Item X

State of California
Seismic Safety Commission

Memo

To: Seismic Safety Commission

From: Fred Turner, Staff Structural Engineer
California Seismic Safety Commission
1755 Creekside Oaks Drive, Suite 100
Sacramento, CA 95833
Phone: (916) 263-0582 Fax: (916)263-0594 Email: Turner@StateSeismic.com

Date: April 26, 2013

Subject:

Background

The Seismic Safety Commission funded a grant for $49,900 to disaster medical experts from the Johns Hopkins University in Baltimore through a contract with the Pacific Earthquake Engineering Research Center at UC Berkeley to survey hospitals that experienced disruptions in recent earthquakes in Mexicali (2010) and Christchurch, New Zealand (2010 and 2011). Field surveys were conducted using data collection methods developed after prior earthquakes including the Haiti and Chile Earthquakes 2010. The experiences that surveyors have documented from interviews with hospital personnel responsible for administration, facility support and medical services will help improve emergency response capabilities and our understanding of the major causes of disruption in medical care.

Progress Update

We received the attached comparative study and executive summary last month and our staff requested edits that were addressed in the last week of April. In addition, we received a paper presented at the 2012 New Zealand Society of Earthquake Engineering Conference. Due to travel and budget restrictions and the inability to videoconference at the capitol, no one from PEER or Johns Hopkins can make a presentation. Our contract with PEER ended March 31.

On a related note, Commission staff has been working with California Hospital Association staff to develop a presentation on this and other Commission-funded results at an upcoming convention titled “Disaster Planning for California Hospitals” to be held in Sacramento September 23 to 25.

Here is a brief summary of major findings:

Emergency Communications: The El Centro Regional Medical Center, the Cinco de Diciembre and Mexicali General Hospitals were included in the survey. Loss of emergency communication capabilities was cited as the most consistent challenge facing hospitals after recent earthquakes. In Mexicali and El Centro experienced disruption to landlines and cellphones for under a day in the three hospitals surveyed. However disruptions to land lines extended to 5 days in New Zealand and 7 days for hospitals in Chile. Cell phones have generally been restored faster than land lines.

In the Baja earthquake, satellite phones and 800 MHz radios as well as runners were used as backup. In contrast, when Chile experienced a much larger earthquake than the Baja’s, the lack of a coordinated emergency communications backup system as well as disrupted roadways resulted in hospitals that were isolated and out of communication with the country's health system headquarters for days.

Emergency Backup Power: Many hospitals experienced loss of power. While power backups worked well in Mexicali and El Centro, New Zealand experienced scattered problems with sediment clogging backup fuel intakes and interrupting backup power. Backup power worked for only three of seven hospitals in Chile.

Water and Wastewater Damage: Surveyors found that hospitals in El Centro and Mexicali do not have backup water storage on site. While they experienced no disruptions in water and wastewater, in Chile, five of seven hospitals lost municipal water. All seven of Chile's hospitals had backup water storage but they experienced problems distributing water within the hospital buildings because of damage to pumps and other water distribution components. New Zealand relies on backup pumps to access emergency water sources, but pumps were clogged due to silting caused by the earthquakes. They faced difficulty in maintaining pressure in the system for fire sprinklers in the upper floors.

Nonstructural Damage: Broken pipes, collapsed ceilings, cracks in partitions, dislodged tanks, elevators, and equipment are often the primary reasons for evacuating hospitals. All of the surveyed hospitals had experienced such damage or the fear of such damage to varying degrees. While the first impulse is to evacuate, it may be more prudent to shelter patients and staff in damaged buildings until such time that repairs or alternative hospital facilities can be obtained.

Structural Damage: While less frequent than nonstructural damage, a maternity ward and part of an intensive care unit was extensively disrupted in New Zealand. One of seven hospitals in Chile suffered severe structural damage. Other than foundation settlement of one wing of a hospital in Mexicali, those surveyed in California did not experience severe structural damage.

Summary: The vulnerability of emergency communication systems is a critical common factor among all hospital personnel surveyed. Hospitals clearly do not have to collapse or suffer severe structural damage to be rendered inoperable. Functional losses due to non-structural damage are often significant in earthquakes, but do not necessarily warrant evacuations. Vertical evacuations of patients down stairs are far more precipitous than horizontal evacuations to move patients to other less damaged portions of hospital wings. Redundancy and backup sources are essential for water, power, wastewater, and communication systems. Information about how to better manage earthquake disasters and reduce vulnerabilities between earthquakes need to be better communicated to hospital personnel and the public.

Staff Recommendation

This is an information item only and no Commission action is required. If Commissioners have ideas, questions or concerns, please share them and staff will convey them to PEER and Johns Hopkins.

The draft document will be provided to the Commissioners at the meeting. Staff will receive comments from Commissioners and a final document will be brought to the Commission at the July meeting for approval.

A Comparative Study on the Seismic Preparedness of Hospitals Following Recent Damaging Events

Executive Summary

Functioning hospitals and other healthcare facilities are a crucial part of disaster response. Despite global efforts to make hospitals safer and continuously functional in disasters, healthcare facilities have suffered great losses due to natural and human-caused disasters. It is, thus, imperative that building functionality and continuity of healthcare services in a disaster be studied and quantified to better manage resources, develop emergency plans, and decide on hazard mitigation actions for future hazard events. In order to properly model building functionality, it is important to accurately capture the relationship between physical damage and loss of specific functions. The report summarizes an international, multi-disciplinary study focused on hospital functionality involving engineers, geologists, epidemiologists, and health and emergency managers in New Zealand, Mexico, and the United States. Input from each of these disciplines is necessary to properly analyze how structural, non-structural, geotechnical failures, and utility lifeline damage disrupts essential healthcare services provided by hospitals.

The research team has highlighted the gaps in existing approaches of assessing hospital performance and resilience estimation from both the literature and hospital emergency management practices. The team utilized damage and loss-of-function survey tools they developed to collect and analyze data of post-earthquake performance of hospital systems in the study areas. Two separate survey tools were used to assess the hospitals for this study: one tool captures baseline and post-impact hospital services and can be completed by a knowledgeable hospital administrator, while the second tool is designed to capture detailed physical damage by direct observation and/or with a facilities manager with first-hand experience from the earthquake.

The report describes: a summary the seismic events; a literature review of hospital resilience definition and quantification; the motivation the research centered around *performance-based earthquake engineering* (PBEE); downtime (loss of function) estimation; a summary of the reconnaissance data collected during the project; a fault-tree analysis methodology that connects physical damage with loss of critical functions in hospitals; and the introduction of new resilience metrics that can be used to inform PBEE models and hazard risk models.

Findings

1. Relatively little severe (i.e., no complete failures or obvious life safety threats) structural damage was observed in any of the hospitals in the study areas. Observations of moderate structural damage include buckled steel roof trusses, severe racking of a penthouse due to torsion, spalled concrete columns, shear-wall cracking, collapsed in-fill walls, permanent lateral deformation, and foundation damage and flooding due to liquefaction. Although the structural damage and geotechnical failures are not considered life threatening, they did provide obstacles to functionality in the following weeks and months, as services were temporarily shut down or relocated during repair work. The lack of communication to the building occupants and the community of what is considered life-threatening structural damage and of the seismic mitigation steps in place led to unnecessary facility closures.

2. Non-structural damage was more common and more widespread at all facilities. Failures of critical utilities (i.e., communications, power systems, and water systems) had the greatest impact on the functionality of healthcare facilities. Common types of damage observed within the facilities in all events include broken piping, collapsed suspended ceilings, damage to

partition walls, damage to cladding, mechanical equipment, and elevators. Nonstructural damage rendered clinical and non-clinical areas inoperative, forcing hospitals to subcontract some services, and to sharply reduce (bed) capacity.

3. There is little or no redundancy in the specialized services provided by the hospitals in the Canterbury District Health Board's system. The Christchurch Hospital is the only one in the city with an emergency department and comprehensive services, thus requiring it to become the center of the healthcare response in the earthquake series despite suffering significant damage and losing capacity.

4. The Canterbury District suffered a sequence of three earthquakes. The first earthquake of the series was the strongest in terms of moment magnitude (M_w) and caused widespread damage in Christchurch, but was not as devastating as the second event in the sequence, which resulted in many fatalities, injuries, building collapses failures, and complete closure of the central business district. Those interviewed in the field study stressed the importance of having experienced this first (less damaging) earthquake served as a 'drill' and helped them identify vulnerabilities in their facilities, implement mitigation repairs and upgrades in their facilities, and revisit their emergency plans. Efforts taken to provide continuity of patient care varied amongst the study hospitals: increased staff; moved patients to alternative spaces within facilities; transferred patients to other facilities; discharged patients; canceled elective procedures; used primary-care physicians to triage and lessen the burden on the hospitals; and used temporary spaces (tents) to deliver care.

5. The developed fault trees have a mixed level of success in predicting loss of functionality in the study hospitals because the current model cannot yet capture the emergent behavior of staff to keep the areas running through nontraditional means. Steps are underway to develop dynamic models that can capture this emergent human behavior.

Recommendations

1. Disaster memory in the community is extremely powerful. If seismic retrofits and mitigation strategies have been implemented at a facility, these efforts need to be appropriately communicated to building occupants and the larger community, so that fear produced by lack of knowledge does not prevent the use of otherwise safe and operational facilities.

2. Non life-threatening damage can be disruptive to healthcare facilities in the response and recovery stages of a disaster. Thus, it is important that subcontracting services and alternative spaces be identified before a disaster to ensure continued functionality of critical clinical and non-clinical areas, and thus continue to deliver essential health care. Battery-powered lighting sources are also critical in the case of failed back-up generators; head lamps were stressed as particularly useful in moving patients through dark hallways and stairwells. Additionally, backups for intra-facility communication are essential to ensure better continuity of healthcare services (especially when patient transfers and exchange of supplies/staff are necessary).

3. It is imperative that hospitals in a region actively liaise with one another pre-event in order to provide efficient care and cope with capacity shortages after a future event.

4. Emergency operations plans should include a variety of alternatives for delivering patient care when physical spaces become compromised in a disaster and when specific clinical and non-clinical services become inoperative.

5. Fault tree analysis offers stakeholders a quantitative approach for estimating overall hospital functionality in future events conditioned on physical damage.

The Impact of the 22nd February 2011 Earthquake on Christchurch Hospital

J.K. McIntosh[1], C. Jacques[2], J. Mitrani-Reiser[2], T.D. Kirsch[2], S. Giovinazzi[1], and T.M. Wilson[1]

[1]*University Of Canterbury, Christchurch, New Zealand.*

[2]*Johns Hopkins University, Baltimore, United States of America.*

2012 NZSEE Conference

ABSTRACT

The 22nd February 2011, M_w 6.3 Christchurch earthquake in New Zealand caused major damage to critical infrastructure, including the healthcare system. The Natural Hazard Platform of NZ funded a short-term project called "Hospital Functions and Services" to support the Canterbury District Health Board's (CDHB) efforts in capturing standardized data that describe the effects of the earthquake on the Canterbury region's main hospital system. The project utilised a survey tool originally developed by researchers at Johns Hopkins University (JHU) to assess the loss of function of hospitals in the Maule and Bío-Bío regions following the 27th February 2010, M_w 8.8 Maule earthquake in Chile. This paper describes the application of the JHU tool for surveying the impact of Christchurch earthquake on the CDHB Hospital System, including the system's residual capacity to deliver emergency response and health care. A short summary of the impact of the Christchurch earthquake on other CDHB public and private hospitals is also provided. This study demonstrates that, as was observed in other earthquakes around the world, the effects of damage to non-structural building components, equipment, utility lifelines, and transportation were far more disruptive than the minor structural damage observed in buildings (FEMA 2007). Earthquake related complications with re-supply and other organizational aspects also impacted the emergency response and the healthcare facilities' residual capacity to deliver services in the short and long terms.

1 INTRODUCTION

The M_w 6.3 Christchurch earthquake struck the city at 12:51pm on Tuesday, the 22nd February 2011 (GNS 2011). The earthquake caused 185 fatalities, and approximately 8,600 injuries, and widespread damage to the built environment. The Christchurch earthquake badly damaged over 6,000 residential properties, forced thousands to leave their homes and communities, and disrupted the city's main lifelines including roads, water and wastewater networks, and electric distribution systems (Giovinazzi et al. 2011). This event compounded the effects of the M_w 7.1 Darfield earthquake, which occurred on the 4th September 2010 and did not (directly) result in any fatalities but did cause widespread property and infrastructure damage.

The 22nd February 2011 earthquake heavily impacted the Canterbury region's healthcare system. The main regional hospital, the Christchurch Hospital, sustained damage following the earthquake that severely strained the hospital's ability to function at regular capacity. The continued functionality of critical infrastructure, such as healthcare facilities, is necessary following a disaster. In order to provide adequate services to patients, hospitals rely on a wide range of internal and external functions (e.g., power, water, communication, laundry, sterilization, etc.), each of which is part of a complex network of interacting systems. The loss of a single internal or external function can severely disrupt the ability to provide care at the level of demand needed during the critical first hours after a disaster (Kirsch et al., 2010).

In a broad effort to support the recovery activities following the Christchurch earthquake, the Natural

Hazard Research Platform (NHRP) of New Zealand funded short-term projects that would connect the skills and knowledge from academic research with the practical needs of these organisations. The joint University of Canterbury/Johns Hopkins research team was awarded one of these NHRP grants for a project titled "Hospital Functions and Services," which was designed to support the Canterbury Health District Board (CDHB) and the Canterbury Primary Response Group (CPRG). One of the project's main goals was to provide the CDHB and the CPRG with standardised methods for collecting and analysing seismic reconnaissance data associated with the healthcare system. These data included photos and surveys of structural, non-structural, equipment, and lifeline damage that disrupted essential hospital functional areas and healthcare services. The impacts surveys include questions regarding the consequence for patient-care systems of losing any one or multiple functions in a hospital due to earthquake damage.

The NHRP project benefited from collaboration with Johns Hopkins University (JHU) researchers, who had developed a survey tool to assess the impact of the Maule and Bío-Bío regions following the 27th February 2010, M_w 8.8 Maule earthquake in Chile (Kirsch et al., 2010). This project adapted the survey tool to match the needs of the CDHB Health Care System based on feedback from relevant CDHB personnel. The survey tool was then administered to several hospitals in the Canterbury region.

2 METHODOLOGY

The survey tool was designed by co-authors Kirsch and Mitrani-Reiser and their colleagues (Mitrani-Reiser et al., 2012) to capture standardized qualitative and quantitative information on the effects of earthquakes to hospital functionality. Their multi-section interview questionnaire can be completed in just one hour with the assistance of a knowledgeable hospital administrator. The survey also includes questions about baseline hospital statistics that are typically collected by phone or email after the interviews. This survey was originally designed based on feedback from Chilean Ministry of Health (MINSAL) employees, so some modification to the survey tool were required to adapt it for the CDHB Health Care System characteristics and the 22nd February 2011 context.

The refined 'Health System Impact Survey' includes two main separate surveys, where one is focused on all physical damage and engineering aspects, and the other is focused on related healthcare and service-area functional impacts. Each of these surveys has multiple sections and can be completed in an hour with relevant hospital personnel. The engineering survey is typically completed based on interviews with facility managers and/or engineers. This survey includes the following sections: site and structural description and impact, non-structural description and impact, geotechnical description and impact, supporting documentation (e.g., floor plans or damage photos), and summary of damage and functional disruption to hospital service areas (e.g., emergency department, kitchen, etc.). The healthcare survey is typically completed based on interviews with chief medical officers, nursing directors and/or emergency planners, and includes the following sections: baseline hospital information, event impact assessment, response (e.g., number of personnel available in the hours/days following the event) to the earthquake, and final observations (e.g., the major lessons learned after the event).

The surveys described above were conducted after the Christchurch earthquake by a multi-institutional (University of Canterbury and JHU faculty and students), multidisciplinary team composed of experts in structural and earthquake engineering, risk assessment, disaster medicine, and international health. The interviews were completed between 8-15 August 2011 via phone and face-to-face interviews with facilities management staff, nurse managers, emergency planners and clinical staff across the CDHB (Table 1). The interviews targeted all the publicly owned hospitals that provide the majority of secondary and tertiary medical care in the Canterbury region, and two main private hospitals in Christchurch. Table 1 summarizes the hospitals that were contacted to be interviewed, the type of personnel that completed the damage and healthcare impact surveys with the research team, and the status of the interviews. As noted in Table 1, the researchers in New Zealand and the US continue to collaborate to complete the interviews in the remaining ten hospitals. This work includes remote interviews, and in-person meetings with stakeholders from the CDHB and the RHISE (Research re the Health Implications of Seismic Events) network.

Table 1. Summary of public and private hospitals in the Canterbury region that have been interviewed or contacted for interviews for this study as of December 2011.

Hospital Type	Hospital Name	Interviewed Personnel	Status
CDHB Public Hospitals	Akaroa Hospital	Nurse Manager	Interviewed in person on 11th August
	Ashburton Hospital	N/A	In Progress
	Burwood Hospital	N/A	In Progress
	Christchurch Hospital	Facilities Manager, Facilities Disaster Planner, and Director of Nursing	Interviewed in person on 10th and 12th August
	Darfield Hospital	N/A	In Progress
	Ellesmere Hospital	Nurse Manager	Interviewed by phone on 9th August
	Hillmorton Hospital	N/A	In Progress
	Kaikoura Hospital	Nurse Manager	Interviewed by phone on 9th August
	Lyndhurst Hospital	N/A	In Progress
	Oxford Hospital	N/A	In Progress
	The Princess Margaret Hospital	Nurse Coordinator, Facilities Manager, and Service Manager	Interviewed in person on 11th August
	Rangiora Hospital	N/A	In Progress
	Timaru Hospital	N/A	In Progress
	Waikari Hospital	N/A	In Progress
Christchurch Private Hospitals	St. George's Hospital	Director of Nursing and Facilities Manager	Interviewed in person on 11th August
	Southern Cross Hospital	N/A	In Progress

The following sections provide a first insight on the relation between engineering damage and loss of functionality following the 22nd February earthquake for six of the hospitals within the Canterbury Region, with a special focus on Christchurch Hospital.

3 PHYSICAL AND FUNCTIONAL IMPACT OF THE CHRISTCHURCH HOSPITAL

The Christchurch Hospital is located near the Avon River on lenses of liquefiable sediment. The site experienced 0.547g peak ground acceleration during the 22nd February earthquake. The hospital's ability to provide emergency care and proximity to the Central Business District (CBD) placed it at the forefront of the emergency response. Unfortunately, high levels of ground shaking and the area's susceptibility to liquefaction led to structural and non-structural damage in the hospital, as well as failure of utilities and mechanical equipment in both clinical and non-clinical buildings (described in Sections 3.1-3.4). The sustained damage severely strained the hospital's ability to operate. Existing back-up resources and the resourcefulness of the entire hospital staff, including that of Facilities Manager, Alan Bavis, Facilities Disaster Planner, Bruce Hall, and Director of Nursing, Heather Gray, played a critical role in stretching the functionality of the hospital in the emergency response phase of this disaster.

3.1 *Christchurch Hospital: Structure and Baseline Hospital Information*

Christchurch Hospital is the largest hospital in the Canterbury Region and the centre of the region's healthcare system. Christchurch Hospital operates the only Emergency Department (ED) and Intensive Care Unit (ICU) in Canterbury and performs the majority of elective surgeries. The hospital serves the geographically largest health district (CDHB) in New Zealand, which includes a population of 560,000. The inpatient wards provide services to over 35,600 inpatients each year, of which approximately two-thirds are admitted acutely; a further 13,000 people are day patients. There are 16,000 theatre visits each year and over 197,000 outpatient attendances, excluding those for radiology and laboratory services. The hospital operated 600-650 beds before the earthquake (Table 2), including 15 ICU beds, 18 high-dependency beds, and 9 step-down beds. Before the earthquake, the hospital typically operated at around 98% occupancy with a 48% admission rate from the ED to other wards. The hospital complex, shown in Figure 1, is made up of several buildings constructed during different time periods using concrete-shear-wall or reinforced-masonry construction. The buildings on the hospital campus include the Parkside Building (built in late 80s to early 90s), the Riverside Building (built in the 1970s), the Nurses Hostel (built in 1931, vacant prior to earthquake for scheduled demolition), the Diabetes Centre (built in late 1950s and early 1960s), and the Christchurch Women's Hospital (built in 2005). The Christchurch Women's Hospital (CWH) is the only base isolated structure on the South Island. The clinical buildings are bordered by the Avon River and Riccarton Avenue and are adjacent to Christchurch's CBD.

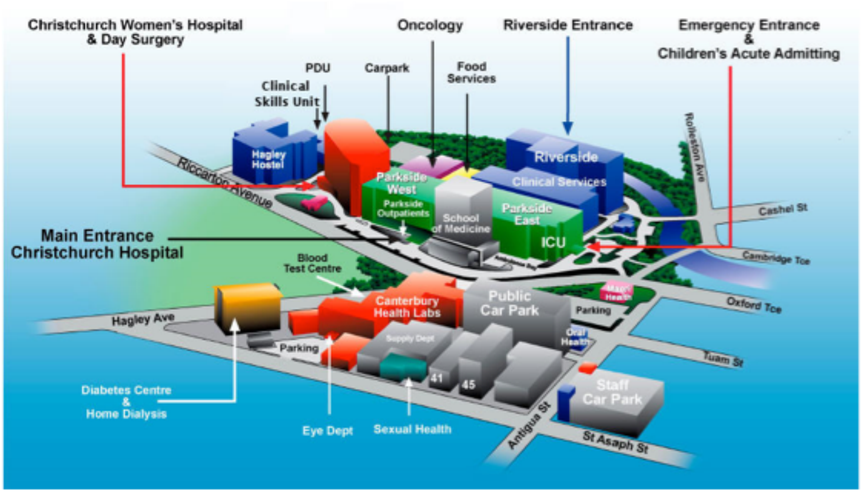

Figure 1. Layout of Christchurch Hospital

3.2 *Geotechnical Failures and Structural Damage*

Geotechnical failures caused widespread damage to the hospital campus. For example, liquefaction caused flooding in the basements of all the buildings, including the Women's Hospital. The Parkside and Riverside buildings suffered the worst flooding. All the retaining walls between the river and the hospital failed, and the lateral spreading near the river caused severe damage to sewage lines (Figure 1a). Additionally, the tunnel that connects clinical facilities and non-clinical facilities across Riccarton Avenue was knee-deep in water after the earthquake.

There were no catastrophic structural failures (i.e., local or global collapses) to any of clinical or non-clinical buildings of Christchurch Hospital that were operating at the time of the 22nd February earthquake. However, severe structural damage did cause some forced closures. For example, the underground tunnel carrying lifelines running below Riccarton Avenue was still unusable at the time of interviews (Figure 1b).

(a)


(b)

Figure 1. Observed damage throughout hospital campus: a) liquefaction-induced damage to the main sewer line, and (b) damage to Riccarton underground tunnel (photo credit, Alan Bavis).

Two administrative buildings on St. Asaph Street also had to be closed. The latter building suffered damage to the connection of the roof to the walls. The hospital's parking structure did experience extensive structural damage, including spalled concrete of its beams and columns and cracking of its steel bracing. The cost to repair the parking structure's damage is estimated to be NZ$2 million. Figure 2a shows damage to concrete columns on the ground floor of the parking structure.

There was also widespread evidence of minor to moderate structural damage in several other buildings, including the Riverside Building, some non-clinical buildings, and the hospital's boiler stack. The Riverside Building, for example, suffered shear wall cracking, where some of these cracks went all the way through the wall. All clinical buildings suffered roof damage. Also several buildings experienced damage across separation joint and firewalls. Figures 2b and 2c show examples of damage found on the Christchurch Hospital campus, including damage to at a separation joint in the Riverside Building and damage to a firewall in the CWH, respectively.

(a) **(b)** **(c)**

Figure 2. Observed structural damage in non-clinical and clinical buildings: a) spalled concrete in ground-floor column of a parking structure, b) separation joint damage in Riverside Building, and c) damage to firewalls in the CWH (photo credit, Alan Bavis).

In AS/NZ 1170.0 (SNZ 2004), critical facilities like hospital buildings are categorised with importance Level 4. The code provisions require that the buildings remain operational, particularly under 500 year serviceability limit state, SLS2, earthquakes (Uma and Beattie 2010). Christchurch Hospital buildings were designed and built as predominantly rectangular buildings with no L- or T- shaped structures, no abrupt discontinuities along the height of the buildings, and no large overhangs. The lack of these building features, along with the presence of separation joints in most buildings, and the base isolation of the CWH likely mitigated structural damage. Additionally, several older buildings on campus had been seismically upgraded before the earthquake. Those with retrofits only suffered cosmetic damage.

Structural building initiatives and regulations alone cannot guarantee uninterrupted operation of a hospital following a large earthquake. Many other factors affect hospital functionality, such as lifelines and support agencies. Damaged non-structural components of a hospital system are typically the most disruptive factor following an earthquake (FEMA 2007). Damage to non-structural components of Christchurch Hospital are described below.

3.3 *Non-Structural Damage*

As is expected in other countries with similar design codes (FEMA 2007), the effects of damage to non-structural building components and equipment, as well as breakdowns in public services (lifelines), transportation, re-supply, and other organizational aspects, were far more disruptive to the functioning of Christchurch Hospital than the minor structural damage observed in buildings and facilities. The non-structural damage included the failures of many components: windows, non-load bearing ceilings, partition walls, floor coverings, medical equipment, and building contents.

The failures of suspended ceilings, particularly the plaster tiles constructed with tongue-and-groove joints, proved to be one of the most disruptive non-structural failures in Christchurch Hospital. These heavy, thick ceilings act as effective fire barriers; however, when damaged, these older tiles are dangerous falling hazards. When the plaster tile ceilings were first installed, they were diagonally braced to the walls. However, at some point after construction, these diagonal braces were replaced with less effective vertical ties that make the ceilings more susceptible to damage. Fallout and sagging (identified by laser level analysis) of ceiling tiles throughout the hospital campus necessitated the replacement of these non-structural components with lightweight ceiling tiles secured to the ceiling grid with clips and diagonal bracing. The ceiling repairs have required parts of the hospital to be closed down for periods ranging from hours to days; these repairs have been going on for months after the earthquake. Most of the inpatient wards were disrupted for two weeks while fire retardant tiles covering suspended ceilings were replaced. Many light fittings became dislodged and had to be replaced alongside ceiling tiles. The failures of suspended ceilings in particular led to precautionary evacuations immediately after the event, as described in Section 3.5.

Non-load bearing wallboard partitions were also heavily damaged throughout the hospital. This mostly cosmetic damage did not cause loss of function immediately after the earthquake, but the areas damaged have had to be shut down for repair work months later. Severe plaster and concrete wall damage as well as damage to ceilings and glazing in the Diabetes Centre caused it to close for an entire month for repairs.

Building components that are critical to vertical egress were also damaged during the earthquake. Most staircases in the clinical buildings were damaged and had to be propped up to remain operational in the emergency phase of the disaster. The stairs were eventually taken out of service one at a time and repaired during the recovery phase. The reason that so many staircases were damaged is that they were constructed with rigid connections to adjacent floors, which led to extensive cosmetic cracking in stairwell walls. Issues with power described in Section 3.4 also caused the emergency lights in some staircases to fail. Vertical egress was further impaired by damage to elevators. All elevators are traction elevators, except for one hydraulic elevator in the kitchen. Most elevators were out of function for a couple of hours because of activated seismic switches that force them to lock out in the event of an earthquake. The damage to these critical means of egress complicated regular hospital function immediately following the earthquake; however, hospital personnel continued to provide healthcare services and move patients through whatever means necessary, including carrying patients through darkened stairwells with the use of torches.

The majority of all pumps and chillers in rooftop plant rooms jumped off their mounts due to strong shaking, even though the snubbers themselves were not damaged. They were on seismic mounts according to NZ standards, NZS 4219:2009 (SNZ 2009). NZS 4219:2009 provides design guidelines for better seismic performance of engineering systems, requiring that all the proprietary components manufactured in New Zealand or overseas need to be verified for the performance level required (i.e. to be operational under serviceability level earthquake for hospital buildings) (Clause 2.4, SNZ 2009). In the CWH chillers moved around and piping for the condenser collapsed.

The most functionally significant non-structural damage was to internal and external roof coverings and roof top water tanks in the Riverside Building. The consequent ingress of water into the top two (5^{th} and 6^{th}) floors of this building caused the immediate evacuation of five adult medical wards, with about 30 patients each. There are no horizontal evacuation routes from these wards, so vertical egress was required. As was previously mentioned, the emergency lighting in the stairwells was not functional, so this patient evacuation took about 35 minutes to complete with flashlights. This was the only permanent loss of capacity at Christchurch Hospital (Section 3.5).

3.4 *Loss of Internal and External Services and Damage to Back-up Systems*

During the 22^{nd} February earthquake, all of the Municipal utility lifelines were damaged to varying degrees (Table 2). The main wastewater, water, and power distribution networks were completely off line (Giovinazzi et al. 2011). Additionally, the hospital suction and back-up power systems experienced partial to complete loss of function for a short period of time.

Loss of power was one of the most major obstacles to the functionality of hospital services. Both the Parkside and Riverside Buildings lost power for one and a half hours. The hospital had back-up generators with 1.5 Megawatt capacity and one and a half days of fuel stock that were regularly tested.

However, some of these generators malfunctioned or were damaged, which effected the immediate functionality of the emergency power supply system. For example, the oil pressure gauge on the Riverside generator broke during the earthquake, which caused that generator to shut down immediately after turning on. The Parkside generators initially ran for a couple of hours, but stopped working because of clogged filters due to sediment in the tanks that had been disturbed by the ground shaking. The filters were replaced, but there some difficulty priming the fuel pumps. This was eventually corrected by syphoning fuel from a groundskeeper's car to prime the pumps. In addition, shortages to the main low-voltage switchboard caused small fires, damaging the main electrical panel and further complicating the power restoration efforts.

Damage to water and sewage systems, including fire sprinkler systems, also proved a major obstacle. Broken sewage pipes had to be replaced. Main water was out completely for a couple of days, and full water pressure was not restored for a week. The hospital had back-up water supplies (<1 day's worth), and access to artesian wells, but these did not prove entirely sufficient. Some water could be successfully extracted from the boreholes immediately after the earthquake, but the silt content in that water was initially too high, which caused issues in moving the water from the ground to the storage tanks. Even when this issue was resolved, the water from the borehole could not be used for drinking. The lack of water impaired other systems as well, including the fire sprinklers, which could not be pressurized. Fortunately, there were no major fires after the event. To prevent this situation from occurring in any future disasters, a ½ million-litre capacity tank system was installed to provide emergency water for crucial systems, including the fire sprinklers.

Suction in the Riverside building was also damaged, but was quickly restored by connecting the Riverside suction systems to the Parkside suction systems via a bypass in CWH. The ventilation system is highly important in maintaining an appropriate pressure gradient in different areas of the hospital. In infection-controlled areas, malfunction of this ventilation system could create a risk of infection to patients and staff (FEMA 2007). The ductwork was un-operational for 30 minutes following the earthquake. Suction was regained by joining Parkside to Riverside buildings via the CWH bypass.

3.5 *Impact on Hospital Functionality and Residual Capacity of Health Care Delivery*

Emergency Phase: Emergency Response and Medical Evacuations

The day of the earthquake, 22nd February 2011, the Hospital admitted and dealt with 160 casualties. The triage after the quake was set up in the parking lot in front of the Emergency Department. There were no deaths related to the 22nd February Earthquake in Christchurch hospital patients or staff, though four staff members were injured during the evacuation of some of the hospital wards. Evacuations of sick or injured patients are potentially dangerous events under any circumstances, but particularly are risky when moving a large group of patients with limited personnel, no power, and no elevators. Due to water damage from leaking roof tanks, the top two floors of Riverside Building, including five adult medical wards, were evacuated immediately after the earthquake. The darkness of the stairwells and the unavailability of elevators (Section 3.3) made evacuation very difficult. Most patients were able to walk down on their own, but some had to be carried down five to six flights of stairs in the dark. Many patients and some staff self-evacuated after the event to areas perceived as safer locations outside the buildings. The third floor of Riverside Building was evacuated in a subsequent phase. All evacuations after the initial Riverside evacuation were simply horizontal movement. These evacuations were triggered by failures of suspended ceilings, the lack of functionality of fire sprinkler system, and the lack of sufficient pressure in the back up water system. The charted oncology unit was also moved to Christchurch's Women Hospital. A total of 350 patients were evacuated from the hospital overall. The Oxford Clinic, a general practice located down the road, evacuated to Christchurch Hospital.

Supplies and non-clinical services were mostly undamaged. The kitchen maintained its functionality, guarantying the provision of food. However, the laundry was shipped out for two days because of short-staffing and lack of water; half of the laundry was handled by Timaru Hospital during this time. Drinking water was provided in bottles brought by a private company. The pharmacy did not run out of pharmaceuticals, blood products, dressings, splints, surgical supplies, or other any other treatment supplies. Similarly, there was no loss or shortage of lab supplies, radiological supplies, or other diagnostic supplies. Two off-site laboratories used by the hospital, one of which was located in the CBD, were shut down, but the onsite laboratory remained functional. All the shelves containing the records tipped over.

Short-term Losses of Health Care Capacity

The hospital never closed completely. The adult wards on the 5th and 6th floor of Riverside were the only closures during the quake, making 106 adult medical beds unusable (or a 16% loss in capacity) One child assessment unit had to be temporarily repurposed to treat adults. Twelve ICU patients were evacuated to other ICUs in the North Dunedin, Nelson and the North Island.

Christchurch hospital stopped all elective surgery and outpatient services immediately after the emergency in order to surge capacity. This decision greatly reduced the number of patients in the clinical buildings. There were approximately 320 inpatients in the hospital after 24 hours, 270 after 72 hours, and 400 after 7 days

Nuclear medicine and clinical engineering were undamaged, but had staffing problems. The Dialysis Centre closed for repairs after the earthquake, though it moved and reopened elsewhere. Outpatient services were lost for one day after the quake, and reduced for the next two weeks. Rehabilitation, and physical therapy were also lost for the first day and partially down for a week.

Long-Term Rebalancing of Canterbury Health System

The evacuation of adult wards in the Riverside building top two floors (5^{th} and 6^{th}) and transfer to Princess Margaret Hospital, (Table 1) to date has been the only permanent loss of capacity at Christchurch Hospital. Due to the lack of horizontal egress and the presence of only a single stairwell, the decision was made to permanently change the use of those floors from clinical wards to administrative space. The loss of those Riverside wards means that 106 beds were lost, which is 16 per cent of the hospital's normal capacity. About 70 beds at Princess Margaret Hospital (PMH) and another 10 beds at Ashburton Hospital were created for long-term care to compensate for the loss. Initiatives like Community Rehabilitation, Enablement and Support Teams, CREST, have been used to reduce the pressure on Christchurch Hospital; the initiative caters to some 240 clients a day. The CDHB predicted a shortfall of 740 elective surgery cases for the year, down 5 per cent on the annual target. About 500 elective surgeries such as hip replacements were contracted out to the private hospitals Southern Cross and St Georges (The Press 2011).

4 PHYSICAL AND FUNCTIONAL IMPACT ON THE CANTERBURY HOSPITAL NETWORK

Canterbury's Health system is comprised of 14 publicly owned hospitals, which provide the majority of secondary and tertiary medical care (Table 1). A smaller not-for-profit private hospital sector specializes mainly in elective surgery and long-term care (Table 1). The private hospitals are operated directly or subsidised by the Canterbury District Health Board. The "third sector" providers, made of non-profit non-government organizations (Health, M. O. 2011), offer other services, including general practitioners (GPs), nursing homes, and ambulance service. Following the Canterbury earthquakes, damage to facilities and lifelines placed considerable strain upon the Canterbury health care system, specifically Christchurch's network of private/public hospitals, GPs, and elderly care facilities. To cope with demand, the health system has had to utilize the entire health network's capacity.

4.1. CDHB Public and Private Hospital System: Structure and Baseline Hospital Information

CDHB public and private hospitals have different specialities. Ashburton Hospital, located outside of Christchurch, mainly performs lab work and radiology, as well as providing maternity and physiotherapy services. Burwood Hospital specializes in recovery. Hillmorton Hospital accounts for most of Christchurch's mental health facilities. Princess Margaret Hospital provides predominantly geriatric care and includes psychiatric wards. Private hospitals St Georges and Southern Cross provide maternity care and elective surgery. Med laboratory, Canterbury laboratory, and Christchurch Hospital laboratory are responsible for most of the blood tests from GPs and hospitals within Canterbury

(Health, M. O. 2010). The Canterbury CDHB/private sector hospital system includes seven rural Regional Hospitals: Rangiora, Waikari, Oxford, Akaroa, Kaikoura, Darfield and Ellesmere. These Regional Hospitals are small (<20 beds) and primarily handle elderly and maternity patients. All hospitals in the region actively liaise with one another in order to provide efficient care and cope with capacity shortages.

4.2. Summary of Functional Loss and Deployed Residual Capacity in the Aftermath of the Earthquake for the CDHB Public and Private Hospital System

Following the 22nd February Earthquake, Akaroa Hospital, Kaikoura Hospital and Ellesmere Regional Hospitals suffered limited damage to their structural and non-structural elements and remained operational (Table 2). Of these hospitals, only Akaroa Hospital lost any external services. That hospital lost electricity and water but had sufficient backup systems (Table 2). Akaroa experienced only minor non-structural cracking following the February 22nd earthquake; however, it was closed down for one week after the 4th September Mw 7.1 earthquake due to damage to the chimneys, which were subsequently removed.

Princess Margaret Hospital lost water main water completely for 12 hours and did not regain full water pressure for a week. Sewage systems were damaged, and may have been inoperable for as long as two weeks. Separation joints in the hospital experienced some damage, and most walls sustained plaster damage. The buildings of PMH are concrete with brick veneer. That brick veneer had vertical, diagonal, and horizontal cracking, generally ranging from 1-4 mm. There were, however, no structural failures to the concrete structure. Water and sewage pipes for this hospital were damaged and diffusers popped out.

Table 2. Summary of Services Loss by Hospital

	Christchurch Hospital	PMH Hospital	St George's Hospital	Kaikoura Hospital	Akaroa Hospital	Ellesmere Hospital
External Services						
Electricity	Y	Y (4hr)	Y	N	Y (1dy)	N
Backup electric	Y(1.5hr)	N	N (4dy)	N	N	N
Water	Y (1wk)	Y(12hr)	Y (14dy)	N	Y (3dy)	N
Sewer	N	Y(2wk)	Y (3dy)	N	N	N
Telephones	Y(20min)	Y(6hr)	Y	N	Y (1dy)	N
Internal Services						
Computers	N	N	N	N	N	N
Medical gases	N	N	Y(4dy)	N	N	N
Suction	Y(30min)	N	Y(3dy)	N	NA	NA
Total Services lost	4	4	4	0	3	0

St. Georges Hospital was closed completely due to structural damage to the maternity ward (permanently closed awaiting demolition) and liquefaction damage to the Cancer Centre (Table 3). St. Georges Hospital's dominant business is elective surgery, but the main recovery wards and operating theatres were closed for two weeks due to loss of services and widespread non-structural damage to walls (Table 2).

Many hospitals were forced to alter the way they provided non-clinical services immediately after the earthquake. The Regional Hospitals were able perform their own services such as laundry (usually done at Hillmorton Hospital) and food preparation in the aftermath of the quake (Table 2). Timaru Hospital provided clean linen to Christchurch Hospital (that lost Laundry services for 2 days, as above mentioned). Princess Margaret's Hospital lost its laundry services for 7 days (Table 2); Ashburton Hospital helped source clean linen, but existing stock had to be conserved.

All the Regional Hospitals participated in the redistribution of capacity from damaged healthcare facilities in Christchurch in the form of accepting transferred elderly care and/or maternity patients in the days after the earthquake. The patients were from Princess Margaret Hospital and various elderly care facilities within badly damaged areas of Christchurch (Table 3).

Table 3. Summary of capacity by Hospital following the February 22nd earthquake

Capacity	Initial capacity	Residual capacity	Patients during EQ	Discharged in first 48 hours	Transferred in first week
1. Christchurch Hospital	650 beds	544beds	-	-	(-) 44
2. Princess Margaret Hospital	147 beds	147 beds	109	1	(+)47
3. St George's Hospital	101 beds	80 beds	52	52	0
4. Kaikoura Hospital	26 beds	26 beds	15	0	(+) 3
5. Akaroa Hospital	8 beds	8 beds	8	8	(+) 8
6. Ellesmere Hospital	10 beds	10 beds	8	0	(+) 3

5 CONCLUSION

The damage that impacted the Christchurch Hospital following the 22nd February Earthquake included minor structural damage to both clinical and support buildings, non-structural damage to ceiling tiles and light fittings, outages of all the city lifelines systems, and damage to internal services and back-up generators. For all the CDHB hospital facilities, the widespread non-structural damage was more disruptive than the minor/moderate structural damage sustained by the buildings. All buildings had been built or retrofitted to comply with the requirement of NZ Seismic Design Standards (SNZ 2004). In Christchurch Hospital, non-structural damage to suspended ceilings, light fittings, and water piping forced wards to be evacuated during the emergency phase and to remain closed in the longer-term, as well as requiring lengthily disruptive repairs to be carried out in the following months. The loss of water, sewage, power, caused disruption to the hospital's functionality and to the delivery of health care in the days and weeks following the earthquake. Hospital planning activities should focus on identifying non-structural and functional vulnerabilities within all critical service areas and mitigating their possible impact with engineering interventions, redundancy systems or alternative resources.

ACKNOWLEDGEMENTS

The financial support of the Natural Hazard Research Platform to the "Hospital Service and Functions" short-term project (PI Dr. Sonia Giovinazzi) is gratefully acknowledged. The additional, financial support from the State of California (Alfred E. Alquist Seismic Safety Commission under Standard Agreement No. SSC 2011-03) and received by USA collaborators is also gratefully acknowledged. We gratefully acknowledge the assistance and support to the "Hospital Service and Functions" project of Canterbury DHB managers: Murray Dickson, General Manager of Organisational Support & Development, Alan Bavis, Facilities and Engineering Manager, Wayne Lawson, Construction and Property Manager, Many thanks to Mark Newsome, CDHB, for providing contacts and facilitating the interview process. We are grateful to Prof. Michael Ardagh, Director of Christchurch Hospital Emergency Department and Chair of the Rhise Group "Researching the Health Implications of Seismic Events" that was joined by the "Hospital Service and Functions" project team members. Special thanks to Viki Robinson, Rhise Group's coordinator Our sincere thanks to all the interviewed persons: 1) Akaroa Hospital: Alison Gallagher, Nurse Manager; 2) Burwood Hospital: Diana Gunn, Director of Nursing; 3) Christchurch Hospital: Alan Bavis, Facilities and Engineering Manager; Bruce Hall, Emergency Planner; Sandra Richardson, Nurse Researcher, Emergency Department; Heather Gray, Director of Nursing; 4) Darfield Hospital: Maureen Gunton, Nurse Manager; 5) Ellesmere Hospital: Linda Lentjes, Nurse Manager; 6) Kaikoura Hospital: Adrianne Carter, Nurse Manager; 7) Lyndhurst Hospital: Kate Paterson, Nurse Manager; 8) The Princess Margaret Hospital: Linda Wood, Service Manager; Becky Hickmott, Nurse Coordinator; Stuart Williamson, Facility Manager; 8) Rangiora Hospital: Suzanne Salton, Nurse Manager; 9) Timaru Hospital: Samantha Powell, Director of Nursing; 10) Waikari Hospital: Helen McDowell, Nurse

Manager; 11) St. George's Hospital: Barbara Fox, Director of Nursing; Gerlad Carpinter, Facility Manager; 12) Southern Cross Hospital: Dorothy Paton, Hospital Manager.

DISCLAIMER

The authors have collected the information contained in this paper via face-to-face interviews with CDHB stakeholders and hospital managers. The authors have made every effort to ensure that the information contained in this paper is reliable, but make no guarantee of its accuracy or completeness and do not accept any liability for any errors.

REFERENCES

FEMA (2007). Design Guide for Improving Hospital Safety in Earthquakes, Floods, and High Winds. F. E. M. A. USA: 32.

Giovinazzi, S., Wilson, T.M., Davis, C., Bristow, D., Gallagher, M., Schofield, A., Villemure, M., Eidinger, J. and Tang, A. (2011) Lifelines Performance and Management following the 22 February 2011 Christchurch Earthquake, New Zealand: Highlights of Resilience. Bulletin of the New Zealand Society of Earthquake Engineering, 44(4), 404-419

GNS (2011) "New Zealand Earthquake Report 22 February 2011 at 12:51 p.m. (NZDT)". GeoNet. Earthquake Commission and GNS Science. 22 February 2011. http://www.geonet.org.nz/earthquake/quakes/3468575g.html. Retrieved 22 February 2011.

Stylianou, G. (2011). Hospital visitors have quake nerves. The press. Christchurch: 1.

Health, M. O. (2010). New Zealand Influenza Pandemic Plan: A framework for action. M. O. Health. Wellington: 196.

Health, M. O. (2011). Structure of the health and disability sector. http://www.health.govt.nz/new-zealand-health-system/overview. Retrieved 1February 2012

Kirsch, T.D., Mitrani-Reiser, J., Bissell, R., Sauer, L.M., Mahoney, M., Holmes, W.T., Santa Cruz, N., de la Maza, F., 2010. Impact on Hospital Functions Following the 2010 Chilean Earthquake. *Journal of Disaster Medicine and Public Health Preparedness*, 4 (2): pp. 122-128.

Mitrani-Reiser, J., Mahoney, M., Holmes, W.T., de le LLera, J.C., Bissell, R., and Kirsch, T.D., 2012 (accepted). A Functional Loss Assessment of a Hospital System in the Biobío Province. *Earthquake Spectra* (special issue expected in June 2012).

SNZ 2009. NZS 4219:2009, Seismic performance of engineering systems in buildings. New Zealand Standards,New Zealand 2009.

SNZ 2004. NZS 1170.5:2004, Structural design actions Part 5: Earthquake Actions- New Zealand. New ZealandStandards, New Zealand, 2004.

Uma S.R. and Beattie G.J. (2010). Seismic Assessment of Engineering Systems in Hospitals – A Challenge for Operational Continuity. NZSEE Conference 2010.