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Earthquake Induced Structural and Non-structural Damage in Hospitals

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The Sichuan (China) and L'Aquila (Italy) earthquakes again highlighted the question of our preparedness for natural hazards. Within a few seconds an earthquake can demolish many buildings, destroy infrastructure, and kill and injure thousands of people. In order to reduce the impact of earthquakes on human life and prepare hospitals to cope with future disasters, this paper discusses earthquake related damage to healthcare facilities. It investigates the damage to 34 healthcare facilities in seven countries caused by nine earthquakes between 1994 and 2004, in order to determine common and specific issues. The investigation shows that structural and architectural damage tended to be different and specific to the situation, while utility supplies and equipment damage were similar in most cases and some common trends emerged.

INTRODUCTION

Earthquakes have always been a threat to human life and a major cause for damage to infrastructure. Previous earthquakes have resulted in physical damage, threatened lives and damaged healthcare facilities whose main function is to save lives and reduce the impact of disasters. Hospital resilience (i.e. strength and robustness) has always been important, but in recent years exclusive attention has been given to this subject specifically after the World Health Organization (WHO, 2008) and the United Nation International Strategy for Disaster Reduction (UNISDR) world campaign '*Hospitals Safe From Disasters*'; the World Health Day (7 April 2009) and the International Day for Disaster Reduction (14 October 2009). "*There are countless examples of health infrastructure — from sophisticated hospitals to small but vital health centres — that have suffered this fate. One such case occurred in the Hospital Juarez in Mexico. In 1985, almost 600 patients and staff lost their lives when this modern (for its time) and well-equipped hospital collapsed in the wake of an earthquake*" (WHO, 2007a). Literature and experience reveal that healthcare discontinuity is common following earthquakes; but it is not very clear what the causes of discontinuity are. The present paper discusses the causes of hospital inoperability in several countries with the aim of identifying the impact of earthquakes on the continuity of healthcare. The objectives are to explore the significance and performance of healthcare facilities in disasters; scrutinize the legislations and standards for healthcare resilience to earthquakes; and compare healthcare facilities response to earthquakes.

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METHODOLGY

Data collection

This study adopted a pluralistic qualitative research method defined as a systematic, empirical strategy for eliciting responses from people in a special social context; and is concerned with information less understood by calculation (Fellows and Liu, 2003). A state of the art literature review, including research papers and reconnaissance reports were performed to identify and explore the key factors affecting the operation of medical facilities. Legislations for seismic resistant design and governmental and non-governmental guidance were also reviewed to identify laws and practices to mitigate seismic effect. Field investigations and interviews with hospital staff (clinical and administrative) were used to comprehensively explore the key factors affecting the operation of healthcare facilities. Between July 2003 and November 2005, ten hospitals located in three countries were investigated following four earthquakes (see Table 1). The information was complemented with two in-depth interviews (in May 2009) with experts from earthquake engineering, and disaster risk management to find the lessons learned from past earthquakes and actions undertaken to mitigate with future events.

Classification of hospital key factors

Healthcare key factors are often classified into two categories: physical and social. The physical category includes structural and non-structural parts; whilst the social category encompasses staff and administrative parts (e.g. partnership with other organizations). The focus of this paper is on the physical category, the social category will be considered in future work. "*The structural parts of a building are those that resist gravity, earthquakes, wind and other types of loads; they include columns; beams and foundations*"; and "*the non-structural parts include all parts of the building and its contents with the exception of the structure*" they "*are composed of: lifeline facilities; medical facilities; and architectural elements*" (DoHS/WHO Nepal, 2004). Although this classification is clear and follows a logical philosophy, it does not provide clear information when describing non-structural damage; for example, in one of the reports we read: "*...many of these structures had equipment and non-structural damage, resulting in extended business interruptions*" (Miyamoto, *et al.*, 2009), this statement does not describe whether the damage is related to utilities, architectural or other items. Furthermore, the European Microseismic Scale (EMS-98, 1998) involves architectural and structural components in the same category when assessing the damage to buildings. In this paper, components are classified into three categories: structural and architectural; equipment; and utilities. This classification does not compromise the importance of healthcare system components (structural and non-structural), "*both the structural system and most of the non-structural systems are required to perform without interruption after an earthquake to enable adequate functionality*" (FEMA, 2007); instead, it provides clearer information about the type of damage, which helps the perceiver to understand what is the impact on hospital operation and who is expected to be involved in the repairs.

Table 1. List of Hospitals investigated

Earthquake/Country	Date	Investigation date	Hospitals visited
Boumerdes/Algeria	21 May 2003	July 2003	CHU and Thenia

Miyagi-Ken Hokubu/Japan	26 July 2003	August 2003	Fukaya and Kashimadai
Bam/Iran	26 December 2003	February 2004 and September 2005	Imam Khomeini and Aflatoonian
Niigata Chuetsu/Japan	23 October 2004	November 2004	Ojiya; Uonuma; Tamiya; and Nakajo

There are significant numbers of case studies illustrating the performance of healthcare facilities after earthquakes; however, difficulty finding complete information was the main reason to limit the cases to thirty four hospitals as shown in Table 2. Unfortunately, there is limited information about the recent performance of Chinese and Italian facilities following the 2008 Sichuan and 2009 L'Aquila earthquakes, although Miyamoto *et al.* (2009) and EEFIT (2009) reported that recently built hospital buildings were damaged.

Table 2. List of investigated hospitals and their relevant earthquakes

Code	Name of hospital	Name of Earthquake	Source of information
NR1	Northridge Hospital	1994 Northridge Earthquake, California, USA	(Pickett, 1997); (Young, 1995); (USGS, 1996); and (McKevitt, *et al.*, 1995)
NR2	Olive View Hospital		
NR3	Holy Cross Medical Center		
NR4	Veteran's Administration Hospital (building #3)		
NR5	LA County Medical Center (mental health building)		
NR6	St John's Hospital		
NR7	USC Medical Center (USC hospital building)		
NR8	Granada Hills Community Hospital		
HN1	Medical College of Kobe University	1995 Hyogo-Nambu Earthquake, Japan	(Shinozuka, *et al.*, 1995); (Schiff, 1998); and (Ukai, 1996)
HN2	Hyogo Medical Center		
KC1	Izmit SSK	1999 Kocaeli Earthquake, Turkey	(Pickett, 2003); (Rodoplu, 2000); and (Scawthorn, 2000)
KC2	Izmit State		
KC3	Adapazari SSK		
KC4	Adapazari State		
CC1	Christian Hospital	1999 Chi-Chi Earthquake, Taiwan	(Yao and Chuang, 2001); (Soong and Yao, 2000); and (Soong, *et al.*, 2000)
CC2	Veteran Hospital		
CC3	Shiun-Tuan Hospital		
BH1	Civil Hospital	2001 Bhuj Earthquake, India	(WHO, 2001); and (Sharma, 2001)
BH2	Jubilee Hospital		
BH3	Branch Hospital		
BH4	Mental Hospital		
BH5	Nursing School Hospital		

BH6	ANM Training School		
BH7	Tuberculosis Centre		
BM1	CHU Centre Hospital	2003 Boumerdes Earthquake, Algeria	Field investigation
BM2	Thenia Hospital		
MH1	Fukaya Hospital	2003 Miyagi-Ken Hokubu Earthquake, Japan	
MH2	Kashimadai Hospital		
IR1	Aflatoonian Hospital	2003 Bam Earthquake, Iran	
IR2	Imam Khomeini Hospital		
NG1	Ojiya Hospital	2004 Niigata Earthquake, Japan	
NG2	Uonuma Hospital		
NG3	Tamiya Hospital		
NG4	Nakajo Hospital		

SIGNIFICANCE AND PERFORMANCE OF HOSPITALS IN EARTHQUAKES

Significance of hospitals following earthquakes

Medical facilities are one of the most critical facilities in any country, along with facilities such as fire departments and police stations. Hospitals are distinctive, however, due to the critical role they play in dealing with the large number of injuries typically associated with large-scale disasters such as earthquakes. Ninety seven percent (97%) of earthquake related injuries occur within the first 30 minutes following the main shock (Gunn, 1995). This urged organizations such as the WHO (2007a) to insist that healthcare facilities "*must be physically resilient and able to remain operational and continue providing vital health services*" following disasters to guarantee immediate medical treatment. Events such as the 2005 Kashmir and the 2008 Sichuan earthquakes caused enormous number of injuries requiring hospitals with large capacity, which was a problem in many cases such as in Taiwan during the 1999 Chi-Chi Earthquake (Soong and Yao, 2000). Hospital occupancy is generally high due to the existence of a large number of patients, visitors, medical staff and other employees at the same time (PAHO, 1993) in addition to the length of stay, which depends on the severity and type of injuries (including patients with mental disorders). A sample of 1,502 earthquake related injuries demonstrated that 31% of patients had to be admitted to hospital, 64.9% were identified with superficial laceration, 22.2% with fractures, and 1% with abdominal injuries requiring debridement and closure under general anesthesia, multiple concurrent procedures and urgent laparotomy (Mulvey, et al., 2008). In other words, all medical departments must be resilient enough to cope with earthquakes and provide diagnosis and treatment to injuries. Although, designing a healthcare facility to be resilient to hurricanes and earthquakes does not cost more than 4.5% extra on top of the total facility cost (Gibbs, 2007), many facilities are not designed to withstand such disasters.

Performance of healthcare facilities following earthquakes

Physical performance

Published reports and papers reflect significant information about hospital performance in earthquakes varying between total collapse and fully operational. The Pan American Health Organization (PAHO, 2000) described a hospital as "*a hotel, an office building, a laboratory and a warehouse*" due to the complexity and interconnectivity of its systems. A typical healthcare facility depends on the state of its building; continuity of its utility supplies; availability and sufficiency of staff, equipment and medical supply; and easy accessibility for its daily operation. The failure of any of these components affects the continuity of medical care. Despite the level of knowledge humanity has reached, easy access to information and considerable reports stating the experience of previous hospitals many hospital buildings are still very fragile to earthquakes: the 1995 Hyogo-Nambu Earthquake (Japan) severely damaged 61% of hospitals in disaster area and completely destroyed four facilities (Ukai, 1996); the 2005 Kashmir Earthquake (Pakistan) destroyed 50% of hospitals in stricken area raging from "*sophisticated*" to "*rural*" facilities (WHO EMRO, 2009); and the collapse of many hospitals and schools caused over 10,000 deaths following the 2008 Sichuan Earthquake in China (Miyamoto, et al., 2009). Structural behavior influences the response of non-structural components as most of them are connected to structure, which transfers earthquake forces onto them (WHO SEARO, 2002). For example, the failure of St. John's Hospital non-structural walls caused the rupture of water lines following the 1994 Northridge Earthquake in the USA (Pickett, 1997); whilst the Christian and Shiu-Tuan hospitals suffered slight structural damage but severe utility and equipment damage during the 1999 Chi-Chi Earthquake in Taiwan (Soong and Yao, 1999). Many healthcare facilities have not been sufficiently physically resilient to cope with earthquakes, although some facilities withstood the shaking due to their base isolation systems which helped to perform well such as the University of South California (USC) Medical Center (Pickett, 1997).

"*Seismic isolation is a technology that protects the structure by effectively decoupling the structure from the damaging effects of the earthquake*" (Constantinou, et al., 2007). Seismic isolation performance and efficiency come from the radical modification of the building seismic response due to: the elongated fundamental period of the structure; the small drift that the building experiences; and the reduction of overall forces (Constantinou, et al., 2007), "*thus the deflections and stresses generated in a base-isolated structure are significantly lower than those of a fixed-base one*" (Su, et al., 1989); for example, the USC Medical Center building forces were reduced by 65% across the plane of isolation and there was no damage in the facility (Di Sarno, et al., 2007). Base isolators, therefore, provide a higher and more efficient performance to buildings than seismic codes demand; this classifies them as an 'ideal' solution for critical facilities such as hospitals.

Social performance

In Japan, following the 1995 Hyogo-Nambu Earthquake, "*the attendance rate of personnel in hospitals on the first day of the disaster was 58.4% for physicians, 35.0% for dentists, 44.2% for nurses, and 31.0% for clerical staff. In the first hours, when the hospitals in the disaster area were extremely busy, less than 50% of personnel were able to attend their hospitals*" (Ukai, 1996) due to reasons such as road damage, being among earthquake victims or having a relative trapped in rubble. Furthermore, personnel who remain at their duties post earthquakes were susceptible to stress and psychological disorders and may need to be treated by mental health professionals along with earthquake victims (Uemoto, et al., 1996). Awareness is adopted as a way to reduce stress and help medical staff to deliver high quality medical service. At present, many facilities throughout the globe are provided with emergency manuals (EMs) and regular trainings, to reduce stress and help towards a better emergency response. These manuals are often prepared based on previous experience and best practices; actions may vary between medical departments and type of disaster but they usually consider pre-, during and post disaster actions. To help with pre-disaster activities, Hirouchi (2009) recommends the use of Earthquake Early Warning (EEW) systems in hospitals to "*prevent surgical errors, e.g., stopping surgery* *and moving equipment away from the patient within the few seconds after the EEW*". A number of publications focused on hospital evacuation strategies such as in Schultz et al. (2003) who suggested that even after a moderate earthquake, hospitals may need to evacuate immediately because of non-structural or delayed structural damage. The aforementioned initiatives are important for staff resuming duties, but a major problem is how to increase the number of attendees among staff members? This requires further investigation and shall be considered in future work.

LEGISLATIONS AND STANDARDS FOR HEALTHCARE RESILIENCE TO EARTHQUAKE

Impact of previous experience

"*If we see the technology and political system, particularly after Kobe Earthquake, a lot of financial resources were allocated for disaster prevention…it is amazing!*" stated one of the interviewees commenting on the impact of previous disasters on Japanese disaster prevention. The poor performance of medical facilities pushed researchers, engineers and decision makers to investigate in depth the causes of failure and take decisions to mitigate future risks. Consequently, new techniques were developed and implemented, and thus protected structural and non-structural components from failure. Interestingly, the implementation of base isolation, for example, ensures the continuity of medical services with relatively low cost: the Chilean Military Hospital spent 0.9% ($US1million) of the total hospital cost for the installation of its base isolation (Boroschek and Retamales, 2002). A week after the 1995 Hyogo-Nambu Earthquake, the WHO Kobe Centre was opened despite the "*wrenching trauma*" of the event, this was highly admired by the WHO and is perceived as a contribution "*to health research as meaningful investment*" (WHO Kobe Centre, 2007). Despite this significant improvement in techniques and practices, many newly built Chinese schools and hospitals collapsed following the 2008 Sichuan Earthquake, mainly due to poor design and poor structure quality thus killing thousands of people (Miyamoto, et al., 2009); and the inadequate detailing and irregularities in design were the cause of the 9 year old L'Aquila Hospital to suffer severe damage in Italy following the 2009 L'Aquila Earthquake (EEFIT, 2009). These cases show that there are strategic problems and authorities are urged to make sure that codes are up to date and enforced in practice. Countries such as Turkey realized this and started conducting comprehensive retrofitting activities to reduce the vulnerability and enhance the resilience of their infrastructure including hospitals, school and bridges (IPDED, 2007).

Legislations

"*The purpose of building codes is to promote and protect the public welfare*" (Hamburger, 2002), thus they are designed to provide a guide for engineers and designers; and are supported by legislations for enforcement. The enforcement of codes is crucial for the resilience of buildings, many countries such as Algeria, Japan and Taiwan recognized the importance of code enforcement for the protection of welfare: interviewees stated that Japanese and Taiwanese "*building codes were improved in terms of implementation as we believe that structural design was strong enough to cope with earthquakes*", and the Algerian code RPA 99 (2003) recognizes that code implementation and poor construction quality are the cause of damage to new buildings after the 2003 Boumerdes Earthquake. Code implementation can be done by enforcing the designers and architects to follow the law, but also it can be done by spreading awareness. For example, Taiwanese authorities use awareness and legislations to push architects and contractors to design and construct resilient buildings; one of the interviewees stated that at present, architects and contractors "*are more willing to comply with seismic detail and willing to pay more attention to what structural engineers suggest*".

Most codes focus exclusively on structural components and when non-structural components are considered, they are limited to architectural, mechanical and electrical components (FEMA, 2007); although these components are important, they are not sufficient to ensure the operation of hospitals. The investigation of Algerian (RPA 99, 2003), Iranian (BHRC, 2007), European (EuroCode 8, 2005) and Californian (SB 1953, 1994) codes demonstrates that the level of exposure to seismic activities and the quality of post earthquake hospital investigations were clear on the development of these codes. The 2003 Boumerdes (Algeria) and the 2003 Bam (Iran) earthquakes caused structural and non-structural damage to hospitals, yet the RPA 99 and the Iranian standards consider only structural and architecture resistance although they were updated recently, after these events. The investigation established that the Californian code is the most comprehensive amongst all investigated codes because it went through a long history of improvement and modification (see Table 3). Engineering investigations after the 1971 San Fernando Earthquake demonstrated that seismic forces in the Veteran's Administration (VA) Hospital site were under-estimated by codes (Holmes, 1976); and that the proper detailing and the beneficial effects of nonlinear soil-structure interaction helped one structure to withstand damage, although two neighboring structures collapsed (Rutenberg, *et al.*, 1980). As a result of this earthquake, the first 'Hospital Seismic Safety Act' was developed (California Seismic Safety Commission, 2001), with a focus on structural and nonstructural resistance (Meehan, 1984); however, the 1994 Northridge Earthquake demonstrated that the Act was successful in protecting structures but damage to non-structural components, such as plumbing and ceiling systems, was still extensive in post-1973 buildings (California Seismic Safety Commission, 2001). The Act was amended by Senate Bill 1953 after the Northridge Earthquake to require seismic evaluations; if hospitals were then found to have structural or nonstructural vulnerabilities, retrofits or replacements were also required. In essence, the legislation in California has been developed on lessons learned from previous experience and reflected the complexity of hospitals systems. There is a need therefore for other regions of the world that are threatened by earthquakes to develop and enforce hospital resilience legislation based in part on lessons learned from Iran, Algeria, Japan, Taiwan, California and other regions.

Assessment methodologies

There are two types of assessment, pre- and post-disaster. Post-disaster assessment is carried out for safety reasons and is done in several countries differently. For example, in Japan and California a three-level damage tagging system: "*Inspected*", "*Limited Entry*" and "*Unsafe*" (FEMA, 2007); and in Algeria, authorities adopted a five-level assessment scale to assess 242 facilities as shown in Table 4. The pre-disaster assessment defines vulnerabilities to enhance authorities, managers and engineers' decision to retrofit and reduce risk of damage. The application of assessment defines the assessment methodology (AM) to follow, which can be qualitative or quantitative based on observed vulnerability, expert opinions, simple analytical models, score assignment or detailed analysis procedure (Lang, 2002). There are many AMs, some of which are generic and others are specific for healthcare facilities: Johnson *et al.* (1999) suggest a scoring generic methodology based on defining systems, evaluating individual components and systems; the WHO (2006, 2007b) and the PAHO (2008) suggest preliminary assessment methods based on visual screening combined with screener opinion; and Achour (2007) suggests also a hospital focused methodology based on modeling and simulation combined with theoretical models and case studies. Unlike codes and legislation AMs are not obligatory for facilities; thus there is a risk that they will be neglected. The previous section underlined problems of 'code' implementation; there is a need therefore to investigate how to encourage hospital managers to evaluate the performance of their facilities.

Table 3. Seismic codes and legislations

Code/legislation	Structural elements	Architectural and filling components	Equipment and Utilities	Retrofitting	Comments
SB 1953 (California)	√	√	√	√	Specific for hospitals
Iranian 3rd Edition 2007	√	√	-	-	Generic
RPA 99 V2003 (Algeria)	√	√	-	-	Generic
EuroCode 8 (French Edition)	√	√	-	-	Generic

COMPARISON OF HEALTHCARE PERFORMANCE POST EARTHQUAKES

Structural and architectural components

The European Microseismic Scale 98 (EMS-98, 1998) classifies damage to buildings into five grades as shown in Table 5. Wenzel *et al.* (2008) allocated to each grade a "*damage ratio*" and a "*central damage factor (CDF)*" expressed in percentage of structural and architectural damage. Grades 1 and 2 do not present a threat to the structure and therefore their severity is assumed as 'Slight'; Grade 3 presents a threat to structure which may affect the operation of the facility, its severity is 'Moderate'. The last two grades illustrate a severe damage; or a total collapse, their severity is assumed as 'Major'. Hospital structural and architectural damage data were distilled from various sources (see Table 2), and damage severity was classified according to Table 5. The severity of damage was classified descriptively, through the description of previous investigations to structural/architectural damage, and visually, through the site visits carried following each event.

Table 4. Algerian post-earthquake assessment scale

Level	Description	Number of facilities
Green 1	Displacement of furniture, equipment	37%
Green 2	Slight damage to non-structural elements	36%
Orange 3	Slight damage to structural elements and severe damage to non-structural elements	14%
Orange 4	Considerable damage to structural elements Very severe damage to non-structural elements	9%

	Cracks on X shape for RC walls, bursting of joint beam-column	
Red 5	Total collapse Very severe deformation Repair cost higher than the building itself	4%

Most of the investigated facilities went through structural and or architectural damage, the severity varied from slight to major (see Table 6). One of the interviewees stated that, following the 1999 Chi-Chi Earthquake, "*failed structures were mostly due to inappropriate design (old buildings did not have seismic design, new buildings had structural system problem of soft storey); construction flaw (the 135 degree stirrup hook is particularly difficult to construct); and inappropriate dismantling of structures (owners changed the structure system for remodeling)*". Poor construction quality has always been a major challenge, but when combined with the age of the structure and the lack of retrofitting the building cannot withstand earthquake shaking such as the case of the Thenia Hospital (BM2) which experienced severe damage during the 2003 Boumerdes Earthquake. The facility comprises two sets of buildings: the first set includes several unreinforced masonry (URM) buildings built in 1870, never undergone anti-seismic retrofitting; whilst the second set includes a few buildings built in recent years (was not investigated). The Veteran's Administration Hospital complex comprises many buildings, some of which collapsed, whilst others performed well, during the 1971 San Fernando Earthquake, due to the proper detailing and "*the beneficial effects of non-linear soil-structure interaction*" (Rutenberg, *et al.*, 1980).

Despite the significant amount of guidance to improve structural behavior, many recent facilities such as the Italian L'Aquila and the Chinese Hanwang (9 years old) hospitals were damaged. Investigations concluded that irregularities (in plan and elevation), poor detailing (steel bars were exposed), and design (a beam is larger than columns) were the main reasons for L'Aquila Hospital's structural failure (EEFIT, 2009); whilst lack of stiffness (i.e. soft storey) was the cause of the Hanwang facility post the 2008 Sichuan Earthquake (Miyamoto, *et al.*, 2009). Furthermore, the impact of culture on the construction industry (Mahmood, *et al.*, 2006, Ngowbi, 2000) and the failure of implementing codes and standards increase the diversity of structural and architectural components resilience, which leads us to conclude that the structural and architectural performance depends on the state of each building (i.e. construction quality, design, site effects, code and guidance implementation and others).

Table 5. Classification of damage severity

Damage Grade (EMS-98)	Description	Damage ratio (%)	CDF (%)	Severity
Grade 1: Negligible to slight damage	- No structural damage - Slight non-structural damage	0-1	0.5	Slight
Grade 2: Moderate damage	- Slight Structural damage - Moderate non-structural damage	1-20	10	
Grade 3: Substantial to heavy damage	- Moderate structural damage - Heavy non-structural damage	20-60	40	Moderate
Grade 4: Very heavy	- Heavy structural damage	60-100	80	Major

damage	- Very heavy non-structural damage			
Grade 5: Destruction	- Very heavy structural damage	100	100	

Utility supplies

Continued operation of healthcare facilities after earthquakes depends on utility systems, the majority are supplied from main grids and networks such as electric power, water supply and telecommunications. Previous experience has demonstrated that these grids and networks were damaged during earthquakes, and that their damage could initiate other disasters: for example, the 1923 Great Kanto Earthquake, Japan, resulted in a fire, which was in the main cause of deaths (Guest, 2004). Measures have been adopted to reduce secondary risks such as switching off mains supply automatically in earthquakes (ABS-Consulting, 2004). In both cases, damage and automatic switch off, the mains supplies are interrupted and thus affects the normal operation of medical facilities. Many of the investigated hospitals were provided with alternative sources to subsidize the loss of mains. Utilities performance depends on the integrity not only of these alternative sources but also of many related components such as pipelines, battery racks, electrical connections to control panels and mufflers (FEMA, 2009). Any damage to these components affects the continuity of medical supply as was found in many facilities (e.g. NR2&6, CC1-3, MH1 and NG1) and can cause the evacuation of facilities such as the Hyogo Medical Center (HN2). It is important to reduce the fragility of each system separately, but more importantly to reduce the interdependency of these systems on each other: the Olive View Medical Center (NR2) had to switch off its power generators due to loss of water used for its cooling system (Pickett, 1997). At present, many facilities are provided with less dependent backup systems such as the Aflatoonian Hospital (IR1) which benefits from a power generator with an air-cooling system (provided a year after the 2003 Bam Earthquake). This represents a significant improvement in backup systems manufacturing; however, ignoring utility systems resilience in codes and official guidance represents a major contribution to their fragility. Most of the investigated codes (Table 2) do not pay attention to utility systems resilience, except the SB 1953. Failing to include utility resilience in codes tends to disregard the importance of backup systems in facilities such was found in some facilities: BM1-2 and IR1 were not provided with any backup systems before the events. In conclusion, utilities could not perform after earthquakes whether the facility is provided with alternative sources or not. There is similarity between utility systems impact on healthcare facilities; however, the outcome of legislations such as SB 1953 and the recent seismic resistance systems (e.g. anti-sloshing tanks) cannot be proven until they go through a ‘real test’, i.e. an earthquake.

Equipment

The continuity of medical services depends on having fully operational equipment to diagnose and treat injuries. Any damage or malfunction to equipment will result in low quality treatment, which in turn can threaten life. A study concluded that “*manpower, medication and equipment for injuries of the knee, lower leg,…and injuries involving multiple body regions may be the most critically needed immediately after earthquakes*” (Zhang, *et al.*, 2009). “*Equipment can become inoperable due to earthquake shaking even if it remains in place*” (ATC, 2008) such as the Aflatoonian Hospital (IR1) radiology unit which was damaged because of internal mechanical/electrical problems. Achour *et al.* (2005) demonstrated that acceleration of 200-300 cm/sec^2 caused damage to 80% of diagnosis and 40% of treatment equipments in hospitals following the 2004 Niigata-Ken Chuetsu Earthquake (Japan). Unstable equipment damages utility installations (Central Sterilization Room of IR1 damaged water pipelines); obstructs evacuation routes (Achour, 2007); causes serious injuries and can cause partial or total structural collapse (PAHO, 2000). Suggestions were to restrain equipment to reduce their damage (PAHO, 2004), although researchers demonstrated that even anchored equipment get damaged, and suggest that it may be more stable if they are left free standing (Makris and Zhang, 1999). The response of equipment to earthquakes can be sliding, slide-rocking, rocking or flying (Housner, 1963) depending on their geometry, static friction and ground acceleration (Shenton III, 1996), although, some researchers believe that frequency is also another factor that affects equipment stability (Achour, 2007).

A characteristic of most healthcare equipment is the excessive use of casters for easy movement, which makes nurses tasks easier. Wheeled equipments are easy to move when subjected to very low accelerations (as small as 50cm/sec^2); despite the chaotic movement, they stabilize in high accelerations and frequencies (Achour, *et al.*, 2007).

Building contents "*are specifically exempted from seismic provisions in model building codes. Regulated by the code or not, contents can pose an additional risk to safety and continuity of operations after an earthquake…The seismic protection of contents is dependent upon an understanding of potential seismic risk followed by action to mitigate that risk on the part of business owners, homeowners, and tenants*" (ATC, 2008). Considering that most codes do not consider equipment stability and that hospital equipments are similar throughout the world, equipment performance is expected to be similar in any facility. This investigation demonstrates that this is true as most facilities had problems with their equipments (see Table 6). The impact of the SB 1953 code on the performance of equipment, however, remains unknown until facilities falling under this legislation are tested.

CONCLUSIONS AND FUTURE WORK

Previous earthquakes resulted in physical damage, threatened lives and damaged healthcare facilities, whose main function is to save lives and reduce the impact of disasters. The significance of hospitals lies with the enormous investment for any country: the destruction of a hospital and the cost of reconstruction impose a major economic burden; also with the significant number of injuries that they treat pre and post disasters. Despite the considerable number of assessment methodologies and the seismic resistance technologies, recent events demonstrated that hospitals are still vulnerable to seismic activities and that there are many challenges facing the continuity of medical service after earthquakes. The performance of healthcare facilities depends on the performance of both social and physical components; however, due to complexity of these two components and the interconnectivity they have, this study focused only on physical components. The investigations demonstrated that the structural and architectural components respond differently to earthquake shaking due to the diversity of causes and the specification of each building. On the other hand, the findings show that there is a similarity between equipment and utility supplies' damage because most facilities are equipped with similar equipments and installations that are not protected by codes.

Most seismic resistance codes were developed universally for all types of buildings regardless of their occupancy. This resulted in a lack of attention to the specification of healthcare facilities and therefore unintentionally 'contributing' to medical care interruption.

There is a need to develop seismic resistance codes for hospitals that provide guidelines for the structural and architectural elements (for new and existing buildings); the continuity of utility supplies; and the stability of equipments. The efficiency of codes depends on the method of their development and the effectiveness of their implementation. Codes should be based on scientific evidence (i.e. field investigation, theory and best practice) with consideration of the local culture of construction method, but most importantly, they must be provided with implementation and enforcement strategies.

The California legislation SB 1953 was based on previous experience and complexity of hospitals systems. It demonstrates how strict the authorities are to ensure the continuity of medical care in earthquakes. The legislation presents an important tool to enhance the physical resilience of hospitals but not the social resilience which may be a cause of medical care disruption. The literature review brought forward the importance of social resilience for the continuity of medical care; this will be investigated in more detail to find out what is the best way to enhance the social resilience and suggest methods to include in hospital codes.

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Table 6. Summary of hospital damage caused by earthquakes

Hospital Code	PGA (cm/sec^2)	Structural Damage				Lifeline Damage/malfunction				Equipment Damage/Malfunction		
		Slight	Moderate	Heavy	Unknown	Power	Water	Gas	Tel.	Anchored	Free standing/ wheeled	Unknown
NR1	-			√		√	√			√		
NR2	910	√				√	√			√		
NR3	1000				√	√	√	√	√			
NR4	940				√	√	√			√		
NR5	490			√			√			√		
NR6	-			√		√						
NR7	490	√							√			
NR8	-		√			√	√	√	√			
HN1	-				√	√	√	√			√	
HN2	-				√	√	√					
KC1	225		√			√					√	
KC2	225		√			√					√	
KC3	400		√			√	√				√	
KC4	400		√			√					√	
CC1	560		√			√	√		√			
CC2	580		√				√	√	√			
CC3	480		√			√	√	√	√	√	√	√
BH1	375*			√						Total collapse		
BH2	375*			√						Total collapse		
BH3	375*			√						Total collapse		

BH4	375*			√						Total collapse		
BH5	375*				√							
BH6	375*				√							
BH7	375*				√							
BM1	340*	√				√	√	√	√	√	√	√
BM2	580**			√		√	√		√		√	
MH1	-			√		√	√		√		√	√
MH2	-		√			√	√			√	√	√
IR1	870***		√			√			√	√	√	√
IR2	870*			√		√	√	√	√	Total collapse		
NG1	790			√		√	√	√				
NG2	772		√			√	√	√	√			
NG3	510		√			√	√		√		√	
NG4	549		√			√	√	√	√		√	

* PGA recorded within the same city as hospital
** PGA recorded 20km from hospital
*** PGA recorded several kilometers from hospital

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