

# Critical earthquake risk detailing in New Zealand's multi-storey building stock: understanding and improving the current perception

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**ABSTRACT:** This paper presents a summary of preliminary findings on critical earthquake risk detailing in New Zealand's multi-storey building stock, derived from discussions with leading New Zealand structural consultants, material suppliers, archivists and historians. Critical details are presented with reference to steel, unreinforced masonry and concrete and precast concrete construction, based upon their prevalence throughout New Zealand and the perceived degree of seismic risk associated with the details. This study is part of an on-going six-year FRST-funded research project on Seismic Retrofit Solutions for NZ, carried out by the Universities of Auckland and Canterbury. The main scope of the project is to develop cost-effective seismic retrofit solutions appropriate to New Zealand's unique construction practices and to prepare a seismic retrofit manual to be distributed to practising engineers as a companion document to the recently released NZSEE guidelines for assessment of earthquake risk buildings. A brief outline of the project is also presented, with further information available on the associated project website.

## 1 INTRODUCTION

The high seismicity characteristics of New Zealand are nowadays well known, at least within the scientific community worldwide. Subsequent to the 1931 Napier Earthquake (van de Vorstenbosch et al. 2002) the general public in New Zealand became aware of the seismic risk to the country's buildings. However this awareness lapsed over time and the structural damage resulting from the 1987 Edgecombe earthquake (Dowrick, 1988) was insufficient to generate meaningful long-term awareness of earthquake risk to buildings. Only in the time period directly following the Napier earthquake was there an awareness of the seismic risk to New Zealand buildings which was sufficient to substantially change construction practices at the time. In countries such as USA (especially California), Japan, and Turkey more recent earthquakes have caused catastrophic damage and generated widespread general awareness of the seismic hazard in their communities, resulting in a substantial research effort committed to the development of appropriate seismic retrofit solutions as well as to increase the know-how of local engineers (see for instance Earthquake Engineering New Zealand 2006). By comparison New Zealand has been slow to develop a national capability in seismic retrofit. The subject is not regularly taught at undergraduate level in university programmes, and few design documents have been available until recently. Those that are available are not typically consulted by many New Zealand designers for assistance in developing seismic retrofit solutions. One of the main concerns is also related to the possible differences in construction details and practice in New Zealand when compared to similar building typology overseas. A strong need to translate and adopt overseas practice in terms of assessment and retrofit of New Zealand's unique building stock, within a general plan of mitigation of the national seismic risk, has been recently recognized.

As a first major step in this undertaking, a document entitled "Assessment and Improvement of the Structural Performance of Buildings in Earthquake" (NZSEE, 2005) has been recently prepared and

was well timed to align with changes to the New Zealand Building Act (DBH 2006). However, the primary focus of the NZSEE document is on the assessment of general potential for poor seismic performance and the evaluation of existing building strength when compared to current code-standard level. Limited attention is thus given to rehabilitation or upgrading strategies, presented in a conclusive chapter in the form of a qualitative discussion with a useful overview of alternative conceptual solutions available. Moreover, during the drafting of the NZSEE assessment guidelines, major international research projects have been promoted overseas on the topic of seismic assessment and retrofit of existing buildings, enabling further development of modelling techniques, vulnerability procedures as well as ad-hoc retrofit solutions. A continuum update of outcomes from overseas research is thus required on both the topic of seismic assessment and on that of seismic retrofit.

In response to this recognized gap of knowledge, the civil engineering departments at the Universities of Auckland and Canterbury secured funding from the Foundation for Research Science and Technology for a six year study developing cost-effective seismic retrofit solutions for New Zealand's multi-storey building stock. The main aim is to adapt and extend existing procedures and technologies to the New Zealand situation, while developing innovative cost-effective retrofit solutions via supplementary research specifically addressing national needs.

At the conclusion of the project, a comprehensive seismic retrofit manual, suitable for use as a solutions guide for practicing structural engineering consultants in the field of seismic retrofit, and as a teaching guide for training structural engineering students will be prepared and released, under the joint support and endorsement of the Structural Engineering Society of New Zealand (SESOC) and NZSEE. This will be a complementary and integrative document to the aforementioned NZSEE assessment guidelines (NZSEE, 2005). In addition, development of assessment procedures and modelling approaches will allow a continuous update of this "live" document on seismic assessment.

In this paper, after an overview of the project outline and framework, a report on a specific sub-task of the project aim of collecting information on typical critical structural details in the New Zealand building stock is presented. More specifically, focus is given in this paper to reporting the preliminary findings derived from discussions with leading New Zealand structural consultants, material suppliers, archivists and historians. In parallel to this contribution, an extensive literature review is being conducted, based on past or on-going national and international experimental and numerical research investigations. By merging these results in a second phase, confirmation or refinement of the current (engineering or non-engineering) perception of the critical earthquake-risk details in NZ will result.

## **2 RESEARCH PROJECT FRAMEWORK**

The "Seismic Retrofit Solutions" project specifically focuses on the investigation and development of adequate retrofit solutions for both pre-1970 and post-1970 buildings, including reinforced and precast concrete, steel, and masonry. In parallel, aspects related to financial analysis are considered in order to support selection of the most appropriate retrofit intervention.

A number of postgraduate students, university research staff and professional engineers are involved in the execution and oversight of the project. Furthermore, the project is being carried out under the direction of a Seismic Retrofit Research Board (SRRB), comprising of representatives from industry as well as local authorities, which ensures that the project meets the needs of the various stakeholder groups relevant to this project. These people collectively have affiliations or are in positions to report to the SESOC, NZSEE, the Department of Building and Housing, the New Zealand Concrete Society, and Precast New Zealand. The involvement of these industry representatives has proven to be of great benefit to the researchers involved in this project, who wish to acknowledge here this valuable contribution. It is anticipated that once further research progress has been made, dialogue will also commence with representatives of New Zealand building owners, and with representatives of the New Zealand insurance industry.

Figure 1 schematically illustrates the project overview as at March 2006. More details can be found on the project website ([www.retrofitsolutions.org.nz](http://www.retrofitsolutions.org.nz)).

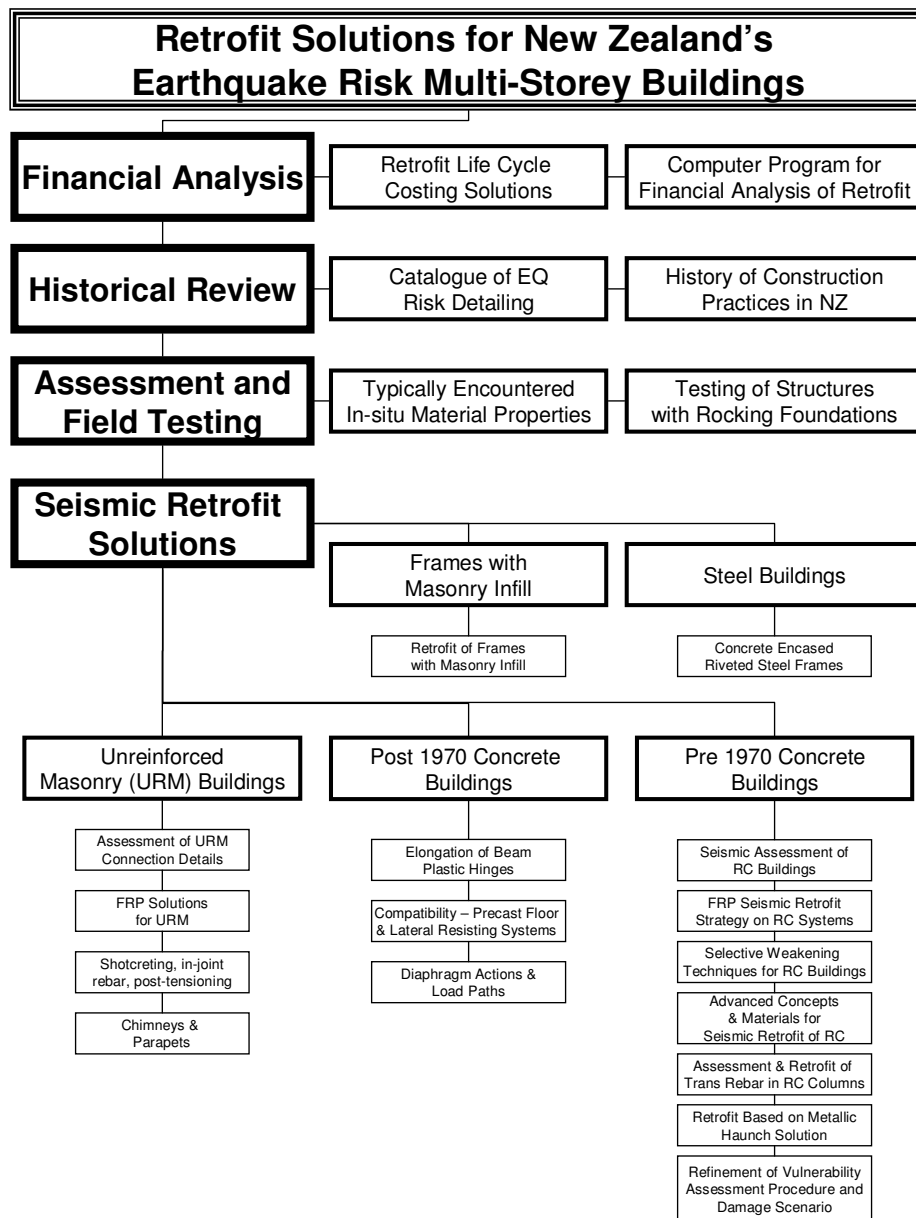


Figure 1 Retrofit Solutions for New Zealand's Earthquake Risk Multi-Storey Buildings – Project Overview as at March 2006

### 3 OVERVIEW OF TYPICALLY RECOGNIZED EARTHQUAKE RISK DETAILS

Buildings designed and constructed before modern concepts of earthquake resistant design were developed (a typical threshold being the early 1970s) did not have a clearly defined inelastic mechanism. Capacity design principles and the associated concept of detailing to develop plastic hinges in discrete intended locations (such as in beams adjacent to columns and at the base of columns adjacent to the foundation) were introduced only in the mid-1970s. Furthermore, NZS 4203 was the loadings standard current until only recently. NZS 4203 was developed prior to 1992, at a time when the numerical integration time history method was rarely used as the required computer resources were beyond the capability of most design offices. Because of this, the requirements of the NZS 4203:1992 loadings standard were general in nature and subjective, especially when “special studies” were required for more complex systems. Although it should seem inevitable that most of the construction before the 1970 will be deficient in terms of earthquake load design, it should be recalled that the Napier earthquake in 1931 prompted many structural engineers to rethink designs and to take into consideration the effects of earthquakes.

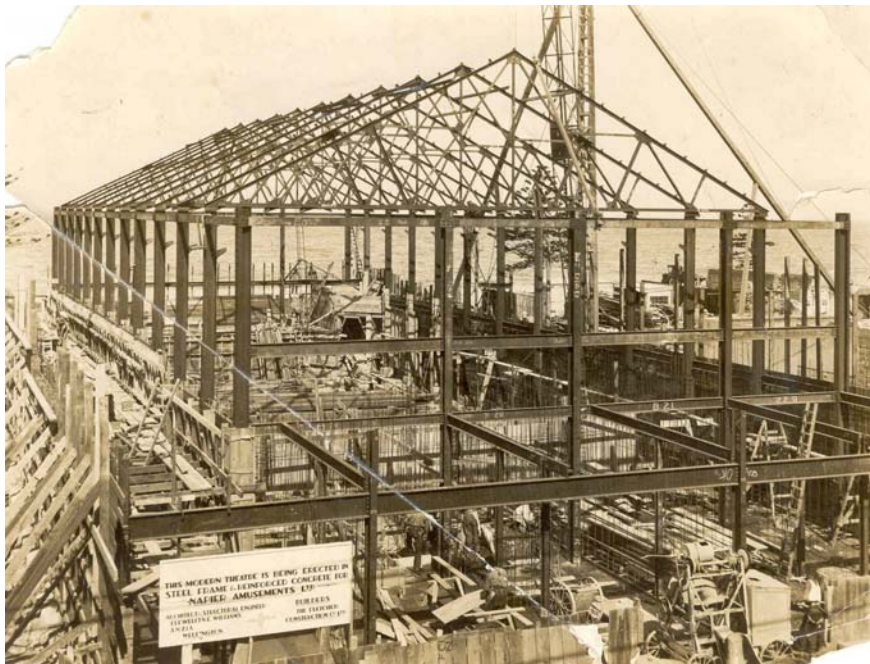


Figure 2 1932 construction of a buildings having a riveted steel frame encased in concrete

[Credit: Fletcher Building Archives]

### 3.1 Steel Buildings

Between approximately 1910 and 1940, construction using concrete encased riveted steel frames (CERSF), was a common practice both in New Zealand and in many other parts of the world, especially for monumental and institutional buildings (see for instance Figure 2). The popularity of this construction technique partly derived from building regulations that limited unreinforced masonry buildings to a height of five storeys. Furthermore, many large buildings such as train stations and hospitals required large wall openings for building operation, suiting steel construction rather than masonry. This method of construction was also very popular in other earthquake prone areas such as San Francisco, and many of the examples in New Zealand were in fact designed overseas.

The detailing used in these buildings has been found to be quite generic, with the steel providing almost all of the strength. It is thought that the primary attribute of the concrete encasement is for fire protection of the steel frame, and there is debate over how much strength the concrete provides. Section C5.8 of FEMA 356 (2000) recommends ignoring any strength that the concrete may provide, whilst designers have commented that as the concrete encasement exists, it is important to understand its influence on structural performance. Concrete strengths are typically low, around 15 MPa, and the quality of aggregate is variable, with many projects constructed near the coast using local beach sand and weathered shells. The concrete detailing is typically specified on the architectural plans rather than the structural drawings. Characteristics regarding composite behaviour and the timing of spawling of the concrete encasement is a primary subject area requiring research attention, so that substantially more accurate studies may be conducted on the non-linear strength characteristics of such buildings. Additional aspects requiring research attention include fracture of the rivets in the steel framing, yielding of support brackets in tension and shear, and section failure. The use of beams in two directions in most of these structures presents the critical detail, with particular focus required on the detail connecting beams with columns loaded in weak axis bending as shown in Figure 3. After World War II the popularity of this construction technique declined steadily as reinforced concrete became the preferred material to utilize in large scale design.

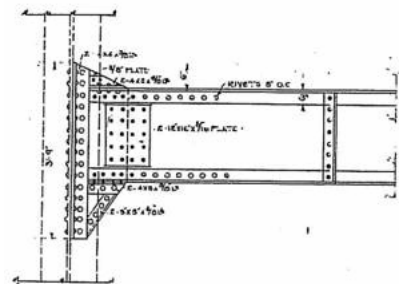


Figure 3 Riveted steel beam-column joint on column weak axis

[Credit: Holmes Consulting Ltd.]

### 3.2 Masonry Buildings

Masonry construction in NZ consists of both unreinforced masonry (URM) and reinforced masonry. Extensive development and research has been carried out in the past in New Zealand on reinforced masonry construction, particularly after the 1931 Napier earthquake. However, unreinforced masonry buildings have been shown countless times to perform very poorly in earthquakes. One of the most critical issues for unreinforced masonry structures is to address their propensity for in-plane rocking of piers between wall openings, which generate face load concerns (CIRIA, 1986). Two examples of URM construction similar to that encountered in NZ, that have failed in recent earthquakes due to out-of-plane actions, are shown in Figure 4. In general URM buildings are only able to sustain low strain levels before failure. Consequently, the promotion of rocking of masonry pier walls (provided proper strengthening of the spandrel beams is carried out) as an effective seismic response mechanism is clearly seen as an effective retrofit technique.

The configuration of unreinforced brick with timber floors has emerged to be a common and vulnerable system to earthquake loading, where connections between floors and walls are insufficient as well as the strength of the floors themselves. In addition upper floor levels and parapets lack strength and require some method of bracing. Where these buildings contain extensive openings in the form of doors and windows, the wall becomes increasingly vulnerable.



Figure 4 Damage to unreinforced masonry buildings in the 1989 Newcastle earthquake (Australia) (left) and the 1994 Northridge Earthquake (USA) (right)

[Credit: GeoScience Australia]

[Credit: Image from the Northridge Collection, EERC, UC Berkeley. Image by Bozidar Stojadinovic.]

Unreinforced masonry buildings may have a single, double or multi wthed configuration. Wire ties were necessary to connect these withes, but are often corroded and in some cases were not used at all. Header bricks were used about every five to seven courses. It has been found that when subjected to lateral loads, many bricks simply pull out of the wall as their strength depends on the strength of the mortar. In the case of lime mortar the bricks hold together but where cement mortar is used bricks tend to tear apart as the strength of the mortar exceeds that of the brick. It is necessary to take into consideration the possibility of the mortar being in original condition or having been re-pointed.

After the 1931 Napier earthquake it became apparent that unreinforced masonry was insufficient in providing the strength to buildings required to withstand earthquake forces, and the construction practice began to decline. Nevertheless, the construction typology remained quite common right through until the late 1940's. After World War II no large buildings were constructed with unreinforced masonry and in 1965, after the introduction of NZS 1900, this construction practice was outlawed.

### 3.3 Pre-1970 Concrete Buildings

Recent extensive experimental and analytical investigations have been carried out on the seismic performance of existing reinforced concrete frame buildings, which were mainly (if not only) designed for gravity loads, and which were typically built in seismic-prone countries before the introduction of adequate seismic design code provisions and the implementation of concepts of capacity design in the 1970s. These studies have confirmed the expected inherent weaknesses of these systems as observed in past earthquake events. Typical structural deficiencies of pre-1970 buildings are:

- a) inadequate confining effects in the potential plastic regions
- b) insufficient transverse reinforcement in the beam-column joint regions
- c) insufficient amount of column longitudinal and transverse reinforcement
- d) inadequate anchorage detailing, for both longitudinal and transverse reinforcement
- e) insufficient lap splices of column reinforcement just above the floor or at the foundation level
- f) insufficient shear reinforcement in wall systems when compared to the expected lateral demand
- g) inadequate design of the foundations to account for overturning moment caused by lateral loading
- h) lower quality of materials (concrete and steel) when compared to current practice, in particular:
  - use of low grade plain round (smooth) bars for both longitudinal and transverse reinforcement
  - low-strength concrete (below 20-25 MPa, and, in extreme cases, below 10 MPa)

As a consequence of poor reinforcement detailing, lack of transverse reinforcement in the joint region, as well as absence of any capacity design principles, brittle failure mechanisms are expected either at local level (e.g. shear failure in the joints, columns or beams) or global level (e.g. soft storey mechanism). As noted in previous studies (Hakuto et al., 2000, Pampanin et al. 2003) different damage or failure modes are expected in beam-column joints depending on the type of joint (exterior or interior) and of the adopted structural details (presence of transverse reinforcement in the joint; use of plain round or deformed bars). Possible damage mechanisms of exterior tee-joints with no transverse reinforcement in the joint region are shown in Figure 5. All of these solutions have been adopted in the past in NZ.

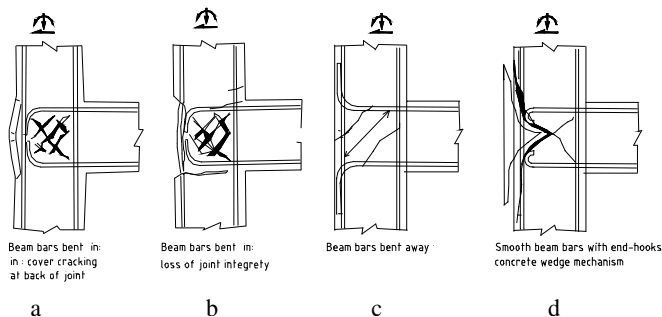


Figure 5. Alternative damage mechanisms for exterior tee-joints: a, b) beam bars bent inside the joint region; c) beam bars bent outside the joint region; d) plain round beam bars with end-hooks: “concrete wedge” mechanism (picture on right side)

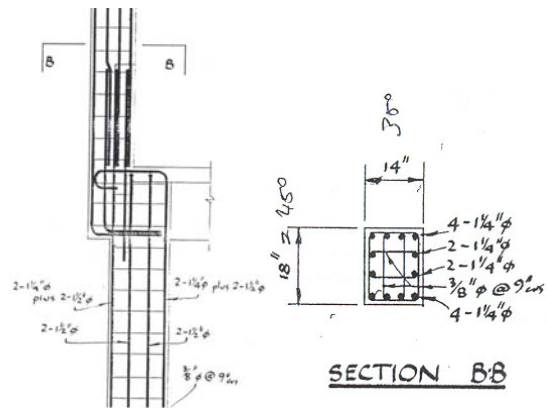


Figure 6. Typical reinforced concrete detail

[Credit: Connell Wagner Consultants Ltd.]

Construction in New Zealand transitioned around the mid 1960’s mainly due to the opening of Pacific Steel in Auckland, which provided increased availability and quality steel reinforcement. Prior to this all steel was imported from the UK, Australia and some from the USA. This imported material was expensive and of variable composition. The carbon content in this reinforcement was not restricted and led to brittle behaviour. In addition most design work followed a working stress limit rather than today’s ultimate limit state method which resulted in material strengths rising well over yield. Plain round bars were consistently adopted at least until the mid-1960s when the establishment of Pacific Steel in 1962 introduced deformed bars into NZ construction. Figure 6 shows a typical detail of a concrete school building built in the 50’s and 60’s. The reinforcement used is plain round bars  $f_y = 250$  MPa and stirrups are 6 mm at 9 inch centres. This detailing might lead to a soft storey mechanism in addition to shear failure in the columns.

### 3.4 Post-1970 Concrete Buildings

As the 1970s threshold has not been clearly taken as a rule to define earthquake-risk or earthquake-prone buildings, it can be dually argued that post-1970 concrete buildings are not expected to suddenly have superior seismic performance. More importantly, this research has confirmed that typical weaknesses of pre-1970s buildings were consistently adopted for several years subsequently. The issue of inadequate transverse reinforcement observed in columns constructed since the 1960s was not completely solved with the provisions in NZS 31012:1982, so that most buildings designed and constructed prior to the 1995 Standards can be expected to have inadequate confinement in their columns. Loss of cover concrete combined with buckling of the longitudinal bars could occur in the lap spliced regions leading to unexpected failure.

Moreover, literature has shown significant interest in displacement incompatibility issues between lateral load resisting systems (i.e. walls or floors) and floor systems. Inadequate structural details could favour local damage and failure mechanisms due to beam elongation and vertical displacement incompatibilities. Experimental investigation on the seismic performance of hollow core seating connections and overall 3-D frame systems (Matthews et al., 2003) has underlined the lack of comprehensive information on this topic.

### 3.5 Effects of masonry infills on the seismic response of frames

Regardless of the extent of inherent weaknesses in the bare frame systems, the presence of infills (e.g. typically un-reinforced masonry) and their interaction with the bare frame, can lead to unexpected and controversial effects (Crisafulli et al., 1997). The effects of infills still represent an open topic, with a critical need of further investigations for the seismic vulnerability assessment of extensive classes of existing buildings.

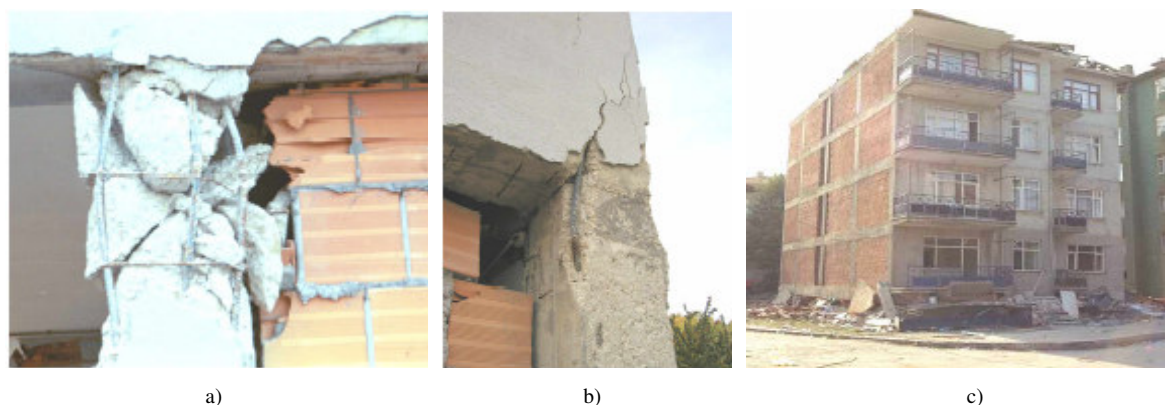


Figure 7 Observed effects of interaction between infills and bare frame: a) shear failure of column and b) exterior joint shear damage (Bonefro, Molise 2002); c) global collapse for soft storey mechanism (Izmit, 1999)

[Credit: NISEE image collection, S. Pampanin University of Canterbury]

The presence of infills can allow higher stiffness and strength, reducing the inter-storey drift demand, while increasing the maximum floor accelerations. A further protective action of the infills can be recognized in the reduction of column interstorey shear contribution as well as in the possible delay of a soft-storey mechanism which might instead develop in a bare frame solution. However, the sudden reduction of storey stiffness due to the damage of the infills can still lead to the formation of a soft storey mechanism, which, due to the interaction with joint damage, can occur any floor level and independently of the distribution of the infills along the elevation (Pampanin, 2005). Furthermore, shear failure in the column, due but not limited to short column effects, can result. Similarly, when investigating the response of 3-D frames under either uni-directional or bi-directional earthquake input excitation, inelastic torsion mechanisms can occur due to the irregular distribution of damage to the infills.

It has been noted (Pampanin et al., 2004), that not only the distribution along the elevation but also the geometrical and mechanical properties of the infills (i.e. one or two withes, solid clay or hollowed bricks of different sorts used as internal partitions, grout type) can have a major impact on the overall response. The NZ construction practice has been characterized by a relative moderate variation of infill

types, when compared to Mediterranean countries. Mainly solid clay bricks have been adopted for exterior frames, with internal partitions mostly relying on timber solutions. A strong need has been recognised for collection of reliable data on the mechanical properties of typical infills adopted in NZ, integrated with experimental laboratory investigation on sub-panel elements in order to calibrate numerical models.

#### 4 CONCLUSIONS

This paper has presented preliminary findings on a study of critical detailing commonly encountered in New Zealand's earthquake risk multi-story buildings. Critical details have been identified buildings constructed with concrete encased riveted steel frames, unreinforced masonry, concrete (divided into pre-1970 and post 1970 construction) and frames with masonry infills. The assistance of the Seismic Retrofit Research Board in the identification of critical earthquake risk detailing and the development of the project plan is gratefully acknowledged.

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