Section 1:

Introduction and background

This section provides introductory information on the scope and purpose of this report, followed by details of the early European settlement of Christchurch. The details provided on masonry construction practices in early Christchurch are a prelude to the critique of the architectural characteristics and the number and seismic vulnerability of the New Zealand unreinforced masonry (URM) building stock that is reported in section 2. Background information on the evolution of New Zealand building codes, with particular attention given to provisions for seismic improvement of existing buildings, is next provided. The section concludes with some brief comments on the seismological characteristics of the 2010/2011 Canterbury earthquake swarm, and in particular information is provided to explain that most URM buildings in Christchurch were subjected to earthquake loads that were well in excess of the assessed earthquake strength of the Christchurch URM building stock.

1.1 Scope and Purpose

The scope and purpose of this report were established at a meeting held on 19 July 2011 with the members of the Royal Commission of Inquiry into Building Failure Caused by the Canterbury Earthquakes. The purpose of this report is to provide a resource, both for the members of the Royal Commission of Inquiry and for other parties wishing to make a submission to the Commission when hearings begin. The scope includes but is not necessarily limited to:

- Details of both stone masonry and clay brick URM buildings, including both iconic buildings and more regular buildings;

- Details of the architectural and structural characteristics of the URM building stock of New Zealand, with particular emphasis on the uniform characteristics of these buildings throughout New Zealand and on their role in defining village atmosphere as local centres in larger cities and as the principal commercial location of smaller cities and towns throughout New Zealand;
- Details of the value of the New Zealand URM building stock and of the assessed seismic vulnerability of this building stock;
- Details of the performance of URM buildings in the 2010/2011 Canterbury earthquake swarm, with particular but not exclusive attention given to the performance of the buildings located within the Christchurch Central Business District (CBD) as defined within the Terms of Reference of the Inquiry as the area bounded by Bealey Avenue, Fitzgerald Avenue, Moorhouse Avenue, Deans Avenue and Harper Avenue. These details include representative examples of failure modes that were observed;
- Statistics on the observed earthquake performance of the URM building stock, and a report of data on post-earthquake building demolitions, primarily pertaining to URM buildings;
- Identification of URM buildings that are or were both representative of their class of building and whose observed earthquake performance was representative. This selection of representative buildings is to include both unretrofitted and retrofitted stone and clay brick URM buildings, and both buildings that performed poorly and buildings that performed well;
- Information on technologies available for the seismic improvement of URM buildings, and on the hierarchy of improvements that may be applied in order to improve the seismic performance of URM buildings;
- Where available, information on the cost of implementing improvements to the national URM buildings stock;
- Comments on the adequacy or inadequacy of current practices and on methodologies that may be adopted in response to the events in Christchurch.

The Terms of Reference of the Royal Commission of Inquiry are reproduced in Appendix A.

1.2 European settlement of Christchurch

1.2.1 Early Christchurch construction

Construction in the early period of colonisation was primarily of timber for residential and smaller commercial buildings due to the proximity and abundance of the local resource in the Papanui and Riccarton Forest. In the late 1850s Christchurch prospered from the wool trade and this allowed the transition from wood to stone and clay brick masonry for the construction of public buildings. The spirit in which the Canterbury settlement was founded instructed a building style that imitated the style of the home country (Wilson, 1984). The city's second town hall was built in stone in 1862-1863, the first stone building of Christ's College was constructed in 1863, and the city's architectural jewel, the stone Provincial Council Chambers, was completed in 1864 (Wilson, 1984). The aesthetic quality of Christchurch city was also regulated in terms of building size and style in order to maintain a regular appearance. In the 1860s and right through to the 1880s a vogue for Venetian Gothic architecture for commercial buildings was indulged, distinguishing the buildings of Christchurch from those of other New Zealand cities that were embracing classical and Renaissance styles. The city was populated with mostly two and three storey buildings that were complementary in height to their neighbouring buildings. This regularity in style and size was accentuated by the rigid regular gridded streets. Construction slowed during a period of economic depression in the 1870s, but allowed for a new period of design to develop by the time that prosperity returned in the late 1890s (Rice, 2008).

Figure 1.1 Victorian Christchurch in 1885 (Coxhead, 1885)

By 1914 the central area of Christchurch had been largely rebuilt, resulting in a city that was “interesting for its architectural variety, pleasing for its scale and distinctively New Zealand” (Wilson, 1984). Figure 1.1 and Figure 1.2 show photos of historical Christchurch from 1885 and 1910 respectively. Two of the many influential architects of Christchurch were J. C. Maddison (1850-1923), whose design focus was inspired by the Italianate style, and J. J. Collins (1855–1933), who in partnership with R. D. Harman (1859-1927) chose brick masonry as their medium for large commercial and institutional buildings. By the 1920s wooden structures in the city were rare, and were seen as small irregular relics of the past.

Figure 1.2 New Zealand Express Company building, Christchurch's first 'skyscraper', photo circa 1910 (Brittenden Collection, 1910)

1.2.2 Rise and decline of unreinforced masonry construction

Brick masonry construction was seen as a symbol of permanency, when compared with the construction of timber buildings. The use of masonry was further justified after a number of fires in inner city Christchurch during the 1860s. The centre of Lyttelton was also destroyed in 1870 (Christchurch City Libraries, 2006; Wilson, 1984). The fire-proof nature of masonry led to it being readily adopted as the appropriate building material for high importance structures such as government buildings, schools, churches, and the Press building that housed the local newspaper company.

In Christchurch's founding years, the city and its surrounding boroughs were subjected to three medium sized earthquakes, and as many as seven smaller earthquakes that were centred closer to the north of the South Island (GeoNet, 2010). The earthquake of 5th June 1869 was the most damaging to the settlement of Christchurch, causing damage to chimneys, government buildings, churches and homes throughout the central city and the surrounding boroughs of Avon (Avonside), Linwood, Fendalton and Papanui (Christchurch City Libraries, 2006). The worst of the damage reported was to the stone spire of St John's church in Latimer Square which was cracked up its entire height (Rice, 2008). In Government buildings, the tops of two chimneys came down, plaster was cracked, and several stones were displaced. Similar damage occurred in some other brick and stone masonry buildings, including Matson's building, the NZ Loan & Trust building and the NZ Insurance building. The majority of the damage to houses was the result of brick chimneys toppling and in one case the exterior brick wall of a house in Manchester Street collapsed. The damage was most intense within the inner confines of the city, decreasing from a MM 7[1] intensity in the city to MM 5 at Kaiapoi and Halswell. However, a few chimneys and household contents were also damaged at Lyttelton (Christchurch City Libraries, 2006). Twelve years later another earthquake was felt in Christchurch, but resulted in less damage than the previous 1869 earthquake (GeoNet, 2010). The only reported damage from the 1881 earthquake was that to the spire of the Cathedral, which was still in construction.

The large earthquake that struck the Amuri District of Canterbury (about 100 km north of Christchurch) in 1888 is thought to have originated on the Hope Fault, which is part of the Marlborough Fault Zone (Stirling, 2008). The earthquake's intensity reached MM 9 in the epicentre area, and caused severe damage to buildings made of cob and stone masonry located in the Amuri District (now part of the Hurunui Territoiral Authority of Canterbury), as well as in Hokitika and Greymouth. This earthquake was felt in Christchurch city, and caused minor damage to buildings (PapersPast, 2010). A later earthquake in 1901 centred in Cheviot damaged the spire on the Cathedral for the third time in its short life and led to reconstruction of the spire in timber. Figure 1.3 shows the damage to the spire from the 1888 and the 1901 earthquakes.

Although these earthquakes early in the development of Christchurch did result in some damage to buildings, and in particular to stone and clay brick masonry buildings, none of these earthquakes had an effect on the construction and design of buildings as did the 1931 Hawke's Bay earthquake (see section 2.1.2).

1.3 The evolution of New Zealand building codes

The construction of URM buildings in New Zealand peaked in the decade between 1920 and 1930 and subsequently declined (see Figure B.3 and Figure B.4), with one of the most important factors in this decline being the economic conditions of the time. The Great Depression in the 1930s and the outbreak of World War II significantly slowed progress in the construction sector, and few large buildings of any material were constructed in the period between 1935 and 1955 (Stacpoole & Beaven, 1972; Megget, 2006). Equally important in the history of URM buildings in New Zealand was the 1931 M7.8 Hawke's Bay earthquake, and the changes in building provisions which it precipitated.

[1] The Modified Mercalli intensity scale is a seismic scale used for measuring the intensity of an earthquake. The scale measures the *effects* of an earthquake, and is distinct from the moment magnitude M_w usually reported for an earthquake (from http://en.wikipedia.org/wiki/Mercalli_intensity_scale)

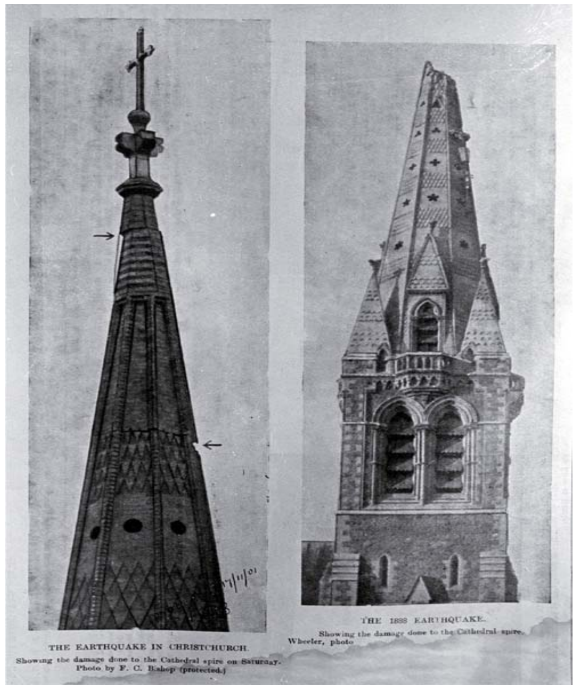
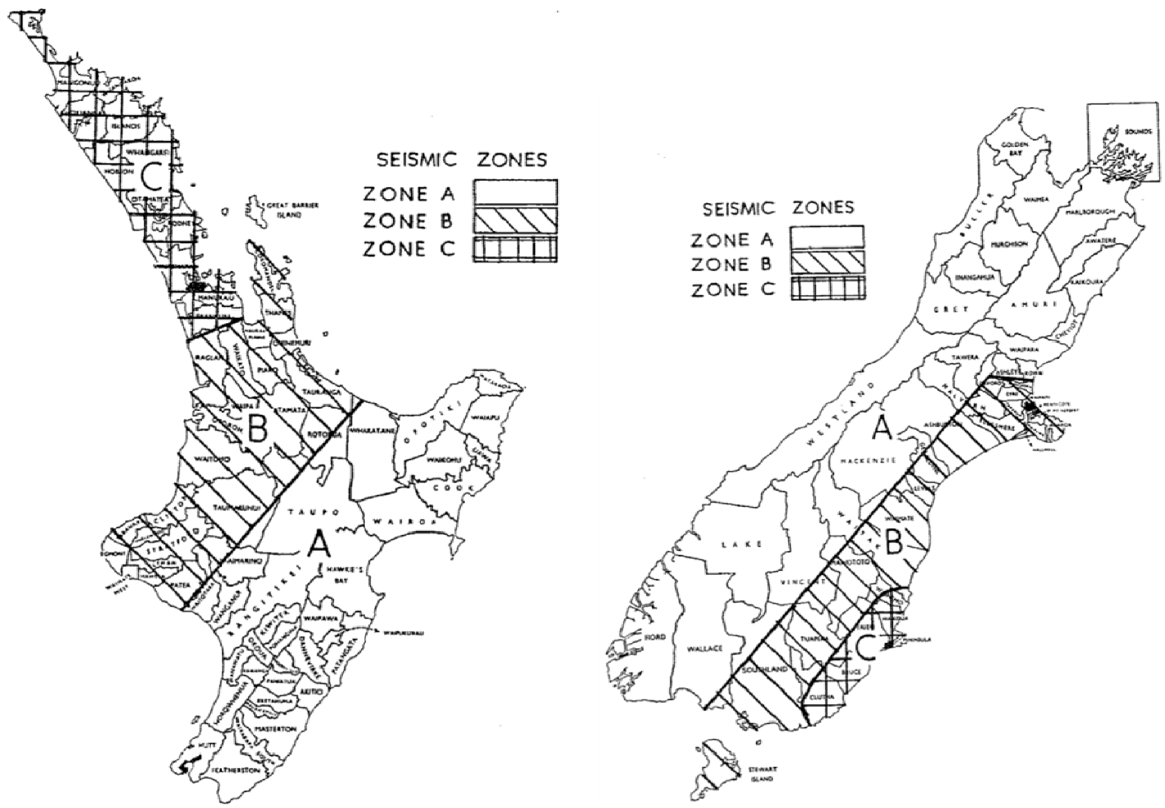


Figure 1.3 Damage to the Cathedral Spire in the 1888 (left) and 1901 (right) earthquakes (Bishop & Wheeler, 1901).

The destruction of many URM buildings in Napier graphically illustrated that URM construction possessed insufficient strength to resist lateral forces induced in an earthquake due to its brittle nature and inability to dissipate energy. Later in 1931, in response to that earthquake, the Building Regulations Committee presented a report to the Parliament of New Zealand entitled “Draft General Building By-Law” (Cull, 1931). This development was the first step towards requiring seismic provisions in the design and construction of new buildings. In 1935, this report evolved into NZSS no. 95, published by the newly formed New Zealand Standards Institute, and required a horizontal acceleration for design of 0.1g, and this requirement applied to the whole of New Zealand (New Zealand Standards Institute, 1935). NZSS no. 95 also suggested that buildings for public gatherings should have frames constructed of reinforced concrete or steel. The By-Law was not enforceable, but it is understood that it was widely used especially in the larger centres of Auckland, Napier, Wellington, Christchurch and Dunedin (Megget, 2006).

The provisions of NZSS no. 95 were confined to new buildings only, but the draft report acknowledged that strengthening of existing buildings should also be considered, and that alterations to existing buildings were required to comply (Davenport, 2004). In 1939 and 1955 new editions of this By-Law were published, and apart from suggesting in 1955 that the seismic coefficient vary linearly from zero at the base to 0.12 at the top of the building (formerly the seismic coefficient was uniform up the height of the building), there were few significant changes (Beattie et al., 2008). It was not until 1965 that much of the recent research at the time into seismic design was incorporated into legislation. The New Zealand Standard Model Building By-Law NZSS 1900 Chapter

8:1965 explicitly prohibited the use of URM: (a) in Zone A; (b) of more than one storey or 15 ft (4.6 m) eaves height in Zone B; (c) of more than two storeys or 25 ft (7.6 m) eaves height in Zone C. These zones refer to the seismic zonation at the time, which have subsequently changed and evolved. Zone A consisted of regions of the highest seismic risk and Zone C consisted of regions of the lowest seismic risk (New Zealand Standards Institute, 1965). Details of the seismic zonation in NZSS 1900 are shown in Figure 1.4. Again, the provisions of this By-Law did not apply automatically and had to be adopted by local authorities.



(a) North Island **(b) South Island**

Figure 1.4 Map of seismic zones (from NZSS 1900 Chapter 8:1965)

The 1965 code required that buildings be designed and built with "adequate ductility", although further details were not given. The next version of the loadings code was published in 1976 as NZS 4203 (Standards Association of New Zealand, 1976), and was a major advance on the 1965 code. Most importantly, the 1976 loadings code was used in conjunction with revised material codes: steel, reinforced concrete, timber and reinforced masonry, which all required specific detailing for ductility. Thus after the publication of this code in 1976, unreinforced masonry was explicitly prohibited as a building material throughout the whole of New Zealand.

The use of URM was implicitly discouraged through legislation from as early as 1935, and although it was still allowed in some forms after 1965, observations of existing building stock show its minimal use from 1935 onwards, especially for larger buildings.

This is thought to be significantly attributable to the exceptionally rigorous quality of design and construction by the Ministry of Works at the time (Megget, 2006; Johnson, 1963). Although two storey URM buildings were permitted in Auckland (Zone C) after 1965, only three existing URM buildings in Auckland City constructed after 1940 have been identified. All three are single storey and they were constructed in 1950, 1953 and 1955.

1.3.1 Provisions for the seismic upgrade of existing buildings

As building codes were being developed for the design of new buildings, attention was also given to the performance of existing buildings in earthquakes. The first time this was addressed in legislation was Amendment 301A to the 1968 Municipal Corporations Act (New Zealand Parliament, 1968). This Act allowed territorial authorities, usually being boroughs, cities or district councils, to categorise themselves as earthquake risk areas and thus to apply to the government to take up powers to classify earthquake prone buildings and require owners to reduce or remove the danger. Buildings (or parts thereof) of high earthquake risk were defined as being those of unreinforced concrete or unreinforced masonry with insufficient capacity to resist earthquake forces that were 50% of the magnitude of those forces defined by NZS 1900 Chapter 8:1965. If the building was assessed as being "potentially dangerous in an earthquake", the council could then require the owner of the building within the time specified in the notice to remove the danger, either by securing the building to the satisfaction of the council, or if the council so required, by demolishing the building.

Most major cities and towns took up the NZS 1900 Chapter 8:1965 legislation, and as an indication of the effect of this Act, between 1968 and 2003 Wellington City Council achieved strengthening or demolition of 500 out of 700 buildings identified as earthquake prone (Hopkins et al., 2008). Auckland City Council, in spite of having a low seismicity, took a strong interest in the legislation and this led to considerable activity in strengthening buildings (see Boardman, 1983). In Christchurch, a moderately high seismic zone, the City Council implemented the legislation, but adopted a more passive approach, generally waiting for significant developments to trigger the requirements. In Dunedin, now seen to be of low seismic risk, little was done in response to the 1968 legislation although strengthening of schools, public buildings and some commercial premises was achieved. As a result, Dunedin has a high percentage of URM buildings compared with many other cities in New Zealand (Hopkins, 2009). Megget (2006) and Thornton (2010) state that much of the strengthening in Wellington was accomplished with extra shear walls, diagonal bracing or buttressing and the tying of structural floors and walls together, and that many brittle hazards such as parapets and clock towers had been removed after the two damaging 1942 South Wairarapa earthquakes (M7 & M7.1) which were felt strongly in Wellington. Hopkins et al. (2008) noted that:

> "there was criticism at the loss of many older heritage buildings and at the use of intrusive retrofitting measures which were not harmonious with the architectural fabric of the building (McClean, 2009). At the same time, this did provide an opportunity in many cases for the land

> on which the old building was situated to be better utilised with new, larger and more efficiently designed structures."
>
> "A major drawback of the 1968 legislation, which endured until 2004, surviving intact with the passage of the Building Act 1991, was that the definition of an earthquake prone building and the required level to which such buildings should be improved remained tied to the 1965 code. Most territorial authorities called for strengthening to one-half or two-thirds of the 1965 code, and many buildings which were strengthened to these requirements were subsequently found to fall well short of the requirements of later design standards for new buildings" (Hopkins et al., 2008).

Wellington City Council found that in January 2008, of 97 buildings which had been previously strengthened, 61 (63%) were subsequently identified as potentially earthquake prone (Stevens & Wheeler, 2008; Bothara et al., 2008). This situation was recognised by the New Zealand Society for Earthquake Engineering (NZSEE), who were also concerned about the performance of more modern buildings, particularly after the observed poor performance of similarly aged buildings in earthquakes in Northridge, California (1994) and Kobe, Japan (1995). NZSEE pushed for new, more up-to-date and wide-ranging legislation. This initiative was supported by the Building Industry Authority, later to become part of the Department of Building and Housing, and a new Building Act came into effect in August 2004 (New Zealand Parliament, 2004). This development brought in new changes as to what constituted an "Earthquake Prone Building". In particular, the definition of an earthquake prone building was tied to the current design standard of the time, and no longer to the design standard of any particular year. The legislation allowed any territorial authority to require the owner of an earthquake prone building to take action to reduce or remove the danger. Each territorial authority was required to have a policy on earthquake prone buildings, and to consult publicly on this policy before its adoption. Policies were required to address the approach and priorities and to state what special provisions would be made for heritage buildings. The 2004 legislation applied to all building types except residential ones, (residential buildings were excluded unless they comprised 2 or more storeys and contained 3 or more household units).

As soon as the 1968 legislation to attempt to mitigate the effects of earthquake prone buildings came into effect, the New Zealand National Society for Earthquake Engineering (NZNSEE) set up a steering committee to provide a code of practice in an effort to assist local authorities to implement the legislation. Since the first draft code of practice published by the NZNSEE (1972), several successive publications have been produced, each extending on the previous version. These guidelines have been instrumental in helping engineers and territorial authorities to assess the expected seismic performance of existing buildings consistent with the requirements of the legislation. Guidelines for assessing and upgrading earthquake risk buildings were published as a bulletin article in 1972 (NZNSEE, 1972) and then separately published the following year, which became colloquially known as the "Brown Book" (NZNSEE, 1973). This document provided guidelines for surveying earthquake risk buildings and for the identification of particularly hazardous buildings and features. The document did not establish or recommend strength levels to which earthquake prone buildings should be upgraded, and thus standards varied from one area to another. It was implicit that strengthening be to more than half the standard required in Chapter 8 of the 1965 NZSS Model Building By-Law.

In 1982, NZSEE established a study group to examine and rationalise the use of these guidelines and to produce further guidelines and recommendations. This activity culminated in the publication in 1985 of what became known as the "1985 Red Book" (NZNSEE, 1985). Again, this document was primarily of a technical nature and the responsibilities of what to do with buildings still rested with local authorities. The publication was intended to promote a consistent approach throughout New Zealand for the strengthening of earthquake risk buildings and included a recommended level to which buildings should be strengthened plus the time scale to complete the requirements. The basic objective was to establish a reasonably consistent reduction of the overall risk to life which the country's stock of earthquake risk buildings represented. Based on overseas experiences, particularly in Los Angeles in Southern California, a philosophy was accepted of providing owners of earthquake risk buildings with the option of interim securing to gain limited extension of useful life, after which the building should be strengthened to provide indefinite future life. The design of interim securing systems was to be based on minimum seismic coefficients which represented two-thirds of those specified in NZSS 1900, Chapter 8 (New Zealand Standards Institute, 1965). For "permanent" strengthening measures, it was recommended that the building be strengthened to the standard of a new building, but with the design lateral forces reduced depending on the occupancy classification and type of strengthening system. This publication was widely used by territorial authorities and designers.

In 1992 the NZNSEE again set up a study group to review the 1985 publication, and this resulted in another publication, which similarly became colloquially known as the "1995 Red Book" (NZNSEE, 1995). This document extended the approach and content of its predecessor and took into account the changing circumstances, technical developments and improved knowledge of the behaviour of URM buildings in earthquakes. In particular, earthquake risk buildings in that document were taken to include all unreinforced masonry buildings, and not just those which were defined as "earthquake prone" in terms of the Building Act of the time, which still referred back to the 1965 code. Another key difference from the 1985 Red Book was that a single stage approach to strengthening was suggested, in contrast to the two stage securing and strengthening procedure of the 1985 document. The guidelines also highlighted the differences in analysis for unsecured buildings in comparison to a building which has positive connections between floor, roof and wall elements, and cantilever elements secured or removed. Greater emphasis was placed on the assessment of the likely performance of URM buildings in their original form and with interim securing only in place, as distinct from the performance of the building with any strengthening work which was subsequently found to be necessary. Furthermore, material strengths were given in ultimate limit state format. Historic or heritage buildings were not given any specific or separate treatment, and the guidelines stated that:

> "the issues of risk versus the practicalities of strengthening associated with historic buildings require evaluation on a case-by-case basis. The principal problem with such buildings is that the greater the level of lateral forces that is specified for strengthening, the greater the risk of damaging the fabric that is to be preserved" (NZNSEE, 1995).

After the introduction of a new Building Act in 2004 (New Zealand Parliament, 2004) the Department of Building and Housing supported NZSEE in producing a set of guidelines, "Assessment and Improvement of the Structural Performance of Buildings in Earthquakes" (NZSEE, 2006). This was a major review and extension of previous guidelines, to account for the wider scope of the proposed new legislation. Prior to enacting The Building Act 2004, the term 'earthquake risk building' related only to URM buildings, but now an earthquake prone building could be of any material; steel, concrete, timber or masonry. The level of risk posed by buildings constructed as recently as the 1970s was more widely appreciated, in particular the inadequate performance of reinforced concrete structures due to deficient detailing. Definitions of "earthquake prone" and "earthquake risk" also changed. Essentially, earthquake prone buildings were defined as those with one-third or less of the capacity of a new building. While The Building Act itself still focussed on buildings of high risk (earthquake prone buildings), NZSEE considered earthquake risk buildings to be any building which is not capable of meeting the performance objectives and requirements set out in its guidelines, and earthquake prone buildings formed a subset of this. Moreover, NZSEE expressed a philosophical change, in acknowledgment of the wide range of options for improving the performance of structures that are found to have high earthquake risk. Some of these options involve only the removal or separation of components, and others affect a relatively small number of members. In line with performance-based design thinking, the term "strengthening" was replaced with "improving the structural performance of", highlighting the fact that such solutions as base isolation were not "strengthening" but were an effective way of improving structural performance.

The 2006 guidelines (NZSEE, 2006) provided both an initial evaluation procedure (IEP) and a detailed analysis procedure. The IEP can be used for a quick and preliminary evaluation of existing buildings, and takes into account the building form, natural period of vibration, critical structural weaknesses (vertical irregularity, horizontal irregularity, short columns and potential for building-to-building impact) and the design era of the building. Based on this analysis, if a territorial authority determines a building to be earthquake prone, the owner may then be required to take action to reduce or remove the danger, depending on the territorial authority's policy and associated timeline. The level required to reduce or remove the danger is not specified in The Building Act or its associated regulations. The Department of Building and Housing suggested that territorial authorities adopt as part of their policies that buildings be improved to a level "as near as is reasonably practical to that of a new building". Most territorial authorities took the view that they could not require strengthening beyond one-third of new building standard, but a significant number included requirements to strengthen to two-thirds of new building standard, in line with NZSEE recommendations. In developing policies on earthquake prone buildings, most territorial authorities recognised the need for special treatment and dialogue with owners when heritage buildings were affected. It is believed by the Department of Building and Housing that "the legislation has required each local community to put earthquake risk reduction on its agenda, and has left the local community to develop appropriate policies that reflect local conditions and perceptions of earthquake risk" (Hopkins et al., 2008).

The details discussed are summarised diagrammatically in Figure 1.5.

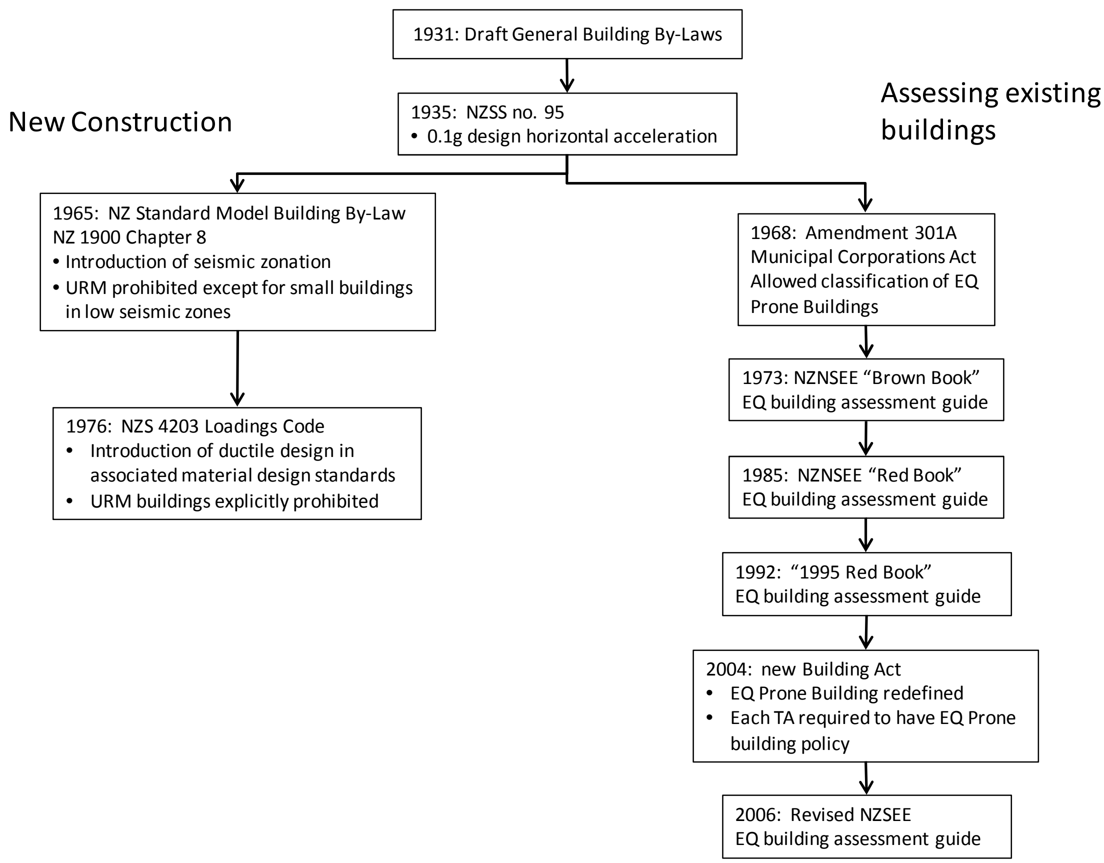


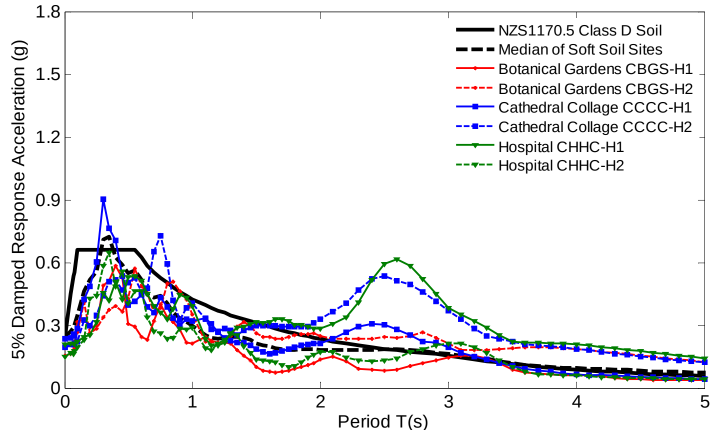
Figure 1.5 Flowchart showing evolution of New Zealand building codes and seismic assessment guides

1.4 Brief comments on the seismological characteristics of the 2010/2011 Canterbury earthquake swarm

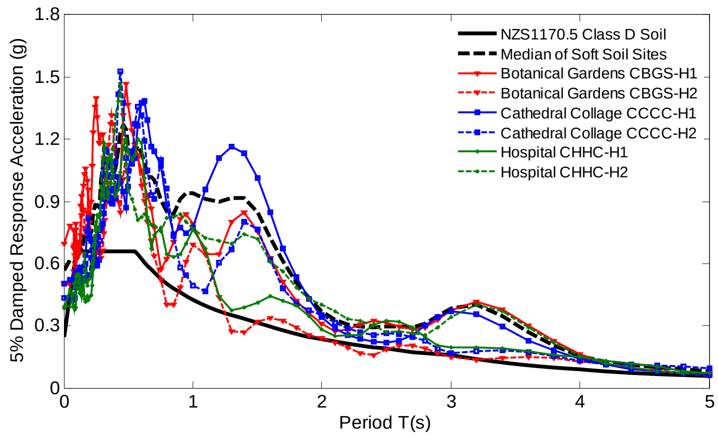
The brief seismological information presented below is provided primarily to illustrate the scale of the earthquake loading that was applied to the URM buildings stock of Christchurch and the surrounding areas with respect to the assessed seismic strength of these buildings and with respect to the design loading that was deemed appropriate for this region at the time of the earthquakes.

As at 23 July 2011 the Christchurch Quake Map website (http://www.christchurchquakemap.co.nz/) reports the location and magnitude of 3690 earthquakes/aftershocks that have occurred since 4 September 2010. Throughout this report this earthquake sequence is referred to as the '2010/2011 Canterbury earthquake swarm', with particular attention given to the two seismic events that resulted in the greatest deployment of resources associated with the collection of data on the performance of URM buildings, being the 4 September 2010 earthquake (referred to as the Darfield earthquake) and the 22 February 2011 earthquake (typically referred to as the Christchurch earthquake but sometimes referred to as the Lyttelton earthquake). It is acknowledged that there were additional events within the earthquake swarm that also caused damage to URM buildings, such as those on 26 December 2010 and on 13 June 2011. However, a study of the behaviour of URM buildings in the 4 September 2010 and 22 February 2011 earthquakes is deemed to be sufficient to convey an understanding of the overall impact of the 2010/2011 Canterbury earthquake swarm on the URM buildings located in Christchurch and the surrounding area.

As detailed in section 2.5 (see Figure 2.10 and Table 2.5), the assessed seismic capacity of all unretrofitted unreinforced masonry buildings in the Canterbury province was expected to be less than 67% of the New Building Standard (NBS), and furthermore approximately 40% of the Canterbury URM building stock was estimated to have a strength of less than 33%NBS. Unreinforced masonry buildings are comparatively stiff structures, with a fundamental period typically in the range of 0.3-0.5 seconds. From Figure 1.6(a) it can be established that for this period range many URM buildings were subjected on 4 September 2010 to earthquake loads that were between 67-100% of NBS (ie the solid line in Figure 1.6(a) corresponding to NZS 1170.5) and that the same buildings were subjected on 22 February 2011 to earthquake loads that were between 150-200% of NBS (see Figure 1.6(b). It is well established that URM buildings perform poorly in large earthquakes and consequently the level of earthquake damage observed in the Christchurch CBD is consistent with expectations for loading of this magnitude.



(a) Spectral accelerations recorded on 4 September 2010



(b) Spectral accelerations recorded on 22 February 2011

Figure 1.6 Earthquake spectral recording from the two principal earthquakes of the 2010/2100 earthquake swarm

Figure 1.7 shows a comparison of the median response recorded in the 4 September 2010 and 22 February 2011 earthquakes, clearly identifying that the February earthquake was far more severe in terms of the load that it applied to unreinforced masonry buildings (and all other buildings having a period of less than 2 seconds). Following the February earthquake a decision was made to increase the seismic zone factor Z to 0.3, and the effect of this modification is also plotted on Figure 1.7. The effect of this increase in the seismic zone factor was to increase seismic design forces and displacements by 36%.

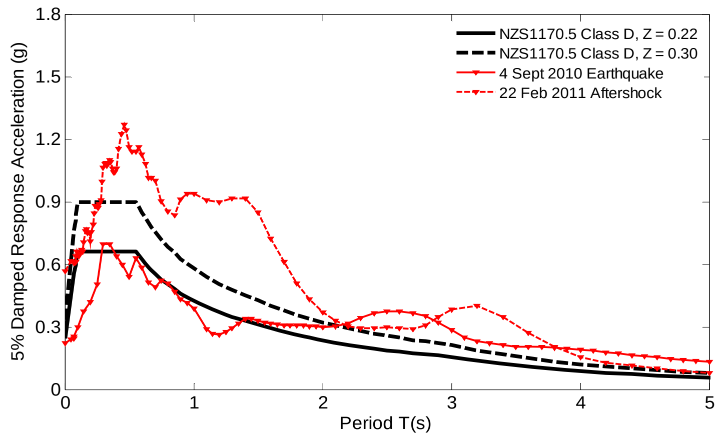


Figure 1.7 Comparison of earthquake spectra for the 4 September and 22 February earthquakes