Canterbury Earthquake Sequence: Detailed Engineering Evaluation of Commercial Buildings

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SUMMARY:
The Canterbury earthquake sequence has caused severe damage through much of the city, both in the residential areas comprising mostly the eastern suburbs, and also in the CBD. Since the earthquake, an Engineering Advisory Group has been assembled, now working under the Department of Building and Housing. A primary role of the commercial workstream of the advisory group has been to develop detailed engineering evaluation procedures and guidelines for assessing damaged buildings. These guidelines augment current methods for assessment of undamaged existing buildings. Particular attention has been paid to the identification and assessment of key vulnerabilities that could lead to collapse. Through the assessment and reporting process, a significant volume of data is being gathered on building types, performance and damage. This data is being assembled over time into a single database that will provide a valuable research tool, as well as to support future evaluations and planning.

Keywords: Canterbury earthquakes, building assessment, vulnerabilities, database

1. INTRODUCTION

1.1 The Earthquakes

The first of the Canterbury earthquakes struck at 4:35am on September 4th, 2010. Centred near Darfield, approximately 40km to the west of Christchurch, the M7.1 earthquake caused moderate levels of damage in the city. The epicentre is marked by the green star in Figure 1 below. Maximum shaking intensity of MM9 was observed, but the most severe shaking was in less populated areas.

The most severe damage in the city was to older unreinforced masonry (URM) buildings. There were no major collapses, but many URM buildings were severely damaged, and there were a considerable number of such buildings that lost parapets or other ornamentation into the street. Fortunately, there were few people in the streets at that time and so there was no loss of life. Had it been during the daytime, the outcome may have been very different.

In addition to the damage to the URMs, there was low level damage to many modern structures. This damage was generally not considered critical, but there was considerable disruption caused to commerce. The main concern however was with the liquefaction in many of the residential suburbs, causing widespread damage. Many houses were uninhabitable, and there was widespread disruption to services.

Immediately following the September 4th earthquake, there continued what seemed to be a reasonably typical aftershock sequence. However, a further pointer of what was to come arrived in the form of a M4.9 earthquake at mid-morning on December 26th 2010. This event was centred beneath the south-east fringe of the city at 5km depth. Although a relatively small magnitude event, the close proximity caused reasonably intense shaking in the central city, while there were many people in the streets. Once again, there was considerable damage to URMs, but little new damage to other buildings.

Five months after the September 4th event, the city was in full recovery mode. Many repairs were well underway, either temporary stabilisation or permanent repairs. A significant number of URMs were closed and cordoned off. Then, on February 22nd 2011, the most damaging earthquake of the sequence struck. The main M6.3 shock (the red star in Figure 1 below) of 12:51pm was centred near Lyttleton, within 10km of the centre of Christchurch, and at only 5km depth. It was followed by four further shocks of M5 or greater within the next four hours, along with numerous smaller events. Shaking intensities of MM9 were felt across the city, with some of the highest ever recorded ground accelerations, in excess of 1.75g lateral and 2.2g vertical in the Port Hills, the region between Christchurch City and Lyttelton.

Since the February 22nd earthquake, there have been another 20 events of M5 or greater, notably on June 13th 2011 (the blue star), and December 23rd 2011 (the pink star). Although not as severe in the central city as the Feb 22nd event, the June 13th events in particular caused further damage to the east of the city, including severe rockfall in the seaside suburbs of Redcliffs and Sumner, and still more liquefaction.

In total at time of writing, there have been over 10,000 earthquakes since the first event of September 4th 2010. Of these, 40 have been in excess of M5, with extensive damage at varying levels spread over the five major events. Figure 1 below illustrates the overall spread of the events, with reference to the major events.

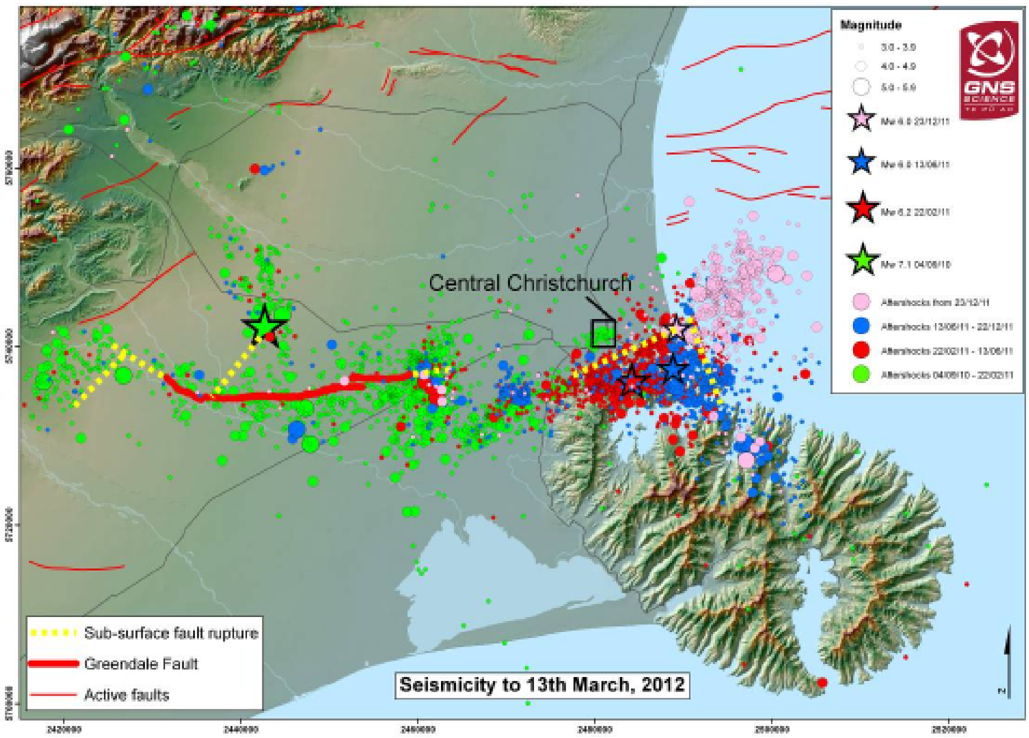

Figure 1. Earthquakes recorded to March 13th 2012 (*from GNS Science*)

1.2 Summary of Damage

The most damaging event was the Feb 22nd 2011 earthquake. Damage in the City was extreme, with intensity MM9 shaking throughout the CBD. Two large concrete buildings and a number of masonry buildings collapsed. There were numerous out-of-plane parapet and wall failures in URMs, with many of the central city streets rendered impassable due to bricks and other debris. Services were out over most of the eastern and central city and the liquefaction was more severe than in September.

The death toll eventually rose to 185, with the 115 in one building, the CTV tower, which collapsed and then burned. Another 18 people died in the PGC building collapse, with a further 42 deaths from building failure, all but one from URMs. It is of significance that 37 of the 42 were not in the building that failed, being either in the adjacent building, or in the street. Five people were killed by rockfall in or near the Port Hills. A detailed review of the performance of the buildings that failed was commissioned by the Department of Building and Housing shortly after the event.

Fortunately there were no further deaths in the subsequent events, although the June 13th 2011 earthquakes led to some near misses, with several engineers and contractors in the act of inspecting already damaged buildings when a second larger earthquake occurred just over an hour after the first.

In aggregate the liquefaction has forced the abandonment of some areas of low-lying land with approximately 7,000 homes being bought back by the Government. These are the worst of the liquefiable areas, generally alongside watercourses where the land is also subject to lateral spread. The worst of these areas have lost up to 1500mm of elevation due to a combination of liquefaction ejecta (removed) and tectonic movement, leading to concerns of flooding. Conversely, areas of the Port Hills have risen up to 500mm.

Well over 100,000 homes have suffered significant damage, with approximately 90,000 to be repaired by EQC (under the NZ Government captive insurance scheme) and at least 12,000 further homes that have suffered damage over the cap limit for EQC, that will have to be repaired by private insurers. Over 9,000 people are estimated to have left the city (of a total population of about 350,000), although some have settled nearby.

In the CBD, it is estimated that up to 1,200 buildings will have been demolished, including many of the taller buildings. The central city has been cordoned off from the general public since shortly after the earthquake of February 22nd 2011, while demolition is completed and the repairs to the remaining buildings are initiated.

The total cost of the earthquake sequence is currently estimated as being in excess of NZ$30B (US$24B). The extent of demolition may have been greater than might have been expected in other countries, due to New Zealand's unusually high levels of insurance cover (approximately 80% of all buildings were covered, compared to more typical levels of 20% or less over much of the rest of the world). However, although this will result in considerable external capital being brought into the city, the cost to the city and the country as a whole has been high, and the ongoing disruption will take years to recover.

2. ENGINEERING ADVISORY GROUP

Following the September 4th 2010 earthquake, the Engineering Advisory Group (EAG) was assembled, initially by the Earthquake Commission (EQC). This group comprised leading consulting engineers (structural and geotechnical) and researchers drawn from industry, and with representation of the technical societies, comprising the NZ Society for Earthquake Engineering, the New Zealand Structural Engineering Society, and the New Zealand Geotechnical Society. Overall responsibility for the group was subsequently transferred to the Department of Building and Housing. The main purpose of the group is to determine solutions for technical issues that emerged as a consequence of the earthquake.

The EAG's initial brief was to develop practical measures for assessment and improvement of foundations for residential housing following the September 4th earthquake. Following the February 22nd 2011 event, the scope and membership of the EAG was broadened to take into account the wider scope of damage, and emerging needs of the commercial sector. The group was split into two, and then later three streams: Residential, Commercial and Geotechnical. Once again, the additional members were drawn from industry, The balance of this paper focuses on the activities of the Commercial workstream of the EAG.

3. BUILDING REVIEW

This section describes building review activities after the February 22nd 2011 earthquake, which was the most damaging to commercial buildings, particularly in the CBD, by a considerable margin. Although there have been damaging earthquakes since that event, the damage has generally been restricted to those buildings already compromised by the February 22nd event.

3.1 State of Emergency Phase

Shortly after the Feb 22nd earthquake, a national state of emergency was declared and Civil Defence took effective control of the city. Emergency rescues were underway all over the city, initially by members of the public, but then by the Fire Service as they mobilised. Urban Search and Rescue (USAR) teams from all over the country were flown into the city and took over coordination of the rescue operations. They were joined within days by international USAR teams from countries including Australia, Britain, China, Japan, Singapore, Taiwan and the US.

While the search and rescue operations were proceeding, Civil Defence and the local councils assembled teams of engineers, many of them volunteers, who began building assessment operations. Rapid assessments were undertaken at two levels, using the NZ Earthquake Engineering Society's Building Safety Evaluation guidelines (NZSEE 2009). Teams of two or three engineers were deployed over city blocks to complete rapid evaluations and placarding of all buildings in the CBD and in the worst affected suburbs.

A Level 1 rapid assessment involves a brief external visual inspection of a building. The Level 1 assessments were a useful tool for Civil Defence co-ordinators in gaining a broad understanding of the scale of the event. However, they were never designed or intended to determine the relative safety of individual buildings for public access. Indeed they proved of little use in this regard due to the extent of possible internal damage typically being unobservable from the exterior of a building. Through the Level 1 assessments, buildings were prioritised for further assessment or possibly demolition, where the buildings were too dangerous to approach.

Level 2 rapid assessments were also relatively brief but, importantly, required access to the interior of the building for more extensive observations. However, these assessments typically do not involve the removal of wall linings, unless there is specific cause for concern. Level 2 rapid assessments were typically used to assign placards defining occupation restrictions prior to lifting the state of emergency.

Three forms of placard were used, similar to established international practice, but slightly modified by the NZSEE Building Safety Evaluation guidelines (NZSEE 2009), and further amended after the September earthquake. These were:

- Unsafe (Red). Assigned to buildings that were considered dangerous, and should only be accessed by engineers and contractors doing assessment, make safe, or demolition work, subject to appropriate safety plans being put in place
- Restricted Use (Yellow). Assigned to buildings with significant hazards, but which could be accessed for limited purposes, such as retrieving possessions, or essential work under appropriate safety procedures.
- Inspected (Green). Assigned to buildings for which no significant hazard was identified that should limit use in the short term, but which would require further assessment

There had already been issues encountered with the wording of the placards and the understanding of the public, after they were used for the first time following the September 4th 2010 earthquake. The most critical issues were the continued use of the term 'safe' for green placards, and the lack of urgency over detailed engineering evaluations, which should have followed the initial placarding. However, it should be noted that the overall magnitude of the task of detailed evaluations was far greater than could have been completed between September 4th and February 22nd.

2.2 Post State of Emergency Phase

After the September 4th 2010 event, it had been apparent to many observers that there were gaps in both legislation and policy that needed to be filled. The Building Act (2004) set requirements for the design of new buildings, and for the assessment of existing buildings for earthquake vulnerability. Local regulations covered in more detail the requirements for upgrade of buildings which failed to meet the minimum capacity requirements of the Act, i.e. were considered earthquake prone. However, neither contained any provisions for dealing with damaged structures.

Following the September 4th 2010 earthquake, building owners and users largely ignored (or at least downplayed) the need to have further detailed evaluation of their buildings completed, despite warnings on the placards that such evaluations were needed. Compounding this, there were no effective guidelines readily available for engineers to determine an appropriate level of evaluation required. Although most engineers had been very busy in the interim, documenting and overseeing repairs, many buildings had consequently not had thorough reviews by the time of the February 22nd event.

The first activity of the Commercial workstream of the EAG was to develop guidelines for the assessment of buildings, known as the Detailed Engineering Evaluation (DEE) Guidelines (EAG 2011). This required a review of existing guidelines and Standards, and consideration of the building failures that had been observed in the earthquakes. The documents are presented in three parts, as follows:

- Part 1: Background. Not yet (1/5/2012) released for public use, this document contains briefing material and discussion of background issues such as seismicity and risk.

- Part 2: Procedures. This was the first part published and describes a consistent evaluation process, described in more detail below

- Part 3: Technical Guidance. This is being published gradually in sections, as it is written. This series of documents is intended to provide detailed guidance on the evaluation of damaged buildings, by type, with reference to existing documents, where possible.

The DEE guidelines are being published initially in draft form through the Structural Engineering Society (SESOC), in the interests of expediency and in order to provide the advice to engineers as soon as possible. The longer term intention is to have the documents updated and approved for use over the whole country, fully endorsed (and published) by the Department of Building and Housing.

3. DETAILED ENGINEERING EVALUATION GUIDELINES

3.1 Existing Assessment Methods

The review of existing buildings in New Zealand has typically been aimed at developing an assessment of a building's capacity in terms of an equivalent new building, expressed as % New Building Standard (%NBS). That is, the capacity of a building expressed as a percentage of the capacity of the same building if designed to current standards.

A commonly used assessment procedure for existing buildings is the Initial Evaluation Procedure (IEP), developed by the NZSEE, and documented in their guidelines - *Assessment and Improvement of the Structural Performance of Buildings in Earthquakes* (NZSEE 2006), commonly known as the Red Book. This is generally a qualitative procedure and is intended primarily as a filter to determine which buildings may be potentially earthquake prone, thereby prioritising buildings for more detailed assessment. It has been successfully deployed in areas such as Wellington, NZ for that purpose.

Such more detailed assessment have generally otherwise followed the remainder of the Red Book, which covers a variety of methods for building assessment according to material type and structural form. A more comprehensive document, *Assessment and Improvement of Unreinforced Masonry Buildings for Earthquake Resistance* (NZSEE 2011), has also been published for detailed evaluation of URMs, following research at the University of Auckland. Both documents are currently under revision.

The threshold capacity (by law) below which a building would be considered earthquake prone, is 33%NBS. A building that fails to exceed that capacity can be required by the local authority to be upgraded, over an agreed timeframe (typically between 10 and 30 years). (Note that after the September 2010 earthquake, the Christchurch City Council amended its earthquake prone building policy to require such buildings to be upgraded to a target of 67%NBS, potentially in conjunction with repairs. These requirements remain under challenge by insurers).

The methods outlined above were developed for existing, undamaged buildings and were hastily adapted for application to damaged buildings. A more focused methodology was required to provide engineers with a consistent evaluation procedure.

3.2 Vulnerability Assessment

The observed building performance during aftershocks highlighted the need to identify and address key vulnerabilities of buildings, particularly with the threat of heightened seismic activity in the medium term. These are vulnerabilities that may trigger significant failure leading to the potential for global or partial collapse in the event of earthquakes only marginally larger than the assessment level. The EAG's activity in this regard was to develop an assessment methodology that would identify and highlight where the key vulnerabilities (termed Critical Structural Weaknesses (CSWs)) might exist.

The Initial Evaluation Procedure evaluates a range of CSWs, but as a high level qualitative method, these may be considered 'global' CSWs. The EAG was concerned at a more detailed level, considering for example elements such as stairs with inadequate seating, inadequate diaphragm collector elements and gravity columns with inadequate confinement to accommodate imposed lateral drift demand. All of these had contributed significantly to building failure in the February 22nd event.

3.3 Detailed Engineering Evaluation Procedure

It had been recognised that the rapid building safety evaluation process used during the state of emergency was effective in establishing overall levels of damage in buildings, but did not lead assessors to consider the significance of damage, and nor did it require assessors to link on-site reviews to potential key vulnerabilities. Consequently the EAG proposed a different approach, in two parts, according to need. (A flowchart describing the overall DEE procedure is presented below in Figure 3).

3.3.1 Qualitative Assessment

The first part of the Detailed Engineering Evaluation Procedure is the *Qualitative Assessment*. A key requirement here is that the assessing engineer must develop an understanding of the structure and its likely behaviour (preferably prior to site investigation) in order to verify whether the critical elements on the load path have suffered damage. In order to do this, the engineer would have to source any existing documentation and, taking note of the buildings age, construction type and form, develop an inspection procedure specific to the building. Key elements should be identified and exposed for inspection. An iterative process may be required if observations of performance did not match the engineer's expectation.

Once all damage has been reviewed and a comprehensive understanding of the building's performance has been reached, an assessment of the capacity of the building can be made. Under the Qualitative Assessment, an IEP may be considered adequate to confirm if a building is not earthquake prone, although for buildings that have less than 33%NBS capacity assigned under the IEP, further review will be necessary eventually. For more modern or undamaged buildings, a simple assessment of current capacity by comparison between current code and the code at time of design is considered acceptable in many cases. Note that the seismic hazard factor, Z, for Christchurch was increased in May 2011 from Z=0.22 to Z=0.3, so a building design to current code requirements immediately prior to the earthquake would have 73%NBS on a comparative basis.

The Qualitative Procedure is summarised in flowchart form below in Figure 2.

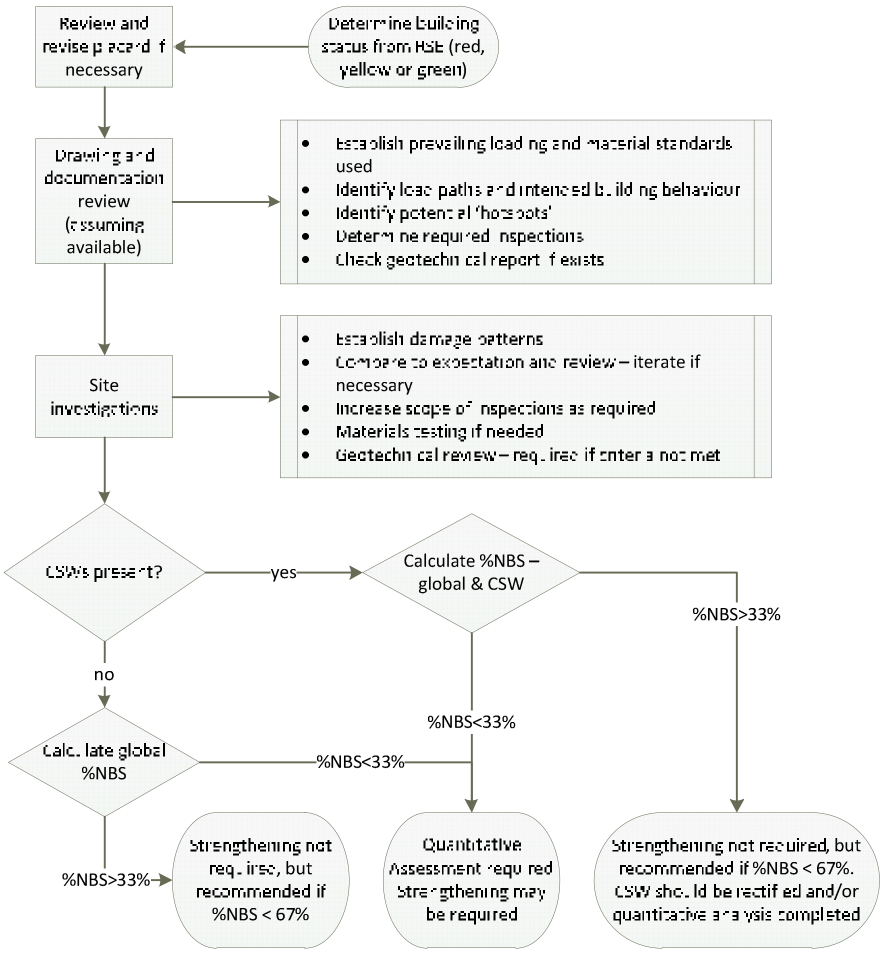

Figure 2. Qualitative Assessment procedure (from DEE Guidelines)

The intention is that those buildings which have no significant structural damage, or those that exceed the earthquake prone threshold would be considered suitable for use with no further assessment, although more analysis may be required before a building consent application could be made to complete building repairs or upgrading.

3.3.2 Quantitative Assessment

For buildings requiring further evaluation after the completion of the qualitative assessment, a *Quantitative Assessment* is required. Generally it is possible to use existing assessment methods such as offered in the Red Book, but additional consideration of the impact of observed damage is required. There were several matters requiring particular attention, as outlined in the sections below.

3.3.3 Critical Structural Weaknesses (CSWs)

For the purposes of this assessment, a CSW could be defined as an element, the failure of which could lead to premature full or partial collapse, or loss of a significant safety feature. Examples are noted in section 3.2 above. Although it is recognized that all buildings have a limit to their capacity, the existence of such a key vulnerability should give greater concern over the life safety performance of a building than the overall capacity of the building. This is because ductile forms of failure give greater warning to occupants and should rarely suffer brittle collapse.

When designing to the NZ Building Code, a building's ability to resist earthquakes larger than that designed for is implicitly satisfied when designers meet the 'deemed to comply' requirements of the various material Standards produced by Standards NZ. In this way, although it is not explicitly checked, buildings should be able to resist earthquakes producing actions 1.5 to 1.8 times larger than the design level.

For many older buildings, this same margin may not exist, either because it was never implicitly covered in the Standards of the day, or because the deemed to comply provisions have since been upgraded to a greater level. This was considered by the EAG, and a simple modification factor, K_d was introduced for calculation of capacities of such elements, such that:

$$\%NBS_{element} = \frac{capacity}{K_d \times demand}, \text{ where } K_d = 2 \text{ for most elements.}$$

The overall reported capacity of the building is then the lesser of the overall building capacity, or the lowest modified capacity of any CSWs.

More detailed analysis could be used in accordance with current materials standards, possibly using methods such as non-linear time history analysis in order to develop a more refined assessment of the vulnerabilities. However the approach outlined above was intended to quickly identify CSWs, and to encourage the mitigation of these.

3.3.4 Low Cycle Fatigue and Impact on Future Building Performance

An issue that is still being researched is the lack of correlation between observed behaviour and that expected after years of laboratory testing of concrete specimens. Both reinforced concrete shear walls and reinforced concrete moment frames commonly exhibited only a few large cracks, compared to expectations of well distributed 'fan-cracking' patterns in hinge regions. This in turn led to concerns over the impact on the reinforcement. This was further highlighted when fractured reinforcing bars were discovered in what had appeared to be only hairline flexural cracks in walls, with little or no other cracking evident.

Early testing performed on the reinforcement in these zones (over a range of approximately 50 buildings so far, using both destructive and non-destructive testing) has shown elevated levels of strain-hardening, with little yield penetration beyond the crack, typically in the region of $0.5d_b$ to $1.0d_b$ in most cases. This indicated that, in many cases, simple epoxy repairs of cracks (such as recommended in FEMA306 (1998)) may not be appropriate.

In order to provide engineers with more guidance on the assessment of cracks in potential plastic hinge regions in shear walls, a direct displacement based assessment methodology was adapted for shear wall structures (and published in the Part 3 guidelines). Following a simple displacement based assessment process, averaged displacement spectra from the February 22nd event are used along with observations of actual crack patterns, to provide an estimate of the strain history of the bars. In this way, engineers may determine a course of action, which may include further testing, or replacement of reinforcement.

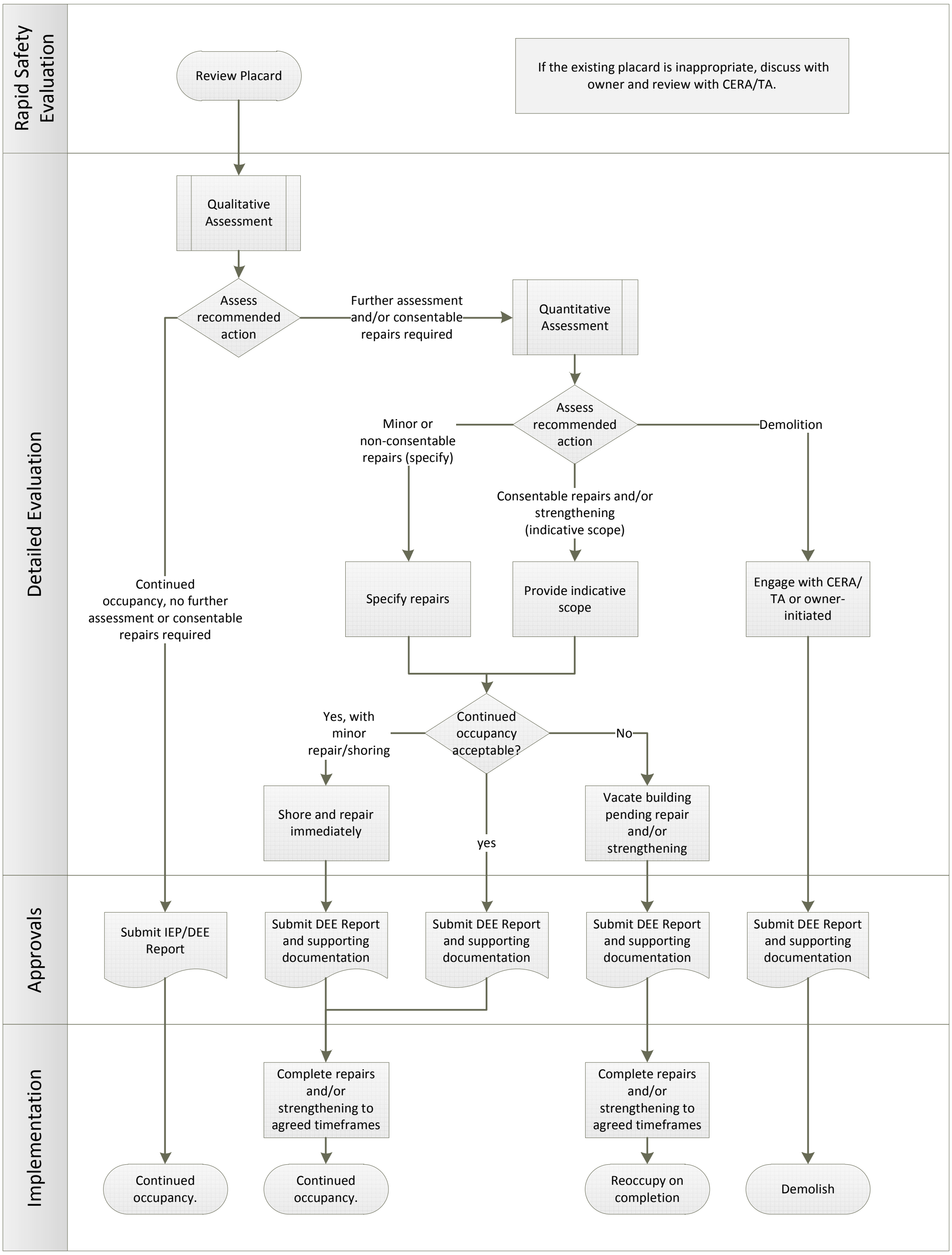

Figure 3. Overall Assessment procedure (from DEE Guidelines)

4. BUILDING DATABASE

The Canterbury earthquakes have provided a unique opportunity to learn from a large sample of both timber framed residential structures and reinforced concrete structures. The latter are subject to significant review under the Detailed Engineering Evaluation procedures, which have been adopted by the Canterbury Earthquakes Recovery Agency (CERA) as a mandated requirement for building owners.

In order to make the management of the review process simpler, and to help capture the data being generated, a Standardised Report Form (SRF) has been developed. Spreadsheet based, all data fields to be captured are named, in order to enable a simple data extraction process, into a single database.

It is intended that this database will be made available over time to researchers as well as the local council as the basis of a comprehensive building database. If successful, this programme could be extended over further areas of New Zealand. The data contained in the database has uses beyond research, potentially assisting future earthquake assessments by providing key information to assessors in a form that could be downloaded to review teams prior to Level 1 or Level 2 assessments.

5. CONCLUSIONS

Although the EAG is still progressing the Detailed Engineering Evaluation Guidelines, there has been significant uptake by the engineering community, supported by CERA and the Department of Building and Housing. The process of dissemination of the information being produced by the EAG has been semi-formal, through presentations to the local engineering societies and by email notifications, reflecting the need to make information available as soon as possible by whatever means available. When time permits, the guidelines are to be completed and formalised into methodologies that will sit alongside other design and assessment guides of undamaged buildings.

The information being generated by the evaluation process will be a valuable platform for future research and assessment, and has the potential to add significantly to the knowledge of the City Council of the overall building stock in Christchurch, and beyond to the extent that it is adopted through the country.

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