Structural and Functional Vulnerability of Hospitals

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Abstract

The importance of hospitals as essential facilities that are required to function during and immediately after an earthquake is presented with a description of some of the methodologies that may be used for structural and functional vulnerability assessment, including a short reference on the energy method. General recommendations that must be kept in consideration for the design of this type of buildings are proposed.

Effects of Earthquakes on Hospital Buildings

During and immediately after an earthquake, the first priority is always to save lives and to assist the injured. Hospitals play a key role among emergency medical services that are mobilized. Nevertheless, from a structural point of view, many hospitals in America are old, or have been modified due to the growing demand for their services; others are new, equipped with modern and expensive technology, with attractive architectural designs, but their structural design do not include provisions for resisting earthquakes in an acceptable way.

A hospital represents a high investment for a country, from a social and an economic perspective. The cost of medical equipment may be higher than the cost of the structure itself. Also, due to its occupation characteristics and because it must keep operating after a major earthquake, special considerations must be kept in mind for the design of a hospital or for a vulnerability reduction project.

In the last decade, earthquakes in Colombia (1983), Mexico (1985), Chile (1985), El Salvador (1986) and Costa Rica (1990 and 1991), caused catastrophic damage to hospital buildings. The recovery of these facilities represented, for the governments of those countries, either a greater external indebtedness, or the delay in normal developing projects because of the necessity of funds for reconstruction. For this reason, actions towards vulnerability reduction in health facilities should occupy an important place in development planning, to guarantee that the high investment they imply is safe (PAHO, 1990).

Code Fundamentals

In the majority of seismic codes, there is an implicit or explicit design philosophy based on the expected behaviour of a structure in case of an earthquake, related to the seismic response at the site of the building. Codes establish that buildings should only suffer minor damage with low to moderate events, repairable damage with moderate to strong events, and that they should not collapse with major events. However, there are significant discrepancies in respect of frequency and categorization of events, as well as in the amount and type of damage that may be repaired. The SEAOC code, for example, permits inelastic behaviour of the structure during a major earthquake, without collapse. Some codes, as the UBC (Building Seismic Safety Council, 1991), define essential structures as those necessary for emergency operations due to natural disasters and, in this case, require greater lateral forces for design.

Generally speaking, all codes try to preserve life, but it is understood that it is not economic designing structures that remain in the elastic range during the earthquake (Committee on Mitigation of Damage to the Built Environment, 1993). In this way, design forces are reduced to obtain advantage of the inelastic deformation or of the absorption of energy and, if the design earthquake occurs, damage should be controlled and neither the structure nor its elements collapse or threaten the safety of its occupants.

Vulnerability, understood as the degree of loss of an element or group of elements at risk as a result of the probable occurrence of a disastrous event (PAHO, 1993), is a concept that depends on the code used and so it is a relative parameter. In the case of a hospital, with the considerations made upon its importance, the level of acceptable damage should be minimal even with a major event, because non-structural damage, though repairable, probably would imply interruption of the service required during the emergency.

Up to date, there is no specific code for rehabilitation of structures in seismic areas, though the Federal Emergency Management Agency (FEMA) of the United States is supporting the National Earthquake Hazard Reduction Program (NEHRP) in the promotion of guidelines for existing buildings. In Japan and other countries, like Mexico, some works have been done in the development of methodologies for evaluation and rehabilitation of existing or damaged buildings. These methods are valid for almost every type of structure, but a hospital should be studied more carefully, especially concerning its resistance capacity and ductility under earthquakes, as well as functional, administrative and organizational vulnerability, before performing a retrofitting project.

Structural Vulnerability Analysis

Vulnerability assessment does not imply only determination of geometric characteristics of a building, but it should also include study of the resistance and integrity of materials, changes in the construction from the original design, details of non-structural elements that may modify the expected seismic behaviour and damages that occurred in the past, in order to have a more precise idea of possible structural model deficiencies (Fernández and Santana, 1990).

Sometimes, and this is particularly true in the case of hospitals, the original drawings and calculations are not available. Additionally, the deterioration of the materials with time may be difficult to determine, even though non-destructive testing may be used. It is mandatory to know the seismic antecedents of the area, in terms of ground characteristics and accelerations, with the purpose of analyzing deficiencies and damages. Usually a structure behaves inadequately because it was designed without a code, or because it required parameters for smaller events.

The methods for vulnerability analysis of an existing structure may be grouped in three general categories (Fernández and Santana, 1990):

a. Qualitative
b. Experimental
c. Analytical

The qualitative methods are used mainly for rapid evaluations, similar to those established for the post-earthquake evaluation, as defined in ATC-20 (Applied Technology Council, 1988), and only lead to preliminary categorization of the structures, in order to decide which ones require more detailed studies. Included in this group are ATC-21 (Applied Technoloy Council, 1989a), the first level of the Japanese method and the Iglesias method for Mexico City, as well as others developed in some countries as adaptations of the post-earthquake evaluation methodology proposed by EERI (Earthquake Engineering Research Institute, 1991; Comisión Nacional de Emergencia de Costa Rica, 1991). In general, these methods only describe the structure in terms of its use, year of construction, gross area, main structural system, materials, architectural characteristics, modification, visible attributes of non-structural elements, geometric irregularities, etc., that do not require complex office calculations.

The experimental methods determine the behaviour of the structure by directly measuring environmental vibrations (PAHO, 1993), and so they only provide information about dynamic response under low amplitude vibrations. For this reason, they may also be used as a preliminary step to establish if more detailed studies are required, and they must be completed with resistance analysis of materials, energy dissipation, analysis of the structural system and geometry, etc.

The analytical methods provide a more detailed evaluation of the vulnerability of an existing structure. Some computer programs such as DRAIN or IDARC may also be considered vulnerability analysis tools (Cardona and Hurtado, 1993); however, for their application they require the use of several earthquake records and special non-complex cases, conditions that make the use of the models complicated.

Among the analytical methods similar to design practices are the following:

The Japanese Method

Also known as "Guidelines for the evaluation of capacity of existing reinforced concrete structures", is issued officially by the Ministry of Construction of Japan. This method establishes three levels of evaluation, from simple to detailed, and grades each floor of a building by an index, using the equivalent static process, and so it may be used only for buildings not higher than seven floors.

In determining the index the following aspects are considered:

a) Resistance of the vertical elements, C.
b) Their ductility capacity, D.
c) Condition of the building and performance in previous earthquakes,time index, T.
d) Influence of form, plane asymmetry, mass and rigidity concentration, etc., varying from 0.4 to 1.2, S_d.
e) Topographical and geotechnical conditions, G.

The seismic index is then determined as:

$$I_s = E_O * G * S_d * T$$

with

$$E_O = \Phi * C * F$$

where Φ is the index of the floor being studied.

This is the first level of the method and is based mainly on averages of resistance of columns and walls. This estimation is conservative for buildings with a main structural system consisting of ductile frames; however, it has proved adequate for structures with predominance of walls. For the second level, it is necessary to know the characteristics of vertical elements, and the third level analyzes the contribution of horizontal elements in energy dissipation or storage in vertical elements.

ATC-14 and ATC-22 (Applied Technology Council, 1987, 1989b):

Both are approved by FEMA, and are based on approximate equations for the estimation of stresses and deformations. The ATC-14 is based on SEAOC design concept of working stress, and ATC-22, on limit design of ATC-3.

Capacity spectrum (Fernandez and Santana, 1990):

This method is based on the "Seismic Design for Buildings 1982", by Freeman. It studies the structural response of a system under a moderate intensity earthquake, and compares it with the behaviour under a major event, developing a curve of elastic and inelastic capacity from the history of yieldings, and finally obtaining a curve that relates shear in the plane with displacements of the superior level, transforming it into a curve of spectral capacity.

Energy method (Cardona and Hurtado , 1993):
This method clearly establishes the weak stories of a building, the elements that tend to fail first, the ductility demands associated to energy absorption of each floor, and so describes the probable response of a structure under a strong earthquake. Instead of conventional spectra, this method uses the spectrum of energy supplied by the earthquake to the building.

It is desirable that energy may be absorbed by means of inelastic deformations, proportionally and by all floors of the structure, leading to a similar ductility factor in all floors. However, in reality, factors such as an irregular distribution of mass or rigidity alter this uniformity, and cause energy to concentrate in some floors, which consequently reach higher ductility factors than those expected.

More details on this method may be found in Aoyama (1981) and Cardona and Hurtado (1993).

Non-structural Vulnerability

The non-structural elements and their supports and anchorages to the main structural system must be evaluated in order to provide a higher level of security, avoiding local damage or collapse during an earthquake, and they should not interfere with the seismic-resistant behaviour of the building nor create hazards for its occupants (International Association for Earthquake Engineering, 1982). In order to obtain this condition, supports and anchorages must be consistent with the level of protection estimated in the design. If a low probability of damage is required, the non-structural component must join the main structure in such a way that it does not follow its deformations during a severe earthquake, unless it is guaranteed that it is rigid enough to avoid deformations greater than those permitted.

These considerations are imperative in the case of a hospital, because it requires that all electrical and mechanical systems remain operational after an earthquake, and that the non-structural elements do not collapse and leave the facility unusable, as happened in Hospital Tony Facio during the Limon earthquake, Costa Rica, in 1991.

For the study of non-structural vulnerability there are few guidelines provided by codes, and the majority of them are design parameters. The quantification of this item is based mainly on visual screening following methods such as those proposed by Grases (1993), Torres and Villalobos (1992), referred to the Uniform Building Code (Uniform Building Code and International Association of Plumbing and Mechanical officials, 1988) or to the ATC-3 (Applied Technology Council, 1984). The latter establish equivalent static methods for the estimation of the seismic loads or for a reduction of such by using dynamic analysis.

In general, the behaviour of non-structural elements under seismic events may be analyzed by one of the following procedures (PAHO, 1990):

a. Dynamic analysis of the structure-component combination.

b. Analysis of the response of the component based on a dynamic analysis of the response in time of the level on which it is located.

c. Analysis of the response of the component based on a dynamic analysis of the maximum (spectral) response of the level on which it is located.

The most important issue in reduction of non-structural vulnerability is that of maintenance. There are different levels of maintenance programmes, which should be considered as an effective mitigation activity in the particular case of hospital facilities:

Emergency maintenance
These are the works that should be performed immediately after a problem is detected. Obviously, it is the least desirable, because the failures are almost always serious, as in the case of damages after an earthquake.

Normal maintenance
These are jobs that do not require the paralyzation of the equipment, and that may be programmed for a convenient time.

Preventive maintenance
This programme requires periodic inspection and cyclic maintenance works, and may be defined as an "Inspection-Detection-Action", before the problem starts. This is the most effective tool for mitigation of damage to non-structural elements.

Finally, for a functional vulnerability assessment, there are some documents that may be used as reference (Office of Construction, Veterans Administration, 1991; Pomonis et al., 1991), that include design and practice of Hospital Emergency Plans, educational and staff training programmes, etc.; studies that do not concern only the structural engineer, but form a multidisciplinary study.

Conclusions

1. The vulnerability assessment of hospital facilities, and its reduction, is not rentable in the short term, but may reduce significantly economic and social losses due to earthquakes.

2. The Japanese and the energy methods for vulnerability analysis lead to a serious questioning of the traditional use of a single ductility factor for a whole structure.

3. It is necessary to estimate and reduce the vulnerability of non-structural components of a hospital, because they represent a high investment and because it should remain operational after an earthquake.

4. Electrical and mechanical engineers, as well as design architects, should be familiar with the concepts of vulnerability and mitigation.

5. Preventative maintenance programmes are the most effective tool for non-structural vulnerability reduction.

6. Level of acceptable damage, as established in most building codes, should be lowered to a minimum for hospital facilities.

7. The structural engineer should participate in the development of Hospital Emergency Plans, and the first step in such a plan should be a diagnosis of structural vulnerability.
8. Vulnerability assessment of hospital facilities should include lifelines to guarantee continuous operation under critical conditions (Zeballos, 1993). Redundant systems may be required.

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