Principles of Disaster Mitigation in Health Facilities

Pan American Health Organization

Regional Office of the
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Disaster Mitigation Series

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Preface

This book presents key principles of disaster mitigation that can be of value to health facilities throughout the Americas. By compiling this information the Pan American Health Organization, the Regional Office for the Americas of the World Health Organization (PAHO/WHO) hopes to reach national and local authorities, hospital administrators, officials and staff, and other human resources connected in significant ways to health facilities. The book is aimed at health professionals, personnel responsible for health facility operations and maintenance, educators, architects and engineers, and members of the construction industry.

During its first meeting, held in July 1997, the PAHO/WHO International Hospital Mitigation Advisory Committee recommended that publications dealing with hospital mitigation have a multidisciplinary approach and include experiences and case studies from throughout Latin America and the Caribbean. Based on this recommendation, the PAHO Emergency Preparedness and Disaster Relief Coordination Program decided to produce a new and extensively revised edition of Disaster Mitigation in Health Facilities, originally comprised of four volumes: General Issues, Administrative Issues, Architectural Issues, and Engineering Issues. As the titles imply, each volume examined a different facet of disaster mitigation in hospitals, and had a different target audience.

Since the Advisory Group recommended a multidisciplinary approach, the four volumes have been condensed into one. Some of the chapters and sections have been simplified and rewritten for a more general audience, and other graphical elements have been introduced to illustrate key concepts, particularly the factors that increase hospital vulnerability to natural disasters. Case studies from countries in the region describe the methodology employed in various mitigation projects and processes, as well as the results of such initiatives, showing that hospital mitigation is indeed practical and feasible.

One of the most relevant success stories in Latin America and the Caribbean has been the inclusion of disaster mitigation issues in the sectoral reforms underway in a majority of countries, thanks to awareness-raising efforts at the political level. Sectoral authorities can therefore proudly point to the positive results, in terms of cost effectiveness, of incorporating mitigation measures into any process aimed at upgrading health facilities, and health care in general.

This book examines the potential problems that can arise when disasters strike health facilities, and offers specific mitigation measures, emphasizing the key components that have to be in place for health establishments to continue providing vital services during and in the immediate aftermath of a major emergency.

Health facilities can be affected by natural phenomena such as earthquakes, hurricanes, landslides, volcanic eruptions, and floods. They can also be damaged by anthropic (i.e., man-made) events such as fires, gas leaks or explosions. However, the emphasis here will be on seismic events, for two reasons. The first is that no other natural disaster affects health facilities as severely as earthquakes do. The second is that in reducing both the direct and indirect effects of seismic events, practically all other hazards are reduced.

Introduction

The planning, design and construction of health facilities in high-risk areas provide multiple challenges to the professionals involved in these efforts, given the importance of such buildings to the everyday life of a city—particularly when disaster strikes. A community's recovery after a major event depends to a significant extent on the ability of health facilities to function without interruption and to provide the extra care needed during an emergency. Many issues must be considered, ranging from the site chosen for construction to the installation of nonstructural equipment, not to mention the architectural design and structural integrity of the buildings.

Many health facilities have suffered severe damage as a result of natural disasters (particularly high-intensity earthquakes and hurricanes), leading to the partial or total collapse of the structures and the interruption of the health services urgently needed by the victims of the event.

It is in this context that existing regulations on the design and construction of health facilities must be revised. They must be reoriented towards disaster mitigation, with the ultimate goal, not only of protecting the lives of their occupants, but of ensuring that these facilities can continue to function after a disaster strikes.

This book compiles information previously published by PAHO/WHO, covering topics related to potential problems generated by natural events as well as the mitigation measures necessary to ensure that a facility will continue to function during and immediately following an event. It aims to encourage the reader to reflect on the planning, design, construction, operational and maintenance criteria governing health infrastructure. It presents techniques for the identification and assessment of hospital vulnerability. Risk mitigation solutions are presented that will protect both the population and the investments made in building or improving health facilities. The book is not intended to cover in detail technical aspects that have been the subject of academic publications, although the necessary references are included for the benefit of the reader who wishes to study these topics more in depth.

Chapter 1 reviews cases of health facilities affected by disasters in the Americas, including descriptions of the types of damage and, more generally, the losses suffered by health facilities as a result of earthquakes in recent years. Other topics include the role of health facilities in disaster situations, the demand for their services in such situations, and the economic and social costs of not having access to them at such a critical moment. Finally, the types of physical vulnerability found in health facilities are enumerated.

Chapter 2 focuses on structural vulnerability. When vulnerability is high, the essential operations of a health facility may be compromised, lives may be lost, and the facility's assets may be destroyed. The chapter discusses architectural practices that augment structural vulnerability, and provides guidelines on how to perform a vulnerability assessment based on the most widely accepted engineering methods. Additional guidelines explain how the facility's infrastructure can be reinforced through retrofitting or rehabilitation.

The vulnerability of nonstructural elements is the subject of Chapter 3, which discusses the behavior of architectural finishes and of medical and support equipment and installations. Steps are outlined for inventorying and assessing nonstructural vulnerability and carrying out the interventions needed for risk mitigation.

Chapter 4 deals with administrative and organizational vulnerability issues that can interrupt or degrade hospital services after a major event. Key concepts are outlined, including sectoral modernization, decentralization and quality control. These concepts provide the framework for the implementation of sectoral guidelines for disaster mitigation.The wrong administrative and organizational procedures can increase this type of vulnerability; recommendations are made on how to prevent or modify them.

One of the most important topics in this chapter is how to use the various vulnerability assessments of the facilities to perfect disaster preparedness activities until the resources are in place for an intervention. However, the connection between disaster preparedness, on the one hand, and functional and nonstructural aspects on the other, can only be explored here superficially, and readers are encouraged to consult the specialized publications produced by PAHO that are included in the references,[1] and which detail the methodologies required to formulate, test and update hospital emergency plans.

The annex outlines current methods used to analyze the structural vulnerability of hospitals.

[1] An extensive bibliography on safer hospitals, including relevant publications on hospitals and disaster preparedness, can be found in Bibliodes # 22, September 1995. Bibliodes is published by the Regional Disaster Information Center (CRID), a resource center for disaster mitigation for Latin America and the Caribbean that is partly sponsored by PAHO/WHO and the Secretariat of the International Decade for Natural Disaster Reduction (IDNDR).

Executive Sumary

Hospitals, and health facilities in general, are exposed systems that can suffer severe damage as a result of intense natural phenomena. Given the seriousness of the risk, new health facilities must be built to standards that can help them to withstand the natural hazards that surround them. It is also necessary to assess the vulnerability of existing buildings with a view to identifying their weaknesses, and to plan, design, and carry out the physical interventions or retrofitting needed.

Between 1981 and 1996, a total of 93 hospitals and 538 health centers were significantly damaged as a result of natural disasters in Latin America and the Caribbean. Some collapsed. Others were so weakened that they had to be evacuated. According to the Economic Commission for Latin America and the Caribbean (ECLAC), direct losses in the Region as a result of such events reached US$ 3.12 billion over that period. To visualize such an impact, it helps to imagine 20 countries in the region each suffering the collapse of 6 major hospitals and 25 health centers. This underscores the urgency of reviewing design strategies and construction practices of health facilities located in disaster-prone regions.

When it comes to disaster mitigation, hospitals require special attention due to the vital functions they perform, their high level of occupaancy, and the role they play during a disaster situation.

At any given moment, hospitals can have a large population of resident patients, outpatients, staff members and visitors. In the event of a disaster, they must continue to treat the patients who were already in their care, while tending to the needs of the injured. For this to happen, the staff must be in place and must know how to respond to the situation. It is just as important, however, for the infrastructure and equipment to remain functional after disaster impact.

The systematic organization and easy mobilization of the staff, equipment and supplies in a safe environment are crucial if disaster response is to be prompt and effective. Buildings, technology and processes are both interdependent and critical. Deficiencies in any of the functional aspects of a hospital can plunge the institution into a crisis.

Moreover, due to the high cost of health facilities and the vital services they provide, major damage can have a severe impact on public finances and the production capacity of a country due to the high costs of repair and reconstruction.

Hospital facilities include clinical services, diagnostic support services and general services, all of which have specific functions and yet must interact for the hospital to operate effectively. The relationship between administration, intermediate or outpatient services, general services, outpatient consultation, emergencies, and inpatient services is critical, and when designing the facilities attention must be paid to their operations and physical distribution in the event that a massive number of patients must be assisted. The areas surrounding the hospital and hospital access routes play a particularly important role in disaster response. A hospital can be the victim of a functional collapse, a danger that is often detected only in the middle of an emergency.

A building may remain standing after a disaster yet be rendered incapable of providing medical care due to nonstructural damage. In most buildings the cost of nonstructural components is considerably higher than that of structural components. This is particularly true of hospitals, where between 85% and 90% of the value of the facilities lies in the architectural elements, the mechanical and electrical systems, and the medical equipment. A seismic event of lesser magnitude, which is far more common than a major earthquake, can damage nonstructural elements. These key components of a hospital, those most directly linked to its purpose and function, are the ones most likely to be affected or destroyed by earthquakes. On the other hand, it is easier and less costly to retrofit them and prevent their destruction or severe degradation.

Many of the problems mentioned above originate in structural and nonstructural safety of the building. The structural components should be considered during the design and construction phase of a new building or during the repair, remodeling, or maintenance of existing buildings. Good structural design is key to a building's survival in an earthquake. Damage may occur, but collapse is unlikely.

Unfortunately, in many countries in Latin America and the Caribbean codes for seismic-resistant buildings have not been followed or have not taken into account the special specifications required by health facilities. Little wonder, then, that every time a major earthquake shakes the region, the most severely damaged buildings will include some hospitals. Hospital vulnerability is high and this must be corrected in order to prevent economic, social and human losses, particularly in developing countries that can ill afford such losses.

Disaster mitigation through the adoption of preventive measures makes economic sense in areas prone to recurring events. For each dollar invested in mitigation before a disaster strikes, enormous savings will be made in losses prevented. Mitigation is ultimately cost-free, since it pays for itself in lives and money saved.

The various mitigation measures have different implementation methods and costs. The simplest and most economical have to do with nonstructural and administrative and organizational aspects; the most complex and costly are the structural measures. If an integrated hospital mitigation plan is carried out in stages, the use of resources can be spaced out over time, making it easier to keep the additional expenses within a reasonable margin of ongoing maintenance costs.

A vulnerability analysis begins with a visual inspection of the facilities and the preparation of a preliminary report. This inspection makes it possible to identify the areas that require attention. The report will be discussed with consultants and hospital authorities in order to set priorities and a timetable for undertaking the work.

In every documented case, cost/benefit analysis has shown the economic and social sense of upgrading the structural and nonstructural behavior of vulnerable hospital buildings. The cost may seem high, but it is always significantly lower than that of repairing or replacing damaged facilities. It is useful to ask questions such as this: how many CT scanners could be bought with the cost of retrofitting the building? And how many of them does the hospital now have? The answer can be surprising, without even considering the other equipment and assets currently housed by the facilities, much less the human lives directly or indirectly at risk due to the current deficiencies and the social cost of losing the services provided by the hospital.

Risk reduction in hospital design is a responsibility shared by architects, engineers, physicians and administrators. The link between architecture and resistant structural systems must be clear to all involved in the design process in disaster-prone areas.

The loss of life and property as a result of an earthquake can be prevented by applying available technology and without great expense. The only thing needed is the will to proceed. With the current understanding of the construction requirements for buildings that can resist earthquakes, hurricanes, and other natural hazards and damage can be minimized as long as the right preventive measures are taken in the design, construction and maintenance of new health facilities.

Recommendations

1. All buildings where health services operate in disaster-prone areas must carry out vulnerability and risk assessments of the structures and essential hospital services.
2. Appropriate mitigation measures must be taken in the design and construction of new health facilities or the remodeling and expansion of existing establishments in accordance with an integrated disaster mitigation plan.
3. Nonstructural mitigation or intervention measures must be included in plans for maintenance, inspection, remodeling, and upgrading existing hospitals.
4. Risk reduction specifications must be met as part of the procedures for acquiring, operating, and maintaining hospital equipment and systems.
5. Hospital disaster preparedness plans must be reviewed to take into account hospital vulnerability.
6. Design and building codes must be enforced in the design and construction of health facilities. They must aim not just to protect the lives of their occupants but also to ensure the uninterrupted operations of the facility after a disaster has struck.
7. Health care administrators, medical staff, builders and maintenance personnel must be made aware of the standards to be met for buildings entrusted to withstand the impact of potential natural disasters.
8. Hospitals must keep up-to-date information and floor plans of their buildings' architectural, engineering and technical design in a safe and accessible place.

This book, ***Principles of Disaster Mitigation in Health Facilities***, has been prepared by the Pan American Health Organization (PAHO) for national and local authorities, building owners, administrators, health professionals, officials, engineers, architects and other personnel involved in the planning, operations, and management of health services. After describing the kinds of damage that may be expected in the event of a natural disaster, guidelines are provided to incorporate seismic risk mitigation procedures in the inspection of existing establishments and the planning, design, and construction of new structures.

Chapter 1
Disasters and Hospitals

Background

A disaster may be defined as an event or occurrence—usually sudden and unexpected—that intensely alters the beings, objects and localities under its influence. It results in loss of life and health in the local population, causes severe environmental damage and the destruction or loss of material goods resulting in a dramatic disruption of normal patterns of life. Such disruption—which may be local, national or even regional in scope—gives rise to the need for immediate intervention and humanitarian aid.

Disasters may be caused by natural phenomena, human actions, or industrial accidents. Some natural disasters are caused by hazards that cannot be neutralized, because there is no way to control their causes. Earthquakes, volcanic eruptions, tsunamis, and hurricanes are examples of hazards that cannot yet be prevented or diverted. On the other hand, appropriate measures can be taken to control or reduce the impact of other natural events, such as floods, droughts and landslides.

The effects of a disaster vary according to the nature of the event itself and the characteristics of the communities and objects affected: the population, their natural environment, their housing, the public services on which they depend, and the physical structures and assets of industry, commerce, and other economic activities that provide goods and livelihoods.

A disaster causes both direct and indirect losses. The physical destruction caused by a disaster is considered a direct loss, and includes the human victims, environmental degradation (i.e., the alteration of the habitat), and damage to buildings, infrastructure, and urban spaces.

Indirect losses are generally divided into social and economic effects. Social effects include the interruption of transportation, communications (including the mass media), and other public services. They can include the negative image that a country or region might acquire in the wake of a disaster. Economic effects include the cost of reconstruction and rehabilitation, the impact of reduced production or consumption on trade and industry, the potential discouragement or flight of foreign investment, and the lack of access to basic services such as health care.

In many developing countries, such as those of Latin America and the Caribbean, disasters lasting 20 to 30 seconds have caused thousands of deaths and hundreds of millions of dollars in damage. The often incalculable economic costs of the direct and indirect losses from these events can represent an enormous percentage of the country's gross domestic product. Such losses increase poverty among the population and stall or set back economic development at the national or regional level.

In order to reduce existing risk levels, disaster prevention measures must be considered a fundamental part of sustainable regional and urban development. Given the negative impact of disasters on the development of the communities they strike, risk assessment must be incorporated into the key social and economic processes of each country or region, comparing the cost of taking preventive measures with that of disaster recovery. In most cases, prevention is more cost-effective than recovery.

In recent years, many publications in numerous fields have addressed the impact of disasters on human activities. Despite occasional differences, most of these publications agree on the components of disaster impact. The Office of the United Nations Disaster Relief Coordinator (OCHA, formerly known as UNDRO) and the United Nations Educational, Scientific and Cultural Organization (UNESCO) held the Natural Disasters and Vulnerability Assessment meeting to propose uniform definitions that have been widely accepted in recent years. The report from this meeting provided the following definitions:

Hazard (H) is defined as the probability that a potentially disastrous event will occur during a given time period in a given place.

Vulnerability (V) is the level of loss that an element or group of elements—people, structures, goods, services, economic or social capital—that are exposed to risk would experience as a result of the probable occurrence of a disastrous event. Vulnerability is expressed on a scale from 0 (no damage) to 1 (total loss).

Specific Risk **(R_s)** is the level of expected loss as a result of the occurrence of a particular event. It is a function of hazard and vulnerability.

Elements Exposed to Risk (E) includes the local population as well as the buildings, civil works, economic activities, public services, utilities and infrastructure that are exposed in a given geographic area.

Total risk **(R_t)** is a quantification of the human losses, injuries, property damage and impact on economic activity that would result from the occurrence of a disastrous event. It is the product of the specific risk R_s and the elements at risk E.

Risk may therefore be evaluated using the following general formula:

$$R_t = E \times R_s = E(H \times V)$$

where exposure E is considered implicit in vulnerability V.

Given hazard H_i (the probability that an event of intensity greater than or equal to i will occur during a period of exposure t) and vulnerability V_e (the intrinsic predisposition of an exposed element e to suffer impact or loss from the occurrence of an event of intensity i), the risk R_{ie} is understood as the probability of a loss to element e due to the occurrence of an event of intensity greater than or equal to i:

$$R_{ie} = (H_i \times V_e)$$

This expresses the probability that the social and economic consequences or effects will exceed a specific predetermined value during a given time period t.[1]

It is therefore possible to craft a more precise definition of two concepts that are sometimes taken for synonyms, but which are in fact qualitatively and quantitatively different:

- *Hazard* is a risk factor external to a subject or system. It involves a latent or potential danger associated with a physical phenomenon of natural or technological origin that could arise in a specific location over a given span of time, producing adverse effects on people, property, or the environment. Hazard is expressed mathematically as the probability of an event of a given intensity taking place in a given place over a given period of time.

1 Cardona, O.D. Estudios de vulnerabilidad y evaluación del riesgo sísmico: planificación física y urbana en áreas propensas. Asociación Colombiana de Ingeniería Sísmica, *Boletín Técnico* No. 33, Bogotá, December 1986.

- *Risk* is the expected level of destruction or loss that will take place given the probability of hazardous events taking place and the level of vulnerability of the elements exposed to these hazards. It is expressed mathematically as the probability that the economic and social consequences of a given event in a certain place over a certain period of time will exceed a given level.

In general terms, *vulnerability* may then be understood as the intrinsic predisposition of a subject or element to suffer damage from potential external events. A vulnerability assessment therefore constitutes a fundamental contribution to the understanding of risk, by analyzing the interactions between susceptible elements and a hazardous environment.

The fundamental difference between hazard and risk is that a hazard is related to the probability that a natural event or one caused by human activity will occur, while a risk is related to the probability that certain circumstances will occur. These circumstances are closely related not only to the elements' level of exposure to an event, but also to their vulnerability to the effects of the event.

Damage to hospitals

The need for health care establishments to be prepared and able to take action in emergency situations is especially critical in Latin America and the Caribbean. In the past, earthquakes, hurricanes and floods (such as those related to the El Niño phenomenon), and other natural hazards have shown hospitals and health establishments to be vulnerable to these disasters, often without the capacity to respond adequately.

Because hospitals play such a vital role in the recovery of a community after an earthquake, many factors must be taken into account when selecting the location of a health facility, as well as when designing, building, maintaining and operating it. These considerations range from structural resistance requirements to disaster response planning to the installation of a range of nonstructural elements and equipment.

Nevertheless, in the wake of intense natural events, many hospitals have ceased to function, suffered serious structural damage or even collapsed, depriving their respective communities of the medical care needed by disaster victims.

Many of the hospitals so affected were designed in accordance with seismic-resistant building codes. The structural design of a hospital requires much greater care than the design of a less crucial building or complex of buildings. Seismic-resistance standards in most Latin American countries are not adequate, because they are frequently based on a philosophy of protecting the lives of the building's occupants, not of guaranteeing the structure's continued functionality (see below).

Philosophy of Existing Seismic Standards

- Structures should withstand events of moderate intensity without damage.
- Damage should be limited to nonstructural elements during events of medium intensity.
- Structures might sustain damage but should not collapse during events of exceptionally severe intensity.

Table 1.1 lists some hospitals that have suffered serious structural damage or collapse, or had their operations curtailed due to nonstructural damage and functional problems during earthquakes; Table 1.2 provides examples of effects of earthquakes on selected facilities.

Table 1.1.
Selected hospitals affected by earthquakes

HOSPITAL	COUNTRY	EARTHQUAKE
Kern Hospital	USA	Kern County, 1952
Hospital Traumatológico	Chile	Chile, 1960
Valdivia Hospital	Chile	Chile, 1960
Elmendorf Hospital	USA	Alaska, 1964
Santa Cruz Hospital	USA	San Fernando, 1971
Olive View Hospital	USA	San Fernando, 1971
Veterans Admin. Hospital	USA	San Fernando, 1971
Social Security Hospital	Nicaragua	Managua, 1972
Escalante Padilla Hospital	Costa Rica	San Isidro, 1983
Benito Juárez Hospital	Mexico	Mexico, 1985
Medical Center	Mexico	Mexico, 1985
Benjamín Bloom Hospital	El Salvador	San Salvador, 1986
San Rafael Hospital	Costa Rica	Piedras Negras, 1990
Tony Facio Hospital	Costa Rica	Limón, 1991
Olive View Hospital	USA	Northridge, 1994
Municipal Hospital	Japan	Kobe, 1995
Antofagasta Hospital	Chile	Antofagasta, 1995
Tena Hospital	Ecuador	Ecuador, 1995
Coquimbo Hospital	Chile	Chile, 1997
Antonio P. de Alcalá Hospital	Venezuela	Cumaná, 1997
Miguel H. Alcívar Hospital	Ecuador	Bahía Caráquez, 1998

O.D.Cardona

Photograph 1. Total collapse of the Benito Juárez Hospital, Mexico City, 1985.

J. Grases

Photograph 2. Partial collapse of the Benjamín Bloom Hospital, San Salvador, 1987.

O.D.Cardona

Photograph 3. Collapse of the fifth floor of the Municipal Hospital, Kobe, 1995.

Table 1.2.
General effects of earthquakes on selected hospitals

Earthquake	Magnitude (Richter Scale)	General Effects
San Fernando, California, U.S.A., 1971	6.4	Three hospitals suffered severe damage and were unable to operate normally when they were needed most.Furthermore, most of the earthquake victims went to two of the collapsed hospitals.Olive View Hospital, one of the most severely affected hospitals, was retrofitted.
Managua, Nicaragua,1972	5.6	The General Hospital suffered severe damage. It was evacuated and later demolished.
Guatemala City, Guatemala, 1976	7.5	Several hospitals were evacuated.
Popayán, Colombia, 1983	5.5	San Jose University Hospital suffered damage and service was interrupted.

Earthquake	Magnitude (Richter Scale)	General Effects
Mendoza, Argentina, 1985	6.2	More than 10% of all hospital beds were lost (state + private = 3,350). Of the 10 facilities affected, 2 were demolished and 1 evacuated.
Mexico City, Mexico, 1985	8.1	Five hospitals collapsed and 22 more suffered serious damage. At least 11 facilities were evacuated. Direct losses were estimated at US$ 640 million. The most seriously damaged hospitals were the National Medical Center of the Mexican Social Security Institute (IMSS), the General Hospital and the Benito Juárez Hospital. Between destroyed and evacuated hospitals, the earthquake produced a sudden deficit of 5,829 beds. A total of 295 lives were lost at the General Hospital and 561 at Juárez Hospital, including patients, doctors, nurses, administrative personnel, visitors and newborns.
San Salvador, El Salvador, 1986	5.4	More than 2,000 beds were lost, with more than 11 hospitals affected. Ten hospitals were evacuated and one completely destroyed. Damage was estimated at US$ 97 million.
Tena, Ecuador, 1995	6.2	Velasco Ibarra Hospital (120 beds) suffered moderate nonstructural damage: cracked walls, broken windows, fallen ceilings, damage to the elevator system and some oxygen and water conduits. Service was suspended and the facilities evacuated.

Natural disasters seriously damaged 93 hospitals and 538 health centers in Latin America and the Caribbean between 1981 and 1996, causing structural collapse or extensive damage that left the health facilities in vulnerable conditions requiring evacuation. Considering an average capacity of 200 beds per hospital and 10 beds per health unit, losses during this period totaled an estimated 24,000 beds. With an average regional cost of US$ 130,000 per hospital bed (the cost is approximately US$ 220,000 in the English-speaking Caribbean and US$100,000 in Latin America), direct accumulated losses in the region are estimated to be US$3.12 billion dollars.[2]

2 Economic Commission for Latin America and the Caribbean (ECLAC). Impactos económicos de los desastres naturales en la infraestructura de salud. Report no. LC/MEX/L.291. Mexico City, January 1996.

Hospitals and disaster situations

For the most part, health services are provided by a variety of health care establishments such as hospitals, health centers, health posts, and clinics. They may be managed by the government or the private sector. Hospitals normally offer emergency services and secondary or tertiary medical care, while health posts offer primary care and some first aid or basic care.

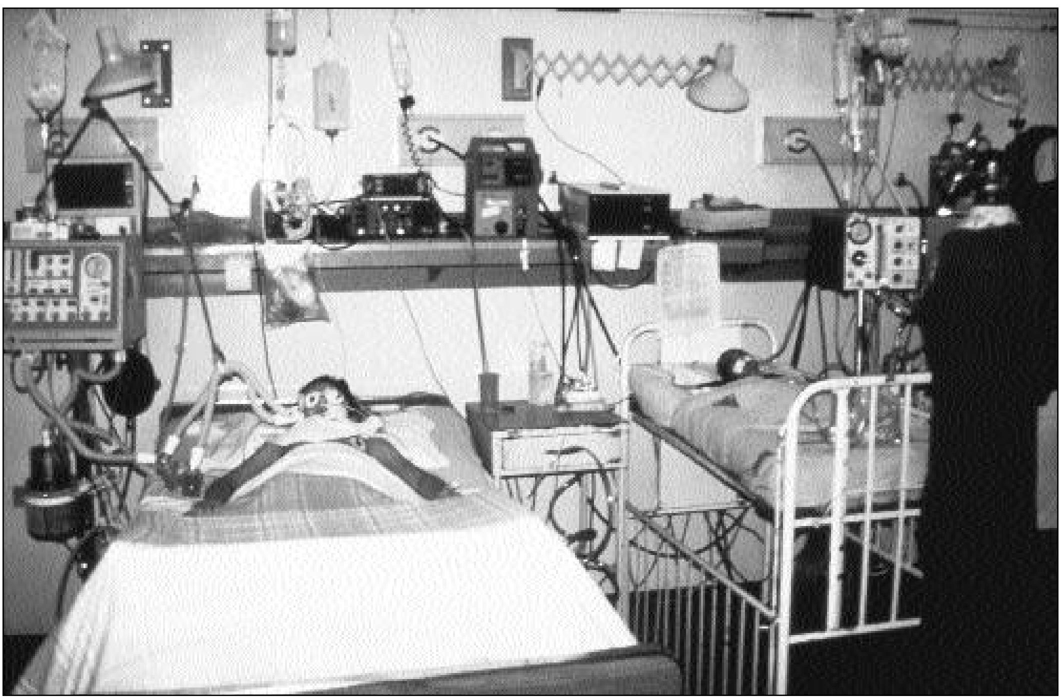
With their specific focus on treating sickness and injury, health care establishments clearly play a critical role in disaster response. As a result, special considerations for risk prevention and mitigation must be made from the moment of a hospital's conception. Two factors make this special approach fundamental to health care establishments:

a) Their complexity and occupancy characteristics;
b) Their role in the preservation of life and health in disaster situations, especially in diagnosing and treating sickness and injury.

Complexity and occupancy: causes of vulnerability

Hospitals are essential to disaster response, but they also tend to be highly vulnerable because of the following characteristics:

Complexity. A hospital is a highly complex facility which, by providing health care, must also function in certain ways as a hotel, an office building, a laboratory and a warehouse. The hotel aspect alone is complex, involving food and beverages as well as lodging. Health facilities generally include many small



R. Boroschek

Photograph 4.The lives of some occupants depends on equipment and uninterrupted supply of electricity and gases.

rooms and long corridors. Patients and visitors will be very confused in the wake of a disaster, when there may not be electrical power and fallen furniture or rubble may block corridors and room exits. Elevators will be out of service and stairways may be difficult to use.

Occupancy. Hospitals have a high level of occupancy, with patients, medical and support staff, and visitors present 24 hours a day. Many patients require assistance and continual specialized care. They may be surrounded by medical equipment, use potentially dangerous gases, or be connected to life-support equipment that requires an uninterrupted power supply.

Critical supplies. Most of the supplies required by hospitals (medicine, splints, bandages, etc.) are essential to patients' survival and crucial to the treatment of disaster victims.

Basic facilities. No facility depends on public services or lifelines more than a hospital, which cannot function without power, water, clinical gases, oxygen, fuel, garbage collection or communications.

Hazardous materials. Many products found in hospitals are dangerous if they spill or leak. The collapse of shelves holding medicines or chemicals can release poisonous liquid or gas. Spilled chemicals, damaged gas cylinders and ruptured oxygen lines can cause fires. The absence of normal security measures can also lead to the abuse of drugs normally kept under lock and key.

Heavy objects. Medical equipment and other appliances are often located above or near patients' beds or on high shelves. During a disaster, such equipment may fall, causing serious injury or obstructing evacuation routes. Other pieces of specialized equipment, such as X-ray machines, backup generators or autoclaves, are extremely heavy and may be tossed about or overturned during an earthquake.

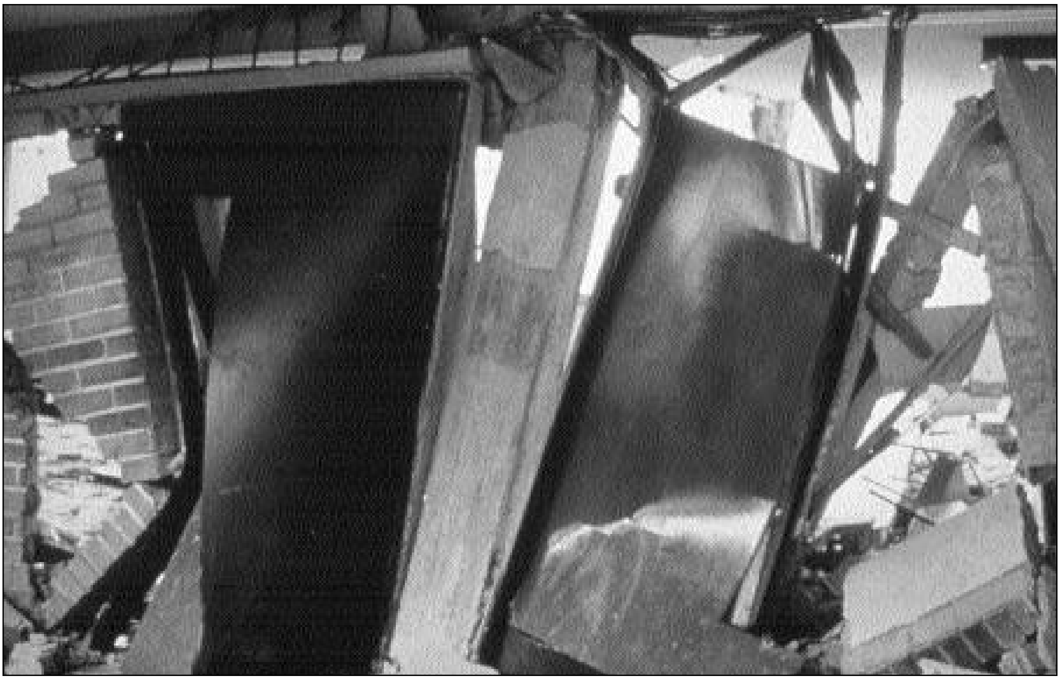
To summarize, a hospital is a complex system that demands uninterrupted power and potable water, continual communications services, solid and liquid waste disposal, and a steady supply of pharmaceutical products, medical and surgical supplies, specialized gases, chemicals and fuels. At the same time, each of these necessities also represents a hazard if improperly stored, handled, or maintained, and can become a hazard during an earthquake, fire, explosion or other disaster.

The hospital in disaster situations

As outlined above, at any given moment, a hospital may have a high population of resident patients, outpatients, medical and paramedical staff, administrative employees, and visitors. As a result, there are three main elements to disaster preparedness planning:

1. Treatment of patients must continue during and after a disaster or emergency.
2. The safety of all occupants must be assured. A vulnerability assessment of the facilities should be conducted. If necessary, the building should be retrofitted according to current design and construction standards. If this is not immediately possible, emergency plans should be adapted in the meantime to take the existing vulnerability factors into account.

3. At some point during an emergency or disaster, it may be necessary to evacuate ambulatory and non-ambulatory patients. This will be more complex if the disaster occurs suddenly and at a time when there are many visitors who are generally unfamiliar with evacuation procedures. Throughout Latin America, the number of visitors at peak hours, such as weekends, can be as high as double the number of patients.


O.D.Cardona

Photograph 5. Column failure during earthquake.

A hospital's capacity for effective disaster response depends on systematic organization and easy mobilization of personnel, equipment and supplies in a safe environment. Procedures, buildings and equipment are all critical and interdependent. A weakness in any element of a hospital's functional system could cause a crisis throughout the institution. The following issues must be taken into consideration:

Emergency procedures. Emergency procedures are especially important in the mobilization of people, equipment and supplies. The design of the necessary procedures includes the formation of a committee to formulate and implement disaster mitigation measures and carry out emergency response planning.

Buildings. Disaster mitigation plans must address the need for repairs in case of damage to the hospital facilities, both before and after a disaster occurs. Past events have demonstrated that existing plans are deficient in this area. The design and construction of hospital buildings must take into account occupants' safety and the preservation of critical areas including the emergency room, diagnostic services, surgery units, pharmacy, and food and medicine storage areas.

In the past, hospital design emphasized optimum use of space and configuration of services so as to provide the most effective interrelation of functions and activities among different departments. Many new hospitals built with modern design and construction techniques have been found lacking when called upon to attend to massive numbers of injured patients. This is often due to defects in the distribution of elements and the location and arrangement of nonstructural components. Many establishments fail due to simple design omissions that could have been corrected at a marginal cost during construction or through later intervention.

O.D.Cardona

Photograph 6. Collapse of stairway during earthquake prevents evacuation.

Equipment. The items found within a hospital building are more likely to become a hazard during an earthquake than during a hurricane. A great deal of damage can be averted through simple, inexpensive mitigation measures, such as securing shelves to the walls and placing equipment strategically in safe locations. Regular inspections and appropriate maintenance can assure that equipment is kept in good working order.

Estimating damage to hospitals after a disaster

The assessment of damage sustained by a hospital should be conducted by a multidisciplinary team including doctors, engineers and architects. The team should develop a strategy that will allow hospital activities to continue effectively despite the upheaval caused by the disaster. The assessment strategy will depend on the kind of disaster. In the case of an earthquake that has caused the partial or total collapse of the physical structure, files on the building's infrastructure, service capacity and the number of people occupying it when the disaster occurred may be destroyed so it may be necessary to gather this information from outside sources.

The assessment process should begin with a precise definition of the type of installation that has been damaged. The level of complexity of the services the facility provided will influence the strategy for compiling data on the type and magnitude of damages.

An estimate of economic loss reflects the value of the assets destroyed at the time of the disaster. Their replacement will be influenced by factors such as the characteristics of the hospitals to be rebuilt, the resources available to the community or country, the level of institutional development in the health sector, the government's priorities for disaster response, and the allotment of budgetary resources. Replacement value is estimated based on the cost of new equipment, which often implies a technological improvement in the facilities. In the case of repairs, assessment is based on the market price of the inventoried assets.

In addition to direct losses from structural destruction, the estimate should include indirect losses, such as the reduced volume of services provided and the cost of attending to disaster victims in provisional facilities or transferring them to other institutions during the reconstruction process.

Although there is a wide range of indirect damages, some especially common types include:

1. Increased risk of transmission of infectious or contagious diseases and other health risks;
2. Increased cost of public and private health care, outpatient care and hospitalization;
3. Reduced standard of living for communities affected by environmental degradation such as the lack or reduced availability of potable water.

A common characteristic of natural disasters is their extreme impact on social resources, especially general services for economically disadvantaged populations. Damage to hospital establishments can accentuate the weaknesses of a national health care system, affecting or delaying the delivery of basic health care to the population.

Risk reduction in hospitals

Health authorities in Latin America and the Caribbean have worked to promote a process of institutional change, seeking to improve the allocation and use of resources and positively influence public health. Their work in hospital management has made inroads toward infrastructure development that reflects the needs of communities. Aspects of this development that relate to reducing the level of risk posed by natural disasters include:

a) Analysis of the demand for hospitals; and
b) Assessment and reduction of vulnerability.

Analysis of the demand for hospitals

Increased demand for health care and the limited supply of services have led to a resource rationalization process that has resulted in the development of planning, organizational and structural concepts such as the following:

1. The hospital network, defined as a system of health facilities that provide different levels of care, where interactions among the facilities are based on the provision of complementary services;
2. The need to prevent the disorganized growth that occurs when a hospital seeks to increase its capacity by expanding and equipping its physical plant without considering limitations such as the supply of basic materials, traffic routes, and hospital vulnerability;
3. Hospital certification or accreditation by level of care which constitutes an essential tool in the creation of a hospital network, and addresses criteria such as the characteristics of the popula-

tion served by the hospital, coverage areas, morbidity, type of services offered, available human resources, hospital safety, and hospital maintenance;

4. Referral and counter-referral systems comprising the standards, protocols and procedures that regulate the treatment and referral of patients from one level of health services to another. Referral systems should maximize the use of resources on the basis of efficiency, effectiveness and opportune health care.

The potential for an increase in the demand for health services after a natural or anthropic disaster requires that changes be made in the way the system functions. To be effective, these changes must take into account the type of event, as well as its magnitude, intensity and duration, and the place, population and infrastructure affected by it. It is also important to take into account epidemiological data, morbidity and mortality rates, and the general state of public health in the region. This information must be applied to aspects of the health system’s ability to provide services in order to develop an optimal supply/demand ratio in the event of a disaster. An assessment of the potential demand for health services is important in order to identify variables that can have a negative influence and address them before disaster strikes.

Assessing and reducing vulnerability

Given the importance of an efficient response to emergencies and the need for a functional health care infrastructure in the aftermath of a disaster, hospital administrators must conduct structural, nonstructural and administrative/organizational vulnerability studies. Hospital vulnerability can only be determined through an integrated vulnerability assessment covering all three of these factors.

> Some of the results of a structural vulnerability assessment will serve as raw data for the assessment of nonstructural vulnerability. Nonstructural assessment, in turn, plays a key role in determining administrative/organizational vulnerability. An integrated hospital vulnerability assessment should address all three elements in the following order: (a) structural vulnerability, (b) nonstructural vulnerability, and (c) administrative/organizational vulnerability.

A vulnerability assessment may begin with a visual inspection of the facilities and a preliminary report by a team of experts that identifies areas in need of attention. The report may be discussed with other consultants and the hospital administration in order to set priorities and time frames for making the necessary changes.

Structural vulnerability

The terms "structural" or "structural components" refer to those parts of a building that are required for physical support. They include foundations, columns, supporting walls, beams and diaphragms (i.e., floors and ceilings designed to transmit horizontal forces occurring in an earthquake through beams and columns into the foundation).

Both existing and planned health care establishments in areas exposed to seismic activity must comply with building codes for seismic resistance. These codes are intended to ensure the safety of the building’s occupants and, secondarily, to allow the facility to continue functioning during and after the event. Although completely earthquake-proof structures are financially unrealistic, seismic-resistance standards provide design criteria to avert collapse and assure functionality after an earthquake.

Nonstructural vulnerability

The term "nonstructural" refers to components that are physically joined to a building's structure (including partitions, windows, roofs, doors, and ceilings), those that are essential to the building's functionality (such as plumbing, heating, air conditioning, and electrical connections), and items located within the building (such as medical or mechanical equipment, or furniture). The three categories of nonstructural elements are therefore architectural components, installations, and equipment. In the case of health care facilities, nonstructural components often represent a greater economic value than the structure itself. Analyses indicate that nonstructural components generally account for more than 80% of the total cost of a hospital.

In some situations, nonstructural components can affect the occurrence of a structural failure. Heavy equipment such as central air-conditioning systems, X-ray equipment, CT scanners, electrical generators, boilers and hydrotherapy pools may be found on the upper stories of a hospital or on a floor dedicated to these central systems. The placement of this equipment can significantly modify the original calculations of a structure's behavior. Unanchored equipment may also slide or roll, causing a partial or total structural collapse. Architectural elements such as unreinforced stucco and heavy facades can also alter the behavior of the building as it vibrates.

In terms of the hospital's functionality, the damage or loss of some nonstructural elements can seriously disrupt the provision of services. While they do not represent a direct danger to building occupants, such losses pose an indirect risk through the failure of equipment or systems. For example, damage to an electrical generator may interrupt the power supply to basic life-support systems, such as the respirators in an intensive care unit.

Administrative/organizational vulnerability

The term "administrative or organizational vulnerability" refers primarily to the distribution of space, and the relationships between these spaces and the medical or health care services provided in the hospital. It also refers to the physical and functional relationships between the different areas, and to administrative processes such as hiring, supply procurement, maintenance routines, and so on. Appropriate zoning and relationships between the areas of a facility can assure adequate functioning not only under normal conditions, but also in case of emergency or disaster. The arrangement and relationship between outpatient consultation areas, areas surrounding the structure, and emergency services, and the creation of a specially protected area for general support services, can ensure appropriate medical treatment and avoid the functional collapse that can occur even if the building has not suffered severe damage.

It is the health care administrator's responsibility to anticipate and address these issues in order to reduce the potential loss of service and the social impact that occurs when efficient health care cannot be provided when it is most needed, after a disaster.

Planning and financing

Health care administrators should seek opportunities to incorporate disaster prevention and mitigation concepts into processes such as maintenance, expansion projects, equipment upkeep and hospital accreditation. Coordination with government and private institutions that study geological, seismological and hydrometeorological conditions will assist in the identification of the different types of hazards facing existing or future health care facilities. This information allows appropriate prevention and mitigation measures to be taken, reducing the hospital infrastructure's overall vulnerability. Administrators should use vulnerability assessments to reach a realistic balance between the required investment and the expected benefit in terms of mitigation of economic and social losses. An acceptable level of risk will be defined and ultimately reached through the application of the appropriate measures.

Hospitals should carry out ongoing risk mitigation planning based on the information described above, within the framework of an institutional policy that formulates the necessary objectives, strategies and activities. Preparations for emergency response are interdependent and complementary to risk mitigation activities.

Promotion and financing strategies

One of the difficulties in implementing disaster mitigation strategies is demonstrating the need for such investment: that is, its cost effectiveness. Factors that can weigh against the investment include the difficulty of predicting certain types of natural events, and the near-permanent economic crises faced by health care facilities in most developing countries. However, a convincing argument can still be made that reducing the vulnerability of health services, in order to guarantee the safety of people, equipment and services when they are most needed, is a highly cost-effective decision in both social and economic terms.

Promotion and financing can take a variety of forms. The approaches listed below are easy to implement, although they obviously require the previous or simultaneous development of a disaster mitigation program for health care establishments. Such a program should include human resource development and training, technological development, the establishment of standards and regulations, and the provision of expert knowledge by consultants.

- *Approval of operating licenses*. The approval or renewal of health care facilities' operating licenses provides an excellent opportunity to require all centers to adopt seismic-resistant construction techniques and take measures for disaster preparedness and mitigation.
- *Approval of investment budgets.* Budgetary line-items represent one of the most common means of promoting specifically focused investments and development processes. This tool can also be used to ensure that institutional development plans include disaster mitigation and preparedness measures. Financing for maintenance or construction projects, such as remodeling or expansion, can be made contingent on the execution of a vulnerability assessment and the inclusion of mitigation measures in the design. As mentioned earlier, it is considerably more cost-effective to build a seismically resistant health care center or retrofit an existing structure than to cope with the economic and social losses from the structural collapse of a hospital, with its consequent morbidity, mortality, loss of equipment and interruption of health care services.
- *Hospital accreditation processes*. The concept of accreditation, which became popular several years ago, involves a centralized entity that stipulates the conditions under which health care can be provided (see box 1.1). Individual institutions are required to fill in standardized forms for the assessment of criteria that can range from the condition of the physical plant to the equipment used and the quality of human resources. The accrediting body reviews the forms and issues a qualification to the institution. The accreditation must be renewed periodically, and can hinge on specific disaster mitigation and preparedness measures.
- *Approval of incentive-oriented budget items.* Economic support is another way to promote mitigation and preparedness measures in hospitals. Incentives can include co-financing for vulnerability studies, consulting or design work, or execution of some of the necessary modifications.

A hospital prepared for disaster situations: The "SAFE HOSPITAL"[3]

The Mexican Social Security Institute (IMSS) has presented an initiative designed to assure that hospitals are safe and prepared for disaster response. The plan has four stages:

1. A vulnerability assessment is conducted in hospitals that provide secondary and tertiary levels of care (i.e., the most complex hospitals). The personnel of each hospital carries out this analysis on the basis of the environmental hazards present. The results of the analyses are used in developing or updating Disaster Health Care Plans (PAISD) appropriate to the vulnerabilities of each establishment. Simple, low-cost corrective measures are implemented to address the problems detected.
2. An Institutional Certification Committee made up of specialized professionals performs an exhaustive vulnerability assessment of any secondary or tertiary level institution that requires such an assessment. The relevant mitigation measures are implemented, and the PAISD revised, according to current standards.
3. A competent national body validates the results obtained in steps 1 and 2.
4. International recognition as a "Safe Hospital" is granted to those establishments that meet the parameters established by the national body mentioned in step 3.

International participation

Risk reduction in hospitals and health care establishments has been consistently promoted in Latin America and the Caribbean in recent years due to the need to raise safety levels in the health care infrastructure in the region. The Pan American Health Organization (PAHO/WHO) has worked to attain the political commitment by health care authorities, encouraged regional exchange of expertise and experience in this area, and has promoted dissemination of information and technical training for the professionals involved, encouraging a multidisciplinary approach. This book, for example, is the result of activities designed to promote risk mitigation in health care establishments.

3 The full description of this project can be found in the report *Hospital preparado para enfrentar situaciones de desastre: "Hospital Seguro,"* prepared by the Mexican Social Security Institute in September 1998.

International Conference on Disaster Mitigation in Health Facilities[4]

In 1996, the Pan American Health Organization, under the auspices of the Government of Mexico and with the support of the Secretariat of the International Decade for Natural Disaster Reduction (IDNDR), the Department of Humanitarian Affairs (DHA) of the United Nations, the Economic Commission for Latin America and the Caribbean (ECLAC), the Organization of American States (OAS), and the World Bank, convened an International Conference on Disaster Mitigation in Health Facilities.

For the first time, health care authorities from throughout the Region made commitments for the 1996-2001 period to reduce the impact of natural disasters in high-priority health care facilities. Priority status was based on vulnerability and each country's political, economic and logistical capacity. Some of the most important commitments for immediate fulfillment included:

- To formally determine which existing health care institutions have priority for vulnerability studies and disaster impact reduction measures;
- To introduce mitigation measures in the design and construction of new health care facilities and in remodeling and expansion of existing facilities;
- To include nonstructural disaster mitigation or intervention measures in all maintenance, inspection, restructuring and improvement of existing hospitals;
- To identify budgetary resources and have hospital disaster mitigation plans classified as a priority.

Several countries in the Region have developed projects to partially or fully comply with the Conference recommendations.

4 Pan American Health Organization. Subcommittee on Planning and Programming of the Executive Committee, 30th session, 30 and 31 March 1998. SPP30/6, Rev. 1, Washington D.C., 29 April 1998.

Recommended bibliography for Chapter 1

Arnold C. and M. Durkin, *Hospitals and the San Fernando Earthquake*, Building Systems Development Inc., 1983.

Bitrán, D. *Estrategias y políticas para hospitales más seguros en América Latina y el Caribe*, unpublished paper prepared for PAHO, preliminary draft, January 1998.

Cardona, O.D. *Estudios de vulnerabilidad y evaluación del riesgo sísmico: planificación física y urbana en áreas propensas*. Boletín Técnico No. 33, Asociación Colombiana de Ingeniería Sísmica, Bogota, diciembre de 1986.

Cardona, O.D. *Términos de uso común en manejo de riesgos*, AGID Report No. 13, EAFIT, I Seminario Andino de Geología Ambiental, Medellín, April, 1990.

Cardona, O.D., and J.P. Sarmiento. *Análisis de vulnerabilidad y evaluación del riesgo para la salud de una población expuesta a desastres*. Cruz Roja Colombiana, 1990.

Centro Regional de Sismología para América del Sur (CERESIS), *Programa para la mitigación de los efectos de los terremotos en la Región Andina*; Proyecto SISRA, Lima, 1985.

Economic Commission for Latin America and the Caribbean (ECLAC). *Impactos económicos de los desastres naturales en la infraestructura de salud.* Reporte LC/MEX/L.291. Mexico, January 1996.

Earthquake Engineering Research Institute (EERI). Glossary of Terms for Probabilistic Seismic-Risk and Hazard Analysis, *EERI Earthquake Spectra, 1* (1):33-40, Committee on Seismic Risk, 1984.

________.The basics of seismic risk analysis, *EERI Earthquake Spectra, 5* (4):675-801, Committee on Seismic Risk, 1990.

Ghosh, S.K. (editor). *Earthquake resistant concrete structures inelastic response and design* (SP-127), ACI, 1991.

Grases, J. *Notas para la estimación de requerimientos hospitalarios en areas urbanas que pueden ser afectadas por sismos intensos.* Seminario Desastres Sísmicos en Grandes Ciudades, ONAD, Bogota, 1990.

Instituto Mexicano del Seguro Social. *Hospital preparado para enfrentar situaciones de desastre: "Hospital Seguro"*, September 1998.

Ministerio de Salud de Chile, *Seminario sobre mitigación de vulnerabilidades hospitalarias*, Universidad de Chile, Facultad de Ciencias físicas y Matemáticas, Santiago, 1997.

Office of U.S. Foreign Disaster Assistance (OFDA/USAID). *Curso de administración para desastres I.* San José, Costa Rica, 1992.

Organization of American States (OAS). *Primer on natural hazard management in integrated regional development planning.* Department of Regional Development and Environment, Washington, D.C., 1991.

_______. *Desastres, planificación y desarrollo: manejo de amenazas naturales para reducir los daños.* Departamento de Desarrollo Regional y Medio Ambiente, Washington, D.C., 1991.

Pan American Health Organization (PAHO/WHO). Planning and Programming Subcommittee of the Executive Committee, 30th Session, March 30 and 31, 1998. SPP30/6, Rev. 1, Washington D.C., 29 April 1998.

_______. *Análisis de riesgo en el diseño de hospitales en zonas sísmicas.* Washington, D.C., 1989.

________. *Disaster mitigation guidelines for hospitals and other health care facilities in the Caribbean*. Washington, D.C., 1992.

Chapter 2
Structural Vulnerability

Background

Structural vulnerability refers to the susceptibility of those parts of a building that are required for physical support when subjected to an intense earthquake or other hazard. This includes foundations, columns, supporting walls, beams, and floor slabs.

Strategies for implementing disaster mitigation measures in hospital facilities will depend on whether the facilities already exist or are yet to be constructed. The structural components are considered during the design and construction phase when dealing with a new building, or during the repair, remodeling, or maintenance phase of an existing structure.

Unfortunately, in many Latin American countries, earthquake-resistant construction standards have not been effectively applied, and special guidelines have not been considered for hospital facilities. For this reason, it is not surprising that each time an earthquake occurs in the region, hospitals figure among the buildings most affected, when they should be the last to suffer damage. The structural vulnerability of hospitals is high, a situation that must be totally or partially corrected in order to avoid enormous economic and social losses, especially in developing countries.

Since many hospital facilities are old, and others have neither been designed nor built to seismic-resistant standards, there are doubts as to the likelihood of these buildings continuing to function after an earthquake. It is imperative to use vulnerability assessments to examine the ability of these structures to withstand moderate to strong earthquakes.

Structural damage

Experience of seismic activity in the past shows that in countries where design meets good seismic-resistant standards, where construction is strictly supervised, and where the design earthquake is representative of the real seismic risk to the area, damage to infrastructure is marginal in comparison to that observed in locations where such conditions are not met.

Adherence to a seismic building code when designing a hospital does not necessarily safeguard against the damage produced by severe earthquakes.Seismic standards establish minimum requirements to protect the lives of occupants, requirements that many times are not sufficient to guarantee that a hospital will be able to function after an earthquake.

From a historical perspective, a code by itself cannot guarantee safety from excessive damage, since codes are rules that establish minimum requirements, which are continually updated in accordance with technological advances and lessons learned through research and study of the effects of earthquakes. Ductility (i.e., energy absorption capacity) and structural redundancy have proven to be the most effective means of providing safety against collapse, especially if the movements are more severe than those anticipated by the original design. Severe damage or collapse of many structures during major earthquakes is, in general, a direct consequence of the failure of a single element or series of elements with insufficient ductility or strength.

Structural damages as a result of strong earthquakes are frequently found in columns, including diagonal cracks caused by shearing or twisting, vertical cracks, detachment of column sheathing, failure of concrete, and warping of longitudinal reinforcement bars by excessive flexocompression. In beams, diagonal cracks and breakage of supports due to shearing or twisting are often seen, as are vertical cracks, breakage of longitudinal reinforcements, and failure of concrete caused by the earthquake flexing the section up and down as a result of alternating stresses

The connections or unions between structural elements are, in general, the most critical points. In beam-column connections (ends), shearing produces diagonal cracks, and it is common to see failure in the adherence and anchorage of the longitudinal reinforcements of the beams because of their poor design or as a consequence of excessive flexural stress.

In the slabs, cracks may result from punctures around the columns, and longitudinal cracks along the plate due to the excessive flexure that earthquakes can cause in certain circumstances. This type of damage has been seen repeatedly in hospital facilities submitted to moderate to strong seismic movements.

Observations in recent years indicate that, in general, stiff construction performs better than flexible construction.This pertains particularly to nonstructural components which suffer less damage because of limited displacement between floors.

Irregularities in height, translated into sudden changes in stiffness between adjacent floors, concentrate the absorption and dissipation of energy during an earthquake on the flexible floors where the structural elements are overburdened. Irregularities in mass, stiffness, and strength of floors can cause torsional vibrations, concentrating forces that are difficult to evaluate. For this reason, a higher standard for these elements must guide the architects entrusted with the design of these buildings.

Few buildings are designed to withstand severe earthquakes in the elastic range, so it is necessary to provide the structure with the ability to dissipate energy through stiffness and ductility, in the places where it is expected that elastic strength may be exceeded. This is applied to structural elements and connections between these elements, which are usually the weakest points.

Recommended safety levels

The 33rd Report of the Applied Technology Council (ATC-33)[1] defines several levels of safety for a building in case of an important seismic event. Table 2.1 presents recommendations for the so-called "Vision 2000" requirements.

1 Applied Technology Council (ATC), *Guidelines for seismic rehabilitation of buildings* (Report 33-03). 3 Volumes. Redwood City, 1995. NEHRP guidelines for seismic rehabilitation of buildings (FEMA 273).

Table 2.1.
Vision 2000 recommended objectives of seismic performance

Seismic Level	**Required performance level**			
	Fully functional	Operational	Life safety	Near collapse
Frequent (50%/30 years)	×		**Unacceptable performance** (For new buildings)	
Occasional (50%/50 years)	◆	×		
Rare (10%/50 years)	■	◆	×	
Very rare (10%/100 years)		■	◆	×

■ = Critical installation, such as hospitals, fire departments.
◆ = Essential or dangerous installation, such as a telephone center, building with toxic chemicals.
× = Basic or conventional installation, such as office and residential buildings.

In accordance with this table, a hospital must be designed in such a way that it may continue to function after a "rare" earthquake (10% probability of occurrence in 50 years), and that it remain in conditions allowing immediate occupation after a very rare earthquake (10% probability of occurrence in 100 years). Criteria for required performance for these safety levels are outlined below.

Fully functional: In this case, the building remains in a suitable condition for normal use, although perhaps with some limitations. All of the supply systems and basic services must continue to operate. To comply with this level, it is necessary to have redundant systems or emergency equipment. A rigorous inspection of the electrical and mechanical systems is required to guarantee that they function correctly after having been strongly shaken.

Operational: In this case, only very limited damages to the structure and to the nonstructural components are seen. Systems resistant to lateral and vertical loads retain almost all of the capacity that they had before the event. Nonstructural damage is minimal, so that access routes and safety systems (such as doors, stairs, elevators, emergency lights, fire alarms, etc.) remain operational, assuming that a power supply is available. Broken windows and slight damage to connections or lights may occur. It is expected that the occupants could remain in the building, although normal use of the establishment could be limited, and cleaning and inspection become necessary. In general, electromechanical components are secure and should operate if required. Calibrations in some equipment could be lost and misalignments or other damage could render them useless. There could be a loss of power and water, and problems with communication lines and gas pipes. While the risk of severe injury is low and the building may be occupied at this design level, it is possible that repairs will have to be made before normal function can resume.

Life safety: At this level significant damage to the structure is present, although a certain degree of protection against total or partial collapse is expected. Damage is greater than in the previous case. The majority of structural and nonstructural components have not failed, and do not constitute a threat inside or outside of the building. Evacuation routes remain operational, but may be limited by accumulations of rubble. Injuries may arise during the earthquake, but they are not expected to be life-threatening. It is possible to repair the structure, although in some cases this may not be practical from an economic point of view.

Near collapse: Damage after the earthquake is such that the building may suffer a partial or total collapse as a consequence of the degradation of the rigidity or the strength of the support system to lateral stresses, the permanent lateral deformation of the structure, or the reduction of its ability to support vertical loads. All of the basic components of the system that are resistant to gravitational loads may continue functioning. While the building may maintain its stability, a serious risk exists for injuries due to falling objects. It is unlikely that it will be practical to retrofit the structure, and the building is not safe for immediate occupation, since aftershocks could cause collapse.

The objective of the seismic-resistant design process is to ensure that the facility will be fully functional, regardless of the severity of the earthquake. It is not possible to carry out an effective assessment of nonstructural and administrative-organizational vulnerability (covered in chapters 3 and 4 of this book) if structural vulnerability has not been assessed. However, the importance of taking measures to mitigate nonstructural and administrative-organizational vulnerability cannot be overemphasized, since these aspects are as susceptible to damage from small to moderate seismic events, which occur more frequently, as they are to earthquakes that can affect structural components.

Assessing the condition of an existing building can raise serious doubts about its ability to withstand seismic events. In some countries, retrofitting campaigns for existing buildings have been launched in order to reduce vulnerability (see boxes 2.1–2.5 for examples of national initiatives). In principle, one would think that retrofitting would be obligatory for essential buildings identified as being structurally vulnerable.

Box 2.1.Legislating hospital assessment in Colombia

The Colombian Seismic-Resistant Construction and Design Standards, known as NSR-98 were signed into law in 1998 (Law 400 of 1997 and Decree-Law 33 of 1998).The law requires that essential buildings located in earthquake-prone areas be assessed as to their vulnerability within a period of three years and inspected or reinforced within a period of six years.This obliges the national,departmental and municipal governments to include budget allotments to that end in the coming years and take into account this type of investment in future development plans.

The Standards define essential buildings as follows:
"Those buildings serving the community that must function during and after an earthquake, whose operation cannot be moved rapidly to an alternate location,such as hospitals with complexity levels of 2 and 3,as well as centers responsible for lifeline operation and control."

Article 54 of the law stipulates that:
"Existing buildings whose use classifies them as essential structures,located in areas of intermediate to high seismic threat, must be assessed for their seismic vulnerability in accordance with the procedures established in these regulations within a period of three years from the date this law goes into effect.

"These buildings must be modified or retrofitted to bring them up to a seismic safety level equivalent to that of a structure newly designed and constructed in accordance with the requirements of this law and its regulations,within a period no greater than six years from the date this law goes into effect."

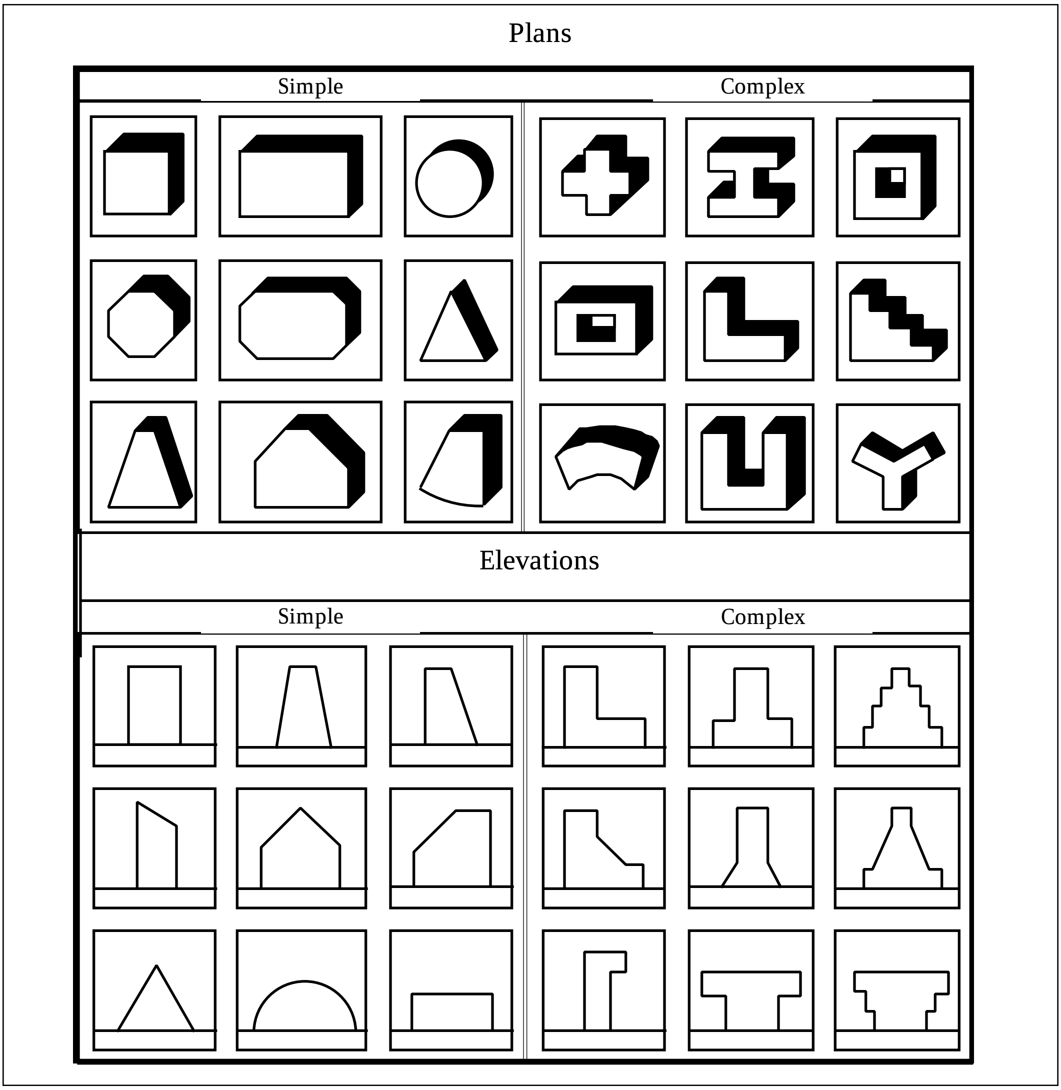
Armed with this judicial instrument,the Colombian Ministry of Health and the National Department for the Prevention and Management of Disasters will be able to strengthen their nationwide program to promote seismic vulnerability assessments of all existing hospitals and their retrofitting,where necessary.This work will provide impetus for national,departmental,and in some cases municipal efforts, through joint financing and matching funds provided by the Ministry of Health,the Social Investment Fund and the National Disaster Fund.Although not all secondary and tertiary hospital facilities in areas with an intermediate to high seismic hazard may have been retrofitted by the designated deadline, the regulations will undoubtedly help to advance the issue and stimulate political resolve among local and departmental governments,which in the case of Colombia share responsibility for the enforcement of this law. Even before the new standards were in place , efforts were underway at the local and departmental levels to design the retrofitting of several key hospitals. Once the new regulations have been publicized,more widespread efforts will likely be seen,translating into an increase in the safety of the country's health infrastructure.

Source: Cardona, O.D. *Las edificaciones hospitalarias en la nueva legislación sísmica colombiana*. Paper presented at the International Conference on Disaster Mitigation in Health Facilities,Mexico, 1996.

Architectural and structural configuration problems

By their nature, hospital facilities tend to be large and complex, which often causes their configuration to be quite complex as well. Configuration does not refer here simply to the abstract spatial arrangement of the buildings and their components, but to their type, lay-out, fragmentation, strength and geometry, from which certain problems of structural response to earthquakes are derived. One of the greatest causes of damage to buildings has been the use of improper architectural-structural configurations. Generally speaking, it may be said that a departure from simple structural forms and layouts tends to be severely punished by earthquakes. Figure 2.1 illustrates simple and complex configurations. Unfortunately, the usual methods of seismic analysis fail to adequately quantify problems related to configuration. In any case, given the erratic nature of earthquakes, as well as the possibility of their exceeding design levels, it is advisable to avoid hazardous configurations, regardless of the degree of sophistication that may be reached in the analysis of each individual case.[2]

Figure 2.1.
Simple and complex forms in plan and elevation



Source: Reprinted from Arnold, Christopher and Reitherman, Robert, ***Building configuration and seismic design*** (John Wiley and Sons, New York: 1982, p. 232).

2 Applied Technology Council (ATC) (Report ATC 3-06), *Tentative Provisions for Development of Seismic Regulations for Buildings.* Palo Alto, 1978. [Spanish version published by the Asociación Colombiana de Ingenieria Sísmica, Bogotá, 1979.]

Geometric configuration

The following briefly describes the most relevant aspects of the impact of geometric configuration on the seismic response of buildings, as well as the corrective measures required. Due to their complexity and their close relationship with buildings' use of space and form, configuration problems must be taken into account from the very earliest stages of architectural design. Architects and designers should have a thorough understanding of the relevant issues.[3]

Configuration problems in the plan

The problems mentioned below refer to the plan (i.e., horizontal layout) of the structure in relation to the form and distribution of architectural space.

> The configuration problems in the plan arise when the floor plans are continuous, that is, when they are not made up of discrete units.Some floor plans that at first glance seem complex, but that rely on seismic expansion joints, may not face performance problems from earthquakes.

Length

The length of a building determines its structural response in ways that are not easily determined by the usual methods of analysis. Since ground movement consists of the transmission of waves, which occurs with a velocity that depends on characteristics of the soil on which the structure stands, the excitation that takes place at one point of support of the building at one time differs from the excitation at another time, a difference that is greater to the extent that the length of the building is greater in the direction of the seismic waves. Short buildings adjust more easily to the waves than long buildings, and undergo similar excitation at all supports.

The usual correction for the problem of excessive building length is to partition the structure in blocks by the insertion of seismic expansion joints in such a way that each block can be considered a shorter building. These joints must be designed to permit adequate movement of each block without the danger of their striking or colliding with each other.

Long buildings are also more sensitive to the torsion or horizontal rotation resulting from ground movements, because the differences in the transverse and longitudinal movements of the supporting ground, on which this rotation depends, are greater.

Concentration of stress due to complex plans.

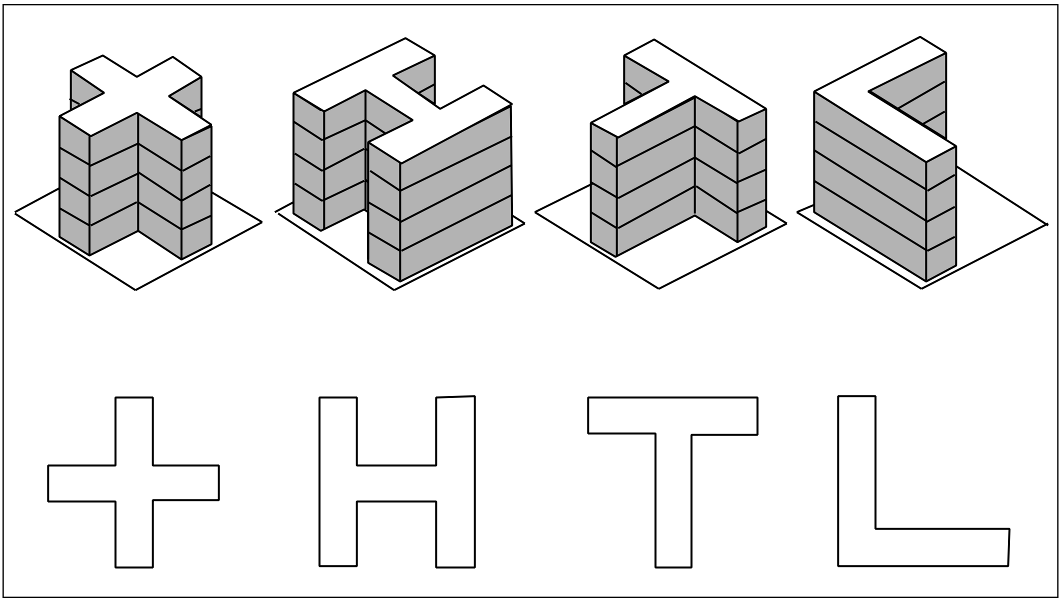
Concentration of stress arises in buildings with complex floor plans, and is very common in hospital buildings. A complex plan is defined as that in which the line joining any two sufficiently distant points lies largely outside of the plan. This occurs when wings of significant size are oriented in different directions, for instance in H, U, or L shapes (see figure 2.2 and photograph 7).

In irregularly shaped floor plans, the wings may be likened to a cantilever built into the remaining

3 Bazán, E., Meli, R., ***Manual de diseño sísmico de edificios***, Mexico, D.F.,: Limusa, 1987

body of the building, a point that would suffer smaller lateral distortions than in the rest of the wing. Large concentrations of stress appear in such transition areas, frequently producing damage to the non-structural elements, the vertical structure, and even the diaphragms (that is, the horizontal resistant elements of a structure such as floors and roofs).

Figure 2.2.
Complex plans



T. Guevara

O.D.Cardona

Photograph 7. Caldas Hospital in Colombia

In such a case, the solution currently used is to introduce seismic expansion joints like those mentioned in the case of long buildings. These joints allow each block to move without being tied to the rest of the building, which interrupts the cantilever effect of each wing. The joints, obviously, must be wide enough to permit the movement of each block without striking adjacent blocks.[4]

Vertical configuration problems

Setbacks

Setbacks in the volume of a building usually arise from urban design demands for illumination, proportion, etc. However, in seismic events they are the cause of abrupt changes in stiffness and mass producing a concentration of stresses in the floors near the site of sudden change (figure 2.3). In general terms, one should ensure that the transitions are as gradual as possible in order to avoid such concentration of stresses.

Figure 2.3.
Buildings with irregular vertical shape

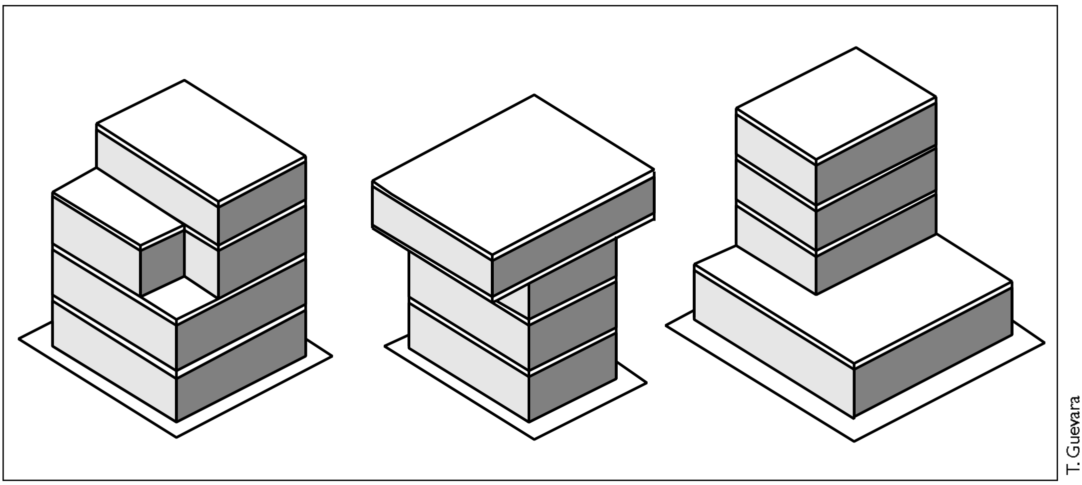
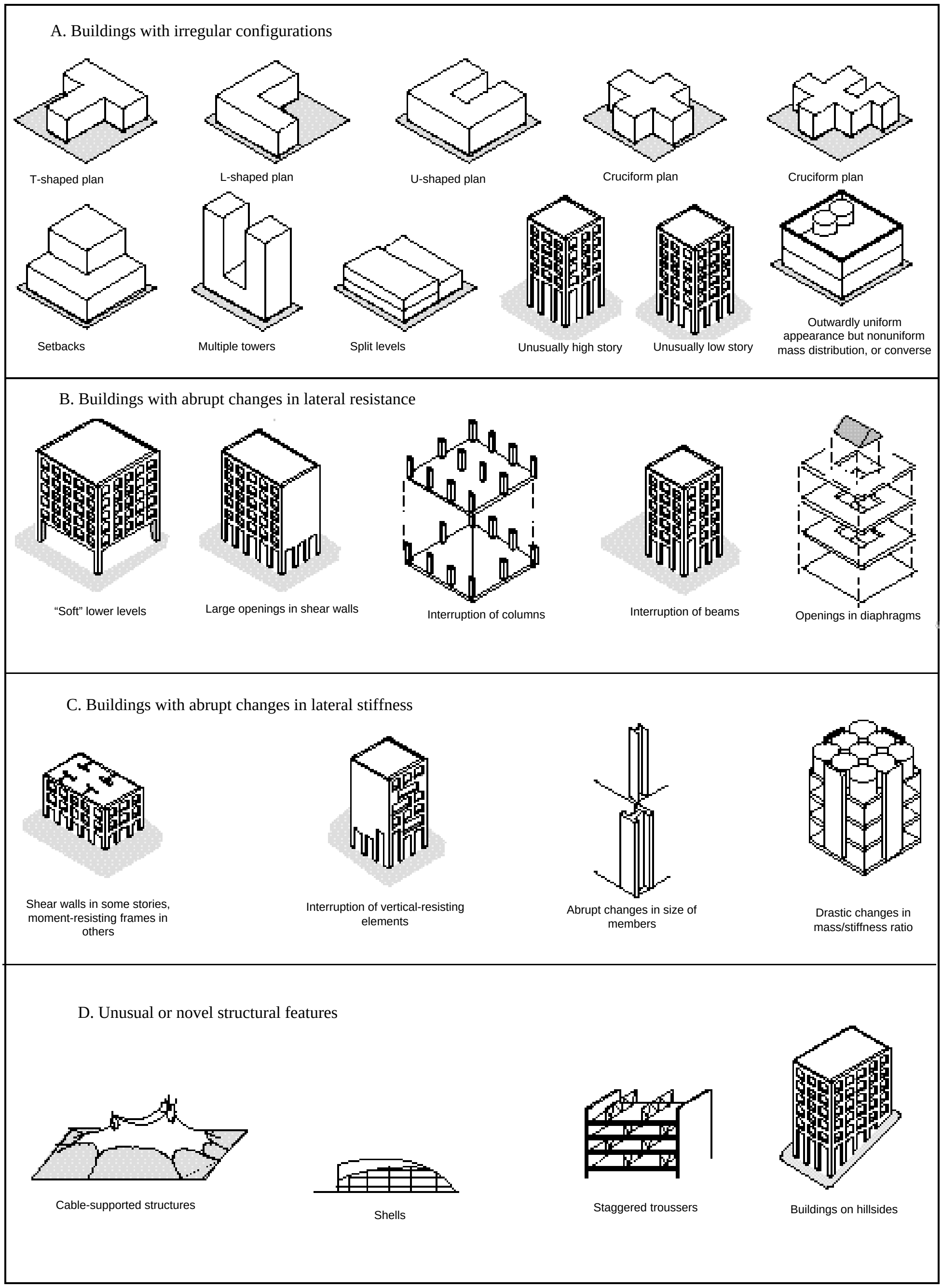


Figure 2.4 shows some characteristics of building configuration that should be avoided in health facilities, due to their inadequate performance in earthquakes.

[4] Dowrick, D.J. ***Diseño de estructuras resistentes a sismos para ingenieros y arquitectos***. Mexico: Limusa, 1984.

Figure 2.4.
Irregular structures



Graphic interpretation of irregular structures or framing systems, from the Commentary to the SEAOC Recommended Lateral Stress Requirements and Commentary. Reproduced in Arnold, Christopher and Reitherman, Robert, *Building Configuration and Seismic Design* (John Wiley and Sons, New York: 1982, p. 8). Reproduced with permission.

Structural configuration

The following section describes issues related to the performance of structural elements in response to seismic events.

Concentrations of mass

High concentrations of mass on a given level of the building are problematic. This occurs on floors where heavy items are placed, such as equipment, tanks, storerooms, or filing cabinets. The problem is greater the higher the heavy level is located, due to the fact that seismic response accelerations increase upward, increasing seismic forces and the possibility of equipment collapsing and causing structural damage (see photograph 8).

PAHO/WHO

Photograph 8. Concentrations of mass, such as water tanks placed on the roof of a hospital, can cause severe damage in earthquakes.

In architectural design, it is recommended that spaces for unusually heavy weights be in basements or in buildings isolated from the main structure. If elevated water storage is required for topographical reasons, it is preferable to build independent towers instead of attaching towers to the main building.

Weak columns

Columns have vital importance as they are the elements that transmit seismic loads to the foundations and keep the structure erect. Any damage to columns can cause a redistribution of loads between the elements of the structure and cause the total or partial collapse of a building.

The use of frames (structures formed by beams and columns) in seismic design seeks to ensure that the damage from intense earthquakes is produced in beams rather than in columns, due to the greater risk of the building collapsing from damage to the columns. However, many buildings designed according to seismic-resistant codes have failed in this regard. These failures can be grouped into two classes:

- Columns with less resistance than beams.
- Short columns.

In the first case, the frame has been designed so that the resistance provided to the beams that meet at a connection is greater than that of the respective columns. When the connection is twisted by seismic movement, the columns yield before the beams.

Short columns are the cause of serious failures in buildings under seismic excitation. There are several circumstances in which the free unsupported length of the columns is drastically reduced and the result can be considered a short column, including:

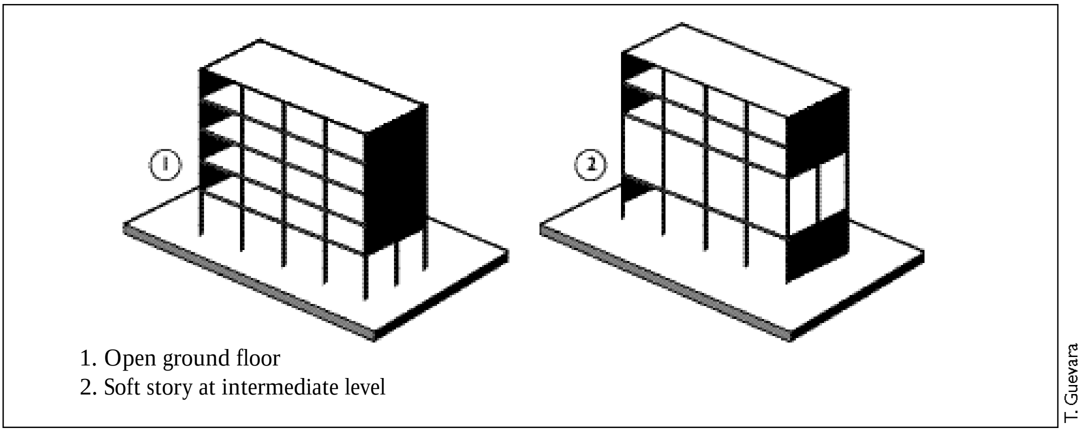
- Partial lateral confinement of the column by dividing walls, facade walls, retaining walls, etc.;
- Placement of floor slabs at intermediate levels;
- Location of the building on a slope.

Soft stories

Several types of architectural and structural plans lead to the formation of so-called "soft" stories, which are stories that are more vulnerable to seismic damage than others due to the fact that they are less stiff, less resistant, or both (see figure 2.5). The presence of soft stories can be attributed to:

- Differences in height between floors;
- Interruption of the vertical structural elements on the floor.

Figure 2.5.
Examples of buildings with "soft story" irregularity.



Source: Guevara, Teresa. "Recomendaciones para crear diseños arquitectónicos sismo resistentes a la luz de la nueva Norma Colombiana NSR-98", Reunión del Concreto 1998, Cartagena, Colombia.

Differences in height between stories arises frequently because of the need for greater space at certain levels of the building, generally for technical (equipment requirements, etc.) or aesthetic reasons (image of the building at the access levels). This results in lessened stiffness of the stories in question, due to the greater height of the vertical elements.

The interruption of vertical elements (walls and columns) of the structure has been the cause of partial or total collapses in buildings subjected to earthquakes, especially when this occurs in the lower floors (see photographs 9–11). The level on which the elements are interrupted is more flexible than the others, which increases the problem of stability, but also because the abrupt change in stiffness causes a greater accumulation of energy on the weaker story. The most common cases of interruption of vertical elements, which occur generally for spatial, formal, or aesthetic reasons, are the following:

- Interruption of the columns
- Interruption of structural walls (shear walls)
- Interruption of partition walls (erroneously conceived as nonstructural walls) aligned with frames

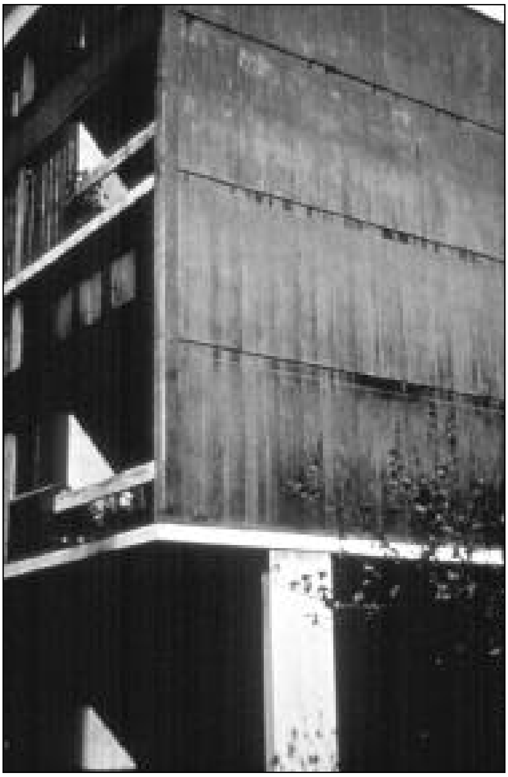

O.D.Cardona

Photograph 9. Failure on ground floor due to soft story.

Lack of redundancy

Seismic-resistant structural design takes into account the possibility of damage to the structural elements by the most intense earthquakes. The design of the structure must take into account that resistance to seismic forces depends on the distribution of stress among the greatest possible number of structural elements. When there is little redundancy (i.e., a reduced number of elements) the failure of any of these can cause partial or total collapse during an earthquake.[5]

5 PAHO/WHO, *Análisis de riesgo en el diseño de hospitales en zonas sísmicas*, Washington, D.C., 1989.



J. Grases

Photograph 10. Interruption of a structural wall on the ground floor

J. Grases

Photograph 11. Structural collapse due to the discontinuity of vertical elements.

Excessive structural flexibility

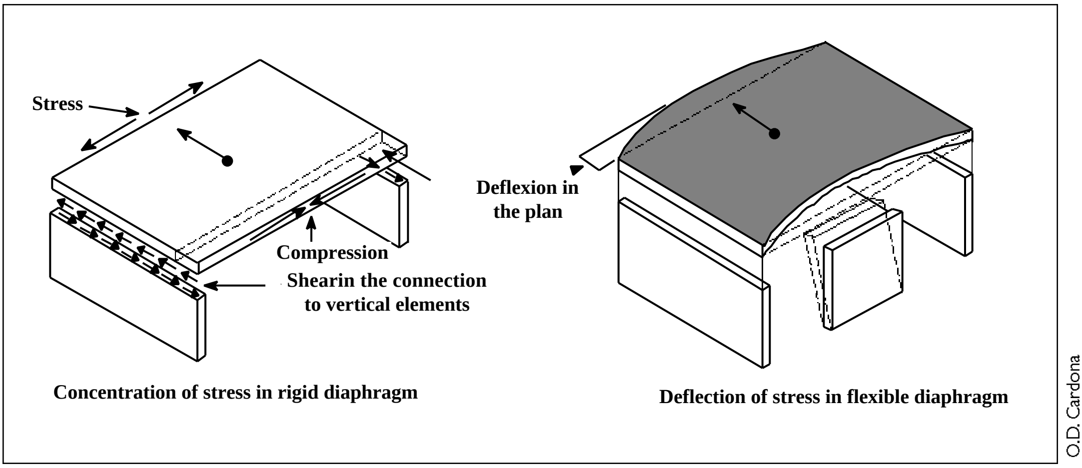
Excessive flexibility of the building to seismic loads can be defined as the susceptibility to large lateral distortions between different stories, or "drift". The main causes of this problem reside in excessive distance between the support elements (clear spaces or clearances), their vertical clearance, and their stiffness. Depending on the degree, excessive flexibility can have the following consequences:

- Damage to nonstructural elements attached to contiguous levels;
- Instability of the flexible floor or floors, or the building in general;
- Not taking advantage of available ductility.

Excessive flexibility of the diaphragm

An excessively flexible floor diaphragm involves non-uniform lateral distortions, which are in principle prejudicial to the nonstructural elements attached to the diaphragm. Additionally, the distribution of lateral forces will not be in accordance with the stiffness of the vertical elements (see figure 2.6).

Figure 2.6.
Rigid and flexible behavior of the floor diaphragm



There are several reasons why there can be this type of flexible performance. Among them are the following:

- *Flexibility of the diaphragm material.* Among the usual building materials, wood or steel decking without concrete are the most flexible.
- *Aspect ratio* (length/width) of the diaphragm. The greater the length/width ratio of the diaphragm, the greater the lateral distortions may be. In general, diaphragms with aspect ratios greater than 5 may be considered flexible.
- *Stiffness of the vertical structure.* The flexibility of the diaphragm should also be judged in accordance with the distribution of rigid vertical elements in the plan. In the extreme case of a diaphragm in which all elements are of equal stiffness, better performance is expected than when there are major differences in this respect.
- *Openings in the diaphragm.* Large openings in the diaphragm for purposes of illumination, ventilation, and visual connections between stories cause flexible areas that impede the rigid assembly of the vertical structures.

There are multiple solutions to the problem of excessive flexibility of the diaphragm, depending on its cause. Measures used to stiffen the diaphragm where large openings occur should be carefully studied; other options include segmentation of the building into blocks.

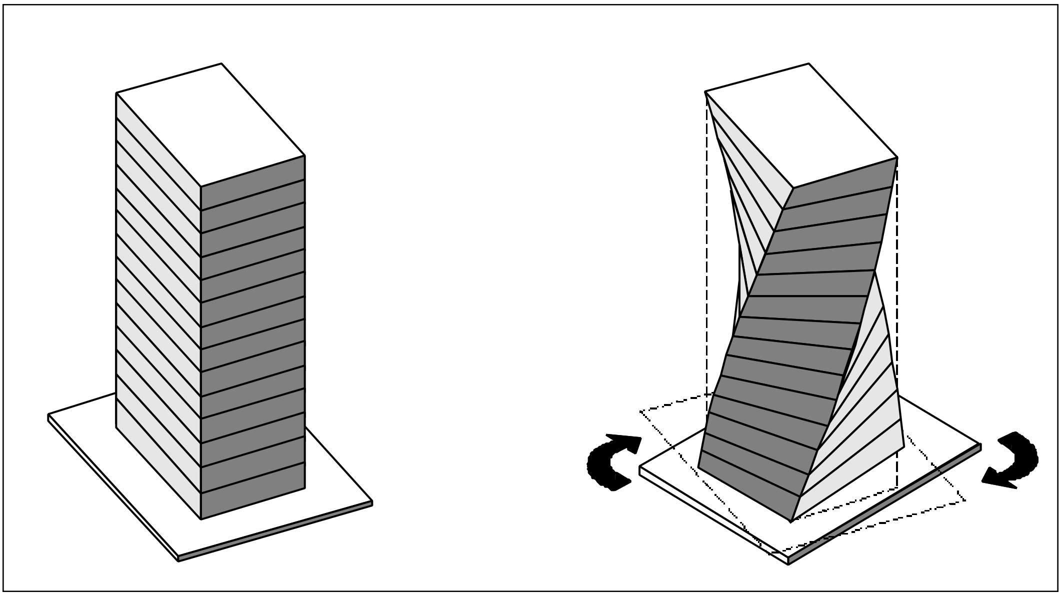
Torsion

Torsion has been the cause of major damage to buildings subjected to strong earthquakes, ranging from visible distortion of the structure (and its resultant loss of image and reliability) to structural collapse (figure 2.7). Torsion is produced by the eccentricity existing between the center of mass and the center of stiffness. Some of the situations that can give rise to this situation in the building plan are:

- Positioning the stiff elements asymmetrically with respect to the center of gravity of the story;
- The placement of large masses asymmetrically with respect to stiffness;
- A combination of the two situations described above.

It should be kept in mind that the dividing walls and the facade walls that are attached to the verti-

Figure 2.7.
Torsion



cal structure are usually very stiff and, therefore, often participate in the structural response to an earthquake and can cause torsion. This is often the case in corner buildings.

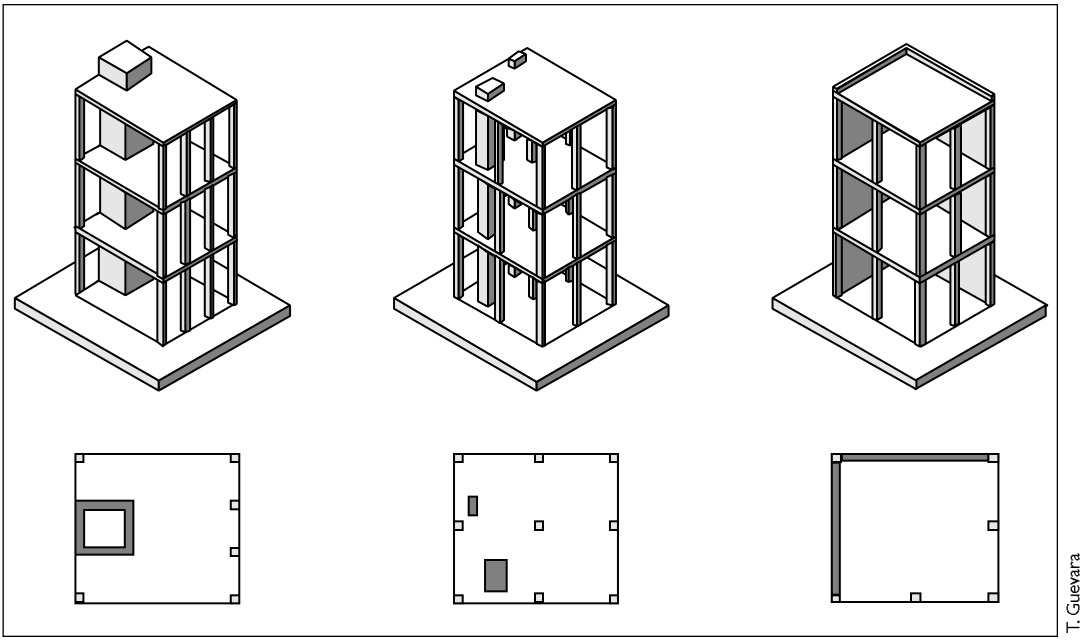
Quantitatively, an eccentricity between the centers of mass and stiffness is considered significant when it exceeds 10% of the horizontal plane dimensions under study. In such cases, corrective measures should be taken in the structural design of the building (see figure 2.8).

Torsion may become even more complicated when there are vertical irregularities, such as setbacks. In effect, the upper part of the building transmits an eccentric shear to the lower part, which causes downward torsion of the transition level regardless of the structural symmetry or asymmetry of the upper and lower floors.

As with all configuration problems, that of torsion should be addressed starting with the design of space and form of the building. The necessary corrections to the problem of torsion may be summarized as follows:

- Torsion should be considered inevitable due to the nature of the seismic event and the characteristics of the structure. For this reason, the suggestion is to provide buildings with so-called perimetric stiffness, which seeks to brace the structure against any possibility of rotation and distribute torsional resistance among several elements.
- In order to control torsion, the layout of the structure in plan and elevation must be studied carefully, as well as the presence and need for isolation of the nonstructural partition walls that could structurally intervene during an earthquake. Finally, the objective of these measures should be to provide to the structure the greatest possible symmetry of stiffness with respect to the mass.

Figure 2.8.
Eccentricity between centers of mass and stiffness increase effects of torsion.



Seismic-resistant design

Seismic-resistant design of structures is more complex than the design for static gravity loads, due to some of the following factors:

a) The random nature of the characteristics of an earthquake;
b) The uncertainty of the response of the structure, due to the heterogeneous quality of materials, interactions with nonstructural elements, variation in service loads, variations in construction, etc.;
c) The failure and energy dissipation mechanisms that entail the least risk for human life and property;
d) The social cost entailed in the failure of buildings, especially those essential for responding to disasters, as in the case of hospitals.

Seismic-resistant design should attempt to take into account all of these aspects.[6] Normally, design codes address some of these problems by means of simple quantitative formulas for overall or localized safety considerations. Often, mindless adherence to these quantitative formulas in the design of structures causes the basic principles behind such simplifications to be forgotten or disregarded. However, in the design of any building, and especially essential facilities such as hospitals, the implications of each important decision must be assessed in the light of the principles and advances of seismic engineering.

Below is a summary of these implications of seismic design of hospitals.

6 Asociación Colombiana de Ingeniería Sísmica, *Normas colombianas de diseño y construcción sismo resistente NSR-98* (Law 400 of 1997, Decree Law 33 of 1998), Bogotá, 1998.

Design spectra

In the design spectra recommended by seismic resistance codes, decisions must be made about:

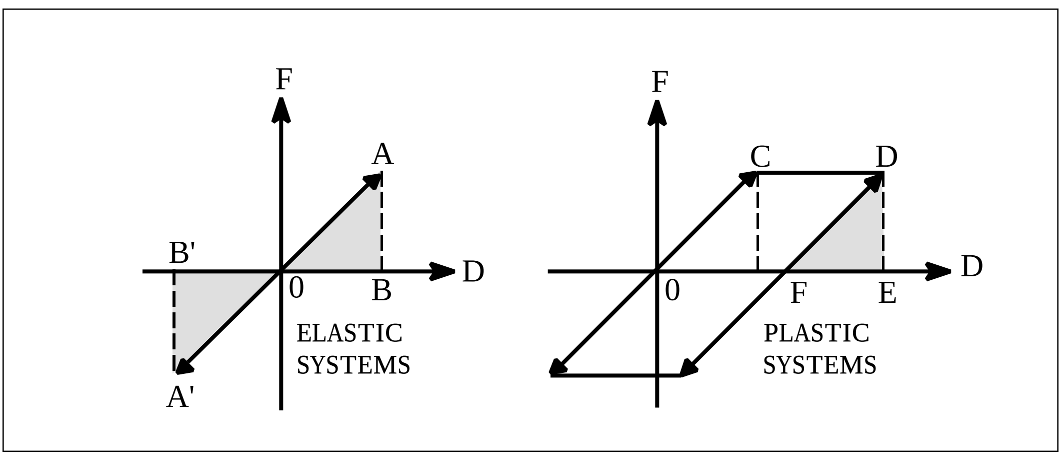
a) *The probability of exceeding the design earthquake in a period of time considered to be the average useful life of buildings*. Normally, this is considered to be a probability of 10% in an average useful lifetime of 50 years. In the case of hospitals, however, the useful life far exceeds that number. Construction of hospital facilities is decidedly less common than housing and other types of buildings. This is a critical issue in developing countries, where construction of large hospitals is rare because of the high costs involved. Health facilities are meant to last a very long time in some countries, and careful thought must be given to their design.

b) *Dominant frequencies and maximum responses.* Normally, the spectra of earthquakes exhibit narrow frequency ranges in which the maximum responses are found. However, to dispel the uncertainties associated with the distance from the occurrence of the event and its frequencies, design spectra present a broad range of maximum responses as well as amplification factors of the responses in soft ground with respect to responses in firm ground. These ranges are based on performance observed in various locations around the world. In the case of hospitals buildings a design spectrum should be prepared in accordance with the geological and geotechnical characteristics of the construction site.

Nonlinear performance

The criteria for traditional design of buildings subjected to strong earthquakes have been to allow the materials some degree of nonlinear response for the purpose of absorbing energy through permanent deformations. Figure 2.9 illustrates this criterion for an elasto-plastic system. The line OA represents the maximum stress—maximum deformation diagram of a perfectly elastic system during a given earthquake, while the line OCD represents an elasto-plastic system. Several hypotheses exist for the simplification that must be assumed to evaluate the performance of an elasto-plastic system in a simple manner.

Figure 2.9.
Absorption and dissipation of energy



The structure must be designed for less stress than is produced by the response of the elastic system. If an elastic analysis is done with the stresses obtained in this manner, some distortions will be obtained that, in turn, must be multiplied by the ductility factor to estimate the maximum deformation of the structure, which is of great importance for the study of the performance of nonstructural elements and the stability of the different floors. The structural elements must then guarantee that these inelastic distortions can be achieved. For this reason, these elements should have sufficient ductility, by means of mechanisms that will be discussed in the next section.

Many construction codes make the mistake of considering a reduction of stresses due to inelastic performance only in relation to the maximum deformation reached at any instant of the earthquake, or to the maximum energy dissipated in a cycle, without considering its duration. This ignores important factors such as the progressive fatigue of the materials, as well as the degradation of stiffness, reduced resistance, the progressive increase of deformations, and, therefore, progressive collapse. For this reason increasing emphasis is being placed on design methods that consider the total duration of an earthquake, generally by total energy dissipated or the number of load cycles.

Ductility

The simplified nonlinear methods of design demand the structure to undergo large deformations without collapsing. However, design methods must also ensure that deformation will not affect or cause damage to the building content (nonstructural elements).

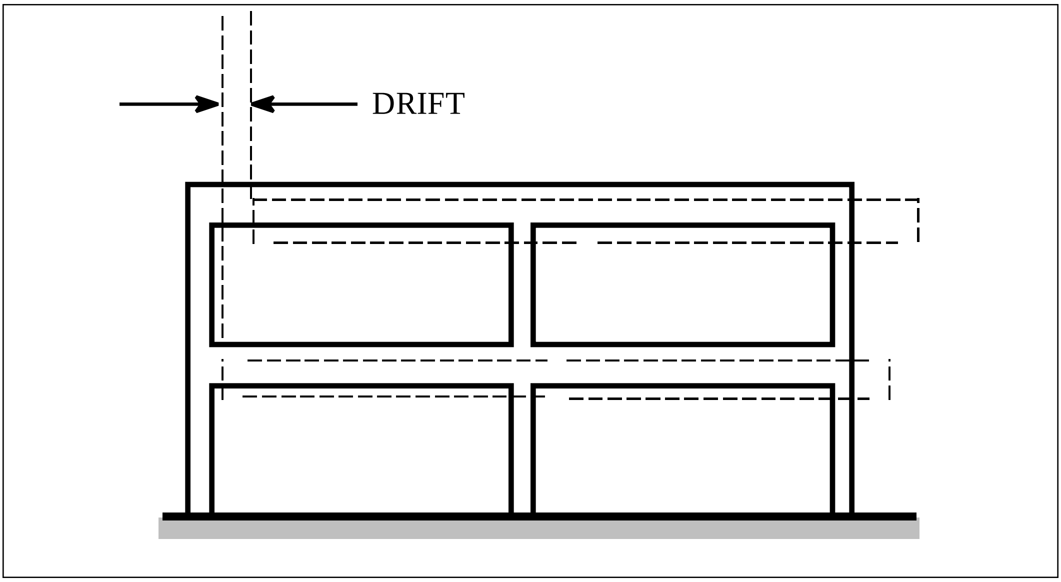
In the design of reinforced concrete structures, the following basic criteria must be taken into account in order to obtain the required ductility:

- *Confinement.* Confinement of concrete guarantees preservation of the material under the alternating stress that occurs during earthquakes. This mechanism allows for greater inelastic deformations than are possible in a structure in which the concrete fails.
- *Controlling shear failure.* Shear failure seriously compromises the integrity of any element of reinforced concrete. For this reason the design codes generally require that shear resistance be greater than flexure resistance. This is achieved by using as a shear design a value that at the very minimum corresponds to the plastic yielding from flexure at the end connections.
- *Controlling the reduction in available ductility due to axial load.* Axial compression load drastically reduces the ductility available in a concrete element subject to this load. The phenomenon, which is more severe in columns than in structural walls, can be attributed to the fact that with heavier compression loads the working stress of the steel is reduced. This can occur with working stress values smaller than yield stresses, which implies an inadequate use of steel in order to develop large inelastic distortions and to dissipate energy in this manner. However, it is not always possible to design the sections of columns so that there are heavy traction stresses on the steel, for architectural and economic reasons.

Drift (relative displacement between floors)

In principle, large lateral displacements between stories, or "drift", put the entire safety of the building in danger, due to the damage that it can represent to nonstructural elements. Depending on the extent of displacement, partial or total collapse of the building can occur (figure 2.10).

Figure 2.10.
Drift and stability



The damage to nonstructural elements attached to the structure is particularly serious in the case of hospitals, and this is covered in detail in the following chapter. For the time being, it is necessary to keep in mind that this damage is associated with the value of the relative inelastic displacement of one level with respect to an immediately contiguous one, or drift. It has been established that drift values higher than 1 or 1.5 per thousand of the clear height between the two levels are not desirable. However, this limit depends heavily on the fragility and resistance of the materials of the nonstructural elements.

Calculating appropriate values of inelastic displacement is of major importance for a suitable analysis of drift and stability. Being conservative in this aspect is more desirable in the case of hospitals than in other structures, due to the implications that damages to nonstructural and structural elements have for the occupants and the community in general.

Duration of the earthquake

The effect of the duration of an earthquake on structural behavior has traditionally been ignored in design codes. This is due in part to the fact that the accelerations spectrum is insensitive to the duration of the earthquake, since it collects information only with reference to the maximum response acceleration at some point during the earthquake and ignores what happens afterwards. However, in long earthquakes complex phenomena of degradation of stiffness and resistance can occur, due to the high number of load cycles that the structural elements must endure. Therefore, the design should be different for short and long earthquakes, regardless of the design acceleration.

According to studies conducted in different countries, the duration of an earthquake correlates with its magnitude and the distance from the epicenter. In contrast, ground acceleration decreases with this distance. There can be earthquakes of equal peak acceleration that would produce the same design acceleration spectrum but large differences in duration and which would produce harmful effects that would not be detected by this spectrum.

In light of the above, the design of hospitals must take into account seismological information related to magnitudes and epicentral distances. If there are sources of high probable magnitudes located at great epicentral distances, much longer and possibly more destructive earthquakes can be expected than from nearby earthquakes. The 1985 earthquake in Mexico City is an example not only of ground amplification effects but also of the effects of long duration, due to the high magnitude (8.1) and large distance from the epicenter (350 km).

Analysis of structural vulnerability

The above sections have dealt with the aspects that must be considered in the planning, analysis, and design of buildings in accordance with recent theories on seismic resistance. In these cases, the most detailed inspection possible of the ability of the structure to resist moderate and severe earthquakes becomes imperative. Before retrofitting a structure, an analysis of the building's existing resistance and ductility, as well as the functional, organizational and administrative vulnerability of the hospital, must be carried out.

> A vulnerability assessment seeks, among other things, to determine the susceptibility or the level of damage expected in the infrastructure, equipment and functionality of a hospital facility from a particular disaster; therefore, to initiate a vulnerability assessment, the phenomenon or phenomena to be considered must be characterized.

In the case of earthquakes, it is worthwhile to select and characterize those events that could arise during the lifetime of the hospital facility. Frequent, low-magnitude earthquakes can affect nonstructural elements; on the other hand, less frequent but more violent earthquakes can affect structural as well as nonstructural elements.

The principal methods for structural assessment are discussed below. Such an assessment will be inadequate if it is not accompanied by a detailed review of the nonstructural elements.

The international literature presents several methods for conducting seismic vulnerability analysis of a building; examples are listed in the bibliography of this publication. In general terms, however, the methods can be classified as qualitative and quantitative:

- Qualitative methods are generally used to evaluate a large sample of buildings or to corroborate the level of safety in a given structure.
- Quantitative methods are utilized when the importance of the building merits it, or rather when qualitative methods have not been able to assess the safety of the building.

Qualitative methods

Qualitative methods are designed to evaluate in a rapid and simple manner a group of buildings, and to select those that merit a more detailed analysis. They can be used to quantify seismic risk in a broad area of a city, but their results cannot really be taken as conclusive in any particular case[7], except to the extent that they corroborate the already established safety level of a building. Boxes 2.2 and 2.3 describe national programs using qualitative and quantitative methods is assessing hospitals.

7 Centro Regional de Sismología para América del Sur (CERESIS), *Programa para la mitigación de los efectos de los terremotos en la Región Andina*; SISRA Project, Lima, 1985.

Box 2.2. Vulnerability assessment: a tool for setting health sector priorities in Chile

The 1985 earthquake in Chile was especially destructive to the country's health infrastructure. The event damaged 180 of the 536 establishments in its area of influence, and left 2,796 of the 19,581 available beds out of service. As a result of this experience and the importance given to the subject of natural disaster prevention in that country in recent years, a program to identify and assess hospital vulnerability was undertaken for the purpose of setting priorities and reducing the risk to health care infrastructure.

Relying upon a multidisciplinary team, the political commitment of the authorities, and scientific information on the level of seismic hazard in the country, a project was formulated with the objective of identifying measures to reduce the vulnerability of the most important hospitals from each of the 26 health services divisions in the country.

An initial sample of 26 hospitals was chosen; of these a group of 14 was finally selected as a representative sample of the different types of construction and the level of exposure to seismic hazards. The development of this methodology was useful in two ways: it provided a tool that did not exist at the time in Latin America, and it identified individual problems and solutions for each hospital studied.

Each of the hospitals was the focus of an intense assessment, including structural, nonstructural, functional, and organizational aspects. The assessment's starting point was the integrity of the structure and the safety of its occupants.

The project included the following activities:

- A description of the health system;
- A brief description of seismicity in Chile;
- Training of personnel;
- Analysis of structural and nonstructural vulnerability;
- Estimation of the vulnerability of the area and development of mitigation plans.

The effectiveness of the assessment was tested when an earthquake with a magnitude of 7.3 on the Richter scale hit the city of Antofagasta on 31 July 1995. The city hospital, which had been evaluated a few days earlier, partially lost its operating capacity due to broken water pipes, broken windows and lighting systems, damage to equipment (hemodialysis and boilers), and general damage in the structural and nonstructural systems. Immediate evacuation of the hospital was considered.

***Source: Boroschek, R., M. Astroza, Cl. Osorio, E. Kausel, "Análisis de vulnerabilidad y preparativos para enfrentar desastres naturales en hospitales en Chile", Universidad de Chile, Study prepared for PAHO/WHO – ECHO, Santiago, Chile, 1996; Chile, Ministry of Health, Seminario sobre mitigación de vulnerabilidades hospitalarias, Universidad de Chile, Facultad de Ciencias Físicas y Matemáticas, Santiago, 1997.**

Box 2.3. Assessing a city's hospitals: experience in Ecuador

Ecuador has an extensive history of destructive earthquakes. In the city of Guayaquil, located 200 km from the fault where the Nazca and South American tectonic plates collide, one can find 90% of the alluvial or soft soils that can amplify earthquakes with epicenters 200 or 300 km away. This effect can have a major impact on reinforced concrete buildings with between 5 and 15 stories. Two such buildings collapsed in a 1942 earthquake measuring 7.9 on the Richter scale. In 1980, an earthquake measuring 6.1 on the Richter scale caused moderate damage to buildings of poor quality.

On the basis of a study called "Seismic vulnerability of important structures in the city of Guayaquil" carried out by the Institute of Research and Development of the Faculty of Engineering of the Catholic University of Guayaquil (IIFI-UC), it was decided to conduct a vulnerability assessment of the city's hospitals. Basic scientific information was relied upon, and the city was divided into microzones. The study was conducted by professionals from the IIFI-UC, with the input of hospital directors, the unconditional support of the National Civil Defense Authority, and technical contributions from PAHO.

The initial objective was the execution of preliminary vulnerability assessments for the 16 most important hospitals of the city. This number was later increased to 20, 12 of which were quantitatively evaluated and the remaining 8, qualitatively evaluated. The methodology employed included the following activities:

- *Structural assessment and census of the hospitals.* Those structural variables were investigated that had the greatest bearing on the seismic resistant performance of the hospitals, as well as structural and nonstructural damages produced by previous earthquakes. An inventory of hospital services was carried out, including the existence of emergency plans.
- *Selection of the 16 most important hospitals of Guayaquil.* By definition, these were facilities with necessary services for large-scale response to an emergency caused by a natural disaster. The final sample was selected on the basis of the recommendations of Civil Defense Authority.
- *Definition of the probable seismic demand.* This was based on the response spectra obtained from the seismic microzoning of the city.
- *Experimental assessment of the resistance of concrete from a sample of 10 hospitals.* Since 95% of the 16 hospitals have reinforced concrete structures, cores were extracted from the concrete columns of the ground floor in 10 of them and underwent simple compression assays.
- *Experimental assessment of dynamic characteristics of the 16 most important hospitals.* The objective of this phase was to evaluate the behavior of the nonstructural elements in the seismic response of the building through measurement of dynamic characteristics for environmental vibrations.
- *Quantitative mathematical analysis of the seismic-resistant performance of 12 hospitals.* This was accomplished by analyzing flow resistance ductility, failure mechanisms and deformation of floors.
- *Qualitative and quantitative diagnoses of structural and nonstructural vulnerability.*
- *Training of technical personnel in charge of emergencies in the hospitals.* Meetings were held to share information on activities and preliminary results of the project. Officials of the Ministry of Health and Civil Defense participated.
- *Categorization of the seismic resistant safety and operating level of the hospital system.* A six-level scale was introduced, with the first category corresponding to slight nonstructural damage and the sixth corresponding to the possibility of total collapse.
- *Conclusions and recommendations to reduce structural and nonstructural vulnerability.* Practical, short-term, and low-cost actions were presented.

This project succeeded in gaining public support thanks to thorough coverage by local media of the different phases of the project. Perhaps the most significant result was the communication and understanding afforded between the project team, made up primarily of engineers and health professionals.

Source: Argudo, J. and R. Yela, Vulnerabilidad estructural de hospitales de Guayaquil - Ecuador, Report prepared for PAHO and ECHO, Guayaquil, 1995.

Some of these methods constitute the first level of assessment of the qualitative or analytical methods. Examples are the Japanese method[8], the assessment designed by Iglesias[9] in the case of Mexico City, and the ATC-21 method[10]. The building receives a rating in accordance with aspects such as its condition, the irregularity of its plan and elevation, soil type, etc. Such ratings generally do not demand very sophisticated calculations. However, the first level of the Japanese method does require the computation of certain variables which are closely related to the higher levels of analysis. The annex to this book presents some of the qualitative methods most frequently used in Latin America to determine the seismic vulnerability of hospital facilities.

Quantitative methods

For the post-seismic recovery of essential buildings, the more rigorous quantitative methods are desirable. As mentioned earlier, these methods also serve to broaden the results obtained from qualitative methods, when these do not provide definitive findings about the safety of the building.

In order to perform a vulnerability assessment using quantitative methods, it is necessary to have certain basic information: characteristics of the materials utilized in the building, attributes of the soil type, and structural plans, among other information. Quantitative assessments generally are performed using mathematical models of the structure, which consider the following:

- Interaction of the structure with the nonstructural elements;
- The loads to which the structure is submitted;
- Analysis of the different types of earthquakes that can occur.

8 Hirosawa, M., "Assessment of seismic safety and guidelines on seismic retrofitting design of existing reinforced concrete buildings." Paper presented at the VI Seminar on Seismology and Earthquake Engineering for Structural Engineers, Tokyo, 1976. See also Hirosawa, M. et al., "Seismic evaluation method and restoration techniques for existing and damaged buildings developed in Japan". Paper presented at the IDNDR International Symposium on Earthquake Disaster Reduction Technology, Tsukuba, Japan, 1992.

9 Iglesias, J., Evaluación de la capacidad sísmica de edificios en la Ciudad de México, Secretaría de Obras, Mexico, 1986.

10 Applied Technology Council, Rapid visual screening of buildings for potential seismic hazards: a handbook (ATC-21 Report), Redwood City, 1988 (FEMA Report 154, July 1988).

Box 2.4. Applying scientific assessment methods in Colombia

Vulnerability assessments were performed of the Evaristo García Departmental Hospital in Cali and the University Hospital of Caldas in the city of Manizales, Colombia. Both studies were conducted by specialists from the Colombian Seismic Engineering Association (AIS) who applied several methods for the purpose of comparison. In the first instance, the ATC-22 method, the Japanese method and the Akiyama energy method were used. In the other case, a method developed by AIS in 1985 (known as AIS-150) was used. This method was later included as Chapter A.10, "Analysis of the seismic vulnerability of existing buildings," of the Colombian standards for seismic resistant design and construction.

Apart from the contribution that this project made to the application and development of technical methodologies, one of the most interesting aspects was the enthusiasm and awareness that the studies generated in hospital and health care authorities of the two cities. The local administrations later took on, with their own resources, the second phase of the studies, which was the design of seismic-resistant retrofitting and rehabilitation procedures.

In spite of the fact that rehabilitation studies of hospitals had already been conducted before in the country due to problems encountered relating to deterioration and remodeling of facilities, these two studies were the first to explicitly treat the subject of seismic vulnerability of hospitals in terms of prevention. They served as examples for the Ministry of Health and the National Agency for Disaster Prevention and Response, organizations that initiated the promotion of preventive retrofitting of hospital facilities in the areas of the country with the greatest seismic hazard.

Source: Asociación Colombiana de Ingeniería Sísmica (AIS), Análisis de vulnerabilidad sísmica del Hospital Universitario de Caldas, Comité de Vulnerabilidad y Riesgo Sísmico AIS-400, Manizales 1992. See also AIS, Análisis de vulnerabilidad sísmica del Hospital Departamental Evaristo García, Comité de Vulnerabilidad y Riesgo Sísmico AIS-400, Cali, 1992.

Measures to reduce structural vulnerability

Many existing hospital buildings do not comply with the necessary technical requirements to ensure continued functioning after natural disasters. Their vulnerability to certain natural hazards can greatly exceed currently accepted levels. Experience shows, however, that the safety of existing structures can be improved with the application of relatively inexpensive measures. Mitigation measures considering the occupation characteristics of the facility and in accordance with the current engineering requirements of each country should be carried out to reduce risk and guarantee adequate performance.

Retrofitting

Assessing the condition of an existing building may raise serious doubts about its ability to withstand seismic events[11], which can lead to the need for retrofitting or rehabilitating the building totally or partially, in order to reduce its vulnerability before an event occurs. This is mandatory for essential buildings that respond to the emergencies derived from earthquakes.

11 Asociación Colombiana de Ingeniería Sísmica (AIS), *Adición, modificación y remodelación del sistema estructural de edificaciones existentes antes de la vigencia del Decreto 1400/84,* Norma AIS-150-86, Bogotá, 1986.

The execution of a retrofitting project should follow a detailed work plan that guarantees the least impact on the normal functioning of the hospital in each stage of the process. This requires the hospital administration to closely coordinate the work of medical treatment and hospital maintenance departments during the process. This coordination has proved to be very important in completing the project in a given timeframe and without interfering with ongoing provision of health services.

Retrofitting design

The analysis, design and construction of any necessary retrofitting must be carried out bearing in mind the following aspects:

1. *Physical and functional aspects*. The retrofitting should not affect the hospital's day-to-day operations.
2. *Aspects of structural safety*. It is essential to reduce vulnerability to acceptable levels, so that the hospital can continue to function after an earthquake
3. *Construction techniques*. Retrofitting should be carried out using construction techniques that have the least impact on normal functions of the hospital, since it would be difficult to shut it down for repairs.
4. *Cost of the intervention*. The cost of retrofitting cannot be ascertained unless a detailed design of the structural solution and of its implications for the nonstructural elements is carried out. Retrofitting costs are usually relatively high, especially when done in a short period of time. However, if the work is done in stages, resources can be used within the range of expenditures for hospital maintenance.

In accordance with the above, the intervention of the structure should seek to reduce the existing vulnerability by responding to existing performance problems. The structural retrofitting should:

- Increase resistance;
- Increase stiffness and therefore decrease deformation;
- Increase ductility;
- Attain an adequate distribution of the stresses between the different resistant elements, as much in the ground plan as in the vertical configuration.

The usual systems of structural reinforcement tend to incorporate the following additional elements (see figure 2.11):[12]

Exterior structural walls

This solution is generally employed when space limitations and continuity of building use make work on the periphery preferable (see figure 2.12). To ensure the transmission of stresses through the diaphragm to the walls, collector beams are used on the edges of the slab. This is not recommended for very long buildings.