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: July 3, 2013

Subject: Preparedness Lessons for Hospitals Following Recent Damaging Earthquakes, a Hospital Evacuation Survey Project Update – Second/Final Reading

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.

Action by the Commission in May

The Commission received a report from the Pacific Earthquake Engineering Research Center and Johns Hopkins and heard a presentation summarizing the report's conclusions from the staff. Chairman Michael Gardner asked Commissioners to read the report and forward comments and questions to Mr. Turner. No comments or questions from Commissioners have been received to date. Staff will share the report with new Commissioners Greg Beroza and Fuad Sweiss.

Staff Recommendation

The staff recommends that Commissioners provide comments or questions and consider accepting the report at the July hearing as revised or submitted.

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

CSSC Project Summary Report—May 2013

Prepared by:

Judith Mitrani-Reiser[a], Caitlin Jacques[b], and Thomas Kirsch[c]

Johns Hopkins University

With:

Mary Comerio[d], Bill Holmes[e], and Stephen Mahin[f]

Collaborators at the UC Berkeley

Sonia Giovinazzi[g], Jason McIntosh[h], and Thomas Wilson[i]

Collaborators at the University of Canterbury

[a] Assistant Professor of Civil Engineering, Johns Hopkins University, Baltimore, MD, USA
[b] Graduate Student, Dept. of Civil Engineering, Johns Hopkins University, Baltimore, MD, USA
[c] Associate Professor of Emergency Medicine, Johns Hopkins University, Baltimore, MD, USA
[d] Professor in the Graduate School of the Dept. of Architecture at the University of California, Berkeley, CA, USA
[e] Senior Consultant at Rutherford and Chekene, San Francisco, CA, USA
[f] Professor of Structural Engineering, University of California, Berkeley, CA, USA
[g] Research Fellow of Civil and Natural Resources Engineering, U. of Canterbury, Christchurch, New Zealand
[h] Graduate Student of Geological Sciences, University of Canterbury, Christchurch, New Zealand
[i] Lecturer of Geological Sciences, University of Canterbury, Christchurch, New Zealand

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.

1. INTRODUCTION

Functioning hospitals and other healthcare facilities are a crucial part of disaster response. As such, they must be able not only to provide emergency care for the victims of any type of event, but also to continue the healthcare services necessary to maintain the health of their catchment community (WHO 2006, FEMA 2008). For more than a decade, the United Nations World Health Organization has made hospital risk and vulnerability reduction a cornerstone of international disaster preparedness through its "Safe Hospitals" Initiative (WHO 2009). In the US, California's Alfred E. Alquist Hospital Facilities Seismic Safety Act establishes seismic safety standards for hospitals, including retrofit requirements to ensure that hospitals continue functioning following a major earthquake (CAHSC, 2011).

Despite these efforts, healthcare facilities have suffered great losses globally due to natural and human-caused disasters. The 1994 Northridge earthquake affected 11 hospitals and lead to evacuations and patient transfers (Schultz 2003). The 2010 Haiti earthquake destroyed or severely damaged 22% of the hospitals throughout the country, including all the hospitals in Port au Prince (PDNA 2010). The 2005 Kashmir earthquake caused the closure of 68% of the healthcare facilities in the affected region (IASC 2010). The 2003 Bam earthquake reportedly destroyed almost all of the healthcare facilities in the affected area, with the loss of almost 50% of the local health staff (UNICEF 2004). In the 2007 Peru earthquake, 20% of healthcare facilities in the affected area were unable to provide services after the event (Doocy, et al., 2010). In the 2010 Bío-Bío earthquake, 10% of the hospitals in the impacted areas had greater than 75% loss of function, 6% were partially operating, and 62% needed repairs or replacement (Mitrani-Reiser et al., 2012a).

It is, thus, important that building functionality be quantified for future seismic events to better manage resources, develop emergency plans, and decide on hazard mitigation actions. In order to properly model building functionality, various computational steps must be completed and critical data must be collected. One very critical piece of information that is needed to model the loss of functionality is the relationship between physical damage and loss of specific functions, conditioned on building occupancy. On the computational side, it is necessary to model the loss of function of building services directly from damage states that are either

empirically collected or simulated using nonlinear structural analysis techniques. Research investigators Kirsch (Director of the Center for Refugee and Disaster Response) and Mitrani-Reiser (Director of the Sensor Technology and Infrastructure Risk Mitigation Laboratory) have been tackling this challenging research question for the past few years in the realm of healthcare facilities. The report summarizes an international, multi-disciplinary study 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.

In addition to assessing the performance of individual facilities, it is also necessary to analyze hospital resilience by looking at as well as the interconnected healthcare system and adopting a holistic and multidisciplinary approach in order to capture the elements of system complexity and strength (WHO 2009). Mitrani-Reiser et al. (2012b) highlighted the gaps in existing approaches from both the literature and hospital emergency management practices and proposed a damage and loss-of-function survey tool to be used for collecting and analyzing data of post-earthquake performance of hospital systems. The survey tool was field tested after the 2010 Bío-Bío earthquake, and then used to collect data on one geographical region of Chile that housed seven public hospitals (Kirsch et al., 2012). The survey tool is designed to assess hospital damage, including structural and nonstructural components, utility services, and equipment, as well as loss of supplies and personnel and the overall impact on the facilities' ability to deliver healthcare services. The Chilean work laid the foundation for comparative studies on the performance of healthcare delivery systems impacted by natural disasters around the world and spawned the current study on the performance of hospitals after the 2010 El Mayor-Cucapah and the 2011 Canterbury Earthquake.

The focus of this study is to assess the physical and operational functionality of hospitals after significant seismic events in New Zealand, Mexico, and the United States, which addresses an important sector of community resilience. The survey tool described above was modified to assess the performance of hospitals in Christchurch, El Centro and Mexicali. 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.

In order to complete the work, collaborations were established with researchers at the University of Canterbury and with the Canterbury District Health Board (CDHB), and were funded by the NZ National Hazard Reduction Program. The NZ and US teams, together, collected data on the damage and functional impact to the Canterbury regional hospitals with a focus on Christchurch Hospital, nearest the badly damaged Central Business District in Christchurch. Both survey tools were completed at all sites. The fieldwork was conducted six months and two years after the seismic events in Christchurch and Baja California, respectively. Therefore, repairs were already underway at the facilities and much of the physical damage was not observed first hand. Instead, physical damage data was collected by interviewing the Construction and Property Manager of the Christchurch Hospital and the Facilities and Engineering Managers of the CDHB (Canterbury District Health Board), of the El Centro Regional Medical Center, of the Mexicali General Hospital, and of the Cinco de Mayo Hospital in Mexicali. This data includes collapse risk of the building as well as damage to structural components (e.g., foundation, columns, and walls), nonstructural components (e.g., cladding, elevators, and partitions), and geotechnical hazards (e.g., apparent liquefaction). In parallel, to assess the impact of the events on hospital service delivery we surveyed hospital administrators (Directors of Nursing and Emergency Planners) on the loss of services they experienced after the event as a direct impact of earthquake damage, and on patient evacuations/transfers and hospital personnel shortage/surge that occurred in the weeks that followed.

The following report describes a summary of the two seismic events, a literature review of hospital resilience, the motivation of our research centered around the methodology of *performance-based earthquake engineering* (PBEE) developed at PEER (Pacific Earthquake Engineering Research Center), the state-of-the-art in downtime (loss of function) estimation, a summary of the reconnaissance data collected during the project, a summary of modified fault trees that are used to connect utility failure with loss of critical functions within hospitals, and the introduction of new resilience metrics that can be used to inform PBEE models and hazard risk models.

2. MOTIVATION OF RESEARCH

The need to improve the provision of healthcare system services after a disaster is of global importance. Currently, many hospitals have plans in place for physical and organizational effects due to seismic events. These plans also often fail to account for physical damage that directly impacts hospital functions (Ardagh et al., 2011; Yavari et al., 2010). Design guidelines in the US for improving safety of hospitals in earthquakes stresses the need for a multi-disciplinary approach in order to achieve better performance of facilities (FEMA 2007). Currently, the vast majority of literature in this field can be divided into two main areas: physical infrastructure, and the human and organizational infrastructures.

2.1 PHYSICAL ENVIRONMENT

A great deal of research within the engineering community has focused on frameworks to characterize seismic hazards, assess structural and non-structural performance, and quantify the resulting vulnerability. Both WHO (2006) and FEMA (2007) agree that structural vulnerability is dependent on three factors: the level to which the seismic hazard forces have been addressed in the structural system, the quality of the materials and construction, and the architectural and structural form of the building. There is also significant research that examines the actual performance of structural and non-structural systems in hospitals, either for specific physical components, specific seismic events, or specific regions. Masi et al. (2012) perform an analysis of the seismic risk level for hospitals in the Basilicata region of Italy based on the building stock of the region's hospitals and the expected structural and non-structural performance under different levels of peak ground acceleration. Miniati and Iasio (2012) describe a rapid seismic assessment of the hospitals in Florence, Italy, including structural and non-structural elements. Uma and Beattie (2010) identify non-structural elements that are critical to hospital performance, and make observations on the performance of these in recent events as well as their specifications in the New Zealand code. Davenport (2004) traces the development of New Zealand's building code and its specifications of structural and non-structural design for seismic hazards over time.

Building vulnerability can be defined in many ways, including economic losses, downtime, and safety impacts. The focus of this study is to assess the vulnerability of hospitals and provide resilience metrics for hospitals. In order to capture loss of building function and properly model

hospital resilience, it is important to quantify how physical damage leads to loss of services typically provided by these critical facilities and to identify the factors that delay the recovery process. Building loss of function may be caused by a number of factors (e.g., forcible building closure, business interruption due to excessive damage and finance planning) that have been incorporated into a PBEE framework for estimating building downtime due to seismic events in Mitrani-Reiser (2007) and in ATC-58 (2012).

PBEE consists of the evaluation, design and construction of structures to meet seismic performance objectives (expressed in terms of repair costs, downtime, casualties, etc.) that are defined by stakeholders (owners, society, etc.). The PBEE methodology developed by the Pacific Earthquake Engineering Research (PEER) Center is shown in Figure 1. This methodology involves conditional probabilities to propagate the uncertainties from each level of the performance analysis, resulting in a probabilistic assessment of the predicted performance. This methodology has six distinct computational steps: (1) facility definition, D, summarizes the site, structure type, and occupancy type, (2) the hazard analysis evaluates the hazard for site D, expresses this hazard in terms of an intensity measure (IM), and identifies ground motion records representative of the site hazard, (3) the structural analysis step creates a detailed model of the structure accounting for element non-linearity, uses the ground motion records to simulate plausible seismic demand, and measures the structural response in terms of engineering demand parameters (EDP), (4) the damage analysis step uses fragility functions to express the probability that a facility and/or building component is in or exceeds a particular damage state as a function of an EDP, (5) the loss analysis step is estimates structural performance conditioned on damage using metrics significant to stakeholders, such as repair cost or loss of function, and (6) the last step of the methodology is to assess whether the design of facility D matches the stakeholders expectations of seismic performance.

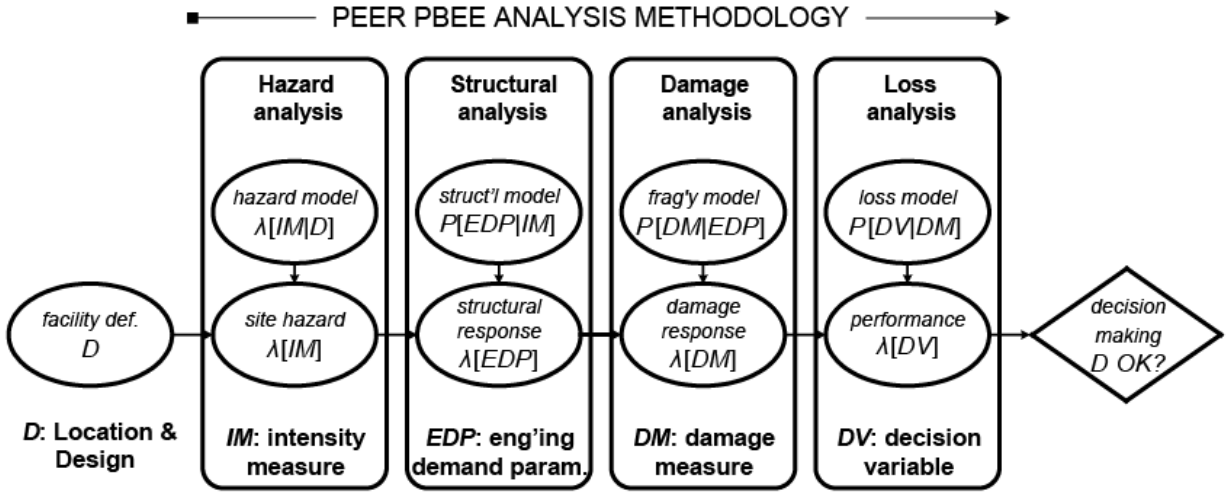

Figure 1. Schematic of the PEER PBEE methodology.

A major strength of the methodology described above is the ability to estimate downtime (a measure of seismic vulnerability) in step (5) above, or the loss of functions in a building and to integrate this functional impact into the building design process. In order to accurately estimate the loss of functionality, the engineer modeling the building performance needs to clearly understand the specific services of facility D, and must have available relationships that correlate building damage and loss of function of building-specific services. The research team has an extensive background in modeling building damage and expected performance outcomes, such as economic losses (Porter et al., 2006; Goulet et al., 2007; Luco et al., 2009; Ramirez et al., 2012), life safety concerns (Mitrani-Reiser, 2007; Krishnan et al., 2008; Mitrani-Reiser et al., 2009), loss of building functionality (Comerio, 2006; Mitrani-Reiser and Beck, 2007), and the impact that these losses have on life-cycle costs (Ryan et al., 2009) to enable more informed decisions about investing in hazard mitigation strategies (Muto et al., 2008).

There are several methods that assess hazard vulnerability and resilience of critical facilities. The Hyogo framework, described in detail in WHO (2006) and UN/ISDR (2005), is an international guide on how to improve hospital resilience; it provides a set of metrics for structural, non-structural, and administrative vulnerability of hospitals. The Leontief model (Haimes and Jiang, 2001), describes complex system interactions by creating a set of mathematical relationships between input perturbations and output losses for each node; it uses optimization algorithms to calculate overall risk. Bruneau et al. (2003) defines a resilient system

as one which shows reduced failure probabilities, reduced consequences from failures, and reduced time to recovery. In this methodology, systems diagrams are used to identify ways to achieve these three components of resilience. Other tools used to identify and assess seismic vulnerability are event and fault trees. Paté-Cornell (1984) describes the fault tree as relating events causally using Boolean logic;, and the event tree as relating events temporally and probabilistically. Murakami (1992), Yeo and Cornell (2003), and Mitrani-Reiser (2007) all demonstrate uses of event trees in the field of earthquake engineering to characterize post-earthquake outcomes. Lee et al. (1985), NRC (1975), and Paté-Cornell and Dillon (2001) describe the utility of fault trees for a wide variety of complex engineered systems. More recently, Porter and Ramer (2012) describe how fault trees can be used to characterize the vulnerability and downtime of a generalized critical system in seismic situations.

The literature offers a variety of perspectives on translating seismic vulnerability to a resilience metric (e.g., Chang and Shinozuka (2004); Miles and Chang (2006)). Cimellaro et al. (2010b) quantify seismic resilience as the integration of system's functionality, $Q(t)$. They estimate $Q(t)$ in terms of quality of service (a function of patient waiting time) at the individual facility level, and in terms of quality of life (a function of healthy populations before and after the event) at the community level. Functionality is defined as a piecewise function that captures the reduction in system performance and ranges from 0% (total loss of system functionality) to 100% (no reduction in system functionality). The equation for resilience (Bruneau and Reinhorn (2004)) is represented mathematically by

$$r = \int_{t_{OE}}^{t_{OE}+T_{RE}} Q(t)dt \qquad (1)$$

where t_{OE} is the time of occurrence of the event and T_{RE} is the recovery time.

The urgency for enhancing the US's resilience was recently highlighted in a National Academies Report (National Academies 2012), which summarized work by a committee comprised of individuals with expertise in physical science and engineering, geographical science, social and behavioral science, economics, and public health with professional experience from research, public policy, emergency and disaster management, nongovernmental organizations, the private sector, and government service. In this report, vulnerability is defined at "how sensitive a population may be to a hazards or disruptions caused by a hazard," which in turn affects these populations to be resilient to disasters (National Academies 2012). It is,

therefore, important to quantitatively relate loss of function and resilience.

Comerio's (2006) work laid the foundation for quantifying loss of function of critical infrastructure. This work defines two distinct portions of downtime related to earthquake damage: the rational and irrational components for downtime. These components of downtime capture the time required to complete repairs of damaged infrastructure as well a the time necessary to relocate, secure financing, prioritization of repair efforts, human resources, and long lead times for special materials and equipment. This work makes the important conclusion that building downtime is conditioned on the impact to the entire community; communities with large building-stock closures experience longer downtimes. Mitrani-Reiser's work on downtime estimation, specifically, is included in the *Next Generation Guidelines for Seismic Performance Assessment of Buildings* (ATC 2012). In attempting to improve the vulnerability assessment models and framework (Matlab Damage and Loss Analysis, MDLA), Mitrani-Reiser has recently been focused on collecting earthquake reconnaissance data firsthand from around the world to better correlate physical damage in hospitals with the loss of functionality of specific service areas (Kirsch et al., 2010; Mitrani-Reiser et al., 2012). This project is the first comparative study of hospital seismic performance using data collected systematically from three countries.

As described in Comerio (2006) and later in ATC-58 (2012), building downtime may be caused by a number of factors: building closure due to red-tagging; building closure and/or business interruption due to repair efforts; business interruption due to excessive nonstructural damage; building inspection; damage assessment; finance planning; architect/engineering consultations; and a possible competitive bidding process. The amount of time that part or all of a building loses functionality is difficult to estimate because of all the above-mentioned factors, in addition to the lack of data that exists that correlates physical damage with the loss of building-specific services. In order to fill this knowledge gap of operation failure of critical facilities, it is necessary to evaluate downtime in the field by assessing the loss of specific critical services/functions in addition to the physical impact, as these services can often be lost with minimal physical damage. This empirical data can ultimately be used to inform downtime models used for building design and/or performance assessment, such as ATC-58 (2012).

The guidelines for *Seismic Performance Assessment of Buildings* (ATC, 2012) currently estimate the occupancy interruption time for a damaged building including the length of time necessary to conduct repairs (i.e., repair time) and the length of time needed to procure items with long-lead times (i.e., mobilization time). These guidelines do not directly include estimation of downtime associated with unsafe placards as a primary source for damage-related downtime, but does suggest it on a case-by-case basis. However, a probabilistic event-tree framework, shown in Figure 2, describes how to include downtime associated with unsafe placards can be found in Mitrani-Reiser (2007). The branches of the event tree are informed by specific damage states of building components. A similar event-tree framework can be developed to describe outage of specific services for various building occupancy types (e.g., hospital) conditioned on physical damage, highlighting the importance of collecting such damage and downtime data simultaneously in the field. Alternatively, deterministic fault trees (described in detail later) may be used for a given simulation to determine the specific services that will be lost conditioned on damage. The goal of this study is to use the collected data from recent seismic events around the world to fully describe the branch structure of the probabilistic event tree model as well as the flowchart structure for fault trees to estimate partial and total closures of hospitals. Ultimately, in order to better quantify hospital resilience, it is necessary to prescribe a probabilistic relationship for downtime conditioned on the earthquake impact to the physical structure, loss of utilities and/or backups, availability of healthcare personnel, supplies and equipment, and throughput of patients.

2.2 HUMAN AND ORGANIZATIONAL INFRASTRUCTURES

A great deal of research has been performed on the impact of disasters on a hospital's human and organizational infrastructures from a purely medical and administrative perspective. IOM (2006) provides an extensive example of this approach. It describes how emergency departments function and interact with other organizations, and how this changes in a disaster. It identifies some of the key human vulnerabilities, including: a lack of surge capacity; variable levels of emergency training; and lack of adequate protection for hospitals and their staff from hazards (i.e., chemicals and infectious agents that may be a part of the disaster). ASPR (2013) takes a similar perspective and identifies crucial capacities that must be considered in the creation of an emergency plan, including: healthcare system preparedness, healthcare system recovery, emergency operations coordination, fatality management, information sharing, medical surge,

responder safety and health, and volunteer management. Both IOM (2006) and ASPR (2013) neglect the possibility that the hospital facilities themselves may somehow be damaged, resulting in loss of critical functions. The World Health Organization (WHO) and the Pan American Health Organization (PAHO) have developed a framework that addresses this problem through the "Safe Hospitals" initiative that focuses on services remaining functional during and immediately following a natural hazard (WHO 2009; PAHO 2007). To achieve this, the initiative identifies key vulnerabilities in three critical areas: structural, non-structural, and organizational. WHO (2006) assesses these vulnerabilities using the Health Facility Vulnerability Evaluation (HVE), which begins with a rapid qualitative assessment of the structural, non-structural and organizational aspects by field-specific experts. In its current form, however, the interconnections between the structural and non-structural performance and the organizational performance are extremely limited since experts with different expertise perform inspections. Additionally, the dependency of hospital functions on the presence of utilities is measured only through the presence of backup systems on site.

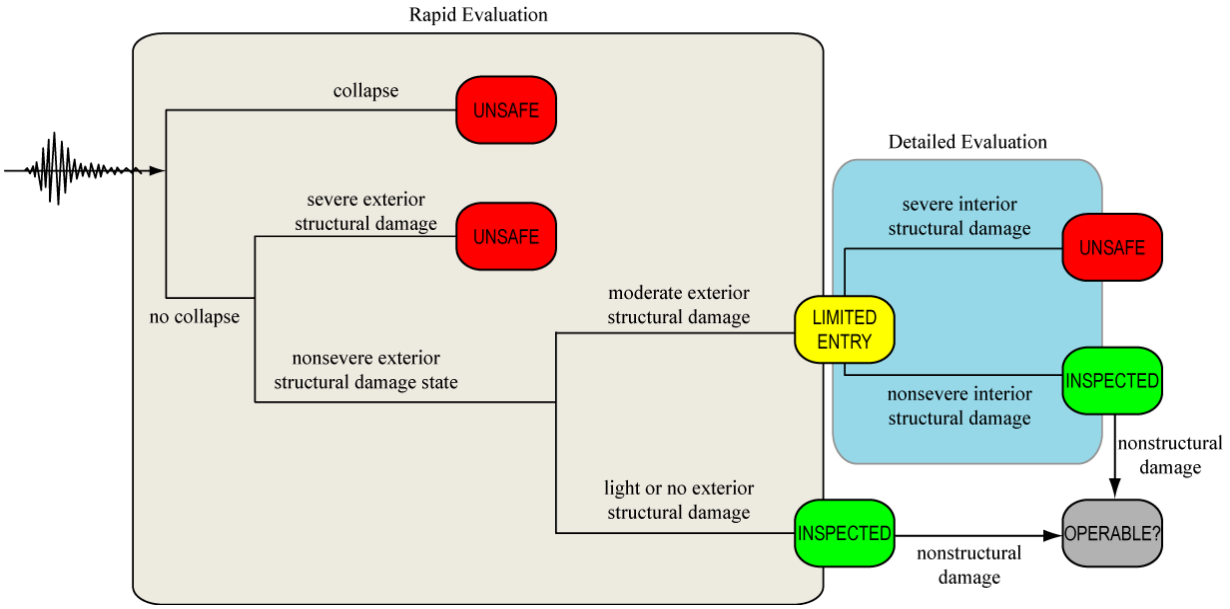

Figure 2. Event tree model for estimating the probabilities of receiving an unsafe placard based rapid evaluation, and detailed damage evaluation procedures.

Some attempts have been made to fill in the gaps of the above methodologies. Hossain and Guan (2012), for example, examine the effect of group interaction on patient treatment within a

hospital organization by using social network analysis to model coordination between the emergency departments of different hospitals during an emergency situation. Fawcett and Oliviera (2000) present a model of patient care after a disaster that includes transportation of patients to healthcare facilities and the response of these facilities after the patients arrive. The necessity for capturing dynamic behavior of both the hospital capacity and the transportation networks was also noted in Cimellaro et al. (2010a). Miniati and Iasio (2012) include both patient care functionality and physical damage as a part of their rapid seismic vulnerability assessment methodology. The "ready, willing, and able" framework described in McCabe et al. (2010) allows for the consideration of damage via its effects on the ability and willingness of providers to respond in an emergency, though it does not currently included damage directly. Detailed analysis of the links between physical damage and loss of function, however, has largely gone unperformed. This paper addresses this by examining how seismic damage influenced the loss of function in the hospitals.

3. BACKGROUND

The project aims to assess the impact of the 22nd February 2011 Canterbury and 4th April 2010 El Mayor Cucapah earthquakes on hospitals and patient care systems by analyzing the ways patient care was delivered to adapt to the loss of certain services (e.g. power outages, etc.) and physical space (e.g., structural, nonstructural, and content damage). The data collected from these reconnaissance trips was compared to data previously collected in Chile. Figure 3 shows the three earthquakes that are compared and the written sections below summarize (in chronological order) the characteristics of the earthquakes and impact they had on the countries of interest. Additionally, this section presents an overview of the healthcare systems in the three countries to provide context for the analysis of the performance and resilience of the hospital system.

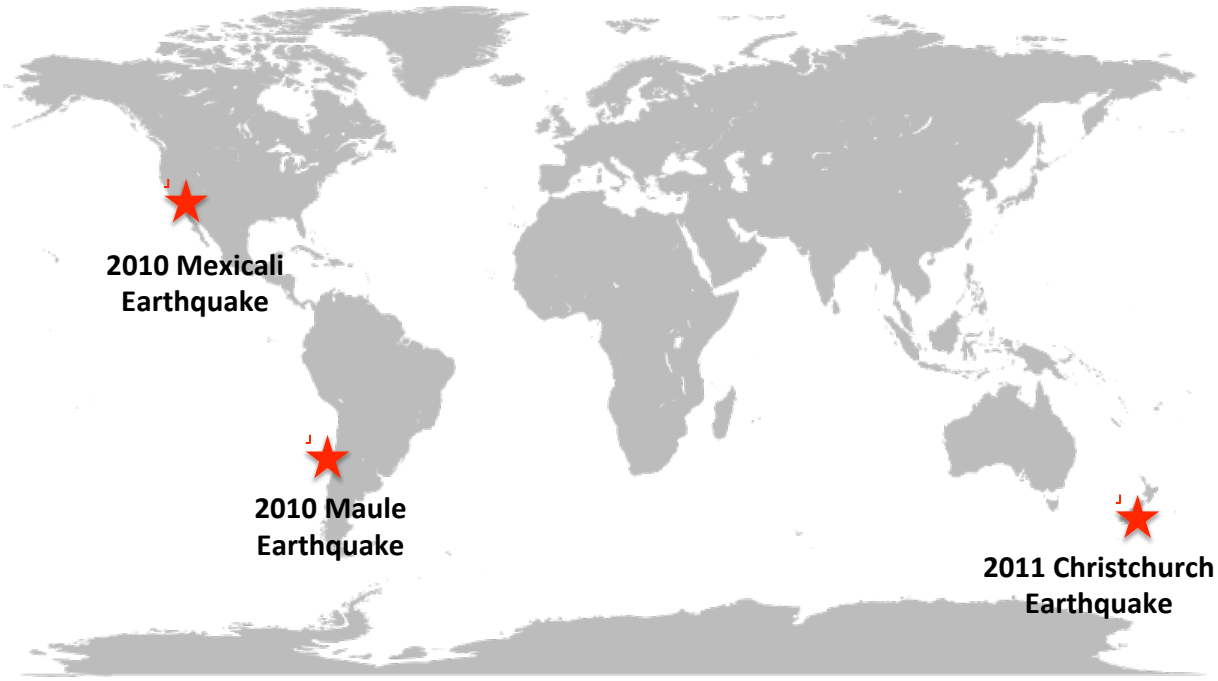

Figure 3. Earthquakes where hospital performance data was collected by the research team.

3.1 THE 2010 MAULE, CHILE EARTHQUAKE

Our reference event occurred on February 27, 2010, at 3:34 am, a moment magnitude 8.8 earthquake off the coast of the, Maule, Chile, 150 km northeast from the city of Concepción, and 434 km southwest from the Chilean capital, Santiago. The rupture at the interface between the Pacific and South American plates extended bilaterally north and south for about 560 km at a depth of 200 km. The event had two main slip hot spots at latitudes 36.19° S and 34.72° S, with maximum displacements of the order of fifteen meters (e.g., Hayes, 2010). The earthquake and resulting tsunami caused at least 523 fatalities, displaced more than 800,000 from their homes, and resulted in losses associated with earthquake damage totaling $30 billion USD, or 18% of the country's GNP (USGS 2011b). The earthquake impacted approximately thirteen million people, which is more than eighty percent of the Chilean population. The earthquake severely damaged infrastructure of all kinds including utility lifelines, healthcare facilities, residential structures, as well as industrial facilities in the private and public sectors. At the time of the reconnaissance trip, the Chilean Ministry of Health's (MINSAL's) reported that of the 135 hospitals in the service area, four became uninhabitable, 12 had greater than 75% loss of function, and seven were partially operating after the main shock. These results helped us identify a study area—the Bío-Bío Province (shown in Figure 4a). We obtained data from all

seven hospitals in the province, which is an inland jurisdiction of the larger Biobío Region. All hospitals were integrated into the central Biobío service area of the National Health Service system, and together cover a population of a little over 500,000. They ranged in size from the service area's referral hospital (Los Angeles) with 433 beds and 5 buildings on site, down to the rural Huépil hospital with only 26 beds and one small building.

(a) (b) (c)

Figure 4. The geographical regions included in this study: (a) Bio-Bio Region, Chile, (b) Baja California, Mexico and El Centro, CA, USA, and (c) Canterbury District, New Zealand.

3.2 THE 2010 EL MAYOR-CUCAPAH EARTHQUAKE

The 2010 El Mayor-Cucapah (i.e. Mexicali "Easter" or Baja California) earthquake occurred on Easter Sunday, April 4, 2010, at 3:40 pm Pacific Daylight Time, with a moment magnitude 7.2. The earthquake occurred at longitude 32.259 and latitude 115.287, at a depth of about 10 km (6.2 mi), approximately 17 km (11 mi) WSW from Guadalupe Victoria, Baja California, and 180 km (120 mi) SE from San Diego, California (EERI 2010). It was the result of slippage on the southeastern part of the Laguna Salada fault system, a set of strike-slip faults on the border between the Pacific and North American plates that run parallel to (but are distinct from) the San Andreas fault system (USGS 2010).

While this event was significantly less severe than the Bío-Bío earthquake, it was still the largest event in the area since 1892, proving larger than the 1940 magnitude 7.1 Imperial Valley earthquake (USGS 2010). The region had experienced the El Mayor-Cucapah earthquake resulted in 2 fatalities, at least 533 injuries, 4,389 residential buildings with major damage, and an estimated more than $50 million in economic losses (USGS 2010, EERI 2010). The earthquake was felt, not just throughout Baja California, but through much of the southwestern

United States, including southern California, Arizona, and Nevada. The aftershock zone ran all the way from near the northern tip of the Gulf of California to 6 miles north of the border between Mexico and the United States (USGS 2010).

This earthquake resulted in significant liquefaction throughout the Mexicali Valley, including Mexicali city itself. Movement and differential settlement of foundations caused the collapse or near collapse of hundreds of residences. Liquefaction also caused the collapse of a railway bridge, destruction of irrigation canals, and disruption of agricultural lands. These agricultural losses have proved particularly problematic to the region's economy (EERI 2010).

3.3 THE 2011 CHRISTCHURCH EARTHQUAKE

The M_w 6.2 Christchurch earthquake occurred at 12:51pm (NZ Standard Time) on 22 February 2011, with an epicenter ~7 km east-southeast of Christchurch city center at a depth of ~4 km (longitude 172.71 and latitude -43.60). The earthquake occurred on a blind oblique-thrust rupture on a shallow fault with high fault friction and co-seismic stress drop, which produced highly directional seismic energy towards Christchurch city (Beaven et al., 2011). The sedimentary basin of interbedded layers of gravels and sands underlying Christchurch amplified the source ground motion waves, thereby increasing damage to the region (Guidotti et al., 2011; Bradley & Hughes, 2012). The peak ground acceleration (PGA) in Christchurch's central business district (CBD) was on average 0.5g in the horizontal and vertical directions. The highest acceleration was recorded at Heathcote Valley Primary School: 1.7g in the horizontal direction and 2.2g in the vertical direction. The earthquake was characterized by a short duration, with the severe shaking only lasting 15 seconds (GeoNet 2011). Significant liquefaction occurred in areas throughout the Christchurch southern and eastern suburbs, resulting in land settlement, lateral spreading, sand boils, and a large quantity of ejected silt mud and water ponding onto the soil surface. The southern and south-eastern suburbs of Christchurch are constructed on the volcanic Port Hills, which lead to extensive rock falls, rock slope failures and several large-scale coastal cliff collapses.

Significantly, the Christchurch earthquake has been classified as part of the 2010-present Canterbury earthquake sequence. This sequence was initiated at 4:35am (NZ Standard Time) on 4 September 2010. The rupture of the previously unrecognized Greendale strike-slip fault beneath the Canterbury Plains of New Zealand's South Island produced a M_w 7.1 earthquake that

caused widespread damage throughout the region, though it produced no fatalities. The 22 February 2011 earthquake resulted in 185 fatalities, approximately 8,600 injuries, and widespread damage to the built environment throughout Christchurch city. The CBD was badly affected, with two major building collapses and various partial collapses of other buildings; the vast majority of fatalities (169) and severe injuries occurred in the CBD.

Initially over 100 city blocks were cordoned off to the general public due to unsafe buildings in this area. As of February 2013, over 1,100 buildings in the CBD (>60% of total damaged buildings in the CBD) have been demolished. Additionally, tens of thousands of residential properties suffered structural and non-structural damage, with over 6,500 properties rendered uninhabitable due to external risks, including liquefaction and rock fall risks. Sixty percent of electricity and water supplies were initially disrupted in the city; 90% of the city was restored within one week. Road networks were disrupted by liquefaction damage and various cordons, resulting in high traffic congestion on Christchurch roads. The region of study for this event is shown in Figure 4c.

3.4 THE HOSPITAL SYSTEMS OF CHILE, MEXICO, AND NEW ZEALAND

The organization of healthcare systems plays a significant role in how the emergency response will be handled. Therefore, the healthcare systems for the three countries of interest are briefly summarized below to provide context for the observations during our field work.

3.4.1 Chile. The Chilean National Health System (NHS) is a hybrid system that covers 93% of the total population of the country (16.8 million people) and can be divided into three organizational levels: (1) the public and private health system; (2) the ministry of health's public health and medical care networks; and (3) the public medical care network.

The first level is composed of all the private and public institutions and individual people that contribute to the promotion, protection, and health recovery of the ill person. The public health system (PuHS) covers 76.8% of the Chilean population and is organized by a single entity, the Ministry of Health (MINSAL); the rest 16.2% of the population is covered by the private health system (PrHS). The PrHS is a collection of three private entities: 16 health providers denoted as ISAPRES (13.5%), the military health system FOSPEN (2.7%), and 3 Health Mutuals (HM) dedicated mainly to prevent and support the recovery of employees injured at work. The PrHS has two main goals, to deliver the health benefits to the public, and to manage the financial

aspects of the system. The organization of the PuHS is considerably more complex, but its roles are similar and include: (i) regulating, supervising, and controlling the PuHS and PrHS, (ii) administrating the financial aspects of the PuHS, and (iii) executing the programs of public health and their administration. In addition to these roles, the MINSAL supervises a transversal health program known as Universal Access with Explicit Guarantees (AUGE), which covers every Chilean in 56 critical pathologies and assures the beneficiary that the benefit be provided by an accredited professional and institution, as well as being within the maximum copayment and waiting time.

At the second level, the internal organizational structure of the MINSAL considers two main departments or sub-secretaries, public health and medical care network. In simple terms, the public health network is responsible for providing the coverage for medical care through the National Health Fund (FONASA) that deals with 12.9 million beneficiaries stratified in 4 groups A through D according to family income; the National Institute of Public Health (ISP) that promotes health, prevention, vigilance, and illness control; and the 15 regional ministry secretaries (SEREMIS). FONASA is financed by the mandatory 7% every Chilean employee, in the private or public system, deducts from his or her monthly salary with a cap of monthly salary of about $2800 USD. The medical care network develops the medical care system through two decentralized entities, one in charge of providing all pharmaceutical and clinical supplies to people and facilities (CENABAST); and the other, the Health Services, is responsible for promoting, protecting, recovering, and rehabilitating ill people. Above both operative departments, there is a Health Superintendence, focused on controlling the medical care network, evaluating the condition of public health, watching for public health issues, enforcing the regulatory health framework, and coordinating the health sector.

The third level is composed of a total of 28 Health Services that are all financed by FONASA and that control the Chilean public medical care network. Depending on the complexity of the medical condition, patients usually start at any of the 1857 medical centers of primary medical assistance. These medical centers include 159 services for urgent primary assistance (SAPU), 1168 rural medical centers, 142 rural medical stations, 44 mental health centers (COSAM), 214 general urban medical centers, 156 centers of primary assistance (APS), 144 centers of family health (CESFAM), and 115 attached centers of primary assistance (CAAP). If the medical situation of the patient is of intermediate complexity, they are transferred from the primary

centers, or from hospital emergency rooms, to the closest of the 68 medical centers for secondary assistance. These include 58 attached specialty medical centers (CAE), 4 therapeutic diagnosis centers (CDT), and 6 referential health centers (CRS). If the condition is serious and requires intensive care, patients coming from primary or secondary assistance or emergency rooms at the same hospital are hospitalized in any of the 194 public hospitals that constitute the tertiary assistance level. Of these public hospitals, 59 are of high complexity and classified as type 1 if they include all subspecialties, or type 2 if they only include some of the subspecialties. The rest of 135 hospitals are denoted as type 3 for less complex procedures including internal medicine, pediatrics, obstetrics, and surgery, and type 4 if it just includes family medicine. In addition, there are two services of pre-hospital assistance, an urgent service of ambulances (SAU) only for Santiago, and the onsite urgent care medical assistance of high complexity (SAMU). In the Bío-Bío province, the general hospital located in the city of Los Ángeles serves as the referral center for the whole region. Two example hospitals from this study are shown in Figure 5.

A total of 117 hospitals that are part of the Chilean public health system reside in the affected region of the earthquake; 23 (20%) of these hospitals suffered some degree of diminished operability as a direct result of earthquake damage. After several meetings with officials at MINSAL, and weighing the extent of hospital damage in the provinces of the impacted area, and accounting for time constraints to complete a full system study, our reconnaissance team decided to focus our efforts on the seven hospitals in public healthcare system of the Biobío Province.

(a) (b)

Figure 5: (a) Front view of Mulchen Hospital, and (b) scale model of the Los Angeles Hospital.

3.4.2 Mexico. The metropolitan area of Mexicali has a population close to 1 million people and El Centro has a population of 43,000 people. Mexicali's economy is based on high-

technology manufacturing and agricultural products. The Mexican public health care system is composed of multiple entities: 80% of workers (all in the private sector) are covered by the Mexican Institute of Social Security (Instituto Mexicano de Seguro Social--IMSS); roughly 17% of workers (all in the government sector are covered by the Institute of Security and Social Services for State Workers (Instituto de Seguridad y Servicios Sociales para los Trabajadores del Estado--ISSSTE); military and naval personnel and petroleum workers have their own health programs; the rest of the population receives healthcare from other government agencies or from a private, for-profit healthcare network. This study surveyed the two government hospitals in the city of Mexicali, the Hospital General "5 de Diciembre" and the Hospital General de Mexicali.

The "5 de Diciembre" Hospital, built in 1970, is a federal hospital and part of the ISSSTE healthcare system for federal employees. It has 60 staffed beds, including 5 ICU beds and operates at 72% occupancy. The emergency department (ED) treats approximately 8,000 patients and there are 18,000 out-patient visits annually. There are 1,550 operative procedures annually. The Hospital General of Mexicali, shown in Figure 6 was constructed in 1977, and is a state-run hospital with 183 staffed beds, including 17 ICU beds, and it operates at 94% occupancy. The emergency department (ED) treats over 47,000 patients and there are 79,000 out-patient clinic visits annually. The hospital has approximately 23,000 inpatient admissions and 1,523 operative procedures annually.

Figure 6: Front views of El Centro Regional Medical Center and the Hospital General of Mexicali

3.4.3 United States. The city of El Centro's economy is based on government, agricultural and service jobs. The El Centro Regional Medical Center (ECRMC), shown in Figure 6, is one of two hospitals serving the Imperial Valley region, but also frequently receives patients from Mexicali. The facility is a full-service, non-profit hospital with 165 general beds, and has an

annual emergency department volume of 46,089 patients. There are four buildings on site: the original one-story facility was completed in 1956 and a two-story annex was added in 2003. The hospital is serviced by a central plant, and an administrative building on the northeast houses the information systems, medical records, and administrative offices.

3.4.4 New Zealand. New Zealand's healthcare system is entirely not-for-profit and is administered by District Health Boards (DHB). Publicly-owned hospitals provide most secondary and tertiary medical care, while the small not-for-profit private hospital sector specializes mainly in elective surgery and long-term care. Independent medical practitioners and specialists provide most ambulatory medical services, and are subsidized by their respective DHB. The "third sector" providers, composed of nonprofit non-government organizations (MoH 2011), offer other services, including general practitioners (GPs), nursing homes, and ambulance service.

Canterbury's hospital network is comprised of 22 public, private and elderly care hospitals and seven rural regional hospitals. Half of the regional hospitals have less than 20 beds, and primarily handle elderly and maternity patients. The private hospitals are subsidized by the CDHB (MoH 2011). A map of Christchurch city is shown in **Figure 7**, which includes the locations of the local healthcare facilities that served as redundant nodes in the hospital system, as well as local characteristics of the earthquake (represented by a liquefaction index and peak ground accelerations). The epicenter and shaking intensity of the Christchurch earthquake (USGS 2012) are shown in the inset regional map (**Figure 7**). The Canterbury hospital network is relatively centralized, with the Christchurch Hospital providing the bulk of care.

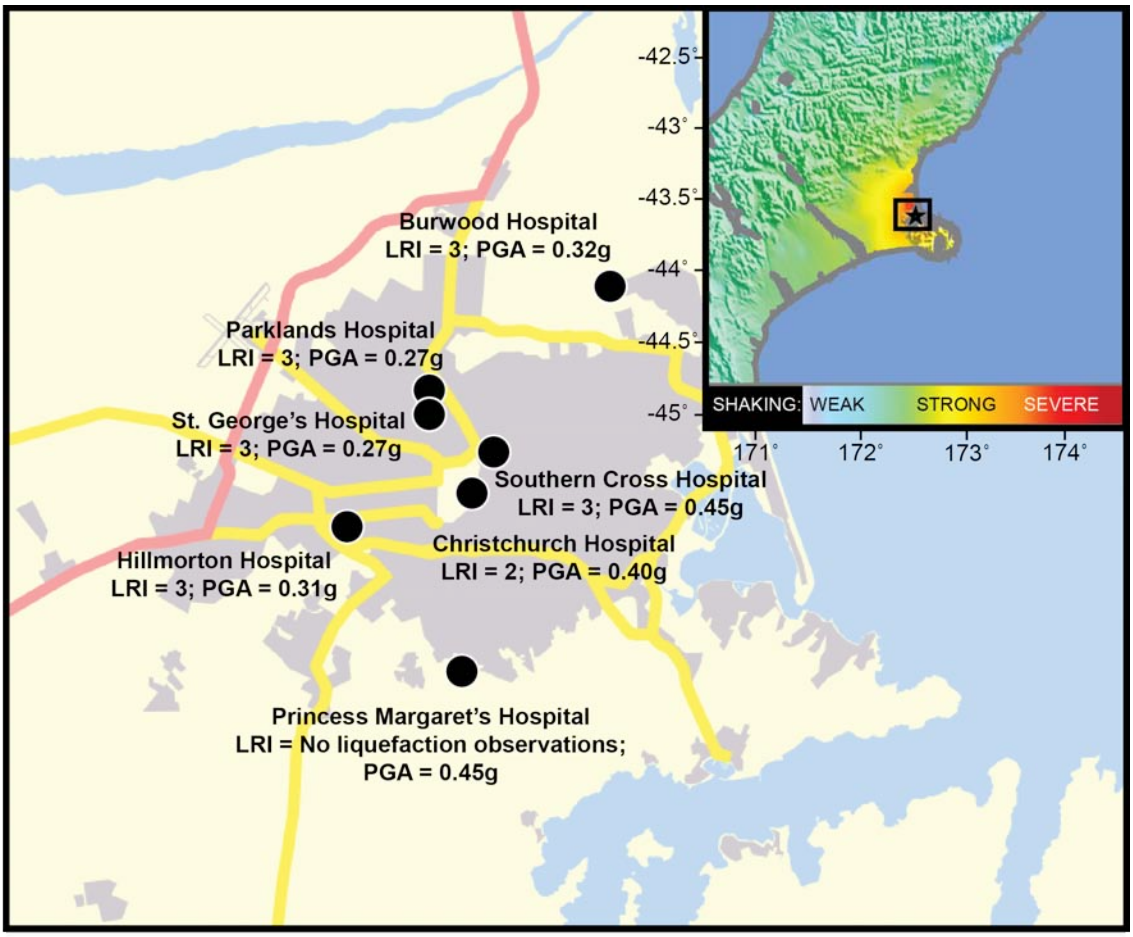

Figure 7: Map of the Christchurch urban area displaying the local healthcare facilities that accepted patients from the Christchurch Hospital, as well as the respective seismic characteristics (LRI and PGA values) at these locations. The inset map (upper right)

Christchurch Hospital, shown in **Figure 8**, is the largest hospital in the system, and operates the only Emergency Department (ED), trauma center and intensive care unit in Canterbury. It also performs the majority of general and specialty surgery within Canterbury. Christchurch Hospital serves a population of 560,000 and admits over 35,600 patients 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. It has 557 staffed beds including 15 ICU beds, 18 high-dependency beds, and 9 step-down beds (4 neurosurgery and 5 respiratory). Before the earthquake, the hospital typically operated at around 98%.

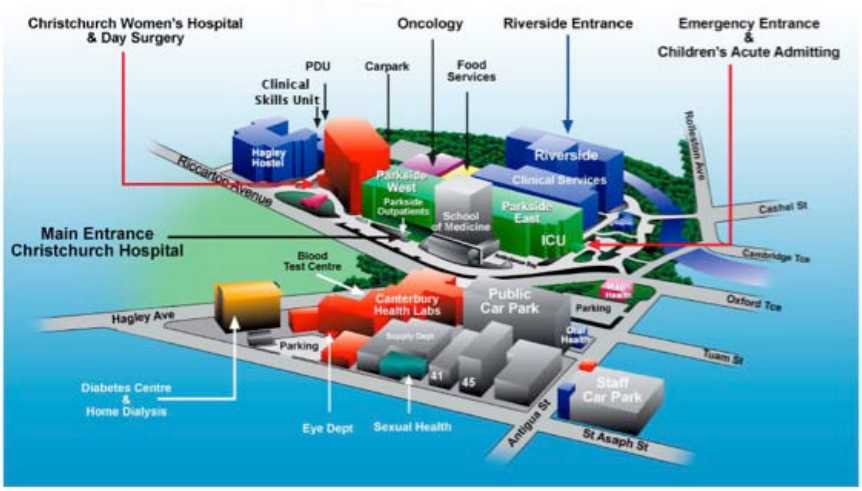

Figure 8: Christchurch Hospital (Christchurch Hospital Website, CDHB 2012)

The hospital complex is made up of several buildings constructed during different time periods and made on concrete-shear-wall or reinforced-masonry construction. The buildings on the hospital campus include: the Parkside Building (built late 80s to early 90s), the Riverside Building (built in the 1970s), the Hagley Hostel (built in 1931, vacant prior to earthquake for scheduled demolition), the Diabetes Centre (built in late 1950s early 1960s), and the Christchurch Women's Hospital (built in 2005 and the only base isolated structure in the South Island). Because the hospital was the only one in the city with an emergency department and comprehensive services it became the center of the healthcare response despite suffering significant damage. Approximately 200 people were being treated at Christchurch Hospital on the night of the earthquake.

There is little or no redundancy in the specialized services provided by the hospitals in the system. Burwood Hospital specializes in rehabilitation and elective orthopedic surgery. Hillmorton Hospital accounts for most of Christchurch's psychiatric care. Princess Margaret (PM) Hospital, shown in Figure 9, is a governmental specialty hospital with a focus on geriatric care, including psychiatric and rehabilitation services. The PM Hospital has approximately 150 staffed beds including a dementia ward and a psychiatric ward. There are also extensive day-hospital programs for mental health and rehabilitation services. There are a variety of hospital-based clinics focused on the needs of the elderly, but no emergency department and no surgical services. Before the earthquake, the occupancy rate of the hospital is usually over 85% and there are 2000 discharges a year, 70% of which are referred from Christchurch Hospital. There is one

large unreinforced masonry (URM) structure from the 1920s at the PM Hospital with some surrounding concrete and wooden clinic and administrative buildings. There was scattered non-structural damage and loose of ceiling tiles and suspended ceilings, but no significant structural damage. All elevators but one were rendered inoperable limiting patient and portable x-ray machine movement. The greatest impact was the complete loss of water and sewers for days. There was no direct damage to any laboratory or radiology equipment.

The private hospitals in Christchurch city, St. George's and Southern Cross, provide maternity care and elective surgery. St. George Hospital is a non-governmental specialty hospital with a focus on a broad range of surgical specialties and maternity services. The hospital has 101 staffed beds, including 23 post-anesthesia care unit (PACU) beds. It does not operate an emergency department but has some out-patient surgery clinics. There are approximately 110 physicians and 320 nurses on staff. Before the earthquake, the occupancy rate of the hospital varied from 100% on weekdays to 30% on weekends. On the day of the earthquake there were 69 hospitalized patients (35 surgery and 17 mothers and 17 newborns). The hospital complex is made up of three buildings: a 1928 URM and reinforced masonry building with delivery rooms and a maternal and nursery ward; a 1990s concrete shear wall building; and a 2000 concrete frame building that house the new Cancer Center and linear accelerator. The Cancer Center structure received the worse damage but the labor and delivery rooms in the older building were non-functional for a month, and that building was condemned.

Despite the lack of redundancy in hospital services, all hospitals in the region actively liaise with one another in order to provide efficient care and cope with capacity shortages. In fact, several facilities accepted transferred patients from Christchurch Hospital after the earthquake due to loss of capacity from earthquake damage; these facilities include Burwood Hospital, Hillmorton Hospital, Parklands hospital, Rosewood Rest Home, Southern Cross Hospital, and St. George's Hospital.

Figure 9: Princess Margaret Hospital

4. METHODS

The works reviewed in Section 2 attempt to define or quantify resilience from both physical and human/organizational infrastructures perspectives. However, none of the methodologies from the literature directly connect the two perspectives. A holistic framework for assessing system resilience is provided by Bruneau et al. (2003), who define four key properties needed to define resilience: robustness, redundancy, resourcefulness, and rapidity. The survey described in the following section offers a method to collect earthquake reconnaissance data that connects these four properties of resilience.

Bruneau et al. (2003) define robustness as a system's ability to withstand stress without a loss of function. The survey tool and the fault tree analysis presented below connect direct physical damage with the loss of functionality of hospitals. The survey and fault tree analysis also captures redundancies in the facilities (i.e., backup power and water supplies, alternative sites for healthcare delivery), and in the hospital system (i.e., a memorandum of understanding to enable transfer of supplies, staff, and patients to accommodate surge). The survey is designed to collect data on the resourcefulness of healthcare providers and staff to help keep hospital operations afloat when physical redundancies are not available. In addition, the survey captures the rapidity or time dependency property by recording the time required to restore functionality of clinical and nonclinical areas of the hospital.

4.1 POST-EARTHQUAKE SURVEY TOOL FOR HOSPITAL SYSTEMS

The survey tool used to capture information on the physical and functional impact of earthquakes was designed by Mitrani-Reiser et al. (2012a), and modified by the authors to include the unique features of the New Zealand and Mexico healthcare systems. The refined 'Health System Impact Survey' includes two main sections: one focused on physical damage, and one on healthcare and service-area functional impacts. The survey is typically completed from interviews with facility managers and/or engineers, and with chief medical officers, nursing directors and/or emergency planners.

The surveys were conducted in Christchurch six months after the earthquake by a multi-institutional (University of Canterbury and Johns Hopkins University), multidisciplinary team composed of experts in structural and earthquake engineering, risk assessment, disaster medicine, and disaster management. The interviews were completed between the 8th and 15th of August 2011 via phone and in-person meetings with staff across the CDHB. The interviews targeted the publicly-owned and two main private hospitals in Christchurch that provide the majority of secondary and tertiary medical care. The reconnaissance effort of the El Mayor-Cucapah earthquake focused on two cities: Mexicali in Baja California, Mexico, and El Centro in California, USA. The interviews were completed in person in between March 19-20, 2012, and targeted three hospitals in the study region.

4.2 COLLECTION AND ANALYSIS OF FURTHER DATA

Additional data was collected for the Christchurch Earthquake, with the assistance of our University of Canterbury colleagues. This data was not collected via the aforementioned survey tool, and were organized within a Geographical Information System (GIS) database linked to the digitized maps of the hospital network. Hospital operational data were made available via the RHISE (Researching the Health Impact of Seismic Events) group. These data include the number of patients present at and transferred from the Christchurch Hospital in the first two weeks following the earthquake, and the average length of stay (ALOS) of patients in Christchurch Hospital. Furthermore, media publications on the redistribution of Canterbury hospital network treatment capacity in the two weeks following the Christchurch earthquake were analyzed.

The transient ground motions experienced by the hospital buildings were measured in terms of peak ground accelerations (Bray et al., 2013; Bradley and Hughes, 2012), and were obtained

via up-to-date New Zealand specific ground motion predictive equations (Bradley, 2010) and a spatial correlation model (Goda and Hong 2008), combined with the actual recorded PGA values at various strong motion stations in the Canterbury region (GeoNet 2011). The liquefaction resistance index (LRI) values are from the LRI map developed by Cubrinovski et al. (2011) that characterize the level of earthquake-induced liquefaction. The LRI map presents the qualitative estimate of observed liquefaction in Christchurch according to a five-level scale, from 0 (most severe) to 4 (less severe); a sixth level exists to represent areas where liquefaction was not observed.

4.3 DEVELOPMENT OF FUNCTION LOSS MODIFIED FAULT TREES

Event trees are commonly used to identify the vulnerabilities of infrastructure and to show the dependence of their probabilities. Event trees, however, relate events in temporal order, and do not examine the causal relationships between event and outcome; they also require that events be mutually exclusive. Standard fault trees lack the temporal and probabilistic elements of event trees, but allow events to be related causally.

The trees developed for this study are modified from standard fault trees. For example, all events are represented using rectangles, regardless of whether they are terminating events in the tree, and switches are omitted. A pattern code is used to show that events are extremely localized or of very short duration. In addition to the “OR” and “AND” gates usually included in fault trees, a Boolean “XOR” gate is included, which is true if exactly one of the input events occurs, but false if two or more input events occur.

In this study, the relationship between failure of physical systems and loss of crucial clinical and support functions within a hospital is of particular interest. Special focus was given to those crucial functions whose functionality was dependent on a large number of utilities and other hospital functions. In the fault tree, the loss of power, general water, drinking water, sewage, information technology, medical gasses, physical medical records, and vertical egress is examined. The effect of severe damage in a service area that renders the area unusable is also included. The hospital services examined for partial or total loss of capacity include: surgery, emergency department, intensive care, in-patient medical care, and obstetrics on the clinical side, and laundry, kitchen, medical records, radiology, and administration on the support side.

For each critical service, differentiation is made between service capacity being reduced and the service being eliminated. Reduction of capacity does not necessarily indicate that the physical number of patients receiving care is reduced. It can indicate that some tasks normally performed in a service area are eliminated, but the service as a whole is still offered (e.g., an obstetrics department may still be able to perform normal deliveries, but be unable to perform an ultrasound). It may also indicate that, while service can still be provided, it will be significantly more difficult to provide it than it would be under normal operating circumstances (e.g., an emergency department may be able to suture wounds by flashlight, but this is significantly more difficult than doing so when general light is available).

5. RESULTS

This section discusses the physical damage observed in the three events and impacts of these earthquakes on hospital functionality. Additionally, utility loss, the modified fault tree, and the validation of that fault tree are provided for the Christchurch Hospital. We document efforts by the medical community to redistribute crucial services through the analysis of patient transfers and of service redistribution. Finally, two new metrics to quantify hospital resilience are also introduced.

5.1 PHYSICAL AND FUNCTIONAL IMPACT OF THE EARTHQUAKES

This section describes findings on the physical damage caused by the three events, including both structural and non-structural damage, as well as development of a fault tree linking utility failure with loss of services. Loss and reduction of service in most hospitals post-earthquake was primarily a result of damage to utilities and lifelines, rather than severe structural damage.

5.1.1 Structural Damage and Geotechnical Failures. Relatively little severe (i.e., no complete failures or obvious life safety threats) structural damage was observed in any of the three events. In Chile, structural damage was observed in just one of the seven surveyed hospitals. This facility suffered buckling in the steel roof trusses (shown in Figure 10a), severe racking of its penthouse due to torsion (shown in Figure 10b), spalled concrete in columns (shown in Figure 10c), cracking in shear walls, and collapsed in-fill walls. In New Zealand, St. George's Hospital experienced severe permanent deformation in its previously damaged maternity ward (shown in Figure 11 a), as well as foundation damage in its cancer care center (shown in Figure 11 b). In Mexico and the US there was no structural damage observed by the

researchers. However, several conflicting physical inspections of the Mexicali General Hospital and hospital staff's fear to inhabit a possibly damaged structure led to the closure of the hospital, which was still closed at the time of the interview. At the time of the earthquake the main tower of the "5 de Diciembre" Hospital was being retrofitted and so was only in partial use. Although there was no structural damage to the tower identified, the building was closed for repairs for eight months. Only the administration building of the El Centro Regional Medical Center sustained significant damage, consisting of extensive nonstructural damage to the facade and minor structural damage, leading it to be forcibly closed.

(a) (b) (c)

Figure 10: Structural damage details from the Chile Earthquake, including (a) buckled steel roof truss, (b) damaged penthouse, and (c) spalled concrete from a column

(a) *(b)*

Figure 11: Observed damage at St. George's Hospital: (a) permanent deformation of maternity ward, and (b) foundation damage in the cancer care center

The main Christchurch Hospital also experienced wide-spread cracking in shear walls (shown in Figure 12a), spalling of concrete in columns of its parking structures (shown in Figure 12b), and well as damage near separation joints (shown in Figure 12c). This structural damage forced the closure of some support areas, such as the tunnel under Riccarton Avenue (the throughway of lifelines across major roads), the administrative buildings on St. Asaph Street, and a hospital parking structure. There was also a great deal of geotechnical damage. Liquefaction induced flooding in nearly all the basements of the buildings in the Christchurch Hospital campus, including the based-isolated Christchurch Women's Hospital. The worst of this flooding occurred in the Parkside and Riverside buildings, resulting in major losses to support services housed there. All clinical buildings on the campus suffered at least minor structural damage, including shear wall cracking, roof damage, and damage to separation joints. This damage was generally not severe enough to cause loss of function in these areas immediately after the event, but it did provide obstacles to functionality in the following weeks and months, as services were temporarily shut down or relocated during repair work.

(a) (b) (c)

Figure 12: Observed structural damage throughout Christchurch hospital campus: (a) shear cracking in exterior panel (b) spalled concrete in ground-floor column of a parking structure, and (c) damage to separation joints (photo credit, Alan Bavis).

5.1.2 Non-structural Damage. Non-structural damage was more common and more widespread at all facilities. The same types of damage were often observed in multiple events. Common types of damage observed in all three events include broken piping, collapsed suspended ceilings, and damage to partition walls. Damage to cladding, mechanical equipment, and elevators was observed in New Zealand, the Unites States, and Chile, though these types of damage were generally much more severe in Chile, than in the United States and New Zealand. Overturning of furniture in both of these events also made paper medical records difficult to

access for some time after the earthquakes. In Chile, nonstructural damage forced the evacuation of at least three buildings and shut down three of the six relatively new operating rooms in one building. Damage to mechanical equipment also rendered the kitchens, laundry, and sterilizers inoperative, forcing the hospital to sterilize equipment off-site, thereby disrupting diagnostic services. In New Zealand, broken water piping in the main hospital forced the evacuation of several wards of the hospital and sharply reduced the capacity. Some of this capacity was still waiting to be restored months after the event. In some cases, even where equipment was undamaged or repaired, occupants' perception of possible danger from that equipment still prevented its use. This was especially noticeable in Mexico and New Zealand, where many undamaged elevators remained unused for some time after the earthquake because occupants were afraid to use them.

Damage to utilities was especially widespread. In all three events, damage to lifelines, as well as various structural and non-structural components, affected the ability of hospitals to provide services. Generally, failures of lifelines such as communications, power systems, and water systems had the greatest impact on the functionality of healthcare systems, whereas structural damage had relatively little impact.

Loss of communications was the obstacle to functionality most consistently identified by hospital administrators. In Chile, the landlines and cellular phones were at least partially disrupted for three to seven days after the event for all seven surveyed facilities. Lack of emergency planning for communication either within single hospitals or between different hospitals lead to isolated health care "islands", where response efforts could not be efficiently coordinated. In Mexico and California, disruptions to landlines and cellular phones occurred, but were of much shorter duration, lasting less than a day for all three surveyed hospitals. The availability of backup systems in the form of satellite phones and radios also somewhat mitigated the impact of communication losses. Performance of communications systems varied from hospital to hospital in New Zealand, with landline disruptions lasting anywhere from twenty minutes to five days, and cellular phone disruptions varying from six to 24 hours, even for hospitals within the city. Communications backups for intra-facility communication were available at Christchurch Hospital in the form of handheld radios and runners, but were not available for communication with other facilities. Specifics of the communications issues at the six focus hospitals are provided in Table 1.

Table 1: Communications Losses and Backups at Focus Hospitals

	Christchurch Hospital	P. M. Hospital	St. George´s Hospital	Los Ángeles Hospital	Hospital General "5 de Diciembre"	El Centro Regional Med. Center
Landline Disruption Duration	20 minutes	1 day	1 day	6 hours	<24 hours	1 – 2 hours
Cellular Phone Disruption Duration	1 hour	5 hours	1 day	9 hours	<24 hours	1 – 2 hours
Available Backups	Handheld radios/ runners	No Backup	No Backup	Satellite phones		Satellite phones/ 800 MHz radios
Major Issue Identified by Administrators	√	√		√		

Disruptions to municipal power occurred in every facility for all three events. In Chile and New Zealand, this was further exacerbated by failures of backup power systems in some facilities. The total duration of municipal power disruption varied between events, lasting up to a week in Chile, but less than 18 hours in New Zealand and less than nine hours in Mexico. During the earthquake, the city of El Centro and the El Centro Regional Medical Center lost power, but the hospital used backup generators. Due to the rupture of a feeder line the HVAC system to the hospital's ICU was lost with repairs taking more than a week. In Chile, the backup generators in four of the seven surveyed facilities failed to turn on at all, and the remaining facilities experienced some issues with insufficient power to run important medical equipment, such as radiology. In New Zealand, the main Christchurch Hospital experienced problems with some of its backup generators, which caused power disruptions in some parts of the hospital lasting up to six hours. Specifics of the power issues for the six focus hospitals are provided in Table 2.

Table 2: Power Losses and Backups at Focus Hospitals

	Christchurch Hospital	P. M. Hospital	St. George´s Hospital	Los Ángeles Hospital	Hospital General "5 de Diciembre"	El Centro Regional Med. Center
Municipal Power Disruption Duration	18 hours	4 hours	<18 hours	9 hours	12 hours	2 hours
Available Backup Generators	√	√	√	√	√	√
Backup Power Disruption Duration	1.5 hours	No Loss	No Loss	5 hours		N/A
Major Issue	√			√		√

Identified by Administrators						

Disruptions to municipal water systems occurred in both Chile and New Zealand, though not in Mexico. In Chile, five of the seven surveyed facilities lost municipal water altogether. In New Zealand, most hospitals experienced some disruption to municipal water. In some facilities, municipal drinking water was not restored for many days, and even after water was restored, damage to piping caused difficulties in achieving sufficient water pressure for sprinklers and boilers. Details of the water system performance are provided in Table 3. All of these failures can be collated and examined across the three events to see which utilities tended to suffer the most damage. A summary of this damage across all three earthquakes is provided in Table 4.

Table 3: Water Losses and Backups at Focus Hospitals

	Christchurch Hospital	P. M. Hospital	St. George´s Hospital	Los Ángeles Hospital	Hospital General "5 de Diciembre"	El Centro Regional Med. Center
General Municipal Water Disruption Duration	1 week	2 days	6 hours	No Loss	1 week	No Loss
Municipal Drinking Water Disruption Duration	15-30 days	>30 days	<14 days	N/A*	N/A*	No Loss
Available General Water Backup	Borehole/ <1 day stored	Borehole/ 1 week	8 hours	72 hours	1 week	No Backup
Available Drinking Water Backup	Bottled water	Bottled water	No Backup	N/A*	N/A*	No Backup
Major Issue Identified by Administrators		√	√			

** Note: This hospital always used only bottled water for drinking.*

Table 4: Infrastructure Damage in Surveyed Hospitals

Utility Lost	Hospitals in Bío- Bío	Hospitals in Baja & El Centro	Hospitals in Christchurch	Hospitals across all events
Municipal Power	7/7	3/3	4/4	14/14
Municipal Water - General	5/7	2/3	3/4	10/14
Municipal Water - Drinking	N/A*	0/1*	4/4	4/5*
Backup Power	3/7	2/3	1/4	6/14
Backup Water - General	N/A*	0/3	2/4	2/7*
Backup Water - Drinking	N/A*	0/3	1/4	1/7*
Sewage/ Wastewater	0/7	0/3	1/4	1/14
Landlines	7/7	3/3	4/4	16/14
Cell phones	7/7	3/3	4/4	15/14

IT	1/7	2/2*	1/4	4/13*
Physical Medical Records	3/7	2/3	1/4	6/14
Elevators	1/7	1/3	3/4	5/14
Medical Gasses	1/7	0/2*	0/4	1/13*

*Note: * indicates that infrastructure was not present at some hospitals, or was not asked about in some versions of the survey.*

Across the three events, these utility failures contributed to loss of services, even those not located in the areas with structural damage still suffered partial or total loss. This is consistent with literature for countries whose building stock and design codes are similar to those of the US (FEMA 2007). Table 5 summarizes the service losses that occurred in across the three events.

Table 5: Services Lost or Reduced in Hospitals Surveyed

Service Lost	Hospitals in Bío- Bío	Hospitals in Baja & El Centro	Hospitals in Christchurch	Hospitals across all events
CLINICAL				
In-patient Medical Care	4/7	3/3	1/3*	8/13*
Emergency Room	2/6*	2/3	0/2*	4/11*
Surgery	1/2*	2/3	1/2*	4/7*
Intensive Care	N/A	2/3	1/2*	3/5*
Out-Patient Care	3/7	3/3	1/4	7/14
Obstetric/Delivery	1/7	2/3	1/3*	4/13*
SUPPORT				
Social Work/Admin	2/7	2/3	0/4	4/14
X-ray/ Ultrasound	6/7	2/3	1/4	9/14
MRI/CT Scan	1/1*	3/3	2/3*	6/7*
Medical Records	3/7	3/3	1/4	7/14
Blood Bank	0/2*	0/3	0/4	0/9*
Kitchen	2/7	0/3	1/4	3/14
Laundry	2/7	0/3	2/4	4/14

*Note: * indicates that service was not present at some hospitals, or was not asked about in some versions of the survey.*

5.1.3 Fault Tree Development. Based on physical connections within hospitals and anecdotal evidence gathered from the surveys conducted in Chile and Mexico (Jacques et. al. 2013), a modified fault tree has been developed to connect failure of utilities and other seismic damage with the loss or reduction of critical clinical and support services; the data from Christchurch was used to validate the predictive capability of the fault tree. An example of this fault tree is shown in Figure 13. In this tree, solid gray indicates complete global loss, dashed gray indicates localized loss, dashed black indicates intermittent global loss, and solid black indicates no occurrence. In this modified fault tree, certain utilities are shown to have especially wide-spread and serious effects on the ability of a hospital to function post disaster. In particular, electricity and water are shown to be crucial. This is consistent with the findings of recent studies (i.e.,

WHO 2006; Kirsch et al., 2012; ASPR 2013), and goes into much greater detail, as it shows the specific clinical and support services that are likely to be effected by this type of loss.

For the Los Ángeles Hospital, upon which the fault tree was based, the predictions from the fault tree are, as one would expect, very close to correct. According to the fault tree, Los Ángeles Hospital would have suffered complete loss of all clinical services and non-medical services, except medical records and administration. The fault tree also designated a partial loss of medical records and no loss of administration. The only discrepancies occurred in the blood bank and the emergency room, which, according to the surveys conducted there, kept functioning in spite of having no power of any kind. It is unclear what allowed these areas to remain functional when all other services were lost, though possibilities include battery-powered lighting and the addition of generators brought from outside the hospital to power those areas when the hospital's internal generators failed.

This modified fault tree has a mixed level of success in deriving what actually occurred at Christchurch Hospital. Outpatient care was eliminated the first day after the earthquake, and limited for the next two weeks, which is accurately reflected by the fault tree assessment. In-patient care was lost in the flooded areas of Riverside, and reduced in the rest of the hospital under the strain of lack of utilities. Also, laundry was indeed relocated to another hospital for a few days because the plant was down and because of short-staffing. The model is less accurate for other services; the intermittent losses in other clinical areas due to failure of backup power did not occur, owing largely to the emergent behavior of staff to keep the areas running through alternate means until the generators could be brought back online. This included horizontal evacuations within the hospital and the use of headlamps. The total loss of the kitchen was predicted by the fault tree but not seen in the field; this discrepancy may be related to the speed at which backups were restored. The inaccuracies reflect the lack of a dynamic fault tree structure. The researchers of this project are working on further developing the fault tree structure to capture dynamic behavior. A summary of tree's performance for all New Zealand Hospitals with significant damage is provided in Table 6.

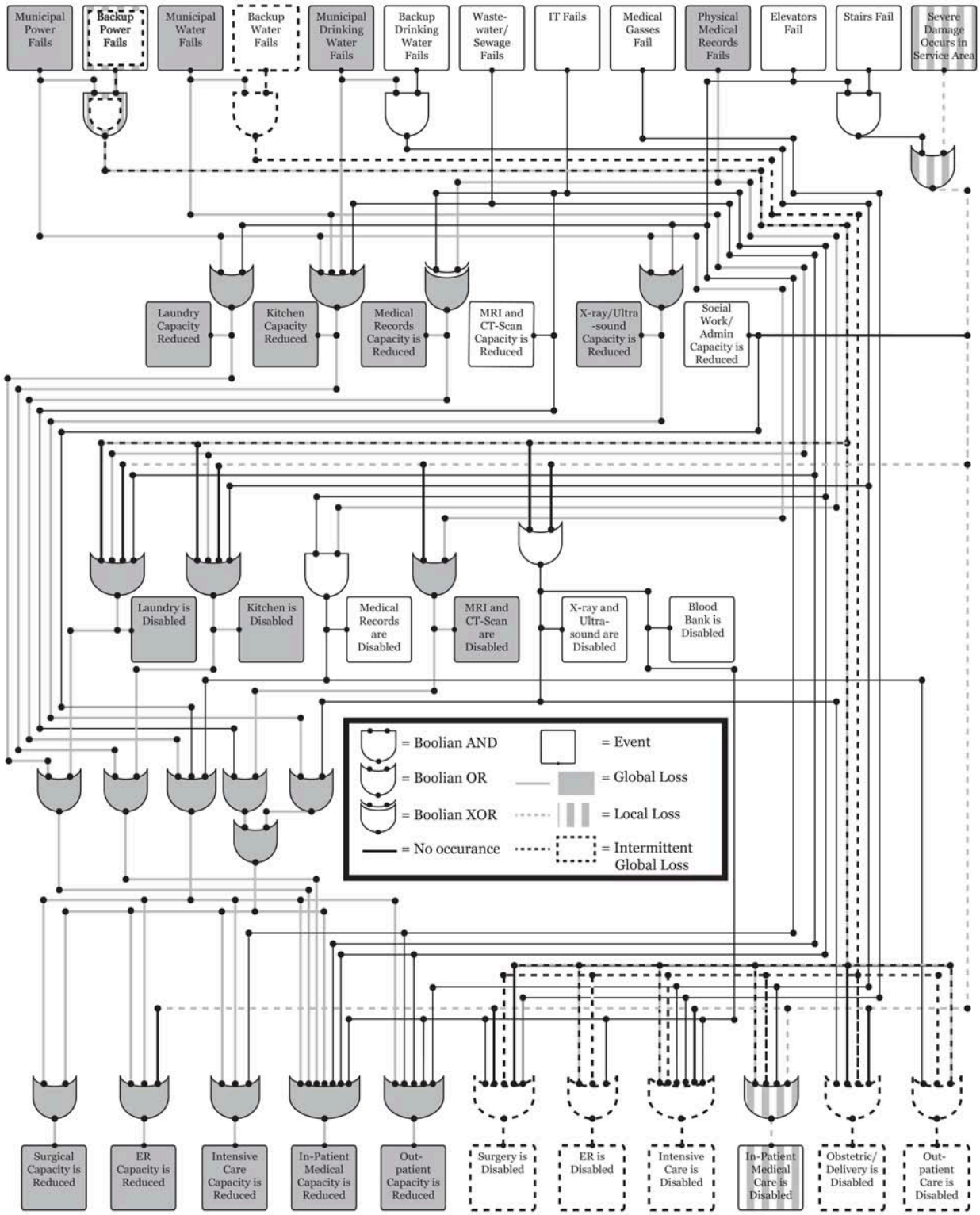

Figure 13: Modified fault tree deriving loss and reduction of Christchurch hospital services based on loss of critical utilities.

Table 6: Global Service Loss and Reduction in Damaged New Zealand Hospitals. Y indicates a loss of service, where R indicates a reduction in service and N indicates no loss of service.

Service	Christchurch Hospital		PM Hospital		St. George's Hospital	
	Actual	Derived	Actual	Derived	Actual	Derived
SUPPORT						
Laundry	Y	Y	Y	Y	Y	Y
Kitchen	N	Y	Y	Y	Y	Y
Medical Records	R	R	R	N	Y	R
MRI and CT Scan	Y	Y	N/A		Y	Y
X-ray and Ultrasound	R	R	N/A		Y	R
Blood Bank	N	N	N	N	Y	N
Administration	N	N	R	N	Y	N
CLINICAL						
Emergency Dept.	N	R	N/A		N/A	
In-Patient Medical Care	N	R	N	R	N/A	
Out-Patient Care	R	R	Y	R	Y	R
Surgery	R	R	N/A		Y	N
Intensive Care	R	R	N/A		Y	Y
Obstetric/ Delivery	N	N	N/A		Y	Y

5.2 HOSPITAL TREATMENT DEMAND AND RESIDUAL CAPACITY

The El Mayor-Cucapah earthquake completely shut down two of the public hospitals in Mexico, forcing redistribution of service in rented space and at other facilities. The Christchurch earthquake severely strained Canterbury region's hospital system, and various steps were taken to surge hospital capacity in the emergency phase. A comprehensive Health System Recovery Plan, consisting of over 200 projects and initiatives designed to restore capacity and improve service delivery across Canterbury, was developed for the long-term recovery (CDHB 2011). The sections below briefly report on these steps and initiatives with particular focus on patient transfers to manage lost bed capacity in the emergency phase and on strategies to surge capacity and redistribute services in the short and long term.

5.2.1 Inter-Hospital Patient Transfers. Following the El Mayor-Cucapah earthquake, the main tower of the Mexicali General Hospital was evacuated spontaneously, leaving only the ICU on

the second floor occupied. Services were then provided in tents on the grounds until patients were discharged or transferred elsewhere. Some inpatient services were moved to local private hospitals and many of the affiliated outpatient clinics have been relocated to other spaces in Mexicali until construction is complete. Also, approximately 180 patients were evacuated from the tower of the "5 de Diciembre" Hospital after the event, but with relatively few injuries in the city there was no surge in patient visits after the event. There were no injuries in the El Centro Regional Medical Center (the damaged administration building was closed because it was Sunday) and no patients were evacuated. There were very few injuries and no deaths in town so there was no increase in patient visits after the earthquake.

After the Christchurch earthquake, all patients were evacuated from St. George's Hospital within a couple hours after the earthquake due to concerns about the structure and aftershocks. Then, after discharging most patients, transferring the few remaining and cancelling all elective surgery the hospital was completely closed for 12 days for repairs. On the day of the earthquake there were 147 hospitalized patients (109 general and 38 psychiatric) at Princess Margaret Hospital, and no patient was injured, killed, or evacuated; the hospital accepted patients transferred out of the damaged areas of Christchurch hospital that night and the following days, opening 30 additional beds.

The majority of the casualties were treated at the Christchurch Hospital since it was close to the location of these casualties. To continuously provide healthcare to earthquake survivors and existing patients with the reduced functionality, Christchurch Hospital had to build capacity. Increased staffing was the most rapid response, with hospital administrators reporting the spontaneous arrival of additional clinical and support staff in less than an hour. The second adaptation was to rapidly discharge and transfer patients to other facilities. Staff also reported that 5-10% of all patients, and 50% of post-partum patients 'self-discharged' in the first few hours.

Christchurch Hospital accounted for 387 of the 455 outgoing transfers from Canterbury hospitals during the first two weeks after the event. Ashburton and Burwood Hospitals accounted for most of the remaining out-going transfers. Approximately 70% of the transfers from Christchurch Hospital occurred in the first week following the earthquake. However, the data doesn't include discharges, which were significant immediately after the earthquake. At the time

of the earthquake, there were 637 patients present in Christchurch Hospital; after 24 hours, there were 320 patients and after 72 hours, this was further reduced to 270 patients. After one week, the number rose to 400 patients as some capacity was restored.

The decision to transfer patients from Christchurch Hospital was made internally, and supported by CDHB resources control and coordination process and in liaison with staff from the receiving hospitals. The transfer/discharge of patients immediately after the earthquake was largely cautionary due to the expected large number of casualties and the 19% (~106 beds) reduction in permanent capacity within Christchurch Hospital. Because the hospital typically operated at around 98% occupancy, there was little room within the hospital's existing facilities to absorb the lost capacity. Therefore, the lost capacity had to be accommodated in other hospitals and by the reduction in elective services.

In the first 24 hours, 32 patients were transferred by truck to Princess Margaret Hospital and 12 intensive care patients were transferred by air to hospitals around the country. Over the first two weeks patients were transferred to 33 different hospitals throughout Christchurch, the Canterbury region, and the rest of New Zealand. Severe earthquake casualties were transferred to ICUs as distant as the North Island along with other non-earthquake patients including geriatric patients. The main mode of transfer for the less critical patients was via roads, using available (and sometimes unconventional) vehicles. For example, elderly patients were transferred from Christchurch Hospital to Princess Margaret's Hospital on the night of the event using furniture trucks. Fixed wing flights and helicopters were used for the long-distance transfers to reduce the transfer time to destinations throughout the South Island and the North Island.

5.2.2 Service Redistribution and Capacity Building Strategies. Following the Christchurch earthquake, many Canterbury hospitals altered their plans for support services. The regional hospitals were able to perform their own services (i.e., laundry usually done at Hillmorton Hospital). Timaru Hospital provided clean linens to Christchurch Hospital for two days. Princess Margaret's Hospital lost its laundry services for seven days, and resorted to using both sides of sheets to extend the lifetime of the linens. Ashburton Hospital helped source clean linens, but existing stock had to be conserved to retain capacity.

5.3 DEVELOPMENT OF PRELIMINARY RESILIENCE METRICS

Based on the findings presented in Sections 5.1 and 5.2 and the framework presented in Bruneau and Reinhorn (2004), two preliminary resilience metrics are proposed for individual hospitals, based on a loss of capacity and a loss of hospital functions.

The capacity-based metric, $Q_c(t)$, measures hospital capacity over time as a function of available beds and the throughput of hospital patients:

$$Q_c(t) = \begin{cases} 0 & \text{if } \left[\left(P_o + P_n(t) + P_e(t)\right) - \left(D_n(t) + D_e(t)\right)\right] > \left(B_o - B_L(t)\right) \\ \dfrac{\left(B_o - B_L(t)\right) - \left[\left(P_o + P_n(t) + P_e(t)\right) - \left(D_n(t) + D_e(t)\right)\right]}{B_o - \left[\left(P_o + P_n(t)\right) - D_n(t)\right]} & \text{otherwise} \end{cases} \quad (2)$$

where B_o is the initial bed capacity, $B_L(t)$ is the number of beds lost due to earthquake damage as a function of time, P_o is the initial number of patients in the hospital, $P_n(t)$ is the number of patients entering the hospital for non-earthquake-related reasons as a function of time, $P_e(t)$ is number of patients entering the hospital for earthquake-related injuries or transfers as a function of time, $D_n(t)$ is the number of routine discharges over time, and $D_e(t)$ is the number of earthquake-related discharges over time. As the hospital restores its original capacity, $Q_c(t)$ approaches 1. The variables of this metric can be populated post-event using admission statistics, capacity loss, and discharges from a seismic event. It can be used predictively using physical damage estimates to determine the loss and recovery of beds, and using earthquake casualty and discharge estimates to determine patient throughput.

The function-based metric, $Q_f(t)$, addresses the quality of care by examining the loss and redistribution of n critical clinical and support services at a hospital. $Q_f(t)$ is defined as

$$Q_f(t) = \frac{\sum_n w_i \left(1 - \left(1 - R_i(t)\right)L_i(t)\right)}{\sum_n w_i} \quad (3)$$

where n is the total number of functions considered, w_i is a weighting term representing the importance of function i, L_i is the loss of function i (ranging from 0-1, or ‘no loss’ to ‘total loss’), and R_i is the redistribution of function i (ranging from 0-1, or ‘no redistribution of hospital functions’ to ‘complete redistribution of hospital functions’). It should be noted that R_i can never equal one when services are redistributed to other facilities, since this metric measures resilience for a single facility. As all functions within a facility are fully restored, this metric also approaches one.

Physical damage can tie into this metric in several different ways. The weighting constants, w_i, can be estimated based on a healthcare perspective or from a physical damage perspective, using fault trees. For facilities using healthcare outcomes to predict resilience, the importance of each function can be assigned based on provider expertise. Importance can also be assigned based the relationship between the failures of different functions. In addition, this metric can be combined with causal relationships between utility failure and functional failure, and probabilistic relationships between physical damage and utility failure, in order to create a prediction of healthcare resilience based upon physical damage.

5. CONCLUSIONS

Hospitals are a particularly crucial and vulnerable component of disaster response. It is vital not only that the complex systems that comprise a hospital sustain relatively little damage, but that all clinical and support functions remain operative. To better understand how physical damage affected the ability of hospitals to function, a guided survey tool originally developed for use in Chile after the Bío-Bío earthquake was modified for use in hospitals affected by the Canterbury 2011 and El Mayor-Cucapah 2010 earthquakes. Data was collected using the modified survey tool in New Zealand (between the 8th and 15th of August in 2011) and in the United States and Mexico (on the 19th and 20th of March in 2012). In New Zealand, supplemental patient capacity and transfer data was provided by the RHISE group. Based on the data collected from the surveys and the RHISE group, a thorough analysis of the effect of earthquakes on hospitals in Mexico, the United States, and New Zealand was performed.

The physical infrastructure of the Canterbury health system in Christchurch showed a fair level of robustness considering that earthquake demands were higher than those mandated by the design standards. The physical damage affected both hospital capacity and services by eliminating a significant number of beds at the main Christchurch Hospital and the private St. George's hospital, and by disabling critical utilities needed to perform some clinical and support services at Christchurch, Princess Margaret, and St. George's Hospitals. However, by increasing staffing, discharging some patients, and transferring some patients to other hospitals throughout the city, the health district, and the country as a whole, Christchurch hospitals created surge capacity, and allowed the Canterbury region to fulfill the healthcare needs of its residents.

The robustness of hospitals after the El Mayor-Cucapah earthquake varied greatly, even though none of the hospitals suffered significant structural damage. Services at the Hospital General “5 de diciembre” were eliminated altogether, save for emergency services provided from tents immediately following the earthquake. Services at Hospital General de Mexicali were disrupted somewhat by a spontaneous evacuation, but were largely able to remain intact. Across the border in California, there were minor issues with availability of electrical and communications, but services continued largely uninterrupted.

This study showed several important trends in the effect of damage on the functionality of hospitals after a seismic event. In both the El Mayor-Cucapah and Canterbury earthquakes, as well as the reference Bío-Bío earthquake, our findings clearly show that hospitals do not have to collapse in order to be rendered inoperable. In fact, most functional losses were due to non-structural damage, especially to utilities. Therefore, it is necessary that the most crucial systems, especially water, power, and communication, have sufficient redundancy to continue to operate after an earthquake. It is also important that efforts to mitigate seismic hazards be clearly communicated to the public, so that fear produced by lack of knowledge does not prevent the use of otherwise safe and operational systems and facilities.

By combining the findings of this study with data taken in Chile, several tools for understanding hospital resilience were also created. These tools included two new preliminary resilience metrics and a modified fault tree. The capacity-based metric measures general ability to provide care as a function of number of available beds and patient population and throughput, while the function-based metric measures one aspect of quality of care by examining how important services are lost and restored. The fault tree analyzes the causal relationships between failures of various utilities and loss and reduction of critical clinical and support services in individual hospitals. These relationships were originally found based on physical configurations of hospital systems and anecdotal accounts from Chile and Mexico, then validated based on findings from Christchurch. This fault tree proved somewhat capable in predicting service loss from utility loss, though its accuracy was limited the lack of a dynamic component in the fault tree structure.

6. EDUCATION AND OUTREACH

The work from this research is directly incorporated into several courses at Johns Hopkins University including Civil Analysis (Mitrani-Reiser), Structural Dynamics (Mitrani-Reiser), and Introduction to Public Health Emergency Preparedness (Kirsch). Additionally, all of the undergraduate and graduate students in Mitrani-Reiser's research group participated in July 2012 in the Johns Hopkins Institute Engineering Innovation Summer Program. Mitrani-Reiser and her students designed an educational module for high school students participating in this program to build 'real' healthcare structures consisting of structural members (straws and popsicle sticks), connections (pins), nonstructural members (spaghetti), and energy dissipating devices (rubber bands). Each healthcare structure had an intensive care unit with patients (marbles). Historic ground motions were used to load the structures so that the students could experience first-hand the havoc that natural disasters can have on our built environment, and the impact using upfront costs to mitigate their buildings. This program was a great success and will be repeated annually.

Additionally, this collaborative work inspired a Workshop on Vulnerable Populations, sponsored by the Dean of the Whiting School of Engineering and the Civil Engineering Department at the Johns Hopkins University. The all-day workshop was attended by faculty and students of the Johns Hopkins University (School of Engineering, School of Medicine, and School of Public Health), one student from the University of Canterbury, and healthcare providers of the Canterbury District Health Board. An equal number of presentations were given by US and NZ participants to share current research and practices of emergency response. The main conclusion of this workshop is that a considerable amount of research needs to focus on how to address the evacuation procedures of patients from nursing homes, and the surge that is created in hospital systems when these long-term care facilities become damaged in an earthquake.

7. DISSEMINATION

The work for this project and ongoing related work on healthcare vulnerability due to natural hazards has resulted in several publications, conference presentations, and invited lectures, including:

Refereed Conference and Journal Papers:

Jacques, C.C., McIntosh, J.K., Giovinazzi, S., Kirsch, T.D., Wilson, T, & Mitrani-Reiser, J., 2013 (accepted). Resilience of the Canterbury Health Care System to the 2011 Christchurch (Mw=6.2) Earthquake, NZ. *Earthquake Spectra* (special issue expected 2014).

Jacques, C., Mitrani-Reiser, J., & Kirsch, T. D. 2013. An All-Hazards Approach for Quantifying Loss of Function for Critical Healthcare Infrastructure. To be presented at the 2013 Structures Congress, Pittsburgh, Pennsylvania, USA.

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), 122-128.

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Mitrani-Reiser, J., Jacques, C., Kirsch, T.D., Giovinazzi, S., McIntosh, J.K., and Wilson, T.M., 2012. "Response of the Regional Health Care system to the 22nd February 2011, Christchurch Earthquake, NZ," Proc. Of the 15th World Conference on Earthquake Engineering, Lisbon, Portugal, September 2012.

Mitrani-Reiser, J., Mahoney, M., Holmes,, W. T., de la Llera, J. C., Bissell, R., & Kirsch, T. 2012a. A Functional Loss Assessment of a Hospital System in the Bio-Bio Province. Earthquake Spectra, 28(S1), 473–502.

Invited Lectures:

Structural & Geotechnical Eng. Dept. Seminar, Universidad Católica de Chile, January 2013
Presentation: *Estimating Loss of Function of Critical Building Systems*

Civil Eng. Department Seminar, University of Puerto Rico, Mayaguez, November 2012
Presentation: *Estimating Loss of Function of Critical Building Systems*

4th Pan American Conference of WADEM, Leesburg, VA, October 2012.
Presentation: *The Impact of Structural and Non-structural Damage on Healthcare System Functions Following the Christchurch Earthquake*

4th Pan American Conference of WADEM, Leesburg, VA, October 2012.
Presentation: *Seismic vulnerability and disaster preparedness of health facilities: comparing predicted performance with observed evidence following the February 22 Christchurch Earthquake in NZ*

Civil Eng. Department Seminar, Carnegie Mellon University, Pittsburgh, PA, May 2012
Presentation: *A Performance Assessment of Critical Building Systems After Recent Seismic Events*

EERI Meeting: Learning from the Past to Protect the Future, Memphis, TN, April 2012
Presentation: *Quantifying Loss of Function of Critical Building Systems due to Recent Seismic Events*

Tulane Engineering Forum, Tulane University, New Orleans, LA, March 2012
Presentation: *Quantifying Loss of Function of Critical Building Systems due to Recent Seismic Events*

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