

Learning from Earthquakes

The M 6.3 Christchurch, New Zealand, Earthquake of February 22, 2011

From February 22 to March 19, 2011, a team organized by the Earthquake Engineering Research Institute (EERI) and the Pacific Earthquake Engineering Research (PEER) Center investigated the effects of the Christchurch earthquake. Led by Mary Comerio, UC Berkeley, and Ken Elwood, University of British Columbia, the team included Russell Berkowitz, Forell/Elsesser; Michel Bruneau, University at Buffalo; James Dismuke, ARUP Australia; Henri Gavin, Duke University; Nathan Gould, ABS Consulting, Inc.; Kishor Jaiswal, U.S. Geological Survey; Thomas Kirsch, Johns Hopkins University; Tao Lai, AIR Worldwide; Justin Marshall, Auburn University; Ronald Mayes, Simpson Gumpertz & Heger; Judith Mitrani-Reiser, Johns Hopkins University; Troy Morgan, Tokyo Institute of Technology; Tim Mote, ARUP Australia; Lori Peek, Colorado State University; Sri Sritharan, Iowa State University; Jeannette Sutton, University of Colorado-Colorado Springs; Fred Turner, California Seismic Safety Commission; Anne Wein, U.S. Geological Survey; and Mark Yashinsky, Caltrans. Tom O'Rourke of Cornell University visited Christchurch the week of April 1st with the TCLEE team and contributed to this report. Robert Fleischman of the University of Arizona also contributed.

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Introduction

At 12:51 pm local time on February 22, 2011, an M 6.3 earthquake shook the city of Christchurch, New Zealand. It was an aftershock of the M 7.1 Darfield earthquake of September 4, 2010 (see the November 2010 *Newsletter* for a report on that earthquake). Although lower in magnitude than the earlier quake, the aftershock was centered closer to the city and caused significantly more damage, particularly in the Central Business District (CBD). While the September 4 earthquake struck in the middle of the night, the February 22 earthquake hit when people filled the offices and cafes of the CBD, leading to 184 confirmed

deaths. Widespread liquefaction in the CBD and the eastern suburbs caused foundation movement in housing and office buildings alike. Two reinforced concrete office buildings and one parking garage collapsed, as did hundreds of unreinforced masonry buildings, including a number of heritage structures. Many other buildings in the CBD were severely damaged, and some required demolition, which necessitated careful controlled access to the CBD in the weeks following the earthquake. The total losses are estimated over NZ \$20 billion.

Christchurch is the largest city on the South Island of New Zealand, and the country's second-largest urban area. It lies within the Canterbury Region and has a population of 375,000. Prior to September 2010, Christchurch was not considered a high-risk seismic area and had a voluntary retrofit ordinance for its unreinforced masonry buildings. That the construction types are similar to those of the United States and

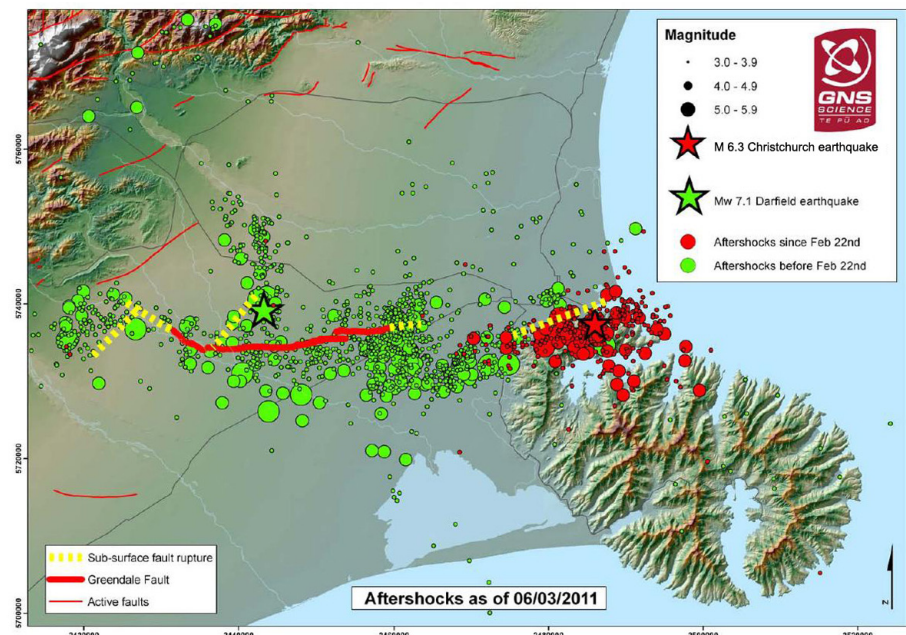


Figure 1. Location of epicenter and aftershock sequence from the M 7.1 September 4, 2010, Darfield (Canterbury) and M 6.3 February 22, 2011, Christchurch earthquakes (source: GNS).

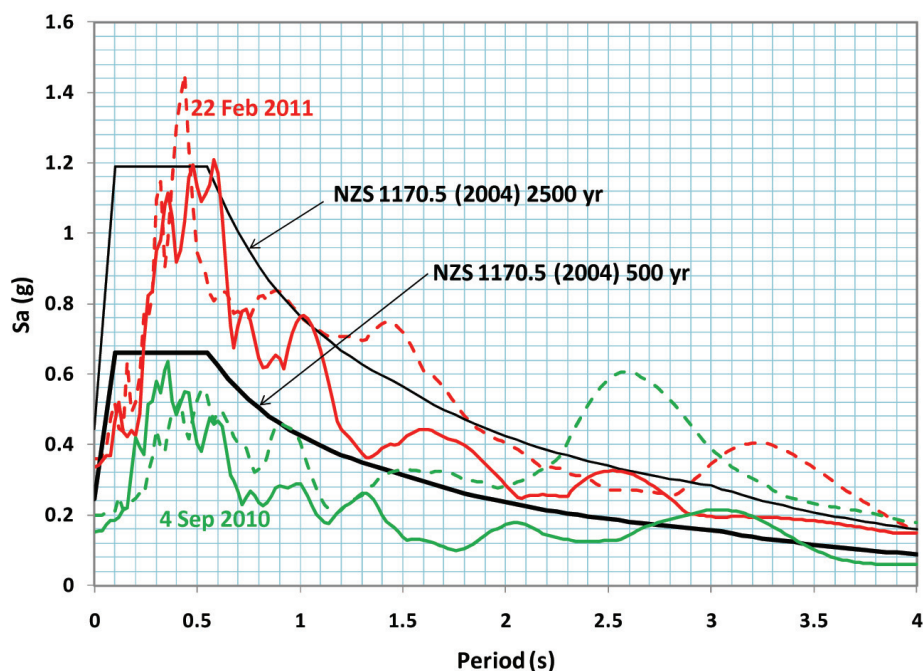


Figure 2. Horizontal spectral acceleration for Christchurch Hospital (8 km epicentral distance) from September 4 and February 22 events compared with NZS 1170.5 elastic design spectra for Christchurch (source: Elwood, ground motion data from GeoNet).

other countries, and that the earthquake was located on an unmapped fault within 10km of the city center make this one of the most significant earthquakes in recent years for code and standard development in the United States and internationally.

Seismicity

The earthquake struck on a fault approximately 6km south of the Christchurch CBD in the Port Hills at a focal depth of 5km (see Figure 1). Focal mechanism solutions show the fault ruptured as oblique–thrust (65° from the horizontal), dipping to the south. Fault slip was as much as 2.5m along a subsurface fault rupture of about 14km. There was no evidence of surface rupture.

The earthquake extended the aftershock sequence of the M 7.1 September 2010 event considerably eastward. The complex pattern of aftershocks delineate a number of east-west and northeast-southwest trending structures. The east-west trending structures are interpreted to be older structures associated

with the Chatham Rise extending into the Pacific Ocean to the east of Christchurch. The fault responsible for the February quake is not believed to be an easterly projection of the fault that caused the September quake (the Greendale fault). The earthquakes represent reactivation of faults broadly associated with regional plate deformation between the Pacific and Australia plates. Before the September 2010 earthquake, these structures were unrecognized under kilometers of alluvial deposits in the Canterbury Plains.

Since the September earthquake, there have been more than 18 aftershocks greater than M 5.0, with the February event being the largest aftershock by a half magnitude. On December 26, 2010, an M 4.9 aftershock near the CBD caused considerable damage to unreinforced masonry buildings.

Strong ground motion recording stations, some set up as temporary stations to record aftershocks from the September 2010 earthquake, report peak ground accelerations up

to 1.5g in Heathcote Valley Primary School, 1 km from the epicenter and 0.72g in the CBD. Unusually high vertical ground motions, sometimes exceeding the horizontal component, were recorded for the event. The strong ground shaking lasted for approximately eight seconds in the CBD.

Ground motions recorded in the CBD generally exceeded the 500-year and even the 2500-year elastic design spectrum from the New Zealand seismic design standard (NZS 1170.5 2004). Under that standard, ordinary buildings are designed for the 500-year return period spectrum using ultimate limit states design principles, and are expected to have a small margin against collapse for the 2500-year spectrum, assumed to be 1.8 times the 500-year spectrum (King et al., 2003). Figure 2 compares the elastic design spectra with the 5% damped response spectrum for the horizontal components recorded during the September and February events at the Christchurch Hospital. The demands at this station are typical of the four stations located in the CBD. The spectral demands for the second earthquake are clearly higher than those from the earlier one for periods less than 1.5 seconds; for longer periods, the two events are similar. The Structural Engineers Society of New Zealand has recommended that the 500-year elastic design spectrum for Christchurch be amplified by 136% for periods less than 1.5 sec, pending further research, to address the increased risk of M 6–6.5 events close to the CBD (Hare 2011).

Geotechnical Effects

The earthquake caused unprecedented liquefaction in the CBD and eastern suburbs as well as significant landsliding and rock falls in the Port Hills in the southern part of Christchurch. These and other geotechnical effects are described in detail in the GEER report (2011). A brief summary of the geotechnical impacts is provided below.

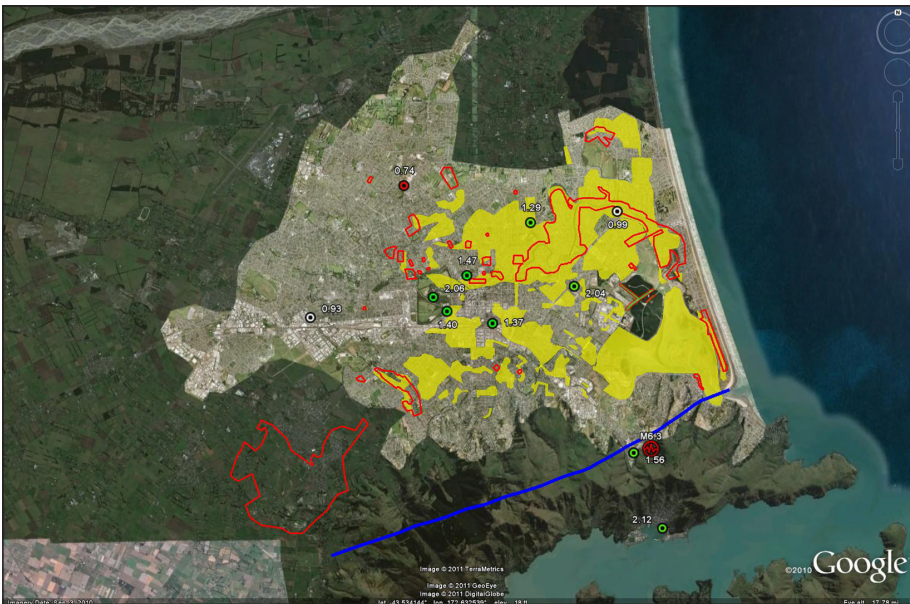


Figure 3. Liquefaction in February 2011 (green) and September 2010 (red contours) (courtesy of R. Green; GEER 2011).

Liquefaction. Liquefaction was widespread in the CBD and surrounding suburbs (Cubrinovski and Taylor 2011), and covered a greater area than had been indicated on the Environment Canterbury liquefaction hazards maps produced by Environment Canterbury in 2004. A range of liquefaction-induced phenomena were observed, including sand boils, settlement, uplift, and lateral spreading. The region affected was considerably larger than that of the September 2010 earthquake (Figure 3), with more than 50% of the Christchurch area affected. As much as 2-3m of lateral spread and 1-2m of settlement were observed in the eastern suburbs. The combined settlement caused by liquefaction during the recent earthquakes and aftershocks has exposed many Christchurch neighborhoods to increased threats from river and ocean flooding, including tsunamis.

Sand boils were the most common evidence of liquefaction, and in many locations sand and silt tens of centimeters thick accumulated in lower-lying areas and filled drainages (Figure 4). Sand boils were frequently accompanied by deformation and settlement of flexible

pavement and concrete hardscape.

Structure settlement generally affected structures with shallow foundations and appurtenant works, such as planters and privacy walls. However, building settlement was not limited to structures with shallow foundations; uplift of utility vaults and below-ground structures was also common.

Lateral spreading in the CBD extended on the order of 10-30m from river banks, based on the location of observable tension cracks and ground surface deformation patterns. The largest fissures and deformations observed were on the order of up to 1m.

Retaining walls. A survey of about 100 retaining walls ranging in height from 1-5+m was conducted in areas of Lyttelton, Mount Pleasant and Sumner. The survey was not exhaustive, and was limited to walls that could be observed from public right-of-ways. Many walls, especially brittle ones such as grouted rock and masonry, exhib-

ited structural failure while leaving a near-vertical soil face intact. Concrete and timber crib walls frequently exhibited settlement and crib cracking, but overall wall shape was preserved. Timber crib and timber pile-supported walls performed well despite deformation and ground cracking at the top of the walls (up to 450mm in one instance). Every type of retaining wall observed exhibited supported-ground failures, with the exception of timber-piled walls.

Rockfall/landsliding. Many rocks fell from cliffs throughout the hillside suburbs of Lyttelton, Mount Pleasant, and Sumner, causing a number of fatalities, damaging structures, and rendering many buildings inaccessible due to fear of more rockfall in aftershocks.

In some cases, entire cliffs collapsed (Figure 5), while in others boulders up to 5m in diameter were dislodged. Tension cracks 10-20m back from the cliff edges, often through residences, are being monitored. The prodigious rockfall was likely due, in part, to a number of source areas having been loosened in the September earthquake; furthermore, the February quake produced significant vertical ground accelerations as well as topographic effects that increased ground motions.

Efforts were underway at the time of the reconnaissance to map boulders, rockfall/debris travel paths,



Figure 4. Severe liquefaction in the CBD (photo: Kam)



Figure 5. Large and damaging rockfall behind Moa Cave Guest house, Red-cliffs (photo: Mote).

and rockfall source areas. Where rock fall was still considered possible in aftershocks, potential hazards were being scaled away with temporary rockfall retaining barriers setup to protect the public. Considerable coordination among the geotechnical inspections, structural inspections, and water infrastructure surveys was required.

Lifelines and Transportation

Lifelines. There was extensive damage to lifelines, including potable water, wastewater, and drainage facilities, roads and highways, and electric power distribution. The damage was caused predominantly by liquefaction; differential settlement and lateral spreading disrupted both potable water pipelines (mostly asbestos cement and PVC) and wastewater pipelines (mostly gasketed concrete and PVC). There are likely thousands of breaks and lesser flaws in these networks, and the total number of required repairs is still unknown. Buoyancy of concrete vaults at potable water and wastewater pump stations, compounded by liquefaction-induced settlement, caused pipes to break at connec-

tions with the vaults. Approximately 1m of settlement at the Bexley Pump Station ruptured the well, which flooded the surrounding neighborhood at 140m³/hr. Massive amounts silt and sand from liquefaction washed into the Bexley sewage treatment plant, damaging the primary settling tanks and overloading the system. Liquefaction also caused differential settlement of the clarifiers, thereby seriously impairing secondary treatment capabilities.

The impact on the electric power distribution network was approximately ten times that of the September earthquake in terms of service disruption and damage to facilities. The electric power administration buildings were badly damaged. All major 66 kV underground cables supplying the Dallington and Brighton areas of eastern Christchurch failed. Over 50% of all 66 kV cables at multiple locations were damaged by liquefaction-induced ground movement.

The water distribution network in Lyttelton and Harwood had been replaced with high-density polyeth-

ylene (HDPE) pipelines after the September earthquake, and there was not a single instance of damage in that system, although Lyttelton had some of the strongest ground motion recorded in the earthquake, and massive liquefaction was observed in Harwood, including lateral spreading and settlements of 1- 2m. Moreover, there was no damage in the medium-density polyethylene (MDPE) gas distribution system, even though the MDPE pipelines were located in areas subjected to liquefaction during both earthquakes.

Bridges. Most bridges in the Christchurch area are short spans of regular configuration and sometimes monolithic or well-restrained; these bridges generally performed well during the earthquake. Although there were no bridge collapses, damage observed in specific types of bridges provides insight into their behavior under large lateral spreading and ground motion.

The Anzac Drive Bridge, constructed in 2000, was composed of precast girders (as are most bridges in New Zealand) and a precast substructure. Much of the damage (e.g., cracking of bent cap) was likely due to lateral spreading.

Damage to recently retrofitted bridges (on Port Hills Road and Horotane Road) was generally of slight consequence, consisting of abutment wall failures, rotation of abutments, and pile cracking—all accompanied by lateral spreading. With a few exceptions, the bridges were reopened to traffic as soon as new ramps could be filled in over the settled approaches. A notable exception was the Moorhouse Road Bridge, which had severe shear-flexural damage to some of its columns, due to poor reinforcing details. That bridge remained closed for five weeks after the earthquake while temporary steps were taken to prop up the deck.

Several bridges (Bridge St Bridge, Fitzgerald St Bridge) exhibited flex-



Figure 6. Differential movement of adjacent buildings (approximately 700mm at roof level) due to foundation rotation (photo: Elwood).

ural cracking of piles due to liquefaction and lateral spreading of the surrounding soil. There may have been similar cracking in piles supporting wall-piers, but those were hidden from inspection.

Utilities carried by bridges (Bridge Street, Fitzgerald Street) were frequently damaged. In some instances, sewer lines spilled their effluent into the river or water mains broke and washed out embankments. In other cases, the high relative stiffness of the utilities damaged the bridge.

Buildings

Reinforced concrete and masonry buildings. Most of the buildings over four stories in the city of Christchurch are either reinforced concrete or reinforced masonry, and are generally concentrated in the CBD. Multi-story steel buildings are noticeably scarce, mainly because industrial relations issues associated with site welding have significantly hindered steel construction in New Zealand since the early 1980s. Some reinforced concrete and masonry structures completely col-

lapsed; others partially collapsed. At the same time, several modern buildings performed well (see the Tagging section for approximate statistics). Though such variations in performance can be attributed to material type, year of construction, and differences in structural layouts, the variation in soil conditions and shaking (measured peak ground acceleration within the CBD varied from 0.36-0.72g) throughout the city no doubt also played a role. Significant liquefaction adjacent to some structures led to several inches of

vertical differential settlement that tilted buildings. Foundation types also varied in the CBD, ranging from shallow foundations to deep foundations with equal or unequal pile lengths and, in some cases, mixtures of shallow and deep foundations. Figure 6 shows the tilting of two adjacent buildings: the building in the foreground was said to be on a shallow foundation, while the building in the background was reported to be on a combination of piles and



Figure 7. Collapsed reinforced concrete buildings: (a) ▲ The CTV Building and core wall (photos: Kam, Berkowitz); (b) ▼ The PGC Building (photo: Elwood).





Figure 8. Punching shear failures in parking garage (photo: Berkowitz).

shallow foundation. Both buildings are expected to be demolished.

Two reinforced concrete office buildings collapsed (Figure 7): the Canterbury Television (CTV) Building, which caused approximately half the fatalities in the quake, and the Pyne Gould Cooperation (PGC) Building, where 12 people perished. The six-story reinforced concrete CTV building was designed in the mid-1980s and consisted of a coupled shear wall on the south side and a core wall on the north side of the building. The entire building, with the exception of the core wall, collapsed (Figure 7a). The PGC building, designed and built in the early 1960s, was a five-story reinforced concrete frame building with a core wall offset towards the rear of the building. The top four stories collapsed onto the intact first story, with some floor slabs appearing to detach from the core wall (Figure 7b).

Punching shear failures of a prestressed floor slab resulted in partial collapse of a concrete parking garage at the south edge of the CBD (Figure 8). After the earthquake, a permanent twist and residual lateral displacement could be observed in the 19-story Hotel Grand Chancellor, one of the tallest buildings in Christchurch (Figure 9). The east side of the building cantilevered over an



Figure 9. A permanent twist and residual lateral displacement in the 19-story Hotel Grand Chancellor (photos: Elwood, Comerio).

adjacent laneway by the means of transfer girders located on the seventh story, and out-of-plane shear failure was observed at the base of the wall providing the prop for the southernmost transfer girders. Three columns in the same grid line as the transfer girders on the sixth story also exhibited shear and axial failures. The building was surveyed for several days following the earthquake and the lateral displacement was not found to be increasing despite many aftershocks. The dam-

aged wall was stabilized within a week of the earthquake, but the building is now set for demolition.

That significant damage to critical elements was visible in a number of buildings is notable, since the quake was short in duration with relatively few cycles of strong motion. This damage (Figures 10 and 11) was found in older as well as modern buildings, but was more prevalent in buildings constructed before the mid-1980s, when capacity design

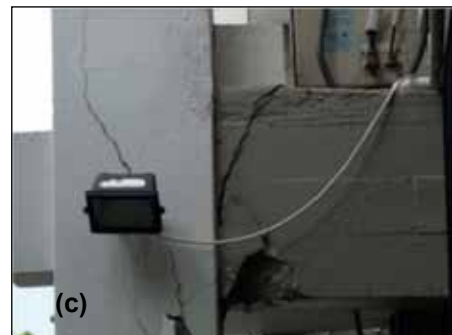


Figure 10. Examples of damage in concrete buildings: (a) column shear failure, (b) precast wall damage, (c) beam-column joint, (d) wall damage (photos: Sritharan).

approaches were introduced in New Zealand. Common observations included 1) irregular configuration of lateral load-resisting systems in plan and/or elevation, 2) non-seismic detailing in the gravity system, and 3) poor grouting of reinforcement in reinforced masonry buildings. In general, significant liquefaction was not observed adjacent to the buildings with these structural damages.

Reinforced concrete moment frame buildings, constructed since the mid-1980s, generally performed well and exhibited limited beam hinging and undamaged beam-column joints. Reinforced concrete shear wall buildings also generally performed well. Exceptions to this good performance included the compression buckling of a wall and fracture of longitudinal bars in a wall boundary zone (Figure 10d). Figure 11 shows what appears to be a regular building with two V-shaped concrete walls on either side of it. The wall on the south side of the building surrounds the elevator and stairs, while the wall on the north side has a direct connection to the diaphragm. It appears the north wall acted as an L-shaped section with a large tension flange contributing to buckling of the unsupported web.

Reinforced masonry buildings are widespread in Christchurch, and some performed well, while others were damaged to an extent neces-

sitating demolition. Typical damage included shear failure of walls and failure of walls and columns due to poor grouting of reinforcement within the masonry cells (Figure 12).

Precast concrete construction is used extensively for the buildings in and around Christchurch and includes 1) emulative precast moment frames for multi-story structures; 2) topped precast flooring elements for multi-story structures and carparks; 3) precast cladding panels; and 4) precast stair elements. With the exception of the precast stairs, the vast majority of these elements and systems performed as intended. Emulative frames developed beam end plastic hinging to a level of damage commensurate with the seismic excitation; floor systems remained seated and intact, with damage limited in most cases to displacement compatibility cracks along the units, though cracking in the end regions of flange-hung double tees was observed and requires closer attention; and precast cladding panels generally remained attached, with only two exceptions noted. Precast stair elements collapsed in at least three multi-story buildings in the CBD (Figure 13), trapping occupants in the buildings for several hours after the earthquake. A hospital building with a self-centering jointed "PRESSS" system (unbonded post-tensioned frame in one

direction, unbonded post-tensioned rocking wall in the other) remained operational with little or no damage.

Steel buildings. Most of the steel buildings in the areas of severe shaking are of recent vintage, designed to the latest seismic provisions, and generally performed well. The Pacific Residential Tower in the CBD (22 stories, completed in 2010) and the Club Tower building (11 stories, completed in 2009) had eccentrically braced frames (EBFs) for which evidence of inelastic deformation was limited to flaking of the brittle intumescent paint on the EBF links at some levels. Both were green-tagged following the earthquake, requiring only some minor repairs of nonstructural components.

In a low-rise parking garage, a few EBFs developed lower flange fractures, with cracking propagating into the link webs; with more than six bays of EBFs in each principal direction, the building survived in spite of the fractures. In other buildings, fractures were observed in connections of concentrically braced frames unable to develop the brace gross-section yield strength, and multiple industrial steel storage racks collapsed. Bruneau et al. (2011) provides a full report on performance of steel structures.

Base isolation. The Christchurch Women's Hospital, completed in 2005, is the only base-isolated

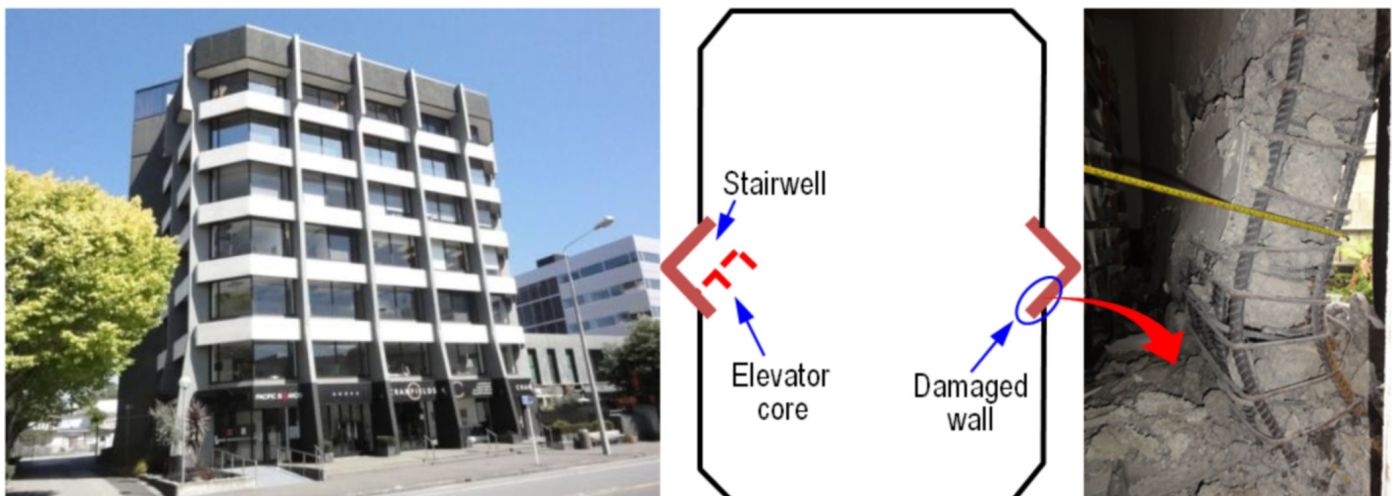


Figure 11. Damaged wall with good reinforcement details (photos: Sritharan, Elwood).



Figure 12. Examples of reinforced masonry damage in multi-story buildings (photos: Jaiswal and Sritharan).

building on the South Island. Its 420mm isolator displacement capacity and its superstructure ductility capacity of 1.8 correspond to 2000-year return-period demands. Because the structure is not instrumented, estimates of seismic responses must be inferred from observations of soil displaced by sliding moat covers, residual displacements in the isolation system, and first-hand accounts. Observations after the September quake revealed damage only to sacrificial nonstructural com-

ponents at the seismic gaps and minor cracking of partitions around window openings. The peak isolator displacements were estimated at 80mm-100mm, with a northward residual displacement of about 25mm. Peak isolator demands for the February quake were estimated from soil displaced by the moat covers to be about 120mm, with residual displacement close to zero.

These isolator displacements are



Figure 13. Collapsed precast concrete stairs in multi-story building (photo: Carri).

less than half of what would be expected given nearby recorded ground motions. This could be explained by evidence of nonstructural elements (crushed macadam, buckled moat covers) binding the motion of the isolation system, and of liquefaction ejecta within the isolation galley. Hospital staff noted fewer reports of nonstructural damage in the isolated women's hospital than in the adjacent fixed-base hospitals in the complex.

Industrial buildings. Most of these structures consisted of steel roof framing with three types of lateral systems: load-bearing tilt-up panels, pre-engineered steel frames with concrete cladding panels, and pre-engineered steel frames with light gauge corrugated steel sheathing. A few examples of the latter were encountered and showed no outward signs of damage.

Several load-bearing tilt-up buildings required temporary shoring. In at least one case, the building had been stabilized but was due to be deconstructed. At its northeast corner, the roof beam-panel connection had pulled out and the panel top moved out-of-plane approximately



Figure 14. Damage to industrial buildings at steel-to-concrete connections: a) roof beam-panel connection in load-bearing tilt-up building; b) steel frame-panel connection in building with nonload-bearing concrete panels (photo: Marshall).

one foot (Figure 14a); note the absence of a continuous ledger at the diaphragm to concrete panel connection. On the west wall, the panels had cracked near midspan and deflected outward six inches.

In several buildings with steel frames and concrete precast panels, flexibility of the steel frame relative to the concrete panels likely resulted in failure of the connection between the frame and precast panels (Figure 14b). In one case, 12 wall panels dropped from a single warehouse. Typically, the end wall panels cracked because they were stiffer than the steel frame.

URM buildings. Hundreds of unreinforced masonry (URM) buildings were heavily damaged or collapsed, roughly two to three times the number similarly damaged in the September quake. Dozens of URM buildings, which were green-tagged with minor or no obvious damage in September, partially collapsed in February. The number of deaths in URM buildings was probably reduced because a number of the buildings had been closed or cordoned off since September.

Many retrofitted URM buildings were affected by the two earthquakes, and provide a tremendous opportunity to learn about their performance over a range of motions. Since New Zealand's building stock, earthquake engineering practices, and retrofit approaches are quite similar to those in the U.S. and other countries, this sequence of events and the documentation of performance will greatly influence practice internationally.

Laws in New Zealand since 1968 required that local governments establish policies for retrofits of earthquake-prone buildings, including URM. Because Christchurch was thought to be in a moderate seismic region (before September 2010), it had a passive policy that triggered retrofits only during major alterations. After the September earthquake, Christchurch strengthened its policy to require retrofits within 30 years

with a target of 67% of the design forces required by the code for new construction. But Christchurch also continued to allow retrofits to 33% of code as a minimum.

In September, the EERI team worked with colleagues in New Zealand to identify previously retrofitted URM buildings and document their performance. These buildings were revisited after the February aftershock, and additional retrofitted buildings were identified (see Figure 15). The 57 URM buildings now thought to have been completely or nearly completely retrofitted represent 7-12% of the URM building stock in the region of significant shaking in February.

Retrofits ranged in age from the early 1900's to 2010, with most performed since 1968. The great majority of the URM retrofits complied with 33% of standards for new construction, although a notable few met higher criteria. A wide variety of retrofit techniques were used, including (in an approximate ranking of most to less frequent) concrete and steel moment frames, concrete and reinforced masonry walls, and steel braces. Three major types of

wall anchorage systems were in common use: through-bolts, adhesives, and wedge anchors. Most buildings were brick or stone and in many cases included terra cotta and concrete elements. Some retrofits were done in conjunction with vertical additions or new buildings constructed behind URM façades. Retrofits in many cases included stabilizing terra cotta ornaments, cornices, chimneys and other appendages.

Most retrofitted URMs likely experienced ground motions well in excess of design motions, and in some cases, higher-than-maximum-considered earthquake motions, and their performances varied widely: 70% were red-tagged or cordoned to prevent public entry, 21% were yellow-tagged, and 9% were green-tagged. In many cases, prior damage in the September earthquake and the many subsequent aftershocks affected performance in February. Bond failures between anchor adhesives and masonry were prevalent (Figure 16), and low strength mortars also contributed to anchor failures.



Figure 15. The EERI Team studies the performance of this heavily damaged, retrofitted URM building that pounded against the building on the left and partially collapsed (photo: Turner).



Figure 16. This adhesive anchor at a URM parapet connection pulled out. A wire screen with white adhesive around the threaded rod had been inserted into a hole in the brick (photo: Turner).

Notwithstanding the failures, however, damage was generally significantly lower in retrofitted URMs than in nearby unretrofitted URMs. Select heritage buildings that had been retrofitted to a high standard performed well.

Nonstructural components. In the CBD, nonstructural damage following the February aftershock was similar in many respects to the damage observed after the September earthquake. In office buildings and retail shops, there was typically damage to ceiling grids with lay-in light fixtures, overturned shelving, broken sprinkler pipes, and broken furniture and contents. Numerous facades of more modern structures, often comprised of glass and light-weight metal panels, were damaged and on occasion fell to the sidewalk, threatening not only exiting occupants, but also search and rescue and inspection teams. A notable success story was found at a major telecom building that had started a ceiling retrofit program after the September earthquake, which included additional restraint for the ceiling grid and independent restraint of lay-in light fixtures. It was completed shortly before the February quake, and ceiling damage was noticeably reduced relative to similar buildings in the area.

East of the CBD, in an industrial area closer to the February epicenter, several manufacturing facilities were

observed with substantial non-structural damage to critical equipment and supporting infrastructure. At one location, high vertical and horizontal accelerations moved 25,000-pound machining equipment about one meter from the original position, as shown in Figure 17. Workers at the facility described seeing the large equipment literally “bounce” across the floor. At a nearby textile facility, precision equipment was damaged by the ground motion; the misaligned equipment would have caused short-term production disruptions, but widespread liquefaction damaged the factory floor slabs and put the facility out of business for an undetermined period of time. As was the case in September, numerous storage rack collapsed in warehouses (Figure 18), necessitating the disposal of damaged goods.

Community Impacts

Central Business District (CBD).

The earthquake devastated Christchurch’s CBD. During the emergency response period, questions about safety and access affected building inspections and decisions on recovery.

First, the Urban Search and Rescue (USAR) teams rescued people who were trapped, and then continued with the hard job of finding and re-



Figure 17. Equipment weighing 25,000 lbs moved approximately one meter (worker’s foot indicates the original position of the equipment) (photo: Marshall).

covering those who perished. Second, city and volunteer engineers conducted level 1 (exterior) inspections for tagging, followed by level 2 (interior) inspections to assess falling and collapse hazards that could result from future aftershocks or instability.

Inspectors cordoned off 114 square blocks initially, but reduced the closed area to 75 blocks ten days later. The area has approximately 200 concrete and 500-600 masonry buildings. About 50% of all the buildings are unusable because they sustained significant damage or because they are adjacent to hazardous buildings.

Before the cordoned area can be reduced, the city must stabilize some buildings slated for demolition to prevent building parts from falling into the streets or onto adjacent buildings. In addition, the city prefers to conduct demolitions while streets are still closed. The city began allowing brief access to green and yellow-tagged buildings on a block-by-block basis three weeks after the earthquake, but the cordon was still in place two months post-event.

The “critical buildings project” was established immediately after the earthquake to address heavily damaged buildings over approximately



Figure 18. Collapse of storage racks (photo: Elwood).

six stories that were considered critical to the reopening of the CBD. Led by top engineers from the Department of Buildings and Housing, the project assessed the stability of the buildings and provided advice on what action the city should take to reduce hazards from approximately 40 buildings. In some cases, temporary stabilization methods were proposed. The project engaged both local and international experts in the evaluations.

There were about 6,000 companies and/or institutions with over 50,000 employees in the CBD, or 25% of the total employment in the city. Of the 50,000 employees, 45% are in government, health care, or professions; these workers are likely to retain their jobs in another location. The other employees are in a variety of sectors including hotels, restaurants, retail, manufacturing, construction, wholesale, transport, communication, finance, insurance, and recreation; many in this group, especially those in tourism, will be unemployed.

The businesses were well insured, so there will be capital for rebuilding, but there is no guarantee that prop-

erty owners will reinvest in Christchurch. Among the concerns are a) potential for financial flight, b) fear of returning to the CBD, and c) intransigence on the part of individual property owners. However, 120 CEOs of Christchurch-based companies have come together to plan for the future of the CBD.

In addition, the Canterbury Development Corporation (CDC), which combined forces with the Canterbury Employer's Chamber of Commerce (CECC) after the September earthquake, is planning for both near-term business survival and long-term revitalization. About NZ\$10 million was made available to the business community after the September earthquake, and there will be another NZ\$200 million after the February event. These funds include government support of NZ\$500 per employee per week for 12 weeks, as well as a "business trust fund" for direct business-to-business support for relocation, IT, marketing, and other needs. These funds will help keep cash flowing in the community, supporting those who are out of work and helping some businesses to restart. Over the longer term, the joint efforts of

the CDC and CECC are aimed at generating economic assistance for recovery and promoting sustainable employment opportunities in a renewed business district.

Looking forward, the planners see increased village centers in suburban areas, and a CBD with low-rise development focused on educational institutions, hospitality, high-end retail and residential projects, and green space along the river. As plans evolve, the mayor and city council will listen to a variety of interest groups, but thus far all seem to want to take care of dangerous buildings quickly, set clear rules for planning, zoning, and building codes, establish tax or other investment incentives, restore symbolic buildings such as the cathedral, rebuild and/or reopen public institutions (city council, museums, schools), and invest in public infrastructure (sidewalks, streets, services) so that businesses can repair and rebuild.

Schools. The earthquake closed 419 early childhood education centers (ECEs), 215 primary and secondary schools in the Selwyn, Waimakariri, and Christchurch City school districts, and leading tertiary institutions including Canterbury and Lincoln Universities. Dozens of post-secondary Asian students died in the collapse of an office building in the CBD that housed an English language school, but there were no other reported fatalities among school-age children.

Out of 161 school damage assessments, there was minor damage to 107 schools (affecting 31,074 students), medium damage to 35 (affecting 15,423 students), and major damage to 19 (affecting 9,695 students). Lack of water and wastewater services prevented school reopening for 70,000 students across the three districts one week after the event. Subsequently, over 8,000 students re-enrolled in schools throughout New Zealand. On March 8, the New Zealand government passed an Order in Council to help



Figure 19. Classroom tents in the car park of the University of Canterbury, March 14, 2011 (photo: Comerio).



Figure 20. Temporary water tanks in front of Christchurch Hospital (photo: Gavin).

speed the recovery process of the school system. The order enabled the Minister of Education and Secretary for Education to (a) temporarily change school enrollment schemes without community consultation; (b) change the definition of a "half day" so schools could share sites; and (c) ensure students could return to their home school if and when it reopened.

On March 14, Christchurch City schools began to reopen, and students arrived armed with bottles of boiled water. Nine learning hubs were established to replace closed primary schools. Four closed high schools shared sites with four open high schools. As of March 21, 97% of school sites were reopened, but only 600 of the 8,000 students who had left the districts had returned. The Order in Council also enabled ECE centers to relocate and/or operate in restricted spaces, such that 76% of ECE services had reopened by March 21.

The University of Canterbury (UC) progressively reopened within 3-4 weeks of the earthquake while promising to deliver a high-quality, full academic year program of teaching and offering grants to compensate students. Across all educational institutions, alternative classroom capacity was created with temporary classrooms (Figure 19), off-site venues, site sharing, correspondence

school, and online instruction. The secondary and tertiary education sectors will be economically affected by the flight of fee-paying international students and the decrease of international student recruitment.

Hospital. The Christchurch Hospital—the South Island's largest tertiary hospital with 600-650 beds—suffered little structural damage, but had to evacuate 160 patients and request support from other facilities to cover functions such as laundry service. The hospital's backup power generators failed due to sludge clogging the filters, forcing patients to be evacuated from the main ward. The hospital also had to move patients from the fourth and fifth levels of the Riverside building due to leaks caused by sprinkler damage. Pipe failures were also discovered in the sewage system. Ceiling damage was prevalent in older buildings with heavy plaster tiles, while lightweight ceilings performed well. The hospital was also suffering from a lack of water pressure due to liquefaction damage to the tunnel housing pipes that carry steam from the boilers across the street to the hospital; as a precaution, the hospital has brought in storage tanks with almost 53,000 gallons of water (Figure 20). There were several instances of mechanical equipment jumping off mounts, as well as overturned furniture. One building on the hospital's campus, the Hagley Nurses Hostel,

a six-story concrete shear wall building from circa 1931, was extensively damaged and will likely be demolished; the building had been unoccupied since the September earthquake.

Housing and insurance. Most dwellings in the Christchurch region are one-story, an average of 150 m², and are built of light timber framing on concrete slab or pile foundations in accordance with NZS 3604 (first published in 1978). A common roofing material is light metal coated with stone chips. Timber weatherboard, plastered stucco or unreinforced brick veneer is used for exterior cladding. The veneers are anchored through small steel ties every two feet horizontally and one foot vertically that are embedded in mortar between bricks and screwed to a stud on the other end.

Overall, houses in Christchurch are maintained well; according to a 2005 report, more than 80% were deemed to be in nearly new condition and only about 3% required some sort of immediate attention. Their average valuation is about NZ\$300,000, including land (Clark et al. 2005; Beattie and Thurston 2006). The earthquake shaking caused only limited structural damage to dwellings, but nonstructural damage was widespread. Chimney failure, brick fence collapse, and plasterboard cracks are common in virtually all earthquakes of this mag-

nitide, and account for significant dollar losses.

As was the case in the September earthquake, soil liquefaction and/or lateral spreading caused most major structural damage to thousands of dwellings, particularly those situated along the banks of the Avon River and in the eastern coastal suburbs (Figure 21). Precise counts of housing damage are still underway, but government sources have reported that as many as 10,000 homes are likely to be demolished, and that some of the land area is beyond repair and will have to be abandoned. On April 4, 2011, New Zealand's Earthquake Commission (EQC) reported 99,042 claims generated by 90% of communities assessed. While the total number of claims may be comparable to the September earthquake, the total economic loss will exceed that of the previous event.

The EQC was established in 1945 to protect residents against the financial impacts of natural catastrophes. The current EQC insurance policy was regulated in the mid-1990s and has remained unchanged since then. It costs homeowners a small fraction of the sum insured, and provides protection of up to NZ\$100,000 for a dwelling (building), NZ\$20,000 for contents, and an amount for the land on which the dwelling is situated. When the actual damage is beyond the EQC limit, homeowners must rely on private insurance or personal funds.

Emergency Response

Search and rescue. An international effort of more than 600 urban search and rescue (USAR) personnel assisted with search and rescue immediately after the earthquake. Teams came from Japan, China, Australia, Singapore, Taiwan, and the United States. The New Zealand government also deployed three New Zealand USAR Task Forces, numerous volunteer fire departments, civil defense teams



Figure 21. A house in Kaiapoi moved on its foundation in both the September and February earthquakes a total of 1.8m (photo: Lai).

(volunteers), police forces, military personnel, and disaster victim identification teams (DVI).

The New Zealand government's logistical support for urban search and rescue operations was robust, and typical logistical challenges were not an issue. Heavy equipment, construction materials, and technical expertise were readily available at a moment's notice. Rescue operations were concentrated in the CBD, where most of the collapsed and damaged structures were URM or concrete; in addition, buildings shored after the September earthquake also collapsed and some buildings under repair suffered further damage. Previous earthquake damage was a consideration in every USAR operation.

Void spaces observed in collapsed structures varied in size and configuration. Unreinforced brick masonry typically had low void potential and survivable spaces. Concrete floor systems typically remained intact and provided more viable and survivable void spaces. Void spaces in parking structures were typically large and viable due to the "vertical support" provided by partially

crushed parked cars. Precast staircase collapses typically had low void-space potential, but in some cases large voids were found. Nonetheless, the probability of surviving the collapse of a precast staircase is low due to the height of fall (typically several stories) and the V-shaped wedging collapse pattern exhibited (see Figure 13).

Typically, USAR teams in the U.S. deploy with three structural specialists, but in this earthquake the U.S. team included five structural specialists. This depth of technical expertise allowed USAID to provide engineering support to other international teams that normally do not include structural specialists. These specialists provided engineering recommendations during searches, demolition surveys, and de-layering operations.

Although USAR operations do not typically become involved in operations involving building demolition identification, the U.S. team was able to provide the New Zealand government this service. This differs from practice in the United States, where this task would typically have

been assigned to the local public works/building department.

Building safety assessments/ tagging. New Zealand uses building safety assessment procedures very similar to those in the U.S., where green (inspected), yellow (restricted use), and red (unsafe) placards indicate approved access to damaged buildings (NZSEE 2009; ATC 1995). Some buildings undamaged in September that had received a green-tag collapsed and caused casualties during the February aftershock. Christchurch instituted several enhancements to the tagging process in February that could be adapted for the U.S. For example, reinspection of buildings following aftershocks was controlled by the response of eight “indicator” buildings specifically selected to be representative of common structural systems. Indicator buildings were inspected following aftershocks for further damage that would trigger reinspections.

During inspections, a blue hazard assessment form for red-tagged buildings was completed by the chartered professional engineer and sent to the national controller to be used in determining whether immediate demolition was required. Assessment team safety was maintained by requiring teams to send a text message to the EOC at 90-minute intervals. Each inspection team had two USAR personnel to ensure safety while traversing the CBD and entering potentially unsafe buildings. Rapid Response teams were “on-call” to respond when building owners needed more detailed structural inspections, evaluation of falling hazard cordoned areas, and tenant escorts to retrieve contents in damaged buildings.

As of April 15, more than 60,000 total assessments have been accomplished, with the following breakdown of red tagged buildings: 1788 residential buildings, 1109 buildings within the CBD, including 395 heritage buildings (Civil Defence 2011). Figure 22 shows the

approximate breakdown of tagging by building type, based on March 18 data.

Social and Economic Impacts

Social science research moratorium. On February 23, 2011, the day following the earthquake, New Zealand Civil Defence declared a state of national emergency. Soon thereafter, the national controller placed a moratorium on social science research until May 1, 2011, in order to protect survivors from additional burdens and to ensure that vital resources were directed toward emergency response only.

In this challenging situation, one team member traveled to Wellington to meet with disaster researchers and to discuss fieldwork objectives. After consulting with New Zealand researchers, the EERI social scientists agreed to listen and observe, but not to launch any formal research efforts.

Risk communication channels and strategies. Widespread power outages followed the earthquake and remained primary issues for thousands of residents for weeks. Water treatment plants and sewage systems were heavily damaged, requiring rapid communication strategies regarding public health and safety issues. The modes of communicating to affected households and businesses included door-to-door pamphleting and posts to community bulletin boards and in other public spaces. Print and broadcast media outlets, briefed daily by government officials, provided regular

updates. Those with access to the Internet could get official and unofficial information online. Several telephone helplines were established to assist affected populations, for example, a 24-hour, seven-day-a-week Canterbury Earthquake Government helpline for those seeking information or emergency financial support, and a Quake Support and Counseling helpline. Recovery Assistance Centres and Work and Income Service Centres were opened throughout Canterbury. Special support was also offered for migrants and refugees, for families with children, school teachers, and for survivors of domestic violence.

Just days after the earthquake, the Christchurch City Council integrated social media into their communication strategies. The Council had not used social media following the September earthquake, but moved rapidly in February to incorporate a new blog, Twitter feed, and Facebook page. Council staff monitored public chatter online to identify unmet needs within the community, posted updated information via Twitter and Facebook, and responded to all requests for information that were posted on their fan pages or in response to messages on Twitter. The University of Canterbury, which enrolled more than 20,000 students before the earthquake, followed a similar protocol in monitoring its

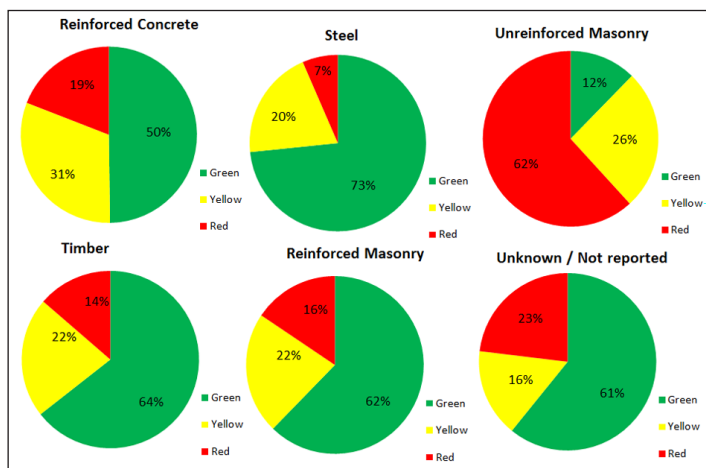


Figure 22. Building Assessments in Central Business District (Kam et al. 2011, Data source: Christchurch City Council)

Facebook page and responding directly to student concerns and requests for additional information.

Unofficial social media presence was also significant, led by a virtual network of online volunteers who created and staffed the Christchurch Recovery Map site. This group—whose work was driven by a determination to get people the information they needed as quickly as possible—posted the first accessible maps, via Google, of the CBD and outlying areas. Major print and online media sources in the Christchurch area then reproduced and published the maps.

Because of the destruction in the CBD and the focus on life-saving activities among emergency responders, technology volunteers launched online resources more quickly than the official responders were able to, providing early access to curated information to those who could get online. The virtual volunteer team stopped its efforts once normal communication channels resumed and directed prior users to visit the official government site at <http://canterburyearthquake.org.nz/>. Rather than leading to “information overload” from competing sources, the spontaneous and official online resources performed complementary functions at different points in the response and early phases of recovery.

Online channels for organizing.

Social media and online channels used to communicate risk and assist with the response were instrumental in organizing volunteers and donations. Many small-scale efforts emerged in the wake of the earthquake, but the Student Volunteer Army (SVA), which mobilized more than 12,000 spontaneous volunteers (about 90% of whom were university students), stands out. Using a Facebook page, text messaging, and a variety of other technologies, the SVA volunteers logged thousands of person hours delivering chemical toilets, shoveling silt, removing fallen bricks, sorting donations, and

delivering informational pamphlets to those directly affected by the earthquake. Many elderly residents called on the SVA for help with removing debris, as did government officials who needed assistance with various tasks. Social media were also used for finding missing persons and as an outlet for remembrance and expressing grief for the deceased.

Risk messaging. Communicating risk and uncertainty in the aftermath of the February earthquake was a high priority for public officials faced with reassuring the population that effective measures were in place to restore infrastructure and protect lives. The importance of these efforts was amplified by the back-to-back earthquakes over a six-month period and ongoing aftershocks, all of which elevated anxiety and concerns about safety. By mid-March, it was estimated that tens of thousands of residents were still displaced. Government officials were unsure when, if ever, these individuals would return and were in the process of developing a strategy for communicating with displaced residents.

Risk perception and the impact on international tourism, which accounts for 9% of the nation’s GDP, was also a major concern among officials. Those who had returned to Canterbury expressed fear of re-entering tall buildings, and there was some misinterpretation of risk regarding the various colored placards that were placed on damaged buildings. As of April 30, 2011, the state of national emergency was still in place, and it will likely continue for several more weeks. Thus, many outstanding questions still remain regarding communicating current and future risk for residents.

Lessons and Conclusions

As in the September earthquake, the liquefaction damage was dramatic and widespread. Some residential areas of Christchurch may not be rebuilt because ground

deformations have left the areas prone to flooding. With peak ground accelerations exceeding 0.5g, the February quake caused collapse in many URM buildings, some of them retrofitted. Data from this event will help us understand the poor performance of some retrofitted URM buildings and develop better design approaches and standards. There is a window of opportunity with the ongoing revisions to ASCE 31/41 guidelines to incorporate these important lessons. Similarly, the extensive damage to concrete buildings, despite the very short duration of the earthquake, holds important lessons for understanding collapse mechanisms and improving seismic assessment techniques. Earthquake engineers from around the world have extraordinary opportunities to collaborate in both academic- and practice-oriented research on building performance, soil-structure interaction, impacts of liquefaction and lateral spreading, consideration of aftershocks in design and post-earthquake assessments, and other key topics.

With reference to post-earthquake safety assessment, it was clearly demonstrated that, when large numbers of buildings are damaged and a large portion of the city is closed, it becomes critical to have access to drawings. This earthquake emphasizes the need for cities to create a centralized and accessible database of structural drawings for use in emergency building evaluation.

On the policy side, the New Zealand earthquakes can provide valuable lessons to those areas of the U.S. where there is either lower seismicity or infrequent, high-consequence events. Some of these areas use “relaxed” or reduced seismic criteria even today and these events suggest strongly that such policies be reconsidered. In addition, this earthquake has again reinforced the need for an Earthquake Buildings Rating System that permits design professionals to

communicate the seismic performance of buildings in terms that are easily understood by the public. The overall performance of modern buildings in the CBD may satisfy our technical performance standards, but was it acceptable to the public?

Furthermore, after all the damage and psychological distress from both quakes, the public trust in all buildings within the heavily damaged area was shaken. The University of Canterbury went to extreme lengths to evaluate all its buildings in order to be able to reassure students and staff that buildings were safe to occupy. This will be important in any large event in the U.S.

Finally, the long-term recovery issues for the CBD are critical. With 25% of the buildings demolished under emergency orders and perhaps another 25% that could be taken down by owners, economic development and a major rebuilding program will be critical. For the engineering professions this raises again the perennial question: what levels of damage are acceptable in existing and new infrastructure, and what performance standards can we provide?

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