geotechnical Engineering*, K. D Pitalakis (ed), Springer, pp. 215 – 241.
4	*End user interaction* Peer reviewed publication	MacRae, G. A., Clifton, G. C., Mackinven, H., Mago, N., Butterworth, J. and Pampanin, S., 'The sliding hinge joint moment connection', Bulletin of the New Zealand Society for Earthquake Engineering (under review).
5	*End user interaction* Peer reviewed publication	Pampanin. S., (2006). 'Controversial Aspects in Seismic Assessment and Retrofit of Structures in Modern Times: Understanding and Implementing Lessons from Ancient Heritage' Bulletin of the New Zealand Society for Earthquake Engineering, June, 39(2), pp. 120-133.
6	*End user interaction* Peer reviewed publication	Pampanin, S. (2007). 'Developments in seismic design and retrofit of structures: modern technology built on the ancients' wisdom'. Chapter 6, *Hazards and the Built Environment*, Lee Bosher (Ed.), Taylor and Francis, pp. 96-123.
7	*End user interaction* Peer reviewed publication	Marriott, D., Pampanin, S., Bull, D., Palermo, A. (2008). 'Dynamic Testing of Precast, Post-Tensioned Rocking Wall Systems with Alternative Dissipating Solutions', Bulletin of the New Zealand Society for Earthquake Engineering, 41(2), pp. 90-103.
8	*End user interaction* Conference presentations (New Zealand)	*2006 NZSEE Conference: Remembering Napier 1931.* New Zealand Society for Earthquake Engineering, Napier, March 10-12. • Eligehausen, R., Ožbolt, J., Genesio, G., Hoehler M. S Pampanin, S. 'Three-Dimensional Modelling of Poorly Detailed RC Frame Joints' • Giovinazzi, S., Lagomarsino S., Pampanin, S. 'Vulnerability Methods and Damage Scenario for Seismic Risk Analysis as Support to Retrofit Strategies: an European Perspective' • Ireland, M., Pampanin, S., Bull, D. K. 'Concept and Implementation of a Selective Weakening Approach for the Seismic Retrofit of R.C. Buildings' • Jensen, J., Bull, D. K., Pampanin, S. 'Conceptual Retrofit Strategy for Existing Hollowcore Seating Connections' • Pender, M., Wotherspoon, L., Ingham, J. M., Carr, A. 'Shallow foundation stiffness: Continuous soil and discrete spring models compared'

		• Pettinga, J. D., Priestley, M. J. N., Pampanin, S., Christopoulos, C. 'Accounting for the Effects on Residual Deformations Due to Torsional Response' • Schofield, H., Ingham, J. M., Pampanin, S. 'Critical Earthquake Risk Detailing in New Zealand's Multi-storey building stock: Understanding and Improving the Current Perception' • Uma, S. R., Pampanin, S., Christopoulos, C. 'Probabilistic Formulation of a Performance-based Matrix Combining Maximum and Residual Deformations'
9	*End user interaction* Conference presentations (New Zealand)	2007 NZSEE Conference: *Performance by design - can we predict it?* New Zealand Society for Earthquake Engineering, Palmerston North, March 30 - April 1. • Akguzel, U., Pampanin, S. 'Experimental Behaviour of Exterior Beam-Column Joint Subassemblies Retrofitted using GFRP Composites' • Clifton, C., MacRae, G., Mackinven, H., Pampanin, S., Butterworth, J. 'Sliding Hinge Joints and Subassemblies for Steel Moment Frames' • Giovinazzi, S., Pampanin, S. 'Mitigation Analyses for the Selection of Effective Seismic Retrofit Strategies at a Territorial Scale' • Jensen, J., Bull, D.K., Pampanin, S. 'Experimental Investigation of Existing Hollowcore Seating Connection Seismic Behaviour Pre and Post Retrofit Intervention' • Marriott, D., Pampanin, S., Bull, D.K., Palermo, A. 'Improving the Seismic Performance of Existing Reinforced Concrete Buildings using Advanced Rocking Wall Solutions' • Weng., K. Pampanin, S., Carr, A., Palermo, A.,'Advanced Flag-Shaped Systems for High Seismic Performance Including Near Fault Effects'
10	*End user interaction* Conference presentations (New Zealand)	*2008 NZSEE Conference: Engineering an Earthquake Resilient NZ*, New Zealand Society for Earthquake Engineering, Wairaki, April 11-13. • Amaris, A., Pampanin, S., Bull, D. K., Carr, A. J. 'Experimental Investigation on a Hybrid Jointed Precast Frame with Non-tearing Floor Connections' • Boys, A., Bull, D. K., Pampanin, S. 'Seismic Performance Assessment of Inadequately Detailed Reinforced Concrete Columns' • Brignola, A., Podestà, S., Pampanin, S. 'In-plane stiffness of wooden floor' • Gardiner, D. R., Bull, D. K., Carr, A. J. 'Internal forces of concrete floor diaphragms in multi-storey buildings' • Giovinazzi, S., Podestà, S., 'Data Processing of observed damage and reconstruction costs after 2002 Molise Earthquake in Italy' • Kam, W. Y., Pampanin, S., Palermo, A., Carr, A. J. 'Design Procedure and Behaviour of the Advanced Flag-Shape (AFS) Systems for Moment-Resisting Frame Structures' • Marriott, D. J., Pampanin, S., Palermo, A. Bull, D. K., 'Dynamic Testing of Precast, Post-Tensioned Rocking Wall Systems With Alternative Dissipating Solutions' • Naderi, M. 'Finite Element Analysis of Riveted Joints in Old Steel Buildings in New Zealand' • Oyarzo-Vera, C., McVerry, G. H., Ingham, J. M. 'Ground motion records for time-history analysis of URM Buildings in

		New Zealand – The North Island' • Peng, B. H. H., Fenwick, R. C., R.P. Dhakal, R. P. ,Bull, D. K. 'Experimental study on the seismic performance of RC moment resisting frames with precast-prestressed floor units' • Russell, A., Ingham, J. M. 'Architectural characterisation and prevalence of New Zealand's URM Building Stock' • Toh, J. C. W., Pender, M. J. 'Earthquake performance and displacements of shallow foundations' • Wilson, A. W., Oyarzo-Vera, C., Omenzetter, P., Chouw, N., Ingham J. M. 'Dynamic performance of timber diaphragms in the 1903 Nathan House' • Woods, L. J., Fenwick, R. C., Bull, D. K. 'Seismic Performance of Hollow-core Flooring: the Significance of Negative Bending Moments'
11	*End user interaction* Conference presentations (New Zealand)	*2008 NZ Geotechnical Society Geotechnical Symposium, "Soil-Structure Interaction – From Rules of thumb to Reality"*, Auckland, 4-5 Sept. • Pender, M. J., Butterworth, J. W. 'Classical soil-structure interaction and the New Zealand structural design actions standard NZS 1170.5 (2004)' • Pender, M. J., Wotherspoon, L. M., Carr, A. J., 'Earthquake resistant design of shallow foundations for low-rise structures' • Pender, M. J. 'Nonlinear pushover analysis for pile foundations' • Wotherspoon, L. M., Pender, M. J., Carr, A. J. 'Modelling of single pile-soil interaction using Ruaumoko' • Toh, J. C. W., Pender, M. J., Davies, M. C. R. 'Performance-based seismic design of shallow foundations' • Rodgers, P., Pender, M. J. 'Field tests on the lateral capacity of poles embedded in Auckland residual clay'
12	*End user interaction* Conference presentations (New Zealand)	*2008 NZ Concrete Industry Conference,* Rotorua, 2-4 Oct. • Boys, A., Bull, D. K., Pampanin, S., 'Seismic Performance of Concrete Columns with Inadequate Transverse Reinforcement'
13	*End user interaction* Conference presentations (New Zealand)	*2009 NZSEE Conference: Why do we still tolerate buildings that are unsafe in earthquakes?*, Christchurch, April 3-5, 2009. • Abdul Karim, A. R., Oyarzo-Vera, C., M.Sa'Don, N., Ingham, J. M. 'Dynamic response of URM house subjected to forced excitation' • Akguzel, U., Pampanin. S. 'Analytical Model for Shear Strengthening of RC Beam-Column Joints Using Composite Materials' • Arefi, M.J., Pampanin, S., Cubrinovski M. 'Effects of SSI on the Seismic Response of Older Structures Before and After Retrofit' • Derakhshan, H., Ingham, J. M., Griffith, M. C. 'Out-of-plane assessment of an unreinforced masonry wall: Comparison with NZSEE recommendations' • Dizhur, D., Russell, A. P., Ingham, J. M., Laursen, P. 'Experience from California, USA on Seismic Retrofit of Unreinforced Masonry Buildings' • Dizhur, D., Derakhshan, H., Cuthbert, J., Ingham, J. M. 'In-situ Out-of-plane Testing of Unreinforced Masonry Partition Walls' • Egbelakin, T., Wilkinson, S., Ingham, J. M. 'Why are

		Building Owners of EPBs Reluctant to Retrofit?' • Jafarzadeh, R., Wilkinson, S. 'Retrofit Cost Modelling of Existing Structures in New Zealand' • Oyarzo-Vera, C., Fleming, R., McVerry, G., Ingham, J. M. 'Seismic Zonation and Default Suite of Ground Motion Records for Time-history Analysis in New Zealand' • Pender, M. J., Algie, T. B., Wotherspoon, L. M., Davies, M. C. R., Toh, J. C. W. 'Performance Based Design and Earthquake Induced Displacements of Shallow Foundations' • Weng, K.Y., Pampanin, S., Bull, D.K. 'Experimental Validation of Selective Weakening Approach for the Seismic Retrofit of Exterior Beam-Column Joints'
14	*End user interaction* Conference presentations (International)	*Proceedings JAEE Kobe 2005 Commemoration Symposium*, Jan. 2005. • Pampanin, S., Christopoulos, C. 'Low-invasive seismic retrofit solution for under-designed reinforced concrete frame system'
15	*End user interaction* Conference presentations (International)	*1st European Conference on Earthquake Engineering and Seismology,* Geneva, Switzerland, 3-8 Sept., 2006. • Giovinazzi S., Pampanin, S., Lagomarsino, S. 'Vulnerability Models and Damage Scenarios for Pre-1970 R.C. Buildings Before and After Alternative Retrofit Strategies' • Kam, W., Pampanin, S., Palermo, A., Carr, A. 'Advanced Flag-Shape Systems For High-Seismic Performance' • Uma, S.R., Pampanin., S., Christopoulos, C., 'A Probabilistic Framework to Develop Performance Objectives Based on Maximum and Residual Deformations' • Uma, S.R., Pampanin S., Carr, A. 'Formulation of Integrated Beam-Column-Joint Model for Seismically Non-Conforming R.C. Frame Systems'
16	*End user interaction* Conference presentations (International)	*8th FRPRCS, International Conference on Fiber Reinforced Polymers for Reinforced Concrete Structures*, Patrass, Greece, July 16-18, 2007. • Pampanin, S., Akguzel, U., Attanasi, G., 'Seismic Upgrading of 3-D Exterior R.C. Beam Column Joints Subjected To Bi-Directional Cyclic Loading Using GFP Composites'
17	*End user interaction* Conference presentations (International)	*8th Pacific Conference on Earthquake Engineering.* Singapore, 5-7 Dec, 2007. • Giovinazzi, S., Pampanin, S. 'Multi-Criteria Approaches for Earthquake Retrofit Strategies at Regional Scale' • Mackinven, H., MacRae, G., , Pampanin, S., Clifton, C., Butterworth, J. 'Sliding Hinge Joints and Subassemblies for Steel Moment Frames' • Pender, M. J. 'Effect of the variability of foundation stiffness on performance based seismic design' • Russell, A. P., Mahmood, H., Ingham, J. M. 'Pseudo-static testing of in-plane unreinforced masonry walls in New Zealand'
18	*End user interaction* Conference presentations (International)	*14th International Brick and Block Masonry Conference (14IBMAC)*, Sydney, Australia, Feb 17-20, 2008. • Ingham, J. M. 'The Influence of Earthquakes on New Zealand Masonry Construction Practice' • Mahmood, H. Russell, A. P., Ingham, J. M. 'Laboratory Testing of Unreinforced Masonry Walls Retrofitted with

		Glass FRP Sheets' • Russell, A. P., Ingham, J. M. 'Trends in the Architectural Characterisation of Unreinforced Masonry in New Zealand'
19	*End user interaction* Conference presentations (International)	*CIB World Building Congress 2007: Construction for development*, Cape Town, South Africa, 14-18 May, 2007. • Ying, F., Wilkinson, S. The Application of Life Cycle Costing for Building Retrofit.
20	*End user interaction* Conference presentations (International)	*International RILEM Conference on Site Assessment of Concrete, Masonry and Timber Structures (SACoMaTiS 2008)*, Varenna, Italy, 1-2 Sept, 2008. • Lumantarna, R., Wilson, A. W., Russell, A. P., Ingham, J. M. 'Field Assessment of the Material Properties of New Zealand's Unreinforced Masonry Buildings'
21	*End user interaction* Conference presentations (International)	*14th World Conference on Earthquake Engineering (14WCEE)*, Beijing, China, 12-17 October, 2008. • Akguzel, U., Pampanin., S. 'Effects of Variation of Axial Load and Bi-Directional Loading on the FRP Retrofit of Existing B-C Joints' • Gardiner, D.R., Bull, D.K., Carr, A. 'Investigation of the Magnitude of Inertial and Transfer Forces in Floor Diaphragms during Seismic Shaking' • Kam, W.Y., Pampanin, S. 'Selective Weakening Techniques for Retrofit of Existing Reinforced Concrete Structures' • Ma, Q. T., Omenzetter, P., Ingham, J. M., Butterworth, J. W., Pender, M. J. 'The Development of Mobile Field Laboratory and Hybrid Testing Facility at NZNEES@Auckland' • Mahmood, H, Russell, A. P., Ingham, J. M. 'Monotonic testing of unreinforced and GFRP-retrofitted masonry walls prone to shear failure in an earthquake' • Oyarzo-Vera, C., Ma, Q.T., Chouw, N., Ingham, J.M. 'Comparison of record scaling methods proposed by standards currently applied in different countries' • Pender, M. J., Wotherspoon, L. M., Toh, J. C. W. 'Foundation stiffness estimates and earthquake resistant structural design' • Personeni, S., Di Pilato, M., Palermo, A. , Pampanin, S. 'Numerical Investigations on the Seismic Response of Masonry Infilled Steel Frames' • Pettinga, J.D., Pampanin, S., Christopoulos, C., Carr, A.J., Rolando, C. B. Experimental Investigation into Residual Displacements due to Inelastic Torsional Response' • Pettinga, J. D., Christopoulos, C., Pampanin, S. 'Predicting Inelastic Torsional Response with the Inclusion of Dynamic Rotational Stiffness' • Russell, A., Ingham, J. M. 'Flange Effects of an Unreinforced Masonry Wall Subjected to Pseudo-Static In-Plane Seismic Forces' • Wilson, A. W., Abdul Karim, A. R., Oyarzo-Vera, C., Omenzetter, P., Ingham, J. M., 'Dynamic testing of a timber floor diaphragm in an unreinforced masonry building'
22	*End user interaction* Conference presentations (International)	*Institute for Operations Research and the Management Sciences (INFORMS) Annual Meeting,* Washington D.C., U.S.A. Oct 12-15, 2008. • Ying, F., and Wilkinson, S., "Developing a Model to Assist

		Earthquake Retrofitting Projects - A Pilot Case Study"
23	*End user interaction* Conference presentations (International)	*Australian Earthquake Engineering Conference, AEES* Ballarat, Victoria, Australia, Nov. 21-23, 2008. • Abdul Karim, A. R., Oyarzo-Vera, C., M.Sa'Don, N., Ingham, J. M. 'Forced Vibration Response of Small Scale URM House with Flexible Timber Diaphragm' • Derakhshan, H., Ingham, J. M. 'Out-of-Plane Testing of an unreinforced masonry wall subjected to one-way bending' • Egbelakin, T. and Wilkinson, S. 'Factors affecting motivation for improved seismic retrofit implementation'
24	*End user interaction* Conference presentations (International)	*2nd International Conference on Concrete Repair, Rehabilitation and Retrofitting (ICCRRRR)*, Cape Town, Nov. 24-26, 2008. • Eligehausen, R., Genesio, G., Ožbolt, J., Pampanin, S. '3D Analysis of Seismic Response of RC Beam-Column Exterior Joints before and after Retrofit'
25	*End user interaction* Conference presentations (International)	*International Operational Modal Analysis Conference*, Portonovo (Ancona), Italy, 4-6 May 2009 • Oyarzo-Vera, C., Abdul Razak, A.K., Chouw, N. 'Modal testing and model updating of an unreinforced masonry house'
26	*Capability development* Masters thesis completions	• Arefi, J. 'Effects of Soil-Structure Interaction on the Seismic Response of Existing Frame Buildings', Masters of Engineering Thesis, ROSE School, Pavia, Italy, 2008. • Boys, A. 'Assessment of Seismic Performance of Poorly Detailed RC Columns under Uni- and Bi-directional Loading', Masters of Engineering Thesis, Department of Civil Engineering, University of Canterbury, 2009. • Galli, M. 'Numerical Investigation on the seismic response of pre-1970 Masonry Infilled RC frames', Masters of Engineering Thesis, ROSE School, Pavia, Italy, 2005. • Goodwin, C. O. 'Architectural Considerations in the Seismic Retrofit of Unreinforced Masonry Heritage Buildings in New Zealand', Master of Architecture thesis, Department of Architecture and Planning, The University of Auckland, 2008. • Hertanto, E. 'Experimental Investigation on Pre-1970 Frame Subassemblies', Masters of Engineering Thesis, Department of Civil Engineering, University of Canterbury, 2006. • Jensen, J. 'Experimental Investigation on the Seismic Performance of Hollowcore Floor Systems Before and After Retrofit Intervention', Masters of Engineering Thesis, Department of Civil Engineering, University of Canterbury, 2006. • Ireland, M. 'Development of Selective Weakening Techniques for Poorly Reinforced Wall Systems', Masters of Engineering Thesis, Department of Civil Engineering, University of Canterbury, 2007. • Wood, L. 'Predicting Damage and Failure Mechanisms in Hollowcore Floor-lateral Resisting System Connections under Seismic Loading', Masters of Engineering Thesis, Department of Civil and Natural Resources Engineering, University of Canterbury, 2008. • Te-Chen, T. 'Development of a Low-invasive Metallic Haunch Solution for Pre-1970 RC frames', Masters of Engineering Thesis, Department of Civil Engineering, University of Canterbury, 2006.

27	*Capability development* Ph.D. Thesis completion	• Brignola, A. 'Evaluation of In-plane Stiffness of Timber Floor for the Performance Based Retrofit of URM Buildings', Ph.D. Thesis, University of Genova, Italy (S. Pampanin co-supervisor), 2009. • Marriott, D. 'The Development of High-Performance Post-tensioned Rocking Systems for the Seismic Design of Structures", Ph.D. Thesis, Department of Civil and Natural Resources Engineering' (thesis submitted, oral defence scheduled for May 2009).

B) Peer Esteem

1. **Awards and Prizes:** Research personnel have received the following awards and prizes:

• Bull, D. K., Otto Glogau Award for best journal paper published by a member, New Zealand Society for Earthquake Engineering Inc., 2004.

• Bull, D. K., Professional Commitment Award, Institution of Professional Engineers New Zealand, 2004.

• Clifton, G. C., Freyssinet Award – the Supreme Technical Award for Engineering Achievers, Institute of Professional Engineers New Zealand (IPENZ), 2009.

• Clifton, G. C., Meritorious Service Award, Standards New Zealand, 2008.

• Clifton, G. C., Keith Smith Distinguished Service Award for Services to the Metals Industry of New Zealand, Metals Industry Conference, 2008.

• Ingham, J. M., New Zealand Concrete Society (NZCS) Sandy Cormack Award for best conference paper, 2006.

• Ingham, J. M., TMS Best Thesis Award (as supervisor of Dr Gavin Wight), The Masonry Society (USA), 2006.

• Ingham, J. M., TMS Best Thesis Award (as supervisor of Dr Kok Choon Voon), The Masonry Society (USA), 2007.

• Ingham, J. M., Alan H. Yorkdale Memorial Award for masonry research, American Society for the Testing of Materials (ASTM), 2008.

• Pender, M. J., Supreme Technical Award for Engineering Achievers, Institute of Professional Engineers New Zealand (IPENZ), 2005.

• Pender, M. J., Turner Award for Professional Commitment, Institute of Professional Engineers New Zealand (IPENZ), 2005.

• Pender, M. J., Butterworth, J. W., NZ Geotechnical Society Geotechnical Symposium best paper award, 2008.

• Pampanin, S., New Zealand Concrete Society (NZCS) Sandy Cormack Award for best conference paper, 2004.

• Pampanin, S., NZSEE, Best Research Paper Award, 2005.

• Pampanin, S., Otto Glogau Award 2005 for best journal paper published by a member

• Pampanin, S., Ivan Skinner Award for the Advancement of Earthquake Engineering Research in NZ, EQC/NZSEE, Inaugural Recipient, 2005.

• Pampanin, S., Carr, A., Kam, W. NZSEE Best Research Paper Award 2007.

• Pampanin, S., NZSEE Best Research Paper Award 2008.

2. **Invited Speaker.** Research personnel have been invited to make presentations at the following events:

• Clifton, GC. 'Fire engineering of multi-storey steel structures in New Zealand', Institution of Structural Engineers, United Kingdom, IStructE Centenary presentation, 17 April 2008.

• Ingham, J. M., Special panel session on "Issues of earthquake engineering for regions of moderate seismicity, and experiences that can be learnt from regions of strong seismicity", *2007 Asian-Pacific Network of Centers for Earthquake Engineering Research*, Hong Kong, China, May 29 – 30, 2007.

• Ingham, J. M. 'The Influence of Earthquakes on New Zealand Masonry Construction Practice', *14th International Brick and Block Masonry Conference (14IBMAC)*, Masia, M., Totoev, Y., Page, A., Sugo, H.(ed.), Sydney, Australia, Feb 17-20, 2008.

• Ingham, J. M. 'NZNEES: Addressing New Zealand's Remoteness from its International Earthquake Engineering Collaborators', *2009 Annual Conference of the Network for Earthquake Engineering Simulation (NEES)*, Honolulu, Hawaii, June 23-25, 2009.

• Pampanin, S. Application of Fasteners for Retrofit of Existing Building. NZCS Seminar Series Anchorage to Concrete 2008, Guest Co-Speaker with Prof. Eligehausen, Auckland, Christchurch, Nelson, Dunedin, Tauranga, 2006, 2007 & 2008.

• Pampanin, S., Innovative solutions for Seismic-Resisting precast structures, Short Courses to Practising Engineers on Seismic Design of Precast Structures, Pavia, EUCENTRE, 2005 & 2006.

• Pampanin, S. 'Sistemas Innovadores en la Prefabrication', Invited Lecture, ANIPPAC, Associacion Nacional de Industriales del Presfuerzo y la Prefabrication, A.C., 2° Encuentro Latinoamericano de Estructuras Prefabricadas, 1er. Congreso Internacional, Veracruz, México 11-3 Oct. 2006.

• Pampanin, S. Edificios Prefabricados con Uniones Postensadas, Short Course to Practicing Engineers, Santiago, Chile, 17-18 April, 2007.

• Pampanin., S. Alternative Performance-Based Retrofit Strategies and Solutions for Existing RC Buildings, International ITU_ELSA Workshop on "Measures for the Prevention of Total Collapse of Existing Low-Rise Buildings", Istanbul 19-20 Nov 2007.

• Pampanin, S. Video Interview as part of the Science Learn Hub funded by MRST http://www.sciencelearn.org.nz/contexts/earthquakes/sci_media/video/learning_from_the_past; 2007.

• Pampanin, S. TVNZ News, 'Building a New Future in Wood', http://tvnz.co.nz/content/1257614/425823.html, 2007.

• Pampanin, S. "Simple and Low-Cost Technology for a Total Damage-Control: the Ultimate Challenge of Earthquake Engineering", Fumio Watanabe Symposium, Kyoto, 24-26 October 2008.

• Pampanin, S. "Emerging Damage-Resistant Connections for the Performance-Based Design and Retrofit of Structures, SILE08", Seminario internacional sopbre ligacoes estruturais, Lisbon, 21 Nov. 2008.

• Pender, M. J. 'Soil structure interaction, site effects and design actions standards', *Annual Conference, European School for Advanced Studies in the Reduction of Seismic Risk*, University of Pavia, Italy, May 30 2006.

• Pender, M. J. 'Seismic design and performance of surface foundations', Theme lecture, *4th International Conference on Earthquake Geotechnical Engineering*, Thessalonaki, June 2007.

• Pender, M. J. 'Earthquake resistant design of earth structures'*, IS -Tokyo 2009 conference, International Conference on Performance-Based Design in Earthquake Geotechnical Engineering — from case history to practice*, Tokyo, June 15-18, 2009.

• Pender, M. J., 'Modelling cyclic behavior pile foundations', *17th International Conference on Soil Mechanics & Geotechnical Engineering* Alexandria, Egypt, 5-9 October 2009.

• Pender, M. J., 'Integrated Design of Structure Foundation Systems', *The Fifth International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*, San Diego, California, May 24-29, 2010.

3. Scientific Advisory Role. Research personnel have been members of the following conference organising committees:

• Clifton, GC., *2007 Pacific Structural Steel Conference*, Wairakei, New Zealand, Chairman of Organising Committee, 13-16 March, 2007.

• Ingham, J. M., *7th Australasian Masonry Conference*, Technical Review Committee, Newcastle, Australia, 13-16 July, 2004.

• Ingham, J. M., *The New Zealand Concrete Industry Conference*, Queenstown, 16-19 September, 2004.

• Ingham, J. M., *ConMat '05, Third International Conference on Construction Materials – Performance, Innovations, and Structural Implications*, International Advisory Committee, Vancouver, Canada, 22-24 August, 2005.

• Ingham, J. M., *New Zealand Concrete Industries Conference*, Sky City Convention Centre, Auckland, 22-24 September, 2005.

• Ingham, J. M., *ACIC 07, Advanced Composites in Construction*, International Science Committee, University of Bath, Bath, UK, 2-4 April 2-4, 2007.

• Ingham, J. M., *14th International Brick and Block Masonry Conference*, International Technical Program Committee, Sydney, Australia, 17-20 February, 2008.

• Ingham, J. M., *14th World Conference on Earthquake Engineering*, International Working Group, Beijing, China, October 12-17, 2008.

• Ingham, J. M., *2009 Annual Conference of the Network for Earthquake Engineering Simulation (NEES)*, Honolulu, Hawaii, June 23-25, 2009.

• Ingham, J. M., The New Zealand Concrete Industry Conference, Rotorua, October 8-10, 2009.

4. Scientific Advisory Role. Research personnel have acted as reviewers for the following funding sources:

• Ingham, J. M., Australian Research Council (ARC) College of Experts, Discovery Projects Scheme (2005, 2006).

• Ingham, J. M., National Sciences and Engineering Research Council of Canada, Discovery Grant, 2007.

• Ingham, J. M., NEESR Research Program Solicitation, National Science Foundation, USA, 2009.

5. Scientific Advisory Role. Research personnel have acted as executive members of the following technical societies:

• Pender, M. J., President, New Zealand Society for Earthquake Engineering, 2006-2007. Immediate Past President 2008-.

• Ingham, J. M., Council member, New Zealand Concrete Society, 2009-.

• Ingham, J. M., Management Committee member, New Zealand Society for Earthquake Engineering, 2009-.

• Pampanin, S. Management Committee member, New Zealand Society for Earthquake Engineering, 2005-.

• Pampanin, S. Council Member New Zealand Concrete Society, 2004-.

• Pampanin, S. Member of *fib (federation internationale du beton;* International Federation for Structural Concrete*)* Committee 7' Seismic Design' 2005-

• Pampanin, S. Co-chairman of *fib* Working Group 7.5 'Seismic Design of Buildings Incorporating High Performance Materials', 2005-

• Pampanin, S. Member of *fib* WG 7.6 'Comparison of Seismic Code Provisions', 2003-

• Pampanin, S. Member *fib* WG 6.10 'Seismic Design of Low-Rise Precast Concrete Buildings in Seismic Regions', 2007

• Pampanin, S. Member of Task Group on Precast Concrete for the revision of the NZS3101:2006 Concrete Code, 2004-2006

• Pampanin, S. Member of the ACI (American Concrete Institute)-440-F Committee for the preparation of Guidelines on Seismic Retrofit of Existing R.C. Building using Fiber Reinforced Polymers, 2006-

• Pampanin, S. Member of the committee 'Precast Concrete Floor Overview Group' (PCFOG) organized by the Department of Building and Housing for the preparation of Guidelines for the Seismic Design, Assessment and Retrofit of Hollowcore floors, 2006-2009.

6. Editorial Board Membership. Research personnel have acted as members of the following editorial boards:

• Pender, M. J., 'Guidelines for Geotechnical Earthquake Engineering Practice in New Zealand', New Zealand Geotechnical Society.

7. New Research Collaboration.

Associate Professor Stefano Pampanin has been invited in 2004 to join a major (17 Million Euro) EU funded project LESSLOSS (2003). The project, coordinated by the University of Pavia (Prof. Gian Michele Calvi), led 46 research teams in Europe.
Dr. Pampanin was awarded ISAT Linkage funds for the development of the Joint EU/NZ Research Project on "Reduction of Seismic Risk for Existing Buildings: Vulnerability Assessment and Retrofit Solutions"

The website of the LESSLOSS project[1] states:

> "In 2004 the University of Canterbury was invited to join with a major EU funded programme in a project entitled Reduction of Seismic Risk for Existing Buildings: Vulnerability Assessment and Retrofit Solutions. This collaboration involves a formal link between an existing 17 million Euro EU funded project on 'Reduction of Seismic Risk and Landslides (LESSLOSS)' and a NZ$3.6 million FRST funded project on 'Retrofit Solutions for NZ's Earthquake Risk Multistorey Buildings'. The linkage will give NZ researchers access to knowledge and information generated by more than 46 research teams involved in the EU project. Direct collaboration will occur between the University of Canterbury and the University of Pavia, with groups led by Stefano Pampanin and Professor Calvi respectively.."

As part of this direct collaboration with the ROSE School, two ME students from the ROSE have visited UoC for 6-9 months each. Mario Galli's thesis focused on the modeling and numerical investigation of the seismic behaviour of pre-1970 reinforced concrete buildings with masonry infilled frames. His work was co-supervised by Associate Professor Guido Magenes, an international expert in unreinforced masonry structures, and presented at a ROSE School seminar in May 2006. Gabriele Attanasi (ROSE Student and alumnus of the Collegio Borromeo in Pavia as Stefano Pampanin) collaborated during his stay at UoC with Ph.D. Student Umut Akguzel on the development and refinement of simplified assessment tool for the design of Fibre Reinforced Polymers (FRP) retrofit in exterior under-designed beam-column joints. The results of experimental validation of the method were first presented in 2007 in Patrass and, after more experimental testing at UoC to account for the variation of axial load, are ready for submission to an international Journal. Collaboration with Dr. Bolognini and Associate Professor Alberto Pavese continued on the topic of FRP strengthening.

8. New Research Collaboration.

Partnership between the University of Canterbury Associate Professor Stefano Pampanin and the University of Toronto Associate Professor Constantin Christopoulos has been initiated and carried out on two topics:

a) Development of a low-invasive retrofit solution based on a diagonal metallic haunch.

The concept was originally proposed by Pampanin and Christopoulos (2003) as an extension of new design or retrofit solutions developed for steel moment resisting frames following the significant number of weld fractures observed after the Northridge earthquake (Gross et al., 1999, Christopoulos and Filiatrault, 2000).

The experimental validation and further refinement of the proposed retrofit solutions has been carrying out at UoC (in partnership with UoToronto) since 2003 with very satisfactory results on the improved response on beam column joints, both 2D and 3D. The ME Student TeChen completed his thesis on the topic in 2006. Dr. Christopoulos from Toronto has been acted as external supervisor.

[1] http://www.lessloss.org/main/index.php?option=com_content&task=view&id=79&Itemid=50

The first test results on a 2D configuration were first presented at the Kobe (Jan) 2005 symposium, following the inauguration of the E-Defence's Shake Table.
A design procedure with validation on 2D beam column joints has been published on EESD in 2007. Test Results on 3D corner joint configuration will be submitted for publication in the near future.

Further refinements of the system (towards a fully fastened solution) have been carried out in collaboration with University of Stuttgart. Prof. Eligehausen's Research Team (see item 9 below).

b) Estimation of residual/permanent deformation on buildings including torsional effects due to in-plan irregularity.

ROSE Ph.D. Student Didier Pettinga (completed in 2007, currently employed in a consulting office in Vancouver), co-supervised by Stefano Pampanin (UoC, Rose School), Constantin Christopoulos (UoToronto) and Prof. Nigel Priestley (ROSE School, Pavia), comprehensively developed this topic originally proposed by Stefano Pampanin and Constantin Christopoulos in previous publications (2002-2003), using both numerical and experimental shake table tests. The extensive results were published into three journal papers and a ROSE report, in addition to the Ph.D. Thesis. As part of the research joint collaboration Mr. Pettinga moved from Pavia to UoC to Toronto with several visits, including two summers at UoC to carry out the shake table tests on a one-storey prototype torsionally-prone building.

9. New Research Collaboration.

A research collaboration has been initiated since 2005 between the University of Canterbury Research Team (Associate Professor Stefano Pampanin) and the University of Stuttgart (Profs. Eligehausen and Josko Ozbolt, Institute of Construction Materials) on two topics:

a) Refined Finite Element Modeling (FEM) of reinforced concrete beam-column joint with substandard detailings (typical of pre-1970 constructions) before and after retrofit technique. Thanks to the direct involvement of Prof. Josko Olzbolt, author of MASA, based on microplane concrete model, a very sophisticated model of the damage mechanism and cyclic behaviour of beam column joint with plain round bars, likely shear failure in the joint and high bond slippage issues has been developed. This refined model has been used for parametric analysis to calibrate the proposed simplified analytical tools

b) Special attention, given the international expertise of Prof. Eligehausen, has been given to the anchorage to concrete elements of some of the proposed retrofit solutions, with particular emphasis given to the metallic haunch system.

   Giovacchino Genesio, Ph.D. Candidate at Stuttgart University, co-supervised by Prof. Eligehausen and Stefano Pampanin, has been involved in the development of the model and validation with several experimental tests carried out at University of Canterbury.
   As part of this collaboration, Giovacchino has been awarded a DAAD (German Research Science Foundation) Study Abroad Scholarship and spent a period of 9 months at UoC to work in collaboration with Umut Akguzel (Ph.D. candidate) on the refinement of the haunch solution towards a fully fastened system.
   Umut Akguzel will revisit the University of Stuttgart for 4 months (May-August) in 2009 to further develop the modeling (and validate with experimental tests he personally carried out) on FRP strengthening of beam column pre-1970s joints when subjected to

uni and bi-directional loading. Direct co-funding and financial support for his accommodation and leaving expenses are provided by U of Stuttgart.

Under the auspices of the NZ Concrete Society, a series of one-day or half-day seminars on anchorage to concrete were given to practitioners, including applications and issues related to seismic retrofits. In the past three years, different venues were covered (Auckland, Christchurch, Wellington, Nelson, Dunedin, Tauranga) by Prof. Eligehausen (fastening technology and design) and Stefano Pampanin (retrofit applications).

In this period, local tests on fastening techniques under cyclic tensile-shear for seismic application have also been carried out at UoC by an internship student from France (Romain Laffont) working with Stefano in cooperation with Prof. Eligehausen (partial sponsoring by the company Wurth) as well as by other UoC research assistants as part of another research and development collaboration for the development of seismic-resisting fasteners with Fischer-Germany and University of Vienna.

10. **New Research Collaboration.** Associate Professor Ingham has developed a new research collaboration with Associate Professor Michael Griffith of the University of Adelaide. This collaboration has dual objectives associated with:

(1) extending the existing research of Griffith et al. associated with the out-of-plane response of single leaf (wythe) unreinforced masonry walls to consider both multi-leaf walls and displacement-based time-history analysis to determine wall instability for New Zealand's identified seismic zones (see Key Output No. 3). This is being achieved via Griffith being co-supervisor of UOA doctoral researcher Hossein Derakhshan; and

(2) co-ordinated research associated with the development of near surface mounted fibre reinforced polymers as a seismic retrofit solution mitigating out-of-plane failure of URM walls whilst respecting heritage characteristics that prevent surface bonding of the URM walls. This is being achieved via the grant:

> Griffith, M., et al. 'Earthquake protection of masonry buildings', *Australian Research Council Discovery Grant, University of Adelaide Grant # DP 0879592, AUS$435,000, 2007.*

The above project is being directed by Griffith, with Dr Masia of Newcastle University (Australia) providing supplementary laboratory testing and Ingham of UOA providing field validation of developed retrofit solutions. Griffith is co-supervising UOA doctoral student Dmytro Dizhur.

(C) User Esteem

1. **Industry partnerships.** UOA software engineers, led by Dr Gerald Weber, have partnered with Patrick Cummuskey, responsible for special projects at Auckland City Council, to develop a searchable database software program to perform the 'Initial Evaluation Procedure' (IEP) that was originally developed by the New Zealand Society of Earthquake Engineering as a paper based assessment tool. The program has been demonstrated to Auckland, North Shore City, Waitekere City, Rodney District, Manukau City, Franklin, and Papakura. Furthermore, the research team is working closely with Claire Stevens, responsible for earthquake prone buildings at Wellington City Council, regarding implementation of the software, and with several leading engineers including David Hopkins, advisor to the Department of Building and Housing, and Craig Stevenson of Connell Wagner. The software is also being distributed to engineering consultants who have communicated to the research team their interest in assisting with ongoing development of the software. Examples include Matthew Williams from Duffel Watts Consulting Group in Dunedin, and Michelle Rafferty of Eastern Consulting Limited in Masterton.

2. **Industry partnerships.** End-user implementation and/or codification into Standards of the research related to assessment and retrofit of R.C. buildings:

- UoC researchers have been engaged in technical discussions with Spencer Holmes Ltd (Director/Principal Peter Smith) regarding the practical implementation of some of the more recently developed and proposed retrofit solutions for pre-1970s Reinforced Concrete buildings including: a) haunch system b) external post-tensioned (rocking dissipating) walls c) selective weakening of existing walls with additional post-tensioning d) development of a dual system (wall-frame) by modifying an interior column within a deficient frame to act as a wider wall.

Example of these building retrofit case studies, some of which are under actual implementation are:

1. Hutt City Council Administration Building – 4 storeys, pre-1970 R.C.. Multiple strengthening schemes developed to a preliminary stage for consideration including haunch, post-tensioned walls solutions. Selected solution consisted of improving the displacement capacity of interior columns.
2. 85 Molesworth St, Thorndon, Wellington – St Laurence Group – 11 storeys, 1970, fully fenestrated R.C. perimeter with upstands above floor level. Change of use required strengthening as per the Building Act. First case of possible application of selective weakening for wall system. Preliminary design only (2005).
3. 3 Plimmer Steps, Lambton, Wellington – KGH Trust – 3 storeys, 1916, URM. Heritage building, strengthening scheme to add 2-storey in timber. Post-tensioned walls solutions considered. Conceptual stages only, some preliminary design completed.
4. 32-24 Currie St, New Plymouth- ASB Building – 3 storeys, pre-1930 R.C. and URM. R.C. frames follow by FRP wrapping. Preliminary design stage.
5. 135 Victoria St, Te Aro, Wellington - Capital Office Fund Ltd – 11 storeys, post-1970, R.C. frames. Weakness in floor diaphragm found during Wellington City Council assessments of buildings with dycore floor systems. Strengthening of floor diaphragm action using post-tensioned tie bars. Implemented Oct/Nov 2007.
6. 41-47 Dixon St, Te Aro, Wellington – Dixon St, Deli – 4 storeys, 1926, Concrete encased structural steel RSJ frames and R.C. walls. Strengthening RSJ columns with additional steelwork and concrete. Strengthening RSJ beam-column connections with additional steelwork to create seismic-resistant joints. Selective weakening of R.C. spandrel beams to front façade. Adding of new R.C. shear walls at ground floor level on front facade. Currently in developed design stage.
7. 61 Molesworth St, Thorndon, Wellington – St Laurence Group – Existing 8 storey building, 1962, R.C. frames. Constructing new 9 storey structure to south and new 11 storey structure to north, adding 2 new levels to existing structure. R.C. shear wall cores to new north and south structures. New and existing floors tied from north to

south with post-tensioned strands, and from east to west with shear dowels into existing structure. Currently in developed design stage.

• Prof Des Bull and Associate Professor Stefano Pampanin have been invited to be part of the Precast Concrete Floors Overview Group (PCFOG) to develop Design Guidelines for the Design, Assessment and Retrofit of Hollowcore floors. The Department of Building and Housing initiated the development of these Guidelines by bringing together representatives of New Zealand Concrete Society, the NZ Society for Earthquake Engineering and the Structural Engineering Society of New Zealand. Most of the content of these guidelines in terms of Assessment and Retrofit (two major chapters) have been based on the research evidences provided by UoC researchers (Obj. 1). It is intended that these guidelines would form a critical document for daily used in any NZ consulting office. Valuable input and feedback has been and is continued to be given from overseas *fib (federation internationale du beton;* International Federation for Structural Concrete*)* committee members (involved in precast concrete research) to guarantee the international relevance and possible use overseas of the same document. DBH has provided financial support to some members.

• Following a similar strategy, an additional effort has been initiated by a Special Group of SESOC (Structural Engineering Society of New Zealand) in collaboration with Prof. Des Bull and Holmes Consulting Group to investigate the seismic performance of Double Tees floor unit. In particular, the so call "pig-tail" details typical of NZ construction practice for flange-hung Double Tee flooring has been assessed by analytical studies and industry-funded experimental testing. As first outcome of this industry partnership, a joined paper on seismic assessment of flange-hung Double Tee floor systems is due to appear on the next issue of the SESOC journal. It is also envisaged that a second DBH working group will be created to develop similar comprehensive guidelines for Double Tee floors as done for the hollowcore document.

3. **Industry partnerships and co-funding:** Collaboration with Germany-based (but worldwide present) companies specialized in anchorage to concrete (Fischer and Wuerth) has been initiated with substantial in-kind or direct co-funding to develop solutions for seismic application of anchors (i.e. fully fastened haunch, shaking table test validation of existing ones). A further joined research proposal with the University of Stuttgart is also under preparation (contract yet to be prepared and signed) for the investigation of post-installed rebars in seismic application. The results of this research, though not being part of any milestone of this project milestones or declared deliveries, nor exclusively limited to retrofit of existing building, are anticipated to be of great interest and benefit for allow broader use of the retrofit solutions proposed in this project (i.e. external post-tensioned walls and columns, fastening of Plug&Play additional energy dissipaters etc)

4. **Industry partnerships.** UoC research has substantially benefited by the collaboration with industry partners including Sika and BBR Contech for the development of applications related to Fibre Reinforced Polymer retrofit and/or post-tensioning systems (beam-column joint or wall selective weakening, etc). Industry partners have offered free labour and materials to the Research Unit. FIP Industriale (Padova, Italy) has provided technical assistance and delivered four viscous dampers prototypes from Europe to be used for the post-tensioned wall system (Advances Flag-Shape) in combination with hysteretic damping systems. Discussion on possible collabroation for the use of Shape Memory Alloys tendons/devices has been initiated.

5. **Industry partnerships.** Consulting Engineers Dunning Thornton Ltd (http://www.dunningthornton.co.nz/) are proposing to use the 'Sliding Hinge Joint' structural detail as a retrofit solution for the Hope Gibbons Building located in Wellington. The Hope Gibbons Building is a heritage 8-storey building, constructed in 1925 and now of mixed commercial and residential use. The Sliding Hinge Joint (SHJ) was originally developed by Associate Professor Clifton for use in new construction, but has been

adapted in the current research programme to be used as a seismic retrofit technique. The SHJ remains rigid under normal conditions, becomes flexible in a major earthquake allowing controlled beam to column rotation to occur in a rigid frame, and then becomes rigid at the conclusion of shaking. It is easily repaired if required following a severe earthquake and is well suited to use in retrofit projects.

6. **Industry partnership and direct co-funding.** The partnerships detailed below are associated with research being performed on the seismic assessment and retrofit of unreinforced masonry buildings:

- UOA have partnered with Reid Engineering Systems Limited and Technology New Zealand to develop a validated shotcrete mix design using Engineering Cementitious Composites (ECC). This partnership has been in contact with Salmond Reid Architects who are heritage and conservation architects responsible for relocation of the historic URM Birdcage Hotel in central Auckland as part of the improvements to the Victoria Park Tunnel and Viaduct. The hotel will be relocated 30 m in order to accommodate the viaduct and tunnel improvement works.
- The UOA research team partnered with John Cuthbert of Dunning Thornton Consulting Ltd to assess the lateral capacity of the unreinforced masonry partition walls of the 1932 Weir House, a student accommodation building owned by Victoria University of Wellington that was scheduled to undergo seismic strengthening. During in-situ out-of-plane testing the face pressure value specified by NZS 1170:5 was satisfactorily exceeded, providing verification that no seismic retrofit was necessary and saving the client over $100,000 of anticipated seismic retrofit costs. The UOA research team was re-approached on 4 March 2009 with a request to conduct further in-situ testing on the top level of the building. If these walls are also found to be satisfactory, a further $50,000 saving is expected.[2]
- In July 2008 UOA research personnel partnered with Mr. Jerry Lahra, the manager of Helifix (Australia), who manufacturer and supply stainless steel reinforcement and related products in the Asia-Pacific region. In January 2009 an experimental research program using threaded stainless steel reinforcement as a retrofit technique for unreinforced masonry walls was agreed on between UOA and Helifix, with Helifix contributing $3,000 in kind.

7. **Industry partnerships.** Details are provided below of industry partnerships associated with gaining an understanding of the factors that influence a building owner's decision process regarding the implementation of seismic retrofits:

- Derek Anderson (Chairman, Christchurch Heritage Trust) and Dave Margetts (Heritage Advisor, New Zealand Historic Place Trust Canterbury) assisted doctoral researcher Temitope Egbelakin with the report 'Incentives, motivation and impediments for improved seismic retrofit implementation in New Zealand', which was prepared for Christchurch Heritage Trust to better understanding how building owners make decisions about when implementing seismic retrofit. Findings have helped Christchurch Heritage Trust develop policies and strategies to motivate owners of earthquake prone buildings to consider seismic retrofitting, rather than demolition.
- Doctoral researcher Fei Ying partnered with Ian Harper, the Facilities Manager for the Auckland District Health Board (ADHB), to develop a Value Focused Thinking decision framework that was applied to the future of Building 5, in Greenlane, Auckland, a Queen Anne Revival Style building opened in 1907. ADHB decided to demolish the building and reserve the land for future use. Results were presented

[2] Results were presented in the articles: (1) Dizhur, D., Derakhshan, H., Cuthbert, J., Ingham, J. M., 'In-situ Out-of-plane Testing of Unreinforced Masonry Partition Walls', *2009 NZSEE Conference: Why do we still tolerate buildings that are unsafe in earthquakes?*, Christchurch, April 3-5, 2009. (2) Dizhur, D., Derakhshan, H., Ingham, J. M., 'In-situ out-of-plane testing of unreinforced masonry partition walls', Paper No. 228, *11th Canadian Masonry Symposium*, Toronto, Ontario, Canada, May 31 - June 3, 2009.

in: Ying, F., Wilkinson, S., Corner, J., (2008) 'Developing a model to assist earthquake retrofitting projects - A pilot case study', *Institute for Operations Research and the Management Sciences (INFORMS) Annual Meeting*, 12-15 October, Washington DC.

8. **Direct Co-funding.** $1,584,600 of direct co-funding has come from NZ and overseas institutions financially supporting doctoral students who are not supported by the FRST research programme funds. Details of these doctoral students, and the source and amount of their financial support, are provided in Appendix 1.

(D) Evidence of Delivery of Benefits to New Zealand

1. Delivery of contracted milestones (see table below)

2. Highlights of delivery

Programme objectives. The primary objective of this research programme is to provide solutions addressing the comparative absence of a national platform of knowledge and expertise associated with seismic retrofit or rehabilitation of the nation's multi-storey buildings. This research is aligned with the goals of the Department of Building and Housing (DBH)), the Structural Engineering Society of New Zealand (SESOC), and the New Zealand Society of Earthquake Engineering (NZSEE). The research addresses the value chain between research providers, research users (structural designers), building owners, and the public, plus the need to stimulate increased investment from owners of New Zealand's multi-storey earthquake risk buildings.

(a) New tools and technology. Tools and technologies developed include:

- A database software tool for performing the NZSEE Initial Evaluation Procedure.
- Low-invasive low-cost diagonal metallic haunch for pre-1970s frame systems.
- Advanced post-tensioned-dissipative concrete (or timber) walls for retrofit of frames combining viscous and hysteretic dampers.
- Plug&Play replaceable dissipaters for existing structures (concrete, masonry, steel). They consist of mild steel rebar fused and grouted in an antibuckling tube.
- Selective weakening solutions for concrete frames, walls or floors.
- Assessment tools and retrofit guidelines manual for hollowcore floors.
- Revised assessment procedure to evaluate the strength hierarchy and event sequence in reinforced concrete beam-column joints before and after FRP retrofit.
- Evaluation techniques for the bidirectional response and displacement capacity of Post-1970s columns with inadequate transverse reinforcement.
- Design methodology and technique for the application of FRP layers to exterior corner beam-column joints with minimum disruption to building use.
- An innovative sliding joint detail for the retrofit of steel buildings.
- A revised assessment methodology for the out-of-plane response of unreinforced masonry buildings.
- A revised detailed assessment process for unreinforced masonry buildings.
- Design tools for retrofitting of unreinforced masonry using multiple intervention techniques.
- Design tools for the utilisation of rocking (1) of buildings having shallow foundations and (2) masonry piers in masonry framed buildings.
- Improved modelling capacity for assessing the effect of structure-foundation interaction on seismic retrofit decision.
- A decision making framework to assist building owners in their determination of appropriate levels of investment in seismic retrofit.
- An internet based tool for determining indicative costs of building retrofits.

(b) End-user uptake of research and industry engagement initiatives. Dissemination via reporting to the Industry Advisory Board and publishing at local conferences and in relevant journals has ensured regular engagement between the research team and its end users. Specific examples of end user uptake include:

- Use of Initial Evaluation Procedure software by Connell Wagner, Eastern Consulting Limited and Duffill Watt Consulting Limited, plus Auckland and Wellington City Councils.
- Feasibility studies and implementation of proposed solutions on concrete buildings.
- DBH guidelines for assessment and retrofit of hollowcore floors.
- Investigation of Double Tee flange-hung detailing, which has resulted in a SESOC statement paper and immediate change of current construction practice.

- Implementation of a sliding joint retrofit intervention by Dunning Thornton Limited on the steel-framed Hope Gibbons building in Wellington.
- Testing of flexible timber diaphragms of 1903 Nathan House.
- Sample extraction and insitu testing following the 2007 Gisborne Earthquake.
- Implementation of URM fibre reinforced polymer retrofit research by Duffill Watt Consultants Limited in conjunction with seismic retrofit at the University of Otago.
- Implementation of Engineering Cementitious Composite shotcrete research in collaboration with Salmond Reed Architects and Sinclair Knight Mertz associated with strengthening and relocation of the Birdcage Hotel in Auckland.
- Engagement with Christchurch Heritage Trust to ascertain factors influencing building owner's decision process regarding retrofit implementation.
- Engagement with Auckland District Health Board to develop a decision making framework for retrofit implementation.

Capability development in leading edge research. Ingham, Pampanin, Wilkinson and Butterworth have been promoted from Senior Lecturer to Associate Professor, and Ingham and Pampanin are currently both on the Management Committee of the New Zealand Society for Earthquake Engineering. Details of the number of project postgraduate students (both New Zealand citizens and international students) are given below. The data provided above excludes undergraduate student researchers associated with the research programme as part of the Bachelor of Engineering degree.

Capability development of postgraduate student researchers	**Graduated**	**Currently Enrolled**
PhD student researchers	2	24
Masters of Engineering	9	1
Masters of Architecture	1	

(c) Recruitment of talented researchers from overseas. Twenty PhD student researchers and one ME student research have relocated from a total of ten overseas countries to NZ to participate in the research programme (see Appendix 2).

(e) Programme management. Programme management has been multi-tiered, with twice yearly reporting of research progress to the Industry Advisory Board, ensuring that the focus and direction of the research programme objectives have remained relevant to end user structural earthquake engineers, and ensuring that separate research tasks were properly integrated. Supplementary ad-hoc meetings of the advisory group were scheduled as required, and a parallel exercise has been executed with members of the research team invited to be part of the PCFOG Committee, coordinated by the Department of Building for the preparation of ad-hoc Guidelines for the Seismic Design, Assessment and Retrofit of Existing Building. Research progress has been presented at the annual conferences of the NZSEE. Finally, management of progress related to specific building types has been facilitated via periodic student symposiums held at the two universities to ensure information sharing amongst the research programme team.

3. Strategic relevance. The New Zealand Building Act requires all Territorial Authorities to develop policies associated with how earthquake-prone buildings will be identified and addressed in their region, and research programme findings have confirmed that there are several thousand buildings that require seismic retrofit implementation in order to be compliant with the Act. Findings from this research programme specifically address this need, and are providing targeted solutions that match New Zealand's unique building inventory. The dissemination of research findings to the country's professional earthquake engineers via nationwide seminars and articles at conferences and in technical journals endorsed or published by NZSEE and SESOC is a well proven mode of dissemination within New Zealand. Several early examples of implementation of research programme findings have confirmed the strategic relevance of this research programme.

Table: Progress on delivery of contracted milestones (UOAX0411)

Milestone	Intended date of completion	Actual date of completion	Status of delivery/evidence
Objective 1 – Retrofit solutions for post-1970 Buildings			
1.1 Assembly of Industry Advisory Group, convened by NZSEE (common to Objectives 1 and 2).	01/12/2004	01/12/2004	In late 2004 NZSEE were addressing a number of strategic issues for the society, and were unable at that time to provide principal support for formation of the IAG. Instead the Structural Engineering Society of NZ (SESOC) were approached, who agreed to oversee this activity. The first chairman was Dene Cook, then an employee of the Cement and Concrete Association of NZ (CCANZ) and chair of the NZS 3101 Standards committee. When Dene retired from the CCANZ in 2006, Peter Smith of Spenser Holmes Ltd agreed to participate as chair of the IAG. NZSEE recently appointed Win Clark as the Executive Officer of NZSEE, and Win has been serving as a member of the IAG. Furthermore, three members of the research team (Ingham, Pampanin and Pender) are now members of the NZSEE Management Committee.
1.2 Reviewed existing retrofit technologies appropriate to New Zealand's post-1970 earthquake risk reinforced concrete multi-storey buildings.	01/06/2005	01/06/2005	• Ireland, M., Pampanin, S., Bull, D. K. (2006). 'Concept and Implementation of a Selective Weakening Approach for the Seismic Retrofit of R.C. Buildings', *2006 NZSEE Conference: Remembering Napier 1931.* New Zealand Society for Earthquake Engineering, Napier, March 10-12. • Jensen, J., Bull, D. K., Pampanin, S. (2006). 'Conceptual Retrofit Strategy for Existing Hollowcore Seating Connections', *2006 NZSEE Conference: Remembering Napier 1931.* New Zealand Society for Earthquake Engineering, Napier, March 10-12. • Pampanin, S. (2007). 'Developments in seismic design and retrofit of structures: modern technology built on the ancients' wisdom'. Chapter 6, *Hazards and the Built Environment*, Lee Bosher (Ed.), Taylor and Francis, pp. 96-123.
1.3 Reviewed analytical modelling methods for retrofit implementation strategies for New Zealand's post-1970 reinforced concrete multi-storey buildings.	01/06/2006	01/06/2006	• Jensen, J. (2006). 'Experimental Investigation on the Seismic Performance of Hollowcore Floor Systems Before and After Retrofit Intervention', Masters of Engineering Thesis, Department of Civil Engineering, University of Canterbury. • Wood, L. (2008). 'Predicting Damage and Failure Mechanisms in Hollowcore Floor-lateral Resisting System Connections under Seismic Loading', Masters of Engineering Thesis, Department of Civil and Natural Resources Engineering, University of Canterbury. • Boys, A. (2009). 'Assessment of Seismic Performance of Poorly Detailed RC
1.4 Developed analytical modelling methods for retrofit implementation strategies for New Zealand's post-1970 reinforced concrete multi-storey buildings.	01/06/2007	2007 -2009	
1.5 Completion of experimental testing of structural sub-assemblies simulating construction of New	01/06/2008	01/06/2008	

Zealand's post-1970 reinforced concrete multi-storey buildings, incorporating targeted retrofit solutions.			Columns under Uni- and Bi-directional Loading', Masters of Engineering Thesis, Department of Civil Engineering, University of Canterbury. • Guidelines prepared by the Department of Building and Housing PCFOG committee (D. Bull and S. Pampanin contributors), 2009.
1.6 Completion of experimental testing of 3-dimensional full-scale sub-structures replicating retrofitted post-1970 reinforced concrete multi-storey buildings, incorporating targeted retrofit solutions.	01/06/2009	Mid-2010 (estimate)	Recognising that the retrofit solutions developed for post-1970 buildings typically focus on floors and columns, it has been decided to currently not perform full-scale testing of a 3D post-1970 building, but to instead focus on more smaller-scale shake table testing of pre-1970s frames (1/3 scale, three floors) with alternative retrofit solution. This more challenging task (in terms of number of specimens and complexity of implementing different options) is currently underway and intended to be completed by mid-2010.
1.7 Completion of financial feasibility analyses of retrofit solutions for New Zealand's post-1970 earthquake risk multi-storey buildings using interactive cost models.	01/06/2010	On track to be achieved	The web-based cost modelling system can be found at www.retrofitcost.net. In addition, see: Ying F, Wilkinson, S. (2007) 'The Application of Life Cycle Costing for Building Retrofit'. *CIB World Building Congress 2007: Construction for development*, Cape Town, South Africa, 14-18 May.
Objective 2 – Retrofit solutions for pre-1970 Building			
2.1 Assembly of Industry Advisory Group, convened by NZSEE (common to Objectives 1 and 2).	01/12/2004	01/12/2004	See Milestone 1.1
2.2 Completion of assessment of prevalence, geographic distribution, and degree of risk for various pre-1970 New Zealand multi-storey building details.	01/06/2005	On track to be achieved	This task took substantially longer to complete than was originally anticipated, due to poor data being available from Territorial Authorities. A qualitative census was conducted based upon statistical records of population density throughout New Zealand, specifically focussing on the 1880-1950 period. This data was correlated against information purchased from ValuationNZ associated with database entries of building surface fabric. Results are presented in: Russell, A. P., Ingham, J. M., 'Prevalence and distribution of New Zealand's unreinforced masonry building stock', *Bulletin of the New Zealand National Society for Earthquake Engineering (submitted April 2009)*
2.3 Reviewed existing retrofit technologies appropriate to New Zealand's pre-1970 multi-storey buildings.	01/06/2006	2006 (concrete) 2009 (URM)	• Pampanin. S., (2006). 'Controversial Aspects in Seismic Assessment and Retrofit of Structures in Modern Times: Understanding and Implementing Lessons from Ancient Heritage' Bulletin of the New Zealand Society for Earthquake Engineering, June, 39(2), pp. 120-133. • Ismail, N., Ingham, J. M., (2009). 'Case study and development of seismic retrofit solution for a heritage URM building', Paper No. 119, 11th Canadian Masonry Symposium, Toronto, Ontario, Canada, May 31 - June 3.
2.4 Reviewed analytical modelling methods for retrofit implementation strategies for pre-1970 multi-	01/06/2007	01/06/2007	• Pender, M., Wotherspoon, L., Ingham, J. M., Carr, A. (2006). 'Shallow foundation stiffness: Continuous soil and discrete spring models compared', *2006 NZSEE*

storey buildings.			*Conference: Remembering Napier 1931.* New Zealand Society for Earthquake Engineering, Napier, March 10-12. • Pender, M. J. (2007). 'Seismic design and performance of surface foundations', Chapter 10, *Earthquake Geotechnical Engineering*, K. D Pitalakis (ed), Springer, pp. 215 – 241. • Naderi, M. (2008). 'Finite Element Analysis of Riveted Joints in Old Steel Buildings in New Zealand', *2008 NZSEE Conference: Engineering an Earthquake Resilient NZ*, New Zealand Society for Earthquake Engineering, Wairaki, April 11-13. • Oyarzo-Vera, C., McVerry, G. H., Ingham, J. M. (2008). 'Ground motion records for time-history analysis of URM Buildings in New Zealand – The North Island', *2008 NZSEE Conference: Engineering an Earthquake Resilient NZ*, New Zealand Society for Earthquake Engineering, Wairaki, April 11-13.
2.5 Completion of development of analytical modelling methods for retrofit implementation strategies for pre-1970 multi-storey buildings.	01/06/2008	4-8/2008	• Akguzel, U., Pampanin., S. 'Effects of Variation of Axial Load and Bi-Directional Loading on the FRP Retrofit of Existing B-C Joints', *14th World Conference on Earthquake Engineering (14WCEE)*, Beijing, China, 12-17 October, 2008. • Marriott, D. 'The Development of High-Performance Post-tensioned Rocking Systems for the Seismic Design of Structures", Ph.D. Thesis, Department of Civil and Natural Resources Engineering' (thesis submitted, oral defence scheduled for May 2009). • Personeni, S., Di Pilato, M., Palermo, A. , Pampanin, S. 'Numerical Investigations on the Seismic Response of Masonry Infilled Steel Frames', *14th World Conference on Earthquake Engineering (14WCEE)*, Beijing, China, 12-17 October, 2008.
2.6 Completion of physical testing of structural sub-assemblies simulating construction of pre-1970 multi-storey buildings, incorporating targeted retrofit solutions.	01/06/2009	On track to be achieved	• Abdul Karim, A. R., Oyarzo-Vera, C., M.Sa'Don, N., Ingham, J. M. (2008). 'Forced Vibration Response of Small Scale URM House with Flexible Timber Diaphragm', *Australian Earthquake Engineering Conference, AEES* Ballarat, Victoria, Australia, Nov. 21-23. • Derakhshan, H., Ingham, J. M. (2008). 'Out-of-Plane Testing of an unreinforced masonry wall subjected to one-way bending' • Hertanto, E. (2006). 'Experimental Investigation on Pre-1970 Frame Subassemblies', Masters of Engineering Thesis, Department of Civil Engineering, University of Canterbury. • Marriott, D., Pampanin, S., Bull, D., Palermo, A. (2008). 'Dynamic Testing of Precast, Post-Tensioned Rocking Wall Systems with Alternative Dissipating Solutions', Bulletin of the New Zealand Society for Earthquake Engineering, 41(2), pp. 90-103. • Te-Chen, T. 'Development of a Low-invasive Metallic Haunch Solution for Pre-

			1970 RC frames', Masters of Engineering Thesis, Department of Civil Engineering, University of Canterbury, 2006. • Russell, A., Ingham, J. M. 'Flange Effects of an Unreinforced Masonry Wall Subjected to Pseudo-Static In-Plane Seismic Forces', *14th World Conference on Earthquake Engineering (14WCEE)*, Beijing, China, 12-17 October, 2008.
2.7 Completion of structural feasibility analyses of retrofit solutions for New Zealand's earthquake risk multi-storey buildings using probabilistic scenarios.	01/06/2009	On track to be achieved	Several structural feasibility studies (and in some cases) implementation of available or newly proposed retrofit solutions have been developed (See Industry Partnership and User Esteem and End-user uptake). Seismic Risk Analysis (within a GIS-environment) has also been carried out as decision making support (based on single or multi-criteria approach) for the seismic retrofit of buildings at a territorial scale. • Giovinazzi, S., Pampanin, S. 'Mitigation Analyses for the Selection of Effective Seismic Retrofit Strategies at a Territorial Scale', 2007 NZSEE Conference: *Performance by design - can we predict it?* New Zealand Society for Earthquake Engineering, Palmerston North, March 30 - April 1.
2.8 Completion of financial feasibility analyses of retrofit solutions for New Zealand's pre-1970 earthquake risk multi-story buildings using interactive cost models.	01/06/2010	On track to be achieved	The web-based cost modelling system can be found at www.retrofitcost.net developed by PhD student R. Jafarzadeh. This is being populated with data from New Zealand buildings, both pre and post 1970's buildings. The model is still being developed and has so far included extensive consultation with New Zealand businesses and government organisations (such as EQC and DBH) to make sure it is suitable for the needs of New Zealand. This cost data base will be used for building owners to give them a thoroughbreakdown of the costs involved in retrofitting their buildings.

Appendix 1: Co-funding for postgraduate student researchers

Postgraduate Student Researcher	**Funding Source**	**Amount** (NZ dollars unless noted otherwise)
Umut Akquzel	UoC Targeted Doctoral Scholarship Christchurch Heritage Trust Scholarship New Zealand Postgraduate Study Abroad Awards (NZPSAA) Conference travel/registration 14 WCEE, Beijing, (from UoC Civil Dept)	$87,500 $2,000 $5,000 $4,000
Tom Algie	UOA Doctoral Scholarship MORST Fulbright Scholarship (One year study at UC Davis)	$87,500 USD$25,000 (≈$43,700)
Jawad Arefi	ROSE School (Pavia, Italy), ME Scholarship	€23,600 (≈$54,600)
Razak Abdul Karim	Doctorate Training Award from Ministry of Higher Education, Malaysia	$104,000
Gabriele Attanasi	Collegio Borromeo (Pavia. Italy), Scholarship for Study Abroad	€ 2,500 (≈$5,800)
Anna Brignola	Italian MoRST Doctoral Scholarship	€ 30,000 (≈$69,500)
Dmytro Dizhur	UOA Doctoral Scholarship	$87,500
Debra Gardiner	Hopkins Scholarship NZFGW Haynes Williamson Fellowship Todd Foundation Award for Excellence NZSEE Research Scholarship Conference travel/registration 14 WCEE, Beijing, (from UOC Civil Dept)	$15,000 $15,000 $5,000 $5,000 $4,000
Giovacchino Genesio	DAAD (German NSF) grant for Study Abroad IWB - University of Stuttgart - Doctoral Scholarship	€6,960 (≈$16,100) €25,000 (≈$57,900)
Anas Ibrahim	Doctorate Training Award from Ministry of Higher Education, Malaysia	$104,000
Najif Ismail	'Overseas Scholarship, Phase-II', Doctoral Scholarship, Pakistan Higher Education Commission	$95,000
Charlotte Knox	UOA Doctoral Scholarship	$87,500
Yi Wei Lin	Tech NZ Scholarship	$25,333
Ronald Lumantarna	UOA Doctoral Scholarship	$87,500
Hamid Mahmood	UOA Faculty of Engineering International Doctoral Fees Bursary	$14,500
Dion Marriott	UOC Doctoral Scholarship Christchurch Heritage Trust Scholarship New Zealand Postgraduate Study	$87,500 $2,000 $5,000

Postgraduate Student Researcher	**Funding Source**	**Amount** (NZ dollars unless noted otherwise)
	Abroad Awards (NZPSAA) NZ Freemason Scholarship Conference travel/registration 14 WCEE, Beijing, (from UoC Civil Dept)	$10,000 $4,000
Claudio Oyarzo-Vera	Beca Presidente de la Republica de Chile Universidad Catolica de la Santisima Concepcion Academic Staff Scholarship	$88,000 $100,000
Lina M.Sa'Don	Doctorate Training Award from Ministry of Higher Education, Malaysia	$36,000
Weng Yuen Kam	Christchurch Heritage Trust Scholarship	$2,000
Aaron Wilson	Tertiary Education Commission Bright Futures Doctoral Scholarship Fulbright-EQC Graduate Award in Natural Disaster Research	$99,000 USD$15,000 (≈$26,200)
Lisa Wood	Kate Sheppard Memorial Trust (travel to Canada) UoC exchange office (travel to Canada) Dick and Mary Earle Scholarship in Technology Todd Foundation Scholarship Conference travel/registration 14 WCEE, Beijing, (from EQC and Holmes Consulting Group)	$5,000 $1,500 $17,000 $5,000 $3,250
Alistair Russell	NZ Postgraduate Study Abroad Award UOA Postgraduate tuition fees bursary	$3,000 $7,250
Total		$1,584,600

Appendix 2: Overseas research personnel who have relocated to New Zealand to be associated with the research programme

Name	Home country	Qualification sought/gained
Jawad Arefi	Iran	ME
Claudio Oyarzo Vera	Chile	PhD
Patricio Quintana Gallo	Chile	PhD
Fei Ying	China	PhD
Adane Gebreyohaness	Ethiopia	PhD
Giovacchino Genesio	Germany/Italy	PhD
Hossein Derakhshan	Iran	PhD
Reza Jafarzadeh	Iran	PhD
Majid Naderi	Iran	PhD
Mohammed Reza Zare	Iran	PhD
Masoud Moghaddasi	Iran	PhD
Gabriele Attanasi	Italy	PhD
Anna Brignola	Italy	PhD
Razak Abdul Karim	Malaysia	PhD
Anas Ibrahim	Malaysia	PhD
Lina M.Sa'Don	Malaysia	PhD
Weng Yuen Kam	Malaysia	PhD
Temitope Egbalakin	Nigeria	PhD
Najif Ismail	Pakistan	PhD
Hamid Mahmood	Pakistan	PhD
Umut Akquzel	Turkey	PhD