



New Zealand Society for Earthquake Engineering

THE CANTERBURY EARTHQUAKES:

Answers to critical questions about buildings

The Canterbury region has had a series of extremely difficult challenges as a result of the 4th of September earthquake and its associated aftershocks.¹ This has led to questions related to the expected building performance, as well as their actual behaviour, in an earthquake. As a result, the following answers have been prepared by the Royal Society of New Zealand, the Institution of Professional Engineers New Zealand, the Structural Engineering Society New Zealand, the New Zealand Geotechnical Society and the New Zealand Society for Earthquake Engineering, who have co-ordinated science and engineering expertise from across New Zealand.

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What are the functions and forms of buildings?

Buildings provide shelter and security. They serve several needs of society: as shelter from weather; as secure, comfortable and healthy spaces in which to live, work, and trade; and, for storage.

Buildings have evolved in form throughout history. Initially this was by trial and error, but subsequently incremental scientific research, innovation, and architectural and technological developments, have enabled the construction of the buildings of today, from modest single story residential houses to multi-functional high rises and monumental forms.

New Zealand's buildings, immediately following European settlement, were mostly built on timber pile foundations, with timber frames, weatherboards, and light galvanised iron roofs. Over time commercial and public building led to an increase in the use of unreinforced cut stone and clay brick, with these materials given preference over timber for their perceived aesthetic and fire resistance qualities. It was not until after the 1931 Hawke's Bay earthquake, and the associated catastrophic collapse of most of the region's unreinforced masonry buildings, that a national building standard, or building code, came into existence; in part to prohibit the use of unreinforced masonry. Reinforced masonry, steel, reinforced concrete, reinforced concrete block, tilt-slab, and light timber frames became approved materials for buildings. Foundations evolved from piles, to piles coupled with continuous concrete perimeter footings, then to concrete slabs. High rise building foundations used longer piles or raft foundations. Accepted roofing types included corrugated iron and pressed metal tiles, concrete tiles, and masonry tiles. Reinforcing details and the tying of brick and concrete block veneers became increasingly detailed over the progressive revisions of the New Zealand building codes.

What controls building design and construction?

New Zealand, like many other developed countries, designs and builds according to standards (building codes), building consents and inspections, and practices that are based on New Zealand and international research and experience. Building performance and quality is dependent on the building industry having appropriately educated, trained, and paid staff in the fields of design, consenting, inspection, and construction.

Building and construction in New Zealand today is legislated via an Act, Regulations, the Code, Standards, and Advisories. The intent is to ensure economic and efficient construction that is fit for purpose, and manages the identified risks to life safety of wind loading, flooding, earthquake, and snow. Risk management includes recognition that some buildings are more important than others,² because they may contain many people (schools, halls, shopping malls) or they serve critical public functions (hospitals); garden sheds are amongst the least important. The most important levels of building are typically stronger and more expensive to construct than the less important. The risk management approach accepts that less important buildings may fail in some manner—with little risk to life—but may need demolition and replacement. It has been judged in the past that our society cannot afford for every building to be very strong, safe, and secure and that society tolerates a level of risk, as in the case of driving or biking on our roads.

How are buildings made earthquake resistant?

It is recognised that there is no such thing as an “earthquake proof” building; however, some level of earthquake resistance can be provided. Early New Zealand buildings were not designed with any earthquake resistance in mind. The introduction of steel and reinforced concrete led to a significant improvement and between 1930 and 1960 the general idea was to create enough strength to resist

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earthquake shaking. Groundbreaking research in New Zealand, coupled with pioneering applications by practicing engineers in the late 1960s, led to a new building design approach that has now been adopted around the world. This approach makes the whole building tough, rather than just its individual parts, providing a greater level of safety against collapse. This is achieved by making the components work in concert; the vital, or brittle, parts of the building, like columns and joints are over-strengthened, with other parts designed to be weaker (or absorb energy) to act like a fuse. The result is a controlled structural yielding, with damage occurring in a predictable way without collapsing, under designed earthquake shaking levels.

The principles of earthquake resistance developed from international experience of earthquakes on buildings include:

- Providing “stiffness” so that buildings do not move much in small earthquake shaking and there is no damage.
- Providing “strength” so that buildings do not have any significant damage to the building frame in moderate levels of earthquake shaking.
- Providing “toughness” so that buildings do not collapse under more extreme earthquake shaking, such as that considered in the design code of the time. This toughness is the ability to absorb energy is called “ductility”. As the building absorbs energy, damage occurs without collapse.



Figure 1: An energy absorbing (ductile) beam hinge in a reinforced concrete building after an earthquake. As these ductile elements yield they absorb energy without loss of strength that would lead to collapse of the building. While some of the cover has fallen off, none of the reinforcing has broken, and the concrete inside the reinforcing cage is intact, so this beam can still carry load.

The performance of a building during an earthquake depends on its: design; quality of construction; age; together with the materials used, how well it has been maintained, and the level of shaking it has had to experience. In general, regularly shaped buildings perform better than more novel shaped ones, containing odd angles and protuberances, unless appropriate attention is made to the effects of these irregularities. Placing a building far enough from another, can prevent one pounding on and damaging the other. The structure of the ground that foundations are on can also have major effects.

Lead rubber bearings, as deployed at Christchurch Women’s Hospital (Figure 2 & 3), Parliament and Te Papa, are an example of a novel device developed by the former NZ Department of Scientific and Industrial Research in order to protect structures against severe ground shaking. This is called base isolation, because it allows the ground to move horizontally beneath the building thereby isolating the structure from the ground and significantly reducing the forces on the building. Te Papa’s base isolators can be seen as a special exhibit just around the corner from the museum’s main entrance.



Figure 2: Christchurch Women's Hospital sits on Lead Rubber base isolators.

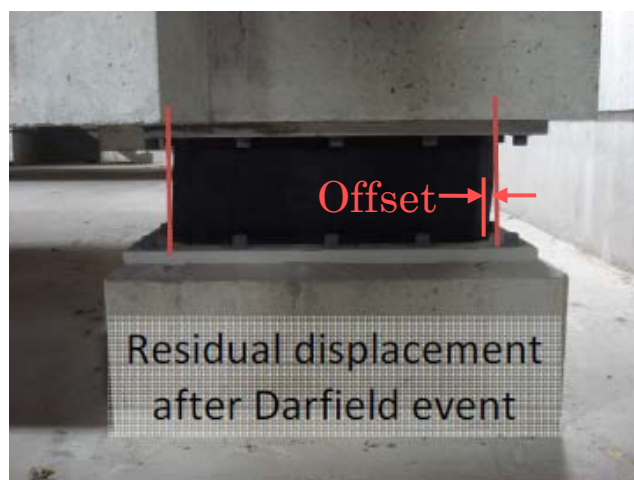


Figure 3. Lead Rubber base isolator under Christchurch Women's Hospital, showing the final resting position of the building after its oscillation during the 4 September 2010 earthquake.

There has also been research on how to strengthen older buildings, and how to add further protection to vital buildings such as hospitals. Some of these methods include: removing particularly vulnerable parts of buildings (e.g. brittle façades and parapets); tying the walls together with steel bracing; bolting façades to the building's frame; adding new support structures; and, wrapping columns and joints with steel and other materials to keep them intact.

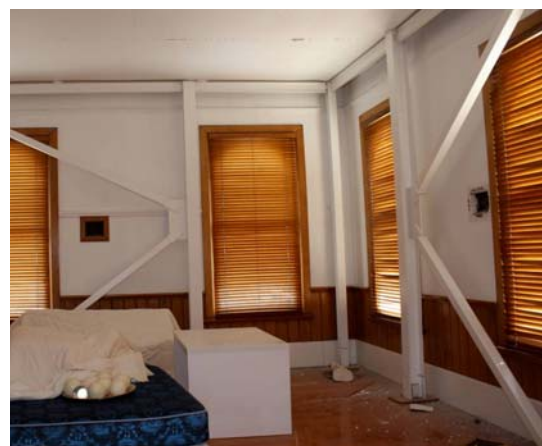


Figure 4: The Lyttelton Fire Station building suffered only minor damage as it has been strengthened with an internal steel frame (Photos Win Clark)

More recently, researchers have developed a new generation of structures which are not expected to have any significant damage during very high shaking, so that not only is collapse prevented, but the building can also be immediately used after the earthquake. Such technology has been used to construct the Southern Cross Hospital Christchurch which behaved well.

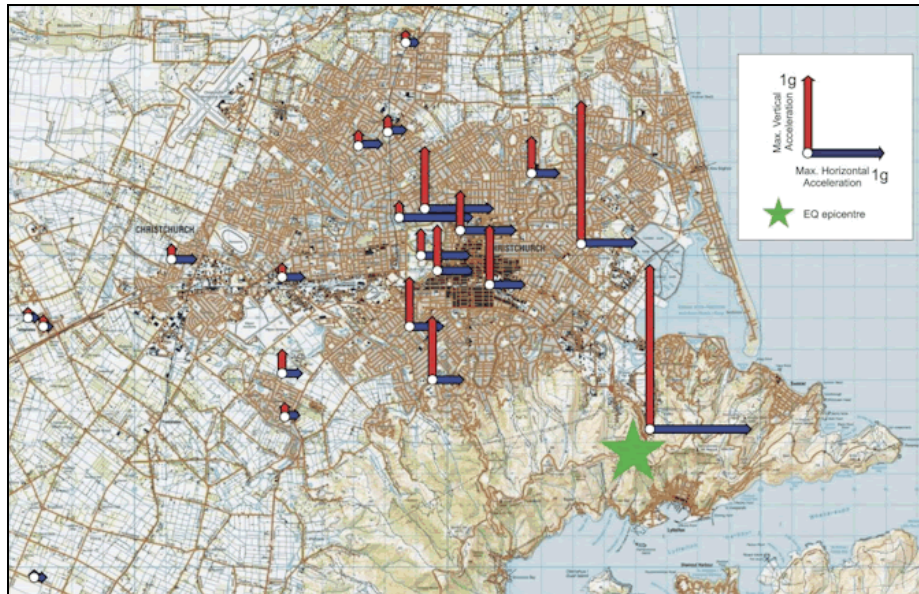
How do earthquakes damage buildings?

Earthquakes affect buildings in several ways. When the earth's crust is convulsed by a major earthquake, enormous amounts of energy are released as shock waves. Many of these are channelled to the surface through the various rock and soil types in the earth. The effect of these waves striking the surface makes the ground move and shake, or even split open. If buildings are not stiff enough to withstand the shaking, but they are still strong, they may experience large displacements and there may be damage to some parts such as windows, wall and ceiling linings. If the building is not strong enough, but has enough toughness, there may be some damage to the building frame but there will not be collapse. If the building is not tough enough, the designed ductility of the building may be exceeded resulting in partial or full collapse.

Despite being only 6.3 on the earthquake magnitude scale, the proximity of the 22 February and 13 June 2011 events to the surface, and to Christchurch, caused ground shaking in the central business district several times as severe as what occurred in the magnitude 7.1 September 2010 earthquake (Figures 5a and 5b). The geology of the area made matters worse by guiding the shock waves towards the city. The peak ground accelerations, as they are called, were amongst the highest to have ever been recorded in a modern city anywhere in the world.

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a)



b)

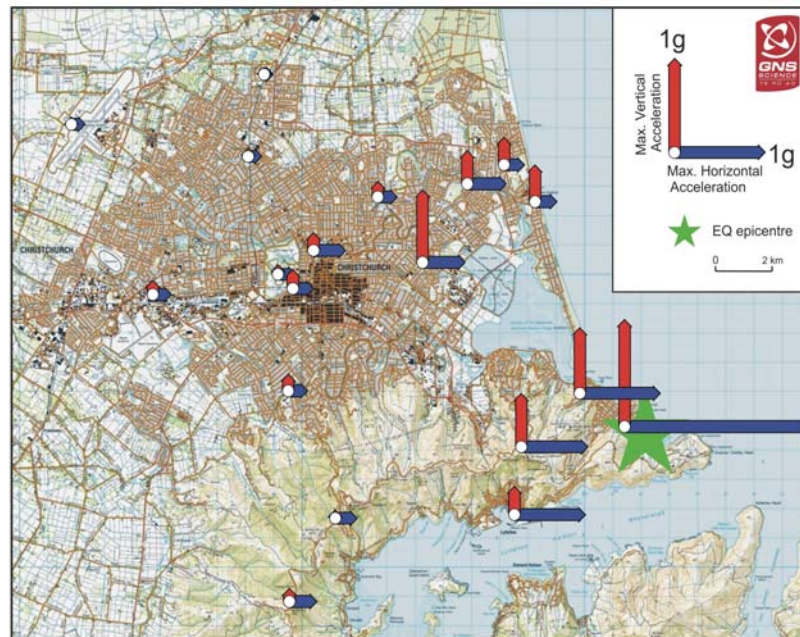


Figure 5a and 5b: Graphic showing the unusually high vertical ground accelerations in central Christchurch recorded during the magnitude 6.3 earthquakes on 22 February and on 13 June 2011. (Source: GNS Science)

That is not the full story; ground may no longer be able to support a building after an earthquake's shock waves have changed the nature of that ground. A now familiar example of this is liquefaction, when the shaking of ground comprised of sands and silts, with a high water-content, results in the ground behaving like a liquid for a short time. When this happens, the soils will not be able to support the weight of the building. Along with liquefaction, lateral spreading is where the ground slumps towards low points, such as rivers and harbours, and can tear buildings apart.

Other ways earthquakes cause damage to buildings include when two adjacent buildings collide as the ground movement makes them sway, causing pounding damage (Figure 6), or when sometimes, parts of one building—like parapets, chimneys or façade veneers—fall on another building and cause damage.



Figure 6: Pounding-induced damage of buildings in Christchurch CBD³

How is the minimum earthquake shaking level for building designs set?

The level of earthquake shaking that a building is expected to withstand, without damage or collapse, is influenced by both safety and economic considerations. If buildings are designed to resist very large earthquakes, they are generally more expensive to build. If they are not designed to resist earthquakes, or to resist only very small ones, they are cheaper to build but they are much more likely to be damaged during strong earthquake shaking, possibly resulting in collapse and death. New Zealand's earthquake design code minimum levels are based on the most current seismic information available at their time of writing, and they are similar to those used in many other countries with similar earthquake risks. The design code specifies a minimum design level; however, buildings may be designed to resist significantly greater levels of shaking due to other factors, such as wind-loading controlling a building's design strength, or due to the requirements of the owner.

For what level of shaking are buildings currently designed?

Most buildings for normal use are designed to safeguard lives in earthquake shaking which has about a 10% chance of occurring in 50 years. This is also called “500-year earthquake” shaking, because the chance of exceeding such levels of shaking is 1/500, or 0.2%, in any one year. Although this means that there is a low likelihood of a significant earthquake occurring, one may happen at any time, even if one has happened only recently.

A building built to code that goes through such 500-year earthquake events is expected to be tough enough to withstand the shaking without collapse but it may be significantly damaged—it may even have to be subsequently pulled down. The code expectation is that everyone can get out alive from a building designed for 1 in 500-year earthquake shaking after the building has experienced shaking up to that level. Critical buildings in New Zealand—those that have important contents or that are expected to function after a big earthquake, such as hospitals and communications centres—have higher standards applied; they may be designed for 1,000 or even 2,500-year earthquake events.

What is an earthquake prone building?

A building is earthquake-prone under the Building Act 2004 if, having regard to its condition and to the ground on which it is built, and because of its construction, the building will in a moderate earthquake be likely to collapse, causing injury or death to persons within that, or any other property, or damaging other property. The latest requirement is for buildings that do not meet more than one third of current code standards to be labelled “earthquake prone”. This then means owners have to take some action in accordance with rules and timetables set by local authorities—generally to bring them up to at least one third of code within a certain number of years. Some local authorities are trying to enforce a minimum of two-thirds of code.



Figure 7. Former earthquake prone buildings.

Every Territorial Authority is required under the Building Act 2004 to have an “Earthquake Prone Building” policy.⁴ The measures in the legislation recognise that local economic, social and other factors have an impact on the implementation of these provisions of the Act. Christchurch City Council had estimated before the September earthquakes that, as defined in the Building Act 2004, there were potentially 7600 “earthquake prone” buildings in Christchurch; these are primarily commercial buildings constructed before 1976.

Those buildings identified as being at the highest risk of collapse were the approximately 960 unreinforced brick and stone masonry buildings, which are likely to fail in a moderate earthquake, although refurbishment and redevelopment for new uses has meant some of the buildings have undergone some level of strengthening. Christchurch City Council had also estimated there are around 490 heritage buildings that are earthquake-prone as defined by the Building Act; the majority (295) are unreinforced masonry, but also 29 reinforced concrete, and 163 with timber-frames or of other types. The Christchurch City Council, in an extraordinary meeting on 10 September 2010, adopted its revised Earthquake-prone, Dangerous and Insanitary Buildings Policy.⁵

The Canterbury earthquakes since September 2010 have caused catastrophic failure of many earthquake prone unreinforced masonry buildings, as well as two multistory buildings; the Christchurch Canterbury Television (CTV) and Pyne Gould Corporation (PGC) buildings with associated loss of 134 lives.

If some buildings were earthquake prone, why were they not retrofitted?

Enforcement of strengthening measures, or “retrofitting”, has proven difficult everywhere around the world. Owners have to pay for the improvement and, of course, recover the cost from the users of the building. As the buildings in question are older and may be less desirable due to location, they typically do not command high rents, and owners face losses as the buildings have to be closed while they are being retrofitted.

Closing down under-code buildings is also not easy as they may provide employment, accommodation and services. Doing this on a large scale would be detrimental to a city’s economy. Another complication is that some buildings already strengthened will need further work because the code has been upgraded; so owners cannot rely on a once-and-for-all solution.

Why did buildings collapse in these earthquakes?

Most buildings did not collapse even though the levels of earthquake shaking were up to about twice the design level for buildings meeting the current code requirements. Even buildings in areas of liquefaction and lateral spreading, as well as strong shaking, did not collapse despite some being badly damaged (Figure 8) or left tilting.

Those buildings that collapsed due to shaking were not tough enough to resist the strong shaking levels. Many of these buildings were identified as earthquake prone, and had been designed and

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constructed before the current building regulations came into force. Some buildings on, or below, hillsides collapsed due to rock fall or landslide. Since the shaking levels were so much greater than the design level for modern buildings, it is surprising that more buildings did not collapse. Investigations into reasons for the collapse of some specific buildings are now being conducted as part of a special investigation. These investigations are expected to consider the buildings construction as well as their design.



Figure 8 Lateral spread crack running through the courtyard and building at St. Paul's church, Dallington, Christchurch, New Zealand (September 2010)⁶

What types of damage occurred to Christchurch buildings?

In addition to building collapse, damage to buildings resulted from ground failure (liquefaction, lateral spreading, rockfall, and landslides), and the strong ground shaking. The damage to buildings compromised their functions of providing shelter from weather, and secure, comfortable and healthy spaces from which to live, work, trade, and for storage.

Ground failure, resulted from the strong ground shaking, affected many buildings and houses, no matter how they were constructed. For example, liquefaction, lateral spreading, and subsidence broke foundations leaving floors deformed, sloping, cracked, and vulnerable to further intrusion of water carrying silt, sand and other matter. Building frames were sometimes left leaning or broken. Some buildings in the hillside suburbs also had to contend with rock falls. These ground failures, individually or together, could compromise the fundamental functions of a building.

Unreinforced masonry buildings, including those of brick and stone, often suffered significant damage due to separation of the bricks, and their walls and roofs sometimes collapsed. Unreinforced masonry buildings that were retrofitted to levels less than the full code level, also often sustained significant damage. Collapsed buildings also totally compromise their basic function.

Other types of building sometimes had different types of failure in one or more of their structural parts, which compromised their safety function in future earthquakes.

Apart from the building structure itself, there was damage to ceiling and wall linings, and partitions in many old and new buildings. Building services, such as light fittings, fell out while heating, ventilating

and fire sprinkler systems sometimes moved and lost their function. Some of these fell and were a life safety hazard. Shelves lost contents, items fell and broke, and filing cabinets and furniture overturned. Also exterior cladding and window glazing damage sometimes occurred. In the hill areas, roof tiles were dislodged and sometimes thrown in the air. This damage compromised weather tightness. Fire damage occurred in only a few buildings after the earthquakes.

What is building safety evaluation?

A declaration of a “state of emergency” gives the Civil Defence controller the power to authorise engineers to conduct building safety evaluations. The results of these evaluations must be obeyed until the state of emergency is lifted, unless special arrangements are made. In Canterbury, the Canterbury Earthquake Recovery Agency (CERA) Act allows for an extension of the time that the results of the evaluations apply.

The first building safety evaluation is a Level 1 rapid damage assessment. These assessments are to be performed rapidly because engineers have to urgently assess many structures—not just houses and buildings. Every building is assessed from outside and results in either a red, yellow or green placard being attached. The colour of the placard has the following meaning

- Red means that the building is clearly unsafe and should not to be entered.
- Yellow means there are safety concerns resulting from the observed earthquake damage, but that some restricted entry for a short period time is not likely to pose a significant safety risk in a significant aftershock.
- Green means that there is no apparent damage that would indicate an increased risk of collapse. Often it is recommended that these buildings should be further examined.

Level 2 assessments, which involve entering buildings, may be carried out for large buildings and critical facilities, and the placard may get changed. More detailed engineering evaluations should follow with the principal objective of ensuring confidence in the state of the building.

Rapid building safety evaluation placards are based on the apparent structural or other safety hazards at the time the building was inspected by the engineers. The purpose is to indicate the state of the building for immediate use following an earthquake or other event, based on a limited evaluation.

Given that a building has been through one earthquake, how do we know how much of its “earthquake life” has been used up?

Every building can be thought of having its own "earthquake life" and this life is different depending on the design and construction of the building. The earthquake life can be used up, and collapse can occur, after one large shake, or after a number of smaller shakes.

In older brittle buildings, very small amounts of shaking often cause little damage; however, when the shaking is large enough to cause the building's strength to be reached, partial or full collapse may occur. For these buildings, if there is no damage, then they probably have close to their full "earthquake life" remaining. If the building is damaged and has not collapsed it is probably close to exhausting its "earthquake life" and the effected parts would require considerable strengthening or replacement before the building can be used again. It should also be noted that the earthquake life for brittle buildings is generally significantly less than that for ductile buildings.

More modern ductile buildings must undergo large displacements, and sustain significant damage, before they are likely to collapse. If they have been damaged, then this is able to be seen visually. In concrete buildings, there will be cracks and possibly fragmentation (spalling) of the concrete and buckling of the reinforcing bars. In steel buildings, damage may be flaking of paint or buckling of the steel. From this observed damage, it is possible to estimate how much of the life for the structure is used, and decisions can be made as to whether the effected building parts should be left as is, repaired or replaced. Guidelines are available as to what can be done in the way of repair, but the final decision also involves economic considerations.

Are earthquake design codes likely to change as a result of this earthquake sequence?

Yes. These building regulations are continually under review as we learn more and more about how earthquakes affect buildings and other structures. This mirrors the actions following the previous very severe earthquake, the February 6th 1931 Napier/Hastings earthquake, which is still New Zealand's most severe earthquake in terms of loss of life and which led to the development of the first earthquake design standard, the first New Zealand Building regulation. Subsequent reviews have been informed from world wide experience and research.

Is all masonry susceptible to damage or collapse in large shaking?

Just because a building is constructed in brick or stone, it is not necessarily a danger. If brick masonry is properly attached to a backing frame, as it is in most residential construction, it can behave well as can masonry blocks filled with concrete and strengthened with steel rods. Brick masonry restrained by a concrete or steel frame, if properly designed, can also behave well and it has been used effectively throughout the world, including Christchurch, as shown in Figure 9.



Figure 9: Orion Local Substation. Constructed in unreinforced brick masonry that has been strengthened with a steel perimeter frame (Photo Win Clark)

New materials and construction techniques are being developed that can enhance the capacity of existing brick and stone masonry buildings to withstand the earthquake effects. These materials include glass and carbon fabrics that are saturated with epoxy resins and then bonded onto the surface of the brickwork, or cut into the matrix of the masonry. Bonding carbon fibres or stainless steel rods into the bedding joints of the masonry can provide additional capacity to carry earthquake loads. Careful design and construction is required to provide an enhanced structural system for the masonry building.

Is there room for improving building safety?

Greater building safety comes at a cost, but this may not always be significant. The best time to increase earthquake safety measures is at the start of a project. Existing structure retrofit is generally a much more expensive way to increase earthquake resistance.

Building safety can be improved by:

- Increasing the level of earthquake design considered in the building code. This would generally have cost implications.
- Increasing quality control and inspections during construction. The amount that this would improve safety is unknown, and again there would be increased costs.
- Developing improved technology to resist damage in larger earthquakes. The new Southern Cross hospital Endoscopy Consultants' Building, Christchurch is an example of new technology that has been shown to reduce the worst damaging effects of earthquakes.
- Learning from the Canterbury, and other, earthquakes around the world, and applying these lessons to new construction and retrofit of existing buildings.

What are some of the new lessons from the earthquake sequence?

There is more to learn but so far:

- Modern buildings on good foundations, constructed according to the building code in force now, protected lives even though shaken to a greater extent than the code design level.
- Better designed foundations than those used at present are needed to counteract the effect of liquefaction, especially for houses. Engineers are already working on this.
- Non-symmetrical buildings can behave poorly if careful design is not conducted.
- Potential rock falls on hillside areas overlooking towns and suburbs have to be recognised, and appropriately considered.

What are some low cost methods of improving earthquake safety?

There are a number of relatively low cost methods of improving earthquake safety.

For homes:

- Secure heavy items, such as header tanks, and tie back water cylinders.
- Brace, strengthen or remove brick or other unreinforced masonry chimneys. Strengthening may be achieved with a galvanised steel tube grouted into the chimney flue. Where the chimney is to

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be removed, demolish completely if located externally, and down to ceiling level if internal. Replace chimneys with code-compliant steel flue. Where architectural form requires a chimney above the roof plane, install a fibreglass replica. Ensure all new chimneys comply with the Building Code.

- When building, use “earthquake friendly” materials like piled or waffle-slab foundations, timber (or light steel frame) walls and lightweight roofs.
- Remove heavy roofs like concrete tiles and replace them with lightweight materials such as steel.
- For remedial works on houses, see the Department of Building and Housing advice at <http://www.ipenz.org.nz/ipenz/practicesupport/compendium-detail.cfm?id=604>

For larger buildings:

- Consider enhanced seismic performance and design requirements at the time of design
- Make structures as symmetric as possible, not necessarily to the detriment of architectural form
- Remove or strengthen poorly attached heavy architectural ornaments and parapets on old buildings.
- Increase the strength of brittle building components, for example by fitting steel bracing frames in low rise concrete frame buildings.
- Strengthen the buildings with strong and ductile systems that have increased stiffness to limit the displacements.

¹ The Canterbury Earthquakes: Scientific answers to critical questions (2011) Royal Society of New Zealand & the Office of the Prime Minister’s Science Advisory Committee
<http://www.royalsociety.org.nz/media/Information-paper/The-Canterbury-Earthquakes-Scientific-answers-to-critical-questions3.pdf>

² Importance Levels 1 – 5 are defined in the Australia/New Zealand Standard for Structural design actions AS/NZS 1170.0:2002

³ Development of pounding model for adjacent structures in Earthquakes (2011) S. Khatiwada, N. Chow and J.W. Butterworth; Proceedings of the Ninth Pacific Conference on Earthquake Engineering Building an Earthquake-Resilient Society; 14-16 April, 2011, Auckland, New Zealand; Paper Number 080

⁴ See - Earthquake-Prone Buildings Policies <http://www.dbh.govt.nz/officials-earthquake-prone-buildings>
accessed 8 June 2011.

⁵ See - Earthquake-Prone Dangerous and Insanitary Buildings Policy 2010
<http://www.ccc.govt.nz/thecouncil/policiesreportsstrategies/policies/groups/buildingplanning/earthquake-pronebuildingspolicy.aspx> accessed 8 June 2011.

⁶ Geotechnical reconnaissance of the 2010 Darfield (New Zealand) earthquake (2010) NZ-GEER Reconnaissance Report http://db.nzsee.org.nz/PUBS/NZ-GEER_Ver_NZ1.pdf