RUTHERFORD & CHEKENE Consulting Engineers • Structural Geotechnical
55 Second Street Suite 600 San Francisco CA 94105 • TEL 415 568 4400 FAX 415 618 0684

September 30, 2011

Justine Gilliland
Executive Director
Canterbury Earthquakes Royal Commission
Unit 15 Barry Hogan Pl, Addington
Christchurch, New Zealand

2011-092S

Subject: **Review of the Report Entitled *The Performance of Unreinforced Masonry Buildings in the 2010/11 Canterbury Earthquake Swarm***

Dear Ms. Gilliland:

In accordance with our agreement with the Royal Commission of Inquiry into Building Failure Caused by the Canterbury Earthquake (the Commission), I am pleased to submit this letter summarizing my review of the August, 2011 *Report to the Royal Commission of Inquiry: The Performance of Unreinforced Masonry Buildings in the 2010/2011 Canterbury Earthquake Swarm* by Professors Jason Ingham and Michael Griffith.

PURPOSE AND SCOPE OF REVIEW

The URM report by Professors Ingham and Griffith is intended to provide an overview of the architectural and structural characteristics of New Zealand's URM building stock, its seismic vulnerabilities, the performance observed in past earthquakes with a focus on the Canterbury earthquakes, and typical seismic rehabilitation techniques and associated costs. The report also makes a series of public policy recommendations involving mitigation of the seismic hazards posed by this class of buildings.

My review of the URM report is intended to provide some international perspective and place the report findings and recommendations in the context of how seismic evaluation and rehabilitation of URM buildings has been addressed in the United States.

My own background is as a practicing structural engineer and one of the principals of the structural and geotechnical engineering firm of Rutherford & Chekene in San Francisco. I have been involved in the design of new buildings and the seismic rehabilitation of existing buildings for over 20 years in the United States. A particular focus has been on URM buildings, including related earthquake reconnaissance, loss estimation, applied research, guideline development, and technology transfer of advice to practicing engineers. Although I led a reconnaissance trip by the

Applied Technology Council to Christchurch earlier this summer, I do not have consulting experience in New Zealand with URM building evaluation and rehabilitation or cost estimation.

In the review below, general comments on significant issues are provided first, then a set of recommendations, and finally additional comments on specific text in the report organized by the sections of the report. An appendix is provided with an annotated bibliography of selected references from the United States on URM building rehabilitation techniques, model codes, cost and loss estimates, and policy summaries. These resources may be helpful to the Commission.

General Comments

The following are general comments on issues of greater significance.

1. *Audience, Purpose, and Scope:* Section 1.1 states "The purpose of this report is to provide a resource, both for the members of the Royal Commission of Inquiry and for other parties wishing to make a submission to the Commission when hearings begin." This is potentially a broad audience that includes both those with technical knowledge and interested lay persons. The information in the report and the level of detail in the writing are suitable for such a broad audience. If a more technical audience of engineers is intended, then greater detail and specificity would be desirable. The purpose of the report to "provide a resource" is rather vague. My understanding is the Commission will use the report, review comments, submissions, planned hearings, and other information gathering activities to help it formulate potential recommendations on addressing the seismic hazards of URM buildings. The URM report will serve as a valuable component in this effort. I hope the review comments below and associated recommendations are helpful as well. Section 1.1 ends with a detailed list of nine items to be covered in the scope of the report. In general, there is information on each of these items within the report. Making policy recommendations is not one of the items listed in the Section 1.1 scope, yet Section 7 of the report provides a series of recommendations with significant financial and public policy implications. These are discussed in detail below.

2. *Types of URM Buildings:* Unreinforced masonry (URM) buildings are typically subdivided into distinctly different structural types. URM bearing wall buildings are those that have masonry walls that serve as gravity load-carrying elements. In the building stock of developed countries, this type of building is typically considered to be the most hazardous class of buildings. URM infill buildings are those that have a concrete or steel frame that provides gravity support for the floors and roofs; after the frame is constructed, it is infilled with URM material. Confined masonry buildings are those where the masonry is erected first, voids are left for columns, the voids are reinforced with reinforcing steel, and then concrete is poured into the voids as well as horizontally at the floor levels. Confined masonry is very common in many parts of the

world, but it is not typically found in the United States. URM infill and confined masonry construction generally perform better than URM bearing wall construction. Finally, there are buildings with URM veneer over other structural materials, typically wood. This is common in residential construction. New Zealand has all of these types of URM construction. The report does not clearly make the above distinctions and review their significance, but it appears to focus primarily on URM bearing wall buildings. This distinction should be clarified as the Commission moves forward. In the United States, the focus of activity, particularly at the legislative level, has been primarily on URM bearing wall buildings, not on URM infill buildings or on buildings with URM veneer.

3. *Seismic Improvement Techniques:* Section 4 provides a useful overview of seismic improvement or rehabilitation techniques for URM bearing wall buildings. Specific comments on individual techniques are noted later. FEMA (2007) provides detailed discussion on URM building rehabilitation techniques. There are several techniques that are used in the United States that are not mentioned in the URM report. They include the following.

    - Addition of supplemental vertical supports: These supports provide a backup gravity load-carrying path for trusses, girders and other elements that impose concentrated gravity demands on the masonry walls in the event damage to the masonry wall impacts its load-carrying capability. These supplemental supports are required by URM seismic rehabilitation codes in the United States.
    - Addition of plywood shear walls: At interior locations, plywood shear walls can be added to reduce the demands on the floor and roof diaphragms as well as the masonry walls. As the plywood walls are much less stiff than the URM walls, the plywood shear walls need to be placed sufficiently far from the URM walls so that they will be effective in resisting tributary loads.
    - Use of crosswalls: In US codes for seismic rehabilitation of URM bearing wall buildings, interior walls (new, existing or strengthened) can serve as “crosswalls” or damping elements to absorb energy. Crosswalls are distinguished from shear walls which are intended to resist seismic forces.
    - Seismic isolation: The report does not mention seismic isolation as a rehabilitation technique. Though relatively rare and expensive, seismic isolation has been used to seismic rehabilitate a small number of heritage (or “historic”) URM bearing wall and URM infill frame buildings in the United States.

4. *The Use of Percentage of New Building Standard (%NBS) for URM Buildings:* The concept of characterizing the adequacy of existing buildings by their percentage of capacity of the current building code for new buildings is widely used in the New Zealand. The %NBS value serves as an easy metric for communication with the public and with the building management community. A building with a value of 33%NBS or

less is defined as potentially "Earthquake Prone," with potential legal implications depending on territorial authority statutes and related requirements in the 2004 Building Act. Buildings with a value of 34%NBS to 67%NBS are termed an "Earthquake Risk". This approach is not widely used in the United States, and this is particularly true with URM buildings.

Recent guidelines for seismic rehabilitation in the United States establish goals or objectives that are either prescriptive or performance-based, and they are generally self-contained, rather than relying on the code for new building design. Prescriptive standards define a required scope of rehabilitation requirements and forces to use in designing the structural elements that are part these requirements. Examples of prescriptive standards for URM bearing wall buildings are Appendix Chapter A1 of the 1997 *Uniform Code for Building Conservation (UCBC) [ICBO, 1997]* and its successor Appendix Chapter A1 of the 2009 *International Code for Building Conservation (IEBC) [ICC, 2010]*. Performance-based standards are contained in documents like ASCE/SEI 41-06 *Seismic Rehabilitation of Existing Buildings (ASCE, 2007).* There, performance objectives are developed that combine earthquake hazard levels with material acceptance criteria. Both the hazard and the acceptance criteria can be varied to achieve higher or lower performance objectives.

The use of %NBS brings with it some important considerations the Commission should appreciate. Section 2.5 of the URM report applies the %NBS approach from the 2006 NZSEE document *Assessment and Improvement of the Structural Performance of Buildings in Earthquakes* (termed the *2006 NZSEE Guidelines* here). Table 2.5 estimates that that only 40% of the URM buildings fall in the Earthquake Prone category, with the remaining 60% in the Earthquake Risk category. The formulas used focus on the in-plane capacity of URM walls. Typical existing URM buildings in the United States and in New Zealand have limited ties connecting the walls and diaphragms. After the falling hazard posed by unbraced parapets, this lack of adequate wall-to-diaphragm connections is the most significant risk to damage and life safety in URM buildings. The majority of damage in the unretrofitted buildings can likely be traced to inadequate wall-to-diaphragm ties. The basic *2006 NZSEE Guideline*s Chapter 3 provisions do not have explicit provisions for accounting for the limited capacity that the lack of adequate ties brings (though there are provisions in an alternate procedure in an appendix). Simply put, without an adequate load path, there is limited to negligible capacity. Thus, in my opinion, it appears that the reported values may be overestimating the actual %NBS values and the actual capacity.

5. *Determination of the Performance Objective:* Section 4.1 very briefly mentions that a range of potential retrofit objectives is possible, beginning with life safety and rising to minimizing damage and preserving building functionality. Later in Section 7, there is a

breakdown of potential rehabilitation approaches into four categories or levels, with some limited discussion of the associated objectives. It is important that the Commission appreciate that there is in fact a wide range of possible rehabilitation levels that could be implemented.

One way to vary the work is to only include certain rehabilitation activities and focus on those with the highest benefit-to-cost ratio. Parapet safety ordinances represent the end of the spectrum where the scope and cost of the work is low but the benefit-to-cost ratio is high. The next step in expanding the scope would be roof-to-wall tie ordinances where ties are designed for tension forces only (forces perpendicular to the face of wall), followed by including resistance to shear forces parallel to the wall in the connection design. Then wall-to-floor diaphragm ties can be added at each level. The next step in expanding the scope of an ordinance would be to include interfloor wall supports or "strongbacks" for bracing tall, thin walls susceptible to out-of-plane failure. Lastly, diaphragm improvements and in-plane wall strengthening can be added. Some communities in California have selected only parapet and roof tie work as mandatory requirements; others have included parapets, wall-to-diaphragm ties and out-of-plane wall bracing; and many have included all of the above activities as part of a comprehensive package of provisions.

The prescriptive model codes noted above such as the 1997 UCBC and the 2009 IEBC have what are often termed "risk reduction" goals, and they include the entire list of activities noted above, at least in zones of high seismicity. The purpose of the 2009 IEBC is:

> *to promote public safety and welfare by reducing the risk of death or injury that may result from the effects of earthquakes on existing unreinforced masonry bearing wall buildings. The provisions…are intended as minimum standards for structural seismic resistance, and are established primarily to reduce the risk of life loss or injury. Compliance with these provisions will not necessarily prevent loss of life or injury, or prevent earthquake damage to rehabilitated buildings.* (ICC, 2010)

This description was much lower than the performance expected of a new building. Note that it does not guaranty a level of performance, but rather describes the goal or target of the model code. With the uncertainties and variations associated with ground motion, soil conditions, existing material properties, current analysis capabilities, and installation issues, there will always be a range of performance that occurs in any population of buildings, even if they are strengthened to the same nominal level.

Another way the rehabilitation approach can be varied is to vary the design loads used in determining the rehabilitation work, such as the forces used on wall-to-diaphragm ties, or shear walls. This is done for new buildings in both New Zealand and the United States through the use of the Importance Factor. Buildings with higher importance are designed to higher levels. I understand from discussions with practicing engineers in New Zealand that this is explicitly done in seismic retrofitting by using the %NBS target. For example, with a 67%NBS target, the forces used to design connection or structural elements are 67% of those in the current building code.

Finally, explicit performance objectives can be stated such as used in ASCE/SEI 41-06, with higher performance levels selected. One of the performance objectives in ASCE/SEI 41-06 is the Basic Safety Objective which combines an earthquake hazard such as one with a return period of 475 years with Life Safety acceptance criteria and a larger maximum capable (MCE) hazard with Collapse Prevention acceptance criteria.

As the Commission considers what to recommend for URM buildings (or any building type), informed discussion of desired performance objectives with relevant stakeholders will be valuable.

6. *Costs of Seismic Rehabilitation:* The cost of seismic strengthening in Section 6.3 appears to have been derived entirely from a staff report to the Christchurch City Council which in turn based its figures on a 2009 consulting report[1] that the Council commissioned. Issues include the following.
   - Clarification of the Scope in Section 6.3: Figures are provided for strengthening to the 33%NBS and 67%NBS levels. It is unclear, however, in both the URM report and in the Holmes report what the scope of the 33%NBS and 67%NBS levels includes. Is a comprehensive scope of all elements included and the only difference is the force level at which elements are checked and evaluated, or are there differences in scope, technique and redundancy?
   - Clarification of the Costs in Section 7: Four "stages" of seismic rehabilitation are given, but they are not linked to the 33%NBS or 67%NBS values in Section 6.3. This is further complicated by the recommendation of Stages 1 and 2 as the minimum required scope. If the Commission wishes to consider the four stages or scopes, it would be prudent to have costs associated with each one and which %NBS value is being used.
   - Challenges and Variation in Estimating of Seismic Rehabilitation Costs: The Holmes report notes that "previous information shows that strengthening costs vary wildly from building to building from about NZ\$250/m^2 to NZ\$700/m^2." It

[1] Holmes Consulting Group, 2009, "Heritage Earthquake Prone Building Strengthening Cost Study," prepared for Christchurch City Council, June 25.

is not clear what performance level or %NBS target is associated with these values, but the range is significant. Wide ranges on retrofitting costs have certainly been the case in the United States as well. FEMA commissioned a study of typical costs that covered all building types (FEMA, 1994), which showed this. Rutherford and Chekene (1990) and (Recht Hausrath, 1993) focused on URM strengthening costs in San Francisco and Oakland, California, respectively. The Oakland study has a detailed description of the many issues related to costs. A few include:

- What costs should be included besides what the owner pays the contractor? Potential categories include engineering/architectural design fees, testing and inspection fees, plan checking and permits, insurance, administration, construction management, load costs, and lost revenue during construction.
- Will the work be done with occupants in place in portions of the building? Are relocation costs included?
- Is the seismic retrofit part of a larger capital improvement program, involving architectural renovations, tenant improvements, and/or mechanical/electrical/plumbing upgrades?
- What is the premium for working in more architecturally sensitive buildings? How detailed will the finish repairs be?
- What level of strengthening is being performed?
- Are abatement costs for hazardous materials like lead paint, buried tanks, or asbestos included?
- Are triggered accessibility costs included?
- Are estimates being used or actual data from past projects?
- When extrapolating costs of individual buildings to portfolios, many factors affect the projected costs. These include the footprint area; the number of stories; the existing structural system; building configuration; occupancy type; the design professional's experience, competence and judgment; soil conditions; plan checking sophistication and rigor; and market conditions. For example, small footprints have higher costs, not just due to economies of scale, but because they have a larger perimeter length to floor area and much of the retrofit costs are associated with work like floor-to-wall ties that is proportional to the perimeter length.

- Estimated Value of URM buildings in Section 2.4: The NZ$1.5 billion value for the URM building stock comes from Quotable Value New Zealand Ltd (QV Ltd). Based on review of the QV website, I understand this is a service that provides either the current market valuation or the council rating valuation. Each represents the expected property value at the time the valuation is made. Valuations were reported between July 2005 and September 2008. It is not clear if the valuation is for the building plus land (called the capital value by QV) or only the building (called the value of improvements by QV). The price that a property can sell for is not the same as the cost to replace it. Rebuilding a URM building with a modern code compliant structure and architectural features similar to the original would be challenging and could be more than the purchase price. A quick comparison of value/floor area is interesting. The NZ$/m^2 value is NZ$1,500,000,000 / 2,100,000 m^2 = NZ$714/m^2. This can be converted to US$ / square foot as NZ$714/m^2 x (m^2 / 3.28 ft/m / 3.28 ft/m) x US$0.80 / NZ$ = $53/sf. Even assuming this is only the value of the building, this is a relatively low value in the United States, and very low compared to California.

7. *Seismic Rehabilitation Policy Recommendations:* Section 7 provides a concise set of recommendations and closing remarks. Comments on each recommendation and closing remark follow; the print in italics is taken from the URM report and provided here for convenience.

   - URM Report Recommendation 1: *Identify all unreinforced clay masonry and stone masonry building stock in New Zealand*. Identification of URM buildings is a typical first step in seismic mitigation ordinances. This serves many purposes. It will help policy makers understand the extent of buildings at issue. Identification can be linked to notification, so that both the URM building owner and potential buyers are aware of the type of building. Senate Bill 547 in California, passed in 1986, required communities to survey their URM buildings, notify the owners they are potentially hazardous, and develop a mitigation plan. Some communities stopped there; others went farther and adopted mandatory strengthening programs. In 1992, a law was passed in California requiring building owners to post warning placards at the entrances to URM buildings. This law was not widely followed or enforced. In 2004, the law was strengthened. The wording to be placed on the placards is: “Earthquake Warning. This is an unreinforced masonry building. You may not be safe inside or near unreinforced masonry buildings during an earthquake” (CSSC, 2006). A survey provides a way of identifying which buildings could be posted. The URM report does not discuss who would identify the buildings, what process would be used, or how it would be funded. These are key issues to be determined.

   - URM Report Recommendation 2: *Successful retrofits showed that it is possible to make strengthened URM buildings survive severe earthquake ground motion.* This appears to be potentially overstated. Experience in the 1994 Northridge earthquake found that retrofitted buildings performed better than unretrofitted buildings, but there was still damage to retrofitted buildings, and in some cases damage was very significant. Statistics on damage to retrofitted buildings are not in the report, but I understand they will be provided in a follow-up report or addendum. This will be very helpful. I assume there will be damaged retrofitted buildings in the statistics as they were observed during our reconnaissance visit. In general, the Commission and the public have to be appreciate that there will be a range of performance from retrofitted buildings in future earthquakes, and some buildings will performance below target levels, just as some will perform better than anticipated.

- URM Report Recommendation 3: Four "stages" or levels or rehabilitation are described. The first covers chimneys, parapets, ornaments and other falling hazards. The second includes wall-to-diaphragm ties and out-of-plane wall braces. The third is described as "ensure adequate connection between all structural elements of the building so that it responds as a cohesive unit rather than individual, isolated building components. In some situations it may be necessary to strength roof and floor diaphragms, flexurally strengthen the masonry walls, and provide strengthening at the intersection between perpendicular walls." The fourth level covers in-plane strengthening of walls. These levels are roughly similar to those that have been used in California studies and discussions and some ordinances. The description, particularly for the third level, needs more clarity and specificity for any implementation or further work. See Rutherford and Chekene (1990) for a detailed example of the scope that was associated with three potential levels of strengthening being considered in San Francisco.

- URM Report Recommendation 4: *All buildings should go through the first two stages of building improvements so that the targeted structural elements have their strength elevated to match that required for equivalent structural elements in a new building located on the same site. For 3rd and 4th stage improvements, building strengthening should aim for 100% of the requirement for new buildings but as a minimum, 67% might be acceptable.* In the United States, rehabilitation model codes and implemented ordinances typically use force levels below that of current code for economic reasons. They also target performance levels that are lower than those of new buildings. Aiming for equivalence to a new building is, in my opinion, likely to be extremely expensive. Designing for the same forces used in to design new buildings will not achieve equivalent performance since URM buildings lack ductility and modern detailing. To achieve equivalent performance to, say, a modern reinforced masonry or concrete building would require additional work and elements to mitigate the hazards posed by the archaic materials used in URM buildings. This would have very significant impacts on the architectural fabric of the buildings.

- URM Report Recommendation 5: *Recommendation 4 should be a national requirement, rather than being left to territorial authorities to draft and monitor* *their own individual policies.* In California, as a political compromise, Senate Bill 547 left each jurisdiction the right to determine what program that would apply to their URM building stock beyond the minimum survey and notification requirements. This has led to a patchwork quilt of ordinances throughout the state, and will result in very different performance if the same level of earthquake shaking strikes a community with a voluntary ordinance vs. a neighbor with a mandatory ordinance. From an engineering point of view, it is much simpler and more efficient to have one standard to comply with, and I concur that a single national approach would provide greater efficiency and uniformity. However, it is a political question of whether this is viable.

- URM Report Recommendation 6: *There is a need for more widespread technical capability for seismic assessment (analysis) and design of URM buildings in the New Zealand community.* I cannot speak knowledgeably about the expertise of practitioners in New Zealand, but in the United States, such a recommendation would certainly apply, particularly outside of the West Coast.

- URM Report Recommendation 7: *In view of the uncertainties regarding the seismic strength of existing URM buildings, it is recommended that field testing be conducted on some URM buildings in Christchurch that are scheduled for demolition.* There has been a substantial amount of testing of URM building components around the world that is relevant to New Zealand's URM buildings, but limited testing of in-situ components and limited testing of assemblies of components. As an example, there are extensive tests of drilled adhesive dowels to masonry, but very few where the connection of the ties to the diaphragm is included. Cavity wall construction was widely observed in Christchurch with widespread damage, but there has been limited testing. In-situ testing of cavity walls or different retrofit techniques of cavity walls would be valuable. This report recommendation would be much improved, however, with a specific list of potential testing topics. It would be unfortunate to lose the unique opportunity and cost effective research that could be conducted in field testing buildings that will be demolished.

- URM Report 8: *Budgeting constraints will likely limit the extent to which URM buildings can be seismically upgraded. Therefore priority should be given to ensuring public safety by implementing Recommendation 3: Stage 1 and 2 as soon as possible for all URM buildings.* I would assume budget constraints will be an integral part of any future public policy decision regarding rehabilitation requirements, but the notion that areas of low seismicity need evaluation or strengthening of walls against out-of-plane failure should be carefully examined. The 1997 UCBC and 2009 IEBC, for example, have a minimum level of seismicity related the spectral acceleration at the site in order to trigger even parapet bracing and wall-to-diaphragm ties and then a higher level before out-of-plane wall strengthening is triggered. These levels could be compared against the seismicity in various parts of New Zealand.

- Closing Remark 1: *There were no surprises amongst collapse mechanisms in URM buildings.* URM failure mechanisms are relatively well understood, and the failure modes observed in previous earthquakes were observed in Christchurch. One noteworthy difference is the extent of cavity wall construction and the associated damage. This type of construction is not common in California, though it is used in other parts of the United States. Buildings with cavity wall construction will be more susceptible to out-of-plane wall damage, so I would expect damage to be higher on average in Christchurch than in California for similar shaking levels.

- Closing Remark 2: *Current building standards are appropriate and are representative of "world's best practice."* I respectfully disagree. Designers in New Zealand currently appear to have only new building codes and the *2006 NZSEE Guidelines* to use in strengthening URM buildings. URM buildings have unique dynamic characteristics that differ from the traditional models upon which codes for new buildings have been developed. URM buildings have comparatively rigid walls and flexible diaphragms, rather than the assumption of rigid diaphragms and relatively flexible vertical elements that underlies the building codes. URM buildings have archaic materials that need property values and capacities not covered by codes for new, ductile materials.

  The *2006 NZSEE Guidelines* are intended for existing buildings, but for URM buildings they only have explicit provisions for in-plane and out-of-plane wall behavior; they do not address the many other types of mitigation measures needed. They are primarily evaluation tools, rather than rehabilitation guidelines. Unlike the 2009 IEBC or 2007 UCBC and the original ABK research these model codes were based on, they do not represent a holistic view of how all the parts of the building work together. The in-plane wall evaluation section also includes rather some rather challenging modeling recommendations that would not be practical or economical in a design office.

  The *2006 NZSEE Guidelines* do not explicitly cover repairing and strengthening of damaged buildings, and New Zealand's Building Act of 2004 was not developed with provisions to address earthquake damage either. There has been some work on this in the United States, in Chapter 34 of the 2009 International Building Code and Chapter 34 of the 2010 California Building Code. More recently, ATC-52-4 (ATC, 2010) provides example language for three model building types (single family residences, multi-family wood frame construction, and concrete wall and frame buildings) on how to address repair and strengthening of damaged buildings. I understand this is an active area of much work in Christchurch. Finally, I am not aware of a specific code for heritage buildings in New Zealand. California has the State Historic Building Code (CBSC, 2010) which is used to provide alternative procedures and increased flexibility in renovating and seismically strengthening historic buildings.

- Closing Remark 3: *The amplitude of ground shaking experienced by URM buildings in Christchurch was well in excess of that prescribed by the current design spectra for Christchurch buildings located on soft soils. Nevertheless, well considered, conceived and implemented seismic retrofits of URM buildings performed well, even when the building experienced ground motion that was well in excess of the design level for Christchurch.* There are plots of spectra derived from strong motion records in Christchurch exceeding related design spectra in Section 1 of the report and in reports by others. It would be useful and instructive to have a more comprehensive treatment of this important issue, and the Commission has obtained this to some extent in other reports it has requested. The second sentence of this closing remark may be more debatable. Statistical information comparing retrofitted and unretrofitted buildings and the associated ground shaking would be quite valuable and would help support this statement.

- Closing Remark 4: *The URM building damage statistics were significantly worse after the 22nd February 2011 earthquake than they were after the 4th September 2010 earthquake due to the severity of the local ground motions in the CBD during the 22 February earthquake.* This appears to be the case.

- Closing Remark 5: *The estimated cost to upgrade all 3867 URM buildings in New Zealand to a minimum of 67% of the NBS is roughly $2.1 billion, which is more than the estimated total value of the URM building stock of $1.5 billion. However, a multi-stage retrofit improvement program has been recommended and it is anticipated that the cost of implementing stage 1 and stage 2 improvements will not be excessive and should be within the budget capability of most building owners.* What is “excessive” and “within the budget capability of most building owners” depends on the perspective and financial situation of the individual owner. This issue was examined in detail by economists in San Francisco and Oakland in Recht Hausrath (1990 and 1993).

RECOMMENDATIONS

In reviewing the URM report and considering the Commission's charges which include inquiry into "the adequacy of the current legal and best-practice requirements for design, construction and maintenance," I offer the following recommendations on additional activities the Commission could consider encouraging or sponsoring to help it formulate well-founded proposals.

1. *Collect Additional Damage Information:* The damage to URM buildings in Canterbury represents an extremely important opportunity to collect data on damage that will be useful for other communities in New Zealand (as well as other areas of the world with similar building stock and seismicity). I recommend collecting the following additional information.

    a. Deaths and Injuries: Section 3.2.1 of the report provides URM building damage statistics for the 4 September 2010 and 22 February 2011 events, but does not cover deaths and injuries. The Commission's website indicates URM buildings were associated with 40 deaths. It would be useful for the Commission to have statistics on the number of deaths and injuries associated with the various building types, including the various categories of URM buildings. The 13 June 2011 event could be added as well.
    b. Retrofitted vs. Unretrofitted Performance: The URM report contains anecdotal information on differences in performance in retrofitted buildings, but not statistics. I understand a follow-up report on the performance of retrofitted buildings is being prepared. This is much needed, and will help the Commission to better quantify the effectiveness of seismic rehabilitation. Given the large sample of building stock available in Christchurch and Lyttleton, the more quantitative the information can be, then the more valuable it will become. It is also important to appreciate that seismic rehabilitation tends to reduce damage, but not eliminate it. Reports comparing damage to retrofitted and unretrofitted building from the 1989 Loma Prieta Earthquake and 1994 Northridge Earthquake showed this; they are listed in the Appendix. Post-earthquake safety evaluation postings should be differentiated between retrofitted and unretrofitted buildings as well. If possible, it is valuable to obtain estimates of the performance of all the buildings within the target area, not just the damaged ones, so that the performance of the class as a whole can be evaluated. It would also be desirable to link the ground motion to the damage, given the wide variation in shaking.
    c. Investigation of the performance of adhesive anchor performance: As noted in Section 4.2.2 of the report, there are reports of poor performance of adhesive anchors that are widely used in the seismic rehabilitation of URM buildings. A study between the University of Minnesota and the University of Auckland is

underway. The Commission should follow the progress of this study and incorporate findings if possible or warranted. It will be important to determine if observed poor performance is due to poor installation practice, to failure of the adhesive, to failure of the substrate to which the dowel is attached, or to a failure of the other aspects of the wall-to-diaphragm assembly. In the United States, manufacturers are required to perform extensive standardized testing through organizations such as the International Code Council Evaluation Service. This testing covers the dowel-to-masonry connection, but not the other portions of the connection assembly. See FEMA (2007) for more information on this issue.

2. *Select Potential Performance Objectives for Seismic Rehabilitation:* As noted above in the "General Comments" section, there is a large spectrum of possible performance objectives and scopes of rehabilitation that could be selected for URM buildings. In determining appropriate public policy, it is often valuable to have a small number of options or choices that can be evaluated. The URM report briefly described four "stages" or scopes. These could be used as a starting point, augmented with engineering descriptions and greater clarity of what exactly is included in each scope. Performance objectives and goals for rehabilitation to each scope should be determined. General force and displacement demands and acceptance criteria for each level should be determined. This can be associated with the %NBS approach used in current New Zealand practice. The scope and demands can be tied to seismicity levels. For example, a version of the 2009 IEBC could adapted for New Zealand. It ties the extent of work and the demands used in the design of mitigation measures to seismicity levels. Thus, requirements in Auckland would be less than Wellington. Clarification is needed on whether URM infill frame, confined masonry and masonry veneer will be included.

3. *Conduct a More Detailed Cost Study of the Proposed Options and Include Loss Estimates:* The 2009 Holmes Group study and the URM report do not provide costs for each of the four scopes. They also do not include any estimates of loss reduction that rehabilitation can bring. Thus, there is no way to quantitatively assess the benefit-to-cost ratios of various options. Losses in include deaths and injuries, property damage, loss of function and business interruption losses, and architectural heritage losses. A cost and loss estimate study would cover the options identified in Recommendation 2. Examples of such studies are Rutherford & Chekene (1990) for San Francisco and Recht Hausrath (1993) for Oakland. In those studies, prototypes were identified that represented the larger building stock, retrofit techniques were described and associated with different retrofit levels, detailed cost estimates were performed for the different retrofit levels, and loss estimates were made for scenario events and as well as annual probabilities. Loss estimates could be compared or tested against the damage statistics acquired for Christchurch.

4. *Develop Improved Guidelines for Seismic Rehabilitation of Undamaged URM Buildings:* I pointed out several concerns in the "General Comments" section with using the *2006 NZSEE Guidelines* for URM rehabilitation. Updated provisions that reflect recent research, much of it performed in New Zealand, and account for the full range of issues URM buildings pose need to be developed. Draft guidelines have been developed at the University of Auckland[2] that could be used as a starting point. The 2009 IEBC is another possibility, and proposals for updating the URM provisions in ASCE/SEI 41-06 are currently being developed. Section 2.2 of the report notes the prevalence of rows of adjacent URM buildings joined by common walls. Consideration of this case is not typically in rehabilitation guidelines, but would be quite valuable in New Zealand. More detailed consideration of liquefaction issues would also be useful, given the experience in Christchurch.

5. *Develop Guidelines for Evaluating Damaged URM Buildings:* Detailed guidelines are being developed for evaluating damaged buildings, including URM buildings, by the Department of Building and Housing Engineering Advisory Group. This will help standardize the evaluation process. During my reconnaissance trip, there were reports of a wide range of evaluation findings being given by different practitioners for damaged URM buildings for the same level of damage. FEMA (1999a) provides a methodology for evaluating damaged concrete, reinforced masonry, URM bearing wall and URM infill buildings that could also be considered.

6. *Develop Guidelines for Repair and Strengthening Damaged URM Buildings*: Rehabilitation guidelines and codes have traditionally focused on undamaged buildings. Once buildings are damaged, other issues come into play. The most basic is whether to permit repair to pre-earthquake levels or whether to require strengthening. Once strengthening is required, the issue is to what level. I understand groups in New Zealand are developing guidelines. Some guidelines in the United States that can serve as resources are Chapter 34 of the 2010 California Building Code (CBSC, 2010) and ATC 52-4 (ATC, 2010).

7. *Determine a Course of Action:* All of the studies and activities above will ultimately be valuable to develop and implement updated policies for effectively mitigating the seismic hazards posed by URM buildings. This will take time. It may be prudent to take interim steps and decisions. Evaluation, repair and strengthening guidelines are urgently needed so that the recovery process proceeds quickly and on a rational engineering basis. Damage statistics should be collected before the information is lost. But undamaged URM buildings remain throughout the country. New Zealand has obviously been addressing URM building hazards for many years, yet many communities, particularly

[2] Faculty of Engineering, 2011, *Assessment and Improvement of Unreinforced Masonry Buildings for Earthquake Resistance*, University of Auckland, February, draft.

those that adopted passive strengthening ordinances, still have large numbers of URM buildings that have not been retrofitted to any level. In moderate to high seismicity areas, the risks to life safety, property damage and business interruption are significant. With the losses in the Canterbury earthquake swarm still vivid, now is the time to consider more aggressive measures in mitigating URM hazards.

SPECIFIC COMMENTS ON REPORT SECTIONS

The following comments cover specific sections or statements in the report.

1. Glossary and Abbreviations

    a. Cavity: The description of the cavity mentions that it provides ventilation and a pathway for moisture to exit the wall. The air in the cavity also has insulation value.
    b. Leaf: The term "leaf" is not included. It is used throughout the document, but not always clearly. In the United States, the parallel term is "wythe". Wythes are the number of layers of masonry units in the direction perpendicular to the face of the wall, just as "courses" are the horizontal layers of masonry units. Pictures could help.
    c. Importance Level: This definition could be made more precise by more specifically tying it to the code language in current New Zealand standards.
    d. Intensity: Intensity is not measured in terms of maximum ground acceleration. It is measured using a classification system that relates intensity to the type of observed building damage, such as the Modified Mercalli Intensity scale.
    e. Period: The first sentence is imprecise and could be removed. Mode shapes define "how the building will shake".
    f. Unreinforced masonry: This defines unreinforced masonry as not having any reinforcing elements. It is worth noting that in some seismic rehabilitation codes in the United States, such as the 2009 IEBC, an unreinforced masonry wall is one with less than 25% of the minimum reinforcing ratios required by codes for new buildings. This was intended in part so that walls with nominal amounts of steel straps in masonry bed joints (as ws done in some types of older construction) would not be considered as reinforced masonry and excluded from the provisions.

2. Executive Summary: Comments on the Executive Summary are given above in the "General Comments" and "Recommendations" sections.

3. Section 1: Introduction and Background

    a. Page 3, last sentence of first paragraph: It is unclear what the "assessed earthquake strength of the Christchurch URM building stock" means. Assessed by whom?
    b. Section 1.2.1, Page 5, first sentence of second paragraph: It is unclear if the phrase "Christchurch had been largely rebuilt" means simply the gradual turnover from wood-framed construction to masonry, or if it referring to the response to a specific event such as a fire.
    c. Section 1.3, Page 8, first sentence: The buildings were also presumably damaged by a lack of adequate connections between building elements such as between walls and diaphragms, not just the brittle nature of URM materials and their inability to dissipate energy.
    d. Section 1.3, Page 9, last sentence of first paragraph: The sentence does not indicate if the By-Law was adopted in Christchurch.
    e. Section 1.3, Page 10, first paragraph: It is unclear what time period associated with "exceptionally rigorous quality of design and construction by the Ministry of Works," and why would it have led to minimal use of URM from 1935 onward.
    f. Section 1.3.1, Page 10, second sentence of the third paragraph: The Christchurch City Council's "more passive approach" to seismic rehabilitation is not discussed or clarified. What specifically was in the legislation and was it actually followed or implemented?
    g. Section 1.4, Page 16, Figure 1.6: The basis of selecting these particular ground motion records from the 4 September 2010 and 22 February 2011 events is not explained.
    h. Section 1.4, Page 17, Figure 1.7: The text indicates that the earthquake records are the "median response", but it does not indicate which records were included in the suite that was considered.

4. Section 2: The Architectural Characteristics and the Number and Seismic Vulnerability of Unreinforced Masonry Buildings in New Zealand

    a. Page 18, second sentence of first paragraph: The timeframe associated with the construction dates for New Zealand's URM buildings may be narrow compared to European norms, but it is similar to that of California.
    b. Section 2.2.1, Page 26, last two sentences: These sentences oversimplify which in-plane behavior modes are most likely to occur. There are many different in-plane behavioral modes that can occur, and their likelihood of occurrence depends on building specific material properties and geometries. FEMA (1999a) gives a comprehensive overview of such modes.

c. Section 2.2.2, Page 27, second sentence: It would be valuable to clarify or confirm that that floor diaphragms in URM buildings are typically wood-framed in New Zealand, rather than concrete. Performance and rehabilitation techniques vary significantly between the two types.

5. Section 3: Observed Performance of Unreinforced Masonry Buildings in the 2010/2011 Canterbury Earthquake Swarm

   a. Page 34, first sentence: The date range covered by the 3690 aftershocks is not indicated.
   b. Section 3.1, Pages 34 and 35: Who conducted the inspection is not indicated, and the source of the numbers is not referenced.
   c. Section 3.1, Page 36, Figure 3.2a: This is the number of stories, not the story height.
   d. Section 3.1, Page 36, Figure 3.2c: "Heritage listed" is not an occupancy type.
   e. Section 3.1.2, Page 37, third paragraph: Use of percentage of damage requires care and caveats. It is typically understood as the cost of repair divided by the cost of replacement. A URM building cannot be replaced, as URM construction is now prohibited, so the cost of replacement presumably assumes a similar but not identical building. The estimate was made in a rapid visual assessment, was unlikely to have been made by a contractor or quantity surveyor with cost estimate experience and represents, and thus the repair cost is likely to vary a fair amount.
   f. Section 3.1.5, Page 40, second sentence: It is not clear why bracing of URM parapets has been required since the 1940s.
   g. Section 3.1.7, Page 44, first sentence, second sentence: This implies that if the cavity wall ties between the outer and inner leaves were properly installed and not corroded, then the wall would not be vulnerable to out-of-plane failure. Even a well tied cavity wall will not be equivalent to a solid wall in its effective height-to-thickness ratio and will be more susceptible to out-of-plane damage.
   h. Section 3.2.2, Page 59, last sentence: It is not clear from the text or photo if the returns lacked interlocked masonry units around the corner as would be typical construction or if they have a vertical mortar joint at the corner.
   i. Section 3.2.2, Page 61, first sentence: This notes that damage in the 22 February 2011 event correlates with the east-west direction of stronger shaking. I understand the 13 June 2011 event had a different orientation of stronger shaking which may have exacerbated the damage in that event.
   j. Section 3.2.2, Page 62, Figure 3.36a: It is unclear how this figure shows the interaction between the nave and bell tower.

k. Section 3.2.2, Page 63, Figure 3.38a: Horizontal movement is depicted, but no obvious vertical differential movement in the photos. It is thus unclear why the separate foundations noted in the text may have led to the damage.
l. Section 3.2.2, Page 64, first paragraph: This implies that seismically designed anchorage and spacing would be sufficient to prevent wall damage. Proof of this is insufficient and elusive. There are examples in the Northridge Earthquake of anchored walls failing.
m. Section 3.2.2, Page 64 and others: It is unclear from the photos whether the anchorage shown is original, a retrofit prior to the 2010/2011 earthquakes, or a repair measure to one of the earthquakes.
n. Section 3.2.2, Page 65, Figure 3.42: The caption indicates this is damage "induced by hammering of the roof." It appears this is actually related to the poor quality of construction materials as the preceding paragraph indicates.

6. Section 4: Techniques for Seismic Improvement of Unreinforced Masonry Buildings

a. Section 4.1, Page 67, last sentence: This says that additional retrofit measures may be taken beyond the basic measures with the "highest performance target conceivable being to have the building and its contents suffer no damage and be immediately functional following the considered earthquake event." With URM bearing wall buildings, this is an impracticable performance objective that would require extraordinary measures to be implemented in order to have a reasonable chance of occurring. It is important for the Commission to appreciate the difficulty in achieving high performance objectives in URM buildings.
b. Section 4.1, Page 69, Figure 4.1: This is an excellent photo illustrating the advantages of anchoring the gable wall to the roof. It is unclear why the virtually identical gable on the right was not anchored.
c. Section 4.1, Page 70, second sentence of first paragraph: It is too strong a statement to say that anchors at corners will prevent return wall separation. It will reduce the likelihood of return wall separation.
d. Section 4.2.1, Page 70, six sentence of fourth paragraph: Use of epoxy injection is not recommended as a bonding agent due to incompatibility with existing masonry properties. Injection grouts have been developed in Los Angeles that are more compatible with the strength, stiffness and permeability of existing masonry (City of Los Angeles, 1991).
e. Section 4.2.2, Pages 72 and 73: This discusses the observation that "there has been a significant number of observed failures of adhesive anchors," Figure 4.4a is, however, being used as an example of such a failure. This shows a very small length of adhesive on the tip of a drilled dowel. This appears to show poor installation practice. A research project is underway to study this as mentioned in the Page 73 footnote. The research findings may be valuable, if they provide

clarity on the extent and frequency of failures and whether they are a result of poor installation, demands in excess of design values, or product deficiencies.

f. Section 4.2.3, Page 75: This discussion raises a few considerations. First, cavity wall construction is used not just as a technique for draining moisture, but also to provide an insulation barrier. Second, grouts need not be made of rigid, cementitious formulations as described, but can be made of more compatible materials, as noted above. Third, the majority of URM walls are likely of solid construction, rather than cavity wall construction. If cavity wall construction provides resistance against moisture intrusion, then is there a correlation between moisture damage and solid wall construction?
g. Section 4.2.3, Page 76, Figure 4.7b: This figure shows a wall brace or kicker where restraint to out-of-plane movement of the wall is provided by vertical stiffness in the floor framing. Many engineers believe this to be a much less desirable and reliable technique than the strongbacks shown in Figure 4.7a. See FEMA (2007) for further discussion.
h. Section 4.2.3, Page 77: The discussion of post-tensioning discusses many of the advantages, but few of the disadvantages of this technique. First, there are concerns with long-term creep in masonry where much of the post-tensioning stress can be lost over time. Second, post-tensioning done for improving out-of-plane capacity can change the in-plane behavior mode from a desirable one, such as rocking, to a less desirable one such as diagonal tension or toe crushing, unless care is taken. Third, drilling holes for the reinforcing, whether it is post-tensioned or not, requires specialized tools. Drilling with dry core technology can minimize staining with water.
i. Section 4.2.3, Page 78, Figure 4.8a: The external post-tensioning, if present in the photo, is not obvious.
j. Section 4.2.4, Page 79: The section on floor and roof diaphragm stiffening does not point out that it is typically additional strength that is needed, not stiffness, and the most basic approach of adding a plywood overlay is not mentioned. See FEMA (2007) for detailed discussion of diaphragm strengthening.
k. Section 4.2.6, Page 82, second sentence of second paragraph: Adding gypsum plasterboard, particle board, or plywood to the inside face of a URM wall will provide negligible additional strength or benefit due to incompatible stiffness and should not be recommended.

7. Section 5: Set of Representative Buildings

   a. General: It is somewhat unclear what is "representative" about these buildings. There is no link, for example, to the typology mentioned Section 2.2.

b. Section 5.1.1, Page 88, last sentence of second paragraph: The narrative mentions the Cathedral had been strengthened prior to the 4 September 2010 earthquake, but provides no information on the scope of work.

8. Section 6: Demolition Statistics and Information on the Cost of Seismic Improvement

   a. Section 6.2, Page 110: The assertions are misleading that "hidden costs" are one of the main contributors to the high cost of retrofitting, and such costs cannot be estimated until rehabilitation work commences or is completed. Proper project management of seismic rehabilitation is no different from other renovation work. With skilled participants, proper planning, adequate investigation of existing conditions in advance, and sufficient contingencies, "hidden costs" can be minimized.
   b. Section 6.2, Page 110: This section does not provide an overview of the components that come into play in seismic strengthening. See "General Comments" and "Recommendations" sections

9. Appendix C: List of Demolished Buildings

   a. Per "General Comments" section, it would be valuable to distinguish the type of URM building: bearing wall, infill frame, confined masonry, veneer.

Sincerely,

RUTHERFORD & CHEKENE

Bret Lizundia
Principal

APPENDIX: USEFUL ADDITIONAL REFERENCES FOR URM BUILDINGS

The URM report provides a good list of relevant references. Some additional useful references developed in the United States are provided below.

Codes, Model Codes, and Related Documents

ABK, 1984, *Methodology for Mitigation of Seismic Hazards in Existing Unreinforced Masonry Buildings: The Methodology*, a joint venture of Agbabian Associates, S.B. Barnes and Associates, and Kariotis and Associates (ABK), Topical Report 08, c/o Agbabian Associates, El Segundo, CA. In the early 1980s, a seminal research program developed a new comprehensive approach to seismically strengthening existing URM bearing wall buildings. Aspects of this research and its recommendations were incorporated into later guidelines, model codes and adopted codes, beginning in Los Angeles. This document summarizes the methodology.

CBSC, 2010, *2010 California Building Code*, Volumes 1 and 2, California Building Standards Commission, Sacramento, California, June. This two-part volume publication includes the California Code of Regulations, Title 24, Part 2, known as the *2010 California Building Code* (CBC), as well as Title 24 Part 8, the *2010 California Historical Building Code*, and Title 24 Part 10, the *2010 California Existing Building Code* (CEBC), Sacramento, California. Chapter 34 of the CBC provides general guidelines for addressing repair and strengthening of earthquake damage. The CEBC is taken from the 2009 IEBC.

City and County of San Francisco, 2010, *San Francisco Building Code*. Chapters 16A and 16B cover San Francisco's mandatory strengthening requirements for URM bearing wall buildings.

City of Los Angeles, 1991, "Crack Repair of Unreinforced Masonry Walls with Grout Injection," Rule of General Application – RGA No. 1-91.

City of Los Angeles, 2010, *Los Angeles Building Code*. Division 88 contains URM bearing wall strengthening provisions.

ICBO 1997, *1997 Uniform Code for Building Conservation* (UCBC), International Conference of Building Officials, Whittier, CA.

ICC, 2010, 2009 *International Existing Building Code* (IEBC), International Code Council, Country Club Hills, IL. Appendix Chapter A1 provides provisions for seismic rehabilitation of URM bearing wall buildings. When the model code agencies were consolidated in the United States and the UCBC was discontinued, the IEBC became the successor document. Both a code and commentary are provided.

SEAOC, 1992, *Commentary on Appendix Chapter 1 of the Uniform Code for Building Conservation, Seismic Strengthening Provisions for Unreinforced Masonry Bearing Wall Buildings*, June 20, Structural Engineers Association of California, Sacramento, California

SEAOSC, 1982, *Earthquake Hazard Mitigation of Unreinforced Masonry Buildings Built Prior to 1934*, Seminar Proceedings, April, Structural Engineers Association of Southern California, Whittier, CA. Provides seminar proceedings for engineers to address design issues related to URM bearing wall strengthening ordinance in Los Angeles.

SEAOSC, 1986, *Earthquake Hazard Mitigation of Unreinforced Masonry Buildings Pre-1933 Buildings*, Seminar Proceedings, October, Structural Engineers Association of Southern California, Whittier, CA. Provides seminar proceedings for engineers to address design issues related to URM bearing wall strengthening ordinance in Los Angeles.

California URM Law Policy Discussions

CSSC, 2006, *Status of the Unreinforced Masonry Building Law, 2006 Progress Report to the Legislature*, California Seismic Safety Commission, Sacramento, California. This report provides an excellent discussion of the status of implementing California's URM law (Senate Bill 547, passed in 1986) in communities around the state.

Hoover, Cynthia, 1992, *Seismic Retrofit Policies: An Evaluation of Local Practices in Zone 4 and their Application to Zone 3*. This describes interviews with San Francisco Bay Area building officials with a focus on URM bearing wall mitigation programs.

Seismic Evaluation and Rehabilitation Guidelines

ASCE, 2003, *Seismic Evaluation of Existing Buildings*, ASCE/SEI 31-03, Structural Engineering Institute of the American Society of Civil Engineers, Reston, Virginia. Provides a three-tiered set of analysis procedures for evaluating different structural systems, including URM bearing wall and infill frame buildings.

ASCE, 2007, *Seismic Rehabilitation of Existing Buildings*, ASCE/SEI 41-06, Structural Engineering Institute of the American Society of Civil Engineers, Reston, Virginia. Provides detailed evaluation and strengthening performance-based guidelines for existing buildings, including URM bearing wall and infill frame buildings.

FEMA, 1997a, *NEHRP Guidelines of the Seismic Rehabilitation of Buildings*, FEMA 273, Federal Emergency Management Agency, Washington, D.C., October.

FEMA, 1997b, *NEHRP Commentary on the Guidelines of the Seismic Rehabilitation of Buildings,* FEMA 274, Federal Emergency Management Agency, Washington, D.C., October.

FEMA, 2000, *Prestandard and Commentary for the Seismic Rehabilitation of* Buildings, FEMA 356, Federal Emergency Management Agency, Washington, D.C., November.

FEMA, 2007, *Techniques for the Seismic Rehabilitation of Existing Buildings*, FEMA 547, prepared by the National Institute of Standards and Technology for the Federal Emergency Management Agency, Washington, D.C. This provides a comprehensive guidance on the techniques commonly used in seismic rehabilitation, including details and discussion of issues. It is written for engineers with limited experience in seismic rehabilitation or other members of the design community such as architects and project managers coordinating rehabilitation projects or programs to better appreciate the potential scope and construction details of such work.

Evaluating the Capacity of Damaged Buildings

FEMA, 1999a, *Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings: Basic Procedures Manual*, FEMA 306 Report, prepared by the Applied Technology Council for the Federal Emergency Management Agency, Washington, D.C., May. This provides detailed evaluation procedures for quantifying the loss of capacity caused by earthquake damaged concrete, reinforced masonry, URM bearing wall, and URM infill frame buildings.

FEMA, 1999b, *Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings: Technical Resources*, FEMA 307 Report, prepared by the Applied Technology Council for the Federal Emergency Management Agency, Washington, D.C., May.

FEMA, 1999c, *The Repair of Earthquake Damaged Concrete and Masonry Wall Buildings: Technical Resources*, FEMA 308 Report, prepared by the Applied Technology Council for the Federal Emergency Management Agency, Washington, D.C., May.

ATC, 2010, *Here Today—Here Tomorrow: The Road to Earthquake Resilience in San Francisco: Post-Earthquake Repair and Retrofit Requirements*, ATC-52-4 Report, prepared for the San Francisco Department of Building Inspection by the Applied Technology Council, Redwood City, California. This provides commentary and model code language establishing repair and strengthening guidelines for damaged buildings. The sample building types are included: single family residences, multi-unit multi-story wood-frame residential buildings, and older concrete buildings.

Earthquake Damage Studies

Lizundia, B., Dong, W., Holmes, W., and R. Reitherman, 1998, "A Summary of Unreinforced Masonry Building Damage Patterns—Implications for Improvements in Loss Estimation Methodologies," in *The Loma Prieta, California, Earthquake of October 17, 1989: Performance of the Built Environment: Building Structures*, USGS Professional Paper 1552-C, editor M. Celebi, USGS, Washington, D.C. This is a summary of Rutherford & Chekene (1993).

Rutherford & Chekene, 1993, *Analysis of Unreinforced Masonry Building Damage Patterns in the Loma Prieta Earthquake and Improvement of Loss Estimation Methodologies: Technical Report to the USGS*, March. Expands the Rutherford & Chekene (1991) study to included extensive correlations with various ground motion parameters and suggestions for improving loss estimation techniques. Funded by the United States Geological Survey.

Rutherford & Chekene, 1997, *Development of Procedures to Enhance the Performance of Rehabilitated URM Buildings*, prepared by Rutherford & Chekene Consulting Engineers, published by the National Institute of Standards and Technology as Reports NIST GCR 97-724-1 and NIST 97-724-2. This provides information on damage to retrofitted and unretrofitted URM bearing wall buildings in the 1994 Northridge Earthquake.

Cost and Lost Estimation Studies

FEMA, 1994, *Typical Costs for Seismic Rehabilitation of Existing Buildings, Volume 1: Summary*, Second Edition, FEMA 156, Federal Emergency Management Agency, December. This, together with FEMA 157, summarizes a collection of seismic rehabilitation project costs and provides guidance on how to adjust the costs for specific projects based on different variables. It covers a variety of structural systems.

FEMA, 1995, *Typical Costs for Seismic Rehabilitation of Existing Buildings, Volume 2: Supporting Documentation*, Second Edition, FEMA 157, Federal Emergency Management Agency, May.

Recht Hausrath, 1990, *Seismic Retrofitting Alternatives for San Francisco's Unreinforced Masonry Buildings: Socioeconomic and Land Use Implications of Alternative Requirements*, prepared for the San Francisco Department of City Planning. This was a companion study to Rutherford & Chekene (1990) that provided detailed economic assessments of the viability of the three alternatives that were being considered by the city for a mandatory URM bearing wall strengthening ordinance.

Recht Hausrath, 1993, *Socioeconomic and Engineering Study of Seismic Retrofitting Alternatives for Oakland's Unreinforced Masonry Buildings*, prepared for the Office of Public Works, City of

Oakland. This is similar to the work done for San Francisco in Rutherford & Chekene (1990) and Recht Hausrath (1990); however, Oakland also included URM infill frame buildings.

Rutherford & Chekene, 1990, *Seismic Retrofitting Alternatives for San Francisco's Unreinforced Masonry Buildings: Estimates of Construction Cost & Seismic Damage*, for the Department of City Planning of the City and County of San Francisco, Oakland, CA, May. This was a major engineering study prepared as San Francisco was considering options for a mandatory seismic strengthening ordinance for URM bearing wall buildings. Fifteen prototype buildings were developed to represent the over 2000 URM buildings in the city. Three levels of seismic strengthening were described and retrofit designs were created for each level for each prototype. Cost estimates and loss estimates were performed for all prototypes and levels. The Loma Prieta Earthquake struck as the study was nearing completion and the loss estimation methodology was tested against actual observations in the earthquake.