Section 9:
Conclusions and recommendations

In this section we recommend that a number of changes be made in the design of buildings for earthquake resistance. These recommendations include changes in the way that seismic design is undertaken and changes to structural Standards. In many cases additional research is necessary to identify specific values that are appropriate for design codes and Standards.

## 9.1 Recommendations related to the Earthquake Actions Standard, NZS 1170.51

9.1.1 The current values for the response spectral shape factor, C(T), for deep alluvial soils found under Christchurch appear to overestimate horizontal accelerations in the short period range and underestimate accelerations in the range of 2.0–4.0 seconds when compared with the derived spectra for the Christchurch earthquakes.

Recommendation

We recommend that:

32. The response spectral shape factor, *C(T)*, for deep alluvial soils under Christchurch, should be revised. The likely change in spectral shape with earthquakes on more distant faults also needs to be considered.

9.1.2 The current spectral values for vertical ground motion are too high in the long period range and may be too low in the short period range for structures located close to some faults.

Recommendations

We recommend that:

33. The shape of response spectra for vertical ground motion should be revised.

34. The implications of vertical ground motion for seismic design actions should be considered and locations identified where high vertical accelerations may be expected
in earthquakes.

9.1.3 Regularity of structures in both plan and elevation and eccentricities between the centres of mass and the centres of lateral stiffness and strength have been shown to have a major influence on seismic performance.

Recommendation

We recommend that:

35. The requirements for regularity in buildings, and for torsion due to the distance between the centre of mass and the centres of stiffness and strength, should be revised to recognise the implications of these parameters on observed behaviour.

36. Design actions for floors acting as diaphragms need to be more clearly identified in the Standard. This includes actions that arise from:

• the weight of the floor and its associated gravity loading and the acceleration of
the floor;

• shear transfer between the lateral-force-resisting elements;

• self-strain forces induced by elongation and bending of beams; and

• local forces induced by structural elements such as T-shaped walls that have differing strengths for displacement in the forward and backward directions.

9.1.4 The magnitude weighting factor recognises the influence of duration of shaking on the damage potential of earthquakes (see Seismicity, Volume 1, section 2).

Recommendation

We recommend that:

37. A more rational theoretical basis should be developed for magnitude weighting, which is used in the development of the design response spectra for structures.

9.1.5 There is an inadequate understanding of;

 • the difference between design inter-storey, and peak inter-storey drifts; and

• the influence of ductile behaviour on the shape profile of a multi-storey building. This
 adjustment is made with the ‘drift modification factor’ in the Standard.

Recommendations

We recommend that:

38. Explanation should be added to the commentary to the Standard to explain:

• the difference between design inter-storey, and peak inter-storey drifts; and

• the influence of ductile behaviour on the shape profile of a multi-storey building.

39. The Standard should be amended to require that the supports of stairs and access ramps be designed to be capable of sustaining 1.5 times the peak inter-storey drift associated with the ultimate limit state, together with an appropriate allowance for construction tolerance and any potential elongation effects.

 Attention is also drawn to section 9.6 of this Volume, where we discuss the design of means of egress from buildings.

## 9.2 Recommendations related to the Concrete Structures Standard, NZS 3101:20062

9.2.1 Literature research is required into the influence of the rate of loading on seismic performance of reinforced concrete structures. This topic has been examined in the reports on a number of projects with varying conclusions. A number of papers have indicated that the influence of loading rates associated with earthquakes has little significant influence on behaviour, while others report that loading speeds consistent with earthquakes can reduce ductility.

 We suspect that ductility is reduced in lightly reinforced members but not in members with moderate or high reinforcement content.

Recommendation

We recommend that:

40. A comprehensive study of the existing literature on the influence of the rate of loading on seismic performance of reinforced concrete structures should be undertaken to address the inconsistencies in the published opinions, and to make appropriate recommendations
for design.

9.2.2 In many structural tests the loading sequence has involved use of gradually increasing cycles of displacement. This may have led to an overestimate of the yield penetration compared with that sustained in an earthquake where the major displacement occurs near the start of the shaking. This overestimate of yield penetration may have resulted in overestimates of available ductility of lightly reinforced and walls and beam-column subassemblies.

Recommendation

We recommend that:

41. Research into the influence of the sequence of loading cycles on yield penetration of reinforcement into beam-column joints and the development zones of reinforcement
is desirable.

9.2.3 The reinforcement content and arrangement in a number of structural walls has been shown to be inadequate to ensure that yielding of reinforcement can extend beyond the immediate vicinity of a single primary crack. Improving ductility may be achieved by:

* the use of higher minimum reinforcement contents;
* changes in the distribution of reinforcement in the wall; and
* de-bonding bars in critical zones. Where the de-bonding option is used the potential negative implications of this action on shear and torsional behaviour in T-shaped walls and in walls forming a shear core in a building should be identified.

Recommendation

We recommend that:

42. Changes should be made to the Standard to ensure that yielding of reinforcement can extend beyond the immediate vicinity of a single primary crack, and that further
research should be carried out to refine design requirements related to crack control
in structural walls.

9.2.4 A number of structural walls did not perform in the earthquakes as well as anticipated. There are a number of possible reasons for this:

* the walls sustained greater axial forces than were anticipated in the design owing to the restraint that other structural elements provided against elongation when the wall developed a plastic hinge;
* vertical reinforcement in a wall in the region between confined compression zones is subjected to compression when the bending moment decreases and reverses in direction. Under these conditions the longitudinal reinforcement may yield in compression, which can result in buckling; and
* the majority of structural tests on walls that have been made to establish design criteria have been tested with in-plane loading only. The effect of bi-axial loading has received little attention, and this aspect needs further research.

Recommendation

We recommend that:

43. The Standard should be modified to include requirements related to confinement of
ductile walls.

 For the ductile detailing length of ductile walls, transverse reinforcement shall be provided over the full length of the wall as follows:

• confinement of boundary regions shall be provided in accordance with NZS 3101:2006, clause 11.4.6, modified to provide confinement over the full length of the compression zone; and

• transverse reinforcement in the central portion of the wall shall satisfy the anti-buckling requirements of NZS 3101:20062, clause 11.4.6.3.

 We note that earlier this year, the Structural Engineering Society New Zealand Inc. (SESOC) published a draft recommendation to this effect.3

9.2.5 Suitable provisions to prevent buckling of walls subjected to moderate and high axial load ratios are currently not considered in the standard.

Recommendation

We recommend that:

44. As a short-term measure, where there is a ductile detailing length in a wall and the axial load ratio, , equals or exceeds a value of 0.10, the ratio of the clear height between locations where the wall is laterally restrained to the wall thickness should not exceed the smaller of 10, or the value given by clause 11.4.2 in the Standard.

 Research should also be carried out to establish more rational expressions for limiting the ratio of clear height to thickness, allowing for both the loading and the imposed deformations on walls.

9.2.6 In a number of buildings occupants reported that after the September earthquake the building was more lively than it had been before the earthquake. There are a number of potential explanations for this. Stiffness degradation caused by yielding in the structure and elongation of the plastic hinges is one possible cause and is supported by a limited examination of test results on structural frame tests made in laboratories (see Figure 113 in section 6.3.5 of this Volume). Knowledge of potential loss of stiffness due to these actions could be of value in assessing the required level of performance for a damage limit state.

Recommendations

We recommend that:

45. Research should be carried out into stiffness degradation due to yielding in the structure and elongation of the plastic hinges, as this could be of considerable value in establishing acceptable design criteria.

46 Guidance should be given in the Standard on the expected magnitude of elongation that occurs with different magnitudes of material strain and structural designers should be required to account for this deformation in their designs.

9.2.7 Elongation in plastic hinges in beams can have a significant influence on the behaviour of other structural elements. For example:

* it can reduce seismic isolation gaps in structures;
* in coupled structural walls, elongation in the coupling beams may be restrained by floor slabs that are tied into the walls. This action has the potential to increase significantly the seismic actions induced in the coupling beams, the coupled walls and the foundations;
* in building bays containing stairs, elongation of beams can reduce the effective width of support ledges for precast stairs or, alternatively, can result in the stairs and associated platforms being subjected to axial forces; and
* in buildings with precast panels allowance should be made for elongation in the design of the fixing of the panels.

Recommendation

We recommend that:

47. Structural designers develop a greater awareness of the interactions between elements due to elongation so that allowance for adverse effects can be mitigated in the design and guidance on these matters should be given in the commentary to the Standard.

9.2.8 Elongation of plastic hinges in beams has a direct effect on the performance of floor slabs, particularly where the floors have been constructed using precast prestressed floor
units. The Standard currently indicates the strength enhancement that may result from this interaction (Clause 9.4.1.6.2 of the Standard). However, some other aspects with important implications for seismic performance are not covered. Research papers have already been published4 that may be of assistance to develop this guidance.

Recommendation

We recommend that:

48. The Standard should be revised to provide guidance on elongation of plastic hinges in beams. This should include:

• the width and location of cracks that may be induced in floor slabs at the junction of the floor and supporting beams and the disruption that these cracks may cause to membrane forces that transfer seismic forces to the lateral-force-resisting elements; and

• details of reinforcement required to ensure that the bars do not fail in tension at the cracks.

9.2.9 The restraint provided to beams by floor slabs, particularly where the floor slab contains prestressed precast floor units, can induce significant axial compression force in beams.
This can cause the beams and associated columns to separate from the floors as illustrated in Figure 143(a). This type of separation occurred in the Clarendon Tower building. It would have been prevented if there had been a beam framing into the column at right angles to the perimeter beam. Alternatively, reinforcement that ties the column into the floor can be provided, as detailed in clause 10.3.6 of the Standard. Figure 143(b) shows the form of deformation seen in the Westpac Tower building. In this case the deformation cannot be practically restrained as very high forces would be required. Some form of ductile tie could be used to enable any cracks that are generated to be repaired. The column rotation shown in Figure 143(c) was observed in structural tests by Peng.5

Figure 143: Compression forces induced by elongation and boundary elements

Recommendations

We recommend that:

49. In the commentary to the Standard attention should be drawn to the significant axial compression force that may be induced in beams by the restraint of floor slabs.

50. Low-friction bearing strips should be used to support double-tee precast units to isolate the precast units and the supporting structure from friction forces.

9.2.10 In one of the large transfer beams in the Hotel Grand Chancellor (HGC), extensive spalling occurred in the cover concrete at the mid-depth region of the beam. This was the location where U-shaped stirrup pairs, proportioned to enclose the top and bottom longitudinal reinforcement in the beam, lapped each other in cover concrete. The transfer of tension between the stirrup legs in the lap zone created significant tension in the concrete, and evidently it was this tension force that caused the spalling. The loss of this concrete would have left the stirrups ineffective and it is fortunate that collapse did not occur. The detailing that was used satisfied current requirements in the Standard.

Recommendation

We recommend that:

51. Where clause 8.7.2.8 in the Standard permits the use of stirrups in the form of overlapping U-shaped bars, the proportion of these bars lapped in cover concrete should not exceed 0.5.

## 9.3 Issues related to the Structural Steel Standard, NZS 3404:20096

 The Standard does not require redundancy in a building that relies on eccentrically braced frames for seismic resistance to ensure that collapse cannot occur in the event of one or two active links failing. We consider there should be a requirement for redundancy in such buildings. This requirement might be satisfied by providing columns with sufficient strength and stiffness to provide an alternative load path for a portion of the lateral force resisted by the eccentrically braced frames in each frame.

Recommendation

We recommend that:

52. The Standard should be amended to require a level of redundancy to be built into structures where eccentrically braced frames are used to provide seismic resistance.

## 9.4 General issues related to structural design

 These recommendations are directed to design engineers, and should be considered by the Structural Engineering Society New Zealand Inc., the New Zealand Geotechnical Society, the New Zealand Society for Earthquake Engineering Inc., the Institution of Professional Engineers New Zealand, and other interested bodies. They should also be addressed in continuing education courses. In some cases information should be added to the commentary to NZS 1170.5.1

9.4.1 Problems associated with foundation soils have been a major issue in Christchurch. These are discussed in detail in Volume 1, section 4 of this Report.

Recommendation

We recommend that:

53. There should be greater cooperation and dialogue between geotechnical and structural engineers.

9.4.2 Load paths need to be defined to ensure that the details have sufficient strength and ductility to enable them to perform as required. For example, inertial forces from the floor slab need to be transmitted to lateral force restraining elements. To protect against very high but short-term forces associated with higher mode effects it is important that the load paths have some ductility.

Recommendation

We recommend that:

54. Designers should define load paths to ensure that the details have sufficient strength and ductility to enable them to perform as required.

9.4.3 The validity of basic assumptions made in analyses should be assessed as a part of structural design. The ‘what if’ approach should be used, with examples including assessing:

* whether ratcheting may occur, and if so what steps can be taken to prevent it; and
* whether an assumed section property, say 0.25 x gross section for a lightly loaded wall, is appropriate for the building and limit state being considered. Values of section properties recommended in NZS 3101:20062 are based on the assumption that the member will have developed flexural cracks at relatively close centres. A check on the magnitude of bending moments may indicate that the extent of flexural cracking is limited, in which case the analysis should be repeated with more appropriate section properties. This process can help to identify the potential ductility of the building and indicate the appropriate detailing that should be used.

Recommendation

We recommend that:

55. Structural engineers should assess the validity of basic assumptions made in their analyses.

9.4.4 Potential problems may arise from ratcheting in structures where:

* gravity loads are resisted by cantilever action;
* structures or structural elements have different lateral strengths in the forward and backward directions; or
* transfer structures are incorporated in buildings.

Recommendation

We recommend that:

56. Appropriate allowance should be made for ratcheting where this action may occur.

9.4.5 Current widely used methods of analysis do not predict elongation associated with flexural cracking and the formation of plastic hinges. This aspect can be of particular concern when assessing axial forces induced in structural walls. The formation of flexural cracking causes the wall to elongate and this is greatly increased if a plastic hinge develops. Elongation can be partially restrained by floors that connect the wall to other vertical elements. This can result in the wall being subjected to much higher axial forces than was indicated in the structural analysis. For this reason care is required in proportioning and detailing walls and other structural elements that support the walls.

Recommendations

We recommend that:

57. Structural engineers should be aware that current widely used methods of analysis do not predict elongation associated with flexural cracking and the formation of plastic hinges.

58. In designing details, compatibility in deformations is maintained between individual structural components.

9.4.6 To understand how the tensile strength of concrete can influence structural behaviour, it is essential to have an understanding of basic concepts relating to crack control. This is necessary to avoid the adverse effects of tensile strength on ductility of buildings.

Recommendation

We recommend that:

59. Structural engineers should be aware of the relevance of the tensile strength of concrete and how it can influence structural behaviour.

## 9.5 Particular issues relating to assessment of existing buildings

 These recommendations are directed to design engineers, and should be considered by the Structural Engineering Society New Zealand Inc., the New Zealand Society for Earthquake Engineering Inc., the Institution of Professional Engineers New Zealand, and other interested bodies. They should also be addressed in continuing education courses.

Recommendation

We recommend that:

60. Training or guidance should be provided so that structural engineers are aware of the following issues when assessing existing buildings:

a In a number of reinforced concrete buildings designed using Standards published prior to 1995, the columns that were provided primarily to support gravity loading had inadequate confinement reinforcement to enable them to sustain the inter-storey drifts associated with the ultimate limit state. There are a number
of reasons for this:

• first, it was not until 1995 that a requirement was introduced for all columns to have confinement reinforcement;

• second, design inter-storey drifts calculated using Standards in use prior to 1995 gave smaller inter-storey drifts than the corresponding values found using current Standards. The difference arises from the use of stiffer section properties, the lack of a requirement for drifts associated with P-delta actions to be included, and the practice of taking the design inter-storey drift as 50 per cent of the peak value (2/SM) while the ductility was calculated on the basis of (4/SM ).

b There are a number of structural weaknesses in existing buildings due to aspects of design not being adequately considered in earlier design Standards. The report by MacRae et al.7 identifies many of these aspects.

c In assessing the potential seismic performance, particular attention should be paid to ensuring that seismic gaps for isolating stairs or separating buildings, or parts of buildings, have been kept clear.

9.5.1 Non-ductile mesh was widely used as reinforcement in the in situ concrete topping on floors containing precast units. This mesh has been found to fail at crack widths of the order of 2mm in width, which in some cases results in a major loss of the ability of the floors to perform as diaphragms.

Recommendation

We recommend that:

61. Where mesh has been used to transfer diaphragm forces that are critical for the stability of a building in a major earthquake, retrofit should be undertaken to ensure there
is adequate ductility to sustain the load path.

## 9.6 Issues raised in our Interim Report related to structural design-means of egress

 A number of recommendations were made in the Royal Commission’s Interim Report.
All these have been addressed in greater detail in this report except the following.

 It was proposed that a maximum considered earthquake limit state be introduced into the Earthquake Actions Standard, NZS 1170.5:20041. The intention was that this limit state be considered for the design of stairs, ramps and egress routes from buildings to ensure that these remained useable following a major earthquake. Having given further consideration to this issue, we now consider that the same objective can be achieved by a different approach that might better fit the existing framework of NZS 1170.51.

Recommendation

We recommend that:

62. Critical elements such as stairs, ramps and egress routes from buildings should be designed to sustain the peak for inter-storey drifts equal to 1.5 times the inter-storey drift, in the ultimate limit state. In calculating this inter-storey drift appropriate allowance should be made for elongation in plastic hinges or rocking joints with an appropriate allowance for construction tolerance. NZS 1170.5:20041 and the relevant materials Standards should be modified to provide for this requirement.

## 9.7 Building elements that are not part of the primary structure

Recommendations

We recommend that:

63. The principles of protecting life beyond ultimate limit state design should be applied to all elements of a building that may be a risk to life if they fail in an earthquake.

64. In designing a building, the overall structure, including the ancillary structures, should be considered by a person with an understanding of how that building is likely to behave in an earthquake.

65. Building elements considered to pose a life- safety issue if they fail should only be installed by a suitably qualified and experienced person, or under the supervision of such a person. The Department of Building and Housing should give consideration to the necessary regulatory framework for this.

## References:

1. NZS 1170.5:2004. Structural Design Actions, Part 5: Earthquake actions – New Zealand. Standards New Zealand.
2. NZS 3101:2006. Concrete Structures Standard – The Design of Concrete Structures. Standards New Zealand.
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4. Fenwick, R. C., Bull, D.K. and Moss, P. J. (2011). Practice Note: Design of Floors Containing Precast Units in Multi-storey Buildings. Structural Engineering Society New Zealand Journal, 24(1).
5. Peng, B. (2009). Seismic Performance and Assessment of Reinforced Concrete Buildings with Precast Concrete Floor Systems. (PhD Thesis). Department of Civil and Natural Resource Engineering, University of Canterbury, New Zealand.
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