Department of
Building and Housing
Te Tari Kaupapa Whare

Technical Investigation into the Structural Performance of Buildings in Christchurch – Final Report

DEPARTMENT REPORT TO THE MINISTER FOR BUILDING AND CONSTRUCTION

31 January 2012

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Chief Executive's foreword

All of New Zealand has been shocked and saddened by the events of 22 February which saw the loss of 182 lives, severe injury and considerable distress to many. The earthquake delivered forces, particularly vertical, which were amongst the highest in any urban area and resulted in the damage to and collapse of many buildings.

The effects of the earthquake sequence will be with people for a long time and we owed it to the bereaved and the survivors to learn from these events to inform the requirements for building and construction in New Zealand for the future.

The Department commissioned technical experts to investigate in depth the reasons for the failure of four multi-storey buildings. This work was quality assured by an Independent Expert Panel, also appointed by the Department. This review of the investigations was both robust and comprehensive. The Department has taken the recommendations from the Expert Panel and has work underway or planned to address all the recommendations.

The Department is committed to learning from the events in Christchurch. Working with others in the building and construction sector, the Department will lead a significant work programme to ensure that learning from these events is applied for the benefit both of the rebuild of Christchurch and the rest of New Zealand.

This report sets out the Department's response to each of the recommendations made by the Expert Panel.

I hope that understanding the extreme nature of the event and the reasons for the collapse and damage to the four buildings, alongside the actions being taken, will be of some comfort to the bereaved, the injured and the survivors both internationally and in New Zealand.

Katrina Bach
Chief Executive

Introduction

The Department of Building and Housing (the Department) was formed in 2004 to bring together under one roof all functions relating to building and construction. The Department's role is to continually review building standards and building science so New Zealand can be assured that we are continually learning and applying that learning in the construction of our buildings.

The Department appointed experts to review why four multi-storey buildings in the Christchurch Central Business District failed during the 22 February 2011 aftershock. These reports were in turn reviewed by an Expert Panel appointed by the Department who have made recommendations for the Department's action.

The buildings included in the investigation were the Canterbury Television Building (CTV), the Pyne Gould Corporation Building (PGC), the Hotel Grand Chancellor Building and the Forsyth Barr Building. Two of these buildings experienced collapse with significant loss of life and severe injury, while the other two experienced significant failure of building components, including stairs, columns and walls, but no loss of life.

The Department's investigation into the collapse of the CTV Building has now been completed and the Expert Panel's Final Report covers the investigations for all four buildings. Further analyses had been found to be necessary for the CTV Building in order to develop a full understanding of its performance in the 22 February 2011 aftershock, and the contributing factors that caused the building to collapse.

The recent earthquake series in Canterbury has been a unique event, both in New Zealand and internationally, and it is important to learn from this event to inform the future. The Department has confidence in the quality and rigour of the investigation, and considers the Expert Panel's report to provide an authoritative and accurate account of the factors that contributed to the failure of the CTV, PGC, Hotel Grand Chancellor and Forsyth Barr buildings.

The Department has carefully considered all of the Expert Panel's recommendations, and will lead a substantial work programme to give effect to the recommendations.

The Department's initial response to the recommendations is included in this report. The Department's approach will be to work with other parties in the sector and balance the need to address the issues highlighted in the Expert Panel report with finding practical solutions that will enable building owners and developers to construct with confidence.

The summary of the investigation into each of the four buildings is followed by a section with the Expert Panel findings, their recommendations and the Department's response. The Expert Panel has assigned a priority of A (urgent), B (high), or C (moderate) to each recommendation and the Panel notes that it is important that action is taken on all of the recommendations as soon as possible.

The Department will continue its work to raise awareness across the building and construction sector of the issues that emerged from the investigations and which are outlined in the nine recommendations to improve overall building quality.

Context

The Magnitude 6.3 aftershock centred near Lyttelton on 22 February 2011 was a part of the sequence of earthquakes that commenced with the Magnitude 7.1 Darfield earthquake which occurred on 4 September 2010. The aftershock caused severe damage to Christchurch, particularly the Central Business District (CBD), eastern and southern suburbs, the Port Hills and Lyttelton. Ground shaking intensities in Christchurch city, both horizontal and vertical, were in excess of those used as a basis for building design at any time up to the present day. As a result of the building collapses in the aftershock on 22 February 2011, 182 people died and many more were seriously injured. Many masonry buildings or parts of these buildings collapsed in the CBD and many modern building structures were critically damaged. At least two multi-storey buildings collapsed and stairs collapsed in some modern multi-storey buildings.

While the impact of the Darfield earthquake was widespread and severe, there were no major modern building collapses and no loss of life. There was substantial damage to unreinforced masonry buildings (URM), largely in the CBD, but the time of the earthquake meant that few people were exposed to the hazard of falling masonry, which represented the bulk of building damage.

Several thousand aftershocks, including several Magnitude 5.0+ aftershocks, followed in the months after the 4 September 2010 earthquake, including the Magnitude 4.9 aftershock on 26 December 2010 that caused further damage in the CBD. The latter event was very close to the CBD and produced significant ground shaking in Christchurch city despite the significantly lower magnitude.

The Magnitude 6.3 Lyttelton aftershock occurred at 12.51pm on Tuesday 22 February 2011, approximately five months after the Magnitude 7.1 Darfield (Canterbury) earthquake. The epicentre of the 22 February 2011 event was approximately 10km south-east of the CBD, near Lyttelton, at a depth of approximately 5km.

Due to the proximity of the epicentre of the 22 February 2011 aftershock to the CBD, its shallow depth and distinctive directionality effects, very strong shaking was experienced in the city centre, the eastern suburbs, and the Lyttelton-Sumner-Port Hills areas.

The shaking intensity of the 22 February 2011 aftershock recorded in the city of Christchurch was much greater than that of the main shock on 4 September 2010. The recorded values of peak vertical accelerations, in the range of 1.8 and 2.2 times gravity (1.8g and 2.2g) near the epicentre, were amongst the highest ever recorded in an urban environment.

However, while these accelerations were very high, the relatively short duration of the events moderated their effects. In the CBD the highest values of peak ground vertical accelerations recorded were between 0.5g and 0.8g.

For the 22 February 2011 event, a wide range of (medium to very high) horizontal ground accelerations were also recorded, with peaks exceeding 1.6g near the epicentre and between 0.4g and 0.7g in the CBD. This variation confirms the strong link to the distance from the epicentre, and also reflects the variability of soil characteristics.

Earthquake engineering standards and practices

Development of earthquake engineering standards and practices in New Zealand dates back to the 1931 Napier earthquake which claimed 256 lives. These standards and practices have been continually upgraded as knowledge has developed through research, earthquake events and international cooperation. New Zealand has been a leader in the research on and the development of standards and practices and has drawn on and contributed to international development in the field, especially by Japan and the United States.

Earthquake-resistant structural design over the past 50 years has sought to prevent the collapse of structures under strong earthquake shaking while recognising that damage, even irreparable structural damage, could occur in such conditions. Over recent years designers have sought to produce greater resilience in key structural components, especially columns and walls, and to control damage to the building fabric generally.

Typically, buildings are designed for earthquake ground shaking intensities expected to occur, on average, not more than once every 500 years. Modern design standards are such that design (and construction) to this level are intended to provide a significant margin of safety against collapse when subject to the design shaking. Many buildings would be expected to survive significantly stronger shaking without collapse.

However, damage to buildings, even those designed and built to the most recent standards, can be expected. In "design-level" shaking, this damage may be beyond repair and thus require the demolition of the building. The underlying design philosophy is to focus on life safety and to accept, or at least tolerate, the possible need to replace the building after such a low probability event.

Despite the level of ground shaking in the CBD on 22 February 2011, many multi-storey buildings in Christchurch CBD came through with damage but did not collapse, enabling people to escape.

In the Christchurch region there is an enormous variety of buildings. Many types of buildings suffered different types of damage due to the differing factors from liquefaction to intense ground shaking. All of this information will inform the repair and reconstruction standards and the direction of future development both in Christchurch and across New Zealand.

The development and application of New Zealand earthquake standards has been a continuous process regardless of the building control system in place at the time. In 1986/1987 when the CTV Building was designed and constructed, buildings were designed and built to the New Zealand Standards of the time, which were adopted as a bylaw by the local council, in this case Christchurch City Council.

If the CTV Building had been built to current requirements, it is unlikely it would have collapsed in the way that it did as evidenced by the performance of the most modern buildings in Christchurch.

Summary of investigation findings

CTV BUILDING

The Department has confidence in the quality of the investigation, and considers the Expert Panel's report to provide an authoritative and robust account of the factors that led to the collapse of the CTV Building.

The building was sufficiently robust to resist the effects of the 4 September 2010 earthquake and the 26 December 2010 aftershock without significant damage. However, the demands placed on the CTV Building by the aftershock of 22 February 2011 greatly exceeded those anticipated in the structural design of the building.

Not only was the building subject to considerable horizontal movement, but also amongst the highest recorded (in any urban environment) vertical acceleration.

The actual mechanism of the collapse cannot be determined in every detail and a range of factors contributed to the collapse; some may have had a cumulative effect.

Three critical factors were identified. These were the:

- intensity of the horizontal ground shaking
- lack of ductility in the columns
- asymmetrical shear wall layout.

The following factors added to or may have added to the effects of the critical factors. These were the:

- low concrete strengths
- vertical ground accelerations
- interaction of columns and spandrels
- separation of floor slabs from the north core
- structural influence of masonry walls.

The limited robustness and integrity of the tying together of building components was not a cause of the collapse but was not sufficient to hold the building together when the collapse started.

The foundations were not a factor in the collapse.

There were three aspects of design and construction for which the standards of the day (1986) were not met. These were:

- column ductility
- asymmetrical layout of shear walls
- column shear strength.

Tests on 26 columns (21% of all CTV Building columns) after the collapse found that the concrete in many columns was significantly weaker than expected. It is not possible to be definitive on the collapse sequence although a likely collapse scenario, which was consistent with the arrangement of the collapse debris and eye-witness reports of an initial tilt of the building to the east, involved initiation by failure of one or more columns on the mid to upper levels on the east face.

Loss of one of these columns on the east face would have caused the gravity load to shift to the adjacent interior columns. Because these columns were already carrying high vertical loads and were subjected to lateral displacements, collapse would have been likely.

The low amount of confinement steel in the columns and the relatively large proportion of cover concrete gave the columns little capacity to sustain loads and displacements once strains in the cover concrete reached their limit. As a result, collapse was sudden and progressed rapidly to other columns. The slabs dropped and pulled away from the north core and the perimeter beams, then the building collapsed onto its footprint pulling over the south wall onto the floor slabs.

PYNE GOULD CORPORATION BUILDING

The five storey Pyne Gould Corporation building suffered a major structural collapse. The structure met the 1963 design requirements of that time for the prescribed earthquake loads, both in terms of strength and level of detailing provided.

The principal reasons for collapse were as follows:

- The intensity and characteristics of the ground shaking caused forces in the core wall of the building (between Level 1 and Level 2) that exceeded its capacity.
- The non ductile design of the structure typical of buildings designed in the early 1960's lacked resilience once the building's strength had been exceeded and was unable to accommodate the shaking associated with the 22 February 2011 aftershock event.

HOTEL GRAND CHANCELLOR

The Hotel Grand Chancellor, a 22 storey complex, suffered major structural damage. The extent of the damage was significantly increased by the collapse of a key supporting shear wall which failed in a brittle manner. The hotel was built 1985 to 1988.

Extremely high compression loads combined with low levels of confinement reinforcing led to the wall failure. The lapping of vertical reinforcing and the slenderness of the cladding also appear to have contributed to the onset of failure. Under the action of high compression loads, a small transverse displacement was enough to initiate failure in unconfined concrete. The high axial loads arose from the building geometry and induced actions resulting from the severe horizontal accelerations. It is highly likely that vertical earth-quake accelerations also contributed to the high compression loads.

The building deformation that resulted from the wall failure were sufficient to initiate a major stair collapse within the building and failures to columns and beams at various locations.

FORSYTH BARR

The 18 storey Forsyth Barr Building designed in 1988 suffered an internal collapse of its stairs. The stairs collapsed on one side of the stairwell up to Level 14 and on the other side up to Level 15. the stairs were designed as a scissor arrangement and were the only means of egress from the building.

The stairs met the 1988 design requirements for the prescribed earthquake loads and the required seismic gap.

The principal reasons the stairs collapsed were as follows:

- The intensity and characteristics of the shaking in the 22 February 2011 aftershock exceeded the design capacity of the stairs in terms of distance provided for the stairs to move on their supports in an earthquake (the seismic gap).
- It is possible that the seismic gaps at the lower supports had been filled with material that restricted movement (including debris, mortar or polystyrene) which reduced their effectiveness.

Expert Panel findings

INTRODUCTION

These are principal findings from the investigations followed by a section with the Expert Panel's recommendations to the Department of Building and Housing on issues identified in the reports on the CTV Building, the PGC Building, the Forsyth Barr Building and the Hotel Grand Chancellor Building, and the Department's response to these. It is recognised that the Department may not carry out the work recommended but will be responsible for the implementation of recommendations.

Although these buildings represent a small sample of the overall building stock affected by the 22 February 2011 aftershock, the issues and recommendations may apply to many other buildings in Christchurch and to other places in New Zealand. Conversely, there may be other issues affecting the performance of buildings not identified in this study.

In presenting these findings and recommendations, the Expert Panel has been aware of the considerable uncertainty surrounding the characteristics of ground shaking at the subject sites and the estimation of actual building response during the aftershock. The analyses and conclusions described in the investigation reports, including postulated collapse mechanisms, need to be interpreted in that light, recognising that there may be other possibilities. Nevertheless, the Expert Panel is confident that the general nature of the findings of the investigations reflects the most likely possibilities.

This section summarises the principal findings for each of the buildings investigated. This is followed by a section with the overall findings of the investigation presented by subject matter with associated recommendations and the Department's response. A full list of the recommendations is summarised at the end of this report.

These recommendations have been assigned a priority by the Expert Panel of A (urgent), B (high) or C (moderate) according to the urgency of the need to take action on the recommendation. However, it is important that action is taken on all of the recommendations as soon as possible. The Expert Panel recognises that the Department will need to schedule resources to implement these recommendations.

BUILDING INVESTIGATIONS

The respective chapters on the four buildings in the report *Structural performance of Christchurch CBD Buildings in the 22 February 2011 Aftershock* present conclusions and recommendations resulting from the investigations. The Expert Panel supports the conclusions of the investigations as to the most likely reasons for, and the modes of, collapse/failure. The following highlights key points of relevance to the recommendations.

CTV Building

A number of possible collapse scenarios were identified. Examination of building remnants, eye-witness reports and various structural analyses were used to evaluate these scenarios. These ranged from collapse initiated by column failure on the east or south faces at mid to high level to collapse initiated by failure of a more heavily loaded internal column at mid to low level. The basic initiator in all scenarios was the failure of one or more non-ductile columns due to the forces induced as a result of horizontal movement between one floor and the next. The amount of this movement was increased by the plan irregularity of the lateral load resisting structure. Additional inter-storey movement due to possible failure of the connection between the floor slabs and the north core may have compounded the situation.

The evaluation was complicated by the likely effect of the high vertical accelerations and the existence of variable concrete strengths. It was further complicated by the possibility that the displacement capacities of columns on the east or south faces were reduced due to contact with adjacent spandrel panels. Many reasonable possibilities exist. In these circumstances it has been difficult to identify a specific collapse scenario with confidence.

The most studied scenario, which was consistent with eye-witness reports of an initial tilt of the building to the east, involved initiation by failure of a column on the mid to upper levels on the east face. Inter-storey displacements along this line were higher than most other locations and there was the prospect of premature failure due to contact with the spandrel panels. Loss of one of these columns on the east face would have caused load to shift to the adjacent interior columns. Because these were already carrying high vertical loads and were subjected to lateral displacements, collapse would have been likely.

The low amount of confinement steel in the columns and the relatively large proportion of cover concrete gave the columns little capacity to sustain load and displacement once strains in the cover concrete reached their limit. As a result collapse was sudden and progressed rapidly to other columns.

Once the interior columns began to collapse the beams and slabs above fell down and broke away from the north core. The south wall together with the beams and columns attached to that wall then fell northwards onto the collapsed floors and roof.

Other scenarios considered had different routes to the failure of a critical column, but in all cases, once the critical column failed, failure of other columns followed.

In reviewing the issues arising from the CTV Building investigation, the Panel concludes as follows:

a) Geometrically irregular structures may not perform as well as structural analyses indicate. Limitations on eccentricity should be reviewed, limits tightened and the concerns brought to the attention of structural engineers and territorial authorities.

b) Particular attention should be given to the evaluation of the actual displacement capacity of gravity-load bearing columns designed according to pre-1995 code provisions. Buildings designed before 1995 with non-ductile columns may be unacceptably vulnerable. They should be checked and a retrospective retrofit programme considered. The minimum confinement requirements for gravity-load bearing columns in 'secondary' structural systems must be reviewed.
c) Adequate attachment of floors to shear walls must be achieved. The methods of assessment of the forces involved and of effective methods to provide for them require re-evaluation. Buildings designed to the provisions of NZS 4203 prior to 1992 should be subject to particular attention, including consideration of the need for retrofit action.
d) There is a need to assess minimum clearance requirements to non-structural components (eg spandrel panels and infill walls) that may detrimentally affect structural performance. Greater awareness of the importance of these requirements is needed amongst structural designers, architects, territorial authorities and builders.
e) There is a need for improved confidence in design and construction quality. Measures need to be implemented which achieve this. Design Features Reports should be introduced and made mandatory. Designers must have an appropriate level of involvement in construction monitoring. There should be a focus on concrete mix designs, in-situ concrete test strengths, construction joint preparation and seismic gap achievement. There is a need to check the strength/quality of concrete achieved in a range of structures throughout the country.

PGC Building

The lack of ductility and strength inherent in the 1963 standards and the strong shaking combined to fail the eastern wall of the building's shear core. The resulting horizontal displacement of the floors led to the failure of the columns and beam-column joints, causing the floors to collapse on top of one another.

In reviewing the issues arising from the PGC Building investigation, the Expert Panel concludes as follows:

a) Walls with centrally located and light reinforcement may be susceptible to failure when significantly overloaded. In such walls the concrete carrying compressive loads is not confined by reinforcement and will therefore behave in a brittle fashion.
b) Older buildings may lack redundancy and be vulnerable if they have only one lateral load resisting system or no alternative load path.
c) Columns and walls that are not regarded as contributing to earthquake resistance must be capable of sustaining the expected inelastic lateral displacements of the structure.

Hotel Grand Chancellor Building

The failure of a critical shear wall was caused by extremely high axial stresses resulting from both horizontal and vertical irregularity and bi-directional loadings. The high axial stresses combined with low levels of confinement reinforcing at the base of the wall resulted in a brittle failure of the wall.

The building irregularity and the critical wall's vulnerability were increased as a result of a design change during construction when permission to support the east face of the building on foundations located in Tattersalls Lane was declined.

High seismic vertical accelerations are likely to have further increased the axial loads/stresses beyond those expected. The inherent redundancy and resilience of the remaining structure prevented total collapse.

A number of other wall failures which had the appearance of high axial stresses and low confinement levels were observed in buildings following the 22 February 2011 aftershock.

In reviewing the issues arising from the Hotel Grand Chancellor Building investigation, the Expert Panel concludes as follows:

a) Vertical accelerations must be considered in situations where there is not a direct load path to the ground (ie horizontal cantilevers) and transfer beams.
b) Minimum confinement requirements in wall/columns of the type that failed should be reassessed.
c) Maximum axial stresses in columns/walls should be reviewed to improve resilience.
d) Slenderness ratio limitations for such walls need to be checked.

Forsyth Barr Building stairs

The strong shaking caused the building to sway beyond design expectations current at the time of the building design. The seismic movement gap at the base of the stair flights was not sufficient to avoid compression in the stair flights. The prescribed seismic gap may not have been achieved in all cases during construction. Material was also found in the spaces intended for seismic movement in the stairs.

This extraneous material may have exacerbated the compression actions that shortened the flights making the collapse of the stairs more likely. However, indications are that the collapses may have occurred even if the stairs had been fully free to move. The collapses may not have occurred if current (2010) design allowances for inter-storey movement had been provided.

While the stair seating detail used at the base of the Forsyth Barr stair units was not widely used, a number of other stair details that were commonly used during the 1980s and 1990s do not provide for sufficient movement when analysed against current seismic displacement expectations. These types of stair connections, together with stairs designed prior to 1976, which commonly have no provision for movement, are likely to require some retrofit.

In reviewing the issues arising from the Forsyth Barr Building investigation, the Expert Panel concludes as follows:

a) Egress stairs must be designed to maintain their structural integrity until the building structure is on the point of collapse.
b) Scissor stairs inherently have less reliability than other stair systems because loss of one flight can result in the loss of the entire egress route. Conservatism is therefore advised.
c) Gap and ledge support arrangements are problematical and conservatism is advised or an alternative arrangement recommended.
d) Seismic gaps must remain completely clear and must not be reduced by construction tolerances, debris etc.
e) Ledges must be generous and evaluated according to expected demand at point of collapse of the building.

Panel recommendations and Department response

INTRODUCTION

The Department has a significant programme of work already underway to support the rebuild of Canterbury which includes foundation design. The Department has already responded to the earthquake sequence by lifting the Z factor (seismic rating) for the reconstruction of Christchurch and the surrounding region. Other work was underway with the sector before the earthquake sequence through the Productivity Partnership, legislative change and capability development.

GROUND SHAKING/BUILDING RESPONSE

Expert Panel finding

1. *Estimating building response:*
The estimated responses of buildings to recorded ground shaking in the Christchurch CBD on 22 February 2011 are shown, in most cases, to be significantly greater than those used in 2010 as a basis for the design of new buildings of the type in the investigations. The investigations highlighted the variability and uncertainty involved in estimating building response from ground shaking measurements.

The earthquake was shallow and very close to Christchurch City, so the intensity of ground shaking in this event (as indicated by the response spectra) was much higher than in the Darfield event.

2. *Vertical accelerations:*
The vertical accelerations measured in the 22 February 2011 aftershock were exceptionally high and may have contributed significantly to vertical forces in columns and walls. The extent of this contribution is generally difficult to quantify, but analyses of the CTV Building indicated that vertical accelerations could have reduced the capacity of critical columns to sustain lateral displacements by around 15 to 35% depending on concrete strength.

3. *Duration of shaking:*
The duration of the 22 February 2011 aftershock was relatively short. A longer duration earthquake is likely to have had a greater effect on buildings, especially on structures that are not well tied together or are not properly detailed in their critical connection regions. It is important that the implications of longer duration shaking be better understood, in particular when assessing the earthquake performance of existing buildings. The availability of extensive ground motion records and information on modern building performance offers an opportunity to improve such understanding and revise current assessment/design /retrofit methodologies.

4. *Seismic hazard coefficients for building design:*
The logic of consideration of large infrequent earthquakes within a uniform risk environment should be re-examined. In particular, the basis for determining seismic hazard coefficients for building design needs to be looked at. Consideration of the consequences of a large earthquake occurring in or near a major urban centre, including the national economic impact, should also be investigated.

Expert Panel recommendation

RECOMMENDATION 1: GROUND SHAKING/BUILDING RESPONSE
(Priority A)
Bring together a comprehensive study that examines the seismic response/performance of buildings in the Canterbury earthquakes, particularly the 4 September 2010 earthquake and the 22 February 2011 aftershock. Such a study should relate building performance (for older and new buildings) and ground shaking measurements, and be aimed at improving the effectiveness and efficiency of earthquake-resistant design in New Zealand and elsewhere. The study should address: • the methods and assumptions used in building design, analysis, standards and practices • the influence of vertical ground motions • the effects of duration of earthquake shaking • the basis for determining seismic hazard factors for building design, assessment and retrofit, particularly for large urban centres.

Department response

The Department will lead a multi-agency, multi-disciplinary research programme to use the experience in the Canterbury earthquakes to improve the understanding of building performance in earthquakes. Research outputs will inform the further development of earthquake engineering's fundamentals of design. This research will lead to potential changes to the Building Act and the Building Code and in turn to the education and training of those involved in design, construction and consenting throughout New Zealand.

The programme will build on research already underway. The Natural Hazards Platform (a consortium of research agencies, universities and Crown Research Institutes) has already been allocated funding for research work and is about to disburse further funding on behalf of the Ministry of Science and Innovation. This funding is for research into seismicity, building performance and modelling, and seismic hazard factors amongst other areas. The Department will work with the Natural Hazards Platform to be assured the research funding is targeted in the national interest.

The Department will engage with researchers both in New Zealand and internationally to secure relevant and applicable research outputs which can be applied in the New Zealand context given our location, urban form and nature, and the age of our building stock.

The Department will also engage with all those entities which have relevant information to ensure this is captured and available to researchers. Such entities will include the universities, GNS Science, CERA, the Ministry of Civil Defence and Emergency Management, Christchurch City Council and other territorial authorities.

The outputs of this research would include:

- performance data across a representative range of buildings and building types in a format able to be readily and comprehensively interrogated
- conclusions as to the performance of buildings with respect to age, type and condition against current and future New Zealand Building Code objectives
- potential to set cost effective new, revised or additional standards for the design of new buildings, and the retrofit of existing buildings including those classified as earthquake-prone.

This research and information will drive the standards and direction for overall improvement of New Zealand's building stock.

GEOTECHNICAL

Expert Panel finding

1. Liquefaction effects:
The effects of liquefaction and lateral spreading were not significant for any of the four buildings in the investigation.

2. Foundation distress:
Foundation distress was not a factor in the collapses or failures of buildings. There was no evidence of significant foundation settlement or failure in any of the buildings.

3. Geotechnical information:
In spite of the above findings, the Expert Panel was concerned at the level of information on site soil conditions used as a basis for decisions on foundations. The level of geotechnical investigation for the subject buildings was noticeably less than is typical for buildings in Auckland and Wellington.

Expert Panel recommendation

RECOMMENDATION 2: GEOTECHNICAL
(Priority B)
Review geotechnical information standards required for urban areas in New Zealand and develop national guidelines for minimum standards of information.

Department response

The Department is leading work with the New Zealand Geotechnical Society and their members to review geotechnical information standards.

In addition the Department will:

- develop appropriate geotechnical information standards for commercial buildings
- work with the sector to establish mechanisms to share geotechnical information.

One of the initiatives the Department is working on as part of the Productivity Partnership with the building and construction sector is the use of the BIM (Building Information Modelling) and BEIM (Built Environment Information Modelling) systems in future building design and consenting processes. This would add significantly to the standardisation of data collection, risk identification and quality assurance. It would also enable geotechnical data to be a component of the consenting process.

Use of this information will facilitate the development of both a risk profile for proposed commercial building and construction work and the agreed quality assurance plan to manage those risks – both of which are components of the proposed new approach to the consenting of commercial buildings (as set out in the Building Amendment Bill (No. 1) currently before the House).

The outcome sought is the appropriate level of geotechnical information to inform the design of resilient new or retrofitted buildings consistent with the seismic risk and ground conditions for the area. This will result in the right building being constructed for the conditions.

POST-EARTHQUAKE INSPECTIONS

Expert Panel finding

1. *Inspections following damaging earthquakes:*
From the information available, it appears that the 4 September 2010 earthquake and the 26 December 2010 aftershock did not significantly reduce the earthquake resistance of any of the four buildings. Nevertheless there is a need to clarify the requirements and expectations of inspections of buildings damaged by earthquakes. This includes the rapid assessments done under civil defence emergency and those done on behalf of the owner or other authorities. Special efforts are needed to improve the public understanding of what the inspections can and cannot achieve.

2. *Post-earthquake inspections – documentation:*
The documentation required for and resulting from post-earthquake inspections needs to be made publicly available and recorded on Council property files. Special efforts are also required to make sure that information that is a) required for post-earthquake building inspections and b) results from post-earthquake building inspections has appropriate electronic back-up systems so that it is able to be accessed remotely in an emergency situation.

3. *Legislative provisions:*
There is a need to better align the powers available with respect to building safety during a state of civil defence emergency and those in the Building Act. The legal status of safety assessments made in the emergency period needs to be clarified and the transition from Civil Defence Emergency Management Act to Building Act aligned.

This may require changes to the Building Act to include specific provisions for the structural assessment and rehabilitation of buildings affected by earthquakes.

Expert Panel recommendation

RECOMMENDATION 3: POST-EARTHQUAKE INSPECTIONS
(Priority A)
Review current methods for inspecting and reporting information on the structural condition of buildings following an earthquake. Such a review should address: • the need for legislation covering the structural assessment and rehabilitation of buildings affected by earthquake • the extent to which building owners are responsible for undertaking a more detailed evaluation of their buildings following earthquakes • the need for public awareness and owner education programmes to improve the general understanding of the roles of post-earthquake inspections/evaluations and their limitations • legislative requirements for the documentation of post-earthquake inspection information and public accessibility to such information.

Department response

In conjunction with the Ministry of Civil Defence and Emergency Management and the New Zealand Society of Earthquake Engineers, the Department will lead the review of methods for post-earthquake inspection of buildings. It is planned to review, refine and develop guidance on:

- methods to raise awareness with building owners and the public on post-earthquake evaluations, what they mean and their limitations
- the process for post-earthquake inspections of buildings and the documentation of those inspections
- assigning responsibility to building owners to undertake detailed evaluations of their buildings following an earthquake
- ensuring that building information is available remotely from the site of an earthquake event so that plans are easily accessible for inspecting buildings post-earthquake
- methods to enable public access to information on post-earthquake inspections of buildings.

The Department will address any legislative issues and issue guidance to assure a nationally consistent approach.

The aim of this work is to ensure post-earthquake inspections are effective and are of value to the community. Practitioners and agencies will be working to consistent understandings, information and standards, and the public of New Zealand will have clarity about the conditions of post-earthquake buildings.

STRUCTURAL DESIGN – GENERAL ISSUES

Expert Panel finding

The investigations highlighted the need to re-examine some general and some specific aspects of structural design to draw on the experience of the Canterbury earthquakes. The issues identified centre on the importance of integrity, ductility and robustness in earthquake-resistant structures, the need to limit irregularity of structural form, and the need to avoid unintended interactions of structural elements with other building components. The general structural design issues are outlined in this section and the more specific structural design issues in the following section.

1. Encouragement of higher standards than code minimums:
The Building Code and related Standards define minimum performance requirements for buildings. A modern building designed according to the current requirements would be expected to suffer significant damage when subject to an intensity of shaking equivalent to that used in its design. Owners and designers need to be encouraged to recognise that achieving higher than the minimum required performance requirements may be more cost-effective, especially if the property market puts a value on good seismic performance.

There is a need to:

- check that minimum structural performance standards match community expectations
- encourage consideration by owners and designers of the value of achieving more than the minimum standards.

2. Structural integrity:
The failure of the CTV Building in particular has highlighted the need for a high degree of integrity (tying together and resilience) of buildings subject to earthquake actions. Greater emphasis on overall structural integrity of buildings is needed.

The Panel is concerned that requirements for the design of structures, particularly reinforced concrete structures, are becoming dominated by excessively detailed procedures and calculations at the expense of attention to the basic fundamentals of structural mechanics that are essential to achieve structural integrity and robust load paths.

There is a need to reassess and simplify the requirements for reinforced concrete design so as to place more emphasis on the need for overall structural integrity and robust load paths.

3. Designing resilient buildings:
The importance of resilience and redundancy was demonstrated during the aftershock by the Hotel Grand Chancellor Building which did not collapse despite the failure of a load bearing wall. In contrast, the collapses of the CTV and PGC buildings highlighted the lack of alternative load-paths or back-up mechanisms in the seismic response. Redundancy within seismic and gravity load paths should be provided wherever possible.

Design approaches need to be re-evaluated and changed as necessary to include specific provisions to avoid progressive and disproportionate collapse in multi-level and large buildings.

4. Irregular structures:
Structural irregularity, both horizontal and vertical, was a feature of three of the four buildings in the investigation, and in all three cases the irregularity had a detrimental effect on the response of the structure. While codes and standards address the issue of irregularity, the Expert Panel questions the effectiveness of design practice (analysis and detailing) in this area, particularly when post-elastic actions and displacements are considered.

Every effort should be made to avoid irregularity in structures. Greater design rigour is needed for buildings with irregularity (horizontal or vertical). More recognition is needed amongst structural designers and architects of the special demands on critical members that can result from structural irregularity and the need to detail these members accordingly.

Greater recognition of the variability and uncertainties associated with design calculations for irregular structures is needed in the training of structural engineers.

5. Capacity design approach:
Capacity design refers to a design process which limits forces in some structural members in order to protect others (eg a weak, but ductile, beam/strong column approach protects columns).

There was evidence in the Hotel Grand Chancellor and the Forsyth Barr buildings that were damaged and yet did not collapse that the capacity design approach helped provide sufficient resilience to prevent total failure. This reinforces the value of the capacity design approach to building design in areas of seismic hazard.

Capacity design principles are vital in controlling the response of structures in the face of variability and uncertainties in the ground motions that may be experienced. There are indications that these principles need reinforcing amongst designers.

A number of actions need to be considered in relation to the capacity design approach:

- Placing more incentives in design standards to encourage the use of the capacity design approach, even in regions of low seismicity. This could include requiring redundancy in buildings and ductile detailing even for elastically designed structures.
- Requiring that designers apply the capacity design approach to the whole building down to the most brittle mechanism/weakest link in the building, not just to the individual components.
- Facilitating professional development of structural designers in this conceptual design approach.

6. Displacement demand:
In the design of new buildings, and the assessment of existing buildings, greater emphasis should be placed on the displacement demand on the structure and the capacity of the structure to accommodate the displacements. This is particularly important when considering the compatibility of elements intended to remain elastic (eg floor diaphragms are affected by frame elongation) and also for secondary structural elements (eg gravity columns subjected to lateral sway). Design should be considered as sustaining load-carrying capacity and integrity as the building deforms. This will highlight displacement incompatibilities.

Building designers should be re-educated on the need to regard earthquake actions in structures as being displacement-induced rather than force-induced.

7. Unintended structural inter-actions:
Unintended effects on the structure by elements such as block walls, spandrel panels and stairs have highlighted, once again, the importance of allowing the structure to deform without the unintended contribution to or detrimental effect of these elements on structural response.

There is a need to reassess the allowances for separation and/or connection of secondary/non-structural elements in design standards and implement any changes required.

8. Critical vulnerability factors:
The buildings that were the subject of the investigation displayed a range of vulnerabilities which, in part, were due to the era in which they were built. Previous design codes and philosophies involved differing structural systems and detailing, differing connection systems between elements and differing seismic resisting systems to those that are applicable today. These vulnerabilities resulted in potential structural weaknesses which could have contributed to the collapse/failure of the buildings. Some examples of these vulnerabilities include a lack of capacity design, poor anchorage details, lack of stirrups in the joint region, inadequate confinement and reinforcement in columns and walls, poor detailing of the plastic hinge regions, irregularity in plan and elevation, and inadequate connections between lateral load-resisting systems and floor-diaphragm.

In order to improve the seismic performance of buildings, designers and reviewers should focus on critical vulnerability factors when designing buildings.

9. Design Features Reports:
Design Features Reports that summarise key information about the design intentions, material properties, structural configuration and other important structural characteristics are a valuable tool in the quality assurance of a building. Almost every building is a "one-off" and what is built and used is the first and only attempt to get it right. There needs to be greater attention to quality assurance checking when buildings are designed and built as there may be no chance to correct mistakes once a building is completed.

To improve the quality of construction, consideration should be given to making it compulsory for a two part "Design Features Report" to be produced for all buildings (other than a single family dwelling) with significant structural engineering content. Part one would cover designs submitted for building consent. Part two would cover the completed work.

It is suggested that the Design Features Report should include:

- a description and schematics of the conceptual design process and design measures adopted to provide structural integrity and redundancy
- definition of alternative load paths or "back-up" mechanisms to prevent disproportionate collapse in case of failure of a single vertical load-bearing element
- identification of the most vulnerable elements (weak links) and mechanisms in the structure
- a description of potential building collapse mechanisms and scenarios
- remediation measures to reduce the risk of a partial or total collapse of a building.

It is suggested that the structural engineer responsible for the design of the building should be engaged to carry out the site observations of the works during the construction phase, to monitor critical features as they are constructed. The design engineer would be able to nominate another engineer provided that engineer could demonstrate familiarity with the design intentions and the overall design process followed for the particular building.

Suitable Design Features Report templates need to be developed that best serve the needs of designers and territorial authorities.

10. Earthquake strengthening when a building is altered or its use is changed:
Current legislation and territorial authority practices should be reviewed with a view to tightening the requirements for earthquake strengthening when buildings are altered or their use changed.

Expert Panel recommendation

RECOMMENDATION 4: GENERAL STRUCTURAL DESIGN ISSUES
(Priority A)
Reassess approaches to and general requirements for achieving earthquake resistance in buildings. See that necessary changes are made in the light of the Canterbury earthquakes. Specifically, amendments should be aimed at: • improving structural integrity and resilience • limiting the irregularity of structures • encouraging capacity design • encouraging displacement-based approaches to design and assessment • avoiding unintended interactions between structural and other parts of a building • identifying and removing critical vulnerabilities • introducing compulsory Design Features Reports for significant buildings – new or retrofit • introducing tighter controls to trigger requirements for earthquake strengthening when buildings are altered or their use changed.

Department response

The Department will lead a programme of work with Structural Engineering Society of New Zealand (SESOC), the New Zealand Society of Earthquake Engineers (NZSEE), the Institution of Professional Engineers New Zealand (IPENZ), and the universities to develop a programme of work, including seminars and guidance material, that addresses the first five issues. The aim will be to ensure as far as is practicable that the best quality design and construction is consistently achieved across the country.

The Department will work with territorial authorities and industry groups including the Association of Consulting Engineers New Zealand (ACENZ) and SESOC to develop Design Features Reports. The purpose of these reports is to support effective building consenting by identifying how seismic risk amongst other risk factors has been designed for and how the design has been applied in construction. Design Features Reports could also be incorporated into the BIM and BEIM system in the future. One of the initiatives the Department is working on as part of the Productivity Partnership with the building and construction sector is the use of the BIM (Building Information Modelling) and BEIM (Built Environment Information Modelling) systems in future building design and consenting processes. This would add significantly to standardisation of data collection, risk identification and quality assurance.

The Department already has underway a review of the Earthquake-Prone Buildings Policy, which will revisit amongst other matters the triggers that will drive the upgrade of earthquake strengthening. The Department will provide advice to Government in October 2012.

As a result of the Building Act review, the Department has already identified and commenced the process to make the necessary legislative changes to support a more robust approach to the consenting of commercial buildings. This is because it has been identified that building consent authorities do not have the right skill sets to perform their assurance function on commercial building consent applications. The change includes a requirement for an upfront risk profile prior to consenting and an agreed quality assurance plan for how those risks will be managed during construction (with the plan being audited by the consenting authority).

The expectation is that there will be earlier identification and consideration of project risks, greater accountability by designers, documented means of managing those project risks (with auditing to ensure the agreed quality assurance plan is being followed) and transparency on liability.

Given that many building consent authorities lack specialist expertise, the Department will investigate establishing a Centre or Centres of Expertise for commercial consenting as part of its work on improving the overall consenting regulatory system.

The Department has a Productivity Partnership with the building and construction sector and it has been identified that there is substantial work to do to address skills and competence. Strategy and implementation plans are being developed. The implementation plan will incorporate skills changes required as a result of the new guidance and other information generated from the learning from the Canterbury Earthquake Sequence.

The Department, through its role in the monitoring and assurance of building consent authorities, will monitor progress on application of the proposed new risk-based approach to consenting commercial buildings after the regulatory changes are made.

The Department, in working with practitioners' boards for engineers and architects, will maintain oversight of their continuing professional development programme on seismic engineering and construction to be assured that the learnings from the Canterbury Earthquake Sequence are applied.

We would expect this to result in all practitioners being well trained in the requirements for the construction of earthquake resilient buildings and all participants in the building and construction system being clear about their roles and accountabilities in delivering on buildings fit for the future.

STRUCTURAL DESIGN – SPECIFIC ISSUES

Expert Panel finding

1. *Walls and columns:*

The failure of a major wall in the Hotel Grand Chancellor, the collapse of columns in the CTV Building, and the failure of lightly reinforced walls in the PGC Building are of serious concern. In the case of existing buildings, such as the PGC and CTV buildings, the lack of strength and ductility was an issue that may require building retrofits.

The Expert Panel has identified a need to:

- review aspects of the requirements for the design, detailing and construction of walls and columns to include consideration of vertical accelerations and lateral sway
- improve ductility capacity and confinement steel to maintain load-carrying capacity in the face of unexpectedly large displacements
- consider legislative/regulatory action to require prompt and effective retrofit measures
- consider the need for retrospective action on buildings, especially those built before 1995 with non-ductile columns.

Changes in design requirements need to be considered, including the following:

- Further limitation on axial stress levels in columns and walls. These must be evaluated with appropriate consideration of bi-directional loading.
- Reduction of slenderness ratio to avoid member buckling failure in the core.

- More stringent detailing for ductility and confinement, whether or not walls or columns are intended to be a primary part of the earthquake-resisting structure.
- Greater emphasis on and practitioner understanding of bi-directional effects and detailing to accommodate lateral displacements.

2. Lightly reinforced shear walls:
Reinforced concrete shear walls like those in the PGC Building are particularly vulnerable in severe earthquake shaking. Usually the reinforcing steel is a central layer and there is no confining steel. This type of construction could have been used in buildings built before 1965 and possibly as late as 1976. This construction method is still used in low seismic areas. Such buildings are not usually classified as earthquake-prone under the Building Act 2004.

There is a need to alert owners of buildings that have lightly reinforced concrete shear walls to their potential vulnerability to collapse in a major earthquake. Owners with concerns should seek advice on necessary structural improvements from a Chartered Professional Engineer.

The vulnerabilities of lightly reinforced shear walls should be covered in the New Zealand Society for Earthquake Engineering assessment guidelines.

3. Limits on axial load levels:
The collapse of the CTV Building and the wall failure in the Hotel Grand Chancellor Building underline the vital importance of the load-carrying capacity of columns and walls and the need for them to be resilient when subject to earthquake movements and actions. The high vertical accelerations experienced in the 22 February 2011 aftershock provide additional reasons to adopt conservative overall limits to axial stresses computed for design purposes. Such a move would be in line with practice in other countries. Consideration should be given to further limiting axial load ratios in columns and walls.

A review is needed of requirements in design standards that place limits on compressive stresses in walls and columns. More conservative requirements should be considered.

4. Buildings with cantilevers and/or transfer beams:
The Hotel Grand Chancellor wall failure highlighted the critical role of the supports to cantilever beams and their particular vulnerability when subject to loads in excess of those expected, such as the effects of vertical acceleration and post-elastic deflections. Cantilever beams and/or transfer beams will tend to progressively deflect downwards (ratchet) when subjected to cyclic post-elastic yielding. Cantilever beams and transfer beams that support frames may be particularly vulnerable to this as a result of seismically induced axial actions in the frames.

There is need to:

- reassess requirements for the design of buildings with cantilevers and transfer beams and implement changes where appropriate
- promote caution amongst designers when supporting a moment resisting frame on cantilever beams or transfer beams, particularly to counter "ratcheting" that can lead to unexpected deflections.

5. Diaphragm connections:
Detailed analyses, particularly those undertaken for the CTV Building, highlighted the importance of connections between floor slabs and structural walls that provide lateral resistance. In particular, it was shown that diaphragm forces may be much greater than are currently estimated for design purposes.

There is a need for a review of design requirements across a range of buildings. This should include a special investigation into the performance of floor-diaphragm connections in the Christchurch earthquakes. New requirements will need to be developed and implemented.

Expert Panel recommendation

RECOMMENDATION 5: SPECIFIC STRUCTURAL DESIGN ISSUES
(Priority A)
Review detailed design requirements for structural design and amend them to resolve concerns identified in relation to: • strength and ductility of walls and columns • vulnerability of lightly reinforced concrete shear walls • limits on axial load levels • vulnerability of buildings with cantilevers and transfer beams • strength and integrity of diaphragm connections.

Department response

The Department will drive the development of strategically important building standards critical to the integrity and safety of homes and buildings so they are accorded the appropriate priority and are developed using the best experts available. These will flow through to Acceptable Solutions. There will be an ongoing process to refine standards as more learning becomes available. The Department is best placed to carry out that work and promulgate the revised standards.

There are already standards and some excellent practices which the Department will build on as a result of the Christchurch earthquakes. As standards are revised, this will drive changes and, where necessary, improvements in practices.

The Department will lead a comprehensive programme of work with the Structural Engineering Society of New Zealand, the New Zealand Society of Earthquake Engineers and universities, together with the building and construction sector, to ensure the provision of revised standards and guidance on:

- design, detailing, and construction of walls and columns
- retrofit approaches to buildings with lightly reinforced shear walls
- axial load limits for walls and columns including ductility (resilience) and confinement requirements
- design of cantilever structures
- suitable analysis and design methodologies for diaphragm connections and diaphragm systems with respect to construction and materials and dealing with torsional or irregular behaviour.

This will be followed by:

- input to curricula and Continuing Professional Development for practitioners in the sector
- promulgation of advice to owners, territorial authorities, New Zealand Property Council, and building owner organisations.

The outcomes will be more effectively designed or retrofitted buildings which will perform effectively in seismic events.

STAIR DESIGN

Expert Panel finding

1. *Stair design:*

The investigation of the Forsyth Barr Building highlighted the need for the approach or methodology adopted for stair design to be reassessed in terms of displacement capacity. Changes in approach to stair support design are required.

For all new or refurbished buildings the main egress routes need to remain functional and be available to the building occupants to allow them to exit the building safely in the event of a fire or earthquake.

To this end, stair supports need to be designed to have a sufficient displacement capacity so that stair collapse is not expected to occur before building collapse. This will require allowances for displacements well above those estimated to occur at the ultimate limit state of the structure.

Consideration needs to be given to extending the protection of the egress routes so that in multi-storeyed buildings the final exit way to the exterior of the building is provided with robust impact barriers to protect the occupants exiting the building from falling debris.

Reviews are needed to check the following:

- Provisions for movement are in line with current requirements. Buildings built before 1992 may have stairs with allowances for inter-storey displacements that are less than currently required or considered adequate.
- Support and separation details are such that they are not compromised by unintended restrictions to movement under earthquake actions.
- Progressive collapse is avoided.
- Allowances for variations in constructed dimensions are provided.

There is a need to develop revised criteria for stair support and to implement the new requirements in relevant design standards. NZSEE and SESOC will need to promote awareness of the new requirements.

Expert Panel recommendation

RECOMMENDATION 6: STAIRS
(Priority A)
Issue a Practice Advisory to warn owners of buildings, especially those in flexible frame buildings, to check that the stairs are designed to accommodate appropriate levels of earthquake-induced displacements. (This is a recommendation from the Stage 1 Report and since that time the Department issued Practice Advisory 13: Egress Stairs: Earthquake checks needed for some, published September 2011, www.dbh.govt.nz/practice-advisory-13). Develop revised criteria for stair support and protection of egress ways and incorporate them into the requirements for new designs and retrofits.

Department response

On 30 September 2011 the Department, with assistance from its Engineering Advisory Group, issued a Practice Advisory under section 175 of the Building Act 2004 to provide guidance to structural engineers and territorial authorities.

The Department has written to the Chief Executives of all the territorial authorities in New Zealand.

The letter requests that:

- Building Warrant of Fitness reminder letters strongly recommend multi-storey building owners seek professional advice on stair egress safety
- building consent applicants for alterations to multi-storey buildings are advised of the Practice Advisory, with a strong recommendation that they check the stairs
- building owners who have concerns are advised to obtain a report from a Chartered Professional Engineer experienced in structural design on the earthquake vulnerability of the stair system, and options to remediate.

The Department has followed up with the 24 largest building consent authorities (BCAs) and all have taken action. The majority have sent this information out to building owners and plan to ensure that any applicant for alteration to a multi-storey building has the Practice Advisory drawn to their attention. Christchurch City Council, through CERA powers, has added this assessment to the building safety assessment. Auckland is working to develop a schedule of the affected buildings as they have over 15,000 with warrants of fitness. Most BCAs plan to follow up their initial action in early 2012.

The Department will follow up with BCAs by the end of March 2012.

The Department sent the Practice Advisory to structural engineers advising them that when they are undertaking detailed assessments of buildings, to strongly recommend to clients that checking the stairs should be included in the building assessment. Engineers should advise owners on retrofit measures necessary to bring the stair earthquake safety performance in buildings to as near as is reasonably practicable to that of a stair in a new building.

The Practice Advisory has also been sent to the New Zealand Property Council, the Property Investors Federation, the Real Estate Institute of New Zealand (commercial buildings only), Registered Master Builders Federation, the Construction Industry Council, the Certified Builders Association of New Zealand, the New Zealand Institute of Architects, and Architectural Designers New Zealand, in order to raise awareness of the issues.

Stairs in all New Zealand buildings will provide a safe means of egress in a seismic event.

CONSTRUCTION QUALITY AND COMPLIANCE

Expert Panel finding

1. *Construction quality:*

Buildings are usually "one-offs" and special attention is needed to see that the design intentions are followed. The investigation highlighted the need for more attention to be paid to the quality of construction, particularly in the areas of quality control, quality assurance, construction monitoring, design review and construction skills. The method for checking quality through all phases of the building cycle, from design to construction monitoring, requires review. One specific aspect identified in the investigations was the need to check the strength and quality of concrete used in buildings.

2. *Compliance and monitoring:*

The present regulatory system is dependent on the various parties in the overall design and construction process all having different responsibilities, with the risk that errors or omissions may be overlooked. Building Consent Authorities currently have a high level of responsibility in granting building consents and certifying Code compliance for complex buildings. Design professionals should have a continuing responsibility throughout the entire design and construction process. This is likely to induce a cultural change in favour of improving the overall quality of construction work and help to minimise the risk of building failure.

Current practices for construction monitoring need to be looked at in order to achieve more effective monitoring and site supervision by those familiar with the design intentions. The Expert Panel strongly believes that the structural engineers responsible for the design of buildings which have a significant structural engineering content should be engaged to observe the works during the construction phase and be in a position to certify that the building has been built to the approved design.

Expert Panel recommendation

RECOMMENDATION 7: CONSTRUCTION QUALITY AND COMPLIANCE
(Priority B)
Review quality assurance processes in all phases of building design and construction, especially in light of the findings of these building investigations. Implement tighter controls and promote more designer involvement to ensure that design intentions are being achieved and that the work complies with the requirements of the approved design documents.

Department response

The Department will work with developers, designers and engineers to drive a change in sector culture which will see the involvement of the designer/engineer from design throughout construction to completion and Code compliance for commercial buildings. This will be reinforced by the use of Design Features Reports and the proposed new approach to risk-based consenting which builds in a substantive quality assurance process.

As a result of the Building Act review, the Department has already identified and commenced the process to make the necessary legislative changes to enable a different approach to the consenting of commercial buildings. This includes a requirement for an upfront risk profile prior to consenting and an agreed quality assurance plan for how those risks will be managed during construction (with the plan audited by the consenting authority). The expectation is that there will be earlier identification and consideration of project risks, greater accountability by designers, documented means of managing those project risks (with auditing to ensure the agreed quality assurance plan is being followed) and transparency on liability.

Building consent authorities (BCAs) have a key role in raising the bar by ensuring the quality assurance is robust. Their expectations need to include explicit identification of vulnerabilties in proposed building design and the appropriate mitigations signed off by experts and peer reviewed by experts if the BCA does not have that skill set.

Given that many BCAs lack specialist expertise, the Department will investigate the establishment of a Centre or Centres of Expertise for commercial consenting as part of its work on improving the overall consenting regulatory system.

The Productivity Partnership between the Department and the building and construction sector will also be working on the strategy and implementation plans for skills required in the industry, including the quality assurance of construction. The work underway on the use of BIM (Building Information Modelling) and BEIM (Built Environment Information Modelling) systems has the potential to substantially assist in improving building design and construction.

These initiatives are expected to result in the people with the right skills being involved in the upfront risk profile and subsequent quality assurance, and consequently the increased likelihood of construction consistent with design. Any required revisions to design would be consistent with the outcome sought, which is a seismically resistant building.

CONCRETE QUALITY

Expert Panel finding

Concrete strength was an important factor in the investigation of the CTV Building, with lower than expected strengths found in several columns. The Expert Panel is concerned that there is very little evidence or record of the strength of concrete in its as-placed condition and that there should be a comprehensive survey across a range of building types and construction eras. This survey should check that measured concrete properties are in line with expectations and identify any required changes to standards and procedures. The aim would be to better inform those responsible for building safety standards and to identify any critical issues.

Expert Panel recommendation

RECOMMENDATION 8: CONCRETE QUALITY
(Priority C)
Work with the concrete industry to review the in situ strength of concrete achieved in a representative range of buildings around New Zealand and recommend any measures required to provide the necessary confidence that specified concrete strengths have been and will be achieved. Measures considered should include further strength testing of in situ concrete in existing buildings and revisions to standards and procedures covering the manufacture, delivery, placement and curing of concrete in new buildings.

Department response

The Department has already agreed to work with Cement and Concrete Association of New Zealand and leading building contractors to review the level of in situ concrete strengths. The Department will then consider actions necessary to revise standards and procedures for the manufacture, delivery, placement and curing of concrete in new buildings. The Department will oversee the implementation of the agreed changes by the relevant industry groups.

The Department will also advise building owners, territorial authorities and the New Zealand Property Council of any potential issue on concrete strength. Building owners will need to assure themselves of concrete strength when they plan to alter or reassess the use of buildings, which may well become a factor in determining earthquake-prone buildings.

All New Zealanders can have confidence that concrete can be relied on when applied consistently with the appropriate standards. Buildings with inappropriate concrete strength will be progressively removed from the stock as they are either upgraded or demolished.

EARTHQUAKE-PRONE BUILDINGS

Expert Panel finding

1. *Definition of earthquake-prone buildings:*

The Expert Panel recognises that this topic will be covered by the Royal Commission, and across a wider range of buildings, but the consultant's findings that the PGC building could have been classified as not earthquake-prone has caused the Expert Panel to consider the need for changes in the legislation and/or approaches for earthquake-prone buildings.

2. *Higher risk urban centres:*

New Zealand has a disproportionately high percentage of national wealth located in a small number of urban centres, the loss of any one of which (eg Christchurch) can have extreme consequences to the country as a whole.

There should be a review of the risk level and performance of buildings of low earthquake resistance, particularly in regions of high population density. The review should also assess the risk and cost to the country of a major earthquake in various parts of the country. Consideration should be given to setting different earthquake-prone thresholds for different parts of the country. For example, urban centres over a certain population size should be required to set their earthquake-prone level at a higher %NBS.

3. *Public safety:*

There should be an assessment of all unreinforced masonry buildings (URMs), especially those contiguous to a public street, to make sure they do not pose any risk to people in or near the building. Structural bracing to unreinforced masonry elements should be required to prevent collapse.

On all new buildings where there are designed pediments or other architectural features on the street facade, the pediments should be restrained and/or verandas should be designed as impact barriers to protect the passers-by or other users of the street.

4. *Public awareness of earthquake risk:*

The Expert Panel considered that there was a lack of public awareness that many buildings which are not classified as earthquake-prone under the Building Act 2004 may nevertheless collapse in a major earthquake. These are buildings rated more than 33%NBS but significantly less than 100%NBS. The probability of such collapse could be significantly reduced by strengthening/retrofit measures that increase earthquake resistance and expected performance. The public also need to be made aware of the importance of achieving earthquake resistant buildings and the methods available to increase earthquake resistance.

Expert Panel recommendation

RECOMMENDATION 9: EARTHQUAKE-PRONE BUILDINGS
(Priority A)
Promote and implement measures, and associated enforcements and incentives, that would result in: • improved definitions of earthquake-prone buildings and more effective implementation of strengthening measures, particularly for buildings likely to fail in a brittle manner • a stronger appreciation of the (private and public) value of good seismic performance of buildings and the benefits of improvement action • effective and economic retrofit strategies that improve the earthquake safety of buildings • adoption by territorial authorities of strongly active policies to reduce the risk posed by buildings of low earthquake resistance • improved public awareness that buildings not classified as earthquake-prone under the Building Act 2004 but which fall short of 100%NBS may nevertheless collapse in a major earthquake.

Department response

The Department is leading a comprehensive review of the policy settings for earthquake-prone buildings and will be providing options to change the settings after considering costs and benefits in October 2012. This review will consider the adequacy of the policy framework, the treatment of differing classes of buildings, the current standards and their adequacy (the 'one third' standard), whether or not there should be a standard for upgrading earthquake-prone buildings, timeframes for retrofit action, the process through which regulations are made, the respective roles of central and local government, and the application of standards to Crown-owned properties.

In parallel with this review, the Department is leading work with key engineering organisations, building owner groups and territorial authorities to develop and implement measures to raise awareness of key seismic risks and the options and approaches to address them.

Future construction and retrofit will be seismically robust.

Building Act reform programme of work

There have been a series of reforms to building control since the Building Act 1991. That Act introduced performance-based regulation and set up the Building Industry Authority (BIA) as the central regulator. The 2004 Building Act, developed in the wake of the leaky homes crisis, replaced the BIA with the Department of Building and Housing, with stronger regulatory powers, and introduced licensing of building practitioners.

In 2009 the Department undertook a substantive review of the Building Act and how it was being applied, working with all those affected by the Act including consumers, builders, developers, practitioners and territorial authorities. The purpose of the review was to reduce costs but not the quality of the building control system to streamline processes where appropriate and lift consumer awareness and confidence.

The review had the following objectives:

- Quality homes and buildings are produced through a business enabling and efficient regulatory framework.
- Consumers can make informed decisions and have confidence in dealing with the building and housing market.
- Homes and buildings are produced cost effectively by a productive sector that has the right skills and knowledge.
- The regulatory system is administered in an efficient and cost effective manner.

The review concluded there had been general improvements in building quality since 2004, but changes are necessary to support other government and industry initiatives to improve the productivity, efficiency and accountability of the building and construction sector.

The major changes recommended were:

- clearer signalling of roles and accountabilities for building work and Building Code compliance between designers, builders, building owners and building consent authorities
- changes to the Act and regulations to provide for a risk-based approach to the administration of building consent and inspection requirements, so that they are proportionate to the risk and consequences of building defects and the skills and capabilities for those doing the work
- work by officials on making improvements to the administration of the regulatory system.

Changes in behaviour are critical to the success of the reforms.

The review also found that skill deficits were a major concern to all parties including skills of building consenting authorities. Accreditation of building consent authorities put in place the first step, but further work is required to lift capability further. It was also clearly identified that more stringent controls on commercial design, quality assurance and construction were required.

Other changes were recommended to specifically address residential construction and the associated consumer protection.

Work is underway to address the findings of the Building Act Review which will address some of the recommendations from the Expert Panel.

Appendix 1: Recommendations

The Expert Panel makes the following recommendations to the Department of Building and Housing as a result of the technical inquiry into the structural performance of Christchurch CBD buildings in the 22 February 2011 aftershock:

RECOMMENDATION 1: GROUND SHAKING/BUILDING RESPONSE
(Priority A)
Bring together a comprehensive study that examines the seismic response/performance of buildings in the Canterbury earthquakes, particularly the 4 September 2010 earthquake and the 22 February 2011 aftershock. Such a study should relate building performance (for older and new buildings) and ground shaking measurements, and be aimed at improving the effectiveness and efficiency of earthquake-resistant design in New Zealand and elsewhere. The study should address: • the methods and assumptions used in building design, analysis, standards and practices • the influence of vertical ground motions • the effects of duration of earthquake shaking • the basis for determining seismic hazard factors for building design, assessment and retrofit, particularly for large urban centres.

RECOMMENDATION 2: GEOTECHNICAL
(Priority B)
Review geotechnical information standards required for urban areas in New Zealand and develop national guidelines for minimum standards of information.

RECOMMENDATION 3: POST-EARTHQUAKE INSPECTIONS
(Priority A)
Review current methods for inspecting and reporting information on the structural condition of buildings following an earthquake. Such a review should address: • the need for legislation covering the structural assessment and rehabilitation of buildings affected by earthquakes • the extent to which building owners are responsible for undertaking a more detailed evaluation of their buildings following earthquakes • the need for public awareness and owner education programmes to improve the general understanding of the roles of post-earthquake inspections/evaluations and their limitations • legislative requirements for the documentation of post-earthquake inspection information and public accessibility to such information.

RECOMMENDATION 4: GENERAL STRUCTURAL DESIGN ISSUES
(Priority A)
Reassess approaches to and general requirements for earthquake resistance in buildings. See that necessary changes are made in the light of the Canterbury earthquakes. Specifically, amendments should be aimed at: • improving structural integrity and resilience • limiting the irregularity of structures • encouraging capacity design • encouraging displacement-based approaches to design and assessment • avoiding unintended interactions between structural and other parts of a building • identifying and removing critical vulnerabilities • introducing compulsory Design Features Reports for significant buildings – new or retrofit • introducing tighter controls to trigger requirements for earthquake strengthening when buildings are altered or their use changed.

RECOMMENDATION 5: SPECIFIC STRUCTURAL DESIGN ISSUES
(Priority A)
Review detailed design requirements for structural design and amend them to resolve concerns identified in relation to: • strength and ductility of walls and columns • vulnerability of lightly reinforced concrete shear walls • limits on axial load levels • vulnerability of buildings with cantilevers and transfer beams • strength and integrity of diaphragm connections.

RECOMMENDATION 6: STAIRS
(Priority A)
Issue a Practice Advisory to warn owners of buildings, especially those in flexible frame buildings, to check that the stairs are designed to accommodate appropriate levels of earthquake-induced displacements. (This is a recommendation from the Stage 1 Report and since that time the Department issued Practice Advisory 13: Egress Stairs: Earthquake checks needed for some, published September 2011, www.dbh.govt.nz/practice-advisory-13). Develop revised criteria for stair support and protection of egress ways and incorporate them into the requirements for new designs and retrofits.

RECOMMENDATION 7: CONSTRUCTION QUALITY AND COMPLIANCE
(Priority B)
Review quality assurance processes in all phases of building design and construction, especially in light of the findings of these building investigations. Implement tighter controls and promote more designer involvement to ensure that design intentions are being achieved and that the work complies with the requirements of the approved design documents.

RECOMMENDATION 8: CONCRETE QUALITY
(Priority C)
Work with the concrete industry to review the in situ strength of concrete achieved in a representative range of buildings around New Zealand and recommend any measures required to provide the necessary confidence that specified concrete strengths have been and will be achieved. Measures considered should include further strength testing of in situ concrete in existing buildings and revisions to standards and procedures covering the manufacture, delivery, placement and curing of concrete in new buildings.

RECOMMENDATION 9: EARTHQUAKE-PRONE BUILDINGS
(Priority A)
Promote and implement measures, and associated enforcements and incentives, that would result in: • improved definitions of earthquake-prone buildings and more effective implementation of strengthening measures, particularly for buildings likely to fail in a brittle manner • a stronger appreciation of the (private and public) value of good seismic performance of buildings and the benefits of improvement action • effective and economic retrofit strategies that improve the earthquake safety of buildings • adoption by territorial authorities of strongly active policies to reduce the risk posed by buildings of low earthquake resistance • improved public awareness that buildings not classified as earthquake-prone under the Building Act 2004 but which fall short of 100%NBS may nevertheless collapse in a major earthquake.

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