THE INFLUENCE OF EARTHQUAKES ON NEW ZEALAND MASONRY CONSTRUCTION PRACTICE

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SUMMARY

The changing nature of New Zealand masonry construction practice is reviewed, with emphasis placed on the role that observed damage from the 1931 Hawke's Bay earthquake had on subsequent construction practices. Early practice was to use solid clay brick unreinforced masonry construction, which resembled construction practices of the time from many other countries. Following 1931 the use of unreinforced masonry rapidly declined, and was eventually prohibited in 1965. Since that time clay brick masonry has generally been used as a veneer on timber framed domestic construction, utilising its durability and architectural characteristics. Concrete masonry construction has largely been modelled on reinforced concrete practices, with recent innovations being the use of post-tensioning and mortarless construction. Currently research effort is being committed to developing seismic retrofit solutions for existing unreinforced masonry buildings, with many being formally classified as New Zealand heritage buildings.

INTRODUCTION

New Zealand's masonry construction heritage is comparatively young, spanning from 1833 till the present time – a period of less than 200 years. Consequently, a study of New Zealand's masonry building stock has a narrow scope in comparison with international norms (see for instance Binda and Saisi 2005; Lourenço 2006; Magenes 2006). This comparatively narrow time period has the advantage of facilitating the documentation and reporting of New Zealand masonry construction practice with a greater degree of accuracy than is often possible in countries with an older and more diverse history of masonry construction (Binda 2006).

This paper begins with a review of pre-European and early European construction, followed by a study of the influence that earthquake damage during the 1931 Hawke's Bay earthquake had on post-1931 masonry construction practice in New Zealand, and concludes with a report on current efforts to develop seismic retrofit solutions for New Zealand's heritage unreinforced masonry buildings. Emphasis is currently being given to the comprehensive development of masonry building typologies and material property characterisation (Russell and Ingham 2007a, 2008), leading to development of both component level and system level solutions for seismic retrofit interventions.

THE EARLY SETTLERS

The first inhabitants of Aotearoa New Zealand were groups of Polynesian explorers who discovered and settled the islands in the period A.D. 800-1000 (King 2003). These people did not develop a tradition of building in masonry, but instead built using timber, earth and most commonly raupo (bulrush). Examples of Maori construction are shown in Figure 1 and Figure 2.

Figure 1. Raupo whare (house) at Wairau Pa, ca. 1880 [Alexander Turnbull Library].

Figure 2. Raupo and timber whares of a Maori village at Maketu, Kawhia, 1895 [Alexander Turnbull Library].

Captain James Cook anchored off the coast of New Zealand on 9 October 1769. This event was followed by a gradual haphazard increase in the population of Europeans in New Zealand over the next 70 years, initially primarily associated with whaling, but also involving kauri timber extraction and gold mining. Jacobs (1985) reports that the European population of New Zealand in 1830 was probably a little more than 300. By 1839 the number had risen to possibly 2000, and at the beginning of the 1850s there was 26,000 Europeans in New Zealand (see Figure 3 for recorded population data). These first European settlers found themselves without their familiar building materials, so initially emulated the style and construction of Maori dwellings (Shaw 2000). For the most significant early buildings, such as churches and assembly buildings, architects from Australia or England were commissioned.

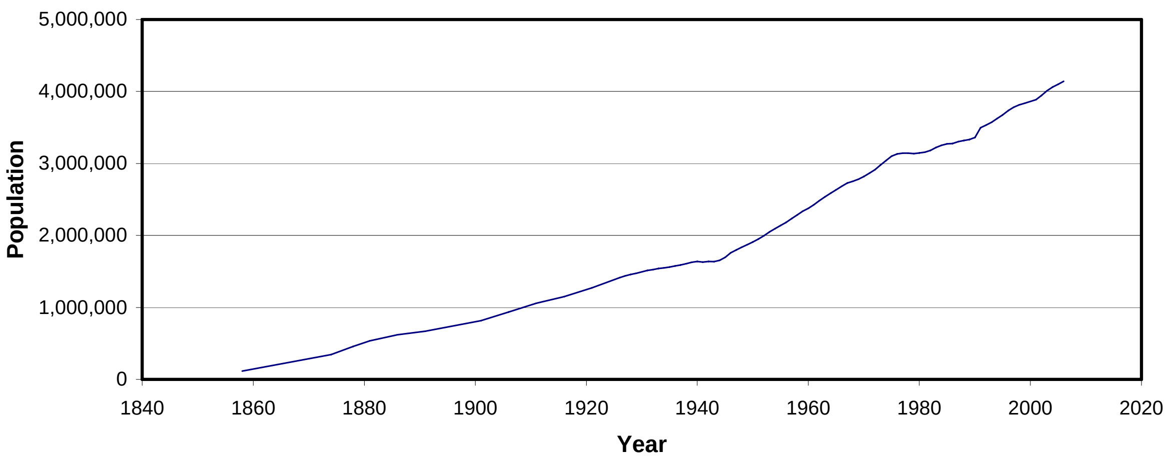

Figure 3. New Zealand total population data, 1858-2007.

Captain William Hobson's arrival in Auckland in 1840 as the First Governor General of New Zealand marked the beginning of New Zealand as a British colony. Auckland's first years were modest, with the city providing the chief port of call for sailing ships in the Pacific Ocean, and providing the garrison for British troops and navy during the 1860s that were present due to tensions between Maori and Pakeha (white New Zealanders) over land ownership. The presence of the troops brought money to the city. However gold mining was eventually to provide greater prosperity for Auckland, with gold rushes in nearby Thames and the Coromandel (Fields and Stacpoole 1973).

Construction of this period was primarily of timber for residential and small commercial buildings (see Figure 4 and Figure 5), but masonry buildings did begin to appear close to the harbour (see Figure 6 and Figure 7). Oliver (2006) reports that clay bricks were first manufactured in Auckland in 1852, with production of about 5,000 bricks per day. Timber was in plentiful supply and indeed it was not uncommon to just burn the timber where it stood rather than mill it, so it was only natural that outside the central city nearly all buildings were constructed of timber. By 1886 timber was being felled nationwide at the rate of several million feet a year, with timber extraction being the country's leading industry. Even within Auckland central city the construction of timber buildings was not restricted until the City of Auckland Building Act of 1856. A fire in central Auckland in 1858 provided further impetus for the transition from timber to clay brick masonry construction.

Figure 4. Shops on Queen Street, Auckland, 1859 [Alexander Turnbull Library].

Figure 5. 1866 view of the east side of Queen Street, Auckland, looking north [Alexander Turnbull Library].

Figure 6. 1866 View of the lower end, west side, of Queen Street, Auckland [Alexander Turnbull Library].

Figure 7. Queen Street and Queen Street Wharf, Auckland, in 1882 [Alexander Turnbull Library]

The lack of durable local building stone meant that the great majority of city buildings were constructed of clay brick with a stucco finish. Figure 8 and Figure 9 illustrate typical construction scenes (although dated from a slightly later period). In other parts of New Zealand there was a more plentiful supply of natural stone, with New Zealand's earliest masonry building having been constructed of stone in 1833 (see Figure 10). Figure 11 shows an example of early rural construction in parts of New Zealand were timber was scarce and natural stone was the primary construction material.

Figure 8. Group photograph of the construction workers, including bricklayers, that built the Stratford Public Hospital during 1906-1907 [Alexander Turnbull Library].

Figure 9. Brick building under construction, ca 1920 [Alexander Turnbull Library].

Figure 10. The 1833 Stone Store at Kerikeri was built by the Church Missionary Society. Stone was used to provide greater strength against possible attack [A P Godber Collection, Alexander Turnbull Library].

Figure 11. Two Chinese miners in front of a stone cottage in central Otago, ca 1860 [Alexander Turnbull Library].

Evident in several of the above figures is a predisposition to emulate 'mother country' British architecture. To some extent this was due to the fact that there were very few architects in New Zealand prior to 1880, with buildings such as the 1865 Bank of New Zealand, the 1888 Auckland City Art Gallery and the 1911 Auckland Town Hall, all being designed by Melbourne based architects (Haarhoff 2003).

Figure 12 shows Auckland at a time where the majority of buildings were of timber, but a number of masonry buildings were becoming prominent. However Figure 13 shows that not all masonry buildings were well constructed. Hodgson (1992) reports that inferior materials and uncertain ground conditions were not uncommon in building projects of this period. Hodgson also reports that the city went through a transformation during the 1870s when almost all timber buildings were replaced by masonry structures, and Figure 14 and Figure 15 show that by 1910 the central city was composed almost entirely of unreinforced masonry buildings. Stacpoole and Beaven (1972) have similarly reported that Auckland's early wooden buildings dating from the 1840s were badly in need of replacement by the 1860s.

Figure 12. Looking down Shortland Crescent, Auckland, circa 1865. Construction is a mix of timber, brick masonry and stone masonry [Alexander Turnbull Library].

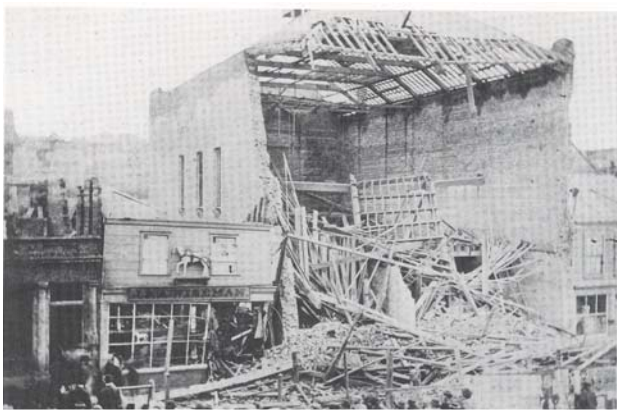

Figure 13. Collapse of a new masonry auction market building, Queen Street, 1865 [Alexander Turnbull Library].

Figure 14. Looking along a row of commercial buildings on Queen Street, Auckland, ca 1910 [Alexander Turnbull Library].

Figure 15. Lorne Street, Auckland, ca 1910 [Price Collection, Alexander Turnbull Library].

WAIRARAPA AND MURCHISON EARTHQUAKES

The Wairarapa Earthquake occurred on Tuesday 23 January 1855 and had an estimated magnitude of M8.2 (Grapes and Downes 1997). It is the largest earthquake to have occurred in New Zealand since the time of systematic European colonisation (see Dowrick and Rhoades 1998 for a catalogue of major New Zealand earthquakes from 1901-1993). The shock was felt across almost the whole country, was highly destructive in Wellington, and

also caused severe damage in Wanganui and Kaikoura. Between seven and nine people were killed in the earthquake, and five others sustained injuries that required hospitalisation.

Figure 16. General store damaged by the 1929 Murchison earthquake [Alexander Turnbull Library].

Figure 17. Damaged business premises after the earthquake of 17 June 1929 [Alexander Turnbull Library].

The M7.8 earthquake that struck Murchison on the 17th of June 1929 was felt all over New Zealand (Dowrick 1994). Fortunately, the most intense shaking occurred in a mountainous and densely wooded area that was sparsely populated. Casualties were therefore comparatively light and the damage was mostly confined to the surrounding landscape, where the shaking triggered extensive landslides over thousands of square kilometres. Nonetheless, the shock impacted with damaging intensities as far away as Greymouth, Cape Farewell and Nelson (see Figure 16 and Figure 17). Fifteen people were killed in the Murchison Earthquake.

Figure 18. Overlooking Napier City, circa 1900 [Alexander Turnbull Library].

Figure 19. Looking over Napier at the buildings ruined by the 1931 earthquake and the fires [Alexander Turnbull Library].

THE 1931 HAWKE'S BAY EARTHQUAKE, NAPIER

As reported above, it was the combustibility of timber homes that prompted the focus in Auckland towards building in clay brick unreinforced masonry, and occasionally in stone masonry. However, early earthquakes in the Wellington region resulted in the region being

slow to adopt masonry construction. This caution proved to be well justified. On the morning of 3 February 1931 the Hawke's Bay region of the eastern North Island was struck by an M7.8 earthquake that completely destroyed the city of Napier (see Figure 18 to Figure 21). Fires swept through the wreckage, destroying much of what was left. Eight nurses died when the reinforced concrete Napier nurses home collapsed, and perhaps the largest brick masonry building to collapse was the Napier Anglican Cathedral (see Figure 22 and Figure 23). The shaking resulted in damage from Taupo to Wellington, and left 30,000 people homeless (see Figure 24 and Figure 25). The official death toll was 256, and the event remains the worst disaster of any type to occur on New Zealand soil (Dowrick 1998; Dalley and McLean 2005).

Figure 20. Hastings Street, Napier, circa 1914 [Alexander Turnbull Library].

Figure 21. View down Hastings Street, Napier after the earthquake 1931 [Alexander Turnbull Library].

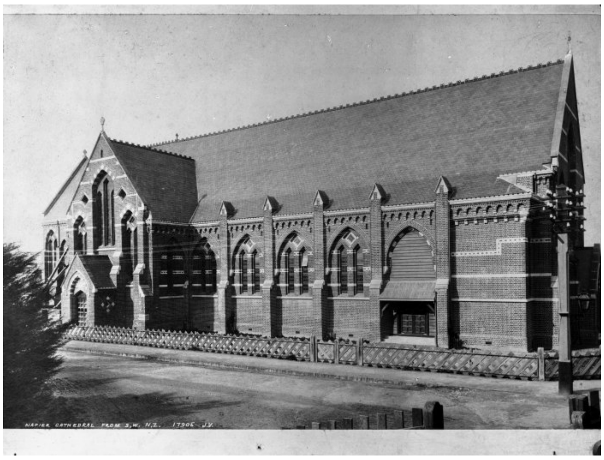

Figure 22. St John's Anglican Cathedral in Napier, circa 1885 [Alexander Turnbull Library].

Figure 23. Ruins of the Napier Anglican Cathedral after the 1931 Napier Earthquake [Alexander Turnbull Library].

FROM THE 1930s TO THE 1970s

Following the demonstrated poor seismic response of unreinforced clay brick masonry during the Hawke's Bay earthquake, much of the city's reconstruction was in reinforced concrete. This expertise translated readily into the use of reinforced concrete masonry, with an associated rapid decline in the use of unreinforced clay brick masonry construction, which

was eventually prohibited in 1965 (NZSI, 1965). The devastation of the 1931 Hawke's Bay earthquake prompted the New Zealand Government to ban the use of unreinforced masonry on public buildings (Oliver 2006) and also prompted the government to develop a national building code, with the New Zealand Standards Institution formed in 1932. This institution has survived to the present day, and is now referred to as Standards New Zealand.

Figure 24. Aerial view of Napier after the 1931 earthquake, showing the refugee camp at Nelson Park in the centre [Alexander Turnbull Library].

Figure 25. Rows of pitched tents in a field at a relief camp in Palmerston North for victims of the 1931 Hawke's Bay earthquake [Alexander Turnbull Library].

Stacpoole and Beaven (1972) report that in the post war period until the mid 1960s, most New Zealand buildings were simple concrete earthquake frames with clay brick infill panels. Gjerde (2006) reports that an eminent New Zealand architect Sir Miles Warren was formative in the promotion of architectural concrete masonry in the 1960s, with a highlight of the period being a townhouse that he designed for himself in 1965 (see Figure 26 and Figure 27). Texture and scale were pursued as beneficial architectural properties of concrete masonry.

Figure 26. The Warren concrete masonry townhouse constructed in 1965 (Gjerde 2006).

Figure 27. Texture and scale were important architectural properties of concrete masonry construction that Warren deployed (Gjerde 2006).

LIMIT STATE CAPACITY DESIGN

In the New Zealand context, Park and Paulay (1975) is typically credited as being the first definitive text on capacity design procedures for the seismic response of reinforced concrete (and therefore reinforced concrete masonry also), with the basis of the capacity design approach first described in a paper by Hollings (1969). NZS 4230:1990 (SANZ 1990) was the first New Zealand design standard to document a limit state design procedure for masonry construction, and was strongly influenced by the research of Professor Nigel Priestley (see for instance Priestley and Bridgeman 1974; Priestley 1977; Priestley 1981, Priestley and Elder 1982; Priestley and Elder 1983; Priestley and Chai 1985; Priestley 1986). These findings have been collectively reported in Paulay and Priestley (1999).

An innovative development in NZS 4230:1990 was the implementation of ultimate limit state design for masonry, utilising rectangular compression stress blocks for unconfined and confined masonry (see Figure 28 and Figure 29) and providing for a strength hierarchy that prevented shear failure during seismic lateral loading. The impact of the earthquake engineering research of Professor Priestley, along with his regular collaborators Professor Robert (Bob) Park and Professor Thomas (Tom) Paulay is irrefutable (EERI 2006), and many of their research findings continue to form the basis of New Zealand concrete and masonry material design standards being used today.

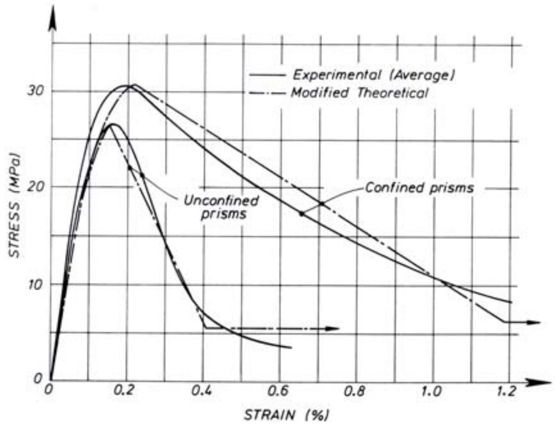

Figure 28. Influence of confinement reinforcement on the compression stress-strain response of concrete masonry (Priestley and Elder 1983).

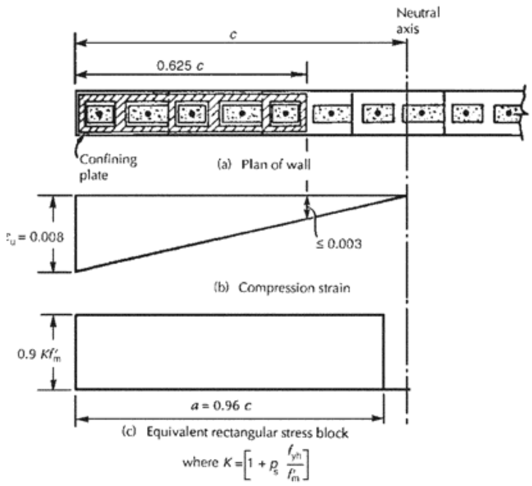

Figure 29. Rectangular stress block used for the design of concrete masonry having horizontal confinement plates in the mortar joints (SANZ 1990).

CURRENT MASONRY DESIGN AND CONSTRUCTION PRACTICE IN NEW ZEALAND

Recognising that all structural masonry in New Zealand is required to be reinforced in order to resist lateral earthquake loads, it follows that masonry units must be cellular in order to accommodate reinforcement. Over time this has lead to the practice where solid clay brick masonry is almost exclusively used as a single leaf veneer mounted to a light timber frame using veneer ties, with the masonry being deployed for its weather tightness and pleasing appearance (see Figure 30 and Figure 31). Oliver (2006) reports that 55% of new dwellings

constructed in New Zealand are clad in clay bricks, with more than 50% of these bricks being imported from Australia. Additionally, concrete masonry construction is always reinforced, and this has been recognised in the appropriate materials workmanship and design standards, which now apply specifically to concrete masonry construction (SNZ 1999; SNZ 2001; SNZ 2004). NZS 4230:2004 stipulates the maximum reinforcement spacing for both horizontal and vertical reinforcement.

Figure 30. Unreinforced clay brick masonry veneer being applied to a light timber framed home.

Figure 31. Light timber framed home with clay brick masonry veneer, nearing completion of construction.

Within the New Zealand construction market, reinforced concrete masonry construction now competes with both precast and cast in-situ concrete. Consequently, reinforced concrete masonry continues to hold appeal because of its attractive patterns, textures, colour and scale, its precast modular nature, and its ability to be formed into a curved surface (see Figure 32 and Figure 33). These characteristics obviously replicate international trends, with the speed and quality of construction also influenced by the availability and the skill of the project mason.

Figure 32. Stack bonded curved concrete masonry wall.

Figure 33. Textured and coloured concrete masonry wall.

The governing seismic design philosophy is selected at the project commencement (see Figure 34) with the most common philosophy being to adopt nominally ductile design ($\mu = 1.25$) as this allows a significant reduction in design lateral loads without requiring additional detailing to accommodate large plastic curvatures associated with member plastic hinge formation. When undertaking a rigorous ductile seismic design using concrete masonry,

μ = 4 is typically adopted. As shown in Figure 35 to Figure 38, design tools have been published to assist the seismic design process. NZS 4230:2004 is intentionally modelled on the corresponding concrete material design standard (NZS 3101:2006 is the most recent version), facilitating ease of use amongst building designers.

Table 3.2 – Design parameters for various design philosophies

Design philosophy	Seismic performance	Structural ductility factor, μ	Structural performance factor, S_p	Required grouting	Method of design
Elastic structures	Potential to form soft stories or brittle failure modes	1.0	1.0	Solid filled or partially filled acceptable	Design exempt from additional seismic requirements. Design shall be in accordance with 3.7.2
Nominally ductile structures	Design to avoid soft stories or brittle failure modes	1.25	0.7	Solid filled or partially filled acceptable	Design exempt from additional seismic requirements. Design shall be in accordance with 3.7.2
Limited ductile structures	Limited dissipation of energy by flexural yielding in specified locations	2	0.7	Solid filled in potential plastic hinge regions. Other regions may be solid or partially filled	Design procedures as outlined in 3.7.3 or capacity design as defined in section 2
Ductile structures	Dissipation of energy by ductile flexural yielding in specified locations	$4<20(1-T_1)<6$	0.7	Solid filled	Design procedures as outlined in 3.7.4 including capacity design as defined in section 2

Figure 34. Table 3.2 of NZS 4230:2004, identifying the target seismic design performance and associated design parameters for a range of seismic design philosophies.

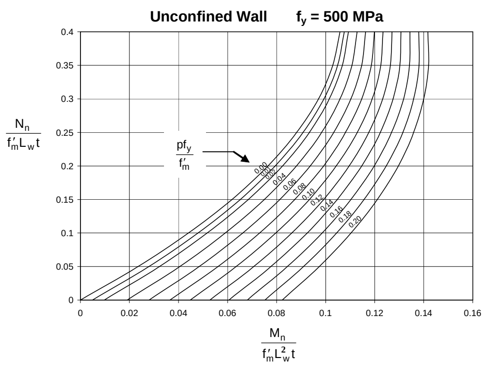

Figure 35. Design tool relating design nominal axial load (N_n) and reinforcement content (p) to nominal flexural strength (M_n) of a reinforced masonry wall (Voon and Ingham 2004).

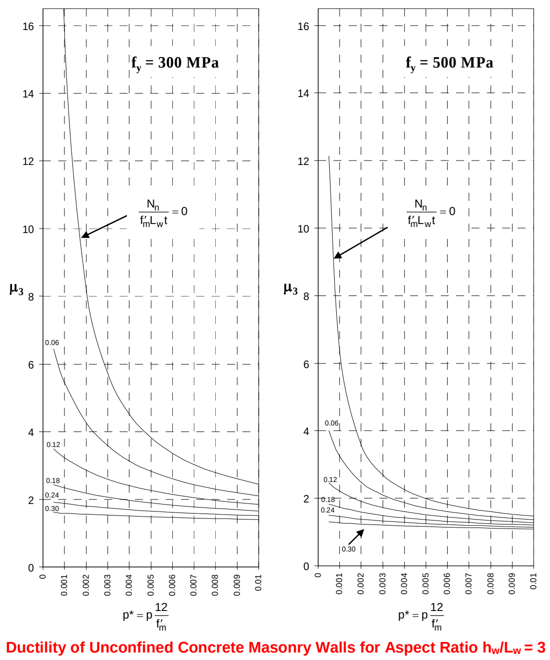

Figure 36. Charts relating reinforcement content (p), masonry compression strength (f'_m) and nominal axial load (N_n) to available displacement ductility of a wall having an aspect ratio of 3 (μ_3) (Voon and Ingham 2004).

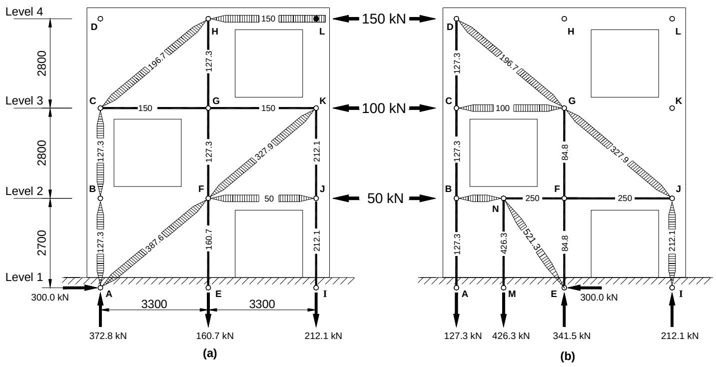

Figure 37. Strut and tie models for determining design actions for masonry walls having irregular openings (Voon and Ingham 2004).

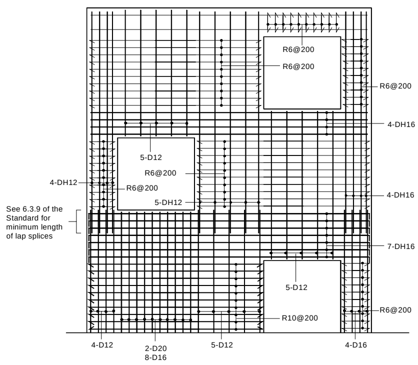

Figure 38. Required reinforcement in a concrete masonry wall having irregular openings (Voon and Ingham 2004).

RECENT INNOVATIONS IN STRUCTURAL CONCRETE MASONRY

In the mid-1990s the New Zealand concrete masonry industry undertook several initiatives with the purpose of facilitating greater use of structural concrete masonry. The first of these initiatives was the production of NZS 4229:1999 (SNZ 1999), which is a non-specific material design standard for concrete masonry buildings that enables a limited scope of reinforced concrete masonry buildings to be seismically designed without requiring a consulting structural engineer, thereby reducing the overhead costs associated with construction using concrete masonry (Ingham 2000). A further innovation of the standard was that the advocated building system employed 140 mm thick concrete masonry units with deformed 12 mm grade 300 MPa vertical reinforcement spaced at 800 mm centres, with blockfill grout only being provided in the cells that contained reinforcement. The contents of the standard are based on rigorous experimental validation (see Figure 39 and Ingham et al. 2001) and a companion user guide was prepared (see Figure 40; Ingham and Gjerde 1999; Gjerde et al. 2001) that was disseminated at a series of seminars held nationwide. The standard and user guide are regularly combined to design concrete masonry homes such as those shown in Figure 41 and Figure 42.

Figure 39. Condition of nominally reinforced partially grouted filled concrete masonry wall after being subjected to cyclic loading.

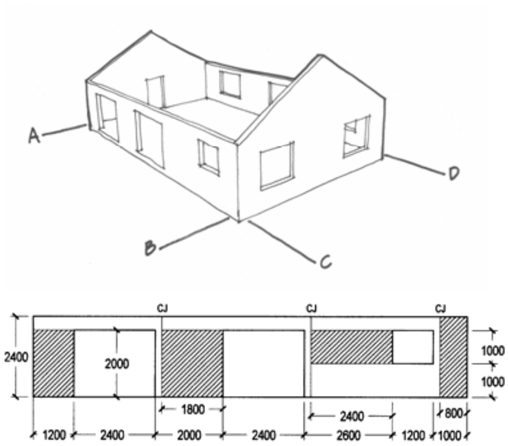

Figure 40. Illustrations from the NZS 4229:1999 user guide identifying panels that provide lateral strength (Ingham and Gjerde 1999).

Figure 41. A two-storey concrete masonry house during construction.

Figure 42. A completed concrete masonry house that has a plastered surface treatment.

A second initiative was to promote the use of unbonded post-tensioned concrete masonry construction. Two doctoral studies were conducted by Laursen and by Wight, who investigated creep and shrinkage properties (Laursen et al. 2006), pseudo-static cyclic response (Laursen and Ingham 2001, 2004a,b), shake table testing (Wight et al. 2006, 2007c), and displacement-based design procedures (Wight et al. 2007b), culminating in the design of an innovative concrete masonry building that utilised both unbonded post-tensioning and mortarless construction (Wight et al. 2007a). Figure 43 and Figure 44 show laboratory experimentation and Figure 45 and Figure 46 show construction of an unbonded post-tensioned concrete masonry house that was built in conjunction with the not-for-profit organisation Habitat for Humanity. Confirmation of the seismic response of masonry shrinkage control joints was also investigated (Ingham et al. 2007).

Figure 43. Pseudo static cyclic testing of a multi-storey concrete masonry wall.

Figure 44. Shake table testing of (1) wall with opening and (2) small structure.

A final initiative was to develop a new design expression for concrete masonry shear strength, recognising that the existing NZS 4230:1990 limit state design expressions for shear were excessively conservative. This study was conducted by Voon (Voon and Ingham 2006, 2007) with the results being implemented into a new version of the New Zealand masonry design standard NZS 4230:2004 (SNZ, 2004).

Currently, innovations in the New Zealand concrete masonry industry are focussed on the use of new or waste products in the manufacture of concrete masonry. The first study to have

reached commercial trial stage is associated with the use of waste latex paint as an admixture for masonry blockfill grout (Haigh et al. 2008).


Figure 45. Applying post-tensioning.


Figure 46. Completed masonry structure.

EARTHQUAKE RISK BUILDINGS AND THE BUILDING ACT 2004

In New Zealand the construction of houses and other buildings is now controlled by The Building Act 2004 (DBH, 2007), which applies to the construction of new buildings and to the alteration and demolition of existing buildings. Territorial Authorities are required by the Act to adopt policies on earthquake-prone buildings, where earthquake prone buildings are defined in the Act as those that would not withstand a moderate earthquake (ACC 2007, CCC 2007, WCC 2007). A moderate earthquake is defined as an earthquake that would have the same duration as the current design level earthquake at the site, but with only one-third of the strength. Technically, any building that has greater than one-third of current new-building strength does not require seismic retrofit intervention. However, it is the view of the New Zealand Society of Earthquake Engineering that any building having less than two-thirds of current new-building strength should be improved. Buildings having strength greater than one-third but less than two-third of new building strength are referred to as earthquake prone (NZSEE 2006; Tonks et al. 2007).

THE SEISMIC RETROFIT SOLUTIONS PROJECT

The absence of a recent major earthquake in New Zealand has led to less awareness of seismic hazard amongst the general public, and a comparative lack of attention by building owners to the need for seismic retrofitting of their structures, than in countries such as Pacific coast USA, Japan, Taiwan and Turkey, that have experienced recent devastating earthquakes. Furthermore, seismic assessment and retrofit is not currently taught in New Zealand's structural engineering degree programs and there is no national technical resource for structural designers wishing to execute seismic retrofits. In response to this, a collaborative research programme considering seismic retrofit solutions appropriate to New Zealand's unique earthquake risk building stock is currently under way as a joint effort between the University of Auckland and the University of Canterbury.

As detailed herein, unreinforced masonry buildings represent the most earthquake-prone class of buildings in New Zealand, and also represent the majority of the nation's pre-1931 heritage buildings. Consequently substantial resources are currently being dedicated to the development of state-of-the-art seismic assessment and retrofit intervention technologies

specifically addressing New Zealand's stock of earthquake-prone unreinforced masonry (URM) buildings. Key features of the study include:

- Characterisation of New Zealand's URM building typologies: This exercise strives to catalogue the existing URM building stock using a framework that facilitates data collection, seismic assessment and the development of seismic retrofit solutions (Tonks et al. 2007; Russell and Ingham 2008).
- Characterisation of URM material properties: This study is focused on testing of existing URM structures to develop a database of masonry material properties to be used in the assessment and retrofit design process (Russell and Ingham 2007a).
- Component and system-level simulated seismic loading (Russell and Ingham 2007b). This involves both laboratory studies and field testing of existing URM building components. Field studies are being conducted in co-operation with several Auckland demolition companies (see Figure 47 and Figure 48).
- Modelling the time-history seismic response of as-built and seismically retrofitted URM buildings.
- System-level seismic retrofit of URM buildings using fibre reinforced polymers.
- Seismic assessment and retrofit of timber diaphragms in URM buildings.
- Seismic assessment and retrofit of URM frames.
- Improved desk-top URM seismic assessment techniques.

Figure 47. Demolition of an unreinforced masonry building.

Figure 48. Site determination of masonry material properties.

The project has a dedicated website [www.retrofitsolutions.org.nz] where more comprehensive details are available. The project is scheduled to conclude on July 2010 and is being conducted with a strong emphasis on international collaboration. Researchers from the University of Adelaide and the University of Newcastle (Australia), Drexel University (USA), University of Minho (Portugal), and the University of Bath (UK) are providing external input or co-supervision of research students.

CONCLUSIONS

New Zealand is a comparatively young country, with formalised European settlement commencing in 1840. The first masonry building in New Zealand was constructed in 1833, with unreinforced clay brick masonry having been a predominant construction material for all non-residential structures until the devastating 1931 Hawke's bay earthquake. Since then the dominant masonry form has been reinforced concrete masonry, with unbonded post-tensioned

concrete masonry construction having recently been trialled. Currently New Zealand masonry research is focussed on developing a national platform of knowledge associated with seismic assessment and retrofit of earthquake-prone pre-1931 unreinforced clay brick masonry. This exercise is not unlike studies previously conducted or ongoing in other seismically active regions of the world, providing an opportunity for effective collaboration and sharing of research findings in order to protect the world's heritage masonry buildings from future devastating earthquakes.

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