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THE RESPONSE CAPABILITY OF HOSPITALS IN SEISMIC DISASTERS: NONSTRUCTURAL ASPECTS

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Background

In recent decades, it has become abundantly clear that hospitals are especially vulnerable to seismic events. For many communities the consequences have been disastrous. Many hospital buildings have collapsed, leaving many victims among patients and staff. The losses in economic resources and technical and professional capabilities cannot be offset in the short term, and the political and social impact can endure for decades after the event.

This situation has occurred in all the cities located in seismically active areas. Yet, the perception of disasters is greater today than ever before, perhaps because until this century, seismic events caused general damage in cities, but hospitals did not exercise roles of particular importance. With the evolution of seismology and seismic-resistant engineering in the twentieth century, systems have been developed, often in the wake of great failures, that control damage and ensure a low likelihood of collapse.

The success of these developments has not had the desired impact, however. One important reason is that certain factors unrelated to safety, such as operational requirements, take precedence in the construction of health centers. In addition, the building codes normally used for hospital design and construction are the same as those used for office buildings and residences—a circumstance that ignores the different objectives that must be pursued. The basic criteria of the building code are usually the protection of life in a serious earthquake and the limitation of structural damage in areas where earthquakes are relatively frequent. The objective of a hospital, however, should not only be to survive a seismic event, but to remain in operation and be able to serve the needs of the affected community.

The repeated instances of severe damage in hospitals around the world have generated fatalism about their capacity to survive seismic events. However studies of positive and negative experiences, such as those conducted in Chile (Boroschek, et. al. 1996) and other countries, provide alternative ways of addressing the vulnerability of health facilities.

Hospitals with Low Vulnerability

In hospitals whose services are essential for meeting the demand generated by an earthquake, top priority should be given to maintaining an appropriate level of operational capacity and to protecting the lives of building occupants.

In addition, the high cost of the buildings and medical and other complex equipment found in hospitals should be kept to a minimum so that the system can return to normal in a reasonable amount of time.

Protecting the operations of a hospital requires consideration of both its organizational and physical aspects; the physical aspects can be broken down into structural and nonstructural elements.

The structural elements are what keeps the edifice standing. Examples include the foundations, walls, beams, and columns. Their principal function is to bear weight and shift it to the foundation.

The nonstructural elements are supported by the structural ones. They include partitions, windows, and false ceilings, and essential networks such as telecommunications, gas, water, and heating, and the contents of the building. The nonstructural elements can be classified as vital lines, architectural elements, or equipment. It is important to point out that not only should the internal elements of the structure be considered but all those that can affect hospital operations.

Economic and Functional Aspects of Nonstructural Damage in Hospitals

Advances in engineering have made it possible to reduce the risk of a structure's partial or total collapse. Nevertheless, economic losses from seismic events continue to be heavy. This is mainly because the costs of the structure account for only 10% to 15% of the total cost of a hospital. The economic losses, therefore, stem from nonstructural damage and the loss and recovery of services.

Two cases illustrate this point: In the United States, in the 1971 San Fernando earthquake, an evaluation of 25 commercial buildings indicated that structural damage represented 3% of the total costs of damage; electric and mechanical damage, 7%; damage to exterior finishings, 34%; and interior finishings, 56%. An evaluation of 50 tall buildings, which were far from the epicenter and thus subjected to a low level of movement, indicated that none incurred structural damage. However, 43 suffered damage to partitions; 18 had damaged elevators; 15, broken windows; and 8, damage to the air conditioning system (FEMA 1985). In the 1985 Mexico City earthquake two major hospitals suffered equipment losses amounting to US$ 640 million.

If nonstructural vulnerability is high, the probability of a hospital being put out of commission will be high as well. A dramatic example is the Olive View Hospital that was hit by the 1971 San Fernando earthquake. Three people died on that occasion; two patients died when life-support equipment failed, and another was killed when struck by a piece from the structure. All the emergency stairways collapsed, and all the ambulances were crushed by a falling ceiling. The hospital was repaired, and its structure was considerably reinforced. However, during the 1994 Northridge earthquake it was again forced to halt operations, this time because of nonstructural damage—broken water pipes in the cooling system and the fire extinguishing system, which caused flooding on several floors. Other examples include the earthquakes that struck Managua, Nicaragua in 1972 where the Baptista Hospital continued to operate until the water supply ran out. During the earthquake of July 1995, damages to the rooftop water tank of the hospital in Antofagasta left it unable to receive new patients and curtailed operations.

The list of poor responses to seismic events is a long one, but the effects of earthquakes on different hospital buildings at different times and places are similar. The disappointing responses are a function of the complexity of health facilities and the procedures and premises underlying their construction and subsequent maintenance.

The Causes of Nonstructural Damage

A hospital is a very complex facility. Some of the characteristics that contribute to its vulnerability are presented below:

- Activities: A wide range of work is performed in hospitals, combining the functions of hotels, offices, laboratories, and storerooms under one roof. Hospitals have large staffs made up of individuals with highly diverse functions and different educational backgrounds and interests; they therefore relate and communicate in different ways as well. This is not an easy staff to organize.

- Spatial Distribution: Because of its assorted functions, a hospital needs different sections with different basic characteristics: wards, operating and recovery rooms, and rooms for intermediate and intensive care, laboratories, outpatient care, an operating theater, a laundry, a food service, sterilization facilities, thermal plant, and many others.

- Occupants: Hospitals typically have large staffs with a variety of personnel—medical, paramedical, administrative, support, patients, and visitors—around the clock. A considerable number of patients have limited mobility and some are dependent on life support systems.

- Dependency: Hospital operations are dependant on access to outside services: utilities (such as electricity, water, and communications lines) and supplies.

- Physical Plant: The physical plant of a hospital can be divided into its architectural elements, equipment (medical, support, administrative, and industrial), supplies, furniture, and distribution or communications networks. Many parts of the physical plant contain hazardous materials.

The complexity of a hospital requires the internal organization of staff and the physical adaptation of structural and nonstructural elements in order for it to meet its operational objectives during and after a seismic event. The history of structural and nonstructural damage and operational shutdowns in health facilities indicates that this complexity is not being handled appropriately.

The current construction and maintenance processes of new health centers are at the heart of the problem. Although in order to reduce the vulnerability of a hospital it is necessary to analyze the facility as a whole, it is best to analyze the structural elements first, before proceeding to nonstructural and organizational aspects.

The aspects concerning structural vulnerability are discussed more extensively in Boroschek et al. (1996a, 1996b). As for the nonstructural aspects, the evidence indicates that seismic protection is rarely carried out because the procedures involved in building a new health center fail to take it into account. A large group of professionals usually participate in this process, coordinated by a medical and administrative board and a group of architects. In practice, the specialist in seismic aspects (if indeed there is one) works only on the protection of the structural system. Nonstructural aspects are left to professionals who are not specialists in this area, and specific responsibility for equipment and furniture is virtually left to the user. Thus, a system is created in which the basic structural design is ignored in the design, selection, location, and protection of the building's contents.

As a result, it is common to find hospital pipes crossing expansion joints between adjoining buildings, partitions between rooms without space left to accommodate movement in floors, and equipment and furniture without seismic protection.

An indication of the situation with respect to nonstructural elements in hospitals can be found in a study that assessed the physical vulnerability of the public health system in Chile (Boroschek et al., 1996a, 1996b).

Fourteen hospitals with a total of 1,245,956 m^2 of construction (53.6% in areas of high seismic activity and 46.4% in areas of moderate seismic activity) were evaluated in this study. In these hospitals, dating from 1930 to 1993, the inventory of critical medical equipment as of 1992 (Disal 1992) was valued at about US$ 160 million (with a distribution of 52% in areas of high seismic activity and 48% in areas of moderate seismic activity). The typical cost of new hospitals in Chile is around US$ 1,400 per square meter, with approximately 75% of this cost arising from nonstructural elements.

Despite the economic importance of nonstructural elements in the sector, 90% of all the structures evaluated had no protection for the equipment, 80% had no protection for the furniture, and 53% were vulnerable to breakage of glass and other architectural elements.

Aspects to Consider in the Evaluation of Nonstructural Vulnerability

It should be noted that in hospitals, as in other buildings, there is a close relationship between structural and nonstructural elements. For example, it is common to find architectural facades that substantially alter the anticipated structural behavior, shortening columns and creating unanticipated weaknesses in structural elements, or to find heavy machinery or water tanks on the upper floors of a structure that can substantially change the response characteristics of the system. This is why an evaluation of nonstructural vulnerability must take structural features into account, just as a structural evaluation must take nonstructural ones into account.

Nonstructural vulnerability studies must examine different complex features that are highly interrelated, so it is helpful to group them in a way that allows common methodologies to be applied. Table 1 presents some of the elements of each of these groups. This list can be modified in accordance with the characteristics of each system.

For evaluation purposes, it is necessary to consider direct seismic effects (inertial forces, velocities, displacements) and the influence or interaction of structural and nonstructural elements in each of the internal hospital systems in an earthquake.

In order to analyze nonstructural vulnerability and ascertain its relationship to the hospital's capacity to meet treatment needs, the typical activities performed in a hospital after a seismic emergency should be identified. This identification must also extend to each of the systems and subsystems within and around the hospital.

Table 2 presents a list of clinical and support services typically found in a hospital. Using this list and assigning priority to activities performed in response to an emergency will make it possible to select the services that should be analyzed in depth. Some of them are presented in Table 3 (Pacheco 1995). The evaluation of nonstructural vulnerability should consider all aspects that ultimately affect hospital operations, with special emphasis on the services identified as priorities.

In evaluating risk, it is necessary to identify equipment, systems, and hazardous elements. Each should be rated according to three main categories: risk to life, risk of loss, and risk of interruption in operations (Steward 1989). Each of these categories should be assigned indicators for its own vulnerability and for its impact on the overall vulnerability of the hospital.

In the category of risk to life it is useful to apply a hospital-related criterion such as the one developed by the United States Veterans Administration (VA 1976). In this classification, dangerous elements are those that produce debilitating injuries, substantially worsen the condition of a patient, or imperil hospital personnel. Thus, a minor cut from broken glass may be considered tolerable while a fracture or more serious cut would not be. A bedridden patient cannot follow the common recommendations for self-protection in seismic situations, such as hiding under furniture or strong structures to avoid getting hit by falling objects.

Evaluations of nonstructural vulnerability should involve qualitative and quantitative safety studies in each hospital and studies of the effects of earthquakes on the operations and vulnerability of the hospital as a whole. Table 4 presents the aspects to be considered in these studies.

It should be noted that this classification of nonstructural elements considers only systems that have a negligible effect on the behavior of the supporting structure. For example, equipment should have a weight no greater than 20% of the weight of the floor on which it rests or 10% of the total weight of the structure, nor should it alter the rigidity and resistance of the structure. Otherwise, the equipment should be considered in the analysis of the structure as a whole.

Architectural elements such as partitions, facades, and lights should be evaluated in terms of the functional and physical consequences of their failure. Typical failures occur as a result of the connections selected, the amount of space between elements, the fragility of the structure, and the stress they must withstand. The failure of these elements can be classified in three broad groups: damage, detachment, and changes in the response of structural and nonstructural elements.

A number of procedures can be used to evaluate the risk of these systems. These usually establish the relationship between the anticipated deformation and the inertial forces to which the architectural element will be subjected and its ability to withstand this stress. The large number and diversity of architectural elements require the formulation of very general recommendations. Thus, the rating procedures presented below will help in conducting a proper evaluation.

For the evaluation and estimate of the risk in equipment and vital lines it is useful first to classify the systems according to their importance. One of the most accepted classifications is the one established by McGavin, (McGavin 1981), which is broken down into the following five categories:

A) Critical: The systems, subsystems (or equipment) needed to operate the main system or life support systems, or whose failure can directly or adversely affect the operation of another system or critical piece of equipment.

B) Support. The systems, subsystems (or equipment) required to support basic functions. The unit that depends on this system can work in a limited fashion in the event of a failure.

C) Support: The systems, subsystems (or equipment) required for long-term hospital operations.

D) Support. All portable systems and subsystems (or equipment) not included under A.

E) Miscellaneous: Miscellaneous systems, subsystems (or equipment).

Another classification is the one presented by Watabe (1989):

Hazardous: Equipment that can injure patients or medical personnel.

Emergency: Equipment that can have a critical impact on medical operations and which cannot be immediately replaced.

Functional: Equipment similar to that classified as "Emergency" but which can be immediately replaced.

Chaos: Equipment that can create confusion in the surrounding area.

Systems are usually composed of subsystems (or equipment). Their classification is therefore a composite one in which the system and each of its component subsystems are classified.

Once the systems and subsystems have been identified and classified, they must be rated for vulnerability. The possible criteria depend on factors such as:

- Function
- Demand
- Design characteristics
- Useful life
- Previous experience
- Proximity and relationship of the system to other systems.

These factors make it possible to establish how in-depth these studies should be. The procedures for rating vulnerability can be grouped in the following way:

- Previous Experience: Risk in isolation under current conditions is evaluated on the basis of experience with similar elements in previous seismic events. In these cases, particular care is required in evaluating the condition of equipment in terms of the seismic stress and the seismic response of the structure in which it was housed at the time of the previous event. Thus, a piece of hospital equipment located on a lower floor should not be evaluated in the same way as equipment on an upper floor. Although the same equipment may be used in both locations and the equipment on the lower floor responded well in the past, it may not necessarily do so in other locations within the structure where the movement characteristics are different.

- Mathematical analysis: Mathematical models should be developed that take into account the equipment, its components, and the conditions for support and attachment to the supporting structure. Static or dynamic analysis can be used depending on the complexity of the system; likewise, simple coefficients, the response spectra, linear or non-linear analyses can be applied at each point. For these types of analyses information is needed on the physical characteristics of the element or equipment (e.g., distribution of mass, rigidity, energy dissipation capacity, internal couplings, and internal elements).

- Laboratory tests: when there is inadequate knowledge about the physical properties of complex equipment or elements in general or when mathematical models are very limited, laboratory tests can be carried out. They may be simple (e.g., estimates of the likelihood of objects overturning or of static slippage) or complex (e.g., tests on a vibrating table or pressure frame).

- Group of Experts: All the above procedures should be carried out by a group of experts. However, it is useful to recognize that economic or physical constraints often will not allow these procedures to be adequately performed. In such cases, a good criterion developed by a group of experts who can apply several experiences to one particular situation may be the only alternative for estimating risk.

Once the vulnerability of a component is established, an estimate of its overall impact on the hospital in terms of operational, physical, and economic aspects should be made.

It should be remembered that damages not only have an immediate effect by limiting service delivery but also represent considerable economic losses that, in terms of typical economic constraints, undercut the ability of the health sector to recover rapidly and reestablish normal levels of service. It is not unusual to find cases in which hospitals continue to suffer the effects of an earthquake several years after its occurrence.

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Table 1. Nonstructural Elements to Consider in the Evaluation of Vulnerability

ARCHITECTURAL	EQUIPMENT	VITAL LINES
· Divisions and Interior partitions · Facades · False Ceilings · Panelings · Cornices · Terraces · Railings · Chimneys · Overlapping surfaces · Glass panes . Attachments (signs, etc.) . Ceilings . Antennas	· Medical Equipment · Industrial Equipment · Office Equipment · Furniture · Contents · Supplies	· Medical Gases · Industrial Gas · Electricity · Telecommunications · Vacuum · Drinking Water · Industrial Water · Air Conditioning · Steam . Pipes in General

Table 2. List of Clinical and Support Services

SERVICE	SERVICE
Internal Medicine	Pharmacy
Pneumology	Food
Medicine	Transport
Surgery	Laundry
Traumatology	Administration
Pediatric Surgery	Wards
Plastic Surgery for Burn Victims	Miscellaneous Hospital Services
Traumatology and Orthopedics	Sonography
Pediatrics	Pathology
Obstetrics and Gynecology	Kinesitherapy
Intensive Care	Endoscopy
Dermatology	Polyclinic Wing
Child Neurology	Nuclear Medicine
Psychiatry	Industrial Equipment
Ophthalmology	Administration
Oncology	Neonatology
Otorhinolaryngology	Dialysis
Urology	Recovery Rooms
Adult Emergencies	Blood Bank
Pediatric Emergencies	Boilers
Laboratory	Water Tanks
Sterilization	Oxygen
Dental	Gas Installations
Imaging	Records

Table 3. Priority Services in Seismic Emergencies

Medical
Recovery rooms
Surgical wings
Intensive care units
Intermediate care units
Emergency
Laboratories
Blood bank
Imaging
Dialysis
Sterilization
Pharmacy
SUPPORT
Storerooms
Boilers and thermal plant
Laundry
Food Service
Records
Gas Installation
Ambulances
Communications

Table 4: Nonstructural Aspects to Consider in Evaluating Vulnerability

NONSTRUCTURAL		
ARCHITECTURAL	**EQUIPMENT**	**VITAL LINES**
Interaction	Interaction	Location
Importance	Importance	Importance
Material	Size	Dependency
Coupling-Support	Coupling-Support	Capacity
Resistance	Dependency	Material
Rigidity	Form	Interaction
Ductility	Proportion	Resistance
Condition	Position	Danger
	Contents	Coupling-Support
	Danger	Condition
	Condition	