The Canterbury Earthquakes

Implications for Building and Construction Standards

Submission to

Canterbury Earthquakes Royal Commission

by

Dr David C Hopkins BE(Hons) PhD CPEng IntPE FIPENZ FNZSEE

Introduction and background

The magnitude 7.1 Darfield earthquake on 4 September 2010 caused extensive damage to buildings and infrastructure in the Canterbury region including areas of Christchurch city and suburbs. The magnitude 4.9 aftershock on Boxing Day caused further damage. Although damage was significant and widespread, there were no major building collapses and no loss of life. The impact on modern building structures was low.

Extensive areas of land in Christchurch city and suburbs and in parts of Waimakariri District were affected by liquefaction and lateral spreading of land. This caused damage to many properties and required remedial work to stabilise the land and improve its liquefaction resistance to future earthquakes.

On 22 February 2011 a magnitude 6.3 aftershock centred near Lyttelton, (the Christchurch earthquake) caused severe damage to Christchurch, particularly the CBD, eastern, and southern suburbs, the Port Hills, and Lyttelton. Ground shaking intensities, both horizontal and vertical, in Christchurch city were well in excess of that used as a basis for building design. Over 180 people died and many more were seriously injured. Many masonry buildings or parts of buildings collapsed in the CBD and many modern building structures were critically damaged. At least two multi-storey buildings collapsed and stairs collapsed in several modern multi-storey buildings.

Further liquefaction and lateral spreading occurred in Christchurch city and suburbs. Effects were generally more severe than in the Darfield earthquake and the effects extended to areas which were not previously affected. Considerable liquefaction and lateral spreading were evident in the CBD and appear to have caused foundation movement in a number of buildings.

Significant areas of the suburbs in the Port Hills and Lyttelton were affected by land instability, including major slope failures and loosening of basalt boulders.

Unreinforced masonry (URM) buildings in Christchurch city were very badly affected. Collapse occurred of all or part of most buildings, including those that had been strengthened or secured.

Secondary elements such as ceilings, partitions, and pre-cast panels suffered damage in some cases. The collapse of stairs in eleven buildings was of particular concern.

Several buildings with pre-cast concrete floors, both double-tee and hollow-core, may have been compromised by the inability of the floor system to tie the main structural frames together, raising questions about the integrity of the building as a whole.

The collapse of the CTV and PGC buildings and stair collapses in Forsyth Barr, Grand Chancellor Hotel and other buildings have raised further questions about the approaches to design of structures for earthquake.

Although, the impact of the earthquake affected the whole range of built assets, this submission focuses on buildings. Nevertheless, many of the comments apply to the design of other assets.

Overview of issues

Devastating though the circumstances were, the Canterbury earthquakes provide an opportunity to examine the impacts on built assets and determine the need or otherwise to change the approaches to and requirements for earthquake engineering design and construction in New Zealand.

The opportunities from these earthquakes to benefit future planning and design processes are many and varied. The existence of ground motion records, widespread liquefaction and the severe testing of modern earthquake designs make these earthquakes hugely important for New Zealand and internationally. Although the costs of repair and recovery are horrendous, it is vital that comprehensive efforts are made to learn from these events. It is an opportunity that must be taken and an obligation that cannot be avoided. The (relatively small amount of) money must be found to make this investment in the future.

This submission examines a range of issues that need attention following the earthquakes of 2010 and 2011 in Canterbury.

1. Earthquake events knowledge

New Zealand is known to be earthquake-prone. Standards for structural design which acknowledge this fact were introduced in 1935 and have been developed since to match increasing knowledge. Research has yielded information about New Zealand's tectonic setting, the existence of active faults, their location, the earthquakes they would generate and estimates of the probability that they would occur.

This knowledge has been taken into account in successive New Zealand earthquake loading standards, starting with a single level across the whole country from 1935 to 1965, three different seismic zones from 1965 to 1976, and a continuous interpretation of seismicity from 1976 onwards. New interpretations were made in 1984, 1992 and 2005.

The latest interpretations are based on an assessment of the intensity of ground shaking (and thus building response) at any place in New Zealand that has a defined probability of occurrence (or exceedance). For most commercial, industrial and residential buildings the basis is 10% probability in 50 years (1 in 500). For important buildings that are critical in emergencies, the basis is 10% probability in 250 years. (1 in 2500).

This uniform risk basis is what gives different seismic coefficients in different parts of New Zealand. The Darfield and Lyttelton earthquakes have served to remind us that the assessment of risk is based on limited data over a geologically very short time. The uniform risk model included a Canterbury Plains earthquake with a return period of 16,000 years. The ground shaking produced in Christchurch by such an earthquake, while quite high, was down-rated in the risk model due to the low probability of the fault rupture. But now that the Darfield earthquake has occurred the risk model has been reassessed. High intensity ground shaking from aftershocks is now almost certain to occur in the next year. Furthermore, the movement of the Darfield fault may have stressed other faults near Christchurch. This influence may have triggered the Lyttelton earthquake.

In relation to overall seismicity, there are thus two main considerations in reviewing the seismic risk and coefficients used in structural design:

- The influence on the 500-year and 2500-year shaking intensity of the revised seismicity assessments of Christchurch given the occurrence of the Darfield and Lyttelton earthquakes
- The adequacy of the probabilistic basis for determining earthquake levels to be used in the design of buildings and infrastructure.

The latter point is significant. A study needs to be done to examine the introduction of a conditional probability into the mix when determining seismic coefficients. In this case, the question is asked: What if this very low probability fault ruptures? In basing designs on probability estimates, engineers have been lulled into thinking that earthquake effects are under control. The impact of the 22 February earthquake is a reminder that earthquakes can occur at any time and with widely varying effects. The principle needs to be considered for all of New Zealand, not just Christchurch or Canterbury.

(In considering seismic coefficients to be used it is essential that a comprehensive study is done of building performance in relation to ground shaking experienced. It may be that the present relationships between likely ground shaking and building performance need to be changed significantly – for two reasons: a) Because (modern) buildings performed better than expected and b) Community expectations of building performance may have changed. The change made to the seismic coefficient for Canterbury from 0.22 to 0.30 took little or no account of building performance and should be regarded as an interim measure. Further comments are made in the relevant sections below.)

Vertical ground motions

Vertical accelerations measured in the 22 February earthquake were significantly higher than those required for design. The extent of the difference depends on the building characteristics. This is likely to have had an influence on building structural performance, especially of columns and walls. Certainly, the difference is enough to warrant a review of design requirements and the degree to which vertical accelerations must be considered in seismic design.

Recommended Actions

Ground motions considered in structural design:

- A review of the NZ Seismic Hazard Model to account for the occurrence of the Darfield Earthquake and aftershock sequence
- Re-assessment of the 500-year and 2500-year expected ground motions from the new model
- A review of the adequacy of the current seismic hazard model to identify and allow for the effects of very low probability faults
- A recommendation to modify the approach to determining the estimated earthquake ground motions that better accounts for the effects of very low-probability fault events.
- A specific review of the likely severity of vertical ground motions leading to recommendations on any changes to present requirements to take account of vertical accelerations in structural design for earthquake.

Ground motion propagation:

- Use of ground motion data, soil profiles, and fault rupture characteristics to check / modify ground motion attenuation / propagation relationships used in seismic assessments.

2. Estimated ground motions

Even when the occurrence of earthquake events is reasonably well known there are considerable uncertainties involved in estimating the ground motions at some, often distant, point. The nature of propagation and attenuation of the ground motions generated at the source varies with the rock and soils they travel through. The NZ Earthquake Hazard Model incorporates empirically-derived relationships for this attenuation. With more than 70 strong motion instruments in the affected area, the Canterbury earthquakes provide an opportunity to refine and better calibrate these relationships, at least for the soils in the Canterbury area.

The Lyttelton earthquake, particularly, may offer much stronger insights into vertical ground motions. Strong motion readings suggest these were much higher than expected.

Recommended Actions

Two main elements need investigation:

- The influence of soil / rock structures on propagation / attenuation of ground shaking, and the impact any changes in modelling may have on the NZ Earthquake Hazard Model.
- An examination of the propagation / attenuation of vertical ground motions and the implications for Canterbury and all other parts of New Zealand. This would inform considerations on any changes needed to design provisions for vertical accelerations on buildings and parts of buildings.

3. Site conditions and site response

Knowledge of the site conditions is critical in the planning and design of built infrastructure. There are two main considerations:

- *Site suitability* for development.
- *Soil characteristics* of the site that influence the nature / extent of development

Site suitability is paramount. The Canterbury earthquakes provide the opportunity to better define criteria for suitability for all kinds of hazard, not just earthquake. Indications are that better knowledge and more sensible application of that knowledge could go a long way to reducing the impacts of earthquakes on our communities. Other specific considerations are flooding, and tsunami.

The Canterbury earthquakes provide an unparalleled opportunity in the case of the effects of liquefaction, and one that could benefit other earthquake-prone countries. Once again this is helped by the data from so many strong motion instruments and reasonable knowledge of the subsurface soils.

Slope stability and rock fall risk are other considerations that require evaluation. This could inform new criteria for site suitability for development.

The *soil characteristics* of the site have been seen in the Canterbury earthquakes to have a fundamental influence on structural behaviour. Settlement and tilting of foundations and buildings were observed in many cases.

Clearly there is a need to examine the extent to which site soils conditions and properties are investigated and then allowed for in design. If shortcomings in knowledge or approach are evident, improvements in code requirements and engineering practice will be needed.

The Canterbury earthquakes must be used to promote the development of a soil profile database for all of New Zealand. Interpretation of results for a particular site can be significantly enhanced if data is readily available for adjacent and nearby sites. Legislation may be needed to require data to be shared.

With the wealth of ground motion data from these earthquakes, there is an opportunity to better understand and estimate site responses to earthquake effects. Current design provisions distinguish between soils of different density and shear wave velocity in order to assess site response and hence building response.

There are opportunities here to learn more about these relationships and apply the lessons of Christchurch and Canterbury to other parts of the country and overseas.

Recommended Actions

Site Conditions

- Legislation and / or regulations are needed to require the sharing of soils information. There should be a requirement on all parties carrying out subsurface investigations to provide basic borelog information to a common, New Zealand-wide database.

Liquefaction / lateral spreading:

- A comprehensive review of the nature and extent of liquefaction and lateral spreading in the 4 September and 22 February earthquakes, throughout the Canterbury region.
- A re-examination of liquefaction / lateral spreading potential in future earthquakes, taking account of any ground improvement measures proposed or carried out.
- Studies to determine the severity limits of liquefaction / lateral spreading effects beyond which development of built infrastructure is not viable.
- Studies of soil parameters and expected ground shaking to determine the geographical areas where development would be prohibited.
- Studies to improve estimation of liquefaction effects and remedial measures needed to limit their effects.

Land instability / loose boulders:

- A comprehensive review of the nature and extent of land instability and rock fall in the 4 September and 22 February earthquakes, throughout the Canterbury region.
- A re-examination of extent of land instability and rock fall potential in future earthquakes, taking account of any improvement measures proposed or carried out.
- Studies to determine the severity limits of land instability / rock fall effects beyond which development of built infrastructure is not viable.
- Studies of land stability parameters and expected ground shaking to determine the geographical areas where development would be prohibited.
- Studies to improve estimation of the effects of land instability and rock fall, and remedial measures needed to limit their effects.

4. Estimated structure response

Estimation of the site response in terms of ground motion is but a first step in estimating the response of a building on the site. The use of computers has made structural analysis easy, but basic assumptions are required to define a mathematical model to analyse. There is a danger that the results of computer analysis are accepted as more accurate than the underlying assumptions could possibly justify. The variability and uncertainties inherent in computer analysis of structures need to be recognised, and the Canterbury earthquakes and response of buildings provide an opportunity to better understand the issues and allowances that must be made.

Given the high level of peak ground motions in the 22 February earthquake, major modern buildings, with two notable exceptions, did a good job in structural terms - the buildings did not collapse and occupants got out safely. Many buildings survived with little damage to the primary structural elements.

Earthquake response spectra derived from the ground motion instruments suggest that the structure responses, in many cases, should have resulted in much more damage to buildings than was evident. This apparent anomaly is probably the single most important aspect to resolve in learning from the 22 February earthquake. There may need to be a fundamental review (paradigm shift) of the way we estimate structure response to earthquake ground motions. And, again, the data is there to help – ground motion measurements and observed building response.

Aspects that need to be included in this examination include:

- Validity of response spectra which assume that free-field motions are the same as those experienced by a massive building.
- Stiffness and strength properties assigned to structural members and supporting soils.
- Modelling of the soil / structure combination, not the two separately
- Efficiency of coupling between the ground and the building. (It may be that the measured ground motions do not wholly transfer to a building because of this.)
- The duration of shaking. Longer duration allows time for displacement to build up. Even without build-up, the more cycles experienced by a structural member, the more damage will occur.

The response of structures to vertical accelerations and the provisions for dealing with this response need review in our standards.

The results of these investigations may have a significant impact on NZ Standards for earthquake loading, and structural design, and on overseas design practice.

Recommended Actions

- A review of the behaviour / response of a selection of buildings of each main type, including reinforced concrete frame, reinforced concrete shear wall, steel frame, steel eccentrically braced frame, tilt-up with slender reinforced concrete panels.
- Comparison of analyses of response by commonly used methods, with those evident from the damage / displacement of the buildings.
- Use of these results to determine any differences between estimated and actual response. Consideration of reasons for any differences, which may include:
    - Validity of response spectra derived from free-field instruments
    - Stiffness and strength properties assigned in analyses
    - Modelling of "structures" to include soil parameters.
    - Efficiency of coupling between ground and building
    - Limitation of forces transferred through soil to the building due to liquefaction.
    - Variability and uncertainty in building properties
    - Existence of unintended critical weaknesses
- A review of the performance of URM buildings to include:
    - Use of the above results to estimate accelerations / displacements experienced by a good cross section of buildings, retrofitted or not.
    - Comparison of performance with expectations
    - Evaluation of the effectiveness of retrofit measures
    - Recommendations for any changes in approaches to evaluation or retrofit design.
    - Recommendations on any changes needed to the Building Act and Code in relation to the requirements for earthquake-prone buildings.
- Similar reviews of bridges, storage rack systems and liquid-retaining structures.

5. Primary structure design

Once the response of a structure has been estimated, the design process involves assigning strength, stiffness and ductility to primary structural members adequately to sustain the estimated response without exceeding accepted limits of strain, stress and displacement.

NZ Standards and associated guidelines set requirements and describe methods of assigning strength, stiffness and ductility in various materials and structural configurations. The Canterbury earthquakes present an opportunity to examine the effectiveness of these requirements and methods in delivering structures that match community expectations and needs.

Among the specific aspects highlighted by the earthquakes are:

- Behaviour of URM buildings and the effectiveness of strengthening measures – technically, legislatively, socially and organisationally.
- Earthquake-prone building issues, especially the need to specify a strengthening level in the Act, the minimum level needed to define an earthquake-prone building, and any special provisions to secure parapets and chimneys.
- Procedures for estimating the capacity of members, particularly columns and walls. This applies to all types of structure and all materials including reinforced concrete, structural steel and masonry.
- Foundation details necessary to take account of soil conditions (adequate strength and limitation of settlement), including the potential for liquefaction and lateral spreading.
- Integrity (tying together) of main structural members.

6. Secondary structures

It is perverse that structural engineers refer to elements such as ceilings, glazing systems, partitions, stairs, pre-cast cladding, industrial storage racks and major services pipes as “non-structural” items. There is ample evidence from the Canterbury earthquakes that these and similar items require structural engineering input if they are to be safely installed. Ceiling systems and industrial storage racks stand out as needing attention to improve seismic performance.

The opportunity needs to be taken to review the performance of each of these secondary structure items. This needs to cover the influence of all items in the procurement chain, from manufacture through final installation to care in use and maintenance. Studies are needed leading to recommendations on changes to standards and practices.

Recommended Actions

- Carefully review the response / performance of secondary structures, particularly:
    - Stairs in multi-storey buildings
    - Suspended ceiling systems
    - Glazing systems in multi-storey buildings
    - Industrial / commercial storage racks
    - Precast cladding panels on multi-storey buildings
- In each case, a review of all steps in the procurement process (design, manufacture, installation) and maintenance / modification after installation.
- In each case a comparison of capacity with expected demand is needed.
- Recommendations for changes in the design, manufacture, installation, maintenance and use of these secondary structures.

7. Detailing for integrity and consequences of failure

The future of some major structures has been compromised by damage to pre-cast floor systems and the collapse of stairs in several buildings. This damage sends a vital signal that integrity of the structure is perhaps the single most important consideration in design of buildings to resist earthquake motions. Buildings that suffered the least structural damage (in some cases none at all) were those that were well tied together.

The performance of commonly used details should be reviewed from this standpoint. It is likely that changes will be needed, particularly for pre-cast concrete floors where a thin topping with nominal reinforcing was relied upon in at least one building to tie the major structural frames together.

Over recent years, there has been concern over the performance of hollow-core floor and double-tee floor construction. Concerns have related to reliance on cover concrete for support, integrity under earthquake-induced displacements, reliance on unreinforced concrete in tension, and adequacy of the reinforcement in the thin concrete topping to maintain the integrity of the primary structure. For example, hollow-core floors have no web reinforcement. If the webs crack, there is no reserve capacity or mechanism to re-distribute the load. This is of particular concern for the deeper units available that are now being used. Test data for the three-dimensional situations is very limited.

Furthermore, it is important to recognise the effects of time on a structure. Most structures are required to perform for 50 years or more. This needs careful consideration when assessing performance and setting design requirements.

In the absence of field data these concerns are difficult to resolve. The Canterbury earthquakes provide an opportunity to investigate the behaviour of such floors and to identify where standards and practices need to be improved.

The collapse of stair units poses important questions about the approach and design requirements. Stairs are commonly separated from the structure in order to prevent bracing of the building. If, as seems the case, some of the collapses are due to the seating proving to be inadequate, a more conservative approach may be needed to allow for unforeseen circumstances such as ground motions which produce greater-than-expected structural responses. *(Note: SESOC and the Department of Building and Housing have taken some interim steps to address the stairs issue, but more work is needed.)*

This links back to the points made about estimation of ground motions and structure response. The uniform risk (probability) basis may need to be extended to include “what if?” scenarios. Better recognition is needed of the limitations of analysis methods to estimate ground motions, and the variability and uncertainties involved in estimating structural response to assumed ground motions.

Recommended Actions

- A review of a good cross section of all non-URM buildings in the CBD with the express purpose of documenting the degree of integrity (tying together) of the building and its influence on structural performance overall. This should include buildings that were retrofitted and those that were not. *(I have a suspicion that such a survey may show that many engineering assessments of %NBS are conservative (ie low), particularly for URM buildings that have been well tied together.)*
- Consideration of the results and the implications for NZ Standards for design and/or construction.
- Comprehensive studies of the details used and performance of precast reinforced concrete floors in their roles to support gravity load, act as diaphragms and provide integrity to the structure overall.
- Use of the results above to recommend changes in approach in the design, detailing and range of uses of precast floors.

8. Construction to building consent requirements

There are two main sources of concern:

- Failure of the building contractor to meet the requirements of the design drawings and specifications
- Changes made by the owner, contractor and/or the designer following issue of the building consent

"Non-compliances" in these areas may not have been a significant factor affecting the performance of buildings in the Canterbury earthquakes, but there were sufficient indications in the damaged elements of some modern buildings to warrant examination of these issues.

In relation to the first item, there is concern in professional engineering circles that the last three decades have seen a significant decline in the engagement of the structural designer to monitor key construction activities to provide greater confidence in compliance – and to provide the opportunities for corrective measures for unforeseen deficiencies. The Canterbury earthquakes may yield evidence on the impact of such trends. Certainly, it will be interesting to compile a list of non-compliances with the drawings and specifications to gauge whether or not it is a significant factor.

Changes made during construction have been known to critically reduce the structural capacity and/or integrity of the building or part of a building. In reviewing the performance of buildings in the Canterbury earthquakes, it will be interesting to note if such changes have had any detrimental effect on structural performance.

The Building Act 2004 included more stringent requirements. Changes made during construction must have a building consent.

An important point that underlines the need for appropriate levels of construction monitoring is that almost all buildings are essentially a prototype – that is, they are the first of their kind. Unlike aircraft and cars, there is not? opportunity to test the early versions and refine the designs before making them available to the public. Getting a building right first time requires appropriate effort at all stages. The expense involved should be considered as a necessary investment, not an unnecessary cost.

Recommended Actions

- A questionnaire should be put to consultants, owners, Christchurch City Council and others to identify any cases where changes made to the design after the building consent was issued had a detrimental effect on structural performance or capacity
- A review of the results of this questionnaire and development of recommendations for any changes in requirements, behaviours or practices.

9. Post-occupancy changes / influences

Changes made by owners and tenants through the life of a building can have a very significant impact on building performance. Typically this relates to building services where the installation or removal of partitions upsets carefully designed air flows. Impacts on structure are relatively rare.

Recommended Actions

Any review of building performance needs to recognise and look out for detrimental effects of post-occupancy changes.

10. Deterioration with time

The Building Code requires buildings to comply with the performance requirements throughout the life of the building. This is normally for 50 years or more. NZ Standards and structural design practices require consideration of corrosion and other time-related effects such as creep, shrinkage and settlement. This is expected to give a good level of protection so that compliance is achieved not just on first occupancy, but for the life of the building.

Nevertheless, time-related effects can reduce structural integrity and capacity.

Reviews of building performance should be alert to the possibility that deterioration of structural materials with time may have influenced the performance of a building. Consideration can then be given to the need for changes in standards and/or practice.

Recommended Actions

- Review and record any instances where the effects of lack of maintenance, corrosion, shrinkage, creep or temperature have significantly reduced the earthquake capacity of the building.

11. Seismic Design Objectives and Approach

Seismic Design Philosophy

The present approach to seismic design accepts, or at least tolerates, damage to the primary structure and to other building elements in the event of a major earthquake. Thus many modern buildings in the Christchurch CBD were seen by structural engineers to have performed well – they did not collapse, allowing people to safely vacate the building. They were, however, damaged beyond repair and need to be demolished. The economic impact of this is very significant. Now would be a good time to make a deliberate and professional attempt to check that this philosophy is acceptable, or at least tolerable, to the community.

Recommended Actions

- Commission a survey of a cross-section of building owners and users to obtain feedback on how well the current philosophy matches community expectations. The survey should be done in all main centres, not just Christchurch. There may be an element of over-reaction if done early, but the results will be of immense value in meeting a very fundamental aim of the Building Act and Code. Follow-up surveys would help to measure any changes in attitude as the time since the damaging events increases.

Seismic Design Coefficients

The free-field ground motions measured or predicted may be greater than those experienced by buildings, for a number of reasons. It is important when setting seismic coefficients for structural design that the reasons for the differences are understood. Decisions on seismic coefficients can then be made which reflect the best attempts to understand the real response of buildings to earthquakes, and do not rely too heavily on theoretical computations.

Recommended Actions

- Set up an expert panel to bring together the latest information on earthquake hazard, ground shaking estimates, soil and rock profiles, geotechnical and structural design. Charge them to:
    - review the overall behaviour of elements of the built environment, particularly buildings, in the Canterbury earthquakes,
    - consider the knowledge of earthquake hazard, including the limitations inherent in the limited time frame of research in this area

- consider the community's needs and reasonable expectations in the structural performance of buildings
- recommend any changes in approach to the estimation of seismic demands on buildings and structures that result

12. Recommendations

This submission identifies the need for considerable investigation, research and consideration of the implications for building standards. Some of these are already under way, but much more work is needed. Above all, when interpreting the performance of a building, building type, or element, care is needed to properly correlate the ground motions likely to have been experienced with the actual performance. This needs then to be related to expectations inherent in existing standards. Only then can informed and sensible decisions be made on what changes to make in the requirements for building design and construction as a result of the Canterbury earthquakes.

A fundamental review is warranted, not simply a tinkering with the details of current standards and approaches.

It is recommended that:

- The various current inputs are co-ordinated and added to a coherent framework of effort.
- Further work is commissioned and funded to complete the coverage outlined above
- A panel of experts be established to oversee progress toward outcomes and to better define the specifics and the resource and funding requirements to draw these necessary lessons from the Canterbury earthquakes

  Funding is sought from NZ government and other sources, including from overseas, to fund the work over the next five years. *(A five-year Canterbury Earthquake Research Programme was proposed by the author after the 4 September Earthquake. This was supported by the Canterbury Earthquake Recovery Commission. It is recommended that the Royal Commission supports this proposal, a copy of which is transmitted with this submission)*

David Hopkins

Dr David C Hopkins

11 October 2011