Wellington City Council
Targeted Assessment Programme

following the

Kaikoura Earthquake of 14 November 2016

Technical Report

7 May 2017

Document Information

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Executive Summary

Overview and Context

The 14 November 2016 Kaikoura Earthquake produced long duration shaking that was close to New Zealand Building Code seismic design levels for certain types of multi-storey buildings in Wellington, particularly in those parts of the city on deeper deposits near the Central Business District waterfront. Damage was concentrated in moment-resisting concrete frame buildings between 6 and 15 storeys in height.

In early December 2016, the Wellington City Council (WCC) received a letter from the Ministry of Business, Innovation and Employment (MBIE) highlighting the early observations from their investigation into the performance of Statistics House, which had experienced the loss of support for some precast flooring units in the lower levels. This letter emphasised the need for systematic and careful engineering inspections to be undertaken for buildings that were of a similar profile to those of the Statistics House, and others of similar form that were known to have sustained significant non-structural damage. The information in the letter from MBIE, in conjunction with the availability of emergency powers to request structural inspections resulting from the amendment to the Civil Defence Emergency Management Act following the Kaikoura Earthquake, formed the basis of Wellington City Council's Targeted Assessment Programme.

The focus of this programme was to address public safety issues by confirming the structural integrity of multi-storey buildings that had experienced significant shaking in the Kaikoura Earthquake. The wider objective was to provide confidence to building owners, occupants and the community that appropriate engineering investigations of buildings most affected by this earthquake were being carried out, and where found necessary, appropriate repairs and remediation were being carried out.

Building Selection

A list of buildings in the central city area that contained characteristics of a similar nature to Statistics House was compiled by Wellington City Council, and formal letters issued to owners in the week commencing 19 December 2016. The list excluded four buildings that were already known to be significantly damaged and/ or under demolition, including Statistics House which was the subject of the MBIE-led investigation.

Eighty building owners were initially notified of the need to commission a targeted damage evaluation. This number reduced following clarification of property addresses, and the subsequent exclusion of four more buildings that were found to have damage requiring more comprehensive engineering evaluations. As these buildings were being closely scrutinised by engineers and Council and appropriate actions were being taken, they did not present public safety concerns. Other buildings that did not meet any of the required criteria and had clearly sustained no structural damage were also subsequently removed from the list. This led to a total of 64 buildings being subject to targeted damage evaluations, in addition to the 8 significantly damaged buildings being excluded from this process.

The Targeted Damage Evaluation Process

The key technical component of the Targeted Assessment Programme was the *Targeted Damage Evaluation Guidelines* that were prepared on behalf of the New Zealand Society for Earthquake Engineering (NZSEE) and the New Zealand Structural Engineering Society (SESOC) by a group of experienced engineers closely involved in the initial response to the earthquake event. These guidelines outlined the process for undertaking and reporting on intrusive investigations of the buildings.

A Targeted Damage Evaluation is primarily a qualitative assessment in which engineers must be satisfied that they can understand the primary load-resisting systems of a building (both gravity and seismic), and can view all critical elements in the load paths. The process did not require a quantitative assessment or rating of the current capacity of the building. However the ability to access and draw upon recent Detailed Seismic Assessments carried out for many of these buildings provided a valuable reference point for those undertaking targeted damage evaluations.

The overall objective of the Targeted Damage Evaluation process was to identify the presence of any critical damage states that could affect either local or global stability, and hence require restriction of the occupancy of part or all of a building and associated repairs.

Principal Findings

A continuum of damage levels was identified across the 64 buildings that were the focus of the Targeted Assessment Programme. The observed damage ranged from isolated and local damage through to damage that is more distributed throughout some buildings, and with varying degrees of severity.

In overview, nine buildings were identified that had distributed floor and/or frame damage in various locations, in addition to the eight significantly damaged buildings. A further 19 had relatively localised floor or frame damage, and another five had only isolated floor damage. No identified structural damage was reported in 31 buildings (43%), but most of these had non-structural damage to ceiling systems and plasterboard linings of varying levels of significance. Some damage was found in precast concrete cladding panels and stairs.

For precast floors, damage ranged from pre-existing shrinkage cracks and other cracks that hadn't been noticeably worsened by the earthquake through to full-depth cracking. Most of the earthquake damage was observed in ductile frame buildings with hollowcore flooring that were constructed during the 1980s. Limited damage was reported in buildings with double tee flooring units and ribbed floors, noting that these systems were present in less than one third of the buildings investigated.

Most of the damage recorded within the primary structure was concentrated in beams of moment-resisting frames. Beam elongation was identified in at least eight buildings within the Targeted Assessment Programme, predominantly affecting those with unrestrained corner columns that were being pushed out from the building. In most cases the extent of residual elongation and the associated floor corner cracking were minor, and none exhibited the degree of beam elongation described in the Statistics House report.

The damage is summarised in the Table 3 within the report. The locations of the buildings, the classes of their foundation soils and the indicative depths to bedrock are shown in Figure 25.

Concluding Observations and Recommended Actions

The Targeted Assessment Programme undertaken by Wellington City Council has provided a basis for systematically evaluating the set of multi-storey buildings considered to have been most affected by the Kaikoura earthquake. The process of undertaking these evaluations has highlighted many instances of damage to structural elements that were unlikely to have been identified without the systematic and intrusive investigations required under this programme.

This programme has identified a number of buildings with various levels of structural damage to precast concrete floors, panels and primary elements. It has addressed the first recommendation of the Statistics House investigation report in relation to the Wellington CBD – namely that buildings of a similar design to Statistics House be investigated as soon as possible. There is a high level of confidence that buildings within this programme have received careful engineering consideration, and that cases of significant damage have been identified. It is however understood that there are some multi-storey buildings with precast floors in the Wellington CBD not included in this programme that do have structural damage, and owners and engineers should be pro-active about undertaking more detailed inspections using the targeted damage evaluation guidelines prepared by NZSEE and SESOC.

In most cases where *isolated* or *local* damage was identified in floor units, remedial work has already been undertaken. For buildings with *distributed* or *significant* damage to floor systems and/or primary structural systems, more careful evaluation of the cause of the damage and appropriate remedial and retrofit measures is required. While the nature of the damage noted to primary frame elements is generally unlikely to require urgent repairs, the extent of the reduction of the capacity will require further detailed engineering consideration in some cases.

Further research is however urgently needed to understand the progression of damage to precast concrete floor systems. For example, relatively few voids of the hollowcore units reported on had been inspected.

The data from the Targeted Assessment Programme should be used to enable a wider understanding of the vulnerabilities and potential community impacts from future earthquakes, and to inform the development of appropriate mitigation strategies.

While the focus of the Targeted Assessment Programme was on buildings most affected in this earthquake – ductile multi-storey buildings with precast floor systems – and there was only limited damage to other older forms of construction, it is essential that efforts be maintained to identify and address other forms of building structures vulnerable to earthquake shaking. Unstrengthened unreinforced masonry buildings remain highly susceptible to damage in closer earthquakes, and medium and high-rise buildings from the 1950s to 1970s era of non-ductile concrete construction need careful assessment given the numbers of occupants involved.

Specific recommendations for priority actions that follow on from the results of this programme and the above issues are presented along with further discussion in Section 6.2.

Contents

1. Introduction

1.1 Background

The 14 November 2016 Kaikoura earthquake resulted in long duration shaking close to the code seismic design levels for buildings in Wellington with fundamental periods between 1 and 2 seconds, particularly in those parts of the city on deeper deposits near the port area. Damage was concentrated in moment-resisting concrete frame buildings between 6 and 15 storeys in height.

While it was generally understood in the immediate aftermath that most engineers were undertaking Level 2 Rapid Building Assessments in accordance with the MBIE Guidelines, Wellington City Council was not able to receive this information as, in the absence of a declared emergency, they had no basis to request this from building owners.

In early December, Council received a letter from MBIE highlighting the early observations from their investigation into the performance of Statistics House, which had experienced the loss of support for some precast flooring units in the lower levels. This letter emphasised the need for systematic and careful engineering inspections to be undertaken for buildings of a similar profile to those of the Statistics House, and others of similar form that were known to have sustained significant non-structural damage.

Utilising the emergency powers enabled by the amendment to the Civil Defence Emergency Management Act passed under urgency on 29 November, the Mayor gave notice of a Transition Period on 14 December 2016. Two subsequent extensions of the 28 day transition period were sought and obtained, through until 8 March 2017.

The information in the letter from MBIE, in conjunction with the availability of emergency powers to request structural inspections, formed the basis of Wellington City Council's Targeted Assessment Programme. A list of 80 buildings in the central city area that contained characteristics of a similar nature to Statistics House was compiled by Wellington City Council, and formal letters issued to owners in the week commencing 19 December. These letters requested that a Targeted Damage Evaluation be undertaken in accordance with the guidelines prepared by representatives of the New Zealand Society for Earthquake Engineering and the New Zealand Structural Engineering Society.

1.2 Overview of This Report

This report was produced for Wellington City Council to summarise the Targeted Assessment Programme and its key findings.

The report outlines the scope of the programme and the buildings included for investigation. An overview of the targeted damage evaluation inspection requirements is provided.

The information from the targeted damage evaluation reports has been analysed by the project team, including QuakeCoRE researchers from the University of Auckland. The key findings are summarised and discussed, along with recommended priority actions.

1.3 Relationship to Other Documents

This technical report draws upon analysis of the data from the targeted damage evaluation reports that were undertaken on behalf of the Council by QuakeCoRE: New Zealand Centre for Earthquake Resilience. This work will be presented in more detail along with further analysis in a subsequent University of Auckland research report. In accordance with the requirements of the emergency powers, all information in the current report has been anonymised with regard to individual properties, as will be done for all future reporting.

The MBIE report *Investigation into the Performance of Statistics House in the 14 November 2016 Kaikoura Earthquake,* released on 31 March 2017, also provides important context to the Targeted Assessment Programme and matters to be considered in assessing ductile frame buildings with precast concrete floor systems.

2. Overview of the Targeted Assessment Programme

2.1 Scope and Objectives

The focus of the Targeted Assessment Programme was to address public safety issues by confirming the structural condition of multi-storey buildings that had experienced significant shaking in the Kaikoura Earthquake.

The wider objective was to provide confidence to building owners and occupants and the community that appropriate engineering investigations of buildings most affected by this earthquake were being carried out, and where found necessary, appropriate repairs and remediation were being implemented.

2.2 Legal Context and Considerations

The Civil Defence Emergency Management Amendment Act imposes significant constraints on the management of the information from building assessments obtained under the emergency powers. A Controller or a Recovery Manager may only use or disclose information from the building assessments obtained under s91 and s94N for the purposes of the CDEM Act 2002 (s83). For example, this means that the information cannot be put on a Land Information Memorandum or used for purposes under other legislation (e.g. the Building Act 2004) without the owner's consent. The outcome of the Controller or Recovery Manager considering the assessment and taking action may however be publicly available - for example, the building may be placarded, evacuated or demolished if the building was found to pose a risk to injury or safety for persons or property as a result of the assessment undertaken.

Wellington City Council submitted a brief report to the Ministry of Civil Defence and Emergency Management in March summarising how the emergency powers under the Civil Defence Emergency Management Act were applied.

2.3 Buildings Included Within the Programme

Wellington City Council received a letter from MBIE on 6 December 2016 outlining the initial observations of the team investigating the failure of floors in Statistics House. This letter highlighted the following characteristics of buildings of a comparable form to the Statistics House that warranted further investigation:

<u>Building characteristics:</u>

- Principal lateral load resistance through concrete moment frames, coupled with precast flooring systems (noting that the most vulnerable to loss of support for precast units are those where there are multiple frame bays in parallel with a single span of flooring);

- A natural period range of 1-2 seconds (typically 8-15 storeys, but note that this occurs in some flexible frames as low as 5 storeys); or
- Sites where the shaking in the period range has been amplified. This amplification may be due to basin effects and/or soft soils.

Building damage:

- Significant loss of contents and/or non-structural damage (partitions, ceiling tiles etc)
- Signs of frame ‘stretch’, for example in carpet tiles; or
- Signs of significant inter-storey drift; or
- Signs of cracking to precast floor units when visible, particularly transverse to the direction of the span of the unit.

A list of buildings in the central city area that contained characteristics of a similar nature to Statistics House (referred to as the *Affected Building Profile*) was compiled by Wellington City Council, and formal letters issued to owners in the week commencing 19 December. The imminent Christmas holiday period required some urgency for this notification, given the short time frames of the transition period.

The list excluded four buildings already known to be significantly damaged and/ or under demolition, plus Statistics House which was subject to the MBIE-led investigation. Eighty buildings were initially notified of the need to have a targeted damage evaluation carried out, but this number was reduced following the subsequent exclusion of four more buildings that found to have damage requiring more comprehensive engineering evaluations. As these buildings were receiving close scrutiny by engineers and Council, with appropriate actions being taken, they did not present any public safety concerns. Three other buildings that were found to have not met any of the above building criteria and had clearly sustained no structural damage were also excluded from the original list.

As a result, targeted damage evaluation reports were obtained from owners of a total of 64 buildings, with all reports being received by the beginning of April. These evaluations had been undertaken by 19 consulting engineering practices.

The locations of the buildings required to have Targeted Damage Evaluations undertaken are shown in Figure 1, with those originally and subsequently excluded due to significant damage shown in red. An analysis of building characteristics such as age and height, predominant lateral force resisting systems and precast floor systems are described in Figure 2 and Figure 3.

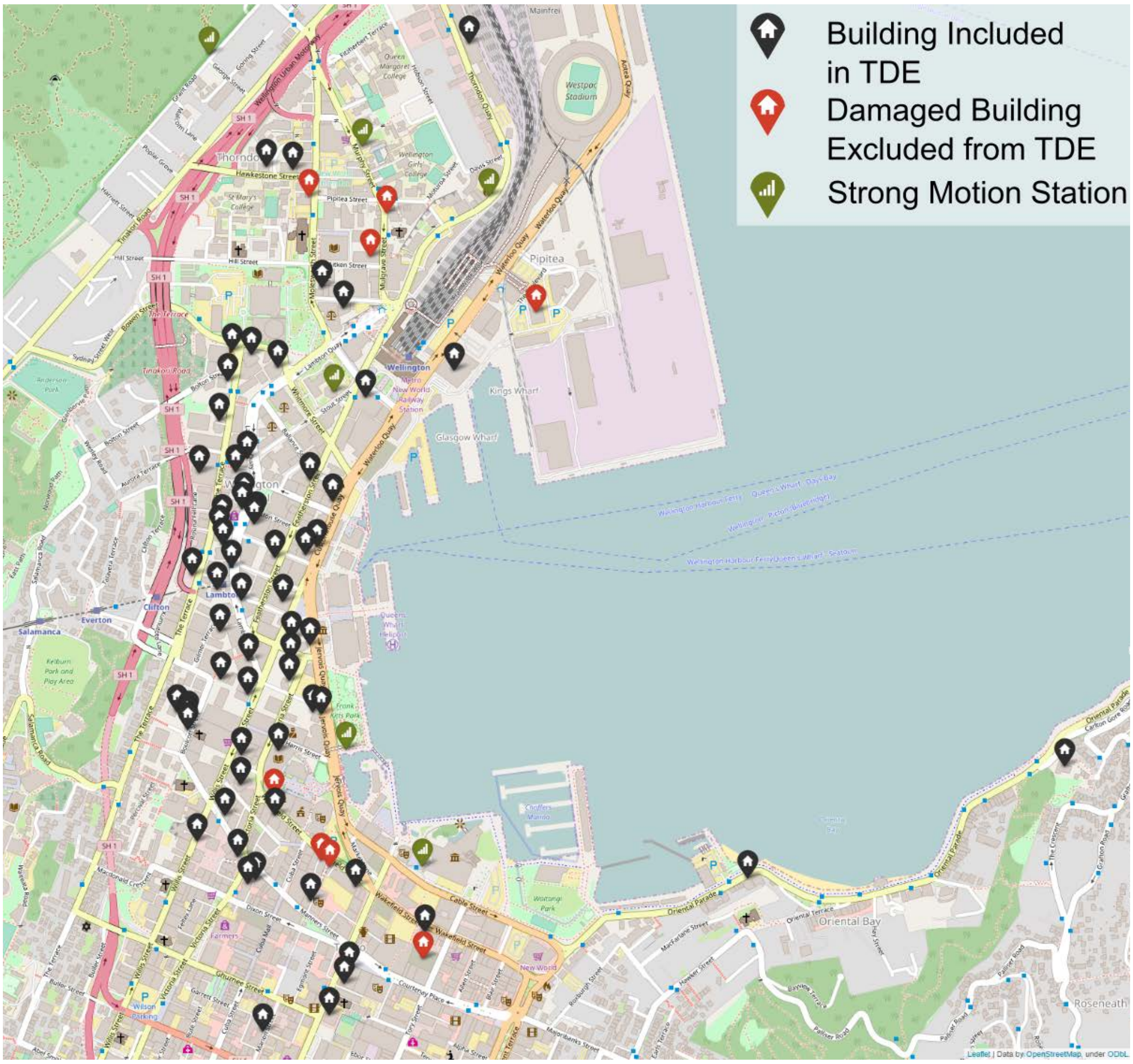
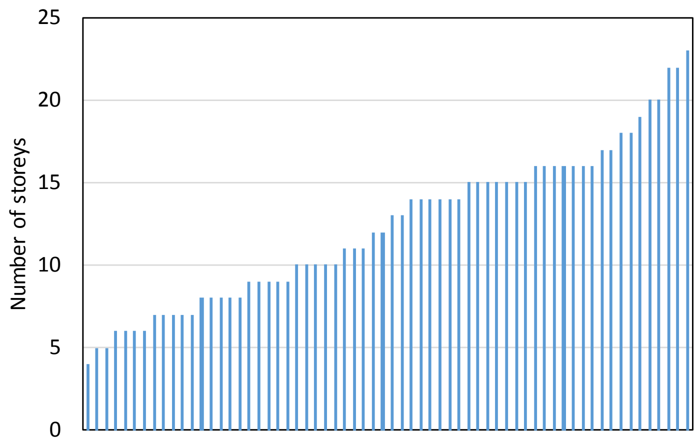
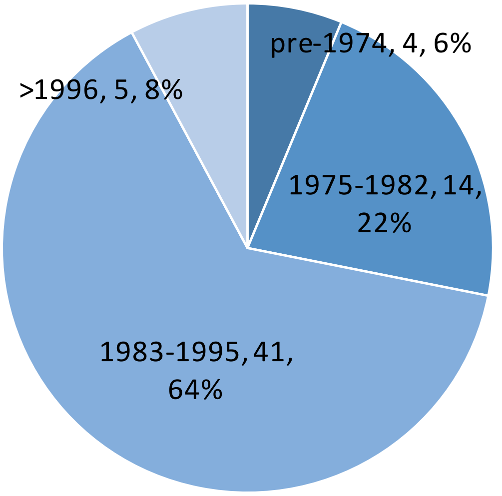
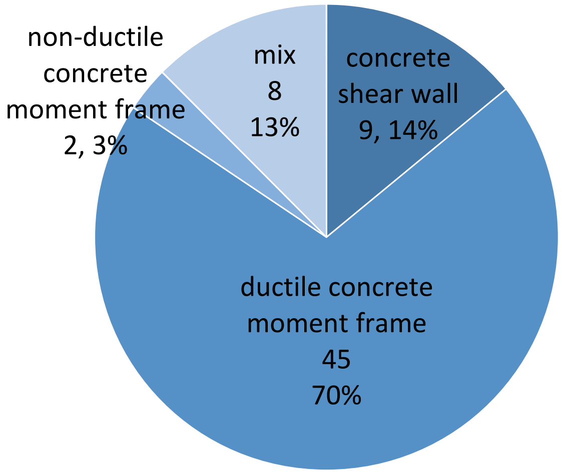


Figure 1: Location of buildings in the Targeted Damage Evaluation dataset (64 buildings) and excluded significantly damaged buildings (8 buildings)







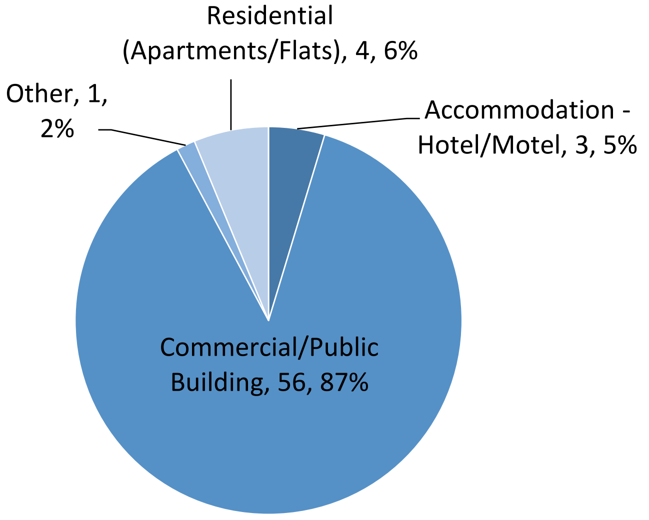
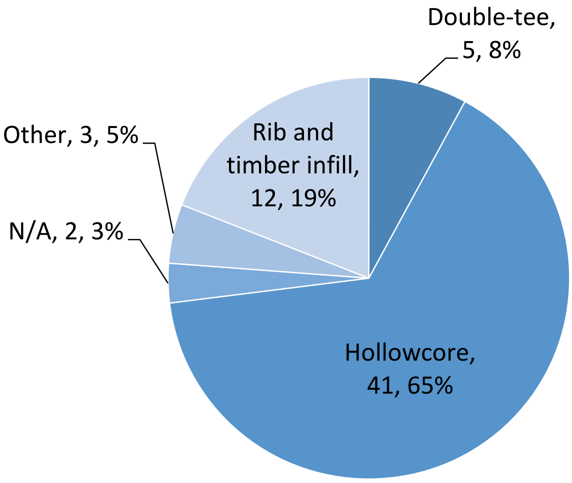
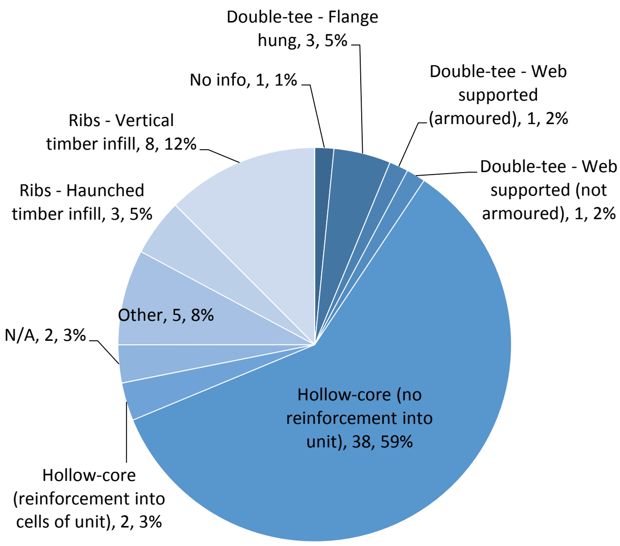


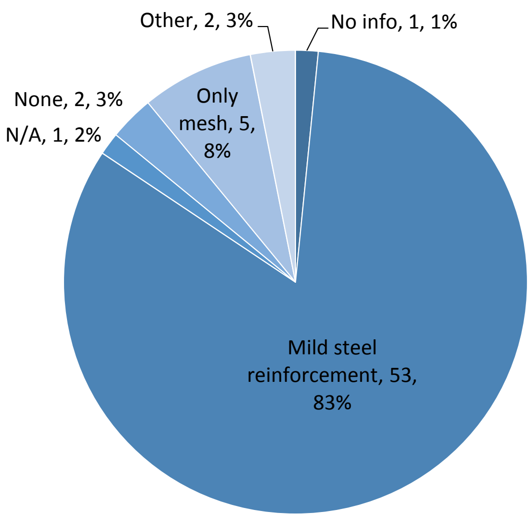
Figure 2: Overview of age and height of the buildings, predominant lateral load resisting systems and ground floor occupancy



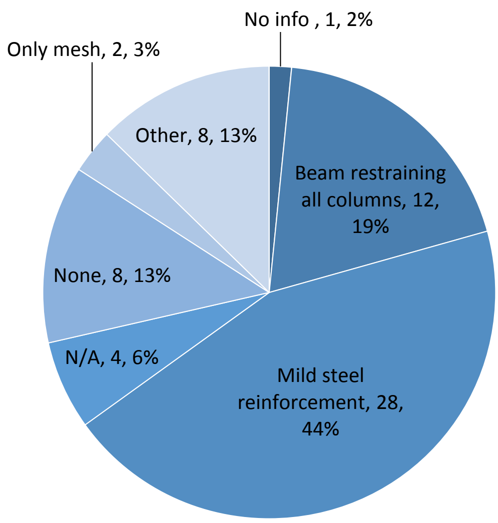
(a) Precast unit type



(b) Precast unit seating detail



(c) Beam to slab continuity reinforcement



(d) Ties from columns into floor (for least restrained column)

Figure 3: Predominant floor type and details

44% (28) of the buildings had already been retrofitted prior to this earthquake, with most retrofitted after the Cook Strait earthquakes of 2013. Of the 14 cases that provided retrofit details, the nature of retrofit encompassed the following (the number of cases in brackets):

- Providing supplemental supports to hollowcore floor units in case of failure (7)
- Increase in stair seating (6)
- Strengthening primary frames and walls (6)
- Tying perimeter frames into floor plates (4)
- Enhancing precast panel connections (2)

2.4 Review and Analysis

The targeted damage evaluation reports received by Wellington City Council were subject to a review by a small group of engineers specifically contracted by Council for this purpose.

This was a high-level review only, focusing on the following aspects:

- The completeness of the report;
- The appropriateness of the investigation;
- The appropriateness of the findings; and
- The clarity of the recommendations to the building owner.

More detailed analysis of the information provided in the summary spreadsheets was undertaken on behalf of the Council by QuakeCoRE, and has formed the basis for this report.

3. Technical Guidance for Targeted Damage Evaluations

3.1 Preparation of the Targeted Damage Evaluation Guidelines

The key technical component of the Targeted Assessment Programme was provided by the document *Engineering Guidelines for Targeted Damage Evaluation following the November 2016 Kaikoura Earthquake*. This document was prepared on behalf of the New Zealand Society for Earthquake Engineering (NZSEE) and the New Zealand Structural Engineering Society (SESOC) by a group of experienced engineers closely involved in the response to this event, drawing upon guidance previously developed by the Ministry of Business, Innovation and Employment following the Canterbury Earthquake Sequence. Input was also provided from regular meetings of the Wellington Engineering Leadership Group, comprising representatives from engineering practices, the technical societies, QuakeCoRE, and GNS Science.

The Targeted Damage Evaluation Guidelines (the Guidelines) provided an overall assessment framework by focusing on the following:

1. Profiles of buildings and damage according to the characteristics of the Kaikoura earthquake and observed shaking and damage patterns.
2. A regime of targeted investigations to be included in Targeted Damage Evaluations of buildings within specifically identified categories of buildings.
3. The requirements for the reporting of the Targeted Damage Evaluations, whether required for the targeted categories of buildings or provided by engineers for other purposes.

The objective of the Targeted Damage Evaluation process is to identify the presence of any local or global *Critical Damage States* that may not have been apparent from the Rapid Building Assessments and may affect continued occupancy. A Targeted Damage Evaluation is primarily a qualitative assessment under which engineers must be satisfied that they can understand the primary load-resisting systems of a building (both gravity and seismic), and can view all critical elements in the load paths. A quantitative assessment of the current capacity of the building is not required under this process. However the ability to access and draw upon recent Detailed Seismic Assessments provided a valuable reference point for those undertaking targeted damage evaluations.

3.2 Critical Damage States

The *Critical Damage States* classify building damage based on risk, with the purpose of focusing the inspection process on damage which could be critical to the future seismic performance of the building. Critical Damage States A, B and C relate to the damage in floors and the primary structure, while Critical Damage State D relates to damage to secondary structural and non-structural elements, addressing exterior as well as interior risks.

Critical Damage State (CDS) A identified damage where the gravity load path may have been compromised in precast floor systems, thus posing a possible risk of local collapse under gravity loading (i.e. without aftershock). While CDS A implies loss of gravity load support, it is noted that several secondary load paths still exist after initial failure of the precast unit (e.g. arching action); however, such load paths are generally unreliable and cannot be assumed to provide support for units with CDS A damage.

CDS B identified damage posing risk of collapse, but only in the case of future aftershocks. CDS B included both local collapse of precast floor units (CDS B1 and B2) and global collapse risk due to loss of lateral support for, or damage to, concrete columns (CDS B3 and B4).

CDS C identified damage, anticipated to be found in many of the buildings, but not posing a direct collapse risk. Identifying this damage to primary frame elements is still important in terms of assessing future seismic performance and repair decisions for the building.

Table 1 on the following page summarises the critical damage states, with additional context such as, for example, the distance out from the supports of floor units within which a CDS applies. Shading distinguishes the damage states that relate to floor systems from those that relate to primary structure and secondary structural elements.

3.3 Targeted Damage Evaluation Process

The Targeted Damage Evaluation process is illustrated in general terms in Figure 4 below, reproduced from the Guidelines.

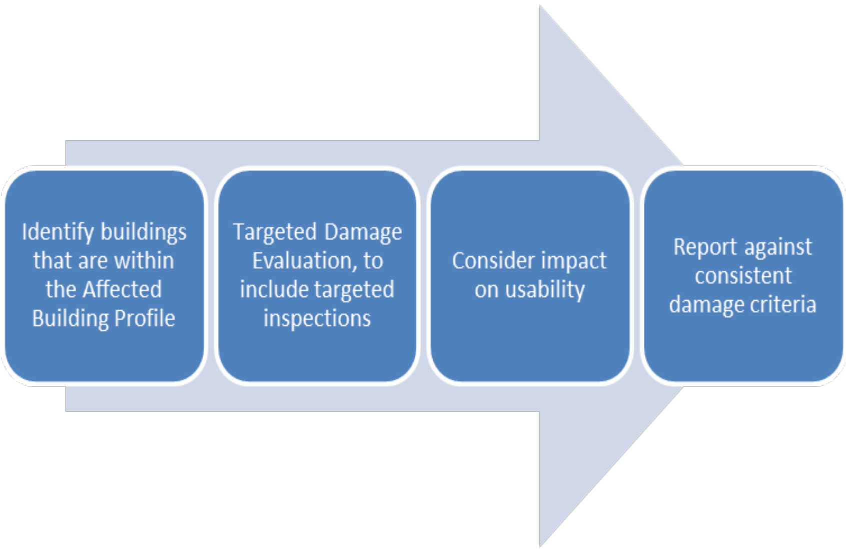


Figure 4: Targeted Damage Evaluation Framework

Table 1: Outline of Critical Damage States

(Key to shading: orange – damage state related to floor system; blue – damage state related to primary structure; green – damage state related to secondary structural or non-structural components)

Critical Damage State	ID	Description	Notes
CDS A: Damage posing local collapse risk (possibly without aftershock)	A1	Transverse cracking at ends of hollow core floor units or diagonal cracking at the ends of ribs	• Within 400mm of the supporting beam • With vertical dislocation or diagonal crack in web*
	A2	Significant damage to support for flange-hung double tee floor units	• With vertical dislocation at the support
CDS B: Damage posing local or global collapse risk in the case of aftershock	B1	Transverse cracking at ends of hollow core floor units or diagonal cracking at the ends of ribs	• Within 400mm of the supporting beam • Not meeting A1 criteria*
	B2	Reduced precast floor unit support	• Evidence of seating loss due to elongation and/or spalling. • Not meeting A2 criteria
	B3	Loss of lateral support for columns over multiple storeys	• Significant cracking adjacent to columns with no reinforcement ties into the floor diaphragm.
	B4	Shear damage to corner columns	• Due to beam elongation and shear demands. • Inclined cracks greater than 0.5mm.
CDS C: Damage to primary structure posing lower risk	C1	Plastic hinge damage	• Criteria provided in TDE Guidelines
	C2	Web cracking in hollow core floor units	• Splitting webs along the length of the unit. • Observed with a borescope camera. • If accompanied by transverse cracking, should be classified as A1
	C3	Longitudinal cracking of hollow core floor units	• Either bottom or top soffit.
	C4	Mesh fracture in floor toppings	• Location of mesh fracture will affect the diaphragm load paths and column lateral restraint.
CDS D: Damage to secondary structural and non-structural elements that may cause increased life safety risk	D1	Stairs	• Damage to stair supports. • Damage to stair unit itself.
	D2	Heavy cladding elements effecting external spaces, especially public spaces	• Damage to panels and/or fixings with inadequate moment allowances or brittle connections.
	D3	Heavy overhead non-structural elements	• Focus on elements posing life safety risk

* Note that for hollowcore units where CDS B1 (transverse cracking at ends) was found, but no investigation of the webs was able to be undertaken to identify the presence of diagonal cracks, this was to be reported as CDS A1.

One of the requirements of the Guidelines is to obtain and review available drawings and information about the building in order to identify 'hotspots' where damage is most likely to have occurred. This approach to planning intrusive investigations reflects the requirements of the Detailed Damage Evaluation procedures developed following the 2011 Christchurch Earthquake.

Where there is no damage to either the primary load-resisting systems or secondary structure and non-structural elements that would impair its continued function or lead to a public safety risk, the building may be considered suitable for continued use on the same basis as prior to the earthquake. Where uncertainty remains, or damage affecting the primary load paths is observed, then the Guidelines require that a Detailed Damage Evaluation needs to be undertaken.

4. Summary of Principal Findings and Observations

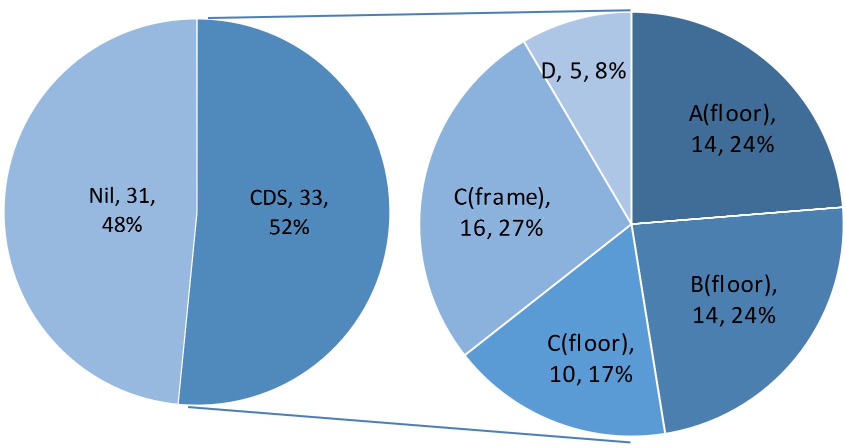
This section provides a summary of the principal findings from the review and analysis of reports received, along with general observations. This section only refers to the data from the 64 buildings subject to Targeted Damage Evaluations, referred to subsequently in this report as the *TDE buildings,* unless specified otherwise.

Key themes are discussed in more depth in Section 5.

4.1 Extent and Nature of Damage

Various levels of damage were noted across the 64 buildings that were subject to Targeted Damage Evaluations. Structural damage was recorded in the majority of the buildings.

Figure 5 provides a summary of the Critical Damage States from Table 1 reported across the TDE buildings. None of the 64 buildings experienced CDS A2 (*Significant damage to support for flange-hung double tee floor units*), B3 (*Loss of lateral support for columns over multiple storeys*), or B4 (*Shear damage to corner columns*). As a result, the only CDS category relating to damage in the lateral system is C1 (*Plastic hinge damage*). All other identified CDS relate to damage in the floor system (A1, B1, B2, C3, C4) or non-structural elements (D1, D2, D3).

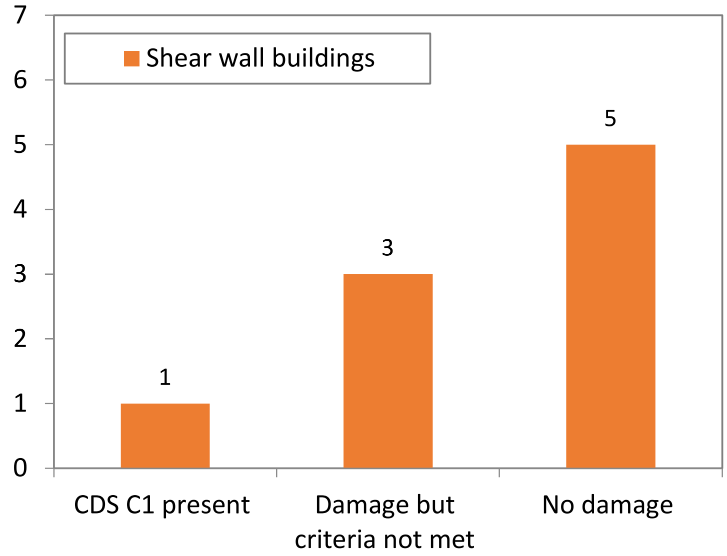


Clusters of CDS	CDS ID
A (floor)	A1, A2
B (floor)	B1, B2
B (frame)	B4, B3
C (floor)	C2, C3, C4
C (frame)	C1
D	D1, D2, D3

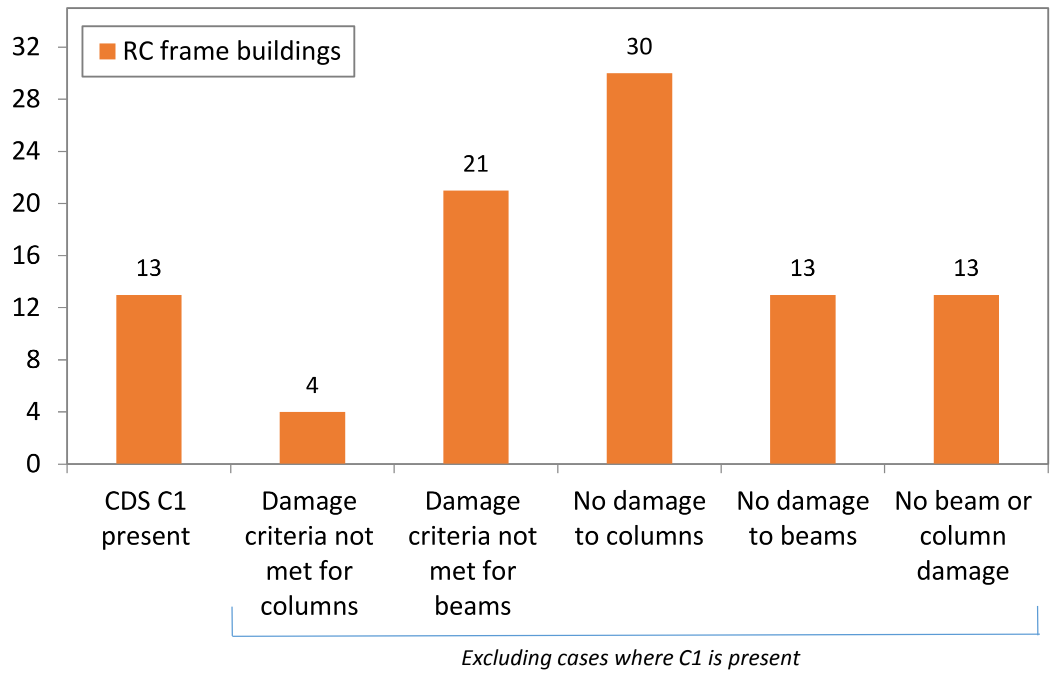
Figure 5: Critical Damage States reported across 64 TDE Buildings

For precast floors, there was a continuum of damage observed. This ranged from pre-existing shrinkage and other cracks that hadn't been noticeably worsened by the earthquake through to full-depth cracking. Most of the earthquake damage was observed in ductile frame buildings with hollowcore flooring from the 1980s, and only some in buildings with double tee flooring units. There were relatively few instances of damage recorded in buildings with ribbed floors, noting that these represented only 19% of the TDE buildings.

In terms of primary structure, most of the damage recorded was to the beams of moment-resisting frames. As shown in Figure 6, for the nine buildings with structural walls as the predominant lateral load resisting system, wall damage meeting the criteria set out in the TDE guidelines was only noted in one building; three others had light damage to the walls.



(a) Shear wall buildings (excluding buildings with mixed lateral system)



(b) Reinforced Concrete frame buildings (excluding buildings with mixed lateral system)

Figure 6: Damage to primary lateral system in (a) Shear wall and (b) Moment-frame buildings

There were no indications of foundation failure or undue deformation of foundations that may have led to the observed superstructure damage.

None of the buildings within the Targeted Assessment Programme were found to be earthquake-prone.

The Critical Damage States typically relate to local damage, and so in order to reflect the overall effect of the recorded damage on the overall building, the following broader structural damage categories have been adopted:

- ***Isolated***
- ***Local***
- ***Distributed***
- ***Significant***

Table 2 provides descriptors for these damage categories and their relationship with the Critical Damage States, for both floor and cladding panel systems and primary structural systems.

Table 2: Outline of Damage Categories and Relationship with Critical Damage States

Category	Descriptor	Critical Damage States
***Isolated* floor or panel damage**	Affecting *one or two* floor units only (or greater numbers but not considered to have been caused by the earthquake)	A1, A2 B1, B2 C2, C3, C4 D1, D2, D3
***Local* floor or panel damage**	*Three to five* units on either one floor or adjacent floors	
***Distributed* floor or panel damage**	*More than five* units and/ or spread across three or more levels	
***Local* damage to primary structure**	Plastic hinging to beams *on one level* and/ or shear damage to corner columns (with cracks greater than 0.5mm)	B4, C1
***Distributed* damage to primary structure**	Plastic hinging to beams on *more than one* level, and/ or shear damage to corner columns (with cracks greater than 0.5mm) or any loss of lateral support to columns on *more than one level*	B3, B4, C1

It should be noted that these categorisations relate only to the locations of damage found in the inspections, and that in some situations there is the possibility of additional damage in other parts of the building.

Table 3 summarises the numbers of buildings with damage in each of these categories, and includes for completeness the eight excluded buildings that were known to be significantly damaged.

Table 3: Summary of Damage by Category

	Structural Damage Category	Number	%age	Comments
	Significantly damaged (excluded from Targeted Damage Evaluations)	8	11%	Includes those already demolished (61 Molesworth St, Readings Car Park) and Statistics House, plus five others which were excluded from the requirement for a Targeted Damage Evaluation
Targeted Damage Evaluation Buildings	Structural damage ***distributed*** across the building	9	13%	5 buildings with distributed damage in frames and floors 2 buildings with distributed damage in frames and local damage in floors 2 buildings with distributed damage in floors but no damage in frames
Targeted Damage Evaluation Buildings	***Local*** structural damage	19	26%	16 buildings with local damage in both frames and floors 2 buildings with local damage in floors but no damage in frames 1 building with local damage in frames but no damage in floors 1 building with local damage in precast panels with no damage in frame or floors
Targeted Damage Evaluation Buildings	***Isolated*** floor unit damage	5	7%	Some of this damage is not thought to be earthquake-related
Targeted Damage Evaluation Buildings	***No identified*** structural damage	31	43%	Non-structural damage was noted in most of these buildings
	Total Buildings	**72**		

For the purposes of this representation, for buildings with different levels of damage between floor systems and precast cladding panels and frames, the building has been classified in accordance with the worst applicable category.

In overview, in addition to those eight significantly damaged buildings, there are nine with more distributed floor and/or frame damage in various locations across the buildings. A further 19 have relatively localised floor or frame issues, and there is only isolated floor damage in another five buildings. No identified structural damage was reported in 31 buildings.

Table 3 indicates that there is a close correlation between damage in the frames and in the floors, with most buildings with distributed damage exhibiting distributed damage in both frames and floors. This correlation is further discussed in Section 5.1.

4.2 Appropriateness of Reporting and Recommendations to Building Owners

The Targeted Damage Evaluation reports summarised the investigations undertaken, the nature of the damaged observed and recommended actions for the building owners. The recommendations for further action are summarised in Figure 7 below. None of the TDE reports recommended demolition of the building.

In most cases the reports were very comprehensive; in all cases the recommendations with respect to any required isolation of areas of buildings (i.e. local cordoning or closure) and further work provided clear directions for owners and agents to follow.

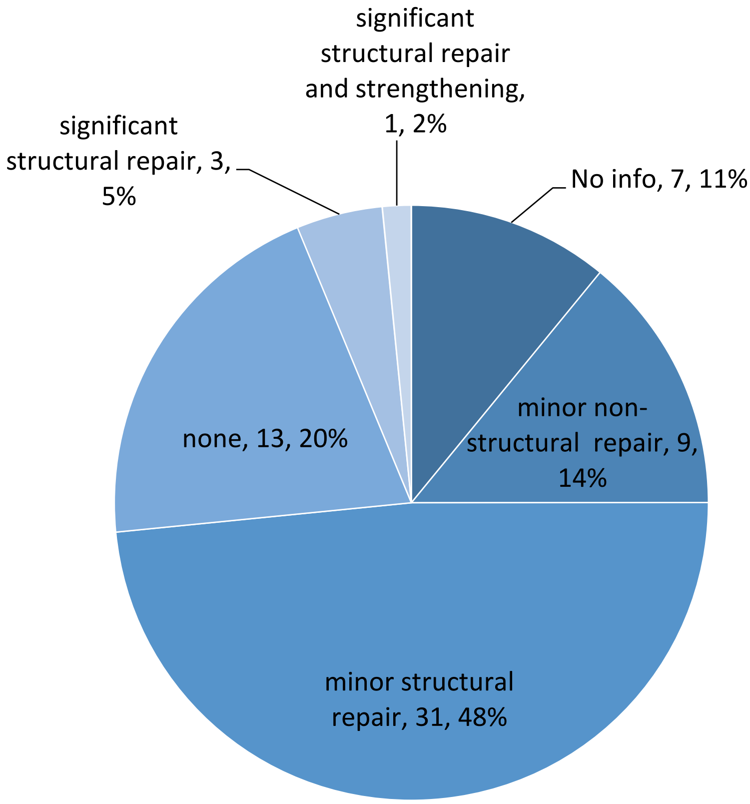


Figure 7: Summary of structural repair/strengthening recommended

Where short-term repairs or remediation were found necessary, it is understood that all of these buildings have either already been repaired or the affected areas have been isolated pending repairs.

5. Discussion of Key Themes

This section discusses in further detail some of the key themes to have come from the review of the Targeted Damage Evaluation (TDE) reports. These cover the nature of damage to moment-resisting frames, the different floor systems and secondary structural elements, the influence of geological and geotechnical aspects and learnings with respect to post-earthquake assessment processes.

5.1 Nature of Damage to Moment-Resisting Frames

5.1.1 Primary frame damage

Over 86% of TDE buildings were designed with concrete moment-resisting frames. Most of these buildings were designed post-1974, and are expected to exhibit strong-column-weak-beam inelastic behaviour. The extent of beam plastic hinging observed in the TDE buildings ranged from minor insignificant cracking to extensive distributed cracking and spalling of cover concrete, as shown in Figure 8, with the majority of buildings exhibiting only minor evidence of beam hinging.

The following criteria were established in the TDE Guidelines to identify cases where the residual capacity of the plastic hinge may need further investigation (i.e. criteria triggering CDS C1):

1. Total crack width in plastic hinge > 0.005d (where d is the beam depth)
2. Sliding has occurred on a crack
3. Wide (>0.5mm) diagonal cracks
4. Concrete degradation, indicated by significant spalling (eg. concrete cover can be removed by hand)

Only 25% of TDE buildings exhibited beam hinging exceeding the criteria set for CDS C1. With few exceptions, this occurred in 10 to 15 storey buildings. While diagonal cracking was observed in some plastic hinge regions, the predominant response of beams was flexural. Initial minor cracking often initiated at the cold joint between the precast beam and cast-in-place joint; however, further demands would typically lead to a distribution of cracks in the beam.

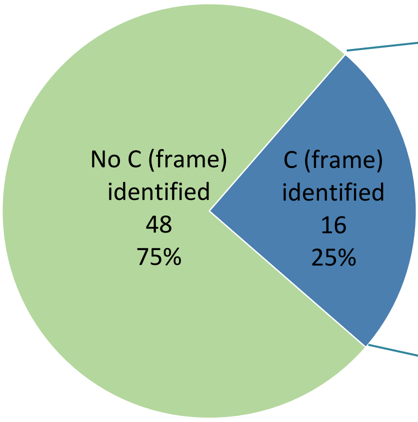
Buildings experiencing damage to the moment-resisting frames tended to also experience damage to the floor system. This observation is illustrated in Figure 9 which indicates that 67% of the buildings experiencing CDS C1 frame damage also exhibit either CDS A or CDS B (floor damage). In contrast, Figure 10 indicates that a building with floor damage is not necessarily accompanied by damage in the frame. The latter conclusion may be the result of the frame being considered undamaged if it exhibits fine cracks (due to reinforcement present in the frame elements), while any width of crack was classified as CDS damage in hollowcore floors due to the brittle nature of unreinforced hollowcore units.

(a) Minor cracking

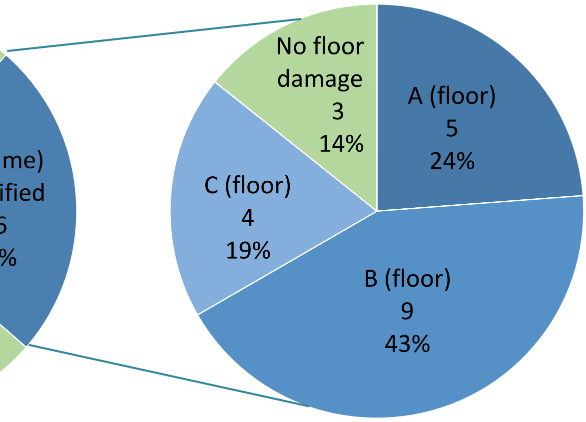
(b) Moderate cracking

(c) Extensive beam hinging

Figure 8: Examples of beam plastic hinging

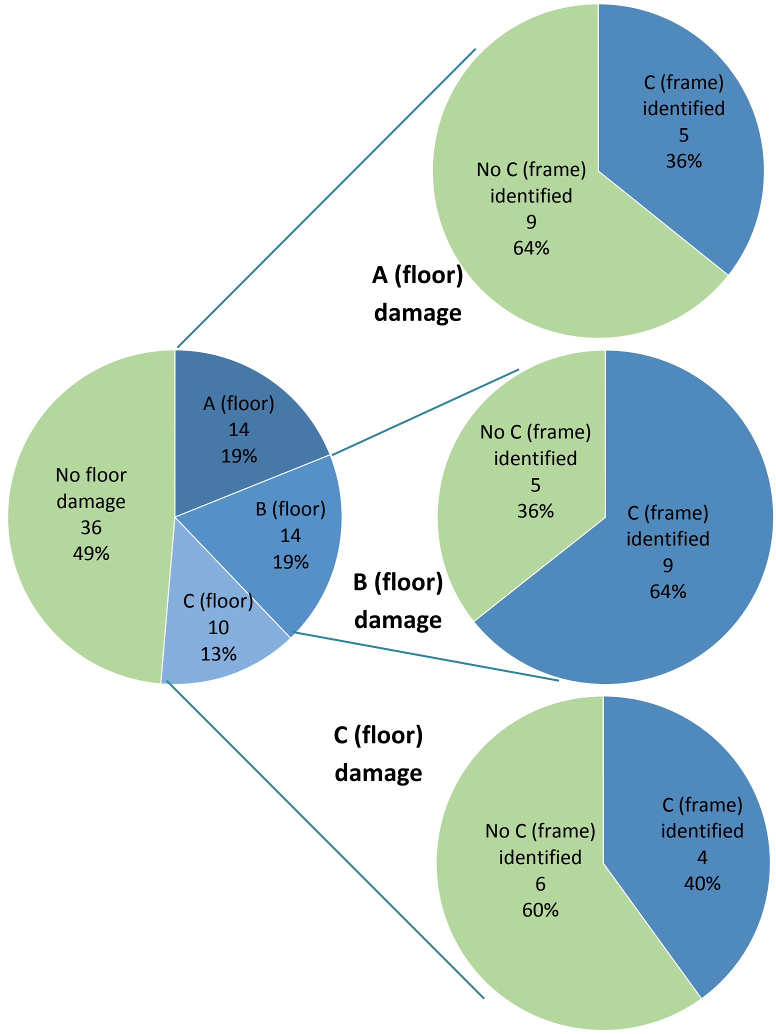


(a) Lateral system damage



(b) Type of floor damage in those building presenting lateral system damage

Figure 9: Lateral system damage vs Floor damage



(a) Type of floor damage *(b) Lateral system damage for each type of floor damage observed*

Figure 10: Floor damage vs Lateral system damage

5.1.2 Frame elongation and reduced precast unit support

Beam elongation was identified in at least eight of the 64 TDE buildings, predominantly affecting unrestrained corner columns that were pushed out from the building, with associated floor corner cracking. It is also recognised that at least 4 of the 8 significantly damaged buildings excluded from the TDE process also exhibited beam elongation. It should be noted that the observed beam elongation represents the residual or permanent elongation that is accumulated after several inelastic cycles, and not the peak deformation that may have occurred during the earthquake. For buildings subjected to moderate drift demands, the beam flexural cracks are likely to have closed with minimal residual elongation. In most cases the extent of residual elongation in TDE buildings was minor, and none exhibited beam elongation of the extent reported in the Statistics House report.

Beam elongation tended to occur in buildings designed for higher ductility. Figure 11 shows that buildings with design ductility below 3 did not exhibit beam elongation. This figure only includes the 64 TDE buildings; consideration of the eight significantly damaged buildings would strengthen this relationship.

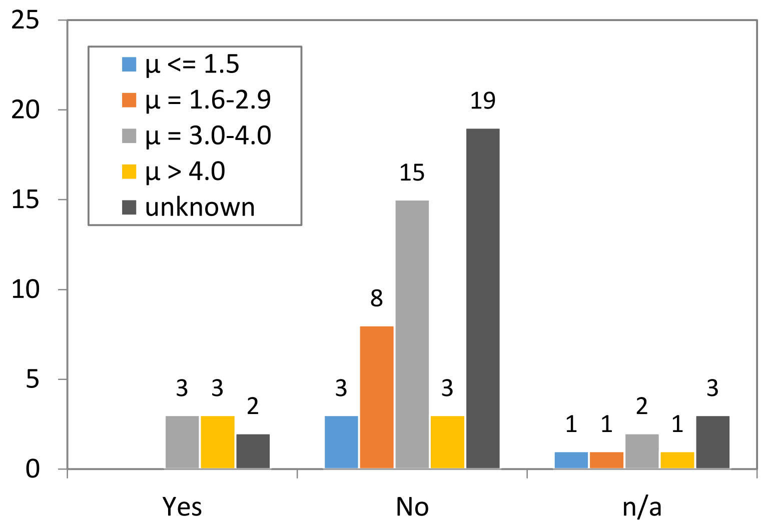


Figure 11: Relationship between design ductility and presence of beam elongation

The presence of beam elongation generally reduced the seating width for units spanning into corners, but with the exception of Statistics House, sufficient residual seating of precast units was maintained. In restrained beams away from the corners, hinging was often less significant, with cracks that had generally closed up leading to minimal residual elongation.

In addition to beam elongation, the building drift and associated rotation of the support beam can also lead to damage at the support. Minor spalling of the support ledge was observed in many buildings with hollowcore floor units seated directly on the support beam, as shown by the example in Figure 12a. The use of a bearing strip, as required by NZS 3101:2006 and used since the mid-2000s, can delay the onset of such minor spalling by allowing the unit to slide relative to the support beam. However, spalling of support ledges is still observed (e.g. Figure 12b) when the building is subjected to high drift demands with bearing stresses and prying effects increased. Examples of significant spalling of the support beam are shown in Figure 12c and d where the entire cover concrete has been lost. The seating length in this building was adequate to ensure that a residual bearing area was maintained to prevent complete loss of support and potential collapse of the floor units. Despite the extensive damage observed, Figure 12c highlights the importance of changes to design standard requirements in NZS 3101:2006 where seating lengths must be sufficient to accommodate demands due to both elongation and rotation, as well as the loss of bearing area due to spalling.

(a) Minor spalling (without low-friction strip) *(b) Minor spalling (with low-friction strip)*

(c) Spalled ledge exposing reinforcing *(d) Deep crack at support ledge*

Figure 12: Examples of support ledge spalling

None of the 64 TDE buildings lost support for the precast floor units. Unit support is dependent on the peak frame elongation during the earthquake, not the residual elongation observed after the earthquake. Hence it is challenging to assess how close any of these buildings were to losing support for precast floor units. The wider issue is therefore understanding the likely peak frame elongation experienced by these buildings through further modelling of those buildings.

5.1.3 Influence of prior retrofit/ strengthening

While several buildings were retrofitted with supplemental supports for floor units, none of these were truly tested since the units did not drop off the beam supports. It is noted, however, that none of the buildings with retrofits reported any bearing damage to the precast units at the edge of the supplemental support, indicating that the retrofit did not negatively impact the performance.

5.2 Nature of Damage to Precast Concrete Floor Systems

5.2.1 General

An overview of the types of precast floor systems in the 64 TDE buildings is shown in Figure 3, with the majority being hollowcore buildings constructed in the 1980s.

Extensive shrinkage to thin topping slabs is present in many buildings with precast flooring systems. These cracks are not thought to have initiated further damage. There is however always a degree of engineering judgement involved in interpreting the cause and significance of minor damage, hence some potential variance in evaluations can result.

Fracturing of mesh was only reported in 3 buildings, despite 81% of TDE buildings being reported as having cold drawn mesh based on the original drawings.

The most commonly observed damage pattern was cracking of floor units in the floor plate corners. Figure 13 indicates this corner cracking typically takes one of three forms:

1) localised with only one or two, typically fine, cracks near corner column (examples in Figure 14);
2) a complex intersection of many, typically wider, cracks, generally limited to the first unit (examples in Figure 15); or
3) a single diagonal crack set back from the corner, crossing more than one unit, and intersecting the frames roughly halfway along the bay lengths.

The first two corner damage patterns result from deformation incompatibility between the beam and the floor unit leading to twisting of the first unit running parallel to the external frame, and can be exacerbated by beam elongation. Extensive research undertaken at the University of Canterbury during the 2000s established that hollow core units are weak in torsion and crack at low deformation demands[1].

Away from the floor plate corners, transverse cracking in hollowcore was less prevalent. When observed, transverse cracking was typically observed in individual units (i.e. not continuing through multiple units). Transverse cracks were sometimes found in floor units randomly distributed across a floor plate, both adjacent to exterior seismic frames and near interior gravity frames. Limited instances of buildings with prevalent transverse cracking across multiple adjacent units, or on multiple floor levels, were reported. All affected units are understood to have been re-supported as a consequential action to the inspections.

[1] *Assessment of Hollow-core Floors for Seismic Performance*", Report 2010-02 - Fenwick, R., Bull D., Gardiner D. Department of Civil and Natural Resources Engineering, University of Canterbury, 2010.

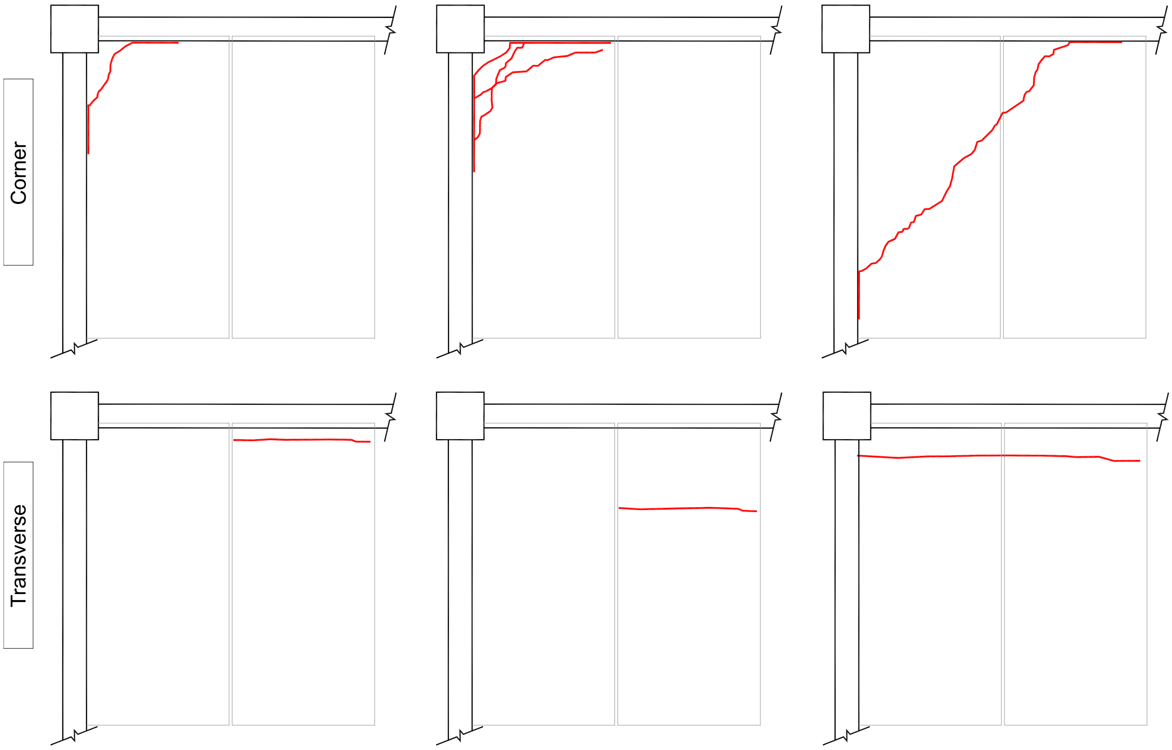


Figure 13: Plan views of typical crack patterns observed in floor units (from below or from above)

Figure 14: Damage in corners of floor plate – Single cracks

Figure 15: Damage in corners of floor plate – Significant cracking

In at least one significantly damaged building, the layout of the structural system led to failure of the diaphragm with wide cracks extending through the topping and hollowcore units (10-15mm wide in some locations with topping steel mesh fracture). The principal crack ran longitudinally along the unit and stepped across cells at discrete locations, with damage to internal webs of the unit being likely. As illustrated generically in Figure 16, connection between the diaphragm and the short seismic frames at perimeter was interrupted by the presence of stairwells, leading to high shear demands on a short length of diaphragm. Floor unit demands were further exacerbated by limited beam elongation in the corner of the building and reasonably high building drifts (estimated at 1.0 - 1.5%).

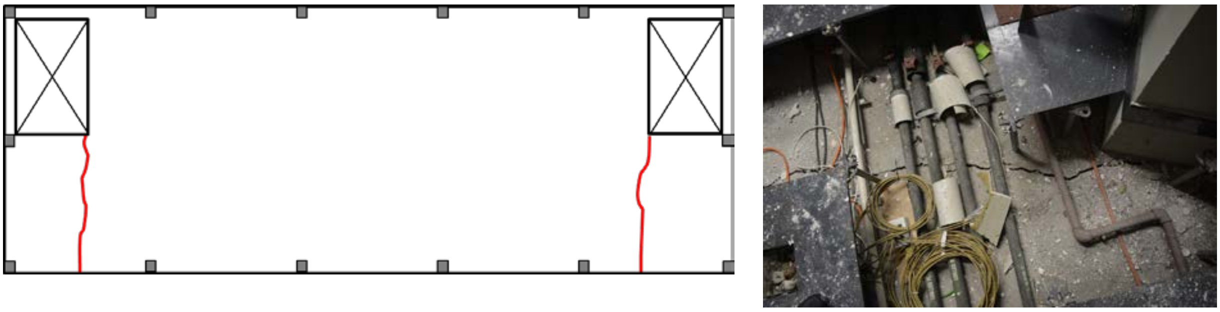


Figure 16: Generic illustration (plan view) of rectangular perimeter moment frame building with diaphragm failure at openings for stairwells

5.2.2 Hollowcore Flooring Systems

<u>Cracking in Hollowcore floor diaphragms</u>

When assessing the critical damage states, it was important to identify whether the cracks in the floor topping concrete had propagated between the joints of precast units or through the unit itself. Different types of cracks found in hollowcore units are shown in Figure 17. Transverse cracking in hollowcore was of particular concern because these units do not include transverse reinforcement, and transverse cracks near the support may impact the bond between concrete and the bottom flange prestressing strand and reduce shear capacity near the support. Transverse cracking in hollowcore units was observed in 14 of the 64 TDE buildings. In three of these buildings the transverse cracks were identified to have propagated diagonally through the web of the hollowcore as illustrated in Figure 17 (CDS A1).

It is noted that a further 11 buildings with transverse cracking were identified where the orientation of the cracking through the hollowcore unit had not been confirmed (and hence have been classified as CDS A1). Further inspection of these units for diagonal web cracking using a borescope camera is recommended.

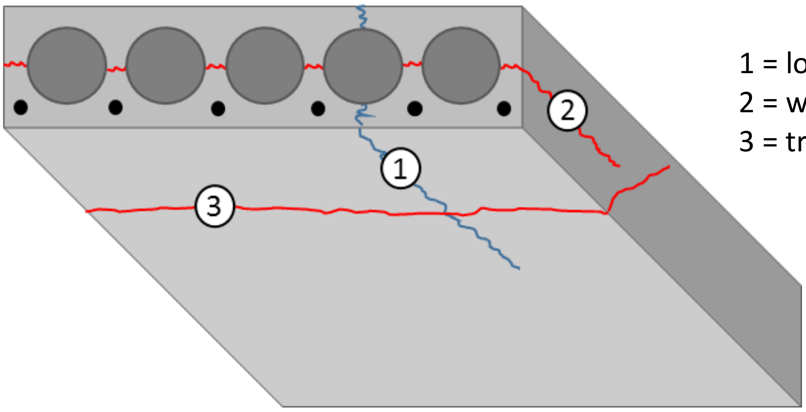


Figure 17: Types of cracks found in hollowcore units

The most common hollowcore floor damage patterns observed can be described as a combination of crack sections shown in Figure 18 and in plan views shown previously in Figure 13. The top row in Figure 18 would be classified as CDS A, as the gravity load support has been compromised with a diagonal crack in the web. If webs were not inspected for cracking via borescopes or other means, the Guidelines instructed the engineer to assume the presence of a diagonal crack, and therefore report the damage as CDS A.

The second and third rows in Figure 18 show damage patterns which are generally of lower risk compared with CDS A; however, cracking at underside near the support is also of concern. Such damage, along with possible retraction of the prestress strand from the end of the unit, can reduce the bond between bottom flange prestress strand and concrete leading to lower shear strength at the end of the hollowcore unit. Inspection of the end of the hollowcore unit for any signs of strand retraction was typically not possible without extensive removal of concrete due to the casting of beam concrete and topping slab over the end of the unit.

It is noted that some cracking of precast concrete floor units may have been pre-existing, however the determination of what caused the cracks is challenging in many cases.

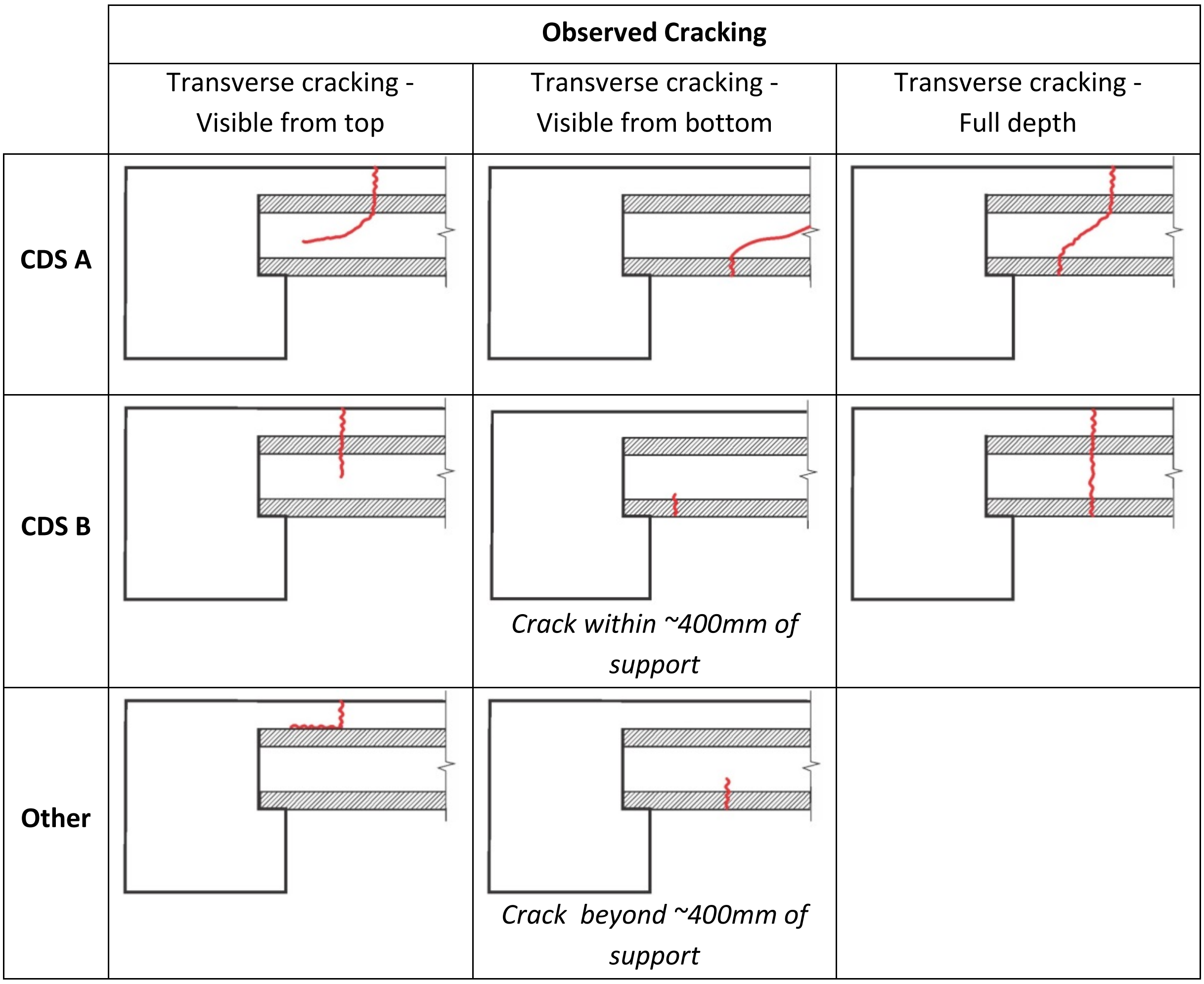


Figure 18: Cross sections of transverse crack patterns in hollowcore floor units and the relationship with Critical Damage States

Figure 19 shows examples of transverse cracking within 100 mm of beam support, where prestress in the strand is unlikely to be significant. In addition, transverse crack at approximately 300 mm from the support were observed in some buildings, as shown in Figure 20. Typically the location of the cracks on top surface corresponded to the end of the starter bars, and in many cases the crack was found to extend vertically for the full depth of the unit. Given the distance of the transverse crack from the support, prestress strand bond is likely sufficient to sustain gravity loads, but further widening of the crack in aftershocks was still a concern. Further research is needed to understand the cause of this cracking pattern and the residual capacity when considering both gravity loading and demands in aftershocks.

Figure 19: Transverse cracking of hollowcore close to support

Figure 20: Transverse cracking of hollowcore away from support

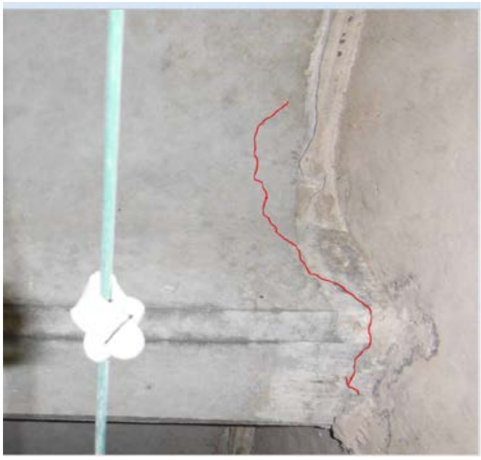
Influence of prior retrofit/ strengthening

As noted above, at least seven buildings were retrofitted with supplemental supports for hollowcore floor units. The use of an angle or RHS section to extend the seating length may help to prevent loss of support due to elongation and/or support beam spalling, but does not address the potential for failure of the precast unit except at the end of the unit. As described above, transverse cracking in hollowcore can occur a significant distance away from the support (>100 mm) and beyond the extended seating. Understanding the cause of such damage and the residual gravity load capacity of damaged units is an urgent need prior to retrofitting buildings with hollowcore floor units.

5.2.3 Double Tee Flooring Systems

In addition to Statistics House, a further five TDE buildings contained double tee precast floor units. Examples of damage are shown in Figure 21. The double tee units in two of these buildings were web supported, and in both cases transverse cracks were observed in the webs close to the supports. The double tee units in the other three buildings were flange supported, and in two cases minor spalling of the support ledge was observed in addition to some unit cracking. Diagonal cracks were observed in the flanges of several double tee units, which is a common damage pattern that poses no significant collapse risk and in some cases may have been pre-existing. More significant spalling of the support ledge is understood to have occurred in at least one of the significantly damaged buildings excluded from the Targeted Assessment Programme.

The beam hinging and frame dilation in the five TDE buildings with double tees was significantly less than that measured in Statistics House. Only minor spalling of ledges occurs, with no significant risk of loss of seating (see Figure 21b).



(a) Cracking of embedded tee rib (crack drawn for clarity)

(b) Spalling of support ledge

Figure 21: Damage to double tee floors

5.2.4 Ribbed Flooring Systems

In general, the damage to buildings with rib and timber floors was less severe with only a few cases of damaged floors discovered. Of the 12 TDE buildings with rib and timber infill floors, only 4 were found to have critical damage states. Damage to precast ribs was discovered in two buildings. This damage consisted of transverse cracking though the ribs close to the support (see example in Figure 22). In one building this was an isolated case with just a single unit damaged, whereas in the other the damage occurred to multiple units in several floor levels. Transverse cracking in ribs typically results from the end of the rib being trapped in the support beam, causing flexural damage in the ribs when the building deforms. This transverse cracking can result in similar failure modes to hollowcore units, due to the lack of development of prestress at the cracked section close to the end of the rib. However, the cracks observed were almost all vertical and did not pose an immediate collapse risk. No cases of significant damage or spalling were observed at rib supports.

Figure 22: Transverse crack at end of rib *(crack drawn for clarity)*

5.3 Nature of Damage to Secondary Structural and Non-structural Elements

5.3.1 Stair Elements

Structural damage to stair elements (Critical Damage State D1) was only recorded in one building from the Targeted Assessment Programme. This situation involved one flight of steel framed stairs, where the insert bolts securing the steel stringers to the concrete floor beam had partially pulled out.

Precast concrete scissor stairs are however understood to have failed at two levels of one of the buildings excluded from the programme. In other buildings, issues with stairs and the reliability of their use as a means of escape in a fire situation or following aftershocks caused some concern for occupants.

The absence of more widespread damage to stairs and their supports can be attributed to the extensive review (and in many cases strengthening) of stairs following the Canterbury and Cook Strait earthquakes.

There were several other instances reported of where stairs and ramps had moved at sliding joints. Particularly for ramps, this continues to be an area where damage commonly occurs, and although not resulting in life safety concerns, can result in buildings being out of service for considerable periods of time.

5.3.2 Heavy Cladding Elements

Damage to heavy cladding elements (Critical Damage State D2) was recorded in four buildings. In one case, this was as a result of significant damage to ground floor concrete masonry infill panels. The other three cases involved damage to precast panel connections, noting that no structural damage was observed to the panels themselves.

The connections where damage was recorded involved a combination of steel brackets with cast-in bolt fixings and weld plates. The damage involved bolts fracturing due to the fixing having exceeded its drift capacity and a separate instance of panel cracking around the weld plate fixing. In two cases the buildings were in the midst of seismic upgrades when the earthquake occurred, and augmentation of the brackets was already underway.

It is noted that cases of damage to precast panel connections was observed in some buildings not included within the set analysed as part of the Targeted Assessment Programme, including the fracturing of fixing bolts.

Of greater concern for future major earthquakes were the several reported incidences of cladding panel connections that had very limited future movement capacity. This was either due to the brackets having been modified from the original design intent (eg. cover plates fully welded (refer Figure 23)) or the intended seismic movement allowance having been taken up as construction tolerance during erection of the panels. The resulting inability to accommodate drift of the primary frames in future events could typically lead to early failure of the connecting bolts in shear at relatively modest levels of ground shaking, with associated public safety implications.

Where these issues were identified, the engineers have recommended to owners that these connections should be reviewed and remediated where found necessary, and these recommendations should be actively followed up on by the owners.

There is an associated implication for previous seismic assessments and ratings, where it has not been routine practice to actively remove interior linings to access and inspect precast cladding panel connections. For buildings with panels with inadequate movement allowance, a lower overall seismic rating may be warranted to reflect the potential life safety hazard presented by the panels.

Figure 23: Precast cladding panel connection with limited movement capacity

There were also some reports of loose bolt fixings to panels and bolts not being installed (refer Figure 24).

Figure 24: Precast cladding panel connection with fixing bolt not installed

5.3.3 Heavy Overhead Elements

No heavy overhead non-structural elements with damage (Critical Damage State D3) were reported.

5.3.4 Non-structural Damage

While not required to be formally reported on in TDE reports, non-structural damage was also noted to many buildings. This typically took the form of damage to plasterboard lining and movement of ceiling tiles. Reports were also received of movement and dislodgement of fire seals and pillows at services penetrations between floors.

Damage to plasterboard lining in stairwells and other fire separations may well have compromised passive fire protection and smoke barriers. Along with the disturbance of fire seals, this requires active investigation and repair to maintain the fire safety integrity of evacuation pathways and floor separations.

5.4 Understanding Geological and Geotechnical Influences

Ground shaking intensity at a given building site is dependent on the ground conditions. Given the distance from the earthquake source, the ground shaking in Wellington from the Kaikoura Earthquake was dominated by long period waves (short period waves damp out more quickly as the waves travel through the earth). As a result, soft soil sites, with a long natural period of vibration similar to the period of the earthquake waves, will tend to amplify the ground shaking more than stiff soil (or rock) sites.

The unique geological setting of Wellington means that the ground conditions change rapidly over the city, even within the boundaries of the CBD, both in terms of the depth to rock and the deposits that make up the soil profile above rock. With these varied ground conditions, and given the basin effects in this area, a significant variation in shaking intensity throughout the city is expected.

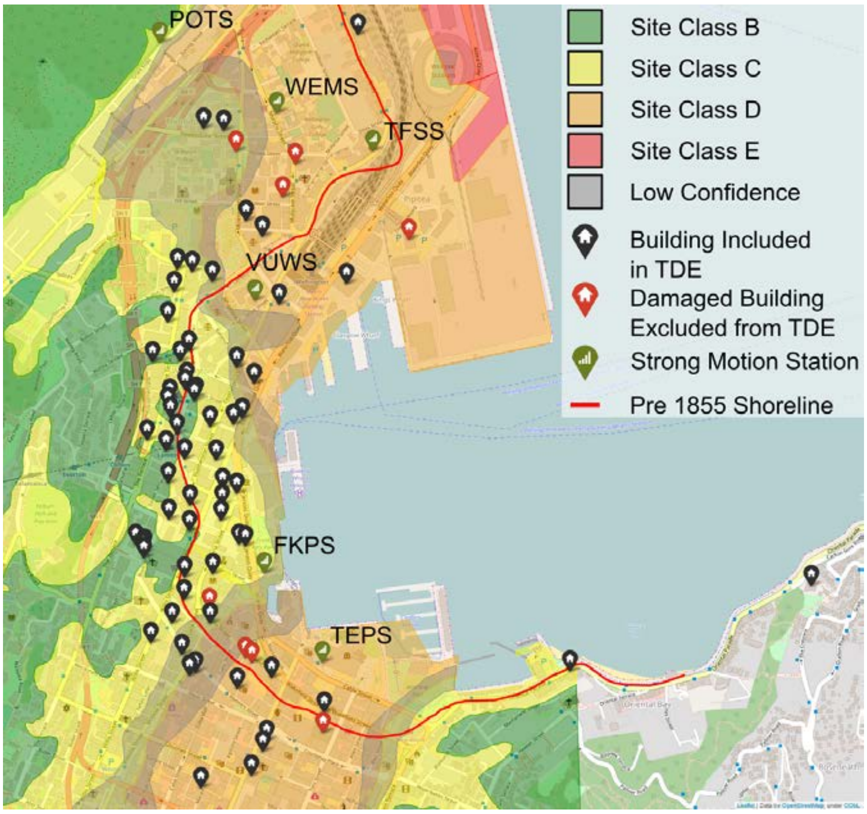
Figure 25 shows an representation of the site subsoil classes across the CBD (Site Subsoil Class B is stiffest and Class E is softest) and the estimated depth to bedrock, along with the location of the buildings and the ground motion recording stations. It is noted that in Wellington the stiffness of a site is generally more closely related to the depth of the soil profile rather than varying stiffness of the ground materials themselves; hence, there is a close relationship between the site subsoil class and depth to bedrock. Response spectra for each ground motion recording station, compared with the ULS design spectra, are shown in Figure 26. While the ground motion recording stations are generally located on site class D (or boundary with C), the buildings are distributed over site classes D (17 buildings), C (29) and B (18). Considering this discrepancy, the variability in ground conditions, and the limited number of ground motion recording stations close to the concentration of buildings in the CBD, it is not possible to reliably determine the shaking demands from the Kaikoura Earthquake on all of the buildings considered in this report. A greater density of ground motion instruments will go a long way to addressing this concern (see section 5.5.2). Despite the lack of specific information on the actual shaking demands on the buildings, it is noted that for buildings designed with high ductility (eg. a ductility of 6) the level of design strength is in fact one-sixth of the elastic ULS spectrum shown in Figure 26, indicating that the recorded demands for most sites exceeded the level of design strength provided and resulted in several cycles of inelastic demands during this earthquake.

Figure 27 shows the relation between the extent of damage for the TDE buildings and the site class and reclaimed land. There is no apparent relationship with the damage and whether or not the building was located on reclaimed land. This is most likely because the materials used for the reclamation often make up only a small portion of the overall soil profile thickness at each location, and the reclamation materials may be stiffer than the underlying natural deposits. 61% of buildings on site class B (rock) exhibited none/minor damage, while 59% of buildings on site class D exhibited distributed or local damage, indicating an emerging trend of an increase in likelihood of damage with softer (deeper) sites. Six of the eight buildings with significant damage were located on site class D, with the remaining two located on Site Class C but very close to the boundary with site class D.

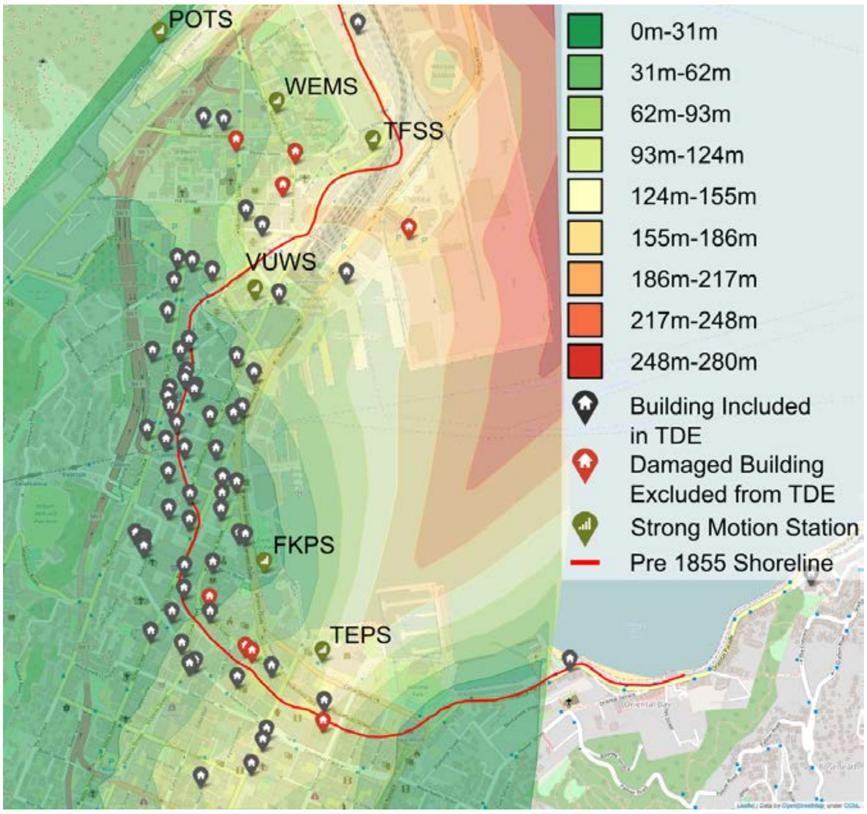
Compared to other locations, Wellington City currently has good soil classification information available to practitioners. It should however be recognised that the site class map in Figure 25 shows considerable uncertainty in the site class boundaries, given the limited amount of data available for the development of the map at the time. The observed relationship between damage and site class suggests an important need to better define these site classes (and soil depth) for the Wellington region. Pending further clarification of the boundaries between Site Classes C and D, and in the absence of site-specific investigations, a conservative approach should be adopted by practitioners.

There was little apparent relationship between foundation type and superstructure damage observed.

The varied effects on buildings supports the need to better understand the influence of basin-edge effects in the Wellington region as recommended in the Statistics House report.



(a) Site class



(b) Depth to bedrock

Figure 25: Map of (a) site class and (b) depth to bedrock with location of buildings[2]

[2] Site Class and depth to bedrock reference: Semmens, S., Perrin, N.D., Dellow, G., 2010, It's Our Fault – geological and geotechnical characterisation of Wellington City. GNS Science Consultancy Report 2010/176

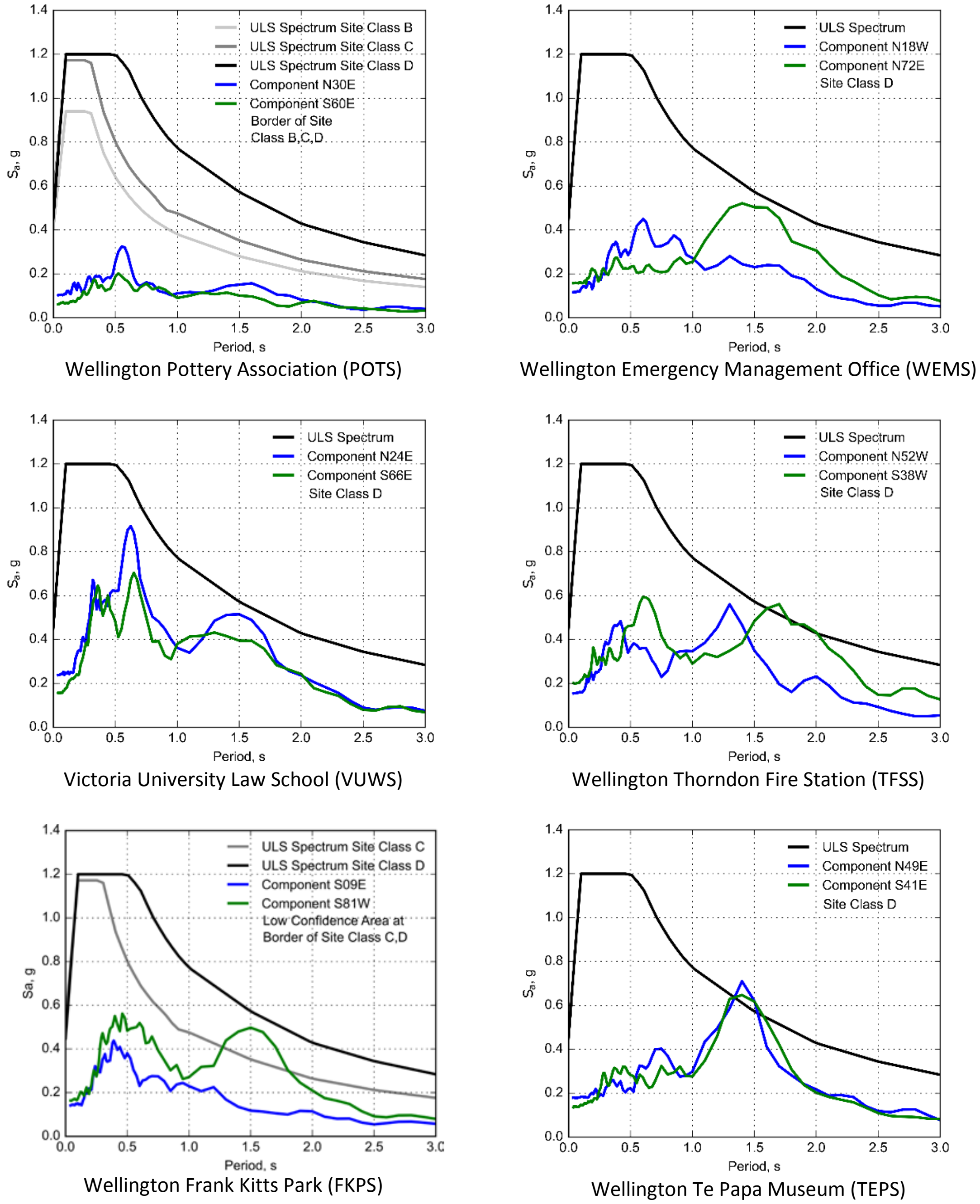


Figure 26: Response spectra for six ground motion recording stations in CBD shown in Figure 25

Figure 27: Relationship between damage extent and (a) site class and (b) reclaimed zone

5.5 Learnings for Post-earthquake Assessment Processes

5.5.1 Limitations of Rapid Building Assessments for Multi-storey Buildings

The objective of the rapid building assessment process is to provide an initial appraisal of the impact of any damage observed on the continued use of buildings following an earthquake, and to identify if more detailed engineering evaluation is required. When collected and analysed by a territorial authority in the more usual situation of a declared emergency, this information also provides a high level perspective of the scope and scale of impacts, and informs the processes to follow. While involving interior inspections of buildings, the Level 2 Rapid Building Assessments process is predominantly non-invasive, and they are not expected to identify all of the structural damage present.

The New Zealand rapid building assessment procedures are based on the US Applied Technology Council's established methodology, which include multi-storey buildings within their scope.

Of the 64 buildings reported on, a total of 57 included rapid assessment summaries following rapid inspections in the days following the earthquake. This comprised 37 Level 2 Earthquake Rapid Assessment forms from the MBIE *Rapid Building Usability Field Guide* and 13 letters written to owners or agents without the forms, and 7 where the rapid assessment was only briefly described in the TDE report.

Of the 37 Level 2 assessment forms, 33 recorded damage at the 'minor or none' level, which corresponds to a broad damage level rating of between 0 and 10% of the value of the building.

While only five of the 57 rapid assessment summaries had flagged some form of structural damage meeting critical damage state criteria, 24 had recommended further investigation. Of the 27 buildings where no further investigation was recommended in the Level 2 form or letter, structural damage (i.e. Critical Damage States) was subsequently identified in 11 buildings via the targeted damage evaluation inspections, with two cases of ***distributed*** frame and floor damage. This information is summarised in Figure 28 following.

This programme has subsequently demonstrated the value of invasive investigations that were targeted at hotspots, which in turn were informed by an engineering understanding of the building and how it was expected to perform. There is a need to review and reconsider guidance on triggers for more intrusive inspections of multi-storey buildings when it is apparent from early event spectra and reports of significant non-structural damage that they are likely to have experienced a significant proportion of their original design loading. This is particularly the case for buildings designed for high ductility, which results in a much lower threshold for inelastic response and associated deformation compatibility issues where precast floor systems are involved.

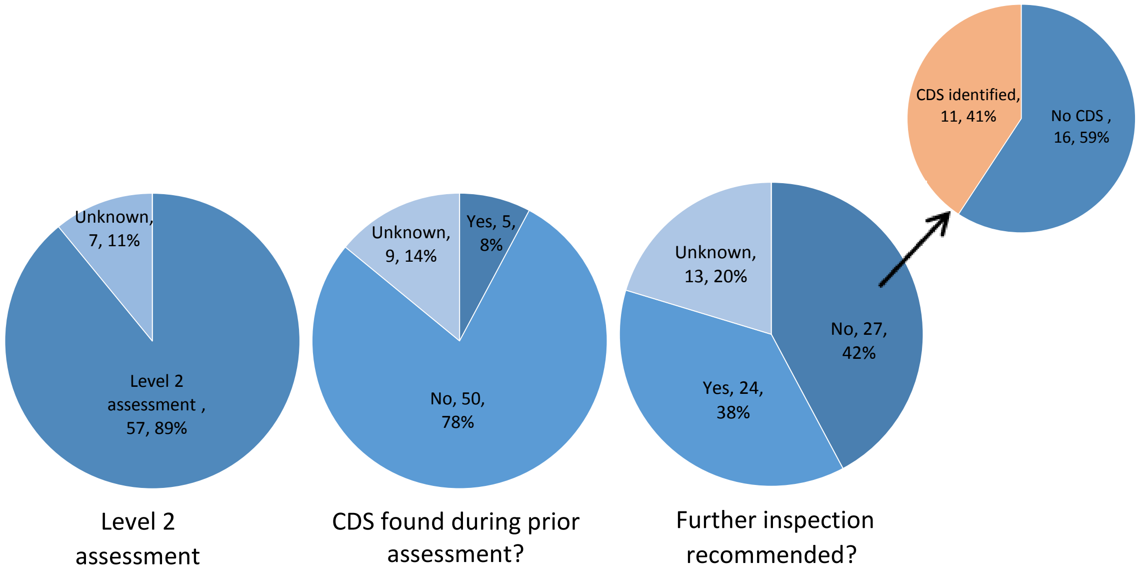


Figure 28: Level 2 assessment information

The more usual situation where these initial assessments are being undertaken for territorial authorities under a declared emergency operation creates additional challenges for multi-storey buildings that also need to be considered. In this situation for commercial buildings, the placarding operation is usually undertaken within a cordoned area by engineers operating on a voluntary basis on behalf of the Civil Defence Emergency Management Controller. Interior inspections are often not possible during this phase due to access restrictions for building owners and managers.

The arrangements for rapid assessments of multi-storey buildings should be revisited and updated, with a focus on the linkages with subsequent more detailed engineering evaluations. This should include how the damage information and extent of inspection is recorded on the rapid assessment forms. Criteria should be developed for when more invasive investigations may be required, acknowledging the time and cost implications, and when a targeted damage evaluation programme should be considered.

5.5.2 Alignment with Instrumentation

The Kaikoura earthquake resulted in varied demands on buildings throughout the Wellington CBD, some exceeding seismic design levels; however the extent of these demands were not well understood due to limited distribution of strong motion instruments in the CBD and mechanisms in place to access this data in a format useful for decision making. The nature of the building damage, concentrated generally in the precast floors, also meant that most of the damage was not immediately apparent after the earthquake and during Level 2 assessments, as noted above. More widespread instrumentation of CBD, both on the ground and in buildings, would enable better understanding of the seismic demands on buildings and the likely building response. With this knowledge, the immediate rapid building assessment processes can be more strategic and targeted with recognition of the particular characteristics of the event. This is especially important for long duration shaking with damage distributed throughout larger CBD buildings.

The current environment following the Kaikoura Earthquake is clearly supportive of increasing the level of instrumentation in buildings and on the ground across Wellington and other cities. There is also support for the establishment of a wider set of pre-earthquake indicator buildings – buildings across the range of structural types, heights and ages in the city, along with land features that can be quickly viewed in the hours following a significant earthquake to understand the extent and range of impacts. Having these buildings and land features instrumented is a key part of this, noting that this will involve instrumenting some older structures.

The *Smart Seismic Cities* programme, an effort initiated by QuakeCoRE in 2016, aims to augment any expansion of instrumentation with a database of building models for all buildings over 5 storeys. The models will be capable of representing the essential dynamic characteristics and the nonlinear response of the buildings. The combination of instrumentation and widespread building models will provide immediate insights on the performance of the building inventory after future events. This information can be used to prioritise building inspections, and, if a targeted assessment is deemed necessary, help identify the most appropriate list of buildings to received further assessments. The instrumentation and building models, combined with indicator buildings, will also be invaluable in the case of aftershocks to help decide if it is necessary to re-inspect the already damage building inventory.

5.5.3 The Need for Council to Have Access to Operationally Experienced Engineers

The response phase in following the Kaikoura earthquake involved a range of professional engineering inputs and collaborative processes operating in support of Wellington City Council. This included the establishment of the Council's Critical Buildings Team, and the Wellington Engineering Leadership Group. Established in the weeks following the Kaikoura Earthquake, this group represents an operational support model that should be followed after significant earthquakes affecting metropolitan areas.

The response of engineers in the first few hours of 14 November was however self-initiated on a voluntary basis. It is clear that Council needs to be able to quickly convene a pre-established panel of specialist advisers to form a view and advise on early stage actions, having due regard to event information from GeoNet and other instrumentation sources.

The need for such a panel will become even greater with the anticipated advances in the instrumentation of buildings and land features, if this information is to be utilised to its potential.

5.5.4 Community Resilience Focus of Post-earthquake Assessments

The initial focus of the rapid building assessment process undertaken by engineers and building control officials under the direction of the Civil Defence Emergency Management Controller is typically on CBD areas. This reflects the risk that significantly damaged commercial buildings can pose to the public, occupants and users of key access routes – whether due to their construction (eg unreinforced masonry buildings) or size (multi-storey buildings).

Establishing the nature, extent and location of damaged CBD buildings informs early-stage decision-making by both city/ district councils with respect to key access routes and individual agencies in terms of their operational bases.

There is however a growing awareness in Wellington of the importance of enabling residents to stay in their homes as part of community resilience planning. Placing greater emphasis on this aspect may lead to a different focus or prioritisation of rapid assessment processes. This requires specific planning, both prior to an earthquake and on the day of an earthquake, in conjunction with the other calibration considerations discussed above.

5.6 Research Utilising Information from this Programme

5.6.1 Informing the recovery from this earthquake

There is still more to be learned from the continuum of damage from this event in terms of both the *cause* and *significance* of some of the cracking observed to precast floors in multi-storey buildings. The information from this programme should be utilised further, especially the key linkage between the damage recorded to frame and floor elements and the global context of the building as a whole, including the ground shaking at the building with respect to site conditions and basin-edge effects.

Research is needed in support of the interim recommendations being developed by the industry on the assessment and retrofit of buildings with precast floors. Some of this research may come in parallel with the development of the interim guidance, while other research may follow as a means to provide validation of recommendations.

There is a strong need to better understand the shaking demands on the TDE buildings such that the observed damage can be linked to the actual shaking experienced by the buildings. Although limited ground motion stations are available, a close study of the ground conditions at the TDE building sites, and a further study of basin-edge effects as recommended in the Statistics House report, will enable better interpolation of the shaking between the stations.

There is also a particular need to understand the progression of damage to precast concrete floor systems under different levels of ground shaking, with a focus on the following specific areas:

1. Understand the cause of transverse cracking to units away from the supports
2. Understanding the gravity capacity of cracked units, both currently and in future major earthquakes
3. Understanding the diaphragm response and load path of floors with cracked units and topping

As an initial step, it is recommended that researchers should work in partnership with consultants to undertake more systematic access and viewing of hollowcore voids, in order to understand the nature and trajectory of transverse cracks. Opportunities for field testing of earthquake-damaged hollowcore units should also be identified.

In early April, funding was approved for a six-month research project to support the recovery from the Kaikoura Earthquake in relation to Wellington buildings. This funding will be applied to testing of damaged floor units and repairs. Testing will be prioritised to address the most important questions noted above: capacity of damaged floor units with cracks away from the supports and the validation of simple rapid repair techniques.

There is a need to share relevant information from this programme with practitioners who are actively working on the repair of damaged buildings. While some practitioners have seen several buildings with different levels of damage, most haven't seen the different building contexts in which damage has (and hasn't) occurred. This wider appreciation of the context of floor and frame damage is considered essential for the current phase of repair and retrofit specification.

Research is needed in support of standard retrofit details to provide for the gravity support of hollowcore and double tee units with transverse or web cracks respectively, and is also a priority. Many of the supplemental seating retrofits (steel angles or hollow sections) employed in buildings mat potentially be ineffective in providing support when transverse cracks form beyond the extended seating length. Rather than exclusively focusing on loss of support, retrofits solutions that mitigate against a range of possible failure mechanisms in precast concrete floors are required.

After every damaging earthquake the question naturally arises as to the residual capacity of damaged buildings; however, very little data exists to quantify this leading to considerable speculation on the part of engineers doing detailed assessments. To help quantify the residual capacity of damaged concrete buildings, damaged frame components (e.g. beams) from buildings being demolished should be extracted and tested in a laboratory. This would be unique data from which engineering models for residual capacity would be developed.

5.6.2 Informing planning for future earthquakes

Access to the building and damage information from this programme should be provided to other researchers upon completion of the current analysis phase to enable a wider understanding of the vulnerabilities and potential community impacts from future earthquakes, and to inform the development of appropriate mitigation strategies. Making this information available (suitably anonymised) is consistent with the wider life safety objectives of the emergency powers of the Civil Defence Emergency Management Amendment Act 2016.

This data is uniquely suited to identify relationships between earthquake demand and damage, leading to the development of fragility curves for typical New Zealand concrete buildings where precast floors are commonly found. Fragility curves (which define the probability of experiencing damage for a given shaking demand) are a key ingredient in any loss assessment study as used by insurance companies. Typically fragility curves used in New Zealand loss assessment studies are based on US studies for buildings with cast-in-place diaphragms, and hence ignore the importance of precast floor damage.

Furthermore, data collected from TDE buildings provides the research community with the unique opportunity to explore further the connection between building damage and decisions on buildings (e.g. closure), thereby informing future key decisions in terms of overall community resilience.

5.7 Other Issues Identified from this Programme

5.7.1 Regulatory Gaps and Uncertainties In Relation to Earthquake Repairs

The Building Act does not require repairs to be undertaken to floor or primary framing elements damaged in an earthquake (or other) event, irrespective of the level of damage. In many respects this can be regarded as a regulatory gap, along with other issues resulting from the exclusion of earthquake from the definition of a dangerous building in section 121 (1) (a) of the Building Act.

However once a decision is made to undertake any repairs, the requirements of section 112 of the Building Act (Alterations) must be met. Any such repairs constitute structural work, and will generally require a Building Consent. From a structural perspective, it should be noted that section 112 only requires that the building complies with the requirements of the building code to the same extent as immediately before the building work began, not prior to the earthquake that generated the damage being repaired.

The process of undertaking structural repairs under a Certificate of Acceptance approach, which sees documentation for urgent repairs being submitted subsequently was not followed consistently by all engineering practitioners, and would benefit from clearer guidance in a post-earthquake situation.

5.7.2 Limited Availability of Final Construction Documentation

The requirement of the Targeted Damage Evaluation guidelines for engineers to review the drawings to understand the structure prior to undertaking intrusive investigations has highlighted the limited access to drawings that reflect the actual construction details.

In the majority of cases, the drawings retrieved from Wellington City Council's archives were only the 'For Permit' or 'For Building Consent' drawings, and not the 'For Construction' sets. There can be a considerable difference between the drawings lodged for Council consent purposes and those finally issued to the building contractors.

While 'For Construction' drawings are typically held by the original design consultants, in most cases those practices have changed ownership, adding to the challenge in accessing them.

This is a particular issue for precast concrete floor systems, where the design and specification was undertaken by specialist sub-contractors, and shop drawings were produced. Accessing these shop drawings some decades later is typically difficult, and adds to the difficulty in assessing these floor systems.

6. Concluding Observations and Recommended Actions from the Targeted Assessment Programme

6.1 Programme Observations

The Targeted Assessment Programme undertaken by Wellington City Council has provided a basis for systematically evaluating the set of multi-storey buildings considered to have been most affected by the Kaikoura earthquake.

The overall objective of the targeted damage evaluation process was to identify the presence of critical damage states that could affect either local or global stability, and hence require restriction of the occupancy of part or all of a building. The process of undertaking these evaluations has highlighted many instances of damage to structural elements that were unlikely to have been identified without the systematic and intrusive investigations required under this programme.

This programme has addressed the first recommendation of the Statistics House investigation report in relation to the Wellington CBD – namely that buildings of a similar design to Statistics House be investigated as soon as possible. There is a high level of confidence that buildings within this programme have had careful engineering consideration, and that cases of significant damage have been identified. It is however understood that there are some multi-storey buildings with precast floors in the Wellington CBD not included in this programme that do have structural damage, and owners and engineers should be pro-active in undertaking more detailed inspections using the targeted damage evaluation guidelines prepared by NZSEE and SESOC. It is also understood that these Guidelines are being applied by some engineers to buildings with similar profiles in Hutt City.

In many cases of ***isolated*** or ***local*** damage for floor units identified from the Targeted Damage Assessment programme, remedial work has already been undertaken. For buildings with ***distributed*** or ***significant*** damage to floor systems and/or primary structural systems, more careful evaluation of the cause of the damage and appropriate remedial and retrofit measures is required.

The nature of the damage noted to primary frame elements within the core set of 64 buildings in this programme is generally unlikely to require urgent repairs. In some cases the extent of reduction of the capacity requires further consideration, noting that determining the criteria for establishing the residual capacity of structural elements that have experienced inelastic activity remains a national research priority.

While the focus of the Targeted Assessment Programme was on buildings most affected in this earthquake – ductile multi-storey buildings with precast floor systems – and there was only limited damage to other older forms of construction, it is essential that efforts be maintained to identify and address other forms of building structures vulnerable to earthquake shaking. Unstrengthened unreinforced masonry buildings remain highly susceptible to closer earthquakes with different forms of energy content, and medium and high-rise buildings from the 1950s to 1970s era of non-ductile concrete construction need careful assessment given the numbers of occupants involved.

6.2 Key Findings and Recommendations

The key findings from the Targeted Assessment Programme are summarised in this section, and specific recommendations for priority actions made where considered appropriate.

Damage and Remediation

This programme has identified a number of buildings with various levels of structural damage to precast concrete floors and primary structural elements following the Kaikoura Earthquake. This ranges from isolated and local damage through to damage that is more distributed throughout some buildings, and with varying degrees of severity. Some damage has also been found to precast concrete cladding panels and stairs. Most of the earthquake damage was recorded in ductile frame buildings with hollowcore flooring, and only in some buildings with double tee flooring units. There were relatively few instances of damage recorded in buildings with ribbed floors. The dominance of hollowcore floor systems in the set of buildings reported on is however acknowledged. Damage was concentrated in buildings constructed after 1982 when ductile systems started to become prevalent in Wellington. Moreover, most of the damage was concentrated in buildings with design ductility greater than 3.

In terms of primary structure, most of the damage recorded was to the beams of moment-resisting frames. Beam elongation was identified in at least eight buildings, predominantly affecting unrestrained corner columns that were moving away from the building with associated floor corner cracking. In most cases the extent of residual elongation was however minor, and none exhibited beam elongation of the extent reported in the Statistics House report.

In virtually all cases where damage was reported, recommendations for further investigation and remedial work provide clear directions for owners and agents to follow. Further research is however urgently needed to understand the progression of damage to precast concrete floor systems. For example, relatively few voids of the hollowcore units reported on had been inspected. Priority should also be given to quantifying the capacity of units cracked beyond the length of typical supplemental supports provided in past retrofits.

There is also a need for standard details to provide for the gravity support of hollowcore and double tee units with transverse or web cracks respectively, both generally and at the corners of buildings.

Recommendation 1: *Owners and managers of buildings in Wellington City with damage identified in targeted damage evaluation reports should follow through on the further investigations and repairs proposed in those reports, with appropriate further engineering input.*

Recommendation 2: *Experimental testing of damaged precast units is urgently needed. This should include more systematic access and viewing of hollowcore voids in order to understand the trajectory of transverse cracks.*

Recommendation 3: *A set of industry-agreed and experimentally verified standard details and corresponding performance objectives should be prepared for retrofitting precast concrete floor systems in ductile moment-resisting frame buildings. This is required urgently to assist work on both buildings with damage from this earthquake and undamaged buildings with precast floors.*

Geological and Geotechnical Influences

Almost two-thirds of buildings on site class B exhibited none or minor damage, while a comparable proportion of buildings on site class D exhibited local or distributed damage. This indicates an increase in likelihood of damage with softer sites with greater depth to bedrock. Six of the eight buildings with significant damage were located on site class D, with the remaining two located on Site Class C but very close to the boundary with site class D. There is however no apparent relationship with the damage and whether or not the building was located on reclaimed land.

Geotechnical and geophysical characterisation of Wellington deposits at an engineering level of detail can be provided through the field testing capabilities of QuakeCoRE. This should be integrated with the current GNS Science geologic models of the region and the existing data collated as part of the *It's Our Fault* project. To leverage off existing investigation data, engineering consultants and clients are encouraged to upload all historic site investigation data in the region into the NZ Geotechnical Database.

Recommendation 4: *Ground conditions across Wellington City and the region should be better defined through enhanced site characterisation for the purposes of both seismic assessment and design, and to enable better estimation of seismic demands on buildings after an event. Local input should also be provided to the national efforts to improve understanding of the influence of basin-edge effects in the Wellington region, as recommended in the Statistics House report.*

Seismic Assessment

Previous research along with the Canterbury, Cook Strait and Kaikoura earthquakes has established the vulnerabilities of precast concrete floor systems when subject to local and global displacements under strong ground shaking, and re-iterated the need to more carefully assess precast floor systems constructed prior to current codes. It should be noted that there have been significant improvements to the design and detailing of precast floor supports connections in recent design standards (e.g. NZS 3101:2006 (Amendment 2) and the draft amendment 3 due to be published). It is apparent that many previous seismic assessments of ductile frame buildings with precast concrete floor systems have not adequately taken account of the response of the floor system, and are likely to have over-estimated the overall performance of the building.

The interaction between ductile primary lateral load resisting elements and more brittle precast floor systems is complex, even for regular floor layouts. A precautionary approach therefore should be taken to rating existing ductile multi-storey buildings with precast concrete floors that have not been designed to current code requirements. It is understood that guidance on this is being prepared for incorporation into the revised national Seismic Assessment Guidelines for Existing Buildings in accordance with Recommendation 2 from the Statistics House investigation report. It is essential that this guidance covers hollowcore, double tee, rib and timber infill and flat slab systems, and that an interim version of this guidance be produced as soon as practicable.

Recommendation 5: *Interim guidance for practitioners on rating existing precast concrete floor systems in ductile multi-storey buildings is needed with some urgency (as per Recommendation 2 of the MBIE Statistics House report). It is recommended that a precautionary approach be taken for assessing such buildings not designed to current code requirements*.

Post-earthquake Assessment Processes and Building Instrumentation

The Targeted Damage Evaluation reports have identified that the Level 2 Rapid Building Assessments were not necessarily identifying all of the structural damage present in some buildings. This programme has subsequently demonstrated the value of invasive investigations that were targeted at hotspots, which in turn were informed by an engineering understanding of the building and how it was expected to perform.

Of the 27 buildings where no further investigation was recommended from the Level 2 assessment, structural damage (i.e. Critical Damage States) was subsequently identified in 11 of these buildings via the targeted damage evaluation inspections, including two cases of ***distributed*** frame and floor damage.

The arrangements for rapid assessments of multi-storey buildings should therefore be revisited and updated, with a focus on the linkages with subsequent more detailed engineering evaluations. Criteria should be developed for when more intrusive investigations may be required - for example, when it early event spectra and reports of significant non-structural damage indicate that some ductile multi-storey buildings are likely to have experienced a significant proportion of their original design loading. Specific inspection procedures for different building types to identify potentially hidden damage may be necessary.

Recommendation 6: *The learnings from this programme should inform an update of the arrangements for post-earthquake rapid assessments of multi-storey buildings, including criteria for when invasive investigations are required.*

The extent of the varied seismic demands on buildings throughout the Wellington CBD, some exceeding seismic design levels, was not initially well understood due to limited distribution of strong motions instruments in the CBD. More widespread instrumentation across the CBD, both on the ground and in buildings, would enable better understanding of the seismic demands on buildings and the likely building response. With this knowledge, and immediate access to building drawings, the initial rapid building assessment processes can be strategic and targeted, taking into account the particular characteristics of the event. This is especially important for long duration shaking with damage distributed throughout larger CBD buildings.

There is also support for the establishment of a wider set of pre-earthquake indicator buildings – buildings across the range of structural types, heights and ages in the city, along with land features that can be quickly viewed in the hours following a significant earthquake to establish an early appreciation of the nature and extent of impacts. Having these buildings and land features instrumented is a key part of this, noting that this involves instrumenting some older structures. Access to building drawings for such indicator buildings and other significant structures immediately after an event is also essential.

Recommendation 7: *Wellington City Council and GeoNet should support expanded instrumentation across the Wellington CBD, both on the ground and in buildings, to rapidly provide information on the shaking demands and likely impacts rapidly after an event. Instrumentation needs to be coupled with a better understanding of the structural characteristics of the building inventory and rapid access to building drawings.*

If the information from expanded instrumentation of buildings and land features is to be utilised to its potential, there is a need to be able to quickly convene a pre-established specialist operational panel to form a view and advise on early stage actions, having due regard to event information from GeoNet and other instrumentation sources.

Recommendation 8: *Wellington City Council, in conjunction with the Wellington Region Emergency Management Office and the Ministry of Business, Innovation and Employment, should establish a specialist operational panel to utilise event information from GeoNet and other instrumentation sources and to provide strategic oversight to rapid building assessment processes.*

Availability of Information from this Programme

The data from the Targeted Assessment Programme should be used to enable a wider understanding of the vulnerabilities and potential community impacts from future earthquakes, and to inform the development of appropriate mitigation strategies. This data is uniquely suited to identify relationships between earthquake demand and damage, leading to the development of fragility curves for typical New Zealand concrete buildings where precast floors are commonly found.

Making this information available is consistent with the wider life safety objectives of the emergency powers of the Civil Defence Emergency Management Amendment Act 2016.

Recommendation 9: *Wellington City Council should provide access to the building and damage information from this programme (suitably anonymised) to other researchers when the current analysis phase is complete, within the current constraints of the Civil Defence Emergency Management Act as amended in November 2016.*

Work in relation to Recommendations 3 and 5 should be undertaken in conjunction with other industry efforts to address Recommendation 2 of the MBIE Statistics House report (*Notify the industry about issues with existing buildings and precast floor systems and frames that may be affected by beam elongation*). It is also important that the philosophies and performance objectives of assessing and retrofitting existing precast concrete floor systems and the design of new systems are aligned together (Recommendation 3 of the Statistics House report). Similar comments apply to further work on basin-edge effects and the impact of duration of shaking (Recommendation 4 of the Statistics House report).

Some of the above recommendations also link back to and build upon recommendations from the Canterbury Earthquakes Royal Commission where further work is warranted. Relevant Royal Commission recommendations include:

- *Recommendation 61 – ensuring adequate ductility to sustain the load path where mesh has been used to transfer diaphragm forces*
- *Recommendation 110 – the connections between floors acting as diaphragms and lateral force resisting elements be examined*
- *Recommendation 138 – the indicator building model should be incorporated into New Zealand's building safety evaluation process*
- *Recommendation 148 – territorial authority building records should be electronically recorded and stored and available off-site*

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