

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.

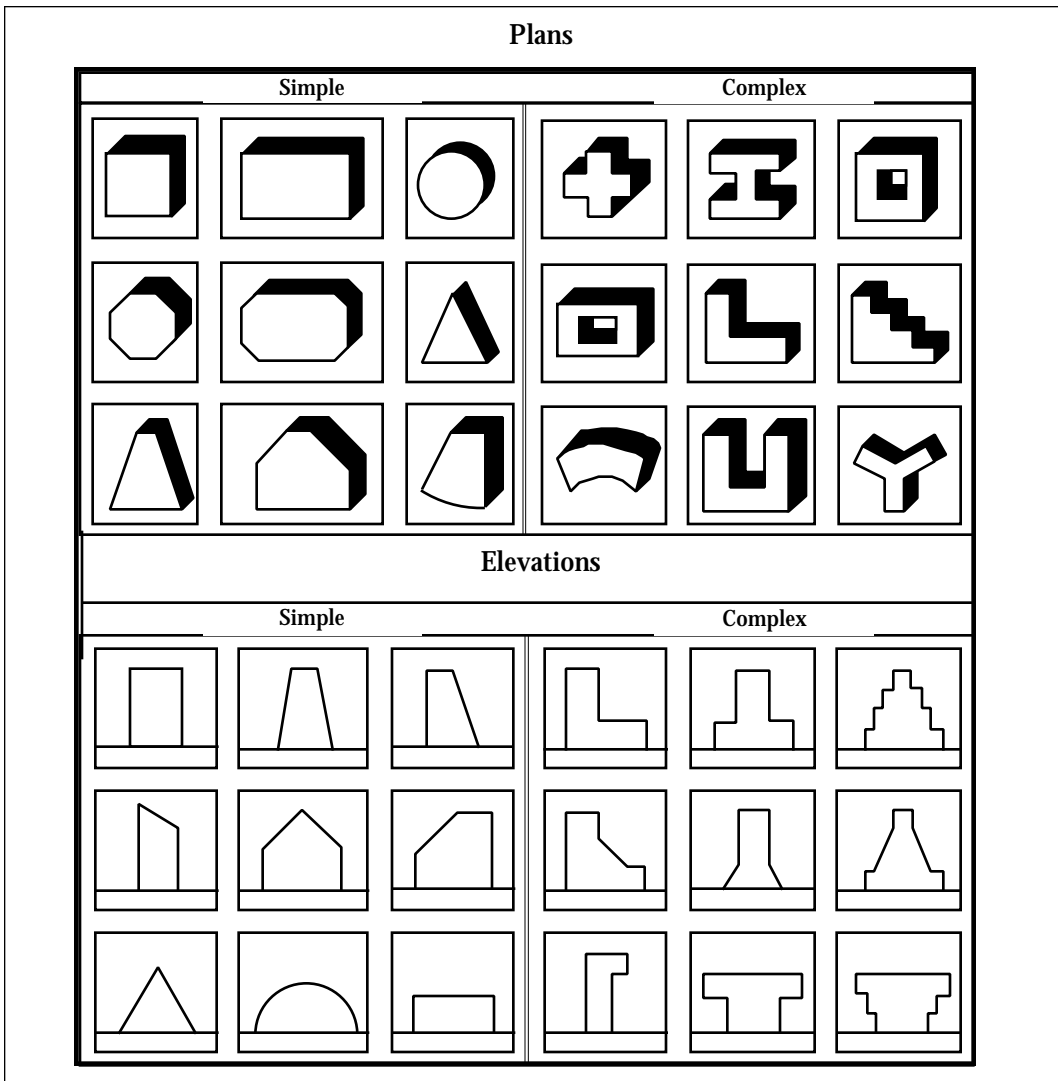
Source: Cardona, O.D. *Las edificaciones hospitalarias en la nueva legislación sísmica colombiana*. Paper presented at the International Conference on Disaster Mitigation in Health Facilities, Mexico, 1996.

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 config-

urations. 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 Ingeniería 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.

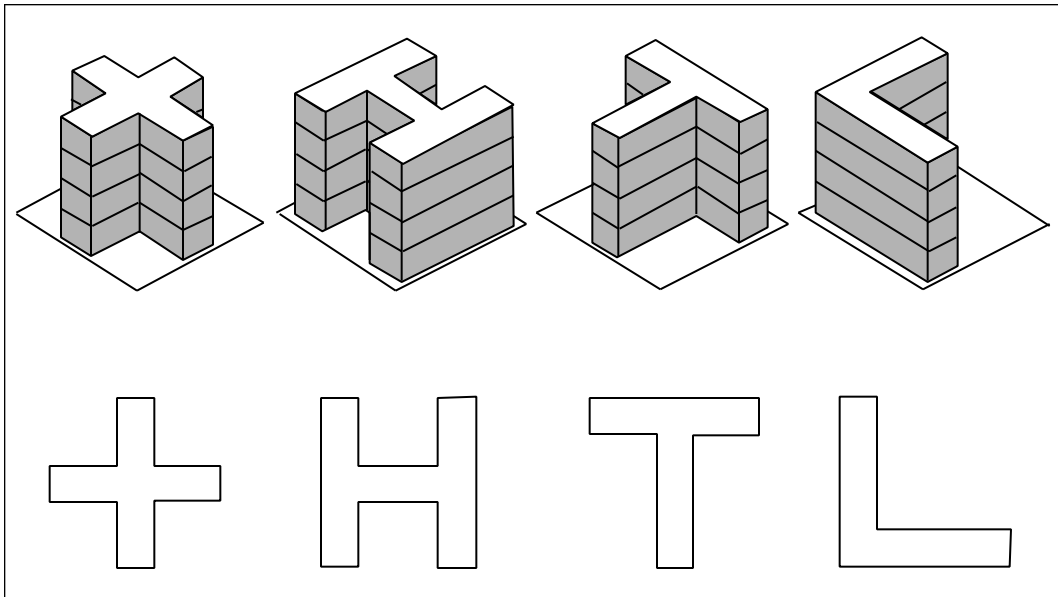
Concentration of stress arises in buildings with complex floor plans, and is very common in hospital buildings. A complex plan is defined as that in which the line joining any two sufficiently distant points lies largely outside of the plan. This occurs when wings of significant size are oriented in 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.E.; 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



Photograph 7. Caldas Hospital in Colombia

O.D. Cardona

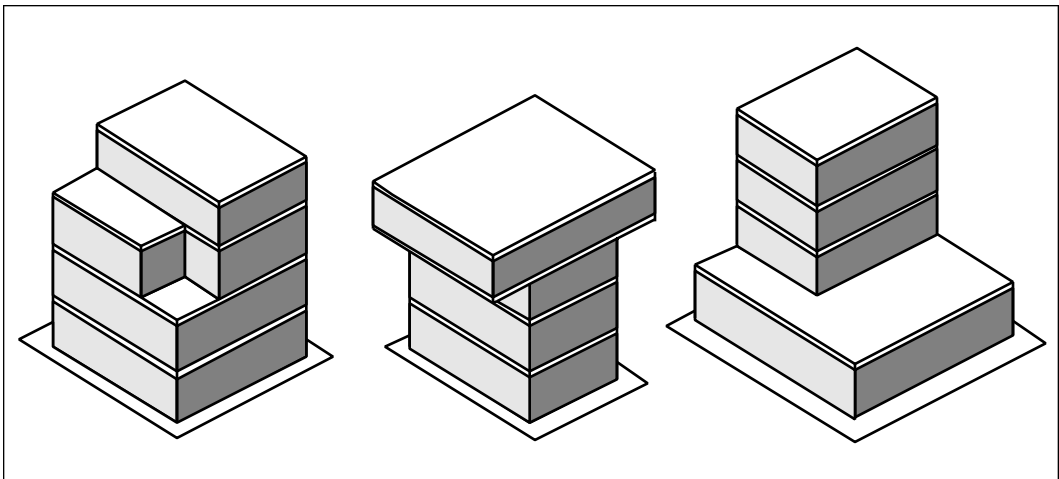
In such a case, the solution currently used is to introduce seismic expansion joints like those mentioned in the case of long buildings. These joints allow each block to move without being tied to the rest of the building, which interrupts the cantilever effect of each wing. The joints, obviously, must 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

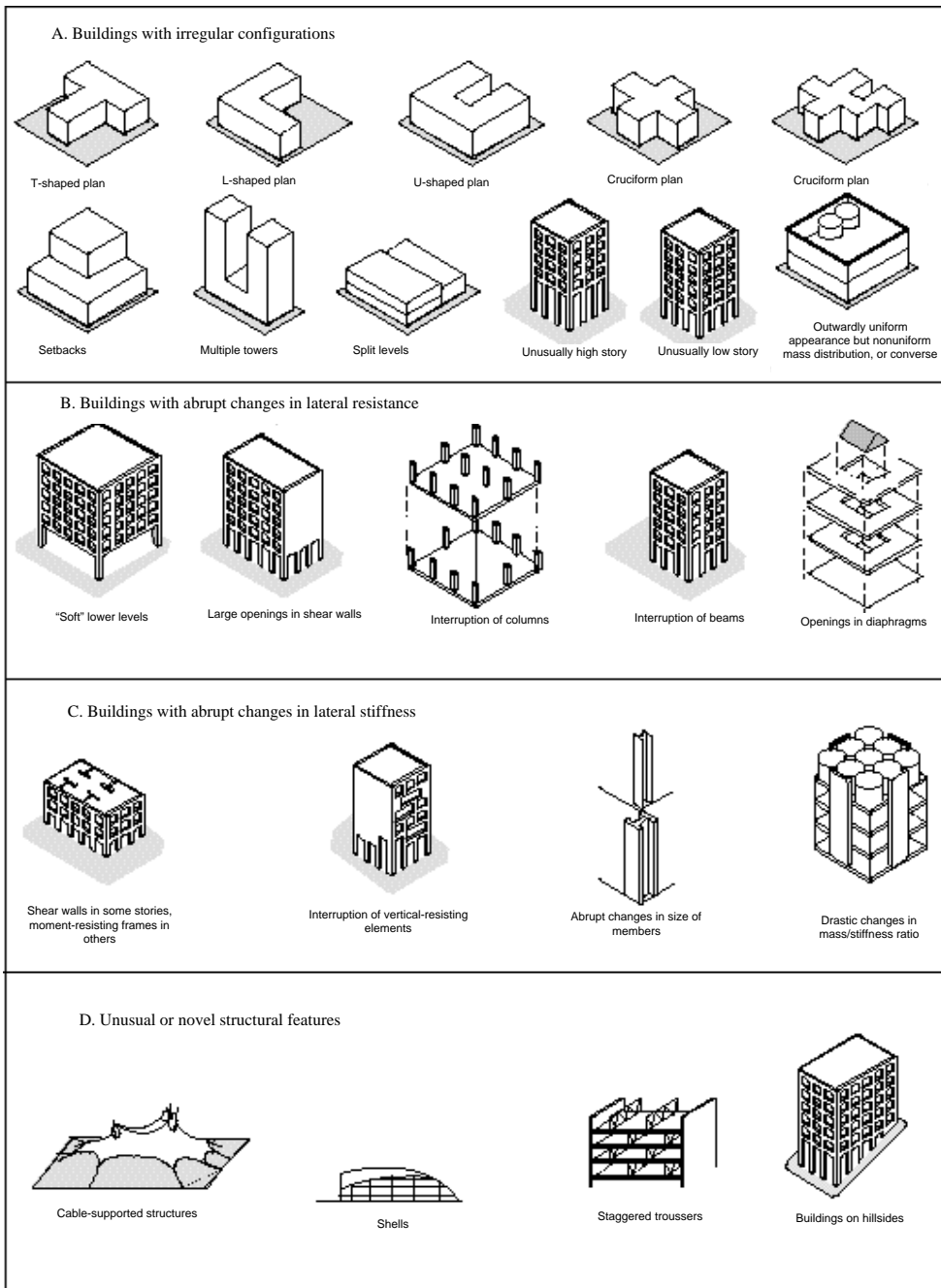


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Figure 2.4 shows some characteristics of building configuration that should be avoided in health facilities, due to their inadequate performance in earthquakes.

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:

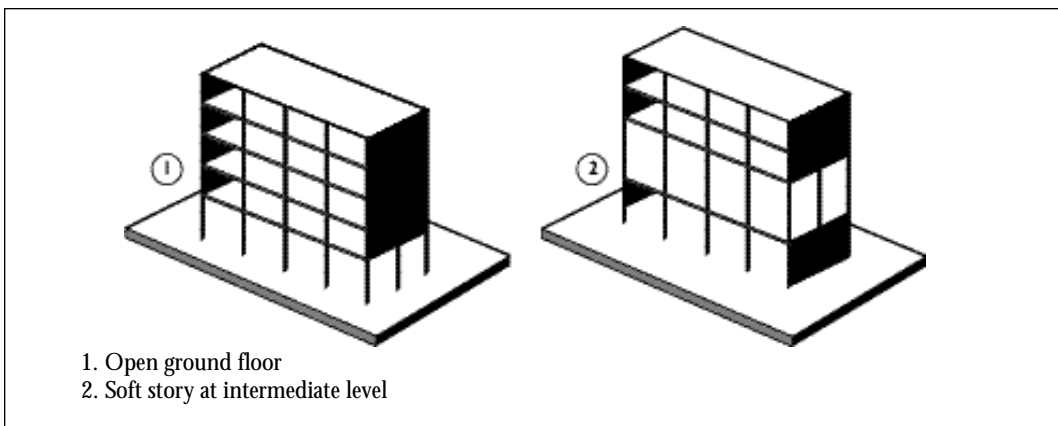
- Partial lateral confinement of the column by dividing walls, facade walls, retaining walls, etc.;
- Placement of floor slabs at intermediate levels;
- Location of the building on a slope.

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



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

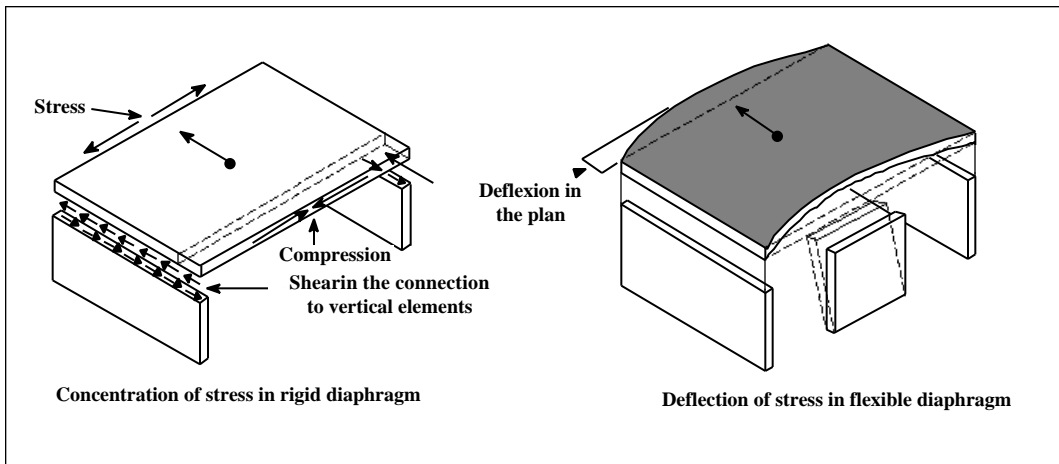
Excessive flexibility of the building to seismic loads can be defined as the susceptibility to large lateral distortions between different stories, or "drift". The main causes of this problem reside in excessive distance between the support elements (clear spaces or clearances), their vertical clearance,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

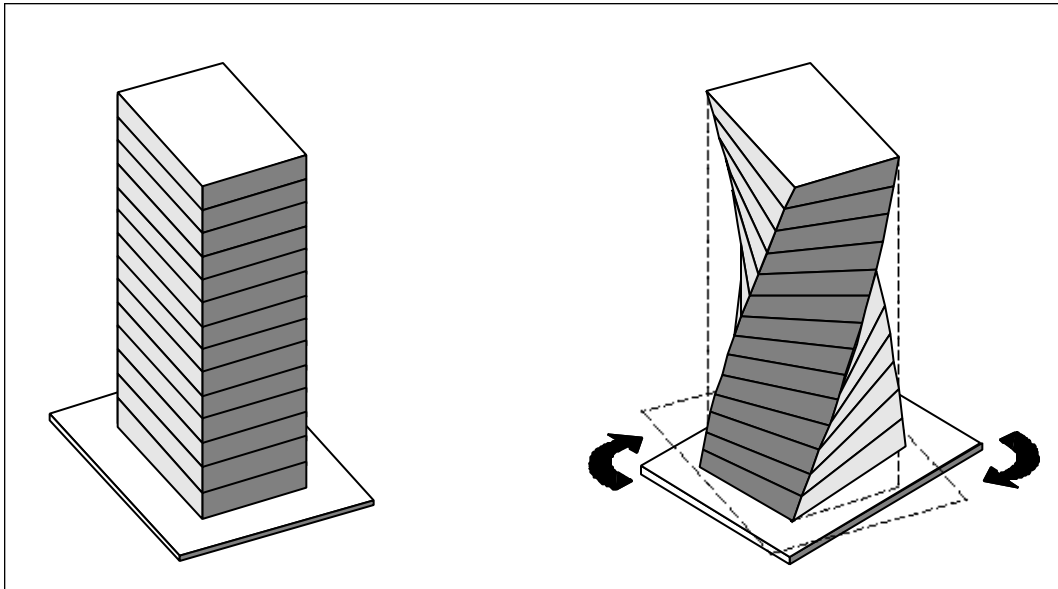
Torsion

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



T. Guevara

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.

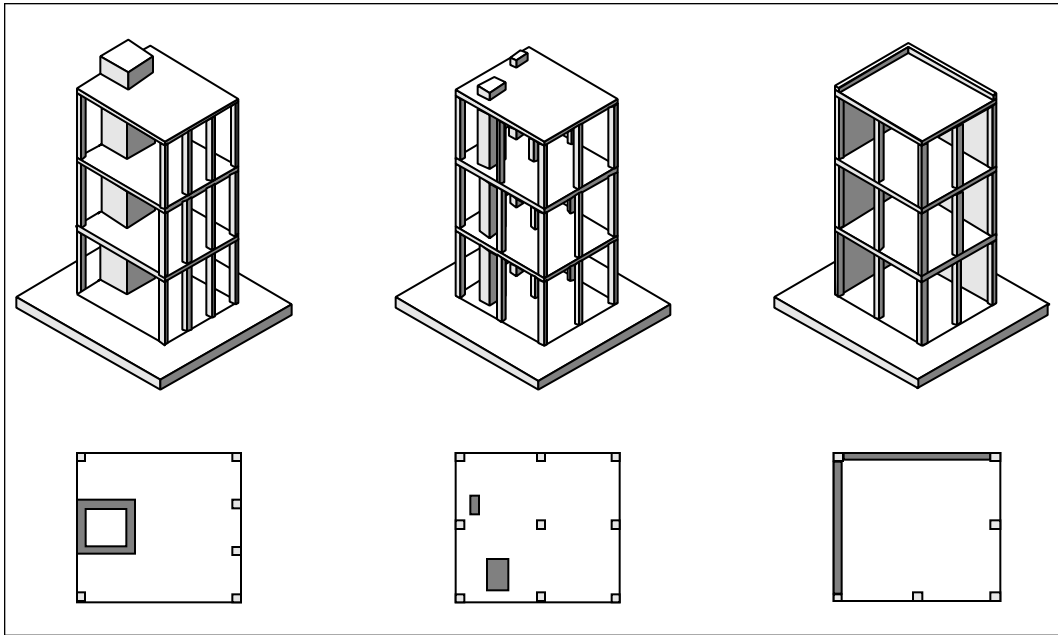
Quantitatively, an eccentricity between the centers of mass and stiffness is considered significant when it exceeds 10% of the horizontal plane dimensions under study. In such cases, corrective measures should be taken in the structural design of the building (see figure 2.8).

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.



T. Guevara

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 sísmo resistente NSR-98* (Law 400 of 1997, Decree Law 33 of 1998), Bogotá, 1998.

Design spectra

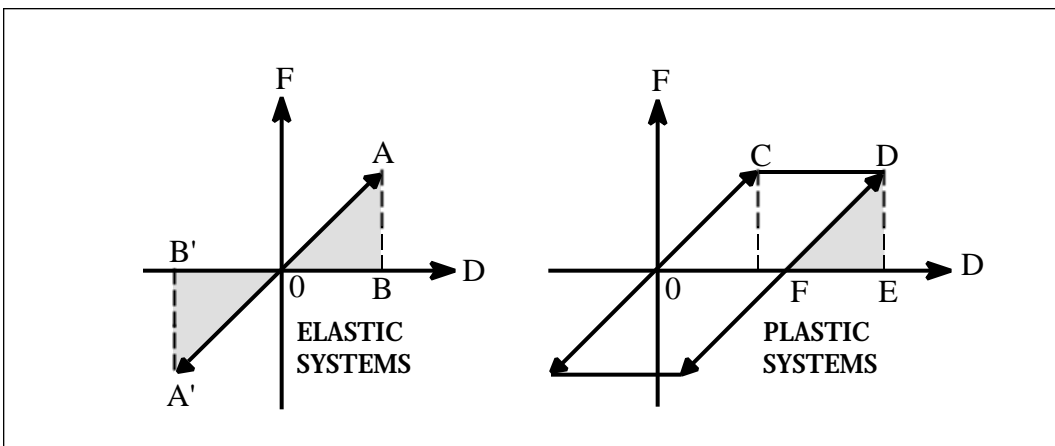
In the design spectra recommended by seismic resistance codes, decisions must be made about:

- 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).

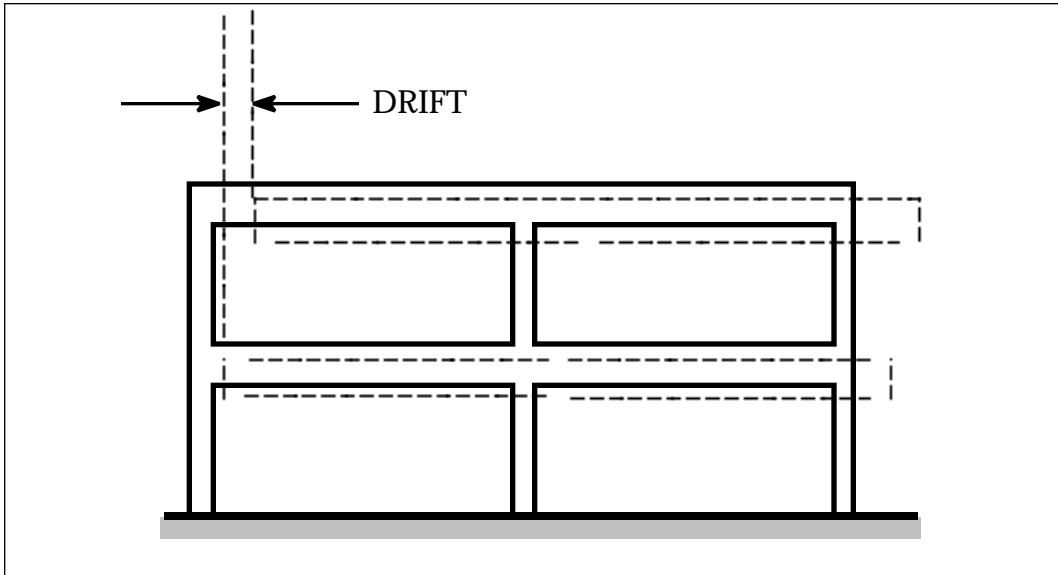
In the design of reinforced concrete structures, the following basic criteria must be taken into account in order to obtain the required ductility:

- *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 case⁷, 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 in 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, non-structural, 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, C. 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 method⁸, the assessment designed by Iglesias⁹ in the case of Mexico City, and the ATC-21 method¹⁰. 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 events¹¹, 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.

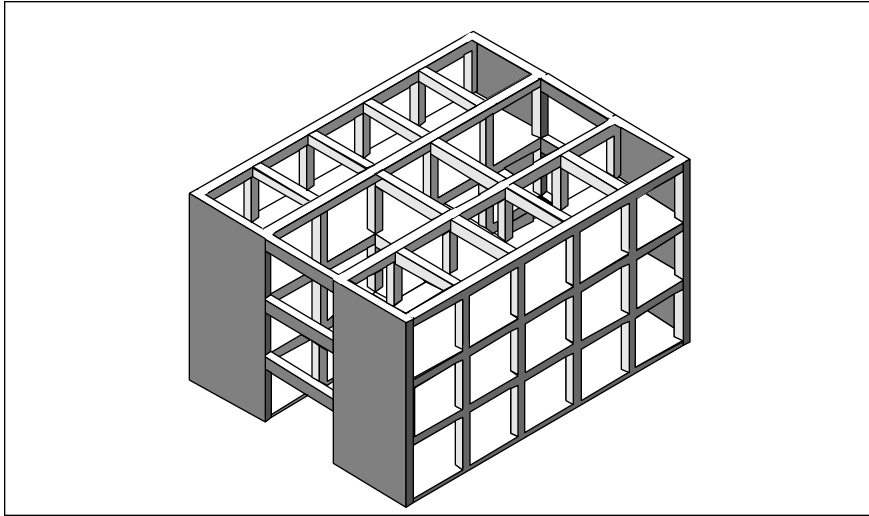
Figure 2.11.
Conceptual solutions for structural reinforcement

Reinforcement measure		Benefits
Interior walls		Increased resistance and reduced drift
Addition of diagonal bracing		Increased resistance and reduced drift
Addition of buttresses		Confinement and reduced drift
Addition of interior or exterior moment-resisting frame		Confinement and reduced drift
Complete rebuilding		High seismic-resistant capacity and control of typical types of damage
Isolation at the base of the building		Protection of the building through control of shaking

AI/A/ACSA

¹² Iglesias, J., *Evaluación de la capacidad sísmica de edificios en la Ciudad de México*, Secretaría de Obras, Mexico, 1986.

Figure 2.12.
Structural walls in the periphery

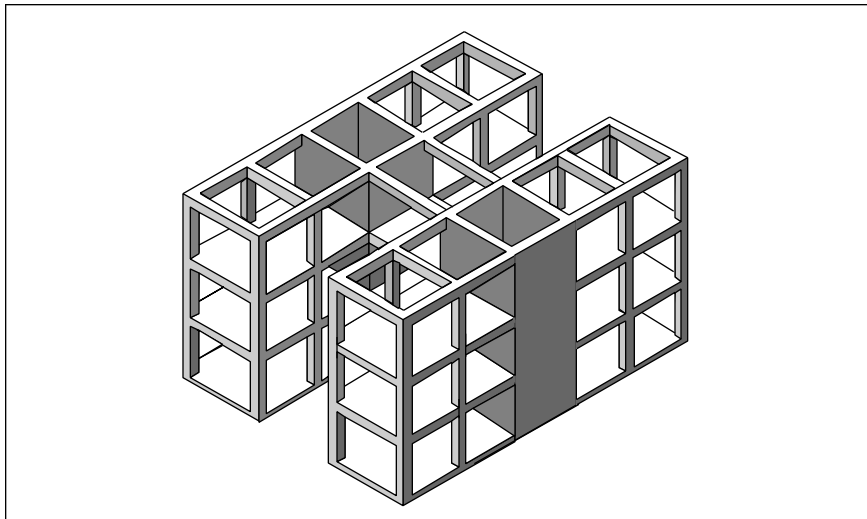


T. Guevara

Interior structural walls

When it is possible to work inside a building, these walls are an alternative that should be considered, particularly in long buildings where the flexibility of the diaphragm must be reduced (see figure 2.13). They are generally inserted through perforations in the diaphragm, through which the reinforcement bars pass. This method of retrofitting was used in the National Children’s Hospital of Costa Rica.

Figure 2.13.
Interior structural walls



T. Guevara

Frame walls

Both inside and outside buildings, a practical solution to the problem of stiffness and resistance is to fill frame openings with concrete or reinforced masonry walls. Due to the connection with the column, the stresses on them will change substantially. If the reinforcement of the column is sufficient for the new situation, the connection with the wall can be done solely with soldered bolts. Otherwise, a sheathing of the column, monolithic with the wall, should be constructed.

Buttresses

Unlike exterior building walls, buttresses are placed perpendicular to the face of the building. Aside from providing rigidity, they are useful in preventing tall, narrow buildings from overturning. The Cardiology Hospital of the Mexican Social Security Institute (IMMS) uses this type of reinforcement (see pho-



Photograph 12. The Cardiology Hospital of the Mexican Social Security Institute was retrofitted using buttresses following the 1985 Mexico City earthquake.

tograph 12). Due to space limitations, however, these are not always feasible.

Braced frames

Another frequent solution consists of including several steel frames with diagonals firmly anchored to the diaphragms, as a substitute for stiff walls (see photograph 13).

Sheathing of columns and beams.

Used for frame systems, this is generally applied on most of the columns and beams in a building in order to increase their stiffness, resistance and ductility alike.

Construction of a new framed system.

On occasion it is possible to carry out a total restructuring by attaching new external perimetric frames to the old structure, like those used in the reinforcement of the Hospital Mexico in San José, Costa Rica (see photograph 14). Usually this is combined with the incorporation of internal structural walls perpendicular to the longitudinal direction of the frames.

Isolation and control of vibrations.

There has been a marked increase in the use of techniques to isolate the foundation and control vibration in structures located in seismic-prone areas. This is an alternative to methods that aim to dissipate energy by tolerance of damage by structural elements entering into the nonlinear range. These systems will undoubtedly be very important in the construction of buildings in general, due to the growing demand for structural and nonstructural safety in the face of strong earthquakes and for comfort amidst environmental vibrations.



O.D.Cardona

Photograph 13. Reinforcement with diagonals.



M. Cruz

Photograph 14. Use of external perimetric frames for reinforcement of the Hospital Mexico in a project carried out by the Costa Rican Social Security Fund (CCSS).

Box 2.5. A demonstration of political will in Costa Rica

Vulnerability assessments of the hospitals in Costa Rica were begun in 1984 as part of a research project at the University of Costa Rica and in response to growing public concern about the recurrence of the disaster experienced in 1983 in San Isidro de Pérez Zeledón. The School of Civil Engineering initiated this work thanks to incentives provided by the National Emergency Fund and to the interest shown by officials of the Costa Rican Social Security Fund (CCSS). PAHO/WHO was another driving force of this initiative, since it represented a new field of research in Latin America.

After the study of the Calderón Guardia Hospital in 1984, the University requested financing from the National Council of Scientific and Technical Research (CONICIT) to study the vulnerability of all the hospitals in the country. CONICIT partially approved the financing requested so the University began the project by studying Hospital Mexico in 1986. This funding was attained in part due to the support given the initiative by physicians of the CCSS. The Hospital Mexico study was the first on integral seismic vulnerability in the country, addressing different levels of risk for structural, nonstructural, administrative and functional aspects of the hospital.

The restructuring of the three buildings that constitute the hospital complex consisted basically of positioning additional columns and beams on the exterior concrete frames and isolating all of the structural walls. In addition, the walls of the emergency stairs were connected to the main structure to decrease the possibility that they would collapse. With this alternative, the stiffness of the buildings was increased which would decrease lateral deformation due to earthquakes; this in turn meant reduced risk of nonstructural and structural damage (see figure 2.14).

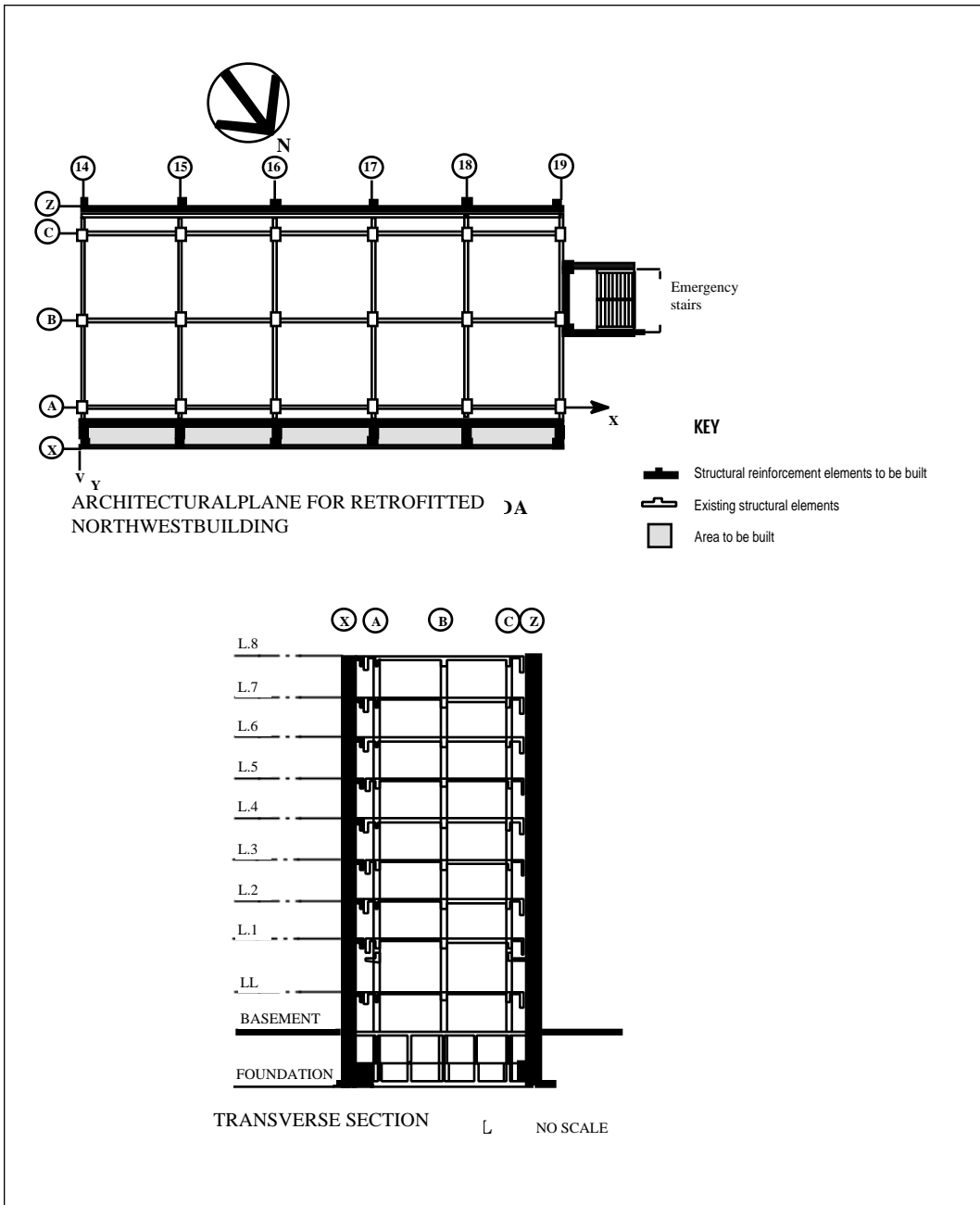
The reinforcement work began in May 1989 and the process required 31 months to complete. The cost of the work was US\$ 2,350,000 dollars, which represented 7.8% of the value of the hospital. The hospital had to reduce its number of beds from 600 to 400 during the process, with a consequent increase in the number of patients waiting for medical attention.

Apart from the Hospital Mexico, the CCSS also conducted vulnerability assessments, retrofitting design and rehabilitation of the Hospital de Niños (Children's Hospital) and the Hospital Monseñor Sanabria. Difficulties in the construction process arose in these two cases due to inadequate coordination with hospital administration. However, these experiences permitted the identification of the aspects of coordination and multidisciplinary work that must be taken into account in order to avoid overspending and problems related to the ongoing performance of the facilities.

Several earthquakes have occurred since 1990 that have demonstrated the good fortune of having reinforced these facilities. Particularly, it is believed that the Hospital Monseñor Sanabria would not have survived the earthquake of 25 March 1990. On the other hand, the damages sustained by the Hospital Tony Facio, which had not been reinforced when the earthquake of 22 April 1991 occurred, confirmed the importance of continuing the assessment and retrofitting process. In fact, the CCSS formally incorporated seismic-resistant design and vulnerability assessments into the formulation phase of new projects. In the design of the new Hospital San Rafael de Alajuela, for example, state-of-the-art techniques were used. The design of this hospital is an example of multidisciplinary work in which seismology experts, scientists, engineers, architects, and public health personnel all participated.

Sources: Cruz, M. F., "Comportamiento de hospitales en Costa Rica durante los sismos de 1990", Taller Regional de Capacitación para la Administración de Desastres, Bogotá, 1991. Cruz, M.F. and R. Acuña, *Diseño sísmo-resistente del Hospital de Alajuela: un enfoque integrador*, International Conference on Disaster Mitigation in Health Facilities, Mexico 1996.

Figure 2.14.
Reinforcement of the northwest building of the Hospital Mexico, Costa Rica



Coordinating the retrofitting process

The retrofitting or reinforcing work requires close coordination between hospital personnel and those responsible for design and construction. The director of the hospital, the administrator, those in charge of affected clinical and support services, the chiefs of maintenance and general services, as well as all of the professionals involved in the design and execution of the reinforcement work, must take part in the process. There must be active involvement at all stages of the project, that is during the design, planning and execution of the measures. It should be kept in mind that the same persons may be participating at different times in the coordination efforts.

Lessening the seismic vulnerability of a hospital building is usually more complex than on other types of buildings. Following are some of the aspects that make this type of work different in health installations:

- Normally, the building cannot be vacated in order to carry out the retrofitting;
- The scheduling of the work must take into account the operation of the different health services so as not to cause serious disruptions;
- A wide number of unforeseen tasks can be expected due to the difficulty of precisely identifying details of the construction process before the work begins;
- The effects of structural modifications on nonstructural elements and on architectural finishes should be identified before beginning the process.

In accordance with the above, the development of a retrofitting project should follow a very detailed work plan that addresses the function of the health services at each step of the process. In the same way, the plan should establish proper coordination with administrative personnel, medical services, and hospital maintenance.

Costs of retrofitting

As mentioned earlier, the cost of modifications can only be calculated on the basis of a detailed design of the structural solution and its implications for nonstructural elements. However, it is possible to formulate an advance budget with some degree of precision and that should be adjusted as little as possible during the process.

The additional costs to make a building resistant to hurricanes, earthquakes, or floods can be considered a form of insurance. Studies have shown that the costs of a building designed and built to withstand hazards like earthquakes may increase the total cost of the building by 1% to 4%.

When the costs of preventing damage to specific items is analyzed, the results are dramatic. For example, an electric generator that is severely damaged could result in the loss of power to the hospital and could cost as much as US\$50,000 to replace. This situation could be avoided by the installation of seismic isolators and braces to prevent the generator from moving for costs as low as US\$250.

In all cases, the high economic and social value of improving the structural performance of vulnerable hospital facilities has been demonstrated. The cost of retrofitting, although it could be considered high in certain instances, will always be insignificant in relation to the provision of health service or in relation to the cost of repair or replacement. One could ask questions such as: The cost of retrofitting would be equivalent to the cost of how many CT scanners? And, how many scanners does the hospital have? The answers could give surprising results, without taking into account the value of all of the other equipment and supplies that are generally in the building, and, of course, the human lives directly or indirectly affected, and the social cost that the loss of health services signifies.

Experience in this area shows that the cost of performing structural seismic vulnerability assessments and designing the required retrofitting may reach between 0.3% and 0.5% of the total value of the hospital. The cost of rehabilitation or retrofitting could range between 4% and 8% of the hospital value (see the example in table 2.2). To illustrate the potential benefit, assume that in a severe earthquake the use of 20% of the existing beds in a hospital would be lost. With an investment in retrofitting of less than 10% of the cost per bed, this loss could be avoided.¹³ These figures, while not precise economic assessments, do attest to the cost/benefit ratio achieved when mitigation measures are applied.

Table 2.2.
Cost of retrofitting hospitals in Costa Rica

Hospital	No. of beds	Duration project (months)	Retrofitting cost (US\$)	Percentage of of total cost of hospital
Hospital Mexico	600	31	2,350,000	7.8
National Children's Hospital	375	25	1,100,000	4.2
Monseñor Sanabria Hospital	289	34	1,270,000	7.5

¹³ PAHO, *Lecciones aprendidas en américa latina de mitigación de desastres en instalaciones de salud, aspectos de costo-efectividad*, DHA, IDNDR Secretariat, PAHO, Washington, D.C., 1997.

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